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DESIGN OF A SEAFLOOR ELECTRICAL SOUNDING SYSTEM FOR OFFSHORE OIL EXPLORATION

by

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ABSTRACT

Oil exploration is moving offshore to the investigation of largely unexplored sedimentary basins. A study of the technical and economic feasibility of the application of seafloor electrical sounding to offshore oil exploration indicates that both direct current (DC) and electromagnetic (EM) methods can determine the thickness of the sedimentary layer overlying an electrically resistive basement. By application of appropriate boundary conditions to Maxwell's and Laplace's equations, the mathematical expressions for the electromagnetic and electrostatic fields, respectively, are developed and modeled to demonstrate the sensitivity of the methods to sedimentary layer thickness.

A DC system consisting of 6 dipole-dipole arrays on a cable with source-receiver offsets on the order of 6 km is proposed and its resolution tested. An offset of 2.5 times the sediment thickness is necessary to sense the underlying basement.

In order to detect a change in sediment thickness of 100 m in a total thickness of 1000 m, a 10% change in measured voltages on the order of 10's of μV must be measured. The major obstacle to this accuracy is the presence of EM noise caused by internal waves on the boundaries between the layers of the density stratified ocean. A small scale prototype which could be tested in an area where the sedimentary layer was known to be fairly thin is suggested in order to determine the

magnitude of the noise, as well as operating parameters such as maximum towing speed, which will determine the economic feasibility of the method.

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INTRODUCTION

PURPOSE

The purpose of this report is to present the results of a study of the technical and economical feasibility of the application of seafloor electrical sounding to offshore oil exploration.

PROBLEM

There are many frontier offshore shelf areas which offer the potential of giant oilfields such as Canada's Hibernia. Evaluation of the potential of these areas for oil production requires knowledge of the presence or absence of basement structure which would favor the accumulation of hydrocarbons. This knowledge may be obtained by determining the thickness of the sedimentary layer overlying the basement.

At present, these areas are not thought to offer enough incentive to justify the cost of a seismic survey, and therefore cheaper basin study methods are employed such as marine gravity and airborne magnetics. Due to the resistivity contrast between the ocean, the sediments, and the basement, electrical methods of sounding the seafloor may be applied to sense changes in the thickness of the sedimentary layer. This, combined with a bathymetric survey, is sufficient to indicate basement structure. If it possesses sufficient resolution, a seafloor electrical sounding system for offshore oil exploration may offer a cost-effective alternative to those basin study methods presently employed.

The problem, then, is to design a seafloor electrical sounding system which can adequately sense changes in the thickness of the sedimentary seafloor layer in offshore shelf areas (typical water depth, 60 m; typical sediment thickness, 2000 m; desired resolution, about 100 m) and compete economically with the other available basin study methods.

SCOPE

The objective and theory of seafloor electrical sounding are described, and the applicability of various methods is examined. The methods are described and evaluated according to criteria such as technical capability and economic characteristics. The results of a field trial of the loop-loop electromagnetic (EM) method are presented, with mathematical development, in Appendix A. The design of a DC seafloor sounding system is described, including estimated costs. The response of the system to varying sediment thicknesses is modeled, and the necessary sensitivity of the voltage measurement determined. The mathematical development of the direct current (DC) method is presented in Appendix B, as well as more detailed computer modeling data than is presented in the body of the report. An estimated cost breakdown comprises Appendix C. The report concludes with a comparison of the design, including economic considerations, with the more conventional basin study methods.

OBJECTIVE OF SEAFLOOR ELECTRICAL SOUNDING

The objective of seafloor electrical sounding is to determine the thicknesses and resistivities of the layers which lie beneath the seafloor. These parameters define the geoelectric structure. Given an understanding of the factors which influence a layer's resistivity, the geoelectric structure can be interpreted in terms of the geological structure of the seafloor.

The factors which influence a layer's resistivity are its degree of sluid saturation, resistivity of the pore fluid, and temperature (Keller and Frishknecht, 1966, pp. 8-10). (The ocean itself has a resistivity of .35 ± .15 ohm-m, depending strongly on salinity, temperature, and to a lesser degree on pressure). Generally, the seafloor consists of a layer of water-saturated sediments with relatively low resistivity (1 to 10 ohm-m, according to Keller (1969)) overlying a pillow basalt layer which in turn overlies a layer of basalt dikes. If the pillow basalt is fairly young, it will be porous (20-40%) and its resistivity will be determined largely by the conductive seawater circulating in the rock. Then, values of resistivity on the order of 10's of ohm-m are expected (Keller, 1969). These resistivity values have been confirmed by geophysical logging of holes drilled as part of the Deep Sea Drilling Project (DSDP) (Kirkpatrick, 1979; Becker et al., 1982). Kirkpatrick also reports that low temperature alteration of the pillow basalt layer fills the pore spaces with low temperature minerals such as carbonates, clay, and lithified nanofossil ooze. He estimates this cementation to be completed in about 30-60 million years. The porosity of the pillow basalt layer is then from 0-15%, and has a resistivity from 100's to 1000's of ohms. Most basin areas of interest will be fairly mature (having large thicknesses of sediments) and so a large resistivity contrast is expected at the base of the sediments.

BASIC THEORY OF GEOELECTRIC SOUNDING

The earth can be thought of as a filter which acts on an input signal. Analysis of the measured output and the known input yields information about the filter characteristics of the earth.

Just as seismic methods yield information about the spatial distribution of acoustic impedance reflections, electrical methods yield the geoelectric structure of the earth.

Electrical techniques consist of measuring an electric and/or magnetic field and, from a knowledge of the primary field, developing a geologically reasonable model of a geoelectric structure which could have produced the measured field.

For offshore oil exploration, the details of the inversion of the measured field to a geoelectric structure are insignificant. It is sufficient that there be a measurable dependence of the observed field on the thickness of the sedimentary layer.

Electromagnetic Methods

With EM methods, a field (either artificial or natural) is measured and, given an understanding of the primary field, can be interpreted in terms of a geoelectric structure which would produce such a field. Natural sources of primary EM fields available in the marine environment include ionospheric and magnetospheric current sheets and those fields generated by the motion of the conductive seawater through the earth's magnetic field, while available artificial sources usually consist of either an electric or magnetic dipole (produced by current oscillating in a straight wire or loop, respectively).

EM energy can be thought of as being transmitted, and then reflecting and refracting from interfaces in the earth between rock types of varying resistivities. Physically, an EM wave is a transverse wave, consisting of an electric field and a magnetic field oscillating at right angles to each other and the direction of propagation. As the wave passes through a medium, the electric field exerts a force on the electrons and protons of the atoms as well as on the free charges which may exist, such as ions in the pore fluid of a rock.

A distinction is made between the resultant currents, that due to the bound charges being known as the displacement current and that of the free charges the conduction current.

The displacement current is mainly a result of the motion of the atoms' electrons. Because of their much higher charge/mass ratio, they respond more easily to the force and oscillate more in phase with the electric field and with greater amplitude than the nuclear protons. The more tightly bound electrons of the inner shells respond to a lesser degree than those of the outer shells.

For the frequencies used in EM exploration, however, these displacement currents are dwarfed by the conduction currents of the free charges, induced by the magnetic field of the EM wave. The conduction currents are the source of information about the conductivity of the medium.

Both currents produce an EM field of their own, of different amplitude and retarded in phase with respect to the incident field, but of the same frequency. This secondary EM field interferes constructively or destructively with the incident field. The part due to the displacement currents causes the familiar effects of reflection and refraction (the domain of optics, and a function of the electric permittivity of the medium), while the secondary field due to the conduction currents is used to advantage in EM methods of geophysics.

In Appendix A, mathematical expressions describing the field due to a vertical magnetic dipole source on the floor of the ocean are developed by application of appropriate boundary conditions to the solution of Maxwell's equations. The results of a field trial (performed by Drs. Keller and Ibrahim on the floor of Monterey Bay) which appear to support the mathematical development are also presented.

Direct Current Method

In direct current methods, current is introduced into the earth by a pair of electrodes. Charge flows into the earth and accumulates at resistivity interfaces. The electric field of these charge accumulations is superimposed upon the field of the charge accumulation on the surfaces of the current electrodes, and a measurement of the electric field thus represents a sum of the gradient of two potentials: a "normal" potential and a "disturbing" potential.

In the case in which the current electrodes are immersed in the ocean, the normal potential is the potential of the electrodes assuming the ocean to be a uniform half-space, with no seafloor. (Thus, the normal potential is the potential due to the charge accumulation on the surfaces of the electrodes and the charge which accumulates on the ocean/air interface).

The disturbing potential is the potential of the charge accumulations which arise on additional resistivity interfaces (ocean/sediment, sediment/basement) and thus is the potential which yields information about the geoelectric structure of the seafloor. Mathematical expressions describing the potential due to a current source are obtained through the application of appropriate boundary conditions to the solution of Laplace's equation, and are developed for the case of a current array immersed in the ocean over a 2-layer seafloor in Appendix B.

EVALUATION OF NATURAL SOURCE METHODS

For a number of reasons explained in this section, natural source EM methods are unsuitable for offshore oil exploration.

Of the natural EM fields available on the seafloor, those of cosmic origin have enjoyed the most application in the field of seafloor electrical sounding (Cox et al., 1970; Filloux, 1977, 1980, 1981; Law and Greenhouse, 1981; Chave et al., 1981). The huge current sheets formed by the interaction of the solar wind (a plasma moving at speeds of 400 km/sec) with the geomagnetic field generate an EM field which induces currents in the earth, known as telluric currents. The magnitude of the induced current density is in direct proportion to the conductivity of the seafloor (Ohm's Law), and so by simultaneously measuring the variations in the electric field caused by these currents and the magnetic fields which induce them, the impedance of the seafloor can be deduced. In practice this consists of measuring the ratio of the horizontal electric field to the perpendicular horizontal magnetic field, and is known as the magnetotelluric (MT) method (Tikhonov, 1950; Cagniard, 1953).

The usual limitation of this method, and the one that stimulated the development of artificial sources for the seafloor, is the band-limited nature of the EM energy. EM energy is attenuated as it travels through a medium in direct proportion to its frequency and to the medium's conductivity. It is attenuated by a factor of e^{-1} in a distance known as the skin depth:

$$\delta = \sqrt{\frac{2}{\sigma\mu\omega}} \qquad (1)$$

δ = skin depth, in meters

σ = conductivity, in Siemens/meter

μ = magnetic permeability, taken as the value in free space,

$\mu_0 = 4\pi \times 10^{-7}$ henries/meter

$\omega = 2\pi f$ = angular frequency, in radians/second

f = frequency of EM energy, in Hertz

A general rule of thumb is that the depth of investigation of a particular frequency is about the same as its skin depth. To investigate a 2 km thick sedimentary basin of resistivity 2 ohm-m, the appropriate frequency would be about 10^{-1} Hz. EM energy of cosmic origin of this frequency range is not significantly attenuated by a 60 m thick ocean layer. However, it is unfortunately swamped by EM energy generated by the interaction of surface wind waves, especially in shallow seas (Chave and Cox, 1982). This invalidates any assumption of a plane wave primary field of cosmic origin, and the unpredictability of the noise makes it impossible to remove.

As seawater moves through the geomagnetic field, a force is exerted on the charges in the water. The mathematical expression for the force on a charged particle moving in a magnetic field is

$$\bar{F} = q(\bar{v} x \bar{B}) \qquad (2)$$

$\bar{F}$ = force on charged particle due to magnetic field, in Newtons

q = electric charge of particle, in Coulombs

$\bar{v}$ = velocity of particle, in meters/second

$\bar{B}$ = magnetic induction, in Webers/meter

Ions of opposite charge are forced in opposite directions, and so there is a net electric current flow perpendicular to the water flow and the magnetic field. Use of the EM energy associated with these currents has been suggested by many researchers (Cox et al., 1968; Sanford, 1971; Chave, 1983; Chave and Cox, preprint). To further this end, global tides have been modeled with some success (Schwiderski, 1981), significant advances are being made in the study of the spatial characteristics of ocean currents (Whalen, 1984), and the EM fields generated by currents and surface and internal ocean waves are being investigated (Petersen and Poehls, 1982; Chave and Cox, preprint). While they offer great potential, especially for deep sounding, these methods are not suitable for the present application because of the very low frequencies produced by currents and tides (on the order of 10^{-5} Hz), the complexity of the primary EM field produced by oceanic surface and internal waves (which are of the appropriate frequency range), and the lack of knowledge of the morphology of microscale phenomena such as the oceanic equivalent of dust-devils which may produce EM energy of the appropriate frequency range, but which are presently a noise source.

EVALUATION OF ARTIFICIAL SOURCE METHODS

The feasibility of both EM and DC methods of determining geoelectric structure using artificial sources has been demonstrated in marine environments. Russian researchers expended considerable energy in the 1950's, achieving success with a DC method (with source-receiver offsets of up to 8 km) in water depths of 50-60 m while mapping the geoelectric structure bevow large parts of the Caspian sea (Terekhin, 1962; Keller, personal communication).

Spiess et al. (1980) and Young and Cox (1981) report success with artificial source EM methods. Edwards et al. (1981, 1984) have developed and are experimenting with a method in which a commercial fluxgate magnetometer protected by conventional pressure vessels is placed on the seafloor to continuously monitor magnetic field fluctuations while a long, vertical bipolar alternating current source is deployed from a ship. They have made accurate measurements of variations at the 10^{-12} Tesla level at 6 km offset, while measurements at lower levels with a decrease in accuracy are possible. They estimate offsets of up to 20 km are feasible.

The crucial drawback of these methods for the present application is the necessity for seafloor deployment of the equipment, with the consequent delays in data acquisition this entails. It is possible to conceive of a towed EM system, but, technical capabilities of the two methods being roughly similar, the overwhelming simplicity of the DC method argues persuasively in the latter's favor.

In the following section, the design of a DC system appropriate for offshore oil exploration is described.

DESIGN OF A DC SEAFLOOR ELECTRICAL SOUNDING SYSTEM

The system consists of 6 dipole-dipole arrays on a long insulated cable: 1 current array and 6 potential arrays, as shown in Figure 1.

A large ship-mounted generator supplies the DC current to the current electrode array, consisting of a positive current electrode (I^+) and a negative current electrode (I^-). The 6 potential arrays measure the horizontal gradient of the electric field produced. The greater the offset r_i, the greater the depth of investigation of the array: Dipole-dipole arrays with an offset of 2.5 or more times the thickness of the sedimentary layer will "see" the effect of the resistive basement while those with a shorter offset will not.

Using an onboard computer, the measured fields are compared with fields calculated for the observed conditions (same ocean depth, source current, towing depth and orientation of arrays, source-receiver offsets), except that the seafloor is modeled as a uniform half-space of the same resistivity as the sedimentary layer. The great the deviation of the measured fields from the calculated fields, the more the actual sedimentary layer departs from the half-space model.

The plot of the ratios of the measured field to the calculated field versus offset form a curve. A suite of such curves is shown in Figure 2 for varying thicknesses of the sedimentary layer. Using a microcomputer and a modeling program similar to the one presented in Appendix B, the curve of the ratios of the measured field to the calculated field versus offset could be rapidly matched to a calculated

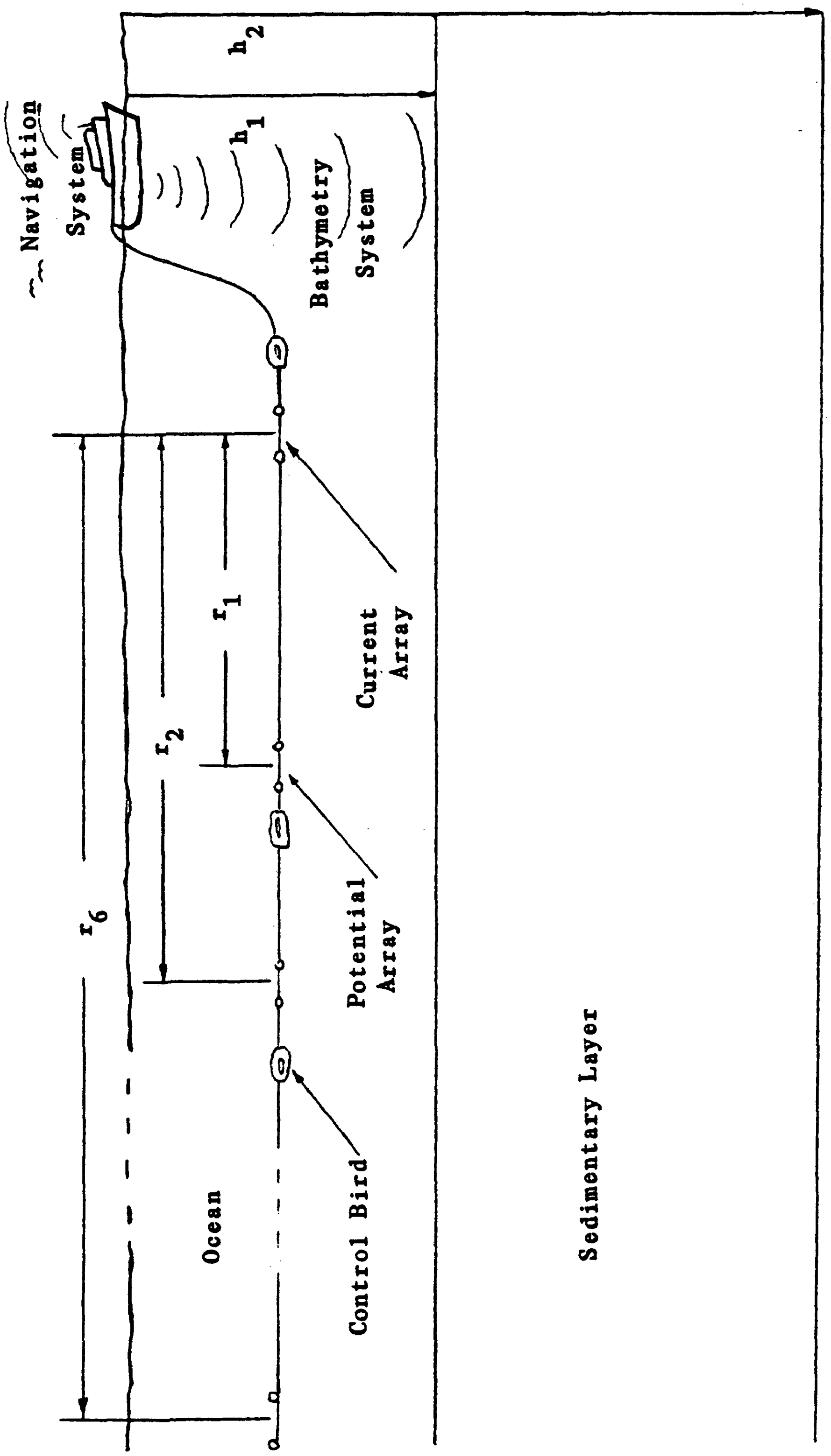

FIGURE 1
Proposed DC System

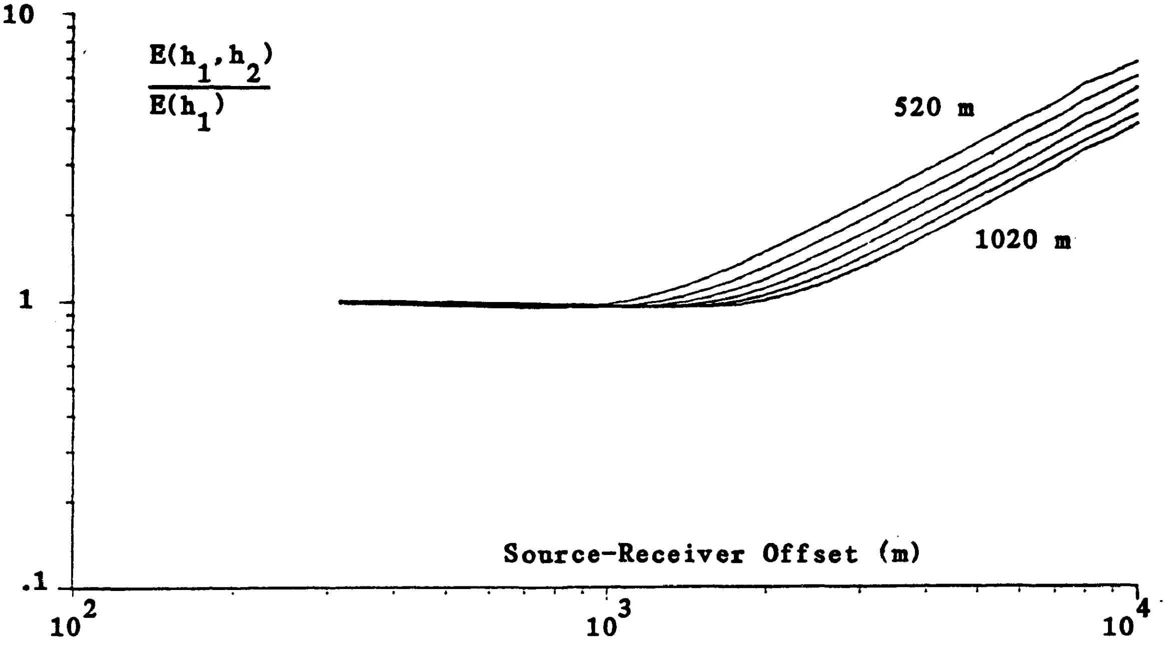

Fig. 2a) For thicknesses ranging from 520 m to 1020 m.

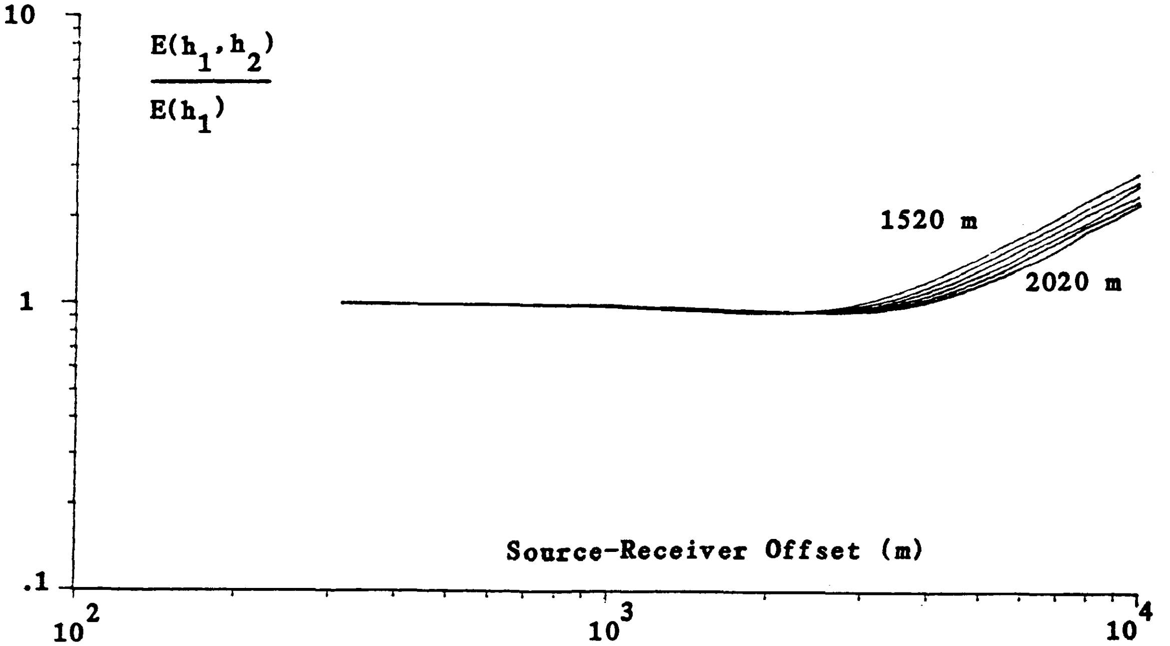

Fig. 2b) For thicknesses ranging from 1520 m to 2020 m.

FIGURE 2: Normalized Field For Varying Thicknesses

curve, and the thickness of the sedimentary layer would then be known. This value could be plotted on an X-Y plotter as a function of ship position and a map of sediment thickness produced in real time.

Signal Strength and Resolution of Method

As an indication of the signal strength to be expected and the measurement resolution necessary to detect changes in sediment thickness on the order of 1000 m, the following example is presented.

The data presented in Table 1 are for a potential electrode spacing of 60 m and sediment thicknesses of 920 m and 1020 m. With a current strength of 1000 A, such as that used for minesweeping in the Second World War, the magnitude of the voltage to be measured is in the 10's of μV. If the method is to determine the 100 m difference in thickness, the resolution of the voltage measurement must be on the order of 10% of this magnitude. This makes the absolute difference to be determined on the order of a few μV for large offsets. Instrumentation noise can be reduced to an order of magnitude less than this, and steady state electrical field noise can be removed by periodic polarity reversal of the current array. If completely random, fluctuating electrical noise due to such sources as internal waves may be removed by averaging successive measurements (at a cost in lateral resolution). If the signal/noise ratio is persistently inadequate, a larger potential electrode spacing could be used, the voltage to be measured increasing linearly with the length of the potential array.

Again, this would decrease lateral resolution, but probably much less than averaging measurements.

TABLE 1

Comparative Signal Strengths

Source-Receiver Offset (m)	920 m Thickness $(V_M-V_N)/I$ (μV/A)	920 m Thickness % Deviation	1020 m Thickness $(V_M-V_N)/I$ (μV/A)	1020 m Thickness % Deviation
1000	.930	−5.6	.936	−5.0
1800	.191	−1.0	.186	−3.5
2200	.109	+10.7	.104	+5.2
2800	.0657	31.3	.0613	22.6
3550	.0410	61.8	.0376	48.7
5000	.0205	126.	.0187	106.

Description of System Components

The components of the system are:

i) Positioning
ii) Power supply
iii) Cable positioning and control
iv) Data acquisition
v) Recording system

Positioning

Any of a number of navigation systems will provide positioning accuracy of a few tens of meters over hundreds of kilometers. The position data would be read directly by the computer.

Power supply

Diesel powered generators were used in WWII as minesweepers and ship degaussers, and may still be available. Otherwise, the type of megasource used in the Colorado School of Mines' time domain electromagnetic surveys could be used. Assuming a grounding resistance of less than an ohm, less than 1000 V would be necessary.

Cable positioning and control

The tow depth of the arrays can be set and maintained through the use of sophisticated "birds" developed by Conoco Limited for their marine seismic surveys. 6 birds would probably be sufficient to maintain control of the cable unless there were exceptionally strong ocean currents.

Data acquisition

The current and potential electrodes commonly used in marine electrical work are available commercially (Corwin et al., 1973) and could be mounted on a stress-bearing cable such as Kevlar with appropriate data acquisition systems. Depending on the noise present in the system, it may be desirable to go to the extreme of digitizing the data at the potential arrays and transmitting it to the shipboard computer by optical fiber. Each potential array would then have its own voltmeter, analog/digital converter, transmitter, and power supply. The data could be multiplexed on a single optical fiber.

Recording system

The recording system would consist of a microcomputer with a multi-channel data acquisition board: 1 for each of the 6 potential arrays, 1 for the sonar bathymetric survey, 1 for each of the 6 cable control birds, and one for the ship location, supplied by the positioning system. If the survey area is close to shore, or in some other area where significant variability of the seawater conductivity was expected, the computer could obtain accurate values from a conductivity meter mounted on the cable.

Comparison with other methods

The most obvious basin study method is marine seismic. The advantage of electrical sounding over seismic is cost. A normal marine seismic operation requires a crew is 40 people, about 4 times that necessary for a DC system, and a sophisticated data processing and storage facility in order to handle the huge amounts of data which are collected. The data collected in the proposed design consist of 6 voltages measured every couple of seconds, as opposed to several thousands of voltages measured every 8 seconds (1000 data points per trace at 2 msec sampling rate for 2 seconds, 96 to 1024 channels). The operating costs of the proposed design system could be much lower because of the lower capital cost of the equipment involved.

The other basin study methods used are airborne magnetics and marine gravity.

Airborne magnetics provide fast coverage of an area at low cost. If the shelf basement is thought to be igneous rock, this is an appropriate method to use. However, such oil traps as carbonate basement structure would be invisible to airborne magnetics, while presenting a likely target for electrical methods.

As far as the costs of the ship and navigation equipment are concerned, marine gravity and marine DC would be about equal. Both require a fairly large ship in order to deal with adverse weather conditions while maintaining production, and both require the same accuracy of positioning. If the data acquisition speed (i.e. the maximum towing speed before noise swamps the signal) of the DC method is significantly greater than that of marine gravity, the advantage of DC is clear. Actual field testing of a towed cable would provide tne necessary parameters to make an informed decision as to a reasonable towing speed.

CONCLUSIONS

It has been demonstrated that the DC method of seafloor electrical sounding can be applied to the problem of determining the thickness of seafloor sediments. The requirement that the source-receiver offset be at least 2.5 times the thickness of the sedimentary layer necessitates measurement of very small voltages (μV) in the presence of an unpredictable (but not necessarily random) noise background which may swamp the signal. If the noise is random, stacking of the measurements offers reduction of the noise at a cost in lateral resolution. The signal strength can be increased by increasing the potential electrode separation, but again at a cost in lateral resolution.

Development of the system described would be expensive (see Appendix C for cost breakdown). The development and controlled testing of a small scale prototype would allow the determination of the feasibility of the method with regard to such considerations as EM noise due to internal waves, which are difficult to predict and will probably be the most difficult noise source to remove, and the speed at which the array can be towed, which is an important factor in economic considerations.

If the signal/noise ratio is acceptable and the operating speed compares favorably to marine gravity, the DC method of seafloor electrical sounding may offer a cost-effective alternative for basin studies.

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APPENDIX A

Theory of Electromagnetic Depth Sounding, With Results of a Field Trial

The behavior of the EM field is derived for the case in which the transmitter is a vertical magnetic dipole (an oscillating current in a horizontal loop of wire) a distance d above the seafloor. The method is essentially that presented by Kaufman and Keller (1983).

For a harmonic source ($e^{-j\omega t}$), Maxwell's equations are

$$\text{curl } \bar{E} = j\omega\mu\bar{H} \tag{A1}$$

$$\text{curl } \bar{H} = \sigma\bar{E} \tag{A2}$$

$$\text{div } \bar{E} = 0 \tag{A3}$$

$$\text{div } \bar{H} = 0 \tag{A4}$$

$\bar{E}$ = electric field intensity vector

$\bar{H}$ = magnetic field intensity vector

$j = (-1)^{1/2}$

ω = angular frequency

μ = magnetic permeability

Our aim is to express the EM field in terms of a single vector potential, $\bar{A}$. Since div $\bar{E} = 0$, let

$$\bar{E} = j\omega\mu \text{ curl } \bar{A} \qquad \text{(A5)}$$

where $\bar{A} = (0,0,A_z)$. Then, upon substitution of (A5) in (A2), we obtain

$$\bar{H} = j\omega\mu\sigma\bar{A} - \text{grad } U \qquad \text{(A6)}$$

Substituting (A5) and (A6) in (A1) and defining

$$k^2 = -j\sigma\mu\omega \qquad \text{(A7)}$$

we obtain

$$j\omega\mu(\text{grad div } \bar{A} - \nabla^2\bar{A}) = j\omega\mu(-k^2\bar{A} - \text{grad } U) \qquad \text{(A8)}$$

Defining div $\bar{A} = -U$, we have

$$(\nabla^2 - k^2)A_z = 0 \qquad \text{(A9)}$$

Now the EM field can be expressed in terms of a vector potential which is a solution of (A9):

$$\bar{E} = j\omega\mu \text{ curl } \bar{A} \qquad \text{(A10)}$$

$$\bar{H} = -k^2 \bar{A} + \text{grad div } \bar{A} \qquad \text{(A11)}$$

For a uniform conductive medium, the vector potential of a magnetic dipole source of magnitude M is

$$A_{oz} = (M\ e^{-jkR})/(4\pi R) \qquad (A12)$$

where R= $(r^2 + z^2)^{1/2}$. By the Weber integral, this can be expressed as

$$A_{0z} = \frac{M}{4\pi} \int_0^\infty \frac{m}{m_1} e^{-m_1 z}\ J_0(mr)\,dm \qquad z \geq 0 \qquad (A13)$$

where $m_1 = (m^2 + k_1{}^2)^{1/2}$. With consideration of the cylindrical symmetry of the system, (A9) is seen to be

$$\frac{\partial^2 A_z}{\partial r^2} + \frac{1}{r}\frac{\partial A_z}{\partial r} + \frac{\partial^2 A_z}{\partial z^2} - k^2 A_z = 0 \qquad (A14)$$

From (A10), we obtain

$$E_\phi = -\ j\omega\mu \frac{\partial A_z}{\partial r}\ ,\quad H_z = -k^2 A_z + \frac{\partial^2 A_z}{\partial z^2}\ ,\quad H_r = \frac{\partial^2 A_z}{\partial r \partial z} \qquad (A15)$$

The electromagnetic boundary conditions are that the tangential components of the electric and magnetic fields are continuous. Thus

$$\frac{\partial A_{z1}}{\partial r} = \frac{\partial A_{z2}}{\partial r} \qquad \frac{\partial^2 A_{z1}}{\partial r \partial z} = \frac{\partial^2 A_{z2}}{\partial r \partial z} \qquad z = d \qquad \text{(A16)}$$

Integrating with respect to r, we obtain

$$A_{z1} = A_{z2}, \quad \frac{\partial A_{z1}}{\partial z} = \frac{\partial A_{z2}}{\partial z} \quad , \quad z = d \qquad \text{(A17)}$$

By separation of variables and algebraic manipulation to determine coefficients satisfying the boundary conditions,

$$A_z = \frac{M}{4\pi}\left[\frac{e^{-jkR}}{R} + \int_0^\infty \frac{m}{m_1}\,\frac{m_1 - m_2}{m_1 + m_2}\,e^{-2m_1 d}\,e^{m_1 z}\,J_o(mr)\,dm\right] \qquad \text{(A18)}$$

For z=d=0, and utilizing the Weber integral, we can express (A18) in terms of elementary exponential functions and their derivatives. The expression for H_z is

$$H_z = \frac{9M}{2\pi(k_1^2 - k_2^2)r^5}\{e^{-jk_1 r(}(1 + k_1 r + 4k_1^2 r^2/9 + k_1^3 r^3/9)$$

$$+ e^{-jk_2 r}(1 + k_2 r + 4k_2^2 r^2/9 + k_2^3 r^3/9)\} \qquad \text{(A18)}$$

The part involving k_1 is that part which reflects the influence of the seawater, while that with k_2 is that of the seafloor. Since k_1 and k_2 are directly proportional to the conductivities of the media they characterize, it is seen from (A18) that the effect of the seawater on H_z decreases more rapidly than the effect of the seafloor. This indicates that there is a frequency above which the method is sensitive only to the seafloor, characterized by k_2. Indeed, this is what is observed in Figure A1, which shows the data collected by Drs. Keller and Ibrahim.

The system consisted of 2 loops. Input current was 1-2 A, and source-receiver offset about 20 m. The frequency response of the system was tested and determined to be flat over the range of frequencies measured.

The data presented are the ratio of measured voltage to transmitted current, the mutual coupling. There is no significant induction in the surrounding media which would tend to reduce the primary magnetic field at frequencies below about 15 kHz, but above that the magnetic field of the induced currents in the seawater start to cancel the field. At frequencies above 17 kHz, there is no longer a significant primary field at the receiver because of induction effects, but the coupling does not decrease as it would in the absence of the seafloor: As frequencies near 20 kHz, the coupling rises again, because of the secondary field of the currents induced in the seafloor.

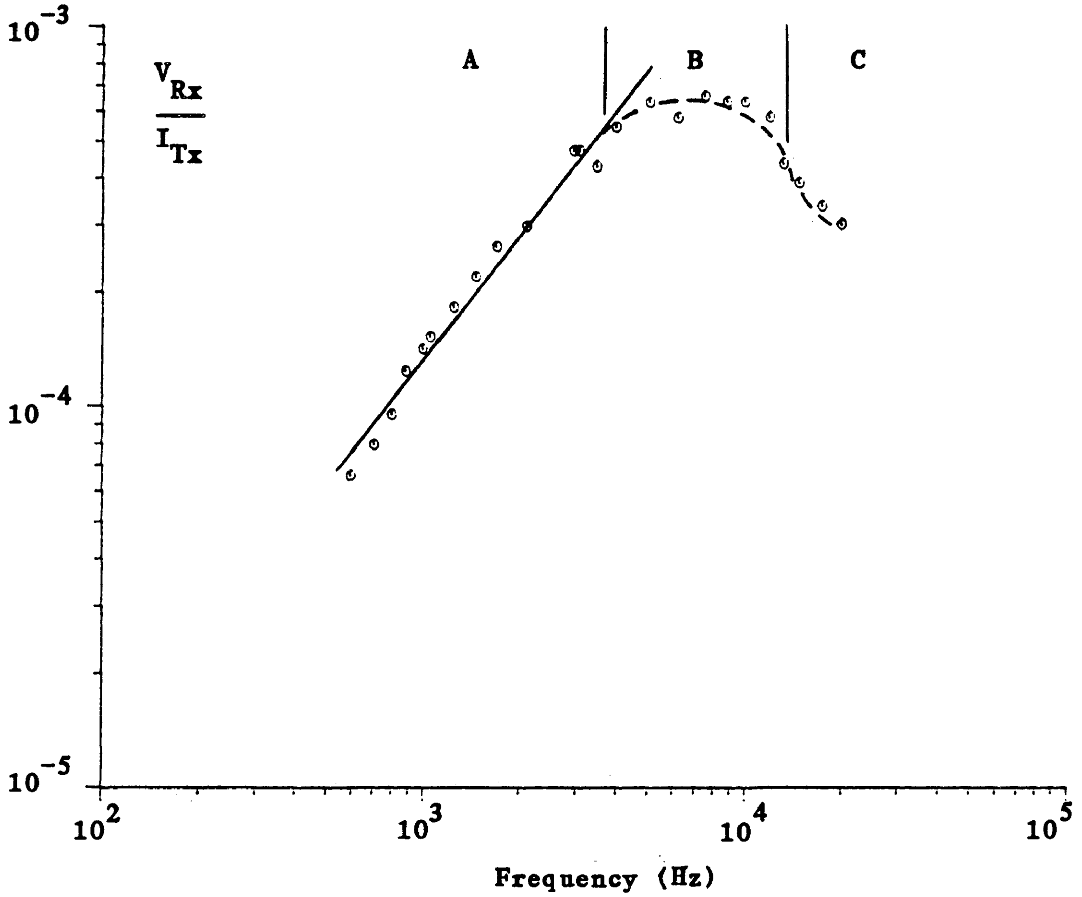

FIGURE A1: Field Data From Monterey

A: Linear rise in coupling, static conditions
B: Attenuation due to induction in seawater
C: Effect of Seafloor

APPENDIX B

Theory of Direct Current Electrical Sounding, With results of computer modeling

The expression for the potential of a current source in layer 1 of the model shown in Figure B1 is derived. The equation which describes the potential is Laplace's Equation

$$\nabla^2 V = 0 \qquad \text{(B1)}$$

By separation of variables and the principle of linear superposition, the expression for the potential in the i'th layer in a cylindrically symmetric system is

$$V_i = \frac{\rho_1 I}{4\pi} \int_0^\infty (\Theta_i \, e^{-\lambda(z-d)} + X_i \, e^{\lambda(z-d)}) \, J_o(\lambda r) \, d\lambda \qquad \text{(B2)}$$

The potential at the interfaces must be continuous...

$$\Theta_i \, e^{-\lambda(h_i-d)} + X_i \, e^{\lambda(h_i-d)} - \Theta_{i+1} \, e^{-\lambda(h_i-d)} - X_{i+1} \, e^{\lambda(h_i-d)} = 0 \qquad \text{(B3)}$$

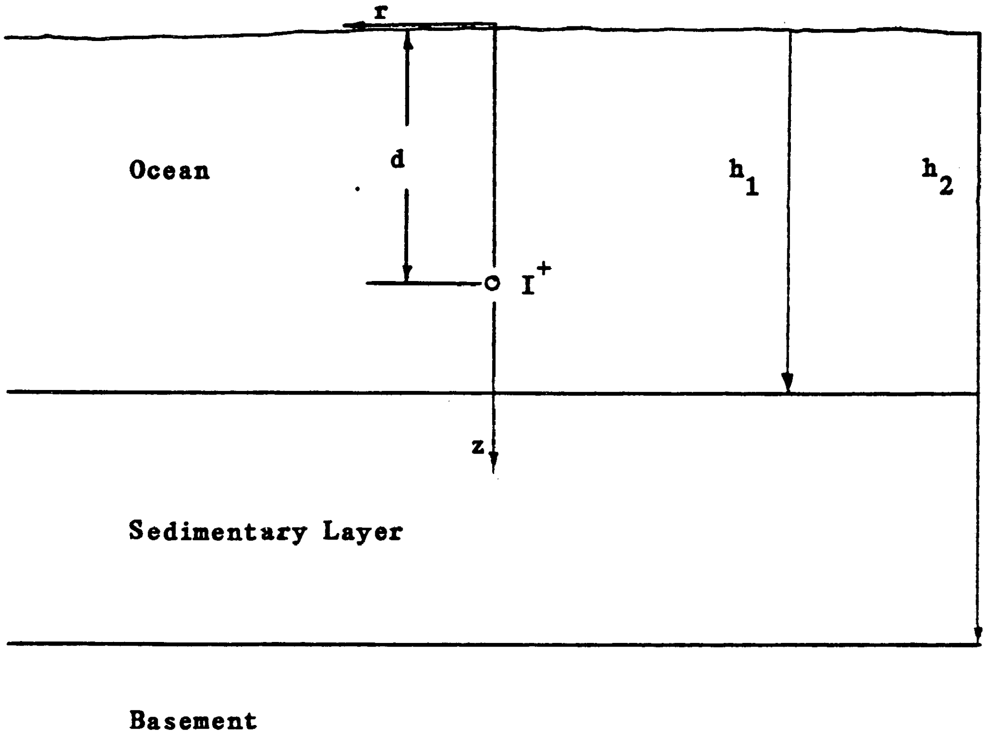

FIGURE B1: Model For Potential of Current Electrode

The normal component of current density must be continuous across the interfaces. From Ohm's Law,

$$J_z = \frac{E_z}{\rho} = \frac{1}{\rho}\frac{\partial V}{\partial z} \tag{B4}$$

$$\frac{1}{\rho_i}\frac{\partial V_i}{\partial z} = \frac{1}{\rho_{i+1}}\frac{\partial V_{i+1}}{\partial z} \tag{B5}$$

Using the conditions that potential is zero at infinity and that no current enters the air, we have a solvable linear system. After much algebraic manipulation, we obtain for the case of a 2-layer seafloor

$$V_1 = \frac{\rho_1 I}{4\pi}\left[\frac{1}{r} + \frac{1}{(r^2 + 4d^2)^{1/2}} + \int_0^\infty \frac{\{k_1(2e^{-2\lambda h_1} + e^{-2\lambda(h_1+d)} + e^{-2\lambda(h_1-d)}) + k_2(2e^{-2\lambda h_2} + e^{-2\lambda(h_2+d)} + e^{-2\lambda(h_2-d)})\}}{1 - k_1 e^{-2\lambda h_1} - k_2 e^{-2\lambda h_2} + k_1 k_2 e^{-2\lambda(h_1-h_2)}} J_o(\lambda r)\, d\lambda\right] \tag{B6}$$

This equation was modeled with the computer program DIPDIP.FOR (included in this Appendix) and the potential differences to be expected for a dipole-dipole survey were obtained for both the 1 layer and 2 layer seafloor. The 2 layer results were normalized by the 1 layer results as described in the body of the report, and curves generated.

```
C                            Program DIPDIP.FOR
C                          Written by J. C. Graham

C      This program computes the ratio of the horizontal E field
C   for a 2-layer seafloor to that for a uniform half-space seafloor
C   as a function of source/receiver offset and layer thickness.

      COMPLEX RHANKS,FSAVE
      COMMON/SAVE/FSAVE(283), GSAVE(283), NSAVE
      COMMON ZE, XH1, XH2, XK1, XK2
      EXTERNAL XKERN, UKERN, RHANKS

C      The ocean depth is modeled as 60 m.

      XH1 = 60.

C      The resistivity contrast at the seafloor is 0.54.

      XK1 = .54

C      The resistivity contrast at the basement is 0.99.

      XK2 = .99

C      The current and potential arrays are each 60 m.

      B = 60.

C      The tow depth of the arrays is 50 m.

      ZE = 50.

C      The ratios are calculated as a function of sedimentary layer
C   thickness, the data for each layer being read into consecutive data
C   files.  The counter J specifies the file to be written to.

      J = 10

C      The depth to basement for this particular program run was
C   varied from 1580 m to 2080 m, thus varying the sedimentary layer
C   thickness from 1520 m to 2020 m.

      DO 15 K=5,10
      XH2 = XH2 + 20. + 100.*K
      THK = XH2-XH1
C     J = J + 1

C      The source/receiver offset is varied from 316 m to 10 km.
```

```
      DO 20 RLOG=2.5,4.0,.05
      R = 10.**RLOG

C          VMNRM is the "normal" potential at V_M caused by the two
C     current electrodes and their images above the ocean surface, and
C     similarly VNNRM.

      VMNRM=1./R +1./(R*R+4.*ZE*ZE)**.5-1./(R+B)-1./((R+B)*(R+B)+
     1        4.*ZE*ZE)**.5

      VNNRM=1./(R-B)+1./((R-B)*(R-B)+4.*ZE*ZE)**.5-
     1        1./R-1./(R*R+4.*ZE*ZE)**.5

C          RFAR and RNER are the distances between the individual
C     potential electrodes and the current electrodes.

      RFAR = R+B
      RNER = R-B

C          VM is the sum of the normal and disturbing potentials of each
C     current electrode at potential electrode V_M, and similarly VN.

      VM=VMNRM+RHANKS(0,R,XKERN,.0001,NF,1)-RHANKS(0,RFAR,XKERN,
     1     .0001,NF,1)

      VN=VNNRM+RHANKS(0,RNER,XKERN,.0001,NF,1)-RHANKS(0,R,XKERN,
     1     .0001,NF,1)

C          The potentials UVM, UVN are the sums of the normal and
C     disturbing potentials of each current electrode at V_M and V_N,
C     respectively, assuming a uniform half-space below the seafloor with
C     the resistivity of the upper seafloor layer.

      UVM=VMNRM+RHANKS(0,R,UKERN,.0001,NF,1)-RHANKS(0,RFAR,UKERN,
     1      .0001,NF,1)

      UVN=VNNRM+RHANKS(0,RNER,UKERN,.0001,NF,1)-RHANKS(0,R,UKERN,
     1      .0001,NF,1)

C          RATIO is the ratio of the potential difference of the layered
C     model to the potential difference of the uniform half-space model.

      RATIO=(VM-VN)/(UVM-UVN)

C          The magnitude XMAG of the potential difference is obtained by
C     using the multiplier ρ_1I/(4π), where ρ_1 is the resistivity of the
C     seawater (.3 ohm-m), and I is the magnitude of the source current.
```

```
C        PDEV is the percent deviation of the layered model response
C    from the response of the uniform half-space model.

         PDEV = 100.*((VM-VN)-(UVM-UVN))/(UVM-UVN)
         XMAG = .3*(VN-VM)/(4.*3.14159)
         WRITE(J,*)R,RATIO
         WRITE(J+10,*)R,XMAG,PDEV,R/THK

C        The program loops back for another increment of R.

20       CONTINUE

C        The program loops back for another increment of layer
C    thickness.


15       CONTINUE

         END

C        The function UKERN computes the kernel function required for
C    convolution with RHANKS' filter weights for the uniform half-space
C    model.

         FUNCTION UKERN(G)
         COMMON ZE, XH1, XH2, XK1

         UKERN=XK1*(2.*EXP(-2.*G*XH1)+EXP(-2.*G*(XH1+ZE))+EXP(-2.*G*
    1          (XH1-ZE)))/(1.-XK1*EXP(-2.*G*XH1))

         END

C        The function XKERN computes the kernel function for the
C    layered seafloor model.

         FUNCTION XKERN
         COMMON ZE, XH1, XH2, XK1, XK2

         XKERN=(XK1*(2.*EXP(-2.*G*XH1)+EXP(-2.*G*(XH1+ZE))+EXP(-2.*G*
    1          (XH1-ZE)))+
    2          XK2*(2.*EXP(-2.*G*XH2)+EXP(-2.*G*(XH2+ZE))+EXP(-2.*G*
    3          (XH2-ZE)))) / (1.-XK1*EXP(-2.*G*XH1)-XK2*EXP(-2.*G*XH2)+
    4          XK1*XK2*EXP(-2.*G*(XH2-XH1)))
         END

C        The function RHANKS computes the Hankel transform by digital
C    filtering with a 283 coefficient filter.  It is printed in full in
C    Anderson's (1979) article.
```

Table B1 indicates the signal strengths to be expected for various thicknesses of sediments.

TABLE B1

Normalized Signal Strengths

(μV/A)

Sediment	Offset (m)					
Thickness (m)	1000	1800	2200	2800	3550	5000
520	.9530	.2560	.1600	.1010	.0634	.0317
620	.9290	.2290	.1410	.0882	.0557	.0277
1520	.9610	.1810	.0930	.0498	.0284	.0135
1620	.9640	.1820	.0927	.0489	.0273	.0128
2620	.9780	.1870	.0943	.0471	.0238	.0093
2720	.9790	.1880	.0946	.0437	.0238	.0091

APPENDIX C

Cost Breakdown

Data Acquisition System	Cost
Microcomputer with 10 Mbyte Winchester storage	$6000
Analog/Digital Board with software	2000
Plotter	1000
Printer	500
6 remote data acquisition units for potential arrays	2500
750 Kilowatt Generator	120000
Navigation System	8000
Bathymetry System	8000
Electrode arrays	
6 km cable (Kevlar/optical fiber)	30-60000
14 silver-silver chloride electrodes	500
Cable Control System	
6 depth control birds	24000
Onboard controller	10000

(The large variability in the cost of the Kevlar/optical fiber cable is a result of uncertainty regarding loading factors.)

The total cost of the system is thus on the order of $250,000, the major items being the generator (which could be rented) and the cable (which probably must be purchased).