GEONICS LIMITED
1745 Meyerside Dr. Unit 8 Mississauga, Ontario Canada L5T 1C6

Tel: (905) 670-9580
Fax: (905) 670-9204
E-mail: geonics@geonics.com
URL:http//www.geonics.com

Technical Note TN-15

TRANSIENT ELECTROMAGNETIC BOREHOLE LOGGING

G.M. LEVY, J.D. MCNEILL

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INTRODUCTION

The technique of transient or time domain electromagnetic (TEM) surveying is finding ever wider application in the field of resource exploration and development. This paper will describe the technique as embodied in the Geonics EM37/BH43 borehole system, describing the basic physical principles which come into play. The nature of the instrument response to conductive overburden, host rock, and confined bodies will be discussed. More detailed treatments can be found in the references listed at the end of the paper.

MEASUREMENT TECHNIQUE

The procedure used in borehole logging is to lay a large loop transmitter (Fig.1), typically hundreds of meters on a side, in the vicinity of the borehole. Often several different loop positions are used to aid in interpretation. The receiver is lowered into the borehole, and data is collected at each station chosen for measurement, using a magnetic tape data logger located at the surface. An HP85 computer is used for final data editing and reductions.

Transient EM is distinguished from the more familiar frequency domain EM by the transmitter waveform, and by the way in which the receiver signal is analysed (Fig.2). In the case of the EM37, a steady current of up to 30 amperes is caused to flow in the transmitter loop, for a time sufficiently long to allow transients induced in the ground by the switched current essentially to dissipate. This current is then turned off sharply, which results in currents being set up in the surrounding medium so as to oppose any instantaneous change in the magnetic field. These currents then decay away according to the conductivity structure of the medium (as will be discussed in more detail below) and it is the field due to these currents - or more precisely the time derivative of this field, dB/dt, - which is measured at the output of the receiver coil.

The EM37 receiver divides the time period after turnoff into 20 segments or gates, covering a range of 2 decades in time from the earliest to the last, or 3 gates per "octave". The signal for each gate is added to the signal for the same gate for previous repetitions of this basic cycle (stacking), until adequate signal-to-noise is reached.

One principle advantage of TEM over frequency domain EM is that, in the above manner, responses which are analogous to responses for 20 single frequencies ranging over 2 decades, are gathered at the same time, rather than having to be recorded separately. With the EM37 operating at a base frequency of 30Hz, the earliest gate is centered 89 μs after the end of turnoff, and the latest gate at 7.2 ms. If later times are important a lower base frequency may be used.

Another advantage is that, since measurements are made while the TX current is turned off, the measurements are insensitive to small variations in the RX orientation, which could otherwise produce changes in coupling with the primary field.

One complication in analysing the response arises due to the fact that the transmitter turnoff is not actually instantaneous, but rather takes place over a finite period of time. In fact, for the 30Hz base frequency, the turnoff ramp is typically 300 μs long, whereas the 1st gate starts less than 100 μs after the end of turnoff. This means that the response measured by the instrument is not quite the same as would be expected for an ideal impulse, but is rather the ideal impulse response convolved with a rectangular waveform of width equal to the duration of the turnoff. As the difference can be quite significant for the earlier gates, this must be taken into account, and a deconvolution operation may be carried out as part of the data reduction procedure.

Other TX waveforms are used in TEM work as well. One particular case of interest is the UTEM system, in which the waveform used is essentially triangular in shape. The effect is to provide a response which corresponds to the B field which would be obtained for the case of an EM37 type of waveform, as opposed to dB/dt. The cost is having to make measurements while the TX is on.

The EM37 reduction software routinely provides B, as it is automatically calculated in the process of deconvolving the waveform, and so may be used with interpretation techniques based on this quantity rather than dB/dt.

SECONDARY RESPONSES -

Resistive environment

Returning to the secondary response due to currents set up in the surrounding medium, it is instructive to examine what we might expect in some idealized situations. The simplest case is, of course, free space. In practice this means an environment with resistivity so large that the currents have decayed to levels below the detection limit by the time the 1st gate begins; rather uninteresting except to note that this has happened.

Thin sheet

Not quite so trivial is the situation of a thin conductive overburden, overlying a highly resistive medium which may be considered again as essentially free space (Fig.3). In this case a current flow is set up in the sheet which at very early times is concentrated very closely in the vicinity of the TX loop. (This distribution mirrors the field which existed immediately prior to turnoff). However, the current very rapidly diffuses across the sheet and the field eventually decays as t^{-3}. The field for the thin sheet may be easily calculated, as image theory tells us that the response is that which would be obtained for a current loop which is the size and shape of the TX loop, but which moves away from the measurement point, in a direction perpendicular to the sheet, with a velocity inversely proportional to the plate conductance.

Half-space

In the case of a conductive half-space, the current distribution is again initially confined to the vicinity of the TX loop; however, in this case, the diffusion of the current proceeds downwards as well as outwards. Figure 4 shows current density contours calculated by Nabighian (1979). (Hoversten and Morrison 1982, have published similar contours for up to 3 layers.) The peak current density is seen to move downwards and outwards at about 30° from horizontal. The shape of the current distribution in the ground is a function of ρt, the product of the resistivity and the measurement time: indeed the peak in current density occurs at a horizontal distance from the TX given by 1.6 $(\rho t)^{\frac{1}{2}}$ km. Nabighian also points out that the field as measured at the surface at late time, is in fact close to that due to a current loop decaying as 1/t and travelling downward and outward at 47°. This is a simplification which is useful in understanding the type of response we see in practical cases.

Figure 5 shows responses along a 45° borehole extending to a depth of 500m in a 50 ohm-meter half-space, for 3 different positions of a 200m radius circular TX loop: centered over the upper end, middle portion and deep end of the borehole respectively. The responses plotted are for the axial downhole component of the field in units of nV/m^2 for a 1 amp TX current. (EM37 noise levels are not discernable with this plotting scale, so these responses will occur at high signal-to-noise ratio.) In Figure 5a we see results for earlier gates - 2,5, and 8, corresponding to ρt values of approximately .005, .01 and .02 ohm-m-sec. The response tends to peak in the upper portion of the drill hole, though there is some indication of the peak becoming deeper and broadening towards the later times. At points within the borehole, it can be seen that at earlier times the response may actually increase in amplitude with time. The detailed shape of the response, as might be expected, depends very much on TX position. In fact, for these gates, the response with the TX loop centered over the deep end of the hole is opposite in sign to the responses for the other 2 TX positions: the upper portion of the borehole is outside the effective current loop in the ground for the one TX, inside for the other 2.

Figure 5b shows the responses for later gates, ρt being .04, .08 and .16 for gates 11, 14 and 17. As the currents move farther from the original TX positions, the responses become smaller, deeper, and broader, and the differences in TX position become less and less important.

Confined Conductors

The response of confined conductors is of considerable interest, as this is a model which can often be used to represent ore bodies. Figure 6 illustrates the physical effects which combine to set up current flow in confined conductors. The important factors to be considered are the electric field vector, $\bar{E}$, and the rate of change of the magnetic field vector, $d\bar{B}/dt$ or $\dot{\bar{B}}$.

The effect of the $\bar{E}$ field is rather involved, and dependent on the conductivity and shape of the target body, and the conductivity of the host rock as well (Edwards 1974; Kaufman 1978); however the net result is current flow in the conductive body in the direction of and in proportion to the field itself - the so-called current gathering effect or Galvanic response - accompanied by a diffuse return current in the host medium. Note that if the host medium is highly resistive, the field dies away rapidly, as does this current, according to a $t^{-5/2}$ power law.

The secondary field produced by the Galvanic component of the current can be useful in determining the position of the body; however much more information can be obtained about the body if effects of vortex currents, produced by $d\bar{B}/dt$, can be observed. As in the case of the thin sheet or half-space, any change in the magnetic field sets up currents which initially are confined to the surface of the body and which oppose the change in the field. The currents at this time can be considered as loops at the surface of the body, circulating in planes perpendicular to the $\dot{\bar{B}}$ vector excitation. Once the initial $\dot{\bar{B}}$ disappears, these currents diffuse to the interior of the body, in a manner which is determined by its shape and conductivity. Conceptually, the currents may be resolved into component currents, the paths of which are characteristic of the body's shape (eigen-currents). These eigencurrents each decay exponentially at rates which reflect the effective L/R time constants for the different current paths. At sufficiently late time (late stage), the current path with the largest decay time constant will dominate (Kaufman, 1978).

In the case of a thin, plate-like body, the currents will quickly be reduced to those in the plane of the plate, although the distribution within the plane will continue to change until the late stage for the largest loop is reached.

Examination of the secondary field due to vortex currents in a confined conductor can reveal several properties. The longest decay time constant is proportional to the conductivity times the smallest cross section of the body. The spatial variation of the field is indicative not only of the position of the body, but also of the orientation of the effective plane of the vortex current. For example, a thick body will produce a response which corresponds to currents in a plane determined initially by the direction of the primary field, but which eventually rotates to a direction characteristic of the body's own geometry. It may often be distinguished by this type of behaviour from a thin plate-like target in which the vortex currents always remain in the plane of the plate.

At sufficiently early and sufficiently late times, the Galvanic currents due to the $\bar{E}$ field will dominate the vortex currents set up in the confined conductor by $\dot{\bar{B}}$. However under favourable conditions the vortex response may be strong enough to be useful in interpretation. It can be shown that the ratio of the vortex current to the Galvanic current is at its maximum at a time after turnoff equal to a few vortex decay time constants.

Figure 7 shows the borehole response for the late stage vortex currents in a plate-like confined conductor. The shape is constant, but the amplitude decreases exponentially with time. The asymmetry of the shape is characteristic of a body which is dipping with respect to the borehole direction, while the width of the response reflects the distance from the borehole. The actual plate-borehole geometry is shown in Fig. 8 - the curves of Fig. 7 being generated by the plate with the solid boundary. An interpretational problem arises in borehole work when only the field component along the borehole axis is measured, as the response produced by currents in a body in one particular position does not change if the body is rotated arbitrarily about an axis along the borehole. Thus the flat-lying plate in Fig.8 (dashed boundary) can, when suitably excited, produce the same shape response as the vertical plate. The main difference will be the amplitude of the response. Indeed, by using several different psoitions of the TX loop it is possible to resolve such ambiguities, through consideration of the response amplitudes for different possible body positions and how these vary with the TX positions.

Figure 9 shows the vortex response of the vertical plate of Fig. 8, combined by simple addition with the response for the 50 ohm-meter half-space, for the same 3 TX positions used earlier. (Simple adding of the responses is not strictly correct, but often close enough.) The late gates only are shown; at the earlier times the plate response is almost completely lost in the half-space response. As can be seen the plate response is strongest with the TX to the left. Note also the change in sign of the response between the left and the other two TX positions. The variation in behaviour would be very different were the plate lying in the horizontal position.

Another point illustrated by this set of responses is the importance of recognizing the influence of the half-space on the profile shapes. Any attempt to determine attitude parameters for the plate, for example from the shape of the curves with the left TX position, is likely to be considerably in error if the effect of the half-space response is not first removed with sufficient accuracy.

In conclusion, transient EM can be a powerful tool in borehole applications; however, attention must be given to the various interpretational complications if it is to be used most effectively.

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Modes of Operation

Borehole

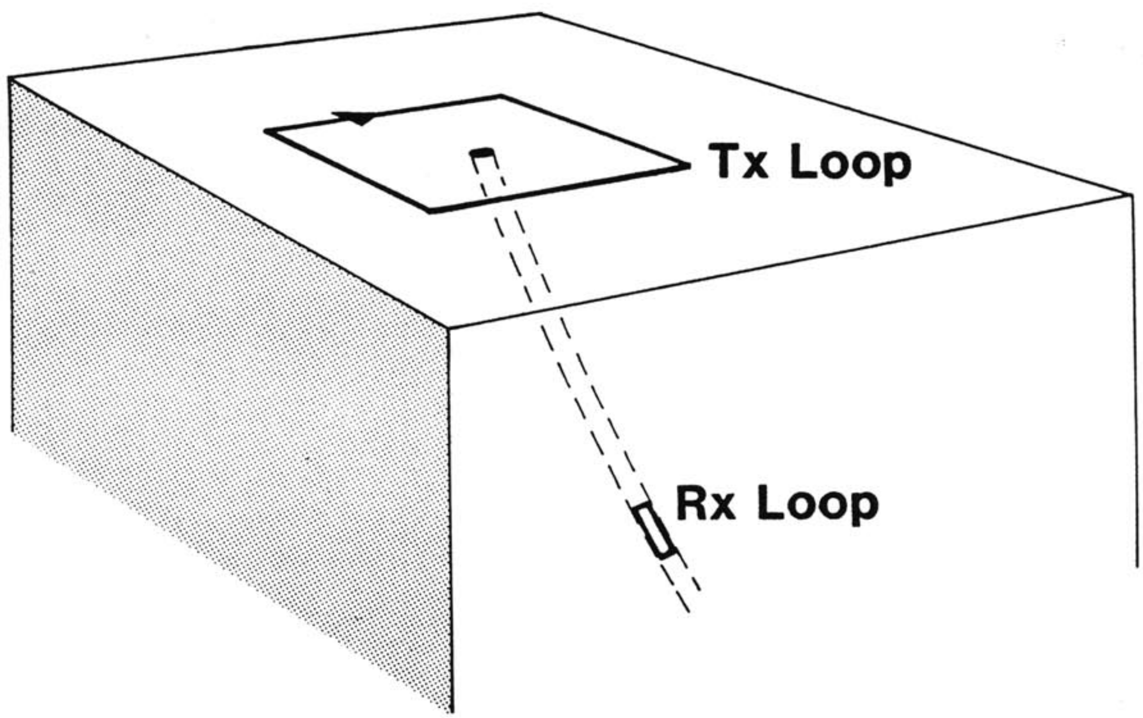


Figure 1

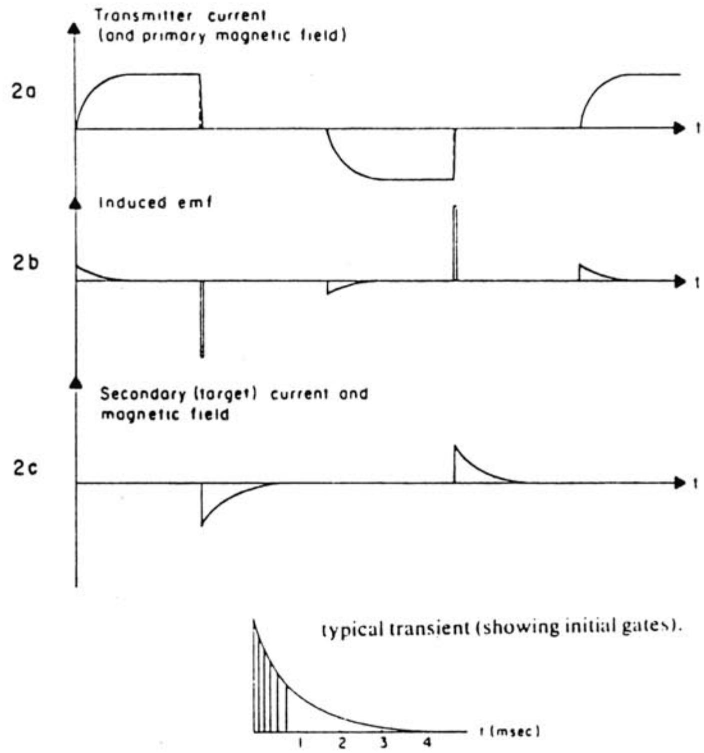
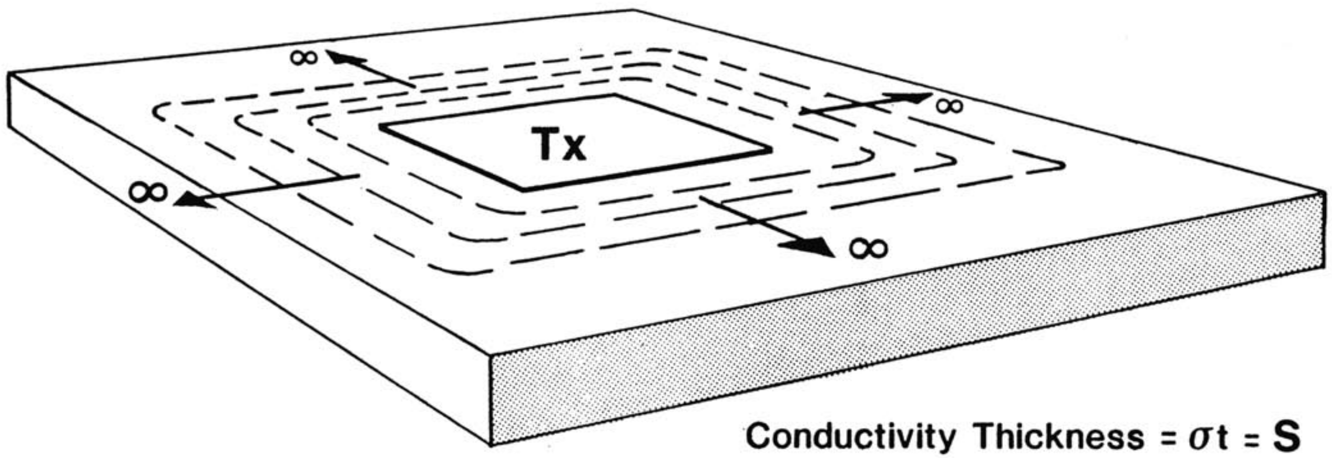


Figure 2. TEM waveforms.

Unconfined Conductors

Horizontal Thin Sheet



Conductivity Thickness = $\sigma t = S$

At late time (horizontal coil receiver)

Signal voltage $\propto \frac{S^3}{t^4}$

Figure 3

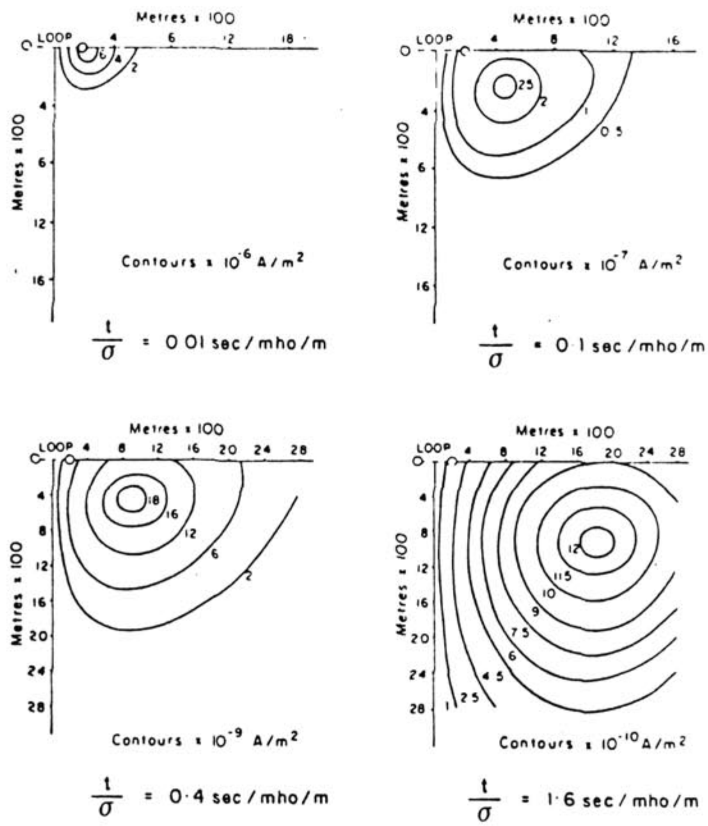


FIGURE 4. *Computed contours of current density passing through loop* centre (loop has dimensions 400 × 800 m) .

HOMOGENEOUS HALF-SPACE RESPONSE

EARLY GATES

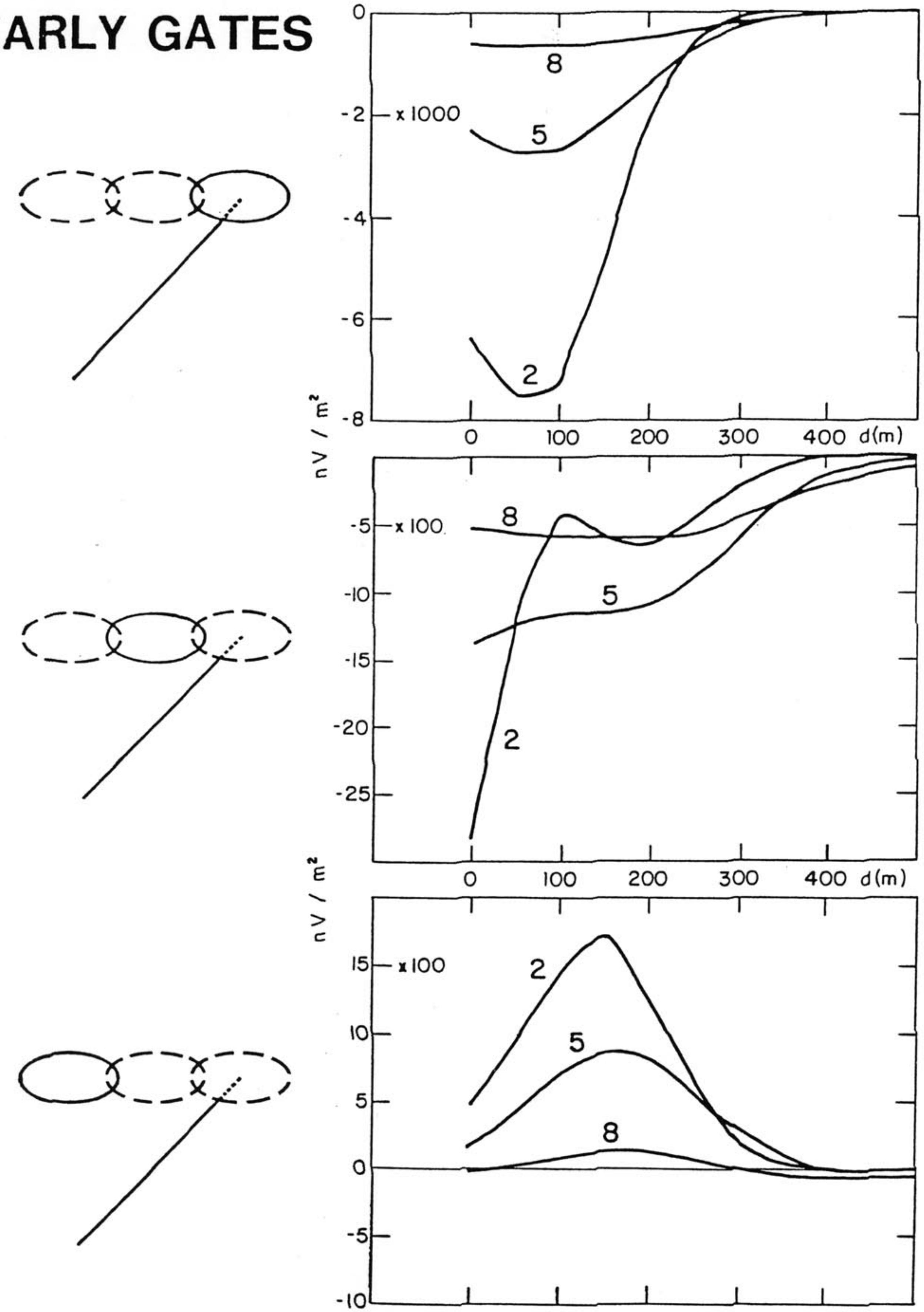


Figure 5A

HOMOGENEOUS HALF-SPACE RESPONSE

LATE GATES

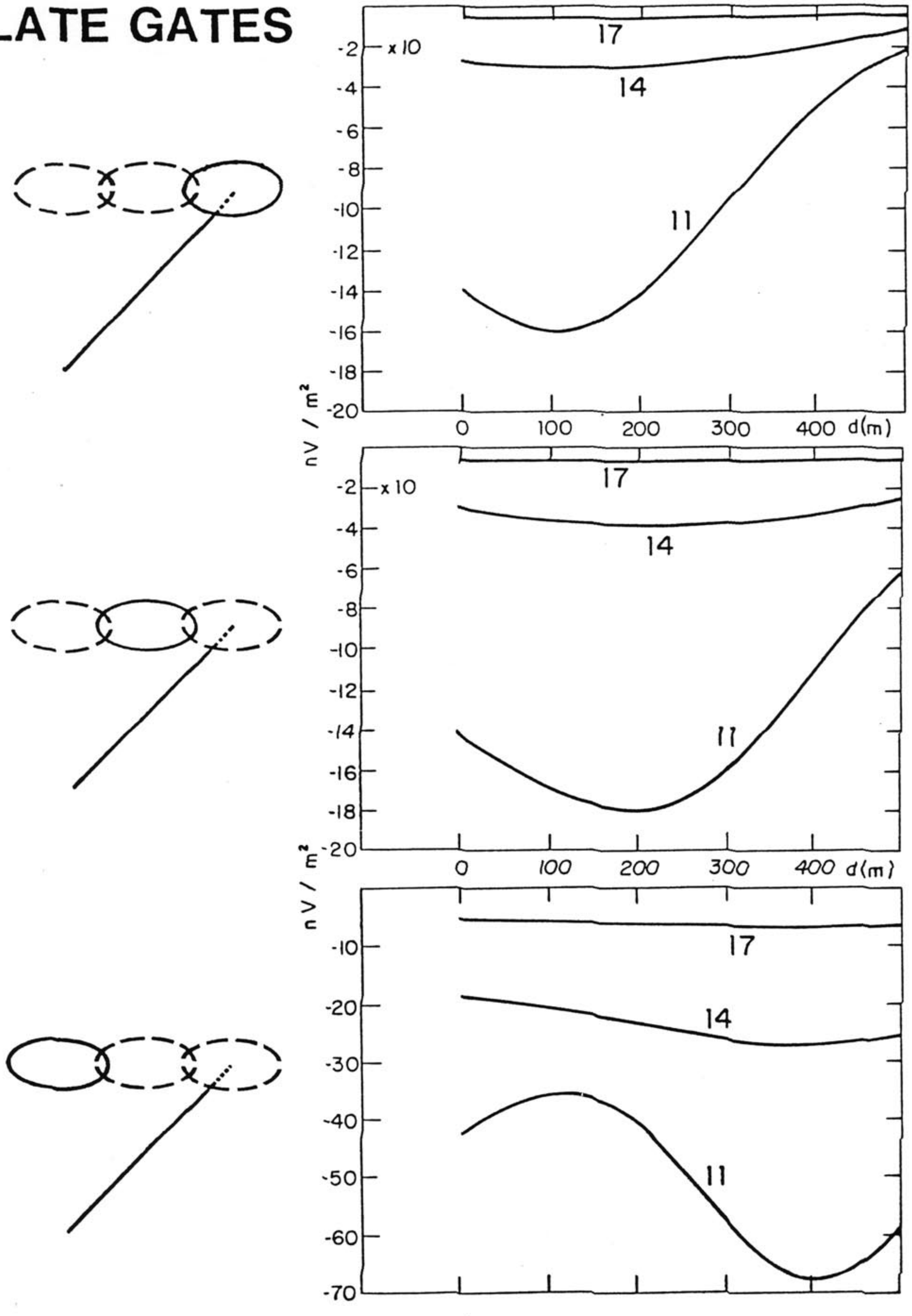
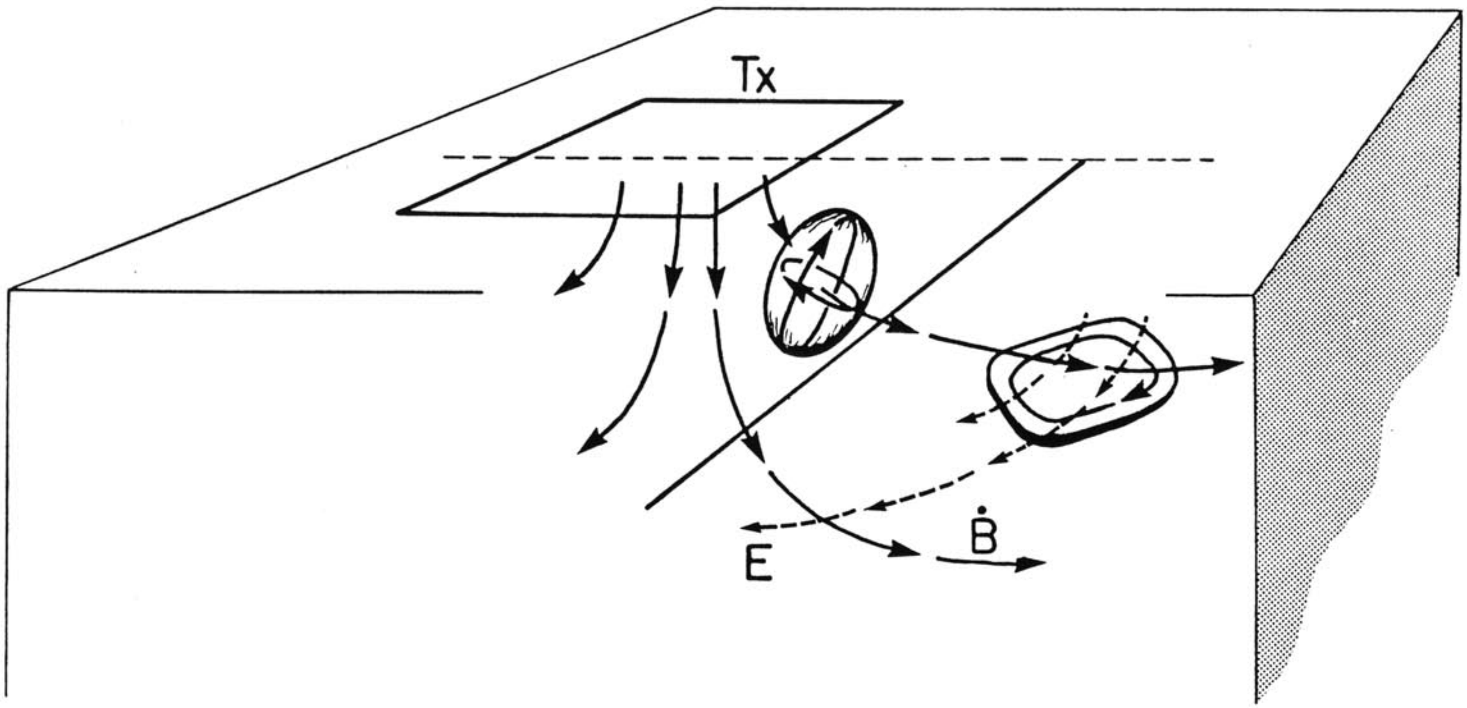


Figure 5B



CONFINED CONDUCTORS

Figure 6

PLATE RESPONSE LATE STAGE

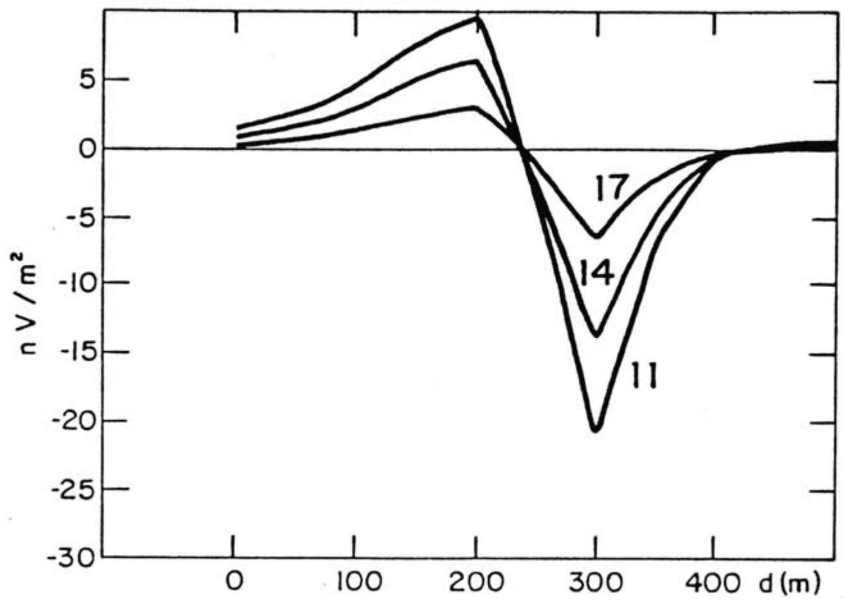
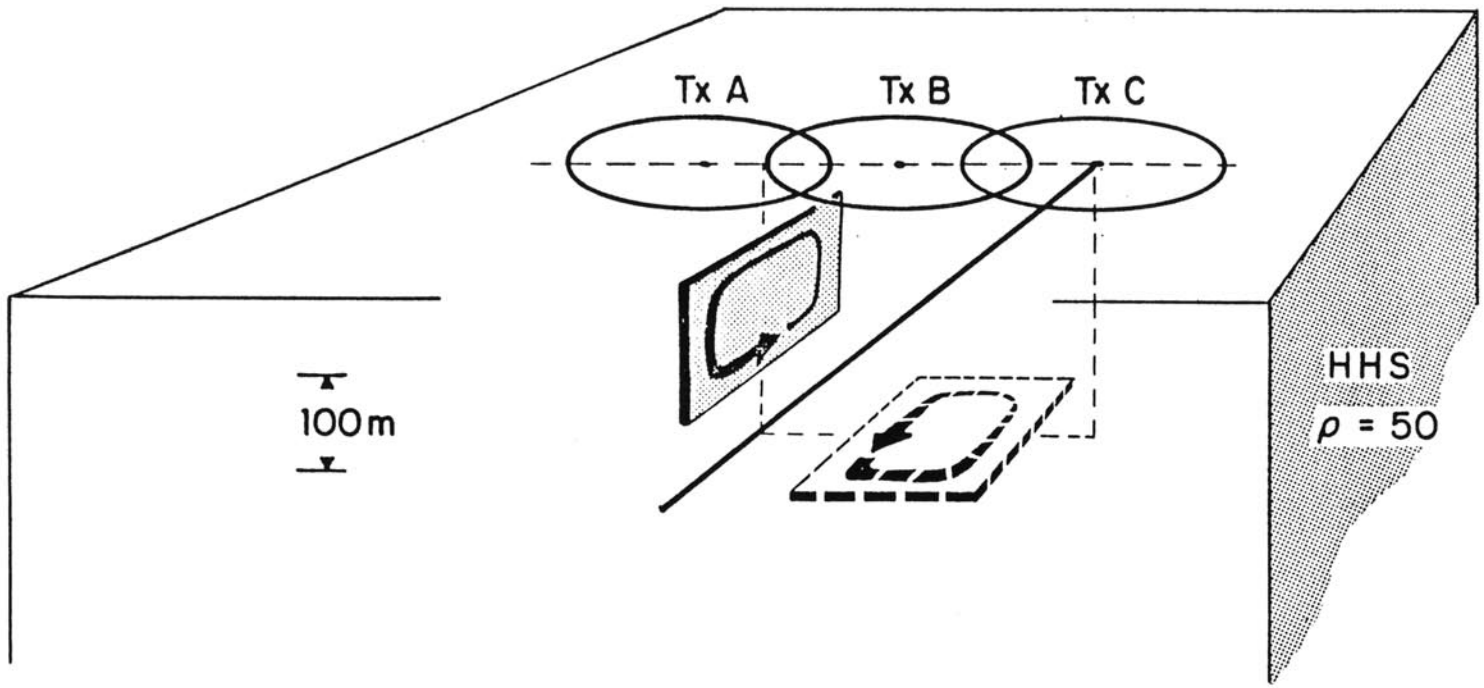


Figure 7



MODELLING GEOMETRY

Figure 8

PLATE AND HALF-SPACE

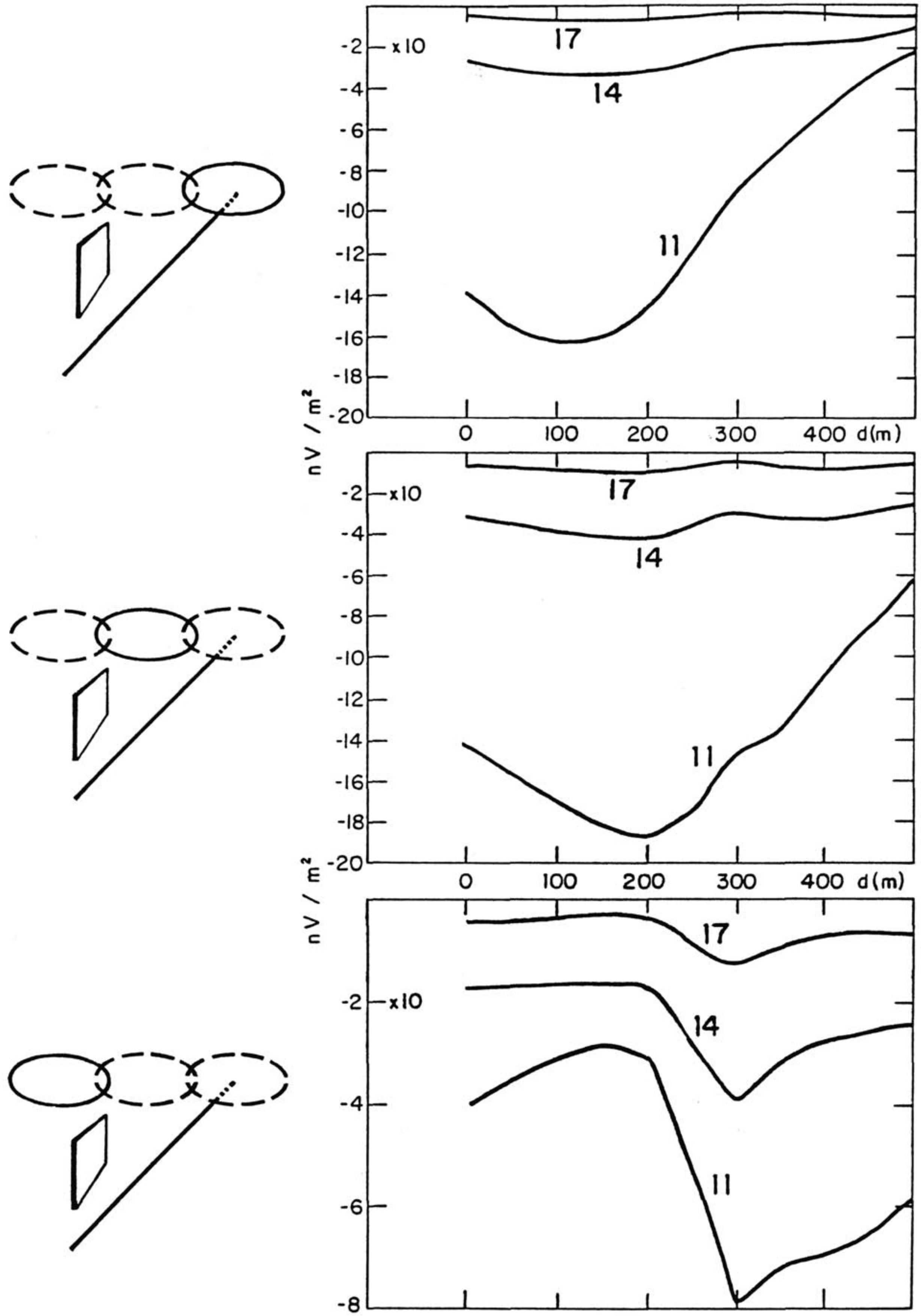


Figure 9