A Preliminary Result of Transient Electric Dipole-dipole Experiment in The Strait of Georgia, British Columbia.

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An off-shore transient electric dipole-dipole experiment has been conducted in the Strait of Georgia, British Columbia in the middle of June, 1988. Measurement of electric field, energized by 3.5 A current from the 1,650 m long transmitter dipole installed at the coast, has been made at 10 sites across the Strait going down the Sechelt Trough up to the MacCall Bank, at distance ranging from 1.5 km to 4.65 km apart from the centre of the source dipole, with depth ranging from 100 m to 170 m. The receiver system consists of three Ag-AgCl electrodes with preamplifier towed in-line from the ship in a direction of the source dipole axis. Potential differences between two of the electrodes were amplified at the bottom, and then signal was processed and recorded on the ship.

An arrival of the diffusing field through the crust has been clearly observed at the nearer sites to the source dipole. Going farther from the source, the crustal field arrival became less conspicuous in the Sechelt Trough, where a seismic reflection survey (Hamilton, et al., 1987) revealed a thick sedimentary layer. However its arrival recognized again on the MacCall Bank. It is obvious that these spatial dependence of the transient nature of the electric field is strongly reflecting the electrical conductivity distribution of the sea floor across the Strait of Georgia. It has been demonstrated that the D.C. limit apparent resistivity also gives some information on the crustal conductivity structure especially when the site separation is much greater than the water depth.

1. Introduction

In recent years a great deal of effort has been taken on the establishment of a survey system using the controlled-source EM method on the sea floor both in theoretical and experimental aspects (e.g. Chave and Cox, 1982; Edwards and Chave, 1986; Cox et al., 1986; Cheesman et al., 1987, 1988; Chave, 1988; Wynn, 1988). The EM soundings using controlled-source are of particular importance in examining the shallower conductivity distribution in the marine geophysics, where the investigation has been widely made by measuring the natural electromagnetic fluctuations. However the natural electromagnetic field strongly attenuates through the conducting sea water at higher frequencies which responds the more sensitively to the shallower structure.

Controlled-source EM sounding methods are employed in the field whose extension ranges typically from 10 meters to a few kilometers, sometimes to a few tens of kilometers. There have been considered a variety of applications of the techniques to the off-shore exploration both with scientific and economic importance. The exploration in the continental shelf area would reveal the promising reservoir of carbon hydrates and other mineral resources. Applied to the survey of ridge area, it may enable us to map the distribution of hydrothermal ore deposits which are characterized by the extraordinarily high conductivity. This technique will reveal the detailed structure of the oceanic lithosphere, which has been hard to investigate with natural source methods because of above-mentioned reason. As for a more practical purpose it is likely to be useful to map the hidden geological features below the off-shore sedimentary basin.

The difficulty in mapping the conductivity with a controlled-source on the sea floor is due primarily to the fact that we can not apply the conventional methods which are widely used in the land surveys. This is because the sea floor material is usually more resistive than the sea water. In some cases the electrical conduction is completely controlled by the conductivity of the sea water rather than that of the sea floor, and thus the measured quantity becomes quite insensitive to the sea floor conductivity. Edwards and Chave (1986) showed that in all plausible methods the transient response to the in-line electric dipole-dipole system provides a high resolution to the less conducting sea floor. They demonstrated using a simple double half space model that the difference in conductivity between sea water and sea floor reflects the different arrival time of diffusing field in each medium which can be given as the characteristic diffusion time,

$$\tau = \sigma \mu_0 l^2 \qquad (1a).$$

where σ, μ_0, and l denote respectively the conductivity of the medium, the magnetic permeability, and the transmitter-receiver separation. A similar characteristic time may be a time where the rate of change in the field intensity becomes maximum and is given in analogous to Eq.(1a) as,

$$\tau_d = \frac{\sigma \mu_0 l^2}{2} \qquad (1b).$$

Along with the electric dipole-dipole system the magnetic dipole-dipole measurement has similar feasibility for mapping the sea floor conductivity as has been demonstrated by Cheesman et al. (1987).

In this paper a receiver system has been developed to measure the transient electric field from a separately installed transmitter dipole under a shallow water. Using this system an experiment has been conducted in the Strait of Georgia B.C., Canada in the middle of June, 1988. The Strait of Georgia is considered to be the boundary between the two tectonic provinces of the Canadian Cordillera; the Cost Plutonic Complex (CPC) to the northeast and the Insular Belt to the southwest. The present nature of the boundary is not well understood with some inference from surface geology and seismic data. White and Clowes (1984) presented a model of the velocity structure with a boundary fault. Despite of many tectonic models in this region require the existence of the boundary fault (e.g. Muller 1977; Monger 1982), the feature has been interpreted as a local feature since it has been observed only one line out of three.

The major purpose of the present experiment is stressed on testing the measuring system rather than mapping the subsurface geology. For that purpose this area was chosen as a survey area since a detailed cross section of seismic reflection profile is recently available (Hamilton et al.,1987) as well as geologic and seismic results mentioned above. The geology in this area has nearly two dimensional feature along the extension of the strait. We can expect a large variation in the thickness of the sedimentary layer across the Strait; thick sediment in the troughs and scarcely on the banks. The difference in the sediment thickness is likely to be reflected sharp variation in the measured EM response. Possible change in the basement rock between CPC and the Insular Belt may also be detected by the measurement. A preliminary result will be presented here including a detailed description of instrumentation.

2. Instrumentation of the receiver system

In this study we employed a separate transmitter-receiver system. Fig.1 schematically shows the measuring system. A transmitter dipole is installed at the shore in right angle to the shoreline. A receiver dipole or a chain of receiver electrodes is towed from the ship to measure the electric field along the extension of the transmitter dipole axis. A transmitter dipole on land (Bostick et al., 1977) may be the alternative way of transmitting the electric current in such a situation. In the open ocean we have to use another ship or anchored buoy system for the transmitter so long as we use the same configuration. Cox et al. (1988) used the self contained receiver system installed on the ocean bottom to measure the electric field transmitted from a dipole towed from the ship moving around the receiver. Using a towed receiver system we can get the signal, stack it and see if it is sufficient or not in real time on board. This is a certain advantage of using the present system. A disadvantage may be that the connection of the receiver system with long cable is likely to induce noise in the signal. However we eliminate the possible noise by use of preamplifier at the bottom to make the transmission impedance low.

The present receiver system consists of a series of three apparently identical electrode units and the cables with which the receiver units are connected (Fig.1). Each unit is composed of three parts; the cable jointer, the amplifier casing and the electrode holder (Fig.2).

We use the Ag-AgCl electrodes for a measurement of the potential difference in sea water. Each electrode is kept in a plastic housing attached at the end of the electrode holder, a 40 cm long epoxy rod, in order to get rid of any possible electrical noise due to the corrosion of metallic parts of the receiver system. The other end of the electrode holder can be screwed in the amplifier casing. The interface is sealed by an O-ring. The Ag-AgCl electrode and the preamplifier are electrically connected by a copper conductor in the epoxy rod.

The preamplifier casing is made of aluminum alloy and contains the amplifier circuit and its power supply. The preamplifier is composed of two operational amplifiers, both of which are operated by two 9V batteries. The total gain of the preamplifier is 34 or 54 dB with frequency range between 0.03 Hz and 10 kHz. The high-pass filter seems to be inevitable in an electric field receiver to eliminate the drift. With two 9 V alkaline batteries the preamplifier works for 20 hours under a room temperature (about 20°C). A typical noise level of the receiver system (including electrode noise) was about 1 μV measured in the laboratory. The amplifier casing casing is screwed in to connect to the cable jointer housing, and the connection is water-tight with an O-ring. This design of the casing makes it easy to replace batteries which must be done every day in the field due to the power consumption of the amplifier. In measuring the electric field we use one of the electrodes as the signal ground. Therefore one of three receiver electrodes is simply connected to the ground line in the cable jointer without preamplifier in the amplifier casing. Thus the potential difference is measured at each electrode with respect to the ground point electrode with a separation of 50 or 100 m.

The cable jointer, made of stainless steel pipe connects the signal cables and the signal lines from the amplifier. The more mechanical strength is required for the material of the jointer housing than other parts of the receiver system. The whole system is towed from the ship by a series of marine cables with insulated armour. The cable has two wires and a shield isolated from the armour, which means that cable can carry two channels of signal, a voltage relative to the ground. The present system consists of three units (electrode, amplifier and jointer), each of which is made completely identical so that everything may be replaceable. It must be emphasized here that a multi-channel receiver system would be an ultimate design. The present system has been designed so as to be easily expanded to a system with more channels because each unit is made identical.

Signal was recorded on the ship. In this experiment we used the DATA 6000 system of Data Precision Corp.. Signal lines are connected to the high input impedance instrumentation amplifiers and then to the DATA 6000. This instrument enables us to make not only data acquisition but also some preliminary data processing on board;i.e. stacking the signal to eliminate the noise and checked on the screen if the stacking was sufficient. Data were recorded on an IBM compatible floppy disk. We believe this is a most reliable and precise way of data acquisition.

3. Experiment

The experiment was carried out in June 1988 in the Strait of Georgia off the Sunshine Coast about 20 km west of Vancouver, B.C. (Fig.3), using the RV John Strickland of the University of Victoria. A 2000 m cable was installed to make the transmitter dipole in the right angle to the coastline. A stainless steel pipe was connected to the off-shore end of the cable for the current electrode and installed at the depth of 140 m. The transmitter and its power supply were set at the shore. Another stainless steel pipe was dropped in the water near the coast to make the another current electrode. The actual length of the transmitter dipole was turned out to be about 1,650 m (Fig.3). The transmitter system was operated with AC power supply.

The transmitted current is a square wave with 3.5 A amplitude. The switching is as sharp as 0.1 msec (Fig.4), while the diffusion time constant of the EM field which is in concern in the present study is estimated to be longer than 1 msec. Therefore, we can conclude that the current may be treated as an ideal square wave.

The alternating frequency was precisely controlled by a crystal clock. An identical, accurately synchronized clock has been used for the trigger of the data sampling. Transmitted signal frequency was 1 Hz for most of measurements. 0.25 Hz or 10 Hz signal was used from time to time depending on the situation.

Table 1 shows a summary of the experiment. We carried out the traverse beginning at the site A-01 near the off-shore transmitter electrode, crossing the trough, up to the site A-10 on the MacCall Bank (Fig.3). The ship position was determined by referring the Loran-C readings (smallest digit is 0.1 minute) and Radar reflections. In this area the Loran position was turned out to be biased as much as about .4 minutes southward. We calibrated the readings later with that at the transmitter electrode position at the coast. The bias is considered to be spatially uniform in such a small area of the present investigation, and therefore the positioning accuracy in this study can be estimated as about 1 nm, i.e. 180 m.

At the beginning of measurement, the receiver system was lowered down from the stern deck of the ship, slowly moving farther from the transmitter to keep the whole system stretched out in a straight line. During the measurement the ship was controlled so as not to drag the receiver system on the bottom, which may cause a fatal electric field noise. After the measurement the receiver system is lifted until the end electrode is above the sea bed to move to the next site.

4. Result

Here we describe the data processing to obtain a complete data showing the actual result. What we finally need is a signal waveform of half period from the instance of the current polarity change to the next polarity change. A real-time signal usually contains a significant level of noise as shown in Fig.5(a). The noise may be ascribed to following sources;(1) AC power (60 Hz), (2) electric current induced by natural EM field variations, (3) electrode and amplifier drift due to temperature or salinity change,(4) system (electrode, cable and amplifier) noise and (5) Electric field due to the motion of the electrode and water.

Noise component (4) is generally of random nature and dominant at high frequencies. This noise component can sufficiently be eliminated by signal stacking as demonstrated in Fig.5(b). Noises (2) and (3) can be regarded as drift components in the measured electric field and the period is usually much longer than that of the signal. Only if the duration is much longer than the total measuring time (i.e. signal period times number of stacking), a monotonically increasing or decreasing component remains in the stacked record. Anyway these components must be originally small in the present system because the preamplifier is band-limited between 0.03Hz and 10 kHz. Noise due to (1) may not be rejected by simple stacking but be seen on the stacked record (Fig.5(b)). It is obvious that the monotonically drifting component will be canceled out by subtracting the later half period of the signal from the former half (Fig.5(c)). Fig.5(c) shows that 60 Hz noise, as well as its higher harmonics, is also eliminated by this subtraction. This is because the frequency 60 Hz is even number harmonic of the signal frequency. Thus we can obtain a clean signal waveform without applying any special technique of digital data processing.

During a measurements the electrode cable is laid down on the sea floor. A small anchor is attached to the cable at about 2 m apart from each electrode. The ship is controlled so as not to drag the receiver system. However a movement of electrode is sometimes inevitable because of the wind to the ship and of the current to the cable, which causes significant noise in the potential difference at the concerned frequency range. At some sites this type of noise forced us to use AC coupling between signal line and the DATA 6000 in order to prevent a input from overflow, especially at a far site where the signal is quite small so that we have to measure the voltage with a small input range.

The time constant of the AC couple is about 0.1 sec which is nearly one tenth of the signal frequency. Fig.6 shows the waveform measured with AC and DC couples at A-01R. The initial bouncing corresponding to the arrival of crustal field can be clearly seen on either of the records since the time constant of the crustal field is much shorter than the cut-off period of the AC coupling of the input. However the feature at later time differs from AC to DC couple. The AC coupled signal $e_{AC}(t)$ can be regarded as a convolution of DC coupled signal $e_{DC}(t)$ and the characteristic function of the coupling $h(\tau)$ written as

$$e_{AC}(t) = \int_0^\infty h(\tau) e_{DC}(t-\tau) d\tau \qquad (2).$$

When a step function is measured with AC couple, we obtain a characteristic curve as shown in Fig.7. Using this input-output relation we can determine the characteristic function $h(\tau)$ with which we can calculate the output signal for any kind of input, and thus make deconvolution from the AC coupled signal to DC coupled signal. The curve CAL in Fig.6 denotes synthetic DC signal thus calculated from AC coupled signal. It is obvious that the accuracy of the deconvolution is quite acceptable.

Going farther in the Sechelt Trough from the transmitter dipole the initial arrival of crustal field became no more conspicuous (Fig.8). At the site A-08 about 2.5 km apart from the source dipole for example, the signal apparently does not contain the bouncing incident of the arrival of electric field diffusing in the resistive crust. This means that the crustal field arrives later here than the site A-01R so that it is almost overlapping with the air wave. However the crustal field was not simply fading out, because we found its reappearance at A-07 and A-10 on the MacCall Bank about 4.6 km from the transmitter, the farthest sites in this experiment. This fact can not be explained without taking into account the inhomogeneity of conductivity distribution in the sea floor of the Strait of Georgia.

5. Discussion and Conclusion

If the sea bed is composed of uniform material, the characteristic time constant of the electromagnetic diffusion is given by Eq.(1a) or Eq.(1b), which gives a guess of apparent resistivity from the time constant of the step on response or the impulse response of the electric field. A precise estimation of the sea floor conductivity requires a precise determination of the characteristic rise time of the signal with various source-receiver separations. Determining characteristic times at various sites along a traverse, then we can interpret them in a similar way as we do with the travel time curve in the refraction seismology.

In practice the rise time can better be determined by taking a time derivative of the measured electric field signal. Fig.9 shows the time derivative of electric field at A-01R given by Fig.6. We can recognize two peaks in the curve;i.e. the signal has usually two maxima in rate of change. The earlier one is corresponding to the arrival time of the crustal field, and the later one with broader peak is considered to be the arrival of the "air wave" or the "over-down mode", which corresponds to the field traveling up first from the transmitter, propagating in the air with a speed of light, and then coming down again to the receiver position.

The characteristic arrival time of the air wave is therefore dependent primarily on the conductivity and thickness of the sea water. Taking into account the source receiver configuration, the distance of "travel path" of the diffusing field at A-01R can be estimated as 230 m typically, between 160 and 300 m since the receiver depth was 160 m and the electrodes were installed 160 m deep and at the coast. The corresponding typical, maximum and minimum time constant are then calculated as 0.11, 0.19 and 0.05 seconds, respectively, from Eq.(1b) letting conductivity of sea water be 3.3 S/m. These values coincide well with the representing parameters of the peak (i.e. peak time and the times of the half peak values) of the time derivative curve (Fig.9). This agreement means that , if we do not know the sea water conductivity, we can accurately estimate it with the arrival time of air wave and water depth.

The conductivity of the crust can be estimated in a similar way using the arrival time of the crustal field. Eq.(1b) gives us a definition of AC apparent resistivity as :

$$\rho_{ap}^{AC} = \frac{\mu_0 l^2}{2\tau_{obs}} \qquad (3),$$

where τ_{obs} denotes the characteristic arrival time of the crustal field which gives the steepest rate of change in the transient electric field intensity. At the site A-01R, for example, the characteristic time is estimated as about 15 msec (see Fig.9). Taking into account that the source receiver separation l is 1.6 km (Table 1), the AC apparent resistivity can be evaluated as about 50 Ωm. We determined the AC apparent resistivity at A-01R, A-02 and A-10 (A-07) as given in Table 2.

Chave and Cox (1982) gave an exact expression for the transient electric field in horizontally stratified medium. Cheesman (1988, in preparation) developed a computer program to calculate the transient field on sea bed with finite water depth. Fig.10 compares observed signal with theoretical curves of transient electric field at A-07 for various sea floor conductivities. Neglecting the initial bouncing and noise, its wave form is roughly explainable assuming the sea floor conductivity to be about 30 Ωm. This is equivalent to the apparent resistivity in conventional dipole-dipole method on land.

Cheesman (1988) showed that, when the source-receiver separation is small compared to the water depth or the sea floor is resistive enough, electric field diffusing in the crust arrives definitely earlier than the air wave; we can determine the apparent resistivity using the arrival time. In this case, sea floor behaves as a nearly perfect insulator letting most of the electric current flow in the sea water so that the signal value at DC limit has least information on the conductivity of the sea floor. On the other hand, with increasing the conductivity of sea floor or the source-receiver separation, the arrival of the crustal field becomes later until we can not recognize it because of the arrival of the large "air wave". Therefore it is usually hard to determine the AC apparent resistivity at far sites. However it was also shown that this situation makes the resolution higher at late time curve and so we can alternatively determine the DC apparent resistivity in that case by comparing the observed and calculated curves as shown in Fig.10.

Thus estimated DC apparent resistivities are tabulated on Table 2. It is obvious that the present result indicates an increase in the bottom conductivity in the Sechelt Trough (from A-01R to A-09) then a sudden decrease up on the MacCall Bank (A-10). So we can conclude the feasibility of the present method. However the result is obtained only from a rough interpretation. As shown in Fig.10 the observed wave form can never be explained by a model with uniform sea bed. Next step may be include the effect of layering. Fig.11 gives a diagram indicative of the effect of layering, where we assume the sea bed is composed of two layers below 200 m deep sea at a site 2000 m from the transmitter dipole, surface layer being 200 thick and having 0.01 S/m, and substratum with varying conductivity. When the substratum is more resistive by one order of magnitude, the crustal field arrives earlier and its amplitude becomes smaller than in the uniform 0.01 S/m medium. On the other hand we can expect a later arrival of larger crustal field for more conductive sea bed. The electromagnetic field propagates effectively in a resistive layer bounded by conductive layers, since the layering makes a sort of wave guide. If sea water and the deeper layer are perfectly conductive, it is TE mode, a mode with electric field perpendicular to the layering, that propagates non-dissipatively from a horizontal electric dipole on the sea bed. The enhancement of the crustal field amplitude can be explained by this effect.

However it is still impossible to interpret such a steep bouncing observed at A-10 (Fig.10). The bouncing is unlikely to be due to noise because identical signal has been detected at A-07 also on MacCall Bank. The feature is therefore very likely to be representing the horizontal variation of sea floor conductivity. It is not quite certain whether the sudden rise up of the sea floor depth has any effect on the phenomenon, so long as we deal with a layered earth modeling. In this paper interpretation has been done implicitly assuming that the definite lateral conductivity contrast between land and sea does not affect the arrival time of the transient electromagnetic field. Ultimately, the data must be interpreted by taking into account the two-dimensional distribution of the conductivity as well as the bathymetry, which will be done elsewhere (Everett et al., 1989, in preparation).

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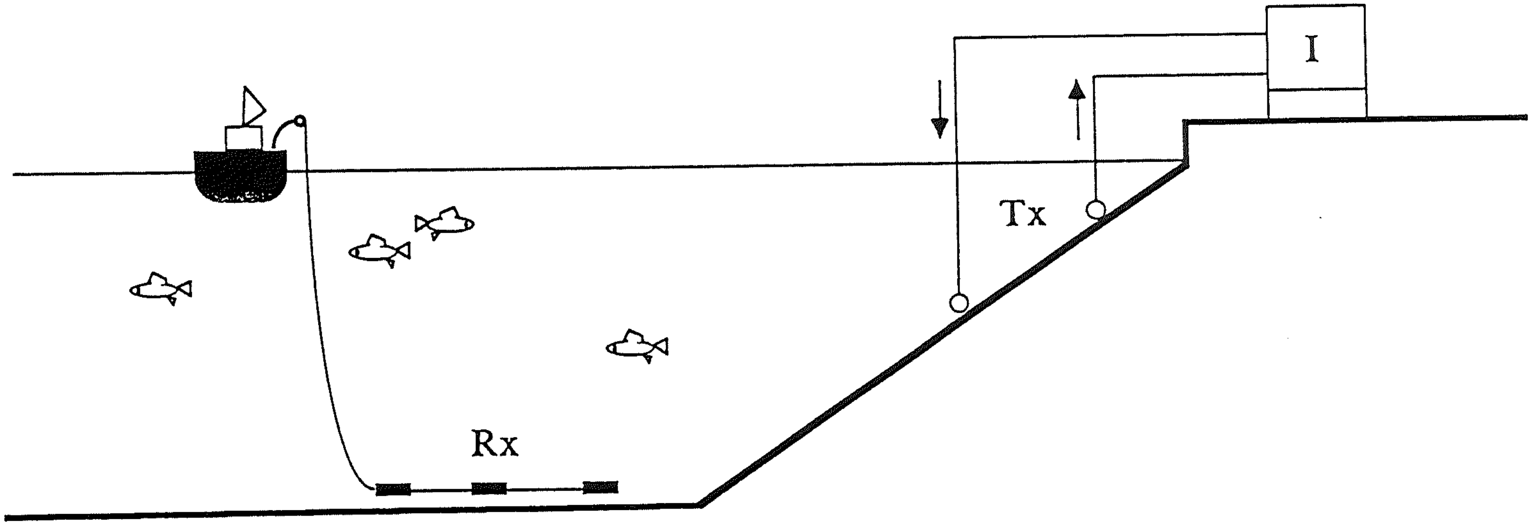

Fig.1 A schematic diagram showing the receiver-transmitter arrangement of the off-shore transient electric dipole-dipole experiment. Three electrodes are towed from the ship, connected by a marine cable.

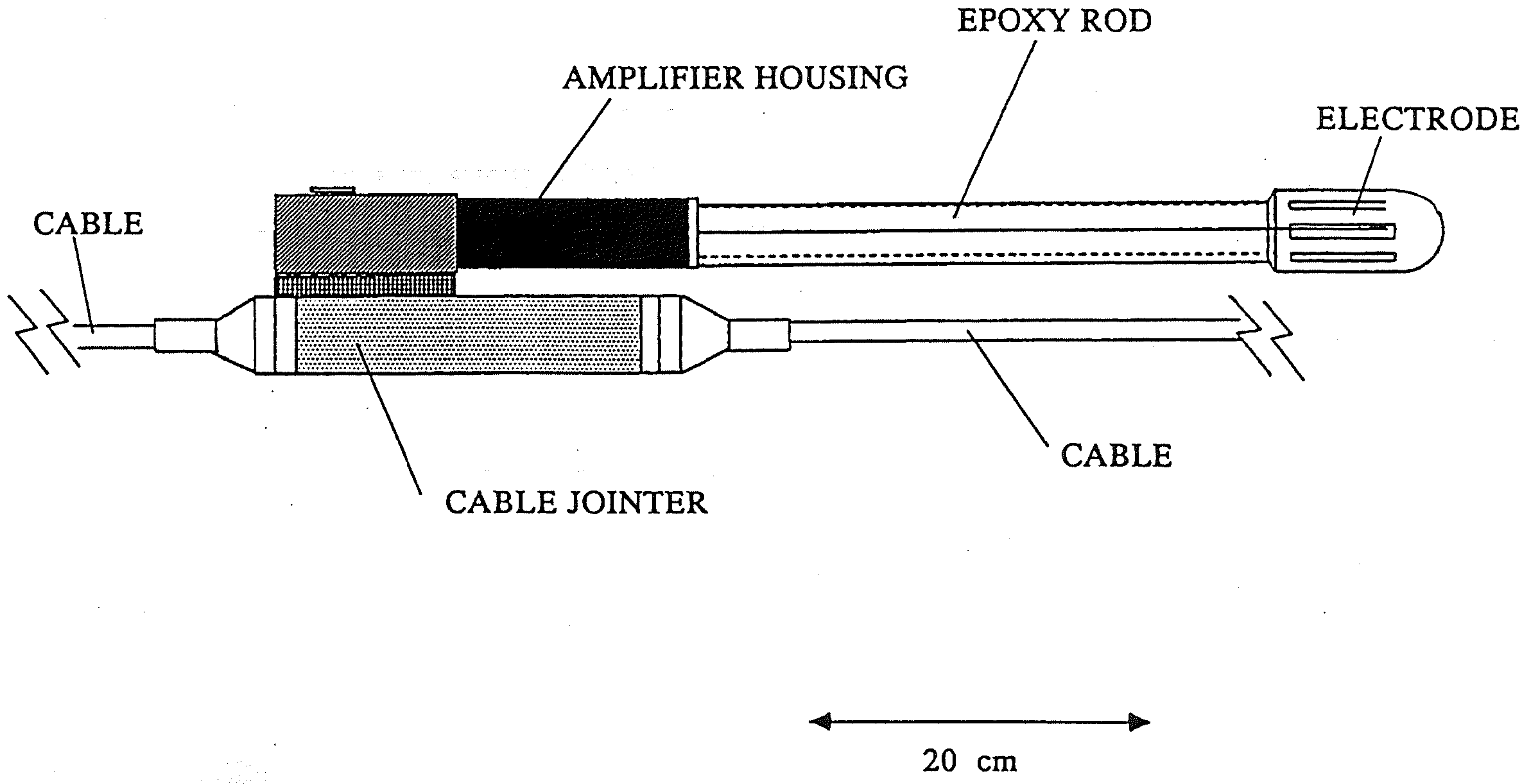

Fig.2 A receiver unit composed of electrode holder, amplifier casing, and cable jointer. An Ag-AgCl electrode is kept in the plastic cover at the end of the holder rod.

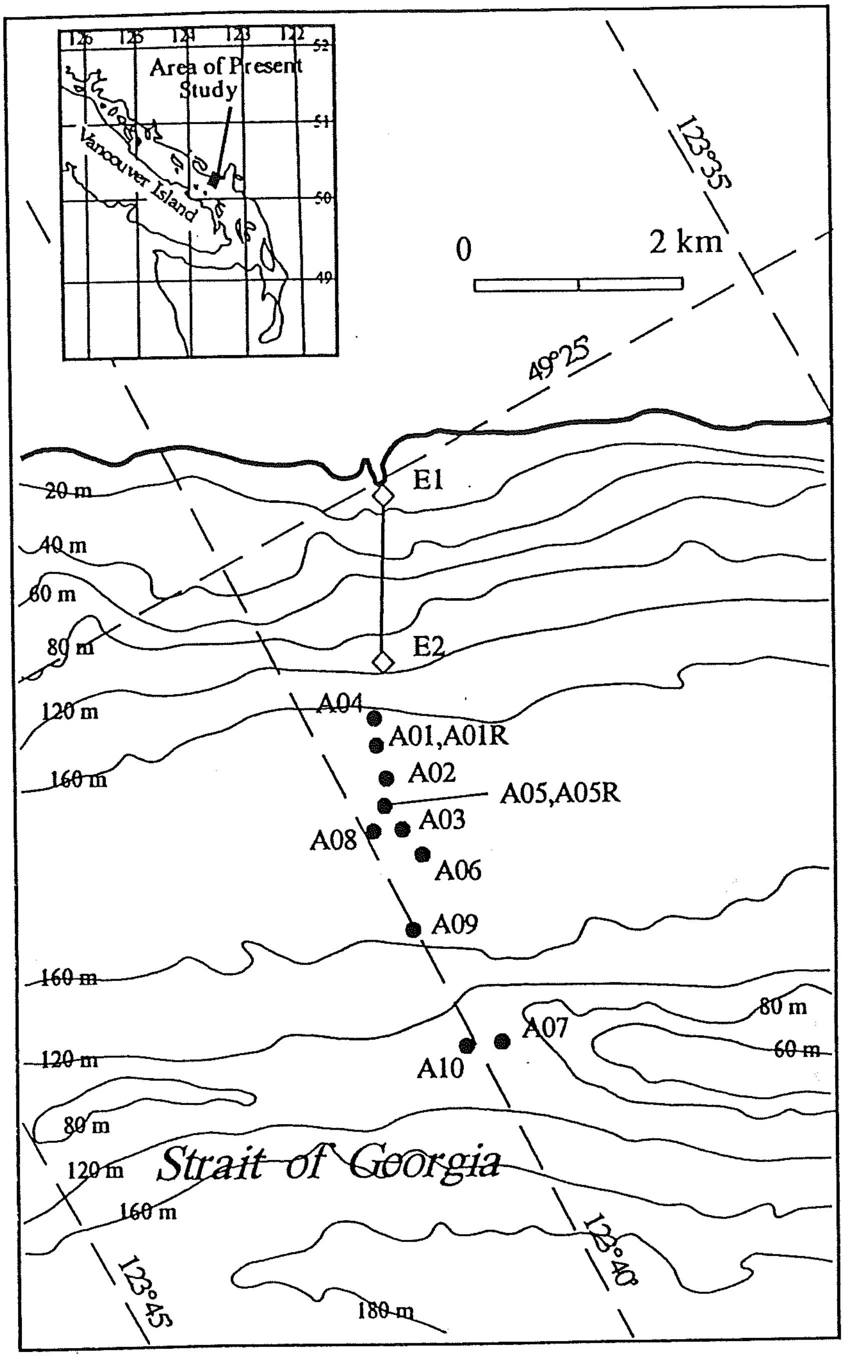

Fig.3 Map showing the survey area. The transmitter dipole (E1-E2) was installed at the Sunshine Coast, and the measurements were conducted at the sites denoted by dots.

TABLE 1. Summary of observations at Strait of Georgia, in June 1988.

site	date	time (PDT)	distance (km)	depth (m)	dipole length (m)	preamp gain (dB)	remark
A01	14	12:15	1.60	160	100	34	
					50	34	
A01R	14	14:50	1.60	160	100	34	
					50	34	
A02	14	17:30	1.92	165	100	34	
					50	34	
A03	15	10:00					no visible signal
A04	15	14:30	1.20	158	100	54	vertical component
					50	54	
A05	15	15:10	2.16	165	100	54	
					50	54	
A06	15	16:20					no visible signal
A07	15	17:30	4.64	110	100	54	
A05R	16	10:50	2.16	160	100	54	
A08	16	11:50	2.48	165	100	54	
A09	16	13:30	3.56	165	100	54	
A10	16	16:05	4.68	130	100	54	

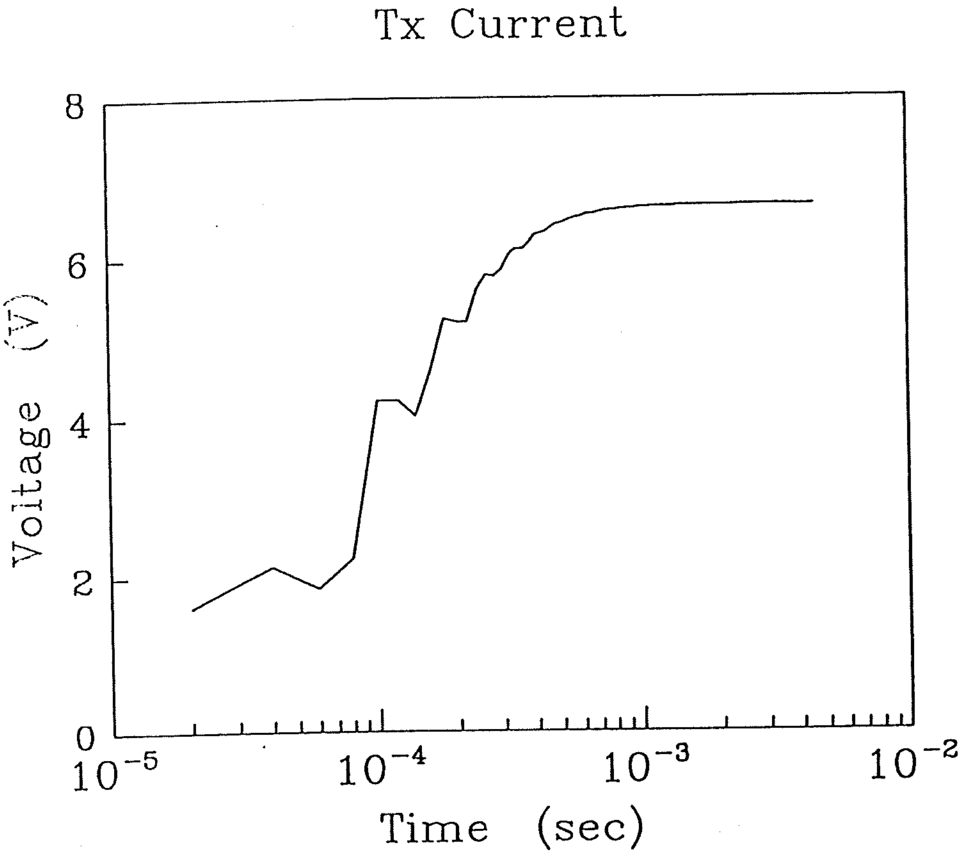

Fig.4 A detailed wave form of the transmitter current.

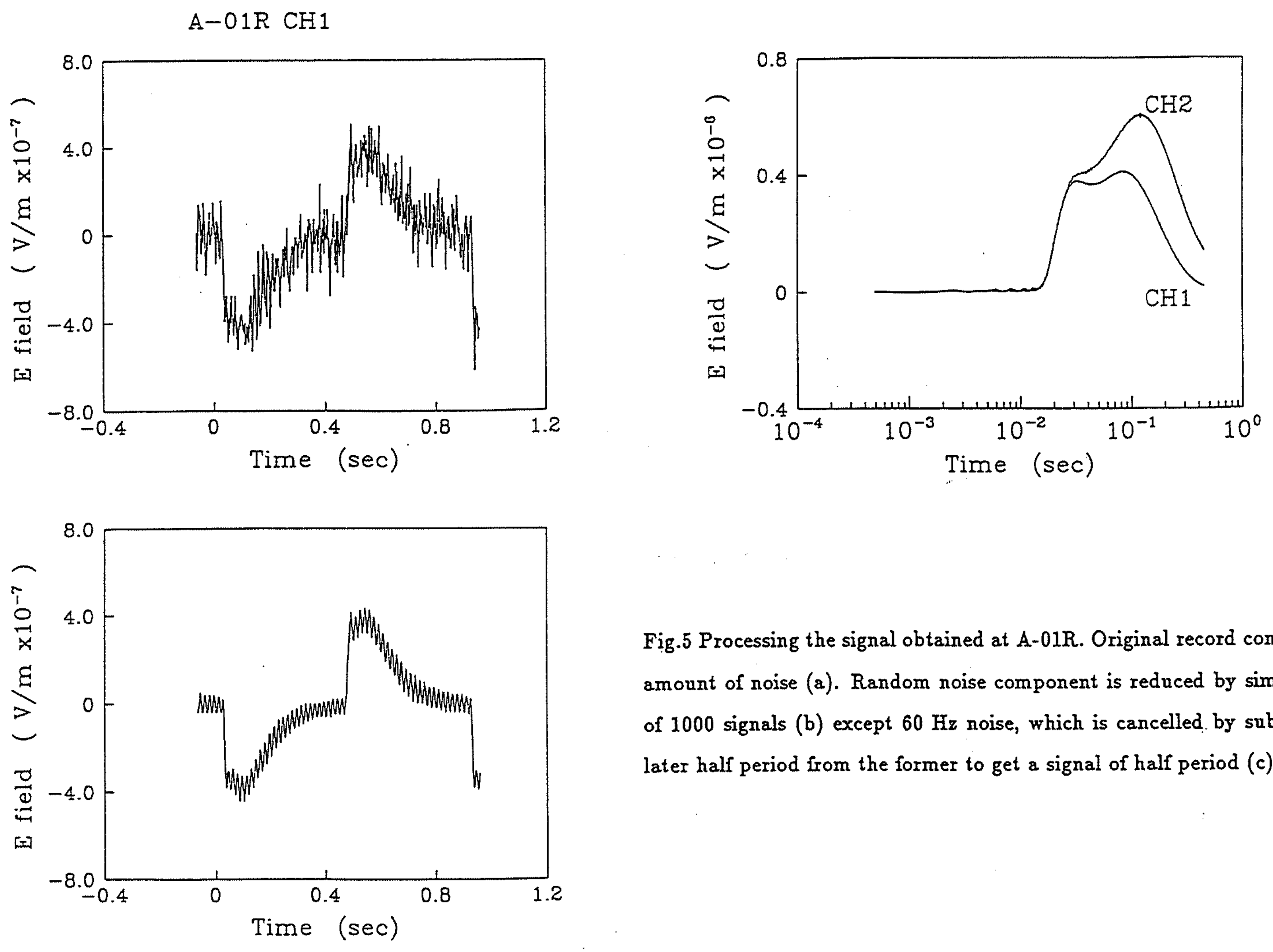

Fig.5 Processing the signal obtained at A-01R. Original record contains a large amount of noise (a). Random noise component is reduced by simple stacking of 1000 signals (b) except 60 Hz noise, which is cancelled by subtracting the later half period from the former to get a signal of half period (c).

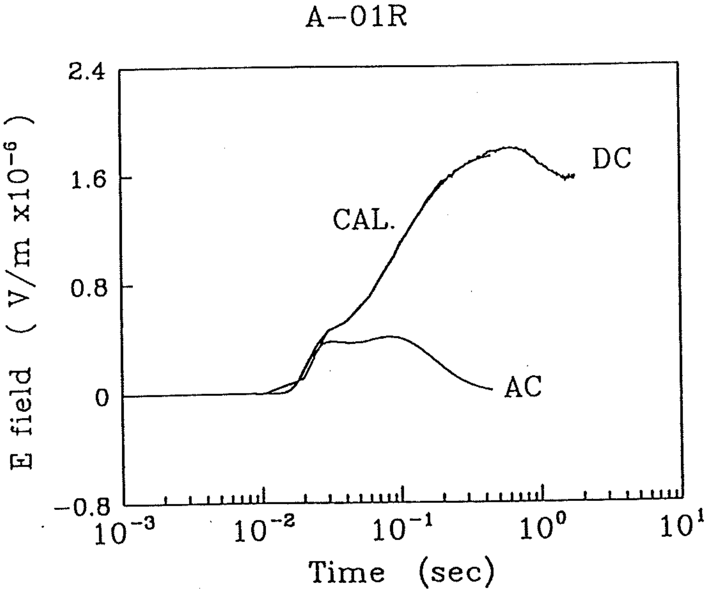

Fig.6 Signals recorded at A-01R. DC and AC denote those measured using DC and AC coupling with DATA6000, respectively. CAL is the synthetic DC signal deconvoluted from AC signal.

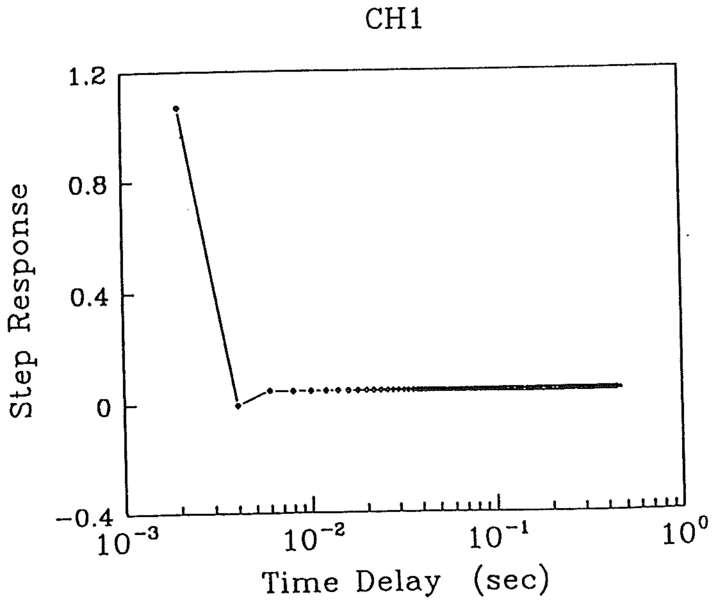

Fig.7 A step function measured by DATA6000 with AC coupling.

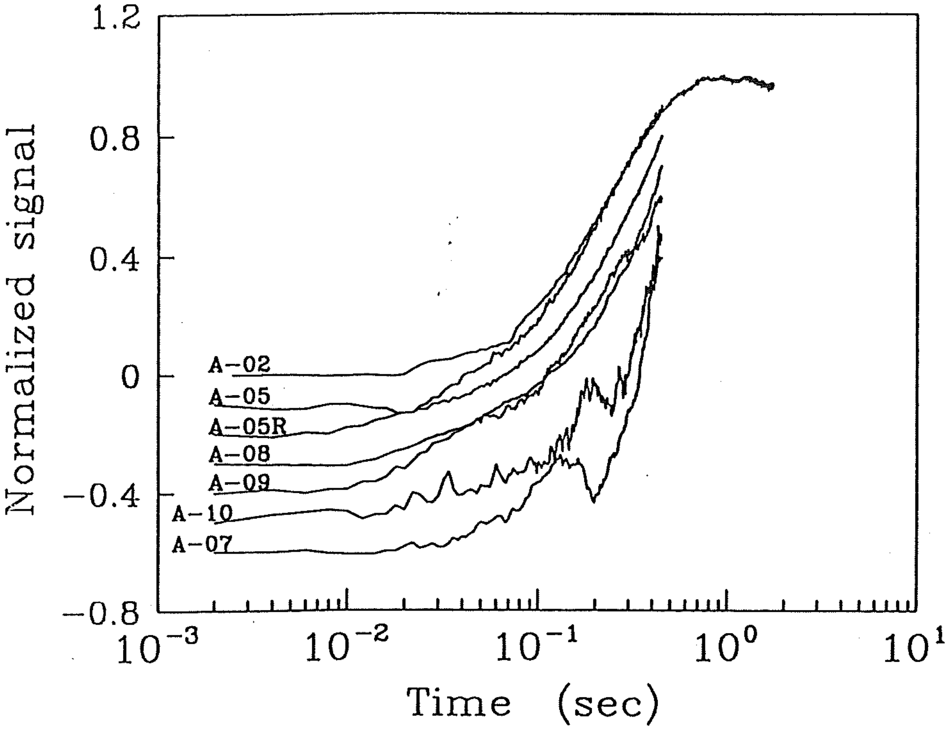

Fig.8 Transient electric field signals observed at A-02, A-05, A-05R, A-08, A-09, A-10 and A-07. Each signal is normalized to its DC limit value. Note that the signal is getting smoother in the Shechelt Trough, while a remarkable initial bounce reappears on the MacCall Bank (sites A10 and A-07).

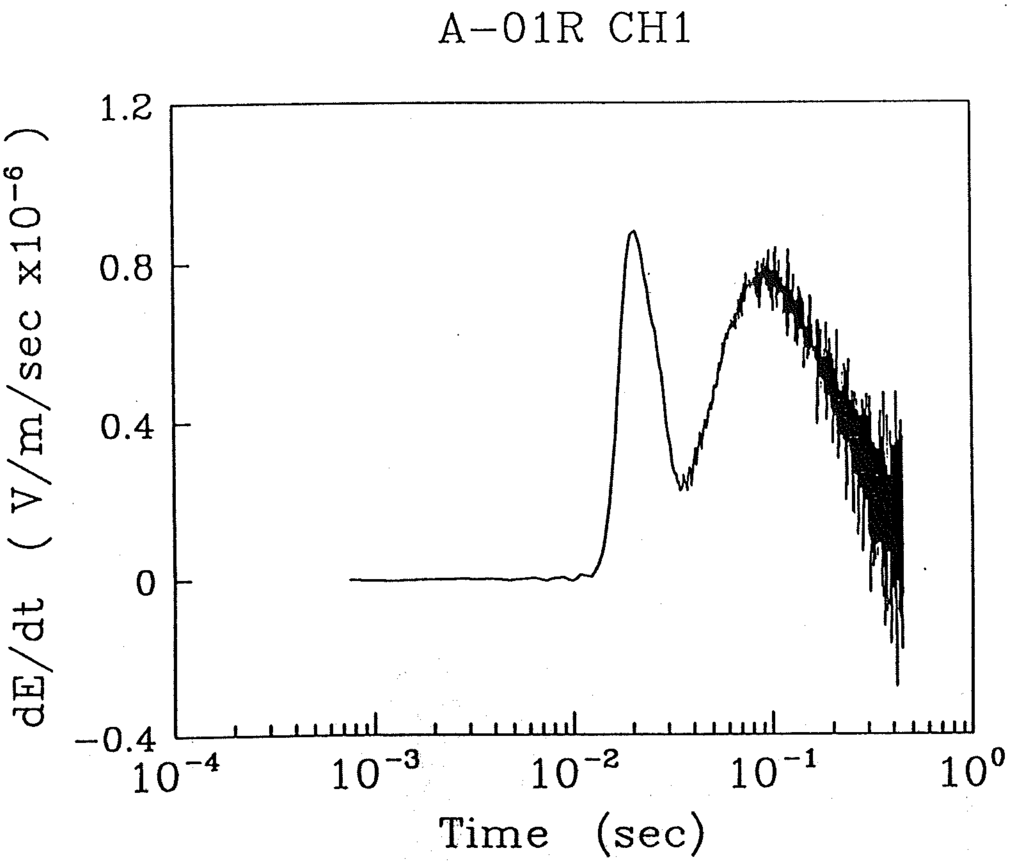

Fig.9 Time derivative of electric field signal at A-01R.

TABLE 2. Estimated DC and AC apparent resistivities.

site	distance (km)	ρ_{ap}^{DC} (Ωm)	ρ_{ap}^{AC} (Ωm)
A-01R	1.60		50
A-02	1.92		30
A-05R	2.16	15-20	
A-08	2.48	6-10	
A-09	3.56	3-5	
A-07	4.64	30-50	110-150
A-10	4.68	20-30	75-90

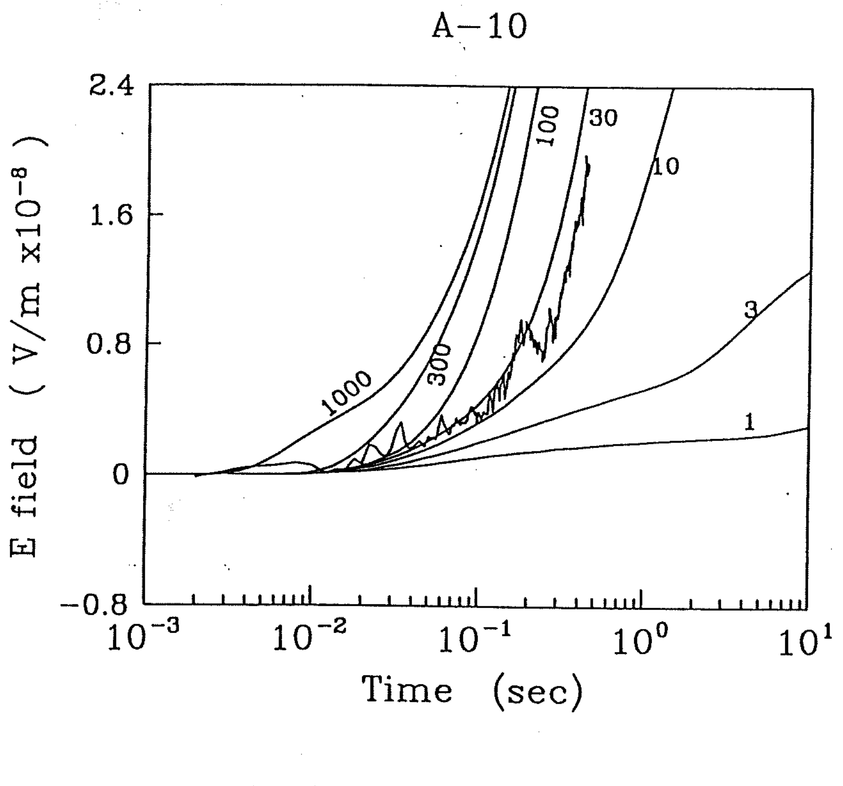

Fig.10 Observed (OBS) and calculated electric field responses at A-10. Calculations are made for the uniform sea floor resistivity values of 1, 3, 10, 30, 100, 300, and 1000 Ωm.

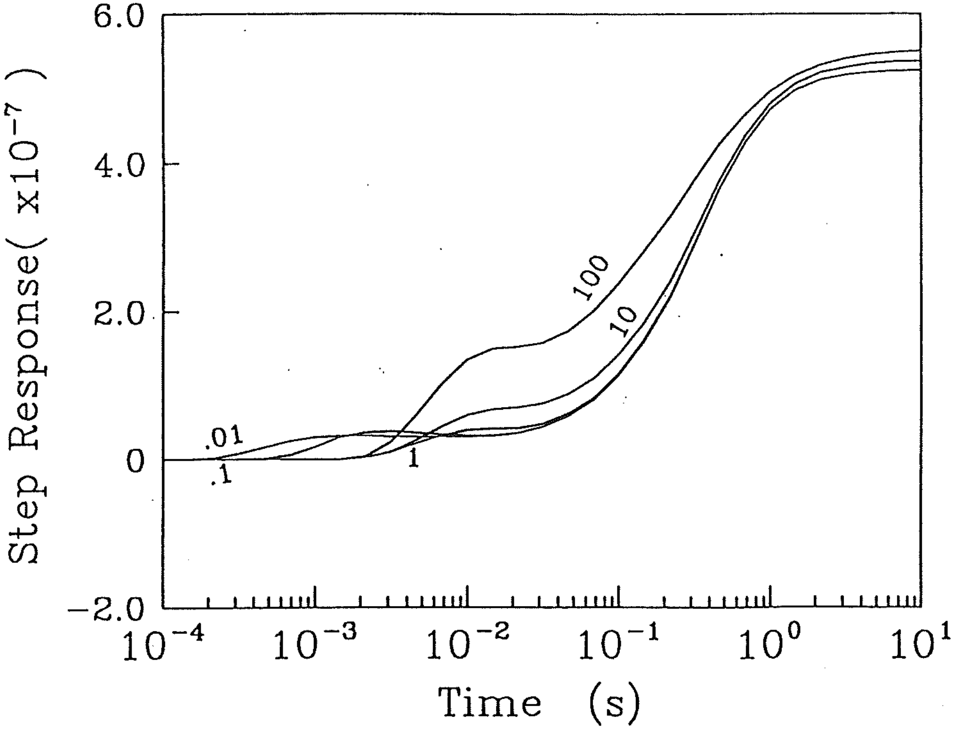

Fig.11 Effect of layering on the transient electric field response with a receiver 2000 m apart from a transmitter dipole of 1000 Am on 200 m deep sea floor. Sea floor consists of two layers; i.e. top surface and a substratum. The resistivity of the top layer has been kept as 100 Ωm. Calculations were done for the substratum resistivities of 1, 10, 1000 and 10000Ωm and for the uniform case.