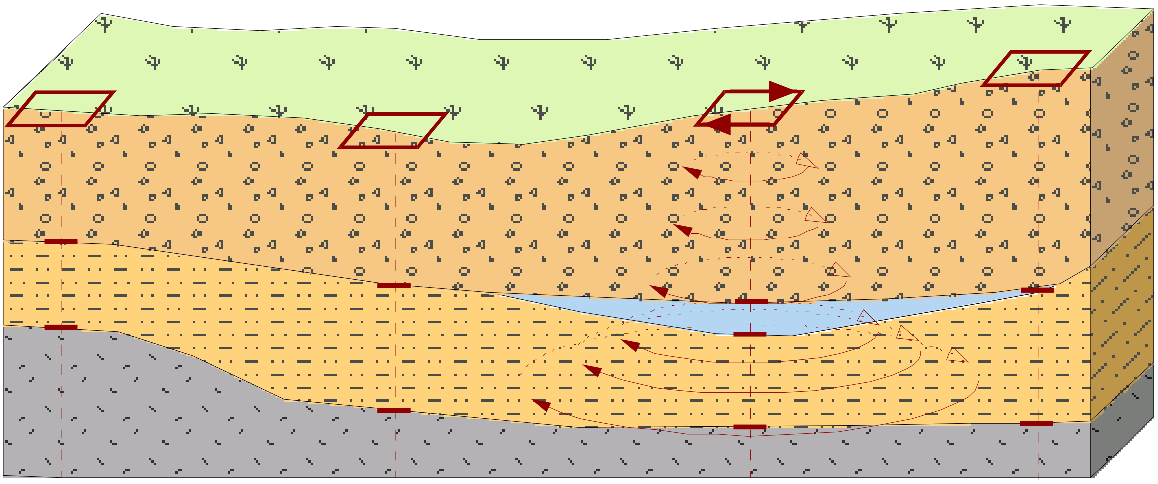
A DISCUSSION OF GEOPHYSICAL TECHNIQUES:

Time-Domain Electromagnetic Explotation

Ground Water
Aggregate Deposits
Aquitard Continuity
Salt Water Intrusion
Contaminant Migration
Permafrost Definition
Mining Applications
and other
Geologic Mapping



(Continued Next Page)

Northwest Geophysical Associates, Inc.
P.O. Box 1063, Corvallis, OR 97339-1063
(541) 757-7231 Fax: (541) 757-7331
www.nga.com info@nga.com

A DISCUSSION OF
GEOPHYSICAL TECHNIQUES

Time-Domain Electromagnetic Exploration

Rowland B. French, Ph.D, R.G.
Northwest Geophysical Associates, Inc.

Time-domain electromagnetic (TDEM) techniques are effective for determining electrical conductivity of soils at depths from 30 feet to 3,000 feet. Since electrical conductivity of soil correlates strongly with soil properties, TDEM is a powerful tool for mapping soils and changes in soil types in that depth range. TDEM is useful in mapping sand and gravel aquifers, clayey layers restricting groundwater flow, conductive leachate in groundwater, salt water intrusion, and depth to bedrock.

TDEM methods have been used for mining exploration for several decades. TDEM methods underwent a renaissance in the late 1970's and early 1980's with the development of efficient and effective field equipment, and computer interpretation techniques. Improved electronics now allows for acquisition of high quality data from depths as shallow as 30 feet, and as deep as several thousand feet.

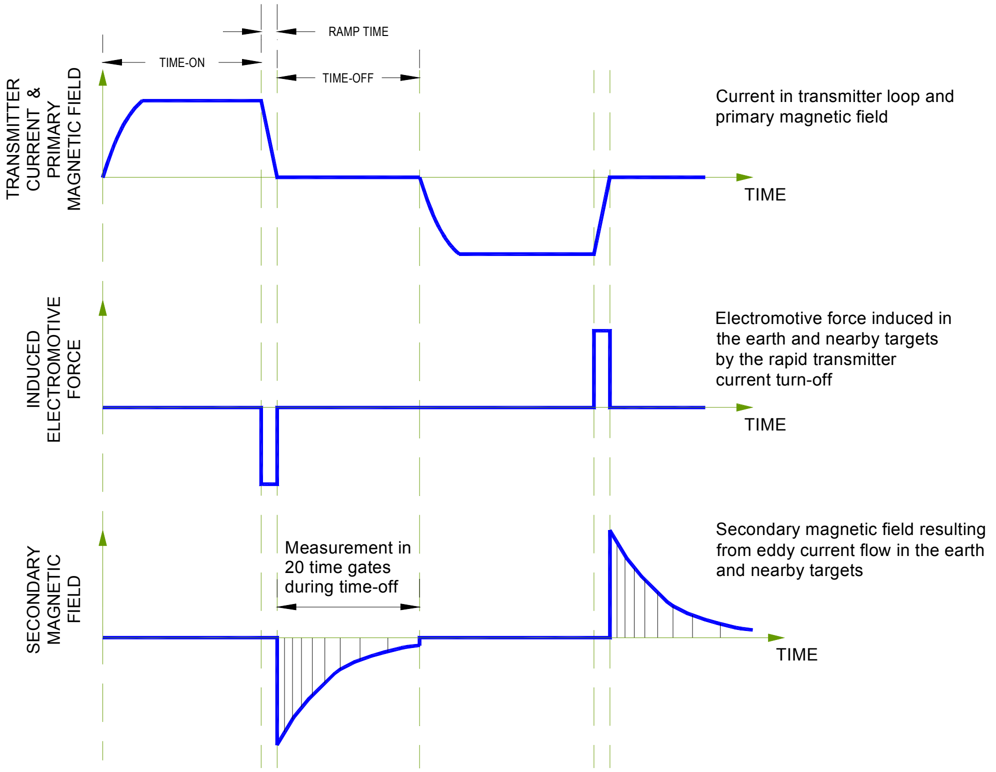
The TDEM technique has several advantages over the more traditional DC resistivity technique. TDEM does not require large electrode arrays and so is less sensitive to lateral changes in the soils. DC resistivity requires long electrode spreads with lengths that are typically three to five times the depth of exploration. Thus, the investigation to depths of two hundred feet requires an area of uniform horizontally stratified soils with a lateral extent in excess of six hundred feet. In contrast, TDEM techniques can obtain depths of exploration of several hundred feet with a 50 foot transmitter loop.

TDEM often has better depth resolution than DC resistivity, particularly for mapping conductive aquitards (confining layers) in resistive sections. Whereas the DC technique has difficulty mapping strata below a resistive layer, the TDEM techniques can easily map conductive strata (e.g. aquitards) beneath a thick resistive section.

THEORY OF OPERATION:

Electromagnetic (EM) geophysical techniques induce electrical currents in the earth using electromagnetic induction. A time varying magnetic field is created using a coil or loop of wire on the earth surface. Faraday's law of induction tells us that a changing magnetic field will produce an electric field, which in turn will create an electric current. Thus, the primary magnetic field from the transmitter loop will create a secondary electric current in the earth. Finally, we measure the secondary magnetic field produced by those secondary electric currents in the earth.

Figure 1 shows the waveform of the primary magnetic field generated by the transmitter and of the primary electric field (electromotive force) accompanying that magnetic field. The primary field impulse (transient) creates eddy currents immediately below the transmitter loop, approximating a mirror image. As the initial near-surface eddy currents decay, they



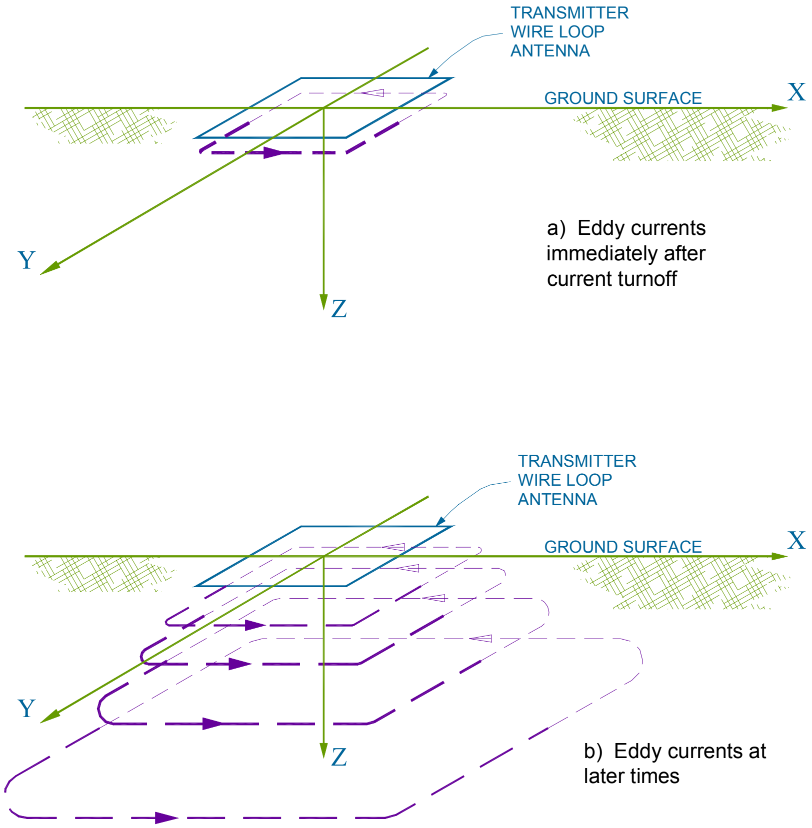
after: McNeill, 1990

FIGURE 1: TDEM Waveforms

in turn induce eddy currents at greater depths. The third panel in Figure 1 shows the waveform of the secondary magnetic field, generated by the series of eddy currents induced in the ground.

The magnitude and rate of decay of those secondary currents depend on the conductivity of the medium, (i.e. the electrical conductivity of the soil) and on the geometry of the conductive layers. The TDEM receiver measures the magnetic fields created by those secondary currents.

In time-domain electromagnetic techniques the inducing signal is a sharp pulse, or transient signal. The induced currents in the earth are initially concentrated immediately below the transmitter loop. This is shown schematically in Figure 2a. With time, those currents will diffuse down and away from the transmitter as illustrated schematically in Figure 2b. An analogy with smoke rings is often used to describe the behavior of the currents in the ground. Initially strong currents form in the ground adjacent to the transmitting loop. The “smoke ring” then expands, weakens, and travels down through the earth. The rate of diffusion depends on the earth conductivity. In resistive media the currents will diffuse very rapidly. In conductive media the currents will diffuse more slowly. A conductive layer at depth may “trap”



after: McNeill, 1990

FIGURE 2: TDEM Eddy Current Flow;
a) early time, b) late time

currents in that layer, while currents elsewhere decay more rapidly.

Measurements of the secondary field are typically made in the time range from 10 micro-seconds to 10 milli-seconds following the "turn-off" of the primary field. Measurements are made in 20 to 30 discrete "time gates", or time intervals, following the primary inducing pulse. For deeper exploration (thousands of feet) in conductive sections, measurement times can extend up to one second. Because measurements are made while the transmitter current is turned off, more sensitive measurements of the secondary field can be made.

INTERPRETATION:

Interpretation procedures generally use "forward modeling". A hypothetical layered earth model is generated and then the theoretical response for that model is calculated. The model is then refined until the calculated response matches the observed or measured field

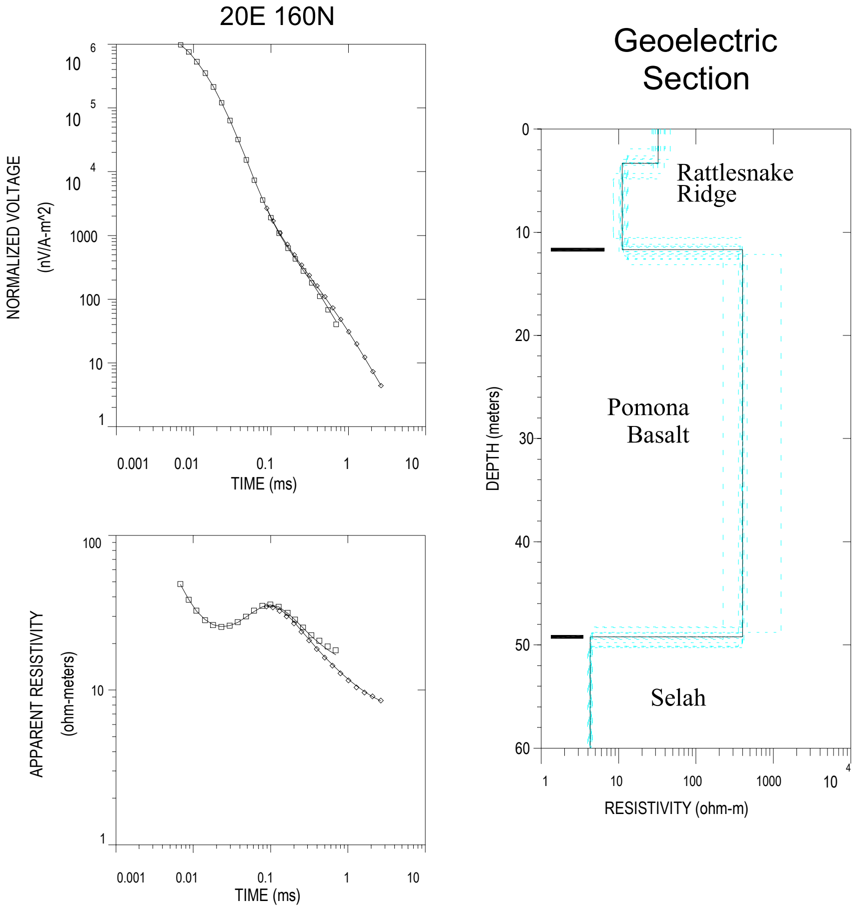


FIGURE 3: TDEM Sounding and Model

response. The model refinements can be made using an automated iterative process or "inversion".

Figure 3 shows a sample sounding curve. The upper panel on the left shows the decay of the magnetic field, decaying over six decades during the course of the recording from 0.006 milli-seconds (ms) to 2 ms. The electrical potential induced in the receiver coil (proportional to dBZ/dt) is reported as "normalized voltage", normalized to a receiver coil moment of 1 turn-m2 (single turn with a coil area of 1 square meter) and a transmitter current of 1 ampere (A).

The second panel on the left of Figure 3 shows a plot of the same data converted to "late-stage" apparent resistivity. The apparent resistivity curve gives a somewhat more intuitive feel for the geoelectric section. However, as explained in the following paragraph, TDEM apparent resistivity is not a true apparent resistivity as observed in DC resistivity of frequency domain techniques.

In concept, the "apparent resistivity" is the resistivity of a uniform earth which will produce the observed instrument response. However, the observed TDEM field is a non-linear function of time and earth resistivity. In fact, the instrument response is not a single valued function of the resistivity over the time range of measurement. For most TDEM soundings we use a "late-stage" apparent resistivity, which is a "true" apparent resistivity only for the latter stage of the decay curve. We generally try to make measurements in this time range but often the first portion of the curve is not truly in late-stage, hence the numerical values may not indicate the earth resistivity for the first few time gates.

The right-hand panel of Figure 3 shows the model geoelectric section used to calculate the model response shown as a solid line in the plots to the left. This sounding was made in the Columbia River Basalt Plateau of central Washington state. The geologic section consisted of sedimentary units of the Ellensburg Formation (the Rattlesnake Ridge Member and the Selah Member) interbedded with the Columbia River Basalts (the Pomona Basalt unit). Here the Selah Member was fairly conductive, consisting of shales and siltstone, while the overlying basalt was a high resistivity, massive flow basalt. This high contrast boundary proved to be an excellent target for the TDEM technique and yielded high quality data with exceptionally good model fits to the observed data.

The dashed lines in the geoelectric section of Figure 3 show “equivalent” models, i.e., models whose response will fit the observed response with a “mis-fit” parameter within 20% of the best fitting model (the solid line).

Currently, one of the major weaknesses of TDEM is the difficulty in interpreting data over three-dimensional geologic structures. Most modeling programs assume a horizontally layered earth. However, with the small transmitter loops used for most groundwater, geotechnical and environmental applications, the earth can often be accurately approximated as a layered earth over the dimensions of the sounding.

Mining applications of TDEM use different modeling techniques which often assume a restricted conductor in a more resistive media (e.g., an ore body within resistive host rock). Those applications do allow restricted three-dimensional modeling.

FIELD PROCEDURES:

Figure 4 shows a typical layout for a “central loop” TDEM sounding. Field procedures involve placing a square loop of wire (typically 50-500 feet square) on the ground surface. A

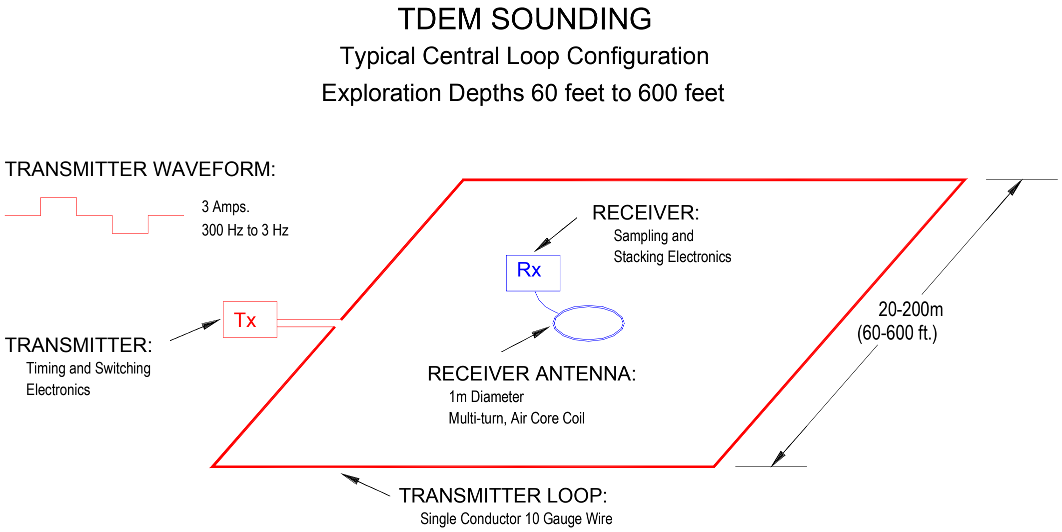


FIGURE 4: TDEM Field Configuration

steady current in the transmitter loop is abruptly turned off. This creates a magnetic pulse or transient in the ground.

Measurements are made with a small receiver coil in the center of the transmitter loop, as the induced electric currents penetrate and diffuse through the earth. The receiver may also be placed outside the transmitter loop in an "offset" configuration.

For typical groundwater applications, the measurement times range from 0.01 to 50 milliseconds after the primary transmitter current is turned off. The receiver electronics average over tens or hundreds of repetitions to increase the signal-to-noise performance of the instrument. Data is recorded digitally, is reviewed by the operator and stored in memory. Data is downloaded to a PC at the end of the day's survey for further processing and interpretation.

FURTHER READING:

Hoekstra, Pieter, and Blom, Mark W., 1990, Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics: in Geotechnical and Environmental Geophysics, ed: S.H.Ward, SEG, IG#5, Vol. 2: P.1-15.

McNeill, J.D., 1990, Use of electromagnetic methods for groundwater studies: in *Geotechnical and Environmental Geophysics*, ed: S.H.Ward, SEG, IG#5, Vol. 1: P.191-218.

McNeill, J.D., 1994, Principles and application of time domain electromagnetic techniques for resistivity sounding: Geonics technical note TN-27, Mississauga, Ontario, p.1-15.

Nabighian, Misac, editor, 1988, *Electromagnetic Methods in Applied Geophysics*: SEG, IG#3, Vol.1&2.

Romig, Phillip, 1992, Engineering and Environmental Geophysics Get Top Billing at SAGEEP.: The Leading Edge Vol. 11, No. 11, P.36-37.

Steeples, Don, 1991, Uses and Techniques of Environmental Geophysics: The Leading Edge, Vol.10, No.9, P.30-31.

Rowland B. French, Ph.D., R.G.
Northwest Geophysical Associates, Inc.
1600 SW Western Blvd., Suite 200
P.O. Box 1063
Corvallis, Oregon 97339
phone: (541) 757-7231
email: rowland@nga.com

FILE: TDEM_TEQ_03.p65
REVISION: 8-FEB-2002