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A SELF-CONTAINED DIVER OPERATED  
CONDUCTIVITY/RESISTIVITY PROBE(U) NAVAL OCEAN RESEARCH  
AND DEVELOPMENT ACTIVITY NSTL STATION MS  
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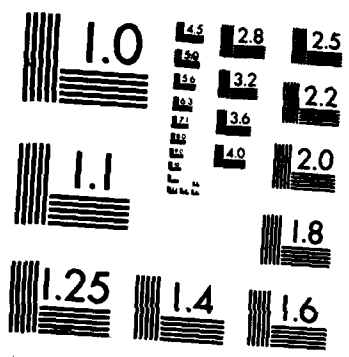
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### A SELF-CONTAINED DIVER OPERATED CONDUCTIVITY/RESISTIVITY PROBE

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#### ABSTRACT

A self-contained, diver-operated conductivity probe was designed to measure directly seafloor conductivity or resistivity, temperature and depth of sensor embedment. Geotechnical/geoacoustic properties derived indirectly from the resistivity probe data include sediment porosity, wet bulk density and sediment property variability.

The conductivity probe system includes a power source, signal generator, differential pressure transducer, signal conditioners, A/D converter, nonvolatile semiconductor memory and control logic. All the electronics are housed in two commercially available plastic underwater camera cases pressure tested to 500 kPa.

The system, selected to achieve measurement goals, is based on the four-electrode contact technique. The sensor head, which contains the four protruding electrodes and a thermistor bead, is wedge-shaped to aid embedment and to minimize sediment disturbance. It is cast from a non-conducting epoxy material.

An alternating current limited to 200 ma at 100 Hz is generated from a lithium power source and applied to the outer current electrodes. The resulting electrical potential is then measured on the two inner electrodes. Both the output and input data and the temperature and pressure measuring systems data are converted from analog and stored in digital memory. The system's memory is capable of storing approximately 600 data sets before it is necessary to dump the data into a shipboard mini-computer for final processing, reduction, and plotting.

#### INTRODUCTION

This paper describes the development and function of a small, diver-held, easy-to-use electrical conductivity probe developed to support Navy shallow water environmental surveys. The electrical conductivities measured by this system can be

converted to reliable estimates of sediment porosity and density. Sediment property variability is obtained to a precision of  $\pm 2\%$  of the measured value with a vertical resolution of 20 mm. These parameters are being used to study sedimentary diagenesis, consolidation history, shear strength variation, and sound transmission and attenuation in the sea floor. The probe is particularly useful for obtaining the in situ porosity and density of sands and silts, where the porosities and densities measured on cores are altered in the coring process.

#### CONDUCTIVITY MEASUREMENT TECHNIQUES

The three techniques for measuring electrical conductivity of marine sediments are: the two electrode, the four electrode and the inductive technique.

#### Direct Techniques

The simplest technique is the two electrode where a known direct-current (DC) is applied to a pair of electrodes having a known separation in the sediment. The resulting electric potential between the electrodes is measured. Application of Ohm's Law yields the apparent resistance of the sediment from which the apparent resistivity and the apparent conductivity can be calculated. The two-electrode, direct-current technique has the advantage of requiring a minimum of apparatus and it is therefore cheap and quick to implement. It suffers from two severe drawbacks: (1) in addition to the electrical resistance of the sediment itself, there is a contribution to the apparent resistivity due to electrochemical, or polarization, resistance, and (2) the current density in the near vicinity of each of the electrodes is very high so that contact resistance at the electrodes can be a major contributor to the apparent resistivity. The contribution to the resistance resulting from

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electrochemical reactions can be minimized by using alternating current rather than direct current with an accompanying slight increase in cost and complexity. The effect of contact resistance can be minimized by using two pairs of electrodes, one for applying a known current and the other for measuring the resulting electrical potential [1]. In marine environments, i.e., seawater pore fluid, the potentials to be measured for both the two-electrode and four-electrode techniques are quite small; therefore, sensitive electronic instrumentation (most of which is commercially available) is required to detect the signal and discriminate against noise. In addition, embedment of the electrodes is difficult, especially in sandy sediments, because: (1) firm electrode contact with the sediment must be maintained; (2) free communication with the overlying, highly conductive seawater must be avoided; and (3) electrode arrays are often of fragile design to satisfy functional criteria. The arrays must be designed with electrode spacing less than 40% of desired resolution, and the electrodes must be of small diameter to minimize sediment disturbance.

#### Remote Techniques

The probe problems with direct measurement techniques are eliminated by using an inductive technique; but, for the complex device required, development time is long and cost is high [2]. Inductive techniques rely upon detection of the secondary electromagnetic field established in conductive materials by an applied electromagnetic field. The field to be applied is produced by an alternating current flowing in a loop or coil of wire; no physical contact is required between the material being studied and either the primary (transmitter) coil or the secondary (receiver) coil.

#### Technique Selected

The four electrode technique was chosen for the diver-held conductivity probe system. The design of a self-contained system which is easily controlled by a diver presented several problems. First of all, the system had to be miniaturized both in the electronics housing and in the probe tip design, so that underwater handling and embedment into the sea floor would be relatively easy. The limited mobility, manual dexterity and visibility of the diver-operator demanded that the measuring system, signal conditioning, analog to digital conversion and data storage be automatic. The device needed required that the diver trigger an on-off switch to begin a measuring sequence, and that he be audibly signalled that the measurement sequence is complete. Then, the diver need only be cognizant of the instrument embedment in the sea floor.

### PHYSICAL SYSTEM

#### Electronics Cases

The conductivity probe is made up of two major components: the electronics cases and the probe tip. The electronics cases are two polycarbonate and acrylic plastic underwater camera cases (Fig. 1). These cases are rated for 91 m water depth (900 kPa); however, during pressure testing, the larger case failed at approximately 275 kPa due to O-ring extrusion at a poorly manufactured lid fit. This problem was corrected by using an oversized O-ring.

With the larger O-ring, both cases were successfully pressure tested to 500 kPa (61 m of water).

Initially we had planned to house all of the electronics in one pressure case. However, the final size and complexity of the electronics system dictated the use of a second smaller plastic case to house a differential pressure transducer and the lithium power source. The larger case housed the electronic control circuitry, digital memory and a power supply. Electrical connections between the two boxes were run in stainless steel tubing and high pressure fittings. This tubing interconnection also served as a carrying handle (Fig. 1). Four other penetrations of the pressure cases were required: two were used for the positive and negative ports of the pressure transducer, one was used for the on-off control switch and one was used to run the four wires from the electrodes into the pressure case. All of these penetrations used commercially available high pressure fittings and/or O-ring bulkhead fittings to make water-tight seals.

#### Probe Tip

The conductivity probe tip is 56 mm wide by 16 mm thick and wedge-shaped to ease embedment and to reduce sample disturbance (Fig. 2). It was cast out of 3M Scotchcast<sub>R</sub> brand electrical resin (Scotchcast<sub>R</sub> is a registered trademark of 3M Corporation) in a machined four piece acrylic mold. The potting compound used has a low exothermic heat rise during cure, a high volume resistivity, low moisture absorption, high compressive, tensile and flexural strength and a hardness of 70 (Shore D). The resin is easy to cast because it has a low casting viscosity and long gel and cure times at room temperature. Two small stainless steel bearing plates were cast into the probe tip to facilitate soldering of the tip to the stainless steel probe shaft. These plates also strengthen the probe tip to help it withstand the severe punishment anticipated during embedment in sand.

The four electrodes protrude 13 mm (0.5 in.) in front of the wedge leading edge (Fig. 2). Rather than spacing the electrodes at equal spacing as in a Wenner Spread [3], the electrodes were spaced unevenly to increase the sensitivity of the probe by flattening the electrical field in front of the probe tip. The outer two electrodes were separated from the two inner electrodes by 6 mm (0.25 in.) while the two inner electrodes were separated from each other by 25 mm (1.0 in.) (Fig. 2). The electrodes were made of AL<sub>R</sub> 29-4 stainless steel wire (AL<sub>R</sub> is a registered trademark of Allegheny Ludlum Steel Corporation) 1.6 mm (0.062 in.) diameter machined to a 45° cone at the leading point. This low interstitial ferritic stainless steel was chosen for its excellent resistance to pitting and crevice corrosion in salt water environments. The wedge-shaped probe tip was cast around the electrodes along with an insulating sleeve for each electrode; only the steel of the 45° machined electrode tip made direct contact with the seawater or sediment. During tests the inner potential measuring electrodes held-up very well with no oxidation detected. However, the outer, current-carrying electrodes exhibited a dark oxidation coating on the surface after several minutes of exposure to the seawater with current flowing through them. In this particular application, the oxidation of these

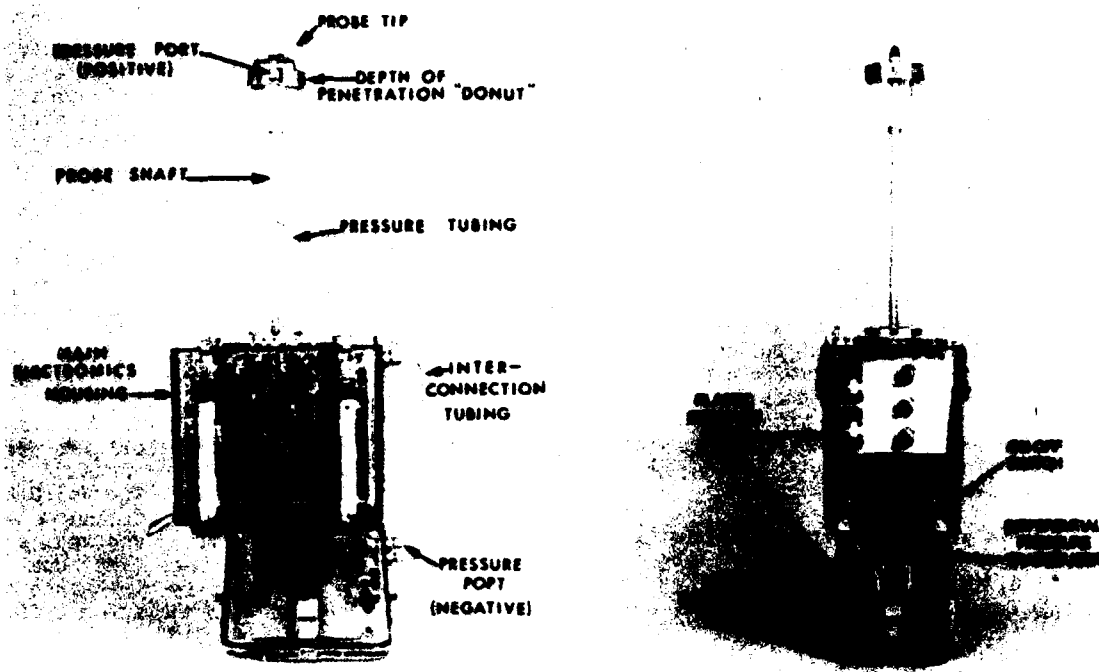


FIG. 1 FRONT AND SIDE VIEWS OF CONDUCTIVITY/RESISTIVITY PROBE SYSTEM

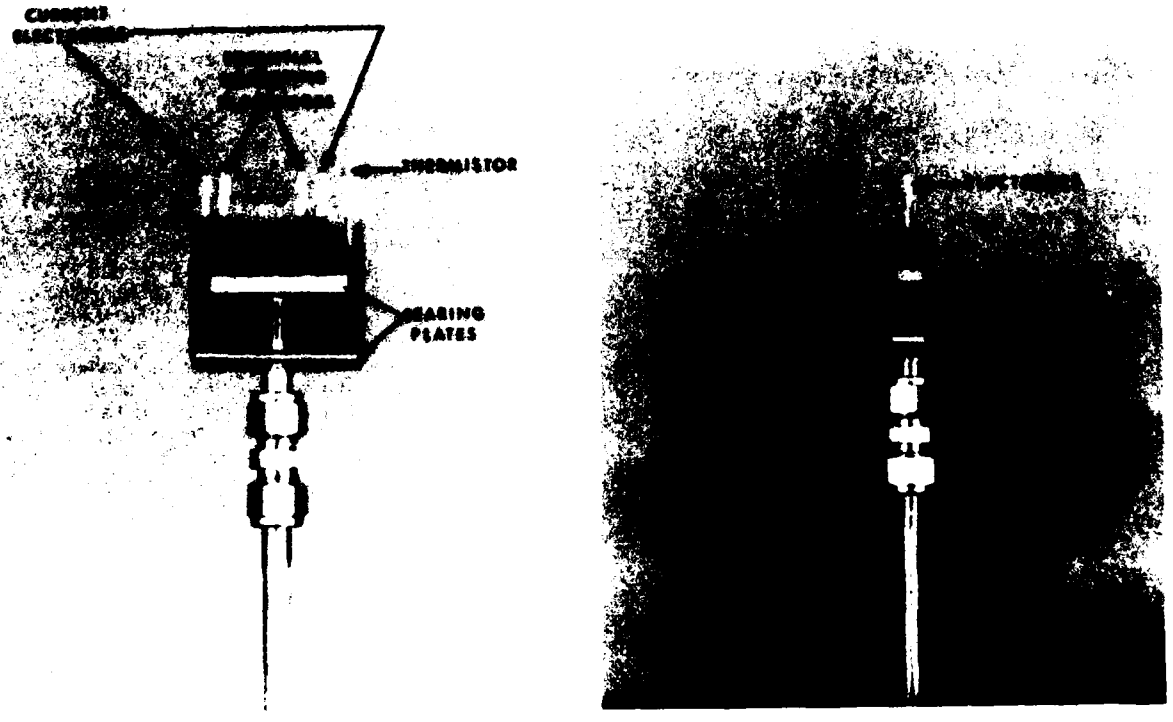


FIG. 2 FRONT AND SIDE VIEWS OF PROBE TIP

electrodes was of little consequence because the probe was calibrated prior to each probe embedment by making a conductivity measurement of the water column.

A 1.6 mm (0.0625 in.), epoxy-encapsulated, dual thermistor bead was potted at the same forward projection as the electrodes and 9.5 mm (0.38 in.) on centers outside one of the outer electrodes. It was used to continually monitor the ambient temperature at the electrode location.

The probe tip was connected to the bottom of the electronics case using a 9.5 mm (0.375 in.) OD, heavy wall (2 mm thick) stainless steel tube approximately 460 mm (18 in.) long (Fig. 1). The connection to the probe tip was an off-the-shelf high pressure fitting and the connection to the electronics case included a flange welded to the top end of the tube and bolted to the electronics case with an O-ring providing a water tight seal. The shaft can be made longer to reach greater penetrations in soft sediments.

The conductivity probe provides continual monitoring of depth of penetration into the sea floor using a 6.9 kPa (0.8 psi) differential pressure transducer. The reference (negative) port of the transducer was vented to the water column through the side of the upper electronics housing. The positive port of the transducer was connected via a short length of oil filled flexible plastic pressure tubing to a plastic sliding "donut" mechanism which rests on the seafloor surface. As the probe tip is inserted into the bottom, the positive and negative port of the transducer move closer together thus changing the reading on the transducer.

## ELECTRONICS SYSTEM

### Overall Design and Logic

The probe electronics is basically a multi-channel data acquisition system with 2.5K of 12 bit word non-volatile digital memory. A spare memory board pair was built to double the measurement capacity. CMOS logic was used for both analog and digital circuitry wherever possible. The power required for the 30 CMOS Non-Volatile Random Access Memory (NOVRAM) chips and the power required to excite the sediment to measurable levels made lithium batteries the necessary selection. High quality precision instrumentation amplifiers were used in all signal conditioning circuitry to ensure accuracy and repeatability of measurement. A diagram of the electronics system is shown in Figure 3.

### Power

Power is provided by an 11.8 v lithium thionyl chloride battery pack composed of three, series-connected, double D cells. Each cell is internally wired with a 4 a fuse and the pack has two 34°C thermal fuses attached to limit temperatures, and thus prevent cell venting. The power supply provides regulated 5 v for logic functions and two  $\pm 15$  v sources, one for the probe driver and the other for the remaining analog circuitry. Battery pack voltage is continuously sampled and power fail logic will move all data to permanent storage when the battery pack voltage falls below 7.5 volts. Battery pack life is four to five hours of continuous use.

### Signal Generator/Probe Driver

Sediment excitation is provided by a buffered, short circuit proof operational amplifier, and a 100 Hz sine wave generator. The amplifier gain is adjusted to provide 200 ma of sine wave current continuously to the probe exciter tips when placed into a short circuit. Output current is sampled by a high precision ( $\pm 0.01\%$ ) resistor.

### Signal Conditioner

The 100 Hz voltage developed across the precision resistor in the probe driver circuitry is sampled by a precision instrumentation amplifier. This voltage is converted to DC, buffered and applied to the input of the multiplexer. The potential developed in the sediment by the excitation electrodes is sampled by the two inner probe electrodes and input to a precision instrumentation amplifier. The amplified sediment potential is converted to DC, buffered and then applied to the multiplexer. The voltage output of the differential pressure transducer measuring probe penetration is amplified and applied to the multiplexer for processing. The dual element thermistor in the probe tip is wired into a budget circuit arrangement and referenced by a buffered high stability voltage reference. Bridge output is amplified and applied to the multiplexer for processing.

### A/D Converter

The four measured parameters (i.e., applied voltage, measured voltage, probe penetration [differential pressure], and tip temperature) are fed to an eight channel 12 bit CMOS A/D converter. All multiplexing and sample/hold functions are built into the connector chip. The four disabled channels are available for expansion. The output data format is complementary offset binary and is placed on the data bus via tri-state buffering.

### Digital Memory

The digital memory is a three by ten array of Non-Volatile Random Access Memory (NOVRAM) integrated circuits (IC). Each IC is arranged in a 4-bit by 256 word format which yields a capacity of 2560 12 bit words. Each block of 256 words is moved into permanent storage as soon as enough measurements have been taken to fill the block. This is accomplished by initiating a write command and setting a failsafe latch which prevents any further change to that block of memory. Data may be clocked back to Random Access Memory (RAM) and placed on the data bus for output to an HP-85 computer. A simple read command from an external computer will produce a 12 bit data word and a ready flag. Output addressing and timing are accomplished by the measurement control circuitry.

### Measurement Control Circuitry

The diver's measurement on-off switch initiates the measurement cycle. Output potential, induced sediment potential, penetration depth, and temperature are measured in fourteen sets at five second intervals. A set of three light-emitting diodes indicate to the diver when measurements are being made, and a piezoelectric transducer emits an audible tone when the fourteen measurement sets have



The sand samples were first rinsed with fresh water to remove salt residue and then oven dried. The sand was then placed in six liter graduated beakers and saturated with 35 o/oo seawater. The density of the sand was varied from loosely packed to densely packed by vibrating and mechanically compacting the saturated sample. The porosity of the sample, determined volumetrically by knowing the volume of sand in the beaker and the amount of seawater used to saturate the sample, averaged 40.8% with a range of less than 1% in four trials.

The apparent resistivity of the 35 o/oo seawater and the seawater and sand mixture then were measured, using the conductivity probe, in order to determine a formation factor. The definition of the formation resistivity factor or Formation Factor (F) as defined by Archie [5] is:

$$F = R_s/R_w \dots \dots \dots (1)$$

where  $R_s$  is the resistivity of the formation (sediment) 100 % saturated with water of resistivity  $R_w$ . Archie also empirically determined an equation relating F to the porosity:

$$F = n^{-m} \dots \dots \dots (2)$$

where n is the fractional porosity and m is the exponent relating F and n and is usually called the shape factor. Further investigation of this relationship by Dakhnov [6] indicated that Archie's formula should be modified to:

$$F = an^{-m} \dots \dots \dots (3)$$

where "a" is not always unity, but is a factor of proportionality which accounts for the clay/silt to sand ratio of a particular sediment.

A formation factor of 3.669 was determined with the conductivity probe for the Panama City sands. These sands have a mean grain size between 2.4 and 2.7φ (fine sand) in the upper 180 mm of the sediment column and are composed of angular to subangular quartz grains with a biogenic calcium carbonate component of 10 to 15%.

Erchul [7] reported coefficients for Equation (3) in 13 sediment types and found that for sands "a" ranges between 1.4 and 1.6 and "m" ranges between 1.0 and 1.1. In general, these coefficients corresponded to porosity values of between 26 and 47% and formation factors between 3.1 and 5.7. In the present study, values of 1.5 and 1.0 for the coefficients "a" and "m" respectively correspond to a formation factor of 3.669 and porosity value of 40.8%. These coefficients corresponded well with Erchul's findings and were used to calculate porosity from resistivity values of the water column and the sediment using the following formula:

$$F = R_s/R_w = 1.5 \times n^{-1.0} \dots \dots (4)$$

## FIELD TESTS AND RESULTS

The conductivity probe was used successfully during two trial dives in the Panama City test area in the fall of 1984. During these dives the instrument was set-up to take 14 sequential resistivity, temperature, and depth of penetration readings, 10 seconds apart. After the 14th reading, the instrument sounded an audible alarm to inform the diver that the series of measurements was complete. During the measuring sequence, a red light in the upper electronics housing signaled the diver that a measurement series was being taken. After each set of 14 measurements the instrument reverted to a ready status waiting for the diver to initiate a new sequence by switching the instrument to "start". After taking two to three initial measurement series in the water column at each station, the diver gradually pushed the probe into the seafloor sediment. Normally the diver attempted to take two to three measurement series in the sediment at each level of insertion. Because of the dense fine sand at the offshore Panama City site, maximum depth of embedment of the probe tip was limited to about 100 mm (4 in.).

The embedment depth measuring system gave inconsistent results that often appeared erroneous. Therefore, accurate records of the depth of each porosity measurement are not available, although it can be assumed that all results were taken within the range of 30 to 100 mm of the sediment surface.

During the first dive, the probe was used to make eight test borings in the sediments at Stations 68 and 69 at the same geographical site. These data are presented in the upper portion of Table 1. Measured porosity values are given as a function of relative depth, although each depth in a boring does not necessarily correspond to the same real depth in another boring. It should be noted that the porosity values listed are averages of two to three readings at each depth interval. However, the individual values measured at a given depth interval normally varied by only a few tenths of a percent. Laboratory determined porosity values from diver-collected "push" cores are shown in the lower portion of Table 1. These two data sets compare very well, particularly if only the core data between 30 and 110 mm are considered. The porosity values in boring number 8 appear low in the last four measurements, but these low readings may result from a concentration of shell material in the sediment.

At Station 73, the diver took measurements both: (1) at increasingly deeper elevations at one location, or "boring", to determine vertical variability, and (2) at several points along a trackline, "pogo" method, to determine near-surface, horizontal variability. Data from both measurement techniques are given in Table 2. The first three columns of data were collected in increasing depth increments between 30 and 100 mm. The last five columns of data were collected using the "pogo" method and should be considered near surface (30 - 50 mm deep) values. For comparison, laboratory measurements were made on two diver-collected cores from the same site and also are given in Table 2.

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TABLE 1. Porosities Measured at Station 68 and 69  
Conductivity Probe Data  
Porosity (%)  
Probe Boring Number

Relative Depth	1	2	3	4	5	6	7	8
1	41.5	40.8	40.4	40.0	38.8	38.1	40.8	39.9
2	40.3	40.2	40.6	40.8	39.6	36.4	38.8	37.6
3	41.1	39.3	39.1	40.6	37.5	36.5		34.8
4	41.9	38.4	39.1	38.3				35.6
5	41.1	41.0	37.6	36.8	37.5	36.5		33.8
6								33.1

Diver Collected Cores  
Porosity (%)

Depth in Sediment (mm)	Core PC 68-1	Core PC 68-2	Core PC 69-1	Core PC 69-2
10	42.3	41.0	41.0	41.7
30	40.1	40.4	39.7	39.2
50	38.3	39.5	38.4	37.9
70	38.6	39.2	38.2	38.1
* 90	38.7	38.9	39.0	39.1
110	38.3	38.6	39.0	38.8
130	37.8	38.6	38.3	38.6
150	37.5	38.8	39.5	38.6
170	36.9	38.5	38.6	38.2
190	34.6	38.2	36.4	37.6
210		35.8		34.8

\* Maximum embedment of probe.

TABLE 2. Porosities Measured at Station 73.  
Conductivity Probe Data  
Porosity (%)

Relative Depth	Probe Boring No.			Single Point Trackline Readings				
	1	2	3	[-----]				
1	40.1	39.6	39.4	41.0	43.0	38.9	39.0	33.4**
2	40.0	36.6	36.5	41.1	39.6	40.0	36.7	36.3
3	38.1	38.5	37.4	40.2	40.3*	38.8	34.8	34.6
4	39.7	37.9	37.9	37.4	41.5	39.9	36.0	37.3
5	40.9	39.8	36.0	42.2	42.5	38.8	37.6	37.7
6	39.8	39.2	36.0	39.7	38.1	35.0	37.4	35.1
7	40.6	35.9	33.2	38.7	39.0	37.3	38.3	37.0
8	38.1	35.7	34.2	24.4	44.5	38.9	35.9	35.3
9		33.4	35.6	37.0	37.0	40.0	37.3	35.4
10		32.5	39.7	32.5	35.6	40.1	37.0	35.7
				35.8	36.5		39.9	
					35.2		39.2	

Table 2 (cont)  
Diver Collected Cores  
Porosity (%)

Depth in Sediment (mm)	Core PC 73-1	Core PC 73-2	
10	42.2	40.2	Notes: *measurement taken in biogenic mound
30	40.5	38.9	
50	38.7	38.2	
70	38.5	38.0	
90	37.7	38.6	
***			**measurement taken in biogenic depression
110	38.1	37.9	***maximum embedment of probe
130	38.8	37.7	
150	38.3	38.1	
170	36.7	37.5	
190		37.2	
210		37.1	

Again, the conductivity probe data correlate well with the laboratory data from push cores, although slightly greater variation appears to exist in the probe data. This variation may be a function of the relative sample size between the two methods. The core measurements were made over 20 mm intervals, thus averaging-out small variability. The conductivity probe is believed to measure over a vertical field somewhat less than 20 mm. In other words, small amounts of shell material or individual shells will have a stronger influence on the conductivity probe porosities than on the laboratory porosities determined from the push cores.

Please note, the in situ porosities measured by the conductivity probe have been compared here to laboratory porosities measured on push core samples. This comparison is not meant to imply that the porosities measured on the cores are any more reliable; in fact, given proper calibration the conductivity probe data are expected to be the more reliable. The corer tube insertion and transportation vibrations are expected to cause more disturbance to sand and silt sediments than embedment of the conductivity probe head; thus, in theory, the conductivity probe should yield the better quality data. Further development is required to verify this thesis.

#### CONCLUSIONS AND RECOMMENDATIONS

The diver-operated conductivity probe worked very well during its initial field tests and met all measurement goals. The electronics system functioned flawlessly during the dives. However, there is room for some improvement in the physical aspects of the probe system, as follows:

1) The complete electronics package should be housed in one stainless steel pressure case. This would make the system more compact and may eliminate the need for adding lead ballast to the case to make its buoyancy slightly negative.

2) The electrodes, particularly the current electrodes, should be made of a material with a lower oxidation potential - possibly gold or platinum alloy. If oxidation of the electrodes is slowly occurring during use of the probe, its calibration also is changing slowly. During the present study,

this change was not a problem as the instrument was essentially recalibrated in the water column prior to each set of measurements. Using the instrument in sand also tends to remove the oxidation from the electrodes. However, if the probe in its present form (stainless steel electrodes) were to be used in a mud environment, the oxidation build-up might cause erroneous measurements.

3) During a third attempted dive at Panama City, rough handling by the divers and the hard sand environment wore-away the protective epoxy coating over the thermistor bead. When this coating failed, the thermistor shorted-out thus halting temperature measurements. At the same time, resistivity measurements were stopped by the electronics system when it detected erroneous temperature data. To better protect the thermistor bead, the forward projection of the thermistor should be reduced and an additional coat of thermally conducting epoxy should be applied.

4) The differential pressure transducer for measuring the depth of embedment did not function properly. However, the concept shows promise and needs to be perfected.

5) The data acquisition and storage portion of the electronics package shows promise as a more universal system: It can be used for data collection with numerous other in situ probes. Some hardware changes will have to be made to accomplish this. If a microprocessor were added to the system, such changes to the system could be made with software at sea in a matter of minutes.

6) The use of lithium batteries in the instrument gave it a dependable and durable power source. However, the lithium batteries are relatively expensive, and are potentially volatile in transportation and disposal. Rechargeable nickel-cadmium battery packs are expected to be adequate to operate the instrument without the potential hazards associated with the lithium batteries.

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