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Applicability of Electrical Methods in Deep Detection and Monitoring of Conductive Lixiviants

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	Mmt	million metric tons
Atm^2	ampere-turn-square meter	ms	millisecond
cm	centimeter	μs	microsecond
Hz	hertz	ns	nanosecond
km	kilometer	Ωm	ohm-meter
m	meter	pct	percent
m^2	square meter	S/m	siemens per meter ($S/m = 1/\Omega m$)
MHz	megahertz	$V/(A \cdot m^2)$	volt per ampere per square meter

APPLICABILITY OF ELECTRICAL METHODS IN DEEP DETECTION AND MONITORING OF CONDUCTIVE LIXIVIANTS

By Jay C. Hanson[1]

ABSTRACT

Various electrical and electromagnetic (EM) geophysical techniques are currently being evaluated by the U.S. Bureau of Mines for their effectiveness in the detection and monitoring of electrically conductive (1 to 5 S/m) lixiviant (leach solution) to depths of 600 m, either above or below the water table. These techniques include magnetotellurics (MT), controlled source audiofrequency magnetotellurics (CSAMT), resistivity and focused resistivity, ground-penetrating radar (GPR), frequency-domain electromagnetics (FEM), and time-domain electromagnetics (TEM). Of these techniques, TEM may be the most effective, but CSAMT and focused resistivity also hold promise.

Geophysical computer modeling of the borehole TEM technique was conducted based on an idealized geoelectric section (layered earth) with characteristics based on the Santa Cruz porphyry copper deposit near Casa Grande, AZ. Layer resistivities and thicknesses were obtained from geophysical data and geologic logs available from the site. Modeling of borehole TEM in both preleach and during leach situations was conducted.

Simulating the TEM method using computer modeling proved to be encouraging since there were substantial differences between leached and nonleached responses. The modeling does not prove the effectiveness of TEM in the field, but does indicate that detection of deep lixiviant zones is theoretically possible.

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INTRODUCTION

Electrical (galvanic) and EM (inductive) methods have been used for many years in the exploration of mineral deposits and, more recently, in the detection and evaluation of various hazardous wastes including brine plumes, oil and chemical leaks or spills, and contaminated ground water (*1-3*).[2] As part of its program to monitor and control fluid flow, the U.S. Bureau of Mines is currently conducting research to assess the use of these methods in the detection and monitoring of acid lixiviants as would be used during copper in situ leach mining.

In situ leach mining is the process of circulating chemicals, such as dilute sulfuric acid, within the subsurface to selectively dissolve, or leach, ore minerals from a deposit (*4*). These chemicals are pumped down vertical boreholes (injection wells), migrate through the natural pores and fractures of the host rock, and collected in and pumped out of nearby recovery holes (production wells). In other variations, leach solutions may be pumped into boreholes drilled from underground mine workings or simply sprinkled onto or injected into rubbled ore. In situ leach methods are relied on in the commercial extraction of uranium from sandstone deposits (*5*). Low-grade copper oxide minerals have been leached from previously mined or rubbled deposits as well (*6*). In situ methods work best when target metals are hosted in porous or highly fractured media, which allow for greater lixiviant contact with the ore minerals.

In fracture-hosted environments, it is necessary to determine fracture and flow orientations at the mine area before leaching actually begins (*7*). This information helps to define the correct positions and depths of the monitoring and recovery wells. If a conductive solution is pumped into designated injection wells, electrical and EM methods could be used to trace the solution as it flows through the major fractures in the rock. The solution, presumably aqueous sodium chloride, would fill the fractures intersected by the borehole and greatly increase the overall conductivity of the rock. This type of analysis may make it possible to predict the lixiviant flow direction prior to mining, aiding in the placement of the monitoring and recovery wells. Tracer tests such as these are not used routinely, possibly because of logistical difficulties.

Commercial in situ leach mines are required to monitor the location of lixiviant in the subsurface to prevent excursions (escape of leach solution from the well field). Most lixiviant detection and monitoring is done with monitor wells drilled in specific locations around an in situ leach mine. While monitor wells provide ground truth by direct observation, they are expensive and provide information in only one location. Geophysical techniques, however, cover a larger area at lower cost, although the information gained must be used to infer subsurface conditions.

The Bureau is primarily concerned with developing geophysical techniques to be used in conjunction with in situ mining for cost-effective lixiviant detection and monitoring as well as prediction of flow patterns. Such techniques would provide information that mining companies may use for placement of production or monitoring boreholes to optimize fluid recovery and monitoring. Periodic geophysical monitoring of plume location can reduce the number of monitor wells needed at the minesite, greatly reducing drilling costs. Furthermore, lixiviant excursions could be detected early and more reliably, assuring regulatory agencies that dependable detection methods exist for environmental protection purposes.

Since the number of boreholes at a prospective in situ mine may be large, methods that can make use of the holes would be highly beneficial. Crosshole geophysical methods, as opposed to conventional surface methods, can be used to investigate the region between two boreholes. High-resolution techniques, such as radar and seismic, have been used in this capacity for many applications (*8*). Crosshole measurements are amenable to powerful data processing techniques, such as tomography. Tomography can be used to reconstruct the ray paths between holes to produce a velocity or attenuation image of the region (*9*).

Crosshole seismic methods have been used experimentally by the Bureau for the detection of water injected between boreholes (*10*). The injected water normally lies above the water table, producing a measurable velocity contrast between wet and dry rock. However, no velocity contrast would exist where leaching fluids are injected below the water table. In such cases, electrical and EM methods could provide effective means of detection, responding to changes in conductivity rather than changes in velocity due to wetted rock.

Several researchers have reported case histories in which electrical or EM methods have been used successfully to outline chemical plumes and contaminated ground water (*11-13*). In at least one instance, under Bureau contract, MT and resistivity techniques were employed to monitor lixiviant migration at a uranium mine in northern Wyoming, but the results were inconclusive (*14*).

To apply any geophysical method to a particular area of interest, some prior knowledge of the area's geologic, hydrologic, or geophysical nature is helpful. Such information aids the geophysicist in choosing the most suitable method, station spacing, and loop size or dipole spacing. At the Santa Cruz site, where the Bureau is conducting an in situ copper leach mining test, geologic and hydrologic information has been provided by drilling. Drilling has

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

defined a deep porphyry copper deposit containing 97 Mmt ore averaging 0.7 pct copper oxide mineralization hosted mainly in fractures in granite as atacamite, a copper chloride, and chrysocolla, a copper silicate (*15-16*). The water table lies at a depth of 150 m. Geophysical information, provided by resistivity logging and downhole-radial resistivity surveys, indicated that the 500 m of overlying strata is highly conductive, averaging 25 Ωm (*17-18*). (An idealized geoelectric section of the Santa Cruz site is shown in figure 1.) Most of these strata consist of various layers of arkosic sands and gravels, conglomerates, and breccia, all containing conductive clays. It is well known that conductive overburden, whose conductivity can be heavily influenced by the presence of clays, presents a formidable barrier to deep penetration by geophysical methods (*19*).

Consequently, the Bureau is concentrating its efforts on the application of deep-penetrating surface systems and borehole systems for lixiviant detection and monitoring. Systems that are capable of exploration depths in excess of 600 m and those that can be converted for use in a borehole are most desirable. One example is TEM. Borehole systems must be capable of lixiviant detection to a radius of 50 m around the borehole to be useful at an in situ minesite. This distance would be representative of the well spacings that would be used.

This report discusses the applicability of various electrical geophysical methods for monitoring the location of deep conductive lixiviants injected into saturated zones. The underlying principles as well as the advantages and limitations of these methods will be discussed individually. Since case studies involving lixiviant detection are lacking in the literature, many of the arguments and the conclusions are based on analogous situations in hazardous waste detection or other related documentation.

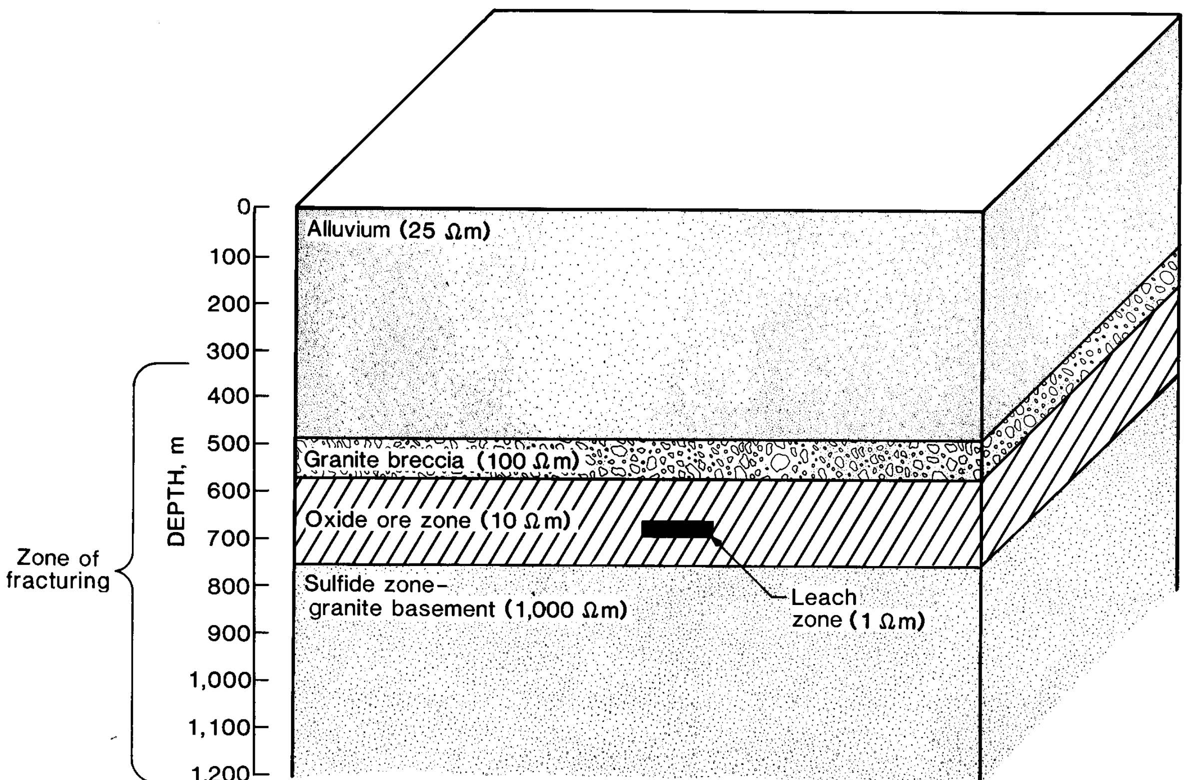

Figure 1.—Geoelectric section and leach zone of Santa Cruz site.

ACKNOWLEDGMENTS

The author wishes to thank Walter L. Anderson, mathematician, U.S. Geological Survey (USGS), Denver, CO, for providing the borehole TEM computer simulations. This material helped solidify some of the conclusions presented in this report.

NATURAL SOURCE METHODS

Natural source methods include all methods that rely on a natural power source rather than an artificial source, such as a transmitter. Natural source methods include self-potential, tellurics, and MT. The self-potential method is sometimes used in mineral prospecting and depends on an oxidation-reduction reaction, which develops between the upper and lower ends of an ore body. The telluric and MT methods depend on the propagation of Earth currents and magnetic fields induced by thunderstorm and related electrical activity. Only the MT method and its artificial source counterpart, the CSAMT method, will be considered here.

MAGNETOTELLURICS

MT fields arise as a result of natural variations in the Earth's magnetic field (*19-20*). These variations, due to sun-spot activity (solar winds) and aurora borealis, influence currents in the ionosphere, which sustain MT fields.

MT fields propagate as a plane (nonpolarized) wave between the ionosphere and the Earth's surface and below the surface at frequencies from about 10^{-5} Hz to several thousand hertz. As a result of this propagation, telluric currents are induced in the earth. For prospecting interests, the major source of EM energy is that generated by worldwide thunderstorm activity because the telluric currents induced by these storms peak at certain distinct frequencies, such as 8, 14, and 760 Hz.

In an MT survey, two orthogonal pairs of electrodes are used to measure the horizontal electric field and coils are used to measure two or three components of the associated magnetic field. A fixed base station of the same electrode-coil configuration can be set up over nonanomalous ground to monitor electric and magnetic field variations, while a mobile configuration measures changes in the electric and magnetic fields over anomalous ground. While the use of a base station is not absolutely necessary, comparison of the two sets of data can be used to reduce noise. The ratio of the magnitude and phase of the electric and magnetic data sets derived from the mobile configuration can be used to determine relative depth and resistivity of an interface. Depending on the frequency chosen, investigation depths of several kilometers may be obtained with the MT method. Another technique called audiofrequency magnetotellurics (AMT) is similar, but uses only the audiofrequency bandwidth (0.1 to 10,000 Hz) produced by thunderstorms (*21*).

In practice, an accurate MT survey is difficult to perform (*19*). Extremely high sensitivity is required of the receiver coil since variations in the magnetic field are very small. Hence, even small movements in the coil can create significant noise in the data. In addition, errors in interpretation arise if the base station is not located in reasonably homogeneous ground. The method also requires sinusoidal variation of the electric and magnetic fields to accurately determine resistivity, a parameter seldom achieved in real-world situations. Because of these problems, it is unlikely that a small leach plume would be consistently recognized at great depth. In addition, MT and AMT surveys are extremely time consuming and expensive. Thus, the Bureau is placing less emphasis on these methods as lixiviant detection and monitoring tools. Perhaps MT and AMT may be useful in delineating larger targets rather than small leach plumes or simply as reconnaissance tools for locating deep fractures, faults, or other structures that may control fluid movement.

CONTROLLED SOURCE AUDIOFREQUENCY MAGNETOTELLURICS

An alternative to MT is CSAMT (*22*). Unlike MT, CSAMT relies on the use of an artificial current source—a transmitter loop or grounded dipole—instead of depending on unpredictable natural fields. This considerably reduces the amount of data scatter. The transmitter may be operated in any of several frequencies in the audiofrequency range (0.1 to 10,000 Hz), depending on depth of investigation desired. At low frequencies, penetration depths of several kilometers may be attained. As in MT, magnitude and phase of the electric and magnetic fields are measured at the receiver, generally located a great distance away from the transmitter, simulating an MT plane wave (fig. 2). These data are then converted to units of resistivity and plotted as a pseudosection, a two-dimensional (2-D) representation of subsurface resistivity distribution.

Recently, CSAMT has been used successfully to map deep structure in oil exploration, geothermal fluids, base and precious metals, and uranium in many environments throughout the world (*22*). Originally developed in the early 1970's for the detection of deep conductive ore deposits, CSAMT has replaced MT in many applications where great depth is desired.

For the detection of conductive lixiviants, CSAMT has definite advantages over MT. Firstly, CSAMT surveys are more reliable and possibly more accurate than MT surveys. This is mainly due to the use of a transmitter, which provides a reliable, stable current source. Secondly, CSAMT surveys can be done more rapidly and are therefore less expensive to perform. Finally, under the right surface geologic conditions, CSAMT has superior lateral and vertical resolution, with the ability to detect a relatively small body at great depth. Superior resolution would be helpful in reliably detecting and monitoring the progress of a nonuniform conductive plume in the subsurface.

A disadvantage of the CSAMT method is its susceptibility to various kinds of electrical and cultural noise sources, such as powerlines, pipelines, and radio interference, as well as natural sources like thunderstorm activity, wind, and telluric drift (*22*). Unfortunately, some or all of these nuisances may be present at an ongoing minesite, and great care would have to be taken in the recording of data. Furthermore, CSAMT must be run with the proper transmitter-receiver distance to simulate plane wave characteristics, and correct relative orientations between source and sensors must also be maintained (*21*). Computer modeling using a geoelectric section, similar to figure 1, may show whether CSAMT would be an effective tool for lixiviant detection and monitoring. Unfortunately, such modeling could not be done because of time and expense constraints. It is encouraging to note that leach solutions have been reliably detected at the Cyprus Casa Grande deposit, a block-cave copper-leaching operation in southern Arizona, using CSAMT methods. The depths of detection ranged from 200 to 350 m. A practical success such as this, in an environment where in situ copper leach mining may be the future mining method, is a strong case for further consideration of the technique.

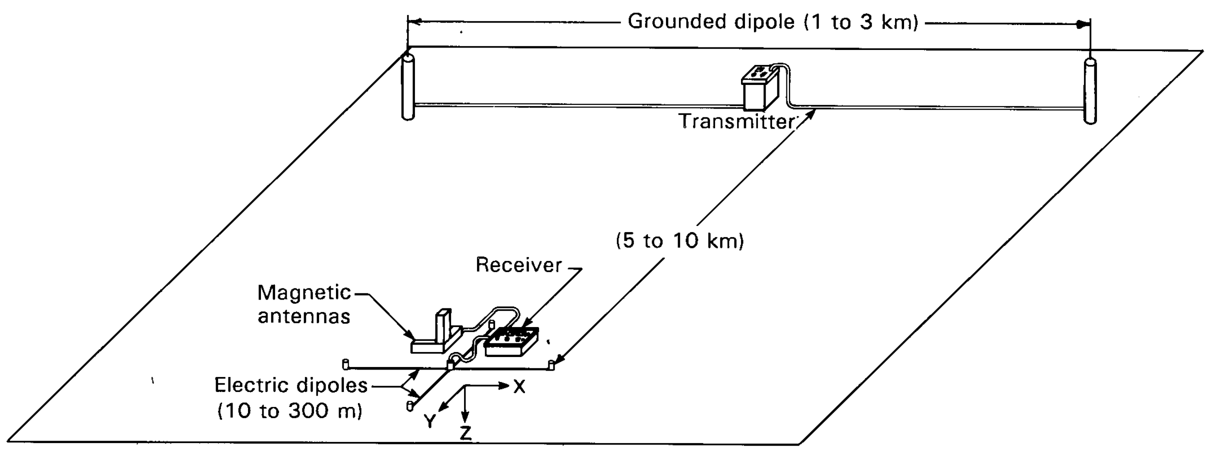

Figure 2.—Equipment configuration for CSAMT surveying.

ELECTRICAL METHODS

Dc electrical methods, also known as galvanic methods, differ from EM methods in one important respect; they employ dc or very low frequency current, rather than ac. Dc measurements require the use of electrodes to make physical contact with the earth, unlike EM methods in which coils may be suspended above the earth. Most dc methods measure the voltage due to an applied current source. Terrain resistivity (reciprocal of conductivity) may be calculated from the voltage, the current, and the geometric parameters of the electrode configuration (array). Techniques using these three factors are commonly called resistivity techniques.

CONVENTIONAL RESISTIVITY

The conventional resistivity method, in its various configurations, may be used to detect and monitor underground leach solutions. The method involves the introduction of current into the ground via two electrodes and simultaneous measurement of the resulting potential with two other grounded electrodes (*19*). These electrode pairs may be placed in one of several configurations for either sounding, using the Wenner configuration (fig. 3*A*), or profiling, using the dipole-dipole (fig. 3*B*) or pole-dipole configuration (fig. 3*C*). Other configurations (not shown) are also available. In sounding, the array is expanded about a center point. In profiling, a fixed electrode separation is maintained while the entire electrode array is moved across the area of interest. Under the right conditions, profiling reveals resistivity changes in a lateral direction at constant depth, while sounding shows changes in resistivity with depth at a single location. Typically, both are used to fully evaluate the resistivity distribution in an area. Resistivity methods can be used in either a surface or borehole configuration.

Surface resistivity methods have been used for many years in the detection of metallic ore deposits, in the determination of bedrock depth and structure, in soil resistivity, and more recently in the mapping of brine plumes and contamination spills (*1-2*). It is reasonable to assume that surface resistivity methods could be applied to the detection of lixiviants or at least to lixiviant-laden fractures in the same way. However, when great depth of penetration is necessary, resistivity techniques present certain logistical problems. Exploration to a depth of 600 m would require a very large power source and several kilometers of heavy gauge wire to implement. Long survey lines would be required to accommodate the large dipole spacings. Such a system makes field surveying very difficult. Furthermore, the technique tends to sample a large volume of earth that may produce ambiguous results unless there exists a large resistivity contrast between lixiviant and host rock (*14*). When conductive lixiviants are investigated, a large resistivity contrast could reasonably be assumed. However, small zones at depth may be completely obscured by the surrounding geologic noise. For shallower in situ mining operations, resistivity techniques may prove more useful, especially as a monitoring tool. Electrodes and wire could be permanently anchored in the ground or in boreholes to constantly monitor plume progress.

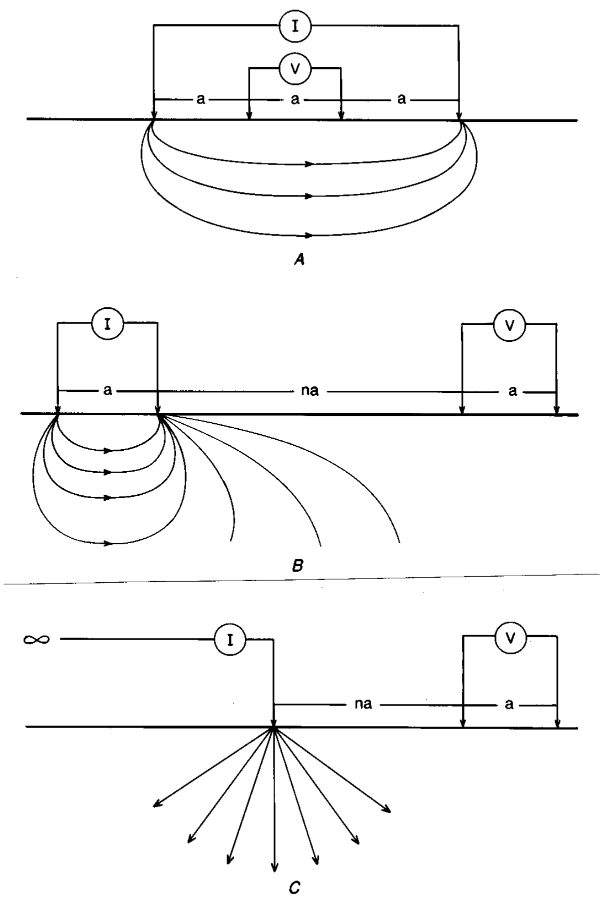

Figure 3.—Three common resistivity arrays. *A*, Wenner; *B*, dipole-dipole; *C*, pole-dipole. (I and V = current and voltage electrodes, respectively; a = electrode spacing; n = spacing multiplier, usually with values between 1 and 10.)

FOCUSED RESISTIVITY

A more promising resistivity configuration that has been used for the detection of voids (underground mine workings) is focused resistivity. Much of the research and development of this technique was undertaken by Southwest Research Institute[3] of San Antonio, TX.[4] Focused resistivity has the advantage of greatly increased penetration depth compared with conventional resistivity. In many conventional resistivity arrays, a single electrode is used as a point source of current; the return electrode is generally located at infinity (fig. 4*A*). Point current sources radiate hemispherically in unlayered earth, and depth of penetration is largely dependent on the rate of current decay with depth. In focused resistivity, more than one electrode is used as a current source and all can be energized to produce a focusing effect. Like conventional resistivity, focused arrays can be placed in any of several configurations. The electrodes are usually buried collinearly along the direction of traverse.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[4]Work done by Southwest Research Institute under Bureau of Mines contract H0245005.

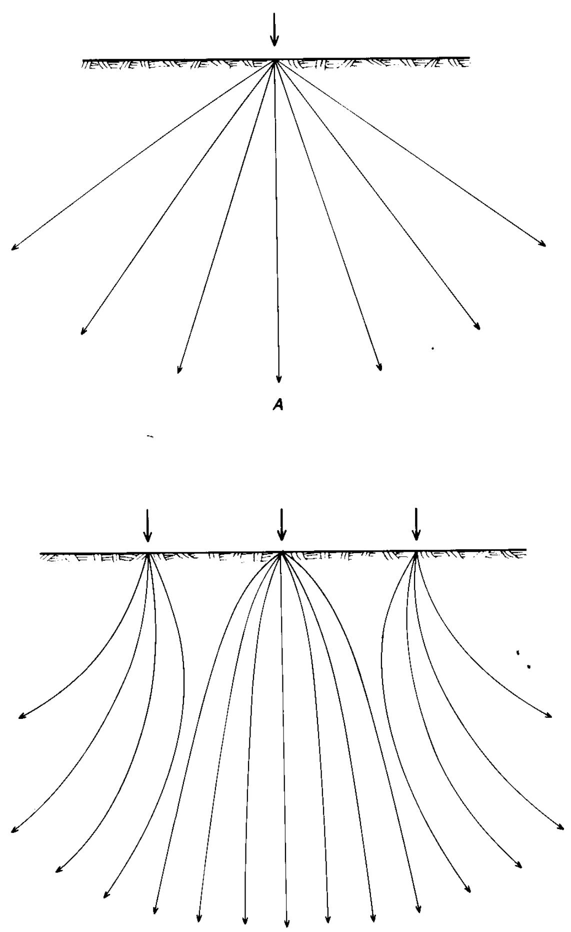

Figure 4.—Comparison of conventional (*A*) and focused (*B*) current injection as used in resistivity surveying.

In the pole-dipole focused configuration, three electrodes are normally used as current sources, while a return electrode is located a long distance away. Potential electrode pairs are located to one side of the central current electrode. Current focusing occurs when the three source electrodes are energized simultaneously with like polarity, the two outer electrodes constraining the current of the center electrode to radiate nearly vertically downward in the shape of a triangular wedge (fig. 4*B*). This wedge of focused current flows to great depth before decaying appreciably. The result is that even small voids lying at a depth of 10 times their diameter produce anomalous signatures 2.5 to 7.0 times greater than in an equivalent conventional resistivity array. Although there hasn't been any published literature of the type of focused resistivity signatures that may be produced by deep conductive lixiviants, personnel at Southwest Research Institute expressed confidence in the technique for this application (*23*).

In another configuration, called the unipole configuration, two current electrodes are situated outside of two potential electrodes, similar to the Wenner array shown in figure 3*A*. The current electrodes are energized with current of the same polarity, while a remote electrode serves as the return. Current focusing is maximized at a particular depth beneath the potential electrodes, depending on resistivity layering and electrode geometry (*24*). Most focused resistivity techniques may be modified for use in borehole or crosshole surveying, making them attractive for deep lixiviant detection.

BOREHOLE RESISTIVITY

In areas where overburden and rock are conductive, certain EM systems may prove ineffective. In these areas, borehole resistivity may hold promise because dc, used in resistivity measurements, passes easily through conductive materials. High-conductivity targets may be detected through moderately conductive rock using conventional borehole arrays or, better still, a focused array. Focused arrays produce sharper, more definitive anomalies because of the focusing effect. Thus, unsaturated fractures (resistive zones) and leach saturated zones between boreholes should be easily identifiable.

In theory, surface-to-borehole or cross-borehole resistivity techniques would be more desirable for the detection of conductive solutions than surface techniques, whether focused or conventional. The injection of current directly into or near the lixiviant plume via the borehole would require far less current to produce a detectable response than that required for a surface system. This would eliminate the need for a very large power supply.

In practice, the borehole method has several disadvantages, owing in part to the borehole itself (*19*). First, borehole resistivity methods cannot be used in the cased portion of the hole. Both metallic (conductive) and plastic (insulating) casing disturb the true nature of the resistivity profile. Second, conductive borehole fluids, such as sulfuric acid, may be present during in situ mining, which would render conventional techniques ineffective. In such cases, it may be necessary to pump the hole dry or, more likely, to apply a focused resistivity array to penetrate the conductive fluid. Finally, depending on available current and resolution desired, most conventional borehole techniques penetrate only a few meters into the surrounding rock, not nearly enough to be used as a proper monitoring device. Certain focusing techniques, however, which force current deeply into the rock rather than along the borehole wall, may have sufficient penetration power to be used as a monitoring device.

Other researchers have suggested that electrodes could be placed outside the casing and permanently anchored.[5] A large number of electrodes, anchored along the borehole wall at small intervals and connected to the surface, would allow several types of arrays and spacings to be used. Electrodes in direct contact with the rock formations would give consistently better data over long periods of time for accurate lixiviant monitoring. Furthermore, survey time would be shortened considerably since the wires and the electrodes would already be in place.

One disadvantage of this concept is that time and effort would have to be spent in designing tools and techniques to implant the electrodes, adding substantially to the initial cost. In addition, boreholes so constructed would have limited use for other survey methods, such as EM induction, magnetic susceptibility, and acoustic (sonic) logs. Such surveys would produce erroneous results near each electrode and, depending on electrode spacing, could seriously hamper resolution. If such surveys were desired, they would have to be performed prior to electrode implantation.

GROUND-PENETRATING RADAR

GPR is a high-frequency, high-resolution EM pulse system that measures reflections of propagating EM energy. In a surface mode, GPR is used for mapping large, shallow features, such as pollution plumes, soil thickness or water table depth, or much smaller features, such as pipes and cables, voids under road or airport surfaces, and damaged zones in building materials (*25*). Because of its high frequency, GPR may be used to locate objects only centimeters in length, making it ideal for many civil engineering and geological applications.

In a borehole mode, GPR could be used to examine conductive (or resistive) zones near the borehole and throughout its length. Such zones include saturated and unsaturated fractures in rock. Fractures, especially those saturated with conductive solutions, should be easily identifiable and help determine predominant flow patterns in the mine area.

GPR radiates energy from an antenna in the form of a transmitted pulse or wavelet (fig. 5), making it somewhat analogous to reflection seismology. If the wavelet impinges upon an interface (reflector), a certain amount of the energy will be reflected and recorded by the receiver. The amount and phase of reflected energy depend on the conductivity and permittivity (polarization of electric charge due to an external field) of the media between reflector and borehole, reflector conductivity, frequency used, and depth or distance to the reflector. A highly conductive reflector will generally produce a phase reversal in the reflection, while a resistive one will not (fig. 6). Highly conductive host rock will generally attenuate or disperse EM waves, reducing their penetration capabilities.

The borehole mode would be the most useful for detecting and monitoring deep lixiviant plumes. Even a small lixiviant front could serve as an ideal reflector for GPR systems and could be detected at virtually any depth in the borehole, provided its distance from the borehole is not too great (fig. 7). (Example borehole data are shown in figure 8.) The surface mode, whose depth of penetration is severely limited in conductive media (saturated clays, for example), is not suitable for deep in situ mining purposes.

A research study of borehole GPR involving computer modeling was done for the Bureau by Sandia Research Associates, Inc., Corrales, NM, during 1988.[6] The purpose of the study was to determine the sensitivity and penetration capabilities of borehole GPR in rock and lixiviants of varying conductivities using various frequencies and reflector distances. By varying these parameters, a better understanding of the limitations of GPR in several subsurface environments was obtained.

The results indicate that at frequencies normally used in GPR, which can have considerable range (1 to 1,000 MHz), EM waves attenuate and disperse very rapidly in conductive media. For example, a wavelet with a frequency of 55 MHz, propagating in a media with a

[5]Work done by Sandia Research Associates, Inc., under Bureau of Mines contract P0281406.

[6]Work cited in footnote 5.

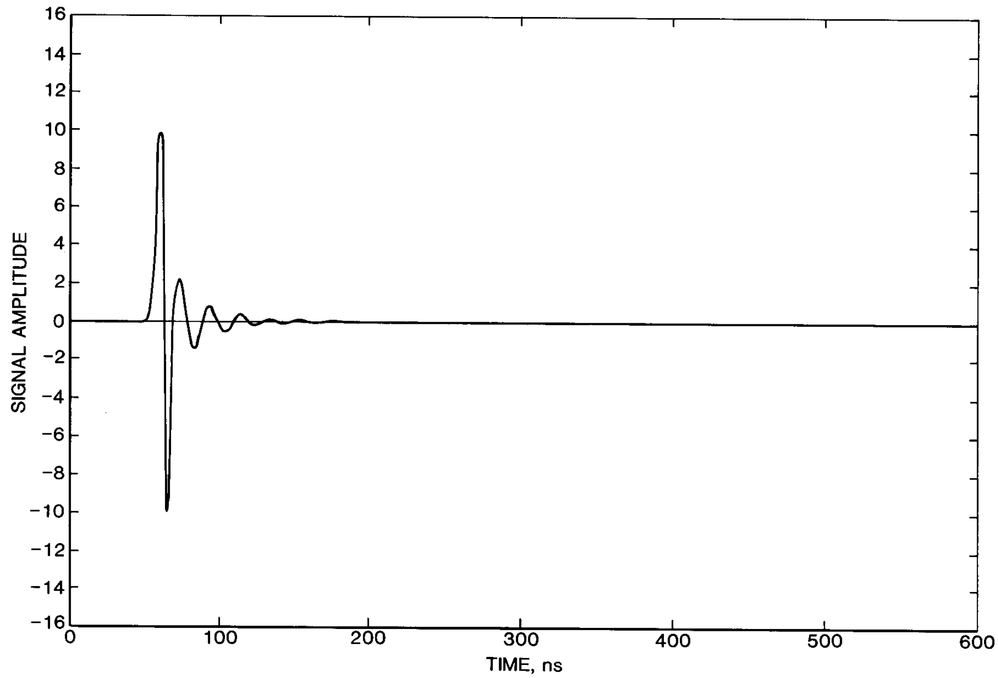

Figure 5.—Transmitted wavelet from GPR antenna.

conductivity of 0.01 S/m (100 Ωm) and a relative permittivity (relative to a vacuum) of 10 (typical for most rocks), exhibits a maximum two-way detection distance to a highly conductive lixiviant zone of approximately 9 m. Pulse dispersion and distortion effects, which cause a sharp waveform to smooth and lose resolution capabilities, also contribute to the decrease of the detection range. Increasing the frequency by an order of magnitude (570 MHz) in this example increased the detection range to 20 m because the higher frequency minimized the dispersion and distortion problems. As another example, a 55-MHz wavelet, propagating through 0.02-S/m (50-Ωm) material with the same relative permittivity, displays a two-way detection range of only 5 m before becoming severely distorted. If the frequency is raised to 570 MHz, the detection range is increased slightly to 8 m for the same reason. In addition to dispersion, the more conductive material of the latter example has attenuated the high-frequency wavelet to such an extent that the detection range is not significantly improved. As a final example, in 0.05-S/m (20-Ωm) ground, wave propagation is reduced to less than 2 m. A reflector, therefore, would have to be less than 1 m from the probe to be detected.

Unfortunately, much of the ground in the desert southwest is highly conductive, a difficult environment for GPR. In most cases, GPR signals would not be able to propagate 50 m and return, as required for effective monitoring. In extremely resistive material (greater than 1,000 Ωm), GPR signals of any frequency can propagate for tens or even hundreds of meters without suffering from severe attenuation or dispersion effects. In general, frequencies must be chosen such that penetration can be maximized and attenuation and dispersion minimized.

In addition to high attenuation rates and dispersion effects, the high-resolution characteristics may produce unwanted reflections from discontinuities, such as fractures or faults near the borehole. These effects could obscure or even eliminate the response from the lixiviant zone, especially if the reflectors are closer to the borehole than the lixiviant zone. For the research study mentioned above,[7] it was assumed that geologic noise was minimal and that the only reflector was the leach solution itself. Under realistic conditions, the maximum reflector distances would probably be less than the modeled values because of unwanted reflections.

[7]Work cited in footnote 5.

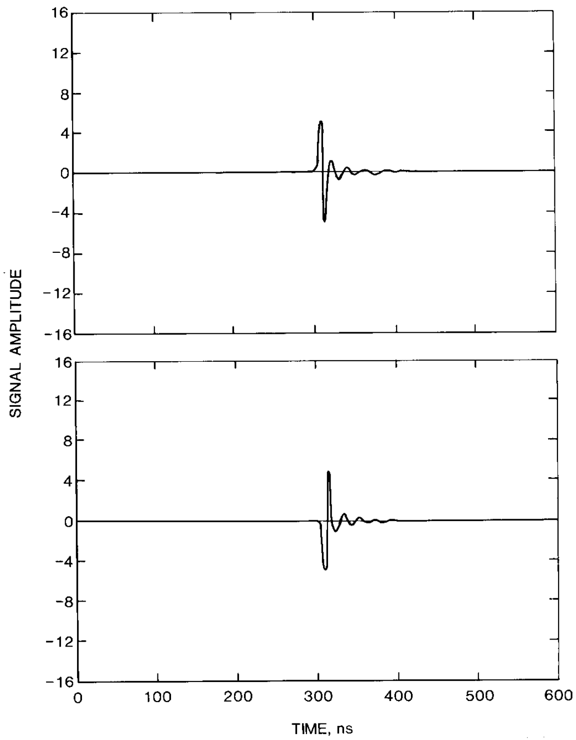

Figure 6.—Comparison of reflected pulses from nonconductor (top) and conductor (bottom).

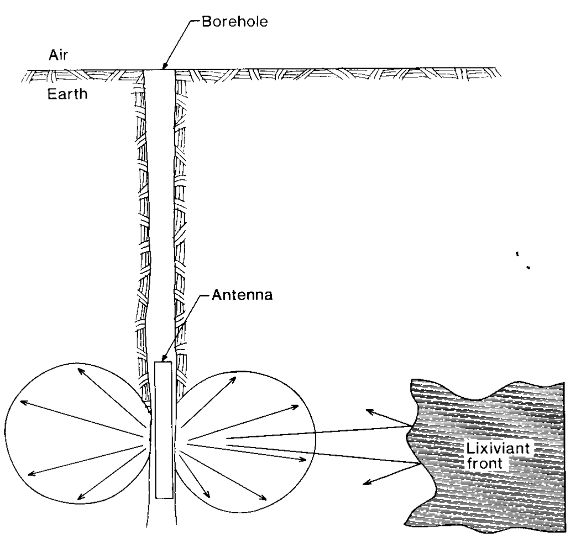

Figure 7.—Borehole GPR used to monitor lixiviant zone.

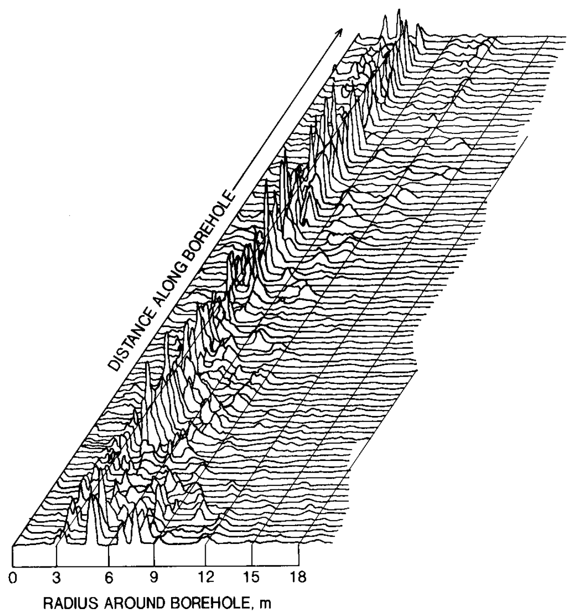

Figure 8.—Example of borehole GPR data.

Crosshole radar, a method by which signals are sent from an antenna in one hole to a receiver in a nearby hole, was also considered by the Bureau. Such techniques have been used to locate subsurface voids.[8]

Crosshole radar differs from conventional GPR in that it does not depend on reflected signals, but rather on complete transmission through the media between boreholes. This is an ideal situation for detecting highly resistive zones, such as voids, but is not suited for detection of highly conductive zones since wave propagation will not continue through the interface. This situation is accentuated further in conductive strata, as discussed above. Crosshole methods would probably prove less effective than conventional borehole GPR in most cases.

Both methods require favorable geologic conditions and low-conductivity rock to be considered effective techniques for detecting and monitoring conductive lixiviants. Sandstone-hosted uranium leaching operations, for instance, would provide an ideal environment for these techniques since the geology is simple and the conductivity is low. The Bureau is not considering using GPR in highly conductive areas or for long-distance monitoring, except under ideal circumstances. In certain situations, however, borehole GPR may be supplemental or even necessary in conjunction with other techniques.

[8]Work cited in footnote 5.

ELECTROMAGNETIC METHODS

EM prospecting methods have been in existence for about 50 years, although it is only in the last 20 years that significant advances in electronics have facilitated their widespread use (*26*). Early systems were large and cumbersome (low-power-to-weight ratio) and had poor resolution, penetration, and noise-rejection circuitry. Today, most systems are portable and high powered and data can be automatically, digitally recorded and processed by built-in computers—a great aid in noise reduction and data interpretation. These systems are used for shallow investigations by the engineering and ground water industries, for deep prospecting of metallic ore deposits by the mining industry (for which EM techniques were originally developed), and for deeper soundings in geothermal and hydrocarbon exploration.

EM methods are based on the principle of EM induction (*19, 26*). If ac is passed through wire in a coil, a primary magnetic field is produced in and around the coil. This primary field propagates through the ground and through space in a manner illustrated in figure 9. In the presence of subsurface conductors, the primary field causes eddy currents to flow within the conductors, which in turn produce weak secondary fields. A receiver coil, tuned to the transmitted frequency, can be used to detect these secondary fields. Hence, the presence of secondary fields indicates the presence of a conductor.

Measurements may be recorded in either the frequency domain or the time domain, depending on the type of EM system. In the frequency domain, measurements are made in the presence of the primary field at a given frequency. In the time domain, measurements are made in the absence of the primary field; that is, after the primary field has been turned off. Secondary fields are measured at discrete times as they decay to background levels (fig. 10). Both systems may be used in surface or borehole configurations.

FREQUENCY-DOMAIN ELECTROMAGNETICS

Developed before time-domain systems, FEM has been in use for many years in the mineral exploration industry (*26*). These systems have been remarkably successful in the exploration of massive sulfides in many parts of the world, such as Canada and Scandinavia. The systems are commonly used as reconnaissance tools to verify the existence of anomalous responses detected by airborne EM surveys.

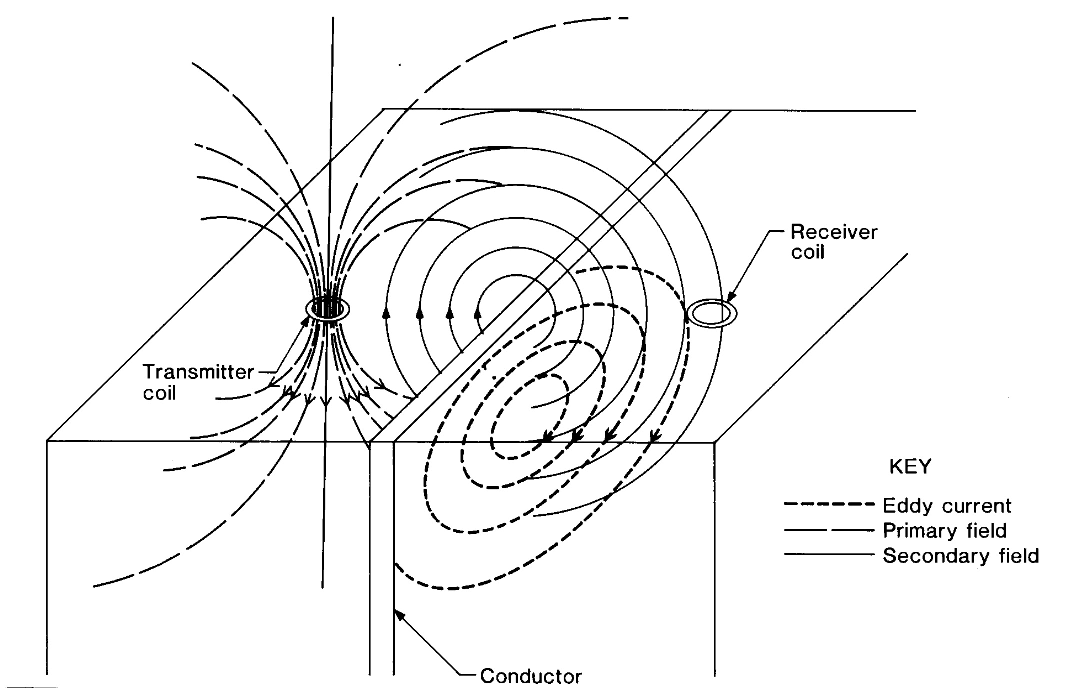

Figure 9.—EM field behavior near subsurface conductor.

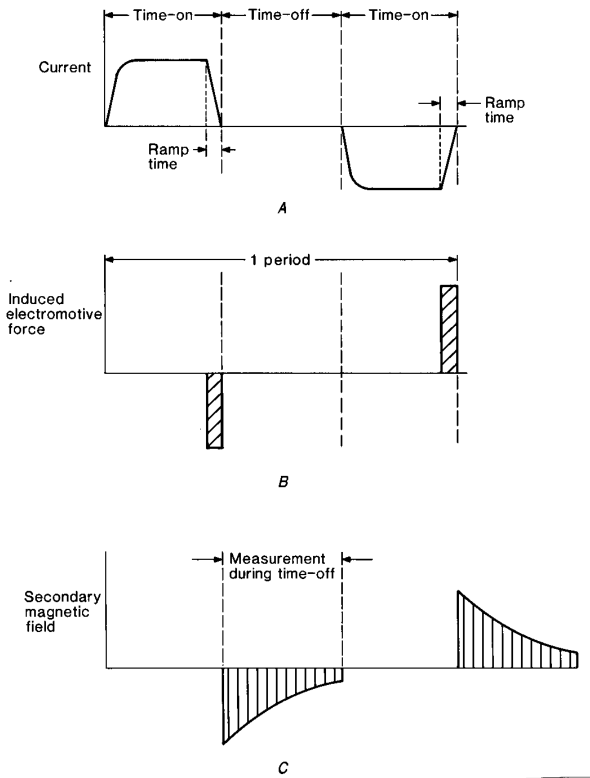

Figure 10.—Current waveforms and resultant secondary field observed in TEM. *A*, Current in transmitter loop; *B*, induced electromotive force caused by current; *C*, secondary magnetic field caused by eddy currents.

Surface FEM works well under conditions of large conductivity contrast between target and host, an example being massive sulfide ore in volcanic rock (*19, 26*). The best penetration occurs when little or no overburden is present or, if present, is resistive compared with the resistivity of the target conductor. Delineation of weak conductors or conductors buried under thick conductive cover is often difficult because of the weak signal and/or masking of signal by the conductive cover. Further ambiguity may result from the presence of clays in the overburden, which produce their own anomalous responses.

Most FEM surveying is done with very low frequency (VLF), the Slingram method, or with ground-conductivity meters (*27*). The VLF method will not be considered here because it is only effective for very shallow features. The Slingram method, a multifrequency, usually horizontal-loop method, measures both the inphase and the quadrature (out-of-phase) components of the secondary field at a constant coil separation. The conductivity-thickness product (conductance) of an anomalously conductive zone may be calculated from the ratio of these two components. Since the thickness of the zone is normally much smaller than the coil separation, the Slingram system is usually used to measure conductance instead of conductivity. Measurements are usually taken at two or more distinctly different frequencies to help determine the source of any anomalous responses, whether they are due to a clay layer in the overburden or an ore deposit in the bedrock. Low frequencies will generally penetrate to greater depths than high frequencies, although transmitter-receiver separation plays the most important role in depth of penetration as the frequency becomes very low (*28*).

Ground-conductivity meters, on the other hand, measure only the quadrature component, which is linearly proportional to ground conductivity, not conductance. Measurements are normally made at several coil separations, each at constant frequency, to determine conductivity changes with depth.

Both Slingram and ground-conductivity meters employ two coils, a receiver and a transmitter, which can be operated by one or two people, depending on the system. The coils can be oriented in any of several positions (horizontal, vertical, coplanar, or coaxial) for maximum (or minimum) coupling with horizontal, vertical, dipping, or multiple or wide conductors. The use of several coil orientations would be an advantage for delineating nonuniform conductors, such as leach-filled fractures. Neither system, however, has the capability for deep penetration.

FEM borehole and surface surveys have been applied successfully to chemical pollution plumes in Europe, Canada, and the United States (*26, 29*). They have also been used to outline ground water salinity and coastal sea water intrusion in many parts of the world (*12, 26*). Although all of these scenarios are important in studying the feasibility of lixiviant detection, none occurred at the great depths often encountered at prospective in situ mining operations. It is one of the Bureau's objectives to locate or develop a monitoring system with deep-penetrating capabilities.

A unique borehole induction logger manufactured by Geonics, Ltd., Ontario, Canada, was designed specifically for the detection and monitoring of shallow (less than 200 m) conductive plumes (*11*; fig. 11). Both the transmitter and the receiver are housed in the same probe, which allows the plume to be energized from the subsurface, an advantage for sensitivity and resolution. Also, a focusing coil is used so that maximum response occurs outside the borehole, away from the influence of conductive borehole fluids. Unfortunately, the extremely small transmitter coil (about 5 cm) produces only a small dipole moment, enough to penetrate only 1 to 2 m into the surrounding rock. This system could only be used if the borehole had actually penetrated the lixiviant plume.

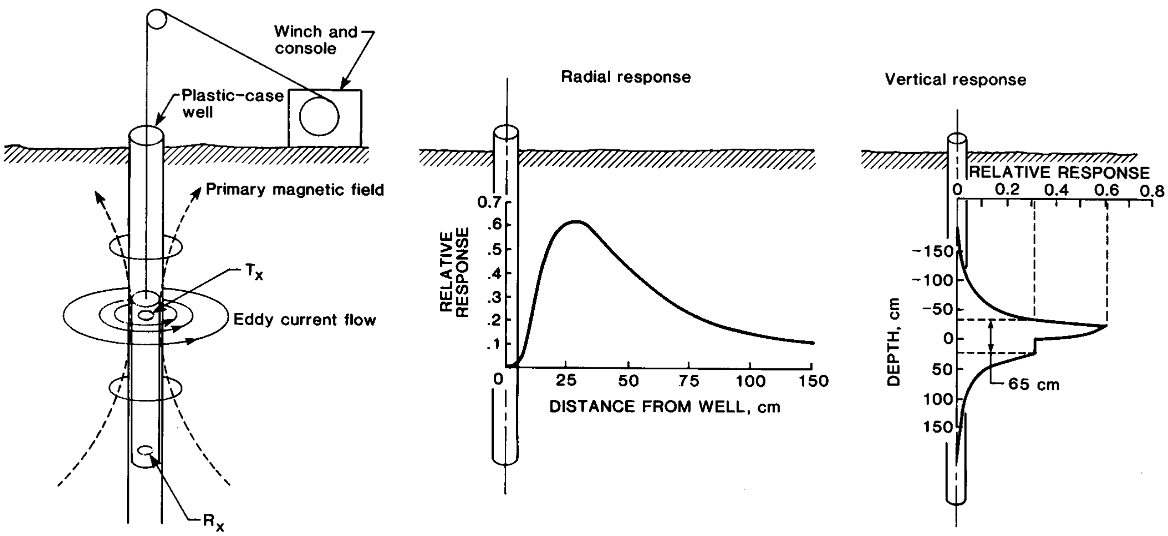

Figure 11.—Principle of operation of commercial borehole induction logger. (T_x and R_x = transmitter and receiver coils, respectively.)

Industry's need for a system to monitor lixiviant from a distance of 50 m or more cannot be met by placing a small transmitter coil in a borehole.

Surface FEM systems can be used for detection and mapping of contaminant plumes, but suffer from somewhat different problems. Although the transmitter coils are larger (1 to 3 m in diameter), depth of penetration is limited by conductive overburden and by noise introduced from intercoil misalignment and spacing errors (*19*). In addition, depth of penetration is largely governed by the separation between transmitter and receiver; the larger the separation, the greater the depth of penetration. Depending on relative coil orientation, frequency used, and size of the target being investigated (thin tabular body versus infinite layered earth, or half-space, for example), depth is approximately 0.5 to 1.5 times this separation (*12, 30*). A large target at an exploration depth of 600 m would require a coil separation of at least 400 m. Separation distances this large would require extremely long survey lines, as well as an extremely powerful (and heavy) transmitter to provide adequate signal strength, and would be impractical for field use. Furthermore, there do not seem to be any commercial FEM systems that permit such large coil separations. It is probable that the highly conductive nature of the overburden, such as that seen in the desert southwest and other areas, would inhibit the effectiveness of any FEM system at 600 m of depth. However, FEM would be useful in shallow applications (less than 200 m).

TIME-DOMAIN ELECTROMAGNETICS

TEM systems are relatively recently developed technologies. The field equipment is depicted in figure 12, and a typical application for in situ mining is depicted in figure 13. In theory, TEM systems have existed since the advent of FEM systems, but practical application had to await the development of high-speed integrating circuitry. This circuitry is used to measure the extremely small time windows (to less than 50 μs), which are necessary to observe the decay of magnetic fields. Some of the early applications of TEM systems were in airborne geophysical surveys for metallic mineral exploration and are still used for this purpose today.

TEM systems are fundamentally similar to FEM systems, but differ in several important aspects. First and most importantly, TEM systems measure a decay of secondary magnetic fields in the absence of the primary field, rather than the intensity of secondary fields in the presence of the primary field, as in FEM systems. By rapidly terminating the current in the transmitter loop and hence the primary magnetic field, a large electromotive force (E.M.F.) is induced in the earth. By taking measurements during "off" time, the distinct advantage of elimination of system noise errors due to coil geometry is realized. Therefore, it is not necessary to compensate for primary field strength at the receiver, resulting in a substantially higher signal-to-noise ratio (*31*). A high signal-to-noise ratio is necessary for deep detection or exploration work.

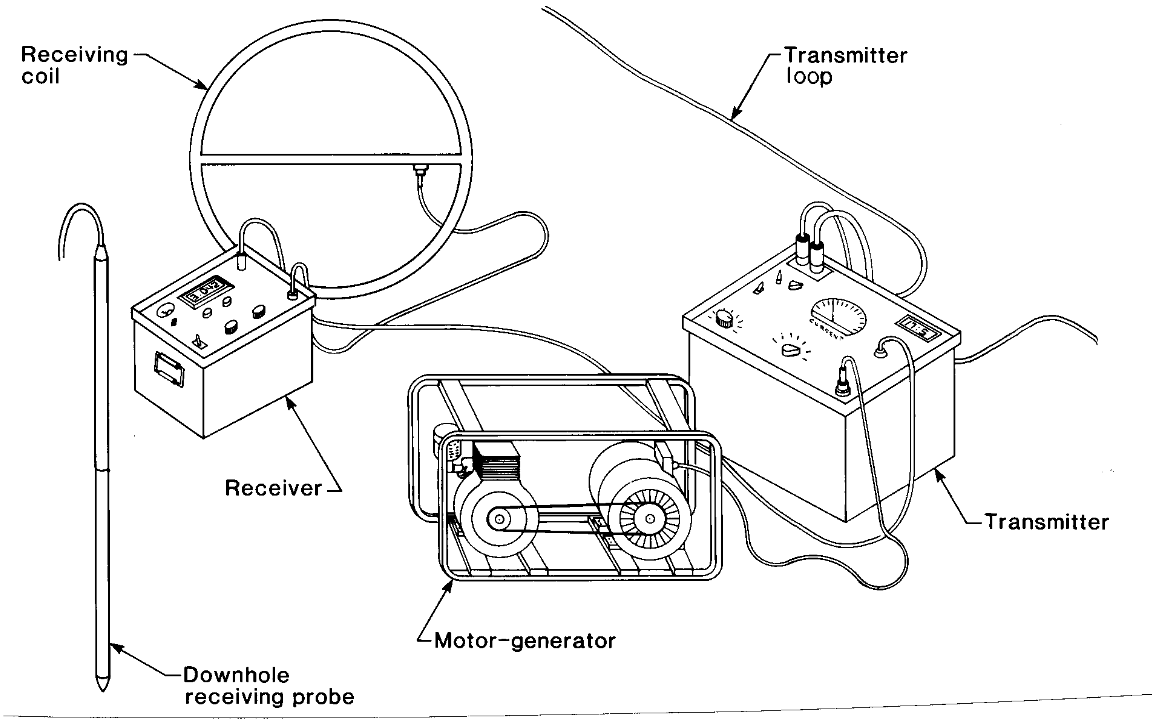

Figure 12.—Equipment used in TEM.

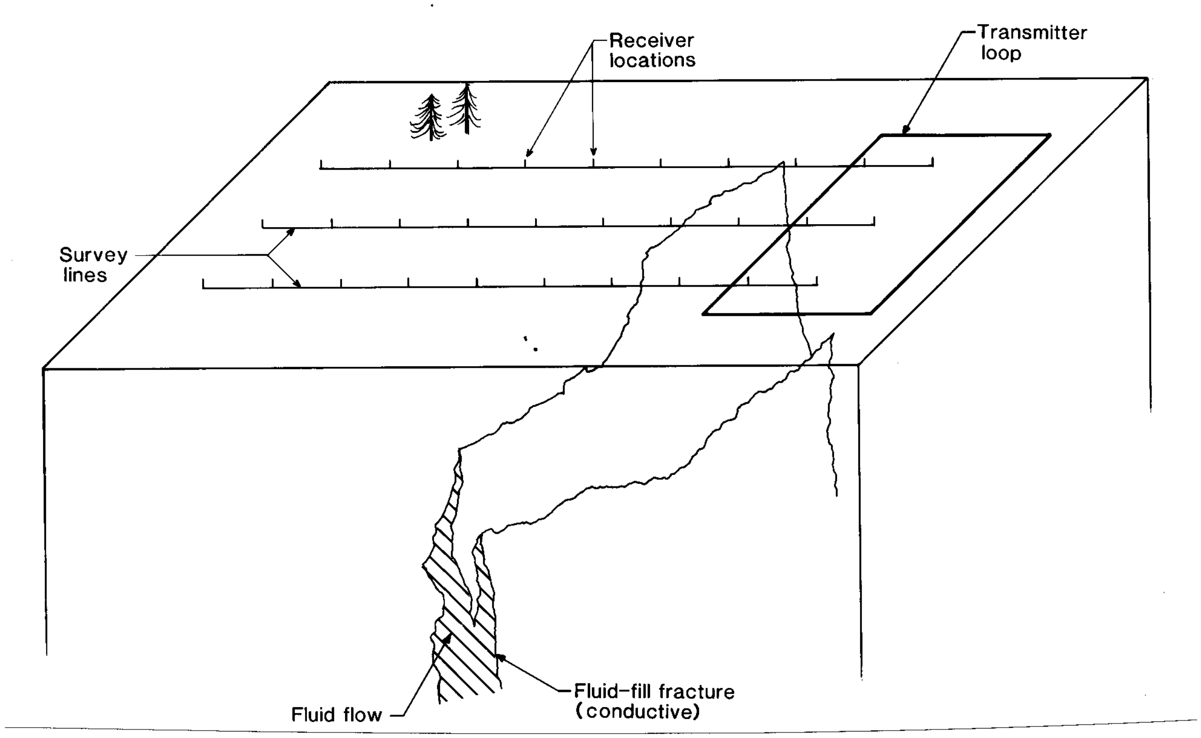

Figure 13.—Surface profiling over fluid-filled fracture zone.

Other inherent advantages of TEM systems can be used to enhance the signal-to-noise ratio. One advantage is signal stacking (*20*). Because of the high repetition rate (approximately 1 to 50 Hz) of the transmitted waveform, the received signal and the associated time gates may be averaged hundreds of times per minute to reduce random noise. Hence, clean repeatable data may be obtained in a relatively short period of time.

TEM systems also have the advantage of the use of very large transmitter loops (up to 1,000 m across) for generation of enormous dipole moments (to several million Atm^2). Together with increasing the signal-to-noise ratio, these large dipole moments allow for deep penetration, as high as several thousand meters in resistive terrain and somewhat less in conductive terrain.

Furthermore, TEM systems may be used in either a surface or borehole configuration (*19*). In the borehole configuration, however, only the receiver is lowered into the borehole rather than both the transmitter and the receiver, as in the case of the FEM borehole induction system described earlier. With the transmitter on the surface, the loop size and the position may be adjusted as necessary according to depth desired and target location. Higher resolution may be attained in the borehole mode than in the surface mode, simply because the receiver is much closer to the target. In the borehole mode, however, only the vertical component of the secondary field is easily measured, whereas in the surface mode, one vertical and two orthogonal horizontal components may be measured. The surface mode gives additional information that allows the interpreter to map changes in depth and conductivity as the receiver is moved from one place to the other.

One major disadvantage of TEM systems, and to some extent FEM systems, is their susceptibility to interference from cultural objects, such as powerlines, fences, or buried pipes, as previously described for CSAMT. These objects, if grounded in certain ways, may produce anomalous responses of their own, affecting data collection for several hundred meters around them in some cases. This is unfortunate because these objects are often encountered at minesites. Lixiviant monitoring systems would have to be designed to avoid or minimize such problems.

In applying TEM systems to the detection and monitoring of lixiviant plumes, both borehole and surface configurations should be used wherever possible. If the plume is large enough, its lateral extent, depth, and conductivity may be mapped using the surface mode, and then its thickness and proximity to boreholes may be determined using the borehole mode. Given the flexibility and high signal-to-noise ratio of TEM systems, it is likely that these systems are the most amenable for the detection and monitoring of lixiviant plumes.

TIME-DOMAIN ELECTROMAGNETIC COMPUTER MODELING

To determine, at least theoretically, whether or not lixiviants might be detected at great depth under conductive cover, a geoelectric section of the Santa Cruz site was produced (fig. 1). Geologic and borehole resistivity data, provided by USGS, were compiled for purposes of computer modeling. The geoelectric section is oversimplified to facilitate the modeling. The deposit is modeled as a block overlain by flat-lying stratigraphy and limited to only four layers. In reality, the ore body is very complex in shape, has been faulted in at least two places, and is covered by many layers.[9] The overlying bedrock is highly fractured, possibly faulted, and is not flat lying. However, the section does provide for a reasonable measure of rock and lixiviant resistivities and a working depth to oxide mineralization. In addition, the thickness of the ore body and lateral dimensions of the lixiviant zone are taken into account. The lixiviant zone is also modeled as a block; its size was estimated, but was based on a reasonably difficult case; that is, a small zone (120 m long by 60 m wide by 30 m thick) inside a large ore body. The value for the lixiviant resistivity (1 Ωm) was obtained from measurements of fluid leached through a whole-core sample of copper-bearing rock. The exact value was 0.14 Ωm, but was adjusted to 1 Ωm to account for the overall resistivity of the rock and fluid combination.

TEM computer modeling profiles were completed at the request of the Bureau by Walter Anderson of the USGS in Denver, CO. All of the profiles were simulated using the geoelectric section and the University of Utah's three-dimensional (3-D) modeling program, called EM3DS. This program calculates the TEM response from a 3-D conductor buried in layered earth (*32*). It is believed that the geoelectric section was accurate enough to determine the feasibility of TEM systems in lixiviant detection.

Only the surface-to-borehole TEM configuration (transmitter on surface and receiver in borehole) was modeled with the program. Surface-to-surface simulations were not performed during the modeling exercise.

Prior to the work by Anderson, TEM profiles (not shown) were generated by Bryan A. James, a consultant formerly employed by the USGS. James used the same computer program, but used a slightly different layered-earth model supplied by the Bureau. The receiver probe was held at constant depth in each borehole, and the borehole locations were somewhat different than in the subsequent study. However, the work by James was very helpful in planning transmitter loop size and position as

[9]L. J. Dahl, geologist, Twin Cities Research Center, provided the geologic information from the Santa Cruz site.

well as lixiviant zone dimensions and borehole locations. Later, new geological and geophysical data from the Santa Cruz site became available, providing a more complete model, and were used for the subsequent work by Anderson. The data submitted by the two researchers are consistent insofar as comparisons can be made.

A one-dimensional (1-D) response was assumed for the layered-earth portion of the geoelectric section, while a 3-D response was used for the lixiviant zone within the layered earth. Measurements were made in a borehole configuration using multiple receiver locations in the vicinity of the lixiviant zone, located between 670 and 700 m below the surface (fig. 14). In all cases, the transmitter loop size was 1,000 m square, carried 20 A of current, and was fixed in position. Profiles were generated with and without the lixiviant zone present for direct response comparison (3-D versus 1-D responses, respectively).

These response simulations were carried out in three separate borehole locations. Borehole 1 is located 30 m from one edge of the leach zone, borehole 2 is 10 m from the same edge, and borehole 3 penetrates the center of the leach zone (fig. 15). These borehole positions would be equivalent to a migrating leach zone. Initial profiles (not shown) were run in boreholes 1 and 2 using a central induction or in-loop configuration, with the transmitter loop being centrally located over the lixiviant zone (fig. 16). This configuration proved unsuccessful as there was no obvious difference between the 1-D and 3-D responses. It is believed that the leach zone was not detected because the maximum current density diffuses down and out, like an expanding ring, from the transmitter loop. The small target lying directly below the loop is outside the path of maximum current density and was not detected (*28*).

Another configuration, an offset loop, was then attempted. In this configuration, the transmitter loop is offset from the target by some distance (fig. 17). For modeling purposes, the transmitter loop center was offset from borehole 2 by 1 km. The offset configuration proved to be much more effective, with peak amplitudes (occurring at about 3.0 ms after current termination) differing by as much as 35 pct in borehole 2 between lixiviant zone (3-D) and layered-earth (1-D) responses, although responses were not as pronounced in the other two boreholes. (Selected profiles are shown for each of the borehole simulations in figures 18 through 26.)

Most of the profiles display a small amount of noise, which shows up during early times (300 to 600 μs). This noise does not affect the general (late time) response characteristics. All profiles show a double peaked appearance, which is simply the result of plotting the absolute values of the data points; the left-hand peak corresponds to negative voltages and the right-hand peak corresponds to positive voltages. The zero crossing occurs between the two peaks. The voltage values change sign because the coupling between the receiver and the diffusing currents changes geometry as time passes (*28*).

To determine how peak TEM response varies with distance along the borehole near the lixiviant zone, three plots were generated that profile the response for each borehole (figs. 27-29). These plots directly compare the 1-D and 3-D responses and indicate a substantial effect from the lixiviant zone, especially in borehole 2. This strongly suggests that a small lixiviant zone can, in fact, be detected under conductive cover, at least within 10 m of the borehole. In borehole 1, 30 m from the edge of the lixiviant zone, the response is less conspicuous, but may still be recognizable, depending on the amount of geological noise.

While these figures appear to fall short of the required 50-m minimum, they cannot be directly compared with borehole simulations located 50 m from an edge of the lixiviant zone since these simulations were not performed. (The 50-m requirement was not considered important at the time the modeling was performed.) However, the theoretical range and depth of detection are clearly demonstrated in the available data, even under conditions of a highly conductive environment.

It is interesting to note that for boreholes located outside of the lixiviant zone (boreholes 1 and 2), the 3-D response is always to the right or positive side of the 1-D response, while for a borehole passing through the target (borehole 3), the opposite is true. This effect is most likely a function of transmitter loop location and geometry of the target and the receiver rather than an effect due to the target itself (*28*). However, it may prove useful in monitoring the progress of a lixiviant plume as it passes a borehole. More modeling will be necessary to verify this and other response characteristics. These preliminary results are very encouraging and warrant further evaluation.

It must be stressed that, in many instances, fitting modeled data to observed data can yield ambiguous results (*33*). That is, an observed data set may be the result of a large number of geologic inhomogeneities and, hence, a large number of models may be created to fit the data. This is commonly called nonuniqueness. One way to reduce nonuniqueness is to impose constraints upon the model in such a way as to make the model geologically realistic. Local rock types, layer thicknesses, and resistivities and strikes and dips obtained from outcrop or borehole data can be used in constraining the model. In general, as the number of constraints increase, the number of models decrease. Normally, the number of models may be reduced to just two or three, each of which may fit the observed data equally well.

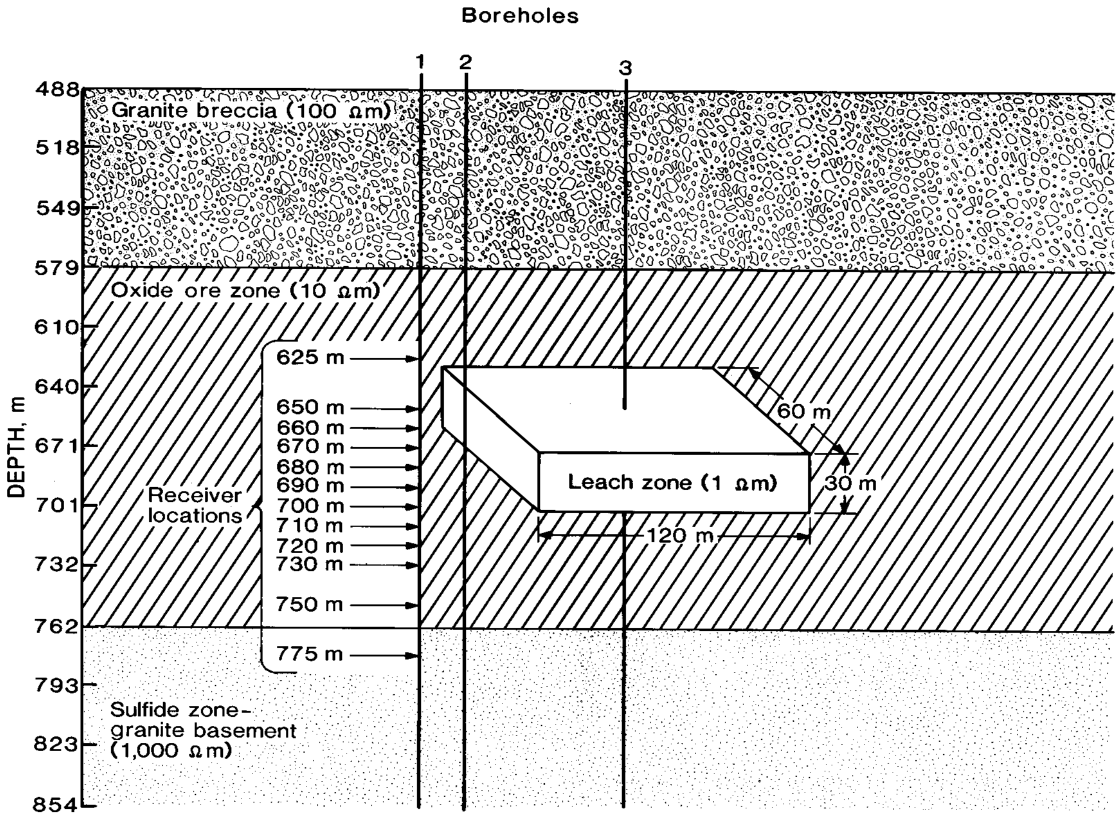

Figure 14.—Layered-earth model and leach zone.

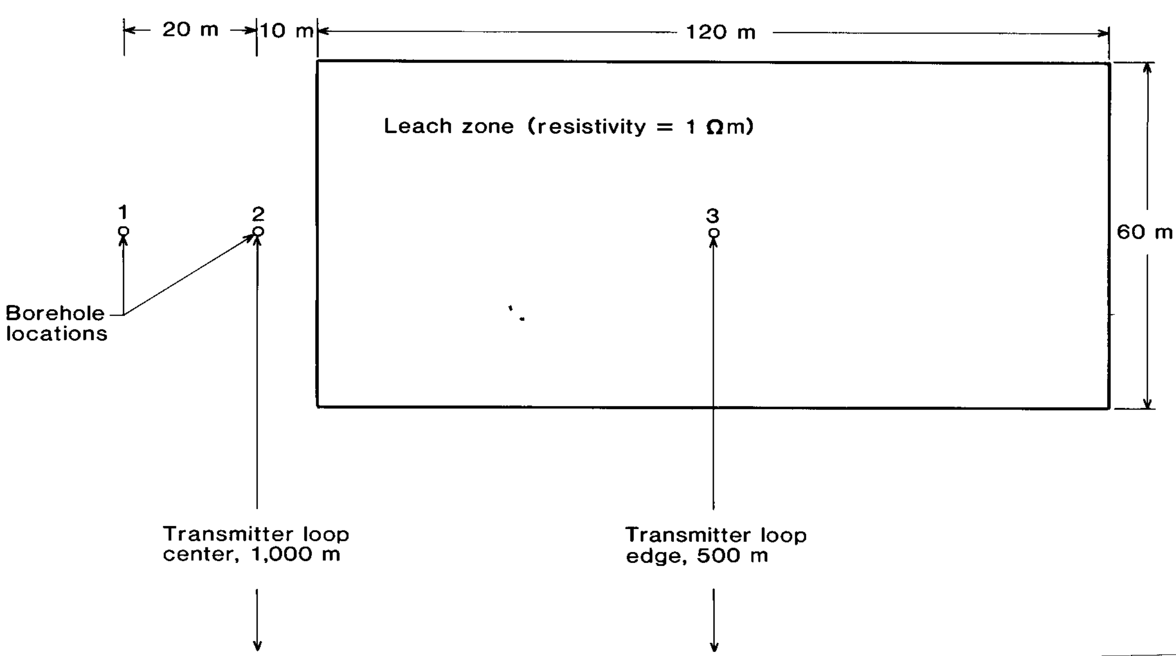

Figure 15.—Plan view of leach zone and borehole locations.

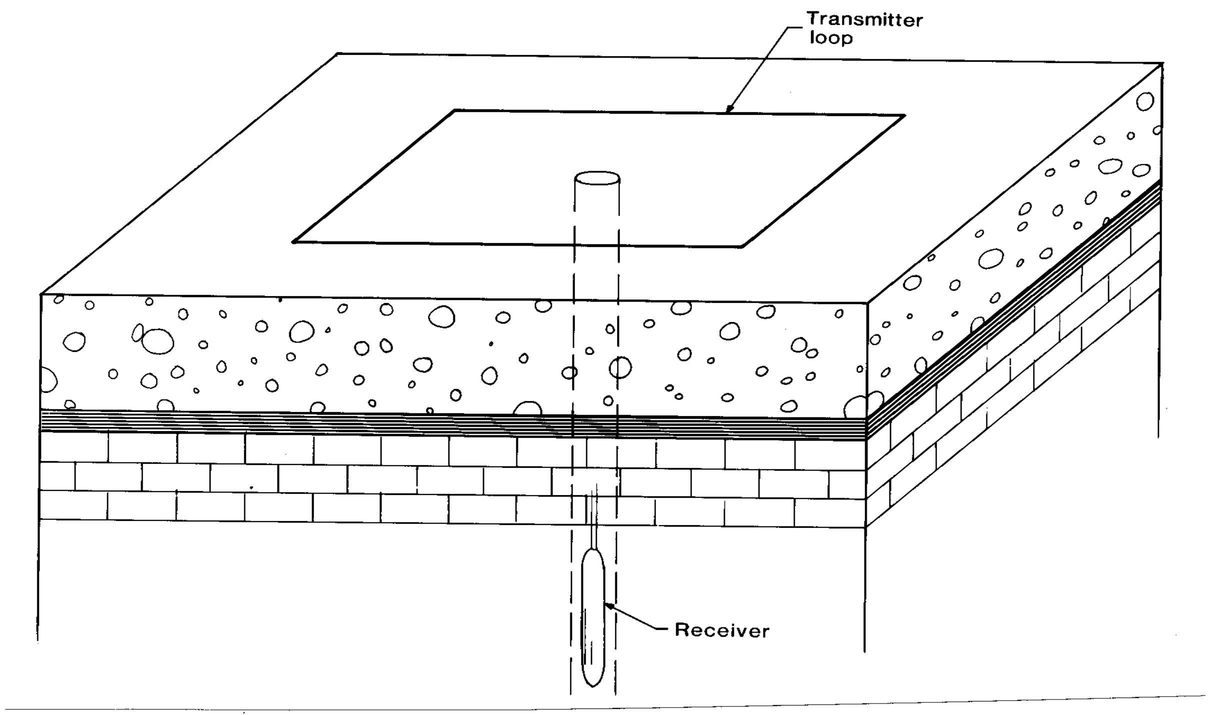

Figure 16.—Central induction configuration.

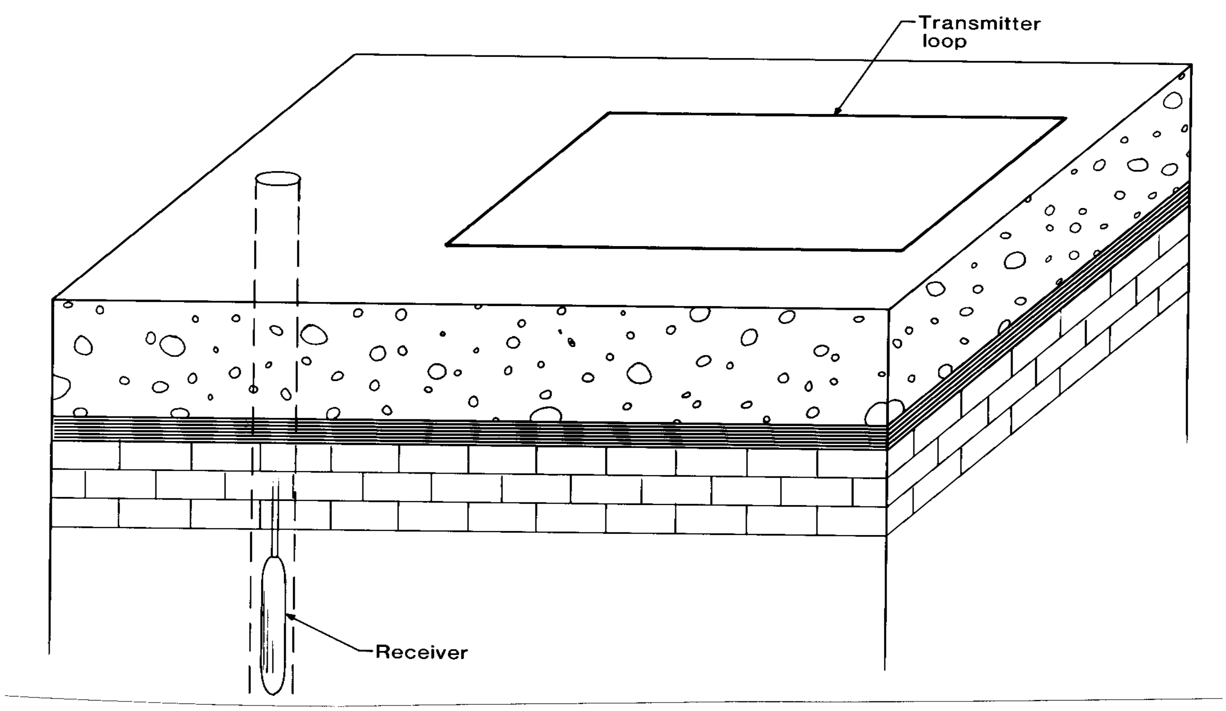

Figure 17.—Offset loop configuration.

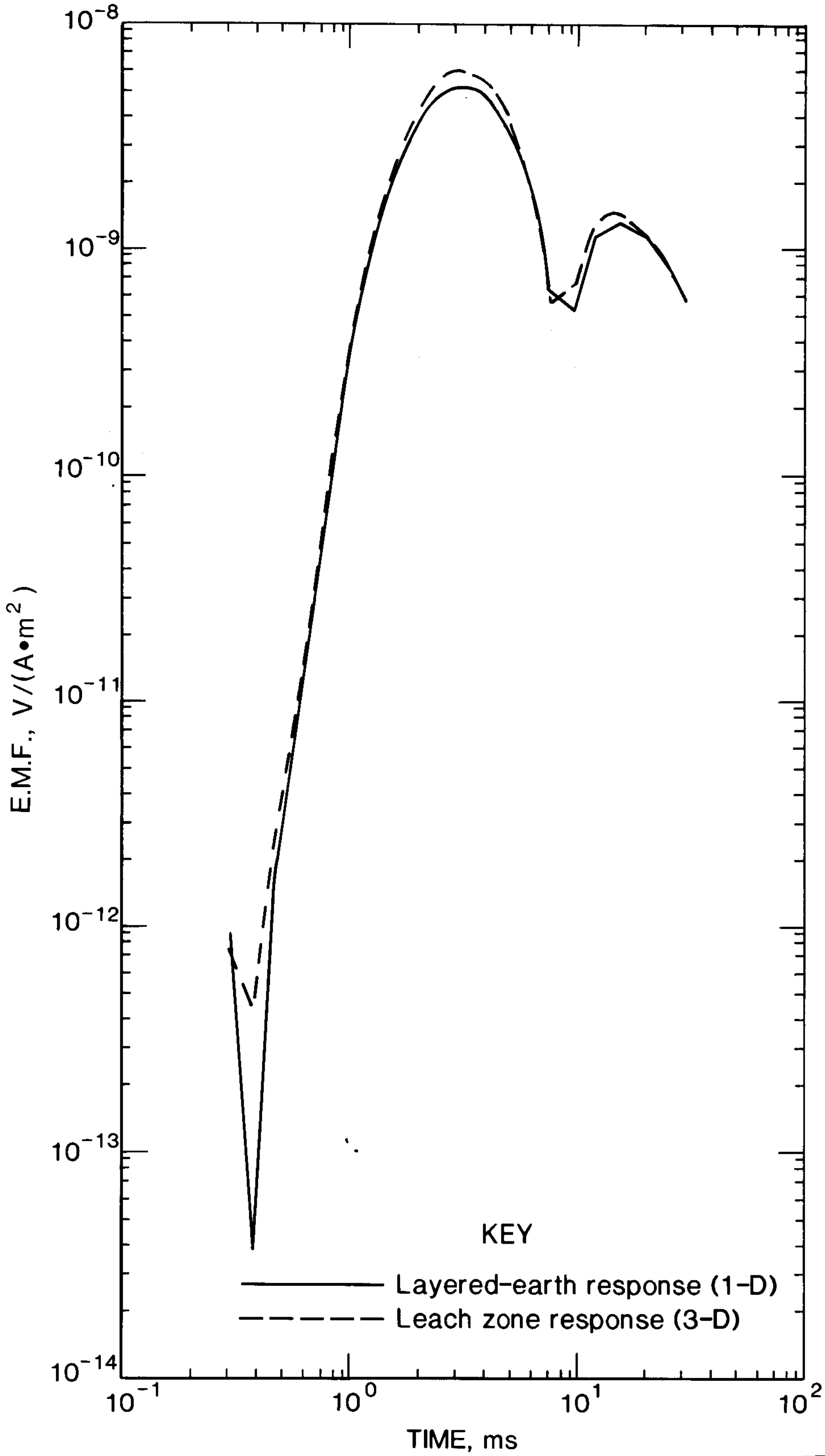

Figure 18.—TEM response in borehole 1 at depth of 660 m. Left peak corresponds to negative and right peak to positive E.M.F.

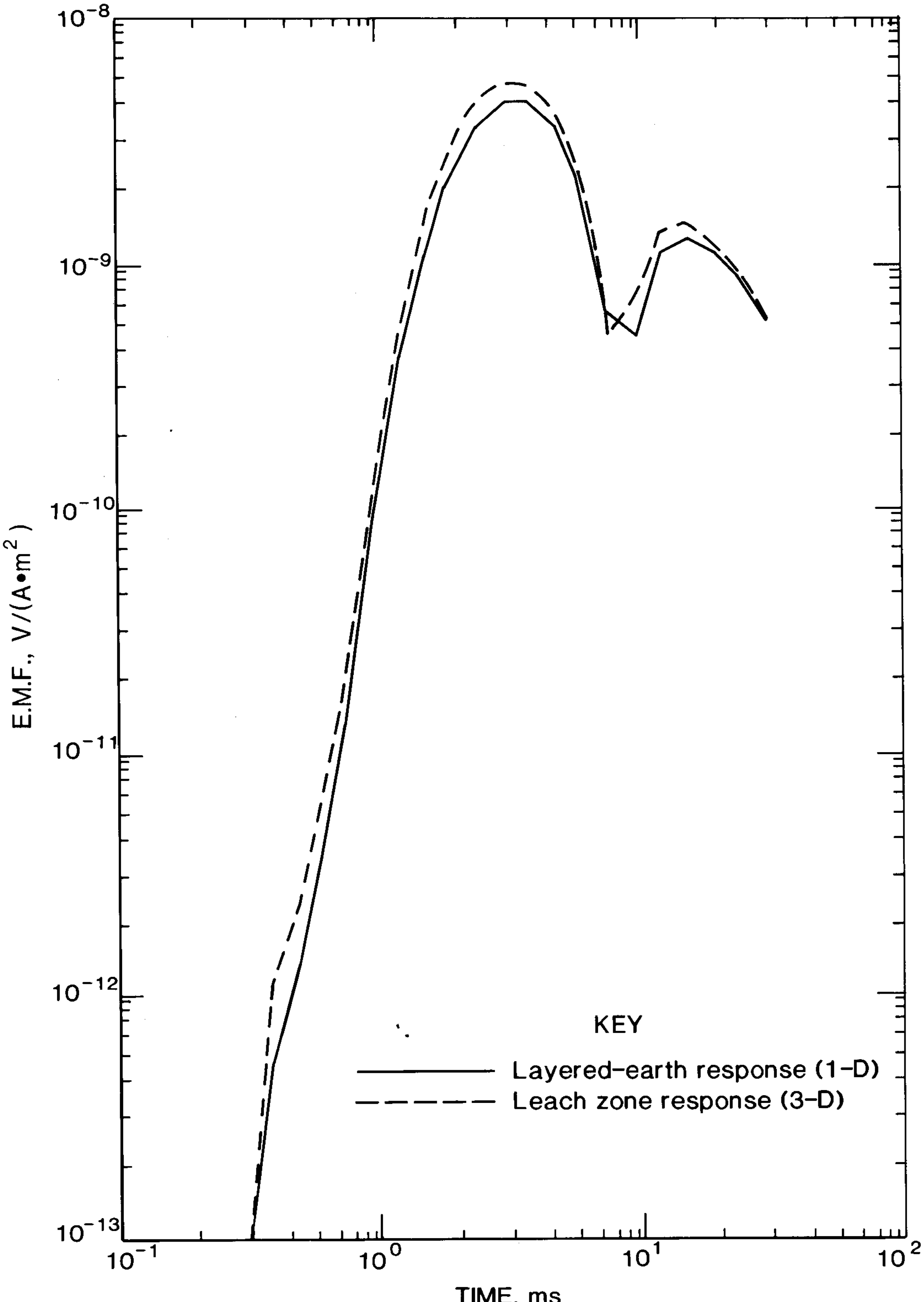

Figure 19.—TEM response in borehole 1 at depth of 690 m. Left peak corresponds to negative and right peak to positive E.M.F.

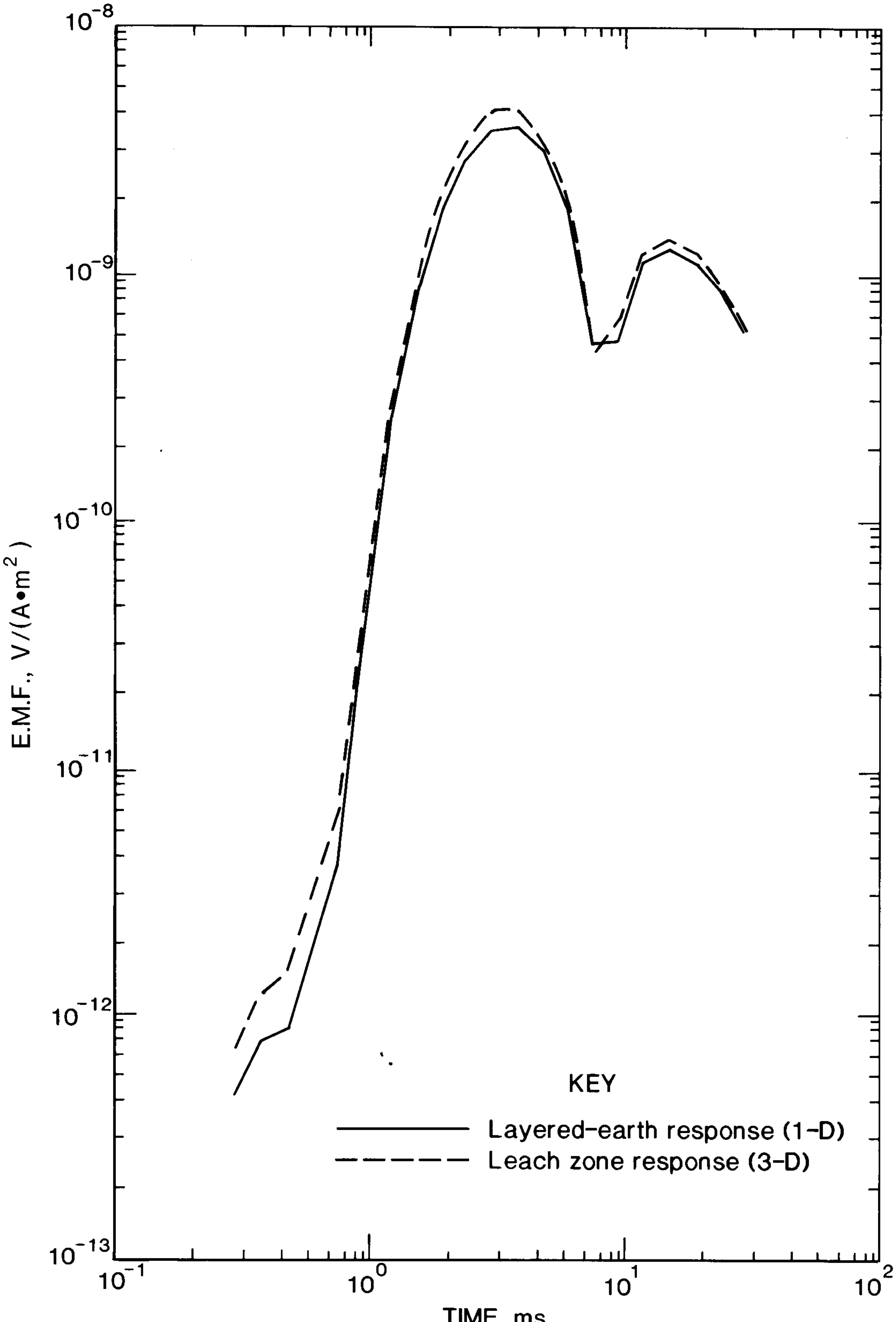

Figure 20.—TEM response in borehole 1 at depth of 720 m. Left peak corresponds to negative and right peak to positive E.M.F.

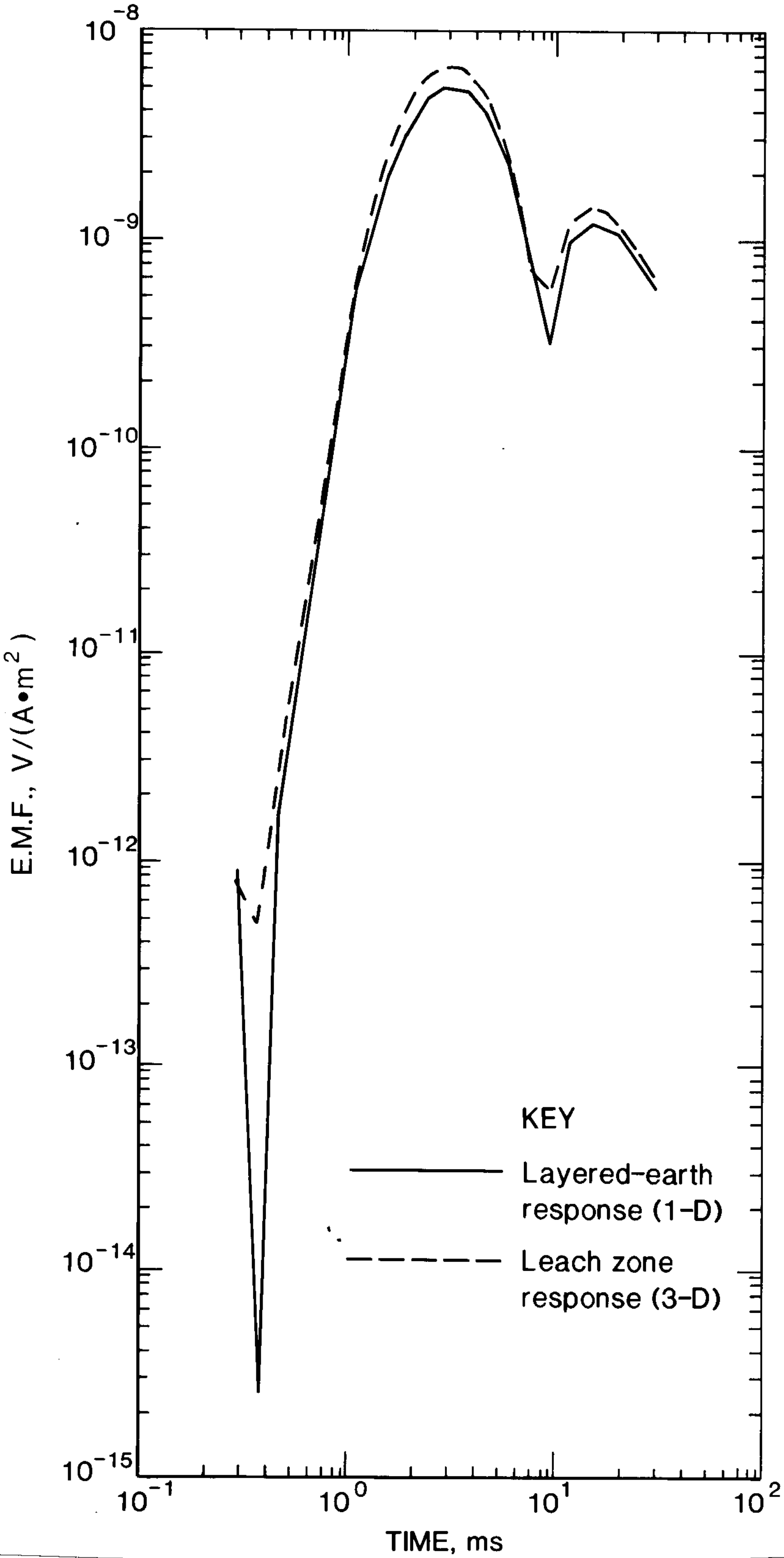

Figure 21.—TEM response in borehole 2 at depth of 660 m. Left peak corresponds to negative and right peak to positive E.M.F.

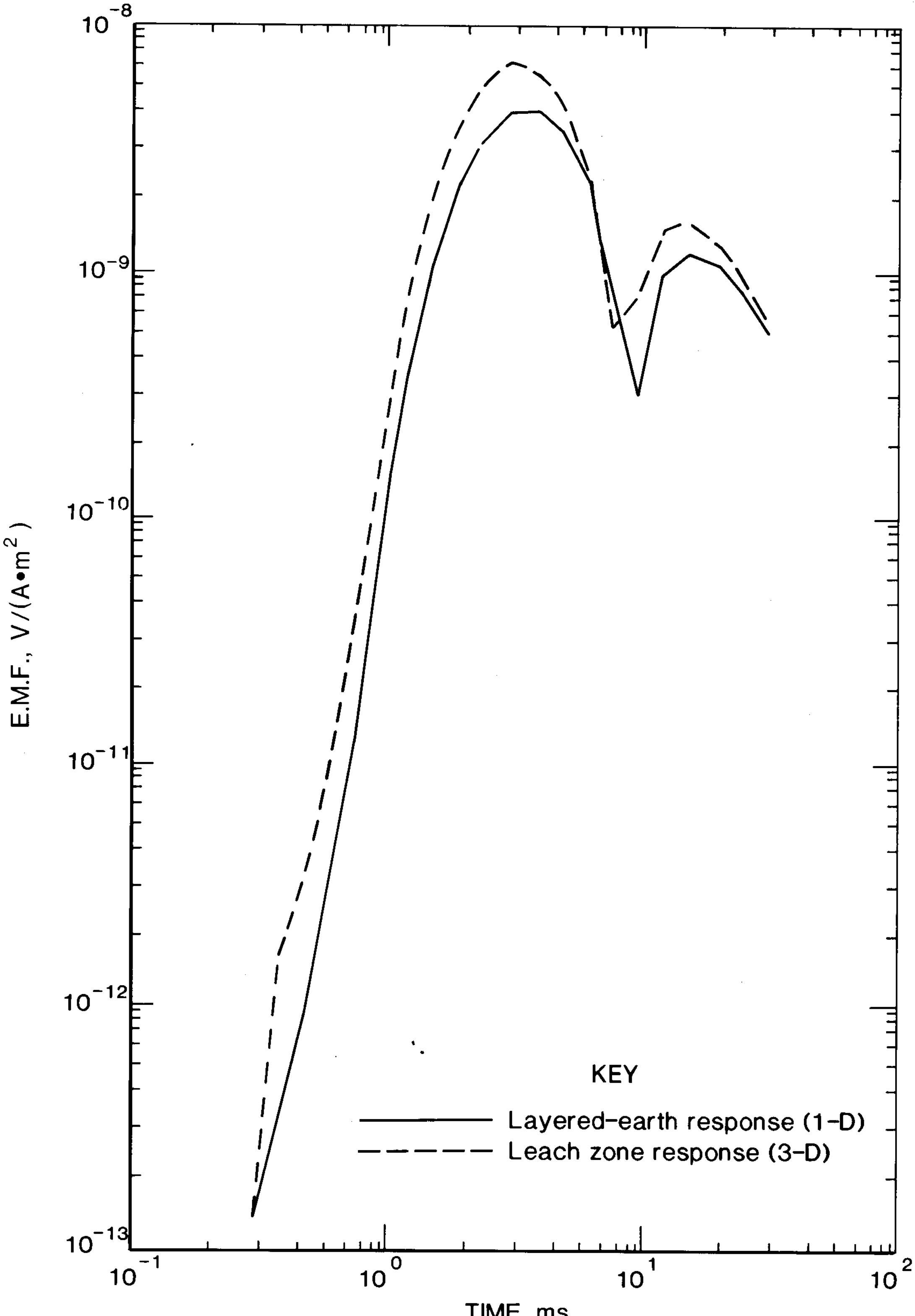

Figure 22.—TEM response in borehole 2 at depth of 690 m. Left peak corresponds to negative and right peak to positive E.M.F.

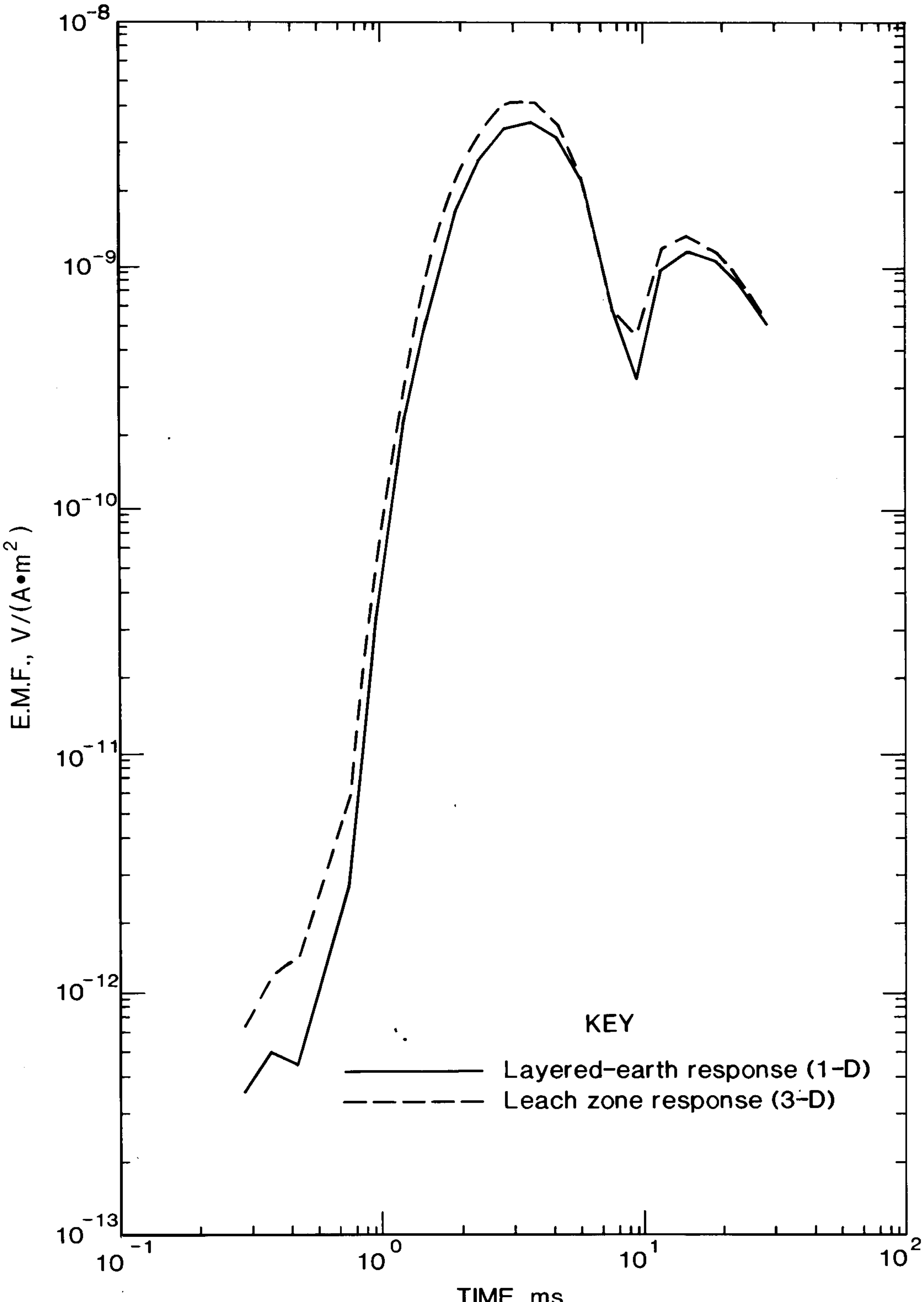

Figure 23.—TEM response in borehole 2 at depth of 720 m. Left peak corresponds to negative and right peak to positive E.M.F.

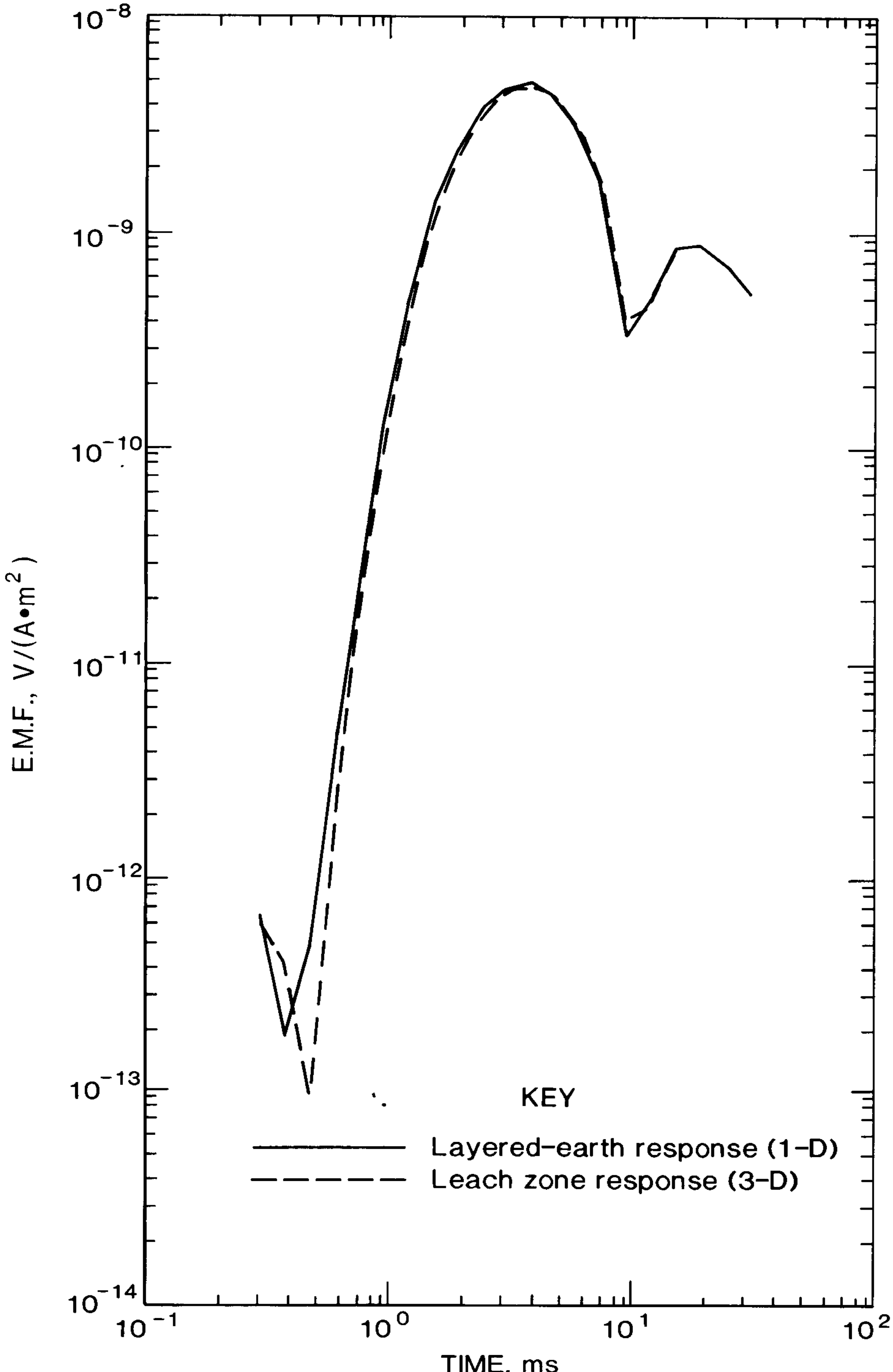

Figure 24.—TEM response in borehole 3 at depth of 660 m. Left peak corresponds to negative and right peak to positive E.M.F.

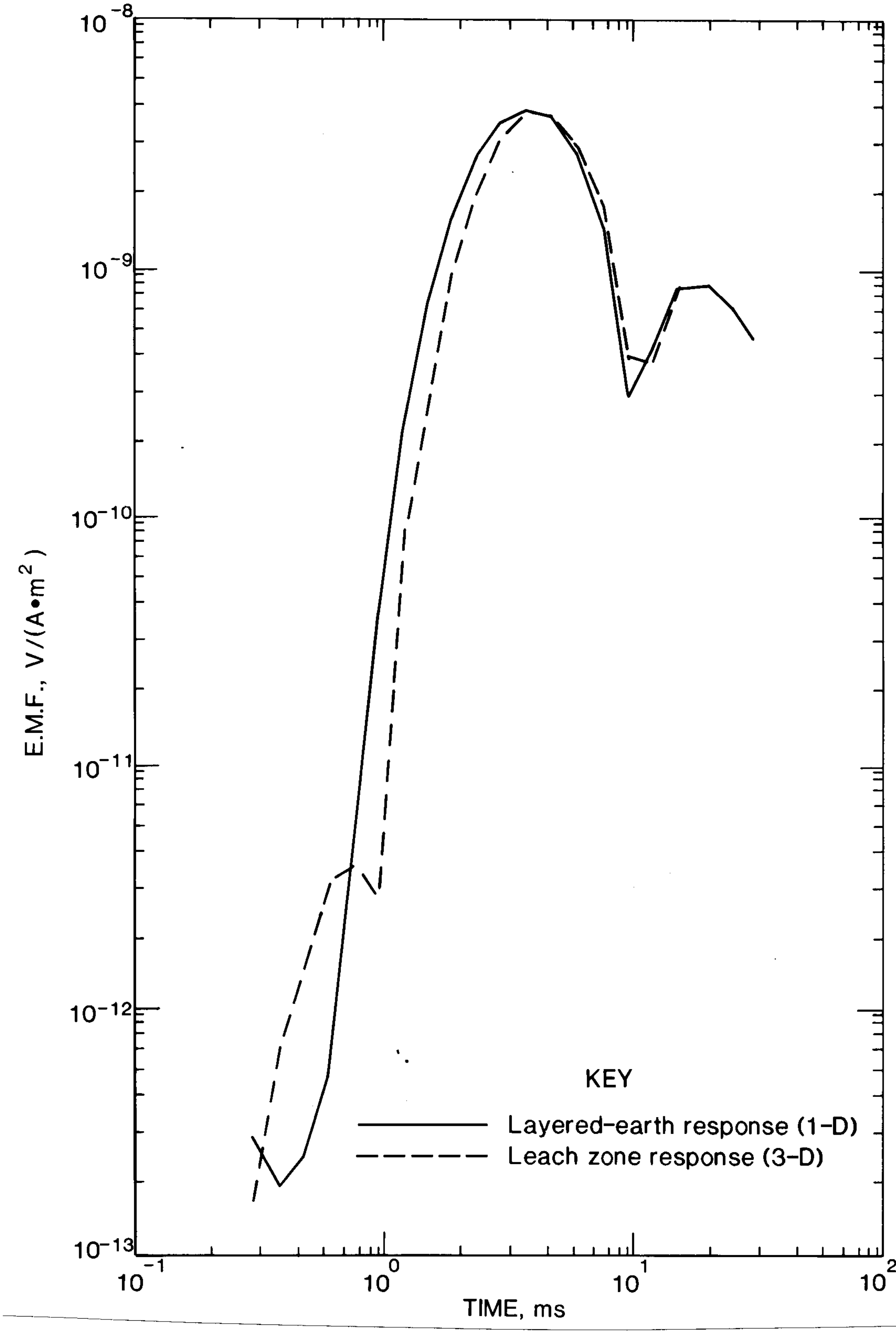

Figure 25.—TEM response in borehole 3 at depth of 690 m. Left peak corresponds to negative and right peak to positive E.M.F.

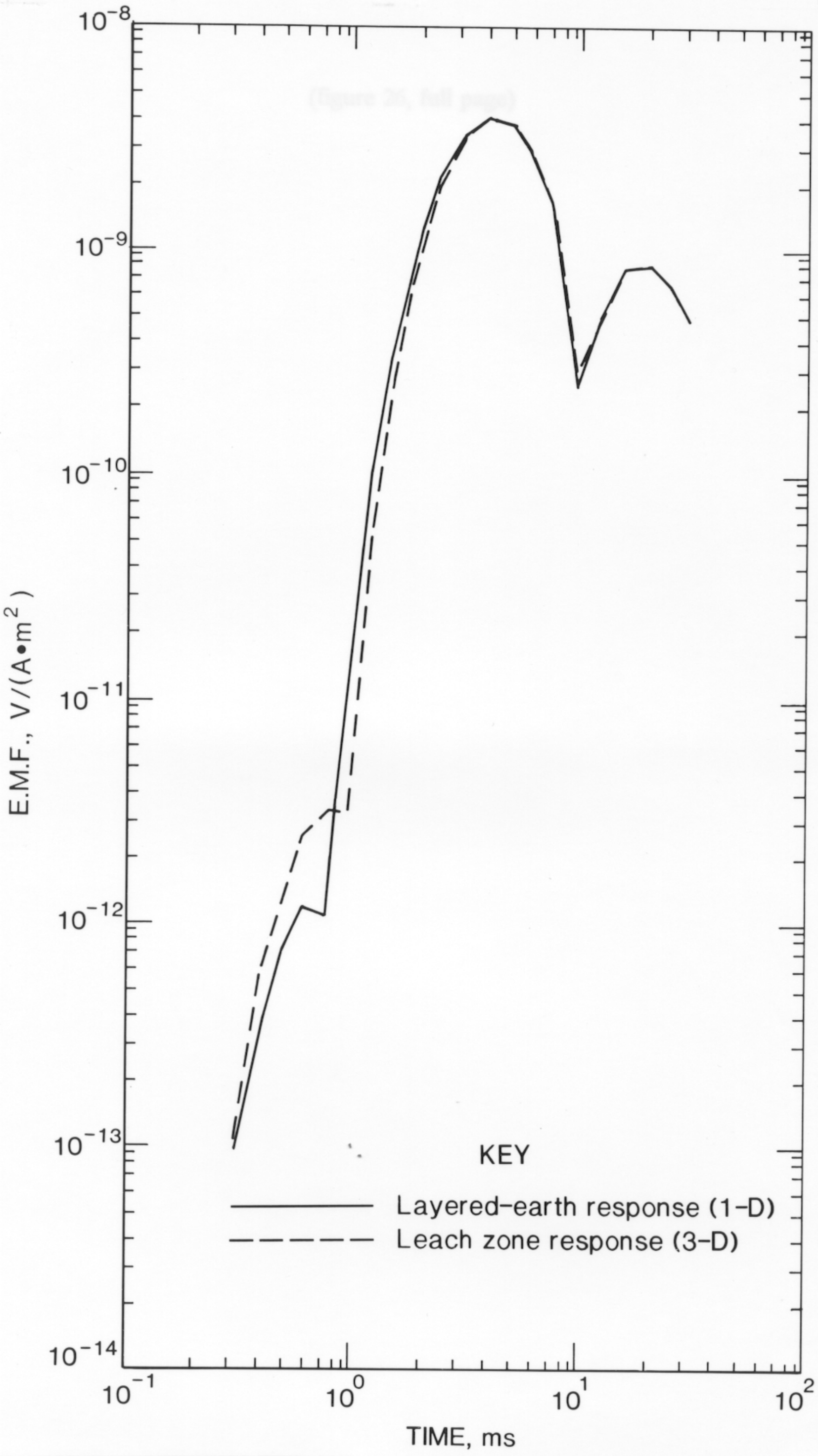

Figure 26.—TEM response in borehole 3 at depth of 720 m. Left peak corresponds to negative and right peak to positive E.M.F.

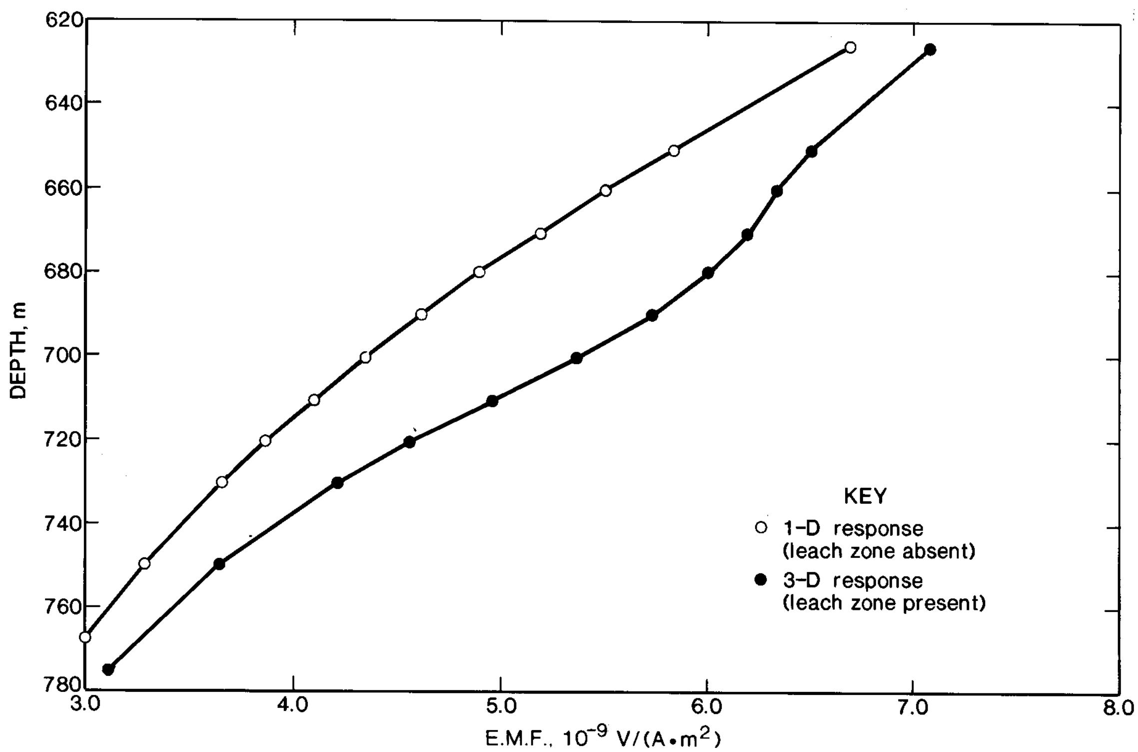

Figure 27.—Depth versus peak TEM response along section of borehole 1.

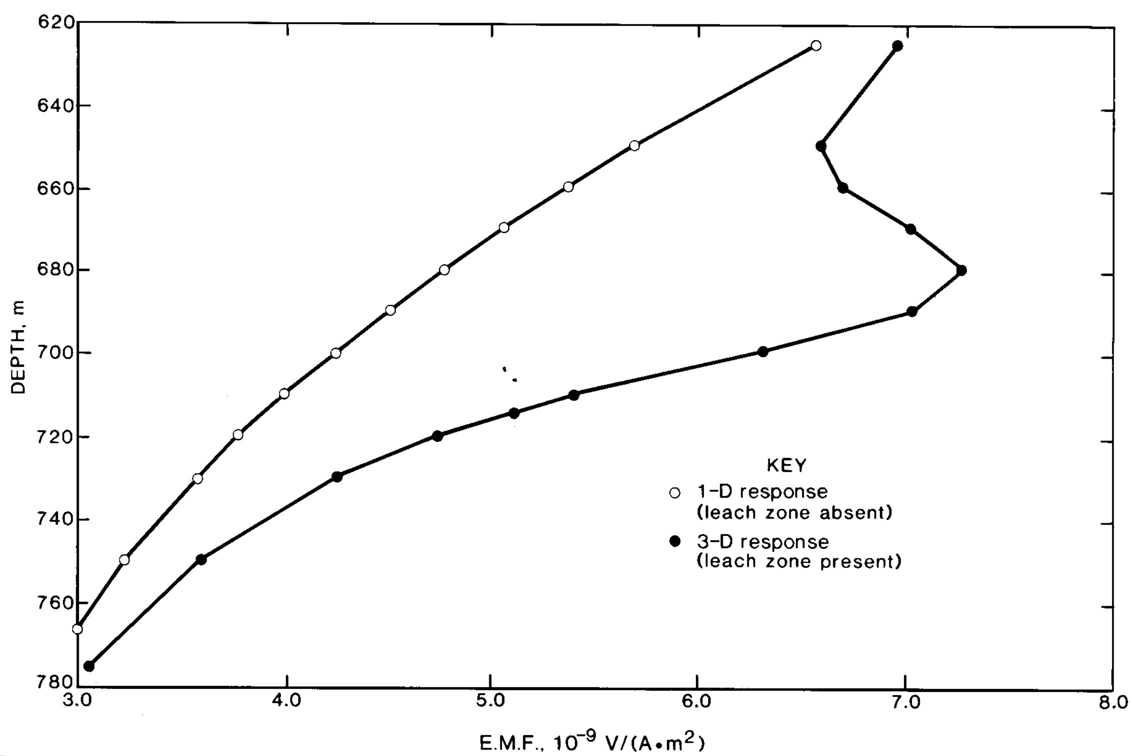

Figure 28.—Depth versus peak TEM response along section of borehole 2.

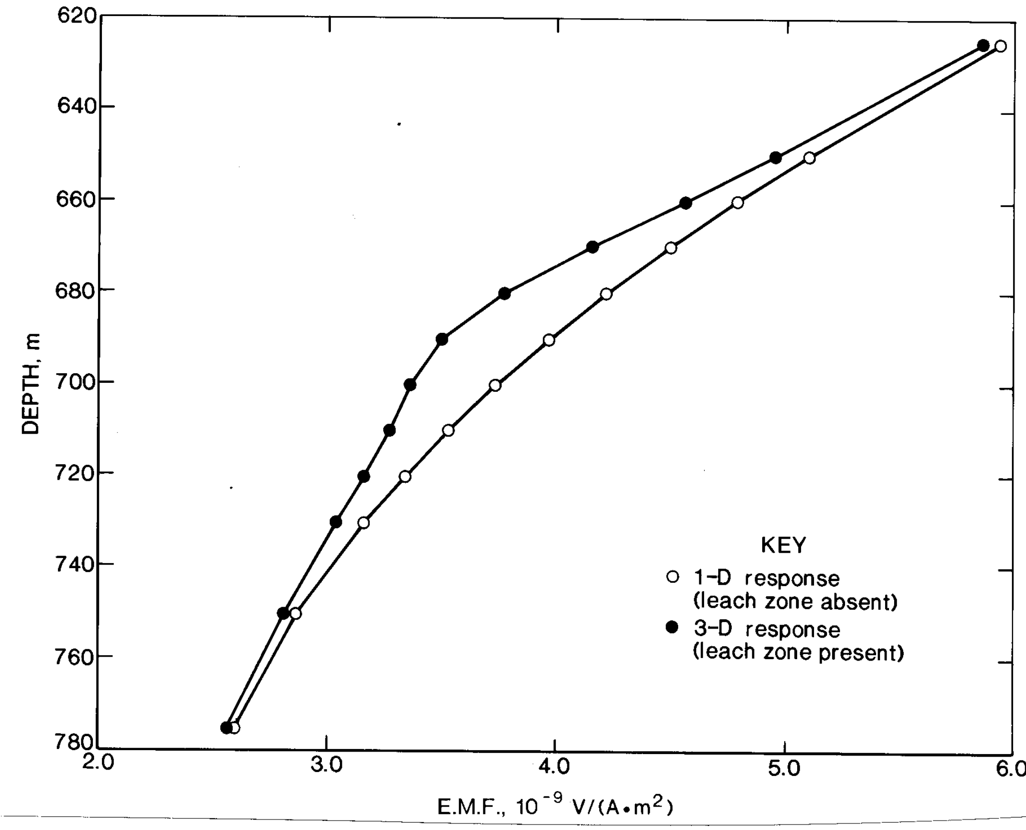

Figure 29.—Depth versus peak TEM response along section of borehole 3.

Computer modeling using a site-specific geoelectric section should be considered an acceptable means of beginning a feasibility study of in situ lixiviant detection. In most cases, the geology at a given mine area has been well characterized because of the extensive drilling prior to development. From these data, layer thicknesses, number of layers, and any other information may be obtained. Layer resistivities and other pertinent information can be taken from borehole geophysical logs or deep-penetrating surface surveys. These measurements may be used either directly or indirectly to create a satisfactory, although idealized, electric cross section of the subsurface. Once this section has been produced, target lixiviant zones of various sizes, shapes, and depths can be added as desired to help determine depth and resolution limitations. This was the approach taken by the Bureau for the TEM simulations presented here, although on a more limited scale.

Of course, certain real-world characteristics cannot be accounted for in the geoelectric section or the computer modeling. Complex structure and unusual or unknown size and shape of the ore body or lixiviant plume cannot and will not be precisely known. Other variables of equal importance include time and spatial conductivity changes in fluid and host rock and the presence of undesirable conductive features, such as saturated or clay-filled faults. Any one of these variables could significantly alter the response curves and make interpretation difficult. Fortunately, however, many of these variables can be identified by conducting an actual field survey prior to leaching. With preleach data, the effect from the leach solution can be isolated and the other factors can be effectively filtered out. It becomes extremely important, therefore, to perform surveys both before and during leaching and to construct computer models of both situations to aid in the detection of lixiviant plumes.

CONCLUSIONS

Several electrical and EM methods have been discussed and their applications are being considered for the detection and monitoring of lixiviant plumes. The advantages and disadvantages of each have been treated in sufficient detail so that it is apparent that some of the methods are more suitable than others. The most feasible include, but are not necessarily limited to, TEM, CSAMT, and possibly focused resistivity. GPR, FEM, and conventional resistivity methods appear to be useful in limited applications, although they do not have the necessary penetration capabilities to detect deep or distant lixiviant zones. Even though these methods are not especially suitable, they were evaluated for the sake of completeness. MT, while having the penetration capability, appears to be too time consuming and unreliable to be used for lixiviant monitoring.

All systems have their inherent resolution, noise, and configuration (borehole versus surface) limitations. TEM systems seem to have the highest probability for success, because of their great depth of penetration, high signal-to-noise ratio, and ease of conversion from surface work to borehole work. In addition, preliminary computer modeling (offset loop) results are encouraging.

CSAMT seems to have been successful in the detection of lixiviant plumes in southern Arizona. However, it is not known how well these systems compare with TEM fluid detection applications since no direct comparison or modeling has been done. Improved technology in CSAMT instrumentation will allow borehole measurements for greater flexibility (*34*). With surface and borehole capabilities, CSAMT methods may also be very effective lixiviant monitoring systems. All geophysical systems, however, are expensive, bulky, and require experienced personnel to operate and interpret results. Care would have to be exercised when data are recorded in areas of cultural or natural interference. If possible, such interference should be minimized or removed. In all cases, regardless of techniques used, surveys performed both before and during leaching will aid in isolating the lixiviant response.

Future Bureau research emphasis will be placed on computer modeling where possible or appropriate, on field experiments, and on previous case histories. If possible, a field survey will be performed at an in situ leach mine to evaluate the best lixiviant detection system.

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