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Conductivity Measurements of Submarine Sediments

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An *in-situ* four-electrode contact resistivity probe system was designed, and field-tested in submarine sediments. Seismic survey was also performed to support and compare the results of electric survey. The probe was designed to be driven to selected depths below the seafloor using a Vibracore system. The four insulated electrodes were, spaced equidistant across the wedge, were extended beyond the probe tip to minimize effects of sediment disturbance by the wedge insertion. *In-situ* measurements of resistivity were recorded on board by precision electronic equipment consisting of signal generators and processors, and by temperature-monitoring systems. Overall limits of uncertainty at respective depths below the seafloor are up to ±10 of the measured values. Best estimates of conductivity are considered to be ±3 percent of the reported values. Resistivity measurements were made at six sites in carbonate sediments to a maximum depth of penetration of about 5 m. Average values of conductivity range between 0.88 and 1.21 mho/m. The results show the seabed is composed of alternating layers of relatively high-conductivity material (0.8 to 1.4 mho/m) in thicknesses of more or less one meter and layers about 30 cm thick having relatively low conductivities (0.4 to 0.8 mho/m).

INTRODUCTION

The electrical conductivity is one of the necessary parameters to develop an understanding of the detailed electrical properties of the seabed. The purpose of this study is to measure electrical resistivity/conductivity in unconsolidated marine sediments with accuracy of ±10 percent and a vertical resolution of 0.3 m, which presents a challenge despite the long history of electrical resistivity measurements in geophysical survey.

An *in-situ* system capable of obtaining conductivities of surficial sediments is expected to provide critical data leading to the determination of porosity and wet bulk density of sediments, and electrical properties of seabed sediments itself. The determination of the geotechnical properties of undisturbed, noncohesive sediments is an area of much-needed research. Density and porosity data are fundamental information required in the study of sedimentary diagenesis, pore fluid migration, and consolidation history, and in numerous engineering applications (Shon, 1995; Shon *et al.*, 2000a).

Resistivity measurements have a long history in geophysical survey for petroleum and other mineral resources (Pirson, 1963; Wyllie, 1963; Griffiths and King, 1965; Keller and Frischknecht, 1966; Parkhomenko, 1967; Ginzburg, 1974; Dobrin *et al.*, 1988; Shon *et al.*, 2000b). Despite this successful use in land, the measurement of electrical conductivity in unconsolidated submarine sediments to the desired accuracy of ±10% with a vertical resolution of approximately 30 cm, presents a challenge (Kermabon *et al.*, 1969; Sweet, 1972; Erchul, 1974; Jackson, 1975).

GEOLOGY OF THE STUDY AREA

The study area is located on the continental shelf off Fort Lauderdale in Florida, USA (Fig. 1a). The narrow Florida shelf (approximately 2.8 km) is bounded by the shoreline to the west and generally the 21 m-bathymetric contour to the east. The seafloor gradient then steepens down to the Miami Ter-

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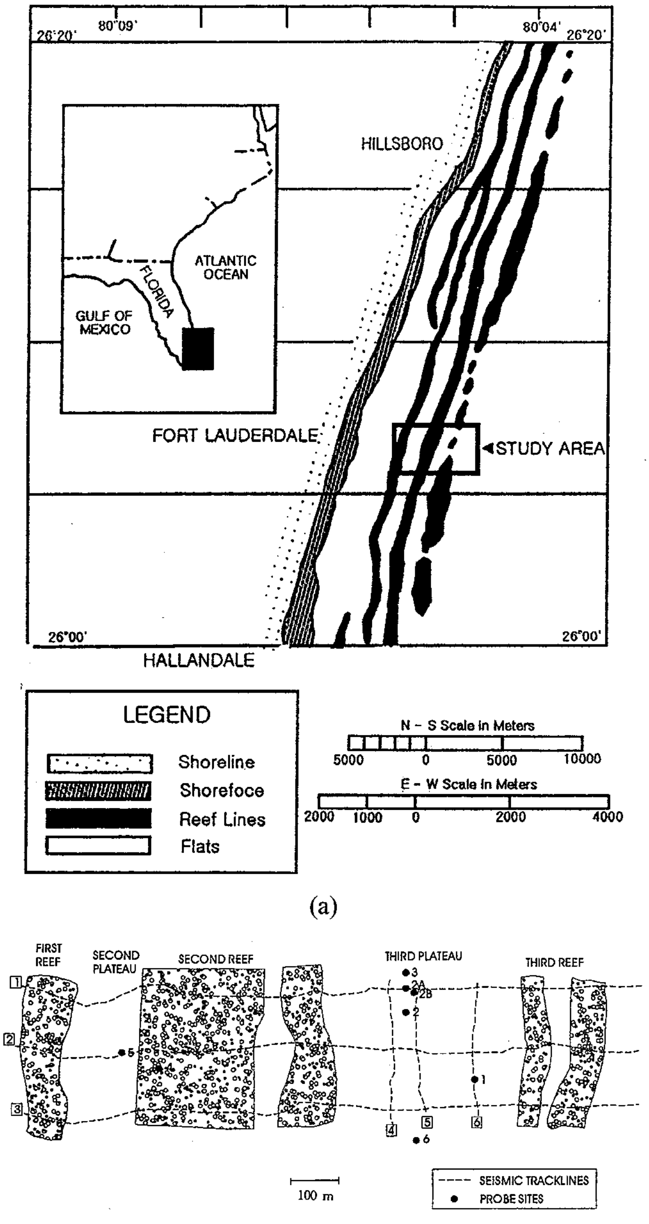


Fig. 1. Map of study area. (a) Southeastern Florida shelf morphology, (b) location of the seismic tracklines and resistivity probe sites in the study area.

race in water depths from 220 to 366 m. The shelf in this area is characterized by a series of three reef ridges running north-south parallel to the shoreline (Fig. 1a). These ridges form highs between a series of plateaus. The reefs are composed of hard substrate, and the lows are depressions filled with white to gray unconsolidated calcareous sands and gravels.

The outer reef is a relic barrier reef that flourished during the early Holocene transgression. This shallow-water, early-Holocene barrier reef has been highly altered and masked by a lithified crust (Lighty *et al.*, 1978). The reef crest is highly irregular at a depth of approximately 15 m and has a relief of 3 to 5 m.

The middle reef is a linear, continuous substrate with an irregular surface averaging approximately 12 m below sea level. The maximum reef thickness is 2.4 m. It is composed of extremely hard, gray "reef rock" indurated by extensive alteration and infilling of massive coral heads that are now nearly crust overlying a lightly cemented, cross-bedded quartz and carbonate sand (Shinn *et al.*, 1977). The underlying sand is believed to be old coastal dunes that controlled the location and linearity of the present ridges. With radiocarbon age dating, unaltered coral attached to the crust is dated 6,300 ± 120 years (Shinn *et al.*, 1977).

A similar process is thought to have formed the inner reef. This ridge occurs at approximately the 10 m contour and has a seaward-dipping rocky and irregular face with 3 to 5 m of relief.

The inner plateau is a broad, low-gradient platform extending from the shoreline to approximately the 10 m contour that marks the western edge of the first reef. The crests of these ridges are usually encrusted by reef-associated organisms. The troughs act as sediment traps, and in places sediment thickness exceeds 3 m, but in most there is only a thin cover (Raymond, 1972).

The second plateau lies between the first and second reefs and has a depth ranging between 11 and 14 m. It is generally level, 100 to 150 m wide, and composed of unconsolidated, poorly sorted carbonate sediments (Raymond, 1972).

The majority of resistivity probe measurements were collected in the third plateau, which is approximately 400 m wide in the study area and is filled with 6 to 8 m of carbonate sand and reef rubble, most of which is unconsolidated. Its floor varies in depth from 18 to 21 m.

MEASUREMENT SYSTEMS

Concepts

Laboratory measurement of conductivity requires recovery of the sediment in a condition sufficiently undisturbed that the conductivity is the same as when the sediment is in place; *in-situ* measurement with the desired resolution appears to require that the measuring device itself be emplaced within the sediment.

Recovery of sufficiently undisturbed sediment samples can be possible in fine-grained deposits, but recovery of undisturbed samples in coarse sand materials, such as the carbonate debris at the study site, is unlikely. For accuracy goals to be met with *in-situ* measurement, the volume of sediment disturbed by device emplacements needs to be small compared with the volume of sediment responding to electrical input.

Several different approaches to making conductivity measurements are potentially capable of yielding satisfactory accuracy and vertical resolution. The most appropriate of these approaches was selected on the basis of additional goals, in particular, completing the measurements within a few days at a minimal cost. Laboratory measurements on recovered unconsolidated samples were rejected for use since the sediment of interest is sandy and the degree of sample disturbance is likely to be too large for accuracy goals to be met. In-place measurements can be made using a variety of techniques that are briefly discussed below.

Review of measurement techniques

The simplest technique is to apply a known direct-current potential to a pair of electrodes having a known electrode-separation in the sediment, and to measure the resulting the potential between the electrodes. Application of Ohm's Law yields the apparent resistance 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 can therefore be made into an operational system relatively cheaply and quickly. However, it suffers from two drawbacks: (1) In addition to the electrical resistance of the sediment itself, there is a contribution to the apparent resistivity due to electrochemical resistance, and (2) the current density in the 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 electrochemical reactions can be minimized by using alternating current rather than direct current. 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 (Keller and Frischknecht, 1966). In submarine environment, the potentials to be measured are quite small; therefore, sensitive electronic instrumentation is required to detect the signal and discriminate against noise. In addition, emplacement of the electrodes is difficult, especially in sandy sediments, because (1) firm electrode contact with the sediment must be maintained, (2) the overlying highly conductive seawater must be avoided, and (3) electrode arrays tend to be somewhat fragile; they must be designed with electrode spacing less than 40 percent of desired resolution and electrode size sufficiently small to minimize sediment disturbance.

These emplacement problems can be substantially reduced by using an inductive technique rather than contact electrodes (Dobrin *et al.*, 1988). Inductive techniques rely upon detection of the secondary electromagnetic field established in conductive materials by an applied electromagnetic filed. The field is produced by an alternating current flowing in a loop of wire; no physical contact is required between the material being studied and either the transmitter coil or the receiver coil. For both contact and inductive techniques, the vertical extent of the sediment contributing to the resistivity measurement can be controlled to a substantial degree by the addition of guard electrodes or coils to which is applied an appropriate electrical waveform (Sweet, 1972).

System design

The system selected to achieve the measurement goals was based on the four-electrode contact technique (Dobrin *et al.*, 1988; Shon, *et al.*, 2000b). The device took the form of a probe (Fig. 2a). The probe is wedge shaped to ease emplacement and minimize sediment disturbance, and is fabricated of nonconductive plastic. The electrodes extend beyond the wedge and are spaced so that (1) the vertical resolution of the measured resistivity is adequate, and (2) the electrode separation is at least three times the expected grain size of the sediment. The electrodes are equally spaced with the two potential-measuring electrodes on the inside, that is, Wenner array (Wenner, 1915; Dobrin *et al.*, 1988; Shon *et al.*, 2000b).

The resistivity probe system electronics are composed of three subsystems: signal generation, processing, and temperature monitoring (Fig. 2b). Alternating current is supplied at up to approximately 20 volts to the outer electrodes. The inner, potential-measuring electrodes are connected to a differential amplifier; output of the amplifier and the current source are monitored. Temperature at the probe tip is monitored with a thermistor circuit since the sediment resistivity varies 1.5%/°C (Boyce, 1967).

FIELD STUDIES

To study the electric conductivity of submarine sediments, resistivity measurements were conducted on the continental shelf off Fort Lauderdale in Florida, USA, during the August of 1999. Seismic survey and sample coring were also performed to compare and interpret the results of measurements.

Seismic survey

A detailed seismic survey of the study area was completed using an EG&G Uniboom shallow-penetration seismic reflection system. Fig. 1b shows the location of the seismic track-lines and the resistivity probe sites.

The seismic survey delineated the sedimentary in

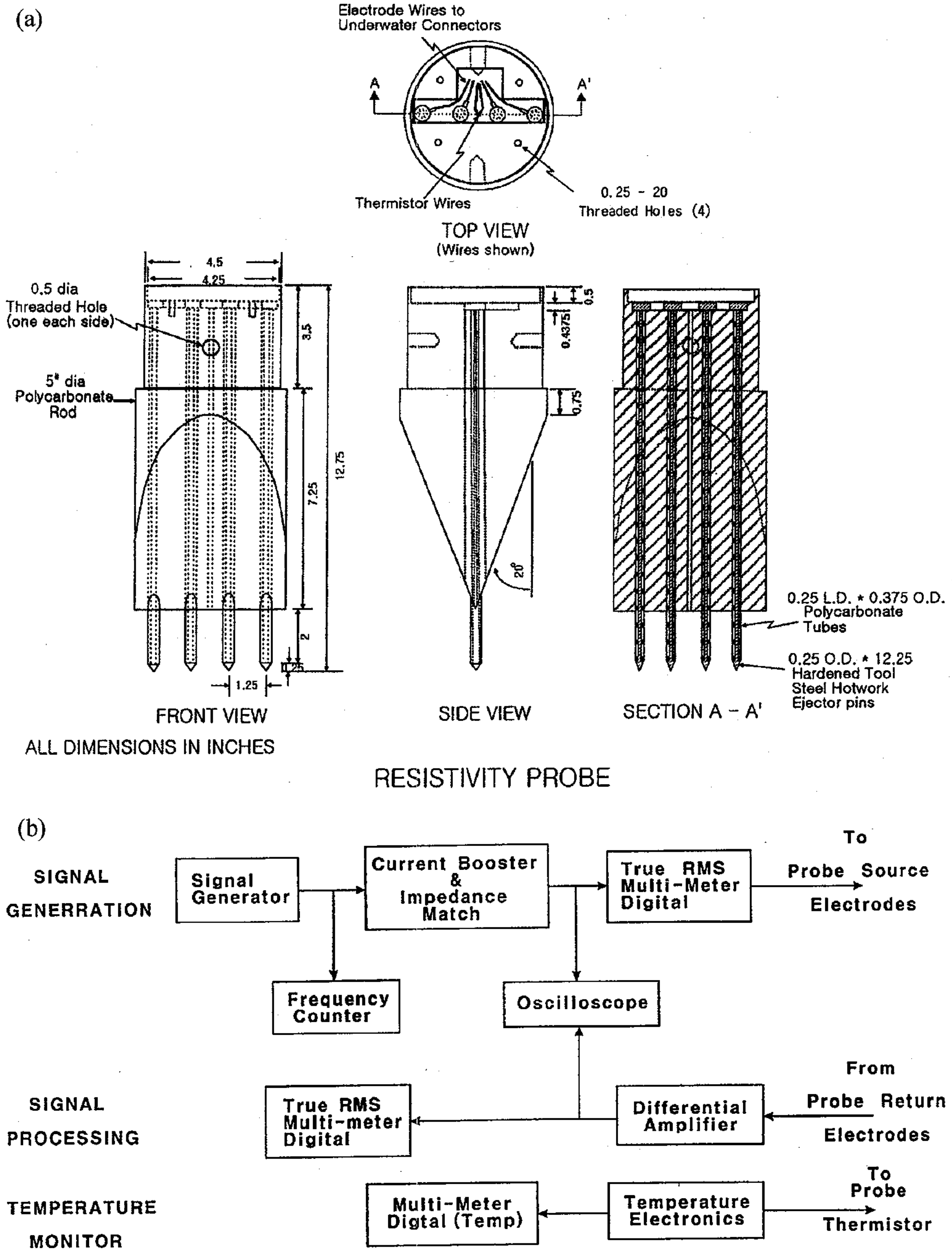


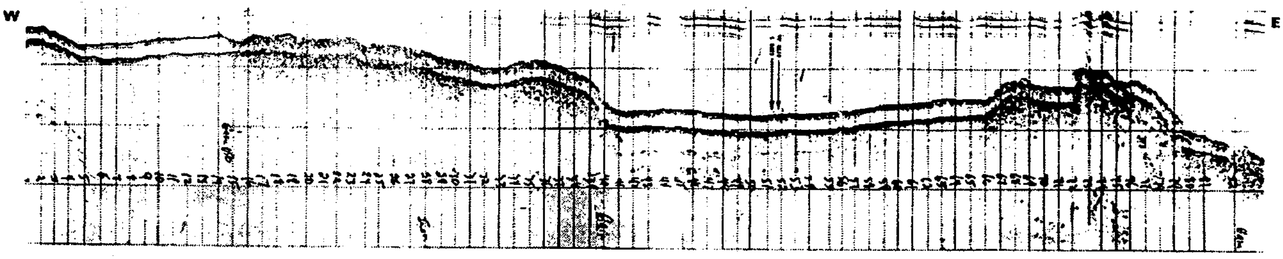
Fig. 2. (a) Mechanical drawing of resistivity probe. (b) Electronic system of resistivity probe.

the series of linear ridges and plateaus north-south as described above. The low at the study site, between the second and third reef, is nearly acoustically transparent except for a strong reflector 0.3 m thick lying 2 to 2.5 m beneath the sediment surface (Fig. 3). This reflector can be traced through the second and third reefs and across the second plateau.

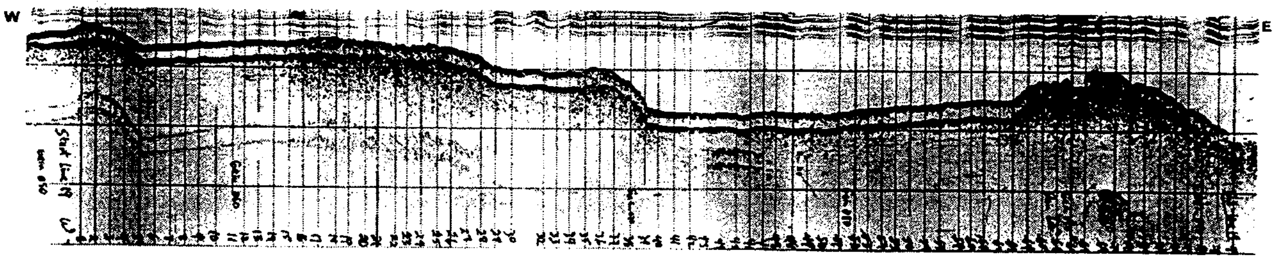
Subsequent deposition of large amounts of coral rubble occurred in the depression behind the reef. During this time the second reef began growing coral on the old coastal dune ridge and soilstone crust as sea level transgressed. Seismic profiles showed that the inter-reef areas, as shown by seismic reflection, were acoustically nearly transparent (Fig. 3).

Resistivity probe operation

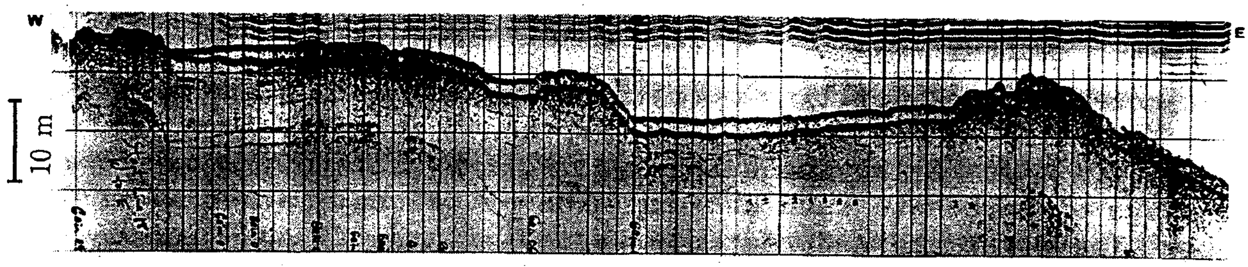
Initial measurements of resistivity were made in the



(a) Line 1



(b) Line 2



(c) Line 3

(d) Line 4 VE 11.5:1 (e) Line 5 VE 9:1 (f) Line 6 VE 9:1

Fig. 3. Seismic profiles. (a) Line 1, (b) Line 2, (c) Line 3, (d) Line 4, (e) Line 5, (f) Line 6.

upper few centimeters of the seabed after lowering of the Vibracore to the seafloor. The probe was inserted into the sediments at approximately 0.3 m increments to the limit of the Vibracore. Resistivity and temperature measurements were made at 30-second intervals for about 3 minutes.

Results and interpretation

Conductivity measurements were made at six sites, five within the third plateau area and one in the second plateau (Fig. 3). Seismic data were interpreted using field coring of sediments. Table 1 summarizes the seismic stratigraphy at each penetration site. Hard and soft sedimentary layers have been delineated from the profiles (Fig. 3). Conductivity data plotted for each site are drawn in Fig. 4. Bars in each figure represent the limits of uncertainty in the conductivity data. Best estimates of the actual conductivity are indicated by a box at each level of penetration. The best estimates of the conductivity are represented by the boxed data. The estimated values at each data point were determined by the analysis of rate of penetration.

It should be noted that the final data points at all sites, except site 5, were obtained in material that the probe could not penetrate. At some sites conductivity was exceptionally low. The hard material that refused entry is presumed to be relatively thin sedimentary layers. It is believed that below these hard layer the sediments become relatively softer and that the sediments have somewhat higher conductivities below the refusal depths.

Regression analysis was carried out on data from sites 1, 2, 2A, 3, and 5. Low conductivity values obtained at some of the sites at refusal depths were not used in the regression analysis since these values represented a small lithologic unit not representative of the total sediment column. The composite was used for further interpretation and to obtain an average analysis for all sites except site 4 (Fig. 5). The measured conductivities were made when the bottom temperatures varied from 21.7 to 22.3°C.

Laboratory tests indicated that 90 percent of the volume of material contributing to the conductivity measurements was within the zone extending vertically 56 mm above and below the probe tips. Thus each measured value of the conductivity reported here represents an average over a vertical range of 110 mm. As the conductivity of a material decreases, the vertical extent of zone contributing to the measurement increases. For the materials encountered in this study, the maximum vertical range is estimated as 0.2 m. In non-homogeneous materials the current tends to flow in those portions having highest conductivity (Keller and Frischknecht, 1966).

Table 1. Seismic stratigraphy analyses.

Site No.	Depth (m)	Description
1	0–0.3	soft
	2	slightly hard reflector
	7.6–2.3	soft
	2.3–2.4	very hard reflector
	2.9–3.0	slightly hard reflector
	4.3–4.6	slightly hard reflector
	5.2–5.5	slightly hard reflector
	5.8	slightly hard reflector
	7.3	slightly hard reflector
2, 2A, 3	0–0.46	soft
	0.46–0.76	slightly hard reflector
	0.9–2.0	soft
	2.0–2.3	very hard reflector
	2.4–2.7	slightly hard reflector
	4.6–4.9	slightly hard reflector
	7.3–7.6	slightly hard reflector
4	0–0.9	very hard reflector
	1.8–2.4	hard reflector
5	0.76–1.1	slightly hard reflector
	1.5–1.8	very hard reflector
	3.0–3.4	slightly hard reflector
	4.6–4.9	slightly hard reflector
	5.2–5.5	slightly hard reflector
	6.1–6.4	slightly hard reflector
	7.0–7.3	slightly hard reflector

CONCLUSIONS

Comparisons among the observed conductivity values as a function of depth, the seismic reflection records, and recovered seabed material of the Florida shelf suggest the followings:

(1) The upper portion of the seabed is composed of layers of material, distinguishable by the strength of the seismic reflection signal or by differing conductivity.

(2) The hard reflectors are typically about 0.3 m thick.

(3) Conductivity of the layers giving more intense reflections is approximately 0.5 mho/m.

(4) Conductivity of the layers giving weak reflections is typically slightly greater than 1.0 mho/m.

The layers giving more intense seismic reflections

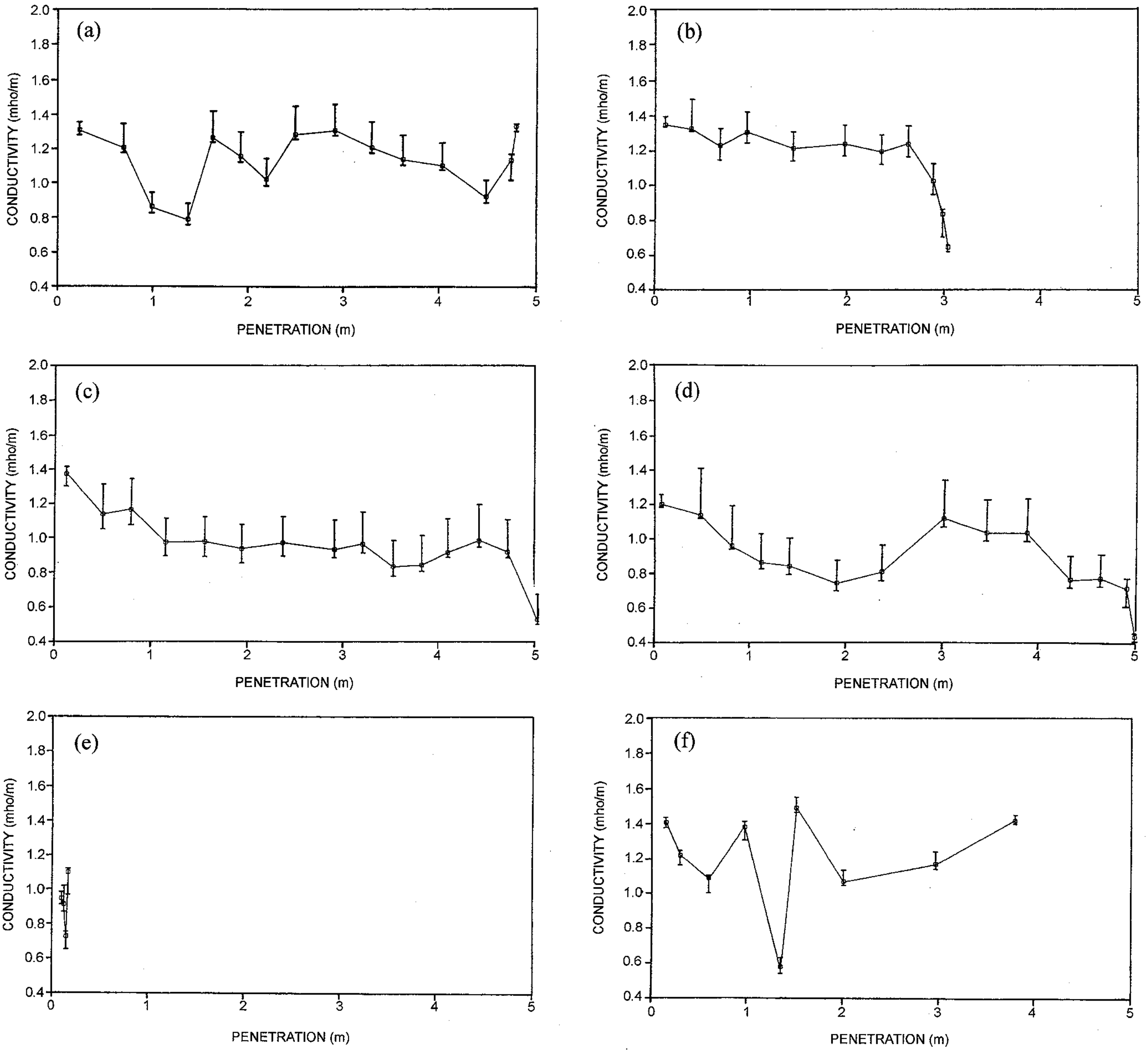


Fig. 4. Conductivity values according to depths. (a) Site 1, (b) Site 2, (c) Site 2A, (d) Site 3, (e) Site 4, (f) Site 5. In each figure, Symbol □ indicates the best estimate and I respresents the limits of uncertainty.

seemed to have greater resistance to penetration by the conductivity probe, probably because of larger coral fragments in these layers. At sites 2 and 3, the probe apparently met penetration refusal with the actual probe tips imbedded in the hard reflector. The average for the area in the upper 4.9 m was about 1.0 mho/m. Regression analysis of the data suggests an average decrease of 0.061 mho/m per meter below the sea bottom (Fig. 5). Measurements on the ridge area at site 4 indicate that the lithified material has a relatively high conductivity, approximately the same as the layers giving strong acoustic reflectivity. Rock conductivities at site 4 are believed to be less than 0.7 mho/m.

For a substantial number of high-resolution conductivity measurements, the use of the probe described should be considered. For additional measurements in coarse of fine-grained sediment at penetration depths up to 5.5 m, the system designed and used in this project should prove satisfactory.

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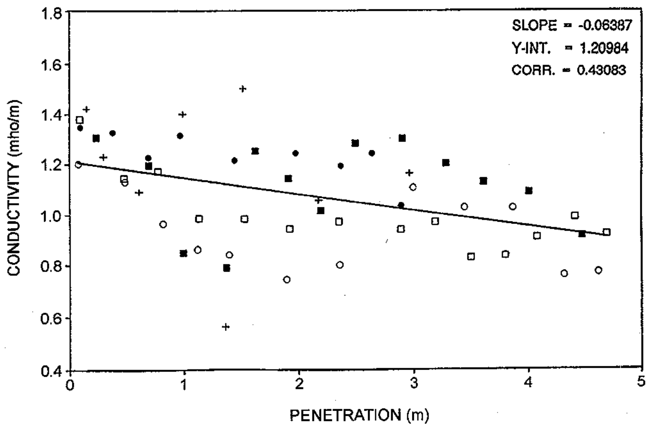

Fig. 5. A composite conductivity regression analysis for five resistivity probe sites in the study area. In this figure, ■ represents the conductivity data of Site 1, ● Site 2, □ Site 2A, ○ Site 3, and + Site 5. Regression curve shows a slope of –0.06387, and correlation coefficient of 0.43083.

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