The Self-Potential Method for Environmental and Engineering Applications

*Robert F. Corwin**

Abstract

The major environmental and engineering applications of the self-potential method have been investigations of subsurface water movement. Specific uses have included mapping of seepage flow associated with dams, dikes, reservoir floors, and other containment structures; studies of general groundwater movement; and delineation of flow patterns in the vicinity of landslides, wells, faults, drainage structures, shafts, tunnels, and sinkholes. The method also has been used to a lesser extent for subsurface thermal investigations such as mapping of steam flood fronts and coal mine fires, and preliminary studies indicate that it could be used to help delineate chemical concentration gradients associated with subsurface contaminants.

Self-potential anomaly amplitudes generated by such environmental and engineering sources tend to be lower than those seen in mineral and geothermal exploration, and spurious anomalies associated with the presence of man-made structures at most field sites often create very high noise levels. Therefore extreme care in the acquisition and reduction of field data, and recognition of characteristic fields associated with artificial and natural noise sources, are critical to the success of environmental self-potential investigations.

Interpretation of self-potential data often is qualitative, using visual correlation between observed profile or contour patterns and known or suspected seepage flow paths or other sources. The use of available geometric source models, including charged points, lines, spheres, cylinders, and sheets, can provide useful first estimates of source depth and configuration. Computer programs based on analytical modeling techniques can be used to calculate self-potentials generated by subsurface gradients of pressure, temperature, or chemical concentration. If in-situ physical property parameters such as cross-coupling coefficients and hydraulic, thermal, and electrical conductivity are known or can be reasonably estimated, these techniques can provide useful information about the nature, location, and strength of self-potential sources.

Introduction

Self-potential (SP) anomalies are generated by flows of fluid, heat, and ions in the earth, so SP investigations have been used to help locate and delineate sources associated with such flows. The method was first used for mineral exploration (a history of the development of the SP method is given in Van Nostrand and Cook, 1966), but in recent years has found increasing use for geothermal, engineering, and environmental applications. As the method offers relatively rapid field data acquisition and the ability to respond directly to flows of interest, it often is cost-effective for reconnaissance or initial investigation of an area prior to more intensive studies using other geophysical and geotechnical techniques.

Because data acquisition and quality-control procedures have not been as thoroughly documented for the SP method as for most other geophysical techniques, a detailed discussion of SP field procedures and sources of noise and irreproducibility is presented first. Descriptions of available techniques for interpretation of SP data and some examples illustrating environmental and engineering applications of the SP method follow.

Data Acquisition and Quality Control

Self-potential data quality depends on survey configuration and procedures, selection and maintenance of

*Consulting Geophysicist, 406 Sea View Drive El Cerrito, CA 94530

equipment, recognition of sources of error and noise, and use of appropriate data reduction techniques. Survey procedures that minimize movement of the reference electrode and account for electrode drift and polarization help reduce the effects of cumulative error. Input impedance of the measuring instrument must be considerably greater than electrode contact resistance to avoid loading of the measurement circuit, and cable insulation integrity is required to prevent introduction of spurious grounding voltages.

Noise sources may be natural or artificial, and may be constant or vary with time. Recognition of noise potentials is important to avoid their being misinterpreted as anomalies generated by sources of interest. The use of a telluric current monitor to record time-varying potentials in the survey area, inspection of the site and of site plans for potential noise sources, and careful field observation assist in noise source recognition. Magnetic or electromagnetic survey data also are helpful for detection of buried metal noise sources.

Self-potential data obtained in support of environmental or engineering investigations often are more severely affected by spatial noise and by error caused by large time-varying potentials than are SP data for mineral or geothermal exploration. The severity of these effects is due to the relatively low SP signal (anomaly) levels generated by sources of interest and to the prevalence of artificial noise sources in the developed areas in which most environmental and engineering geophysical investigations are conducted.

Geophysical reference texts such as Heiland (1940), Parasnis (1966), Semenov (1974), and Telford et al. (1976) give brief descriptions of SP field procedures. However, unlike most other geophysical methods, widely accepted data quality control standards and procedures have not been established for the SP method. Therefore, a detailed discussion of the effects on SP data quality of survey procedures, equipment, data reduction techniques, and natural and artificial noise sources is given; suggestions are offered for minimizing errors and recognizing and compensating for potentials generated by noise sources.

Because SP is a passive, potential field technique (like magnetics or gravity), source parameters cannot be changed to vary depth of investigation or to help differentiate signal from noise. As for other potential field methods, smoothing and filtering techniques can be applied to SP data. However, it is preferable to recognize and remove error and noise to as great an extent as possible before using such techniques.

In the following discussions, "error" is defined as the irreproducible component of a given SP reading associated with the data acquisition process, while "noise" in general is a potential generated by a source that is not of interest for the purposes of the investigation. In some cases (for example, time-varying noise generated by natural or artificial sources) these definitions will unavoidably overlap. Potentials considered as noise for engineering SP surveys (e.g., those generated by corrosion or telluric currents) may be the desired signal for other applications.

Survey Configurations

A variety of survey configurations is used to obtain SP field data. While all of the configurations described have been used successfully, their susceptibility to random and systematic error differs. Descriptions of the most commonly used survey configurations, along with discussions of their advantages and disadvantages, follow. For all survey configurations, SP polarity convention requires the negative terminal of the measuring voltmeter to be connected or referred to the electrode at the survey base station and the positive terminal to be connected or referred to the electrode at the measurement station.

For any survey configuration, it is desirable to lay out the survey lines as a series of loops, to allow determination of loop closure errors by reoccupation of tie points. Although this procedure is not entirely free of error (a detailed discussion will follow), it offers the best quantitative measure of survey data reproducibility.

The gradient configuration [also called the dipole, leapfrog, or fixed-electrode configuration (Parasnis, 1966; Telford et al., 1976)] utilizes two electrodes and a connecting wire of fixed length equal to the separation between measurement stations. The voltmeter is connected between one of the electrodes and one end of the connecting wire. After the potential difference is measured between the two electrodes, the array is moved forward along the survey line, with the trailing electrode occupying the station of the previous leading electrode. Reversal of leading and trailing electrodes between readings (the "leapfrog" technique) helps reduce cumulative error caused by electrode polarization.

The SP value at a given station is obtained by successive addition of individual dipole readings. Polarity must be carefully observed so that the total SP field obtained by summing the gradient readings is properly calculated. To maintain proper polarity, the negative meter lead always is connected to the trailing electrode and the positive lead to the leading electrode. Sometimes the measured dipole readings, rather than their sum, may be plotted. If the dipole length is small relative to the anomaly wavelength, such plots represent essentially the component of the gradient or derivative of the total SP field in the direction of the survey profile (Parasnis, 1966).

The gradient configuration offers a number of operational advantages. The relatively short connecting wire minimizes exposure to animal bites or vandalism, and can be moved quickly to avoid damage by vehicles. Because no wire retrieval is involved, it is not necessary to expend time retraversing the survey line (this is especially significant in difficult or dangerous terrain). Finally, it is easy to inspect thoroughly the wire insulation for damage and to repair or replace the wire if needed.

This configuration also has operational and very significant data quality disadvantages. Efficient data collection requires two people (and sometimes two vehicles); other survey techniques can be efficiently conducted by one field person. The common practice of dragging the wire along the ground between stations increases the probability of insulation damage.

The most significant problem with the gradient configuration is its extreme sensitivity to spurious "anomalies" generated by cumulative error. The components of reading error, discussed in more detail later, include soil contact effects, electrode polarization, and time-varying potentials. The effects of electrode polarization can be reduced by use of the previously described "leapfrog" procedure, but the other two components are difficult to quantify or correct. These components add a random error to each measured value, and because these values are added together in the data reduction process the errors can accumulate to significant levels. If the reading includes an error of constant polarity, error will accumulate even more rapidly.

Statistical random walk or coin-tossing theory (Feller, 1957) can be used to estimate values of cumulative random error. For example, consider an error value that can be either $+e$ or $-e$ mV (but not zero) with equal probability for any given reading. For a gradient survey line comprising 48 measurement stations and $e = 4$ mV, the probability that the absolute value of cumulative random error at the last station equals or exceeds 24 mV ($6e$) is 47.1 percent, and the probability that this value equals or exceeds 48 mV ($12e$) is 11.2 percent. Thus for this typical example there is a significant probability of accumulating error values comparable to typical anomaly levels.

Because of the small electrode separation, the observed magnitude of time-varying potentials for the gradient configuration generally is small. For example, a telluric potential variation (discussed in more detail later) of 20 mV/km amplitude will appear as a deviation of only 0.2 mV amplitude across a 10 m measuring dipole; a virtually undetectable value. However, this deviation is included in the error value previously discussed, and if the period of the variation is long with respect to the measurement time, it will be added to the summed data as a telluric error of the same magnitude as if the reading were made using the fixed-base technique described in the following text.

Therefore, even though time variations may be less obvious across a gradient array, their cumulative effect may be the same as for those configurations using larger electrode separations. The disadvantage of the gradient configuration in this regard is that it is much more difficult to recognize and correct the effect of time-varying noise.

Cumulative errors can be reduced by interconnecting survey lines at numerous tie-in points and distributing tie-in loop closure errors among all the readings around the loop. However, this arbitrary procedure may reduce the amplitude of real anomalies as well as errors. Also, it does not account for errors within a loop, which as previously shown can be considerable. For these reasons, the use of the gradient configuration usually should be restricted to situations where operational difficulties such as vulnerability to wire damage or rough terrain prevail.

The fixed-base (or total field) configuration uses a stationary base electrode, a reel carrying the greatest practicable length of connecting wire, and a moving measuring electrode (Parasnis, 1966; Corry, 1985; Corwin and Butler, 1989). Usually the most practical arrangement is to connect the outer end of the wire to the base electrode and to carry the reel, on foot or in a vehicle, from station to station. The positive lead of the meter then is connected to the measuring electrode and the negative lead is connected through a takeout at the inner end of the wire on the reel to the base electrode. Station locations are determined by presurveying lines, flagging the wire, or using a portable distance-measuring device.

Because the wire is not dragged over the ground during deployment or retrieval, usable wire length is not limited by friction or obstructions as for a stationary reel arrangement. This is an important consideration for data quality, as it allows the maximum number of readings to be made directly from a single base electrode and thus minimizes accumulation of errors. When operational considerations require the use of more than one base station, establishment of multiple tie points helps minimize tie-in errors between the base stations.

A major advantage of this configuration compared with the gradient configuration is the lower level of cumulative error. Although each reading is subject to the three previously mentioned error components, these errors do not accumulate as do those for the gradient configuration. Also, as described in more detail later, it is relatively easy to estimate the magnitude of electrode polarization and time-varying errors and to remove these errors from the readings. Thus the reproducibility of data obtained using the fixed-base configuration generally is considerably better than that for the gradient configuration, and the probability of mapping spurious "anomalies" is lower.

Other advantages of this configuration include flexibility of electrode positioning and ease of reoccupying stations of interest and obtaining additional data detail in anomalous areas. Also, surveys run on foot are easily conducted by a single operator.

Disadvantages include the problem of transporting the wire reel through difficult or dangerous terrain, the necessity to retraverse the survey line to retrieve the wire, and the vulnerability of the long lengths of deployed wire to damage by vehicles, animals, or vandalism. Also, inspection of several hundred to several thousand meters of wire for insulation leaks or other damage can be tedious. Where esthetic and legal constraints permit, disposable wire may be used to mitigate some of these problems. Lightweight magnet wire insulated with a flexible coating can be used for this purpose.

When applied properly, the fixed-base configuration provides high-quality data at relatively low cost. Although equipment investment and maintenance costs are greater than for the gradient configuration, data acquisition costs are comparable and data quality usually is considerably better. Therefore unless the terrain is especially difficult or the probability of wire damage is high, the fixed-base configuration is preferable to the gradient configuration.

A variation of either the fixed-base or the gradient technique is to survey the measurement stations and dig and water electrode holes a few hours to a day in advance of the actual measurements (Semenov, 1974). As discussed later, watering of electrode holes to reduce contact resistance or equalize soil moisture content between stations generally is not necessary. However, if the holes are watered time must be allowed for mobile water to diffuse out of the holes (Corwin and Hoover, 1979). A multielectrode configuration is similar to a long-term SP monitoring network (Koester et al., 1984) in that an electrode is installed at each measuring station and all these electrodes are connected to a base station terminal through a multiconductor cable. Measurements are made by sequentially connecting each electrode through the meter to the base station electrode, or by using a multichannel data acquisition system. If a multiconductor cable is not used, measurements can be made using a gradient or fixed-base procedure.

An advantage of this configuration is the ease of making repeat measurements to check for time variations, and of applying data processing techniques such as stacking or filtering for removal of the effects of such variations. As for the fixed-base array, cumulative error is minimized by the use of a single survey base station. Also, electrode drift can be monitored and readings made after values stabilize. As discussed later, there is some question as to whether initial electrode readings or values recorded after drift has ended better represent potentials related to sources of interest.

Disadvantages of the multielectrode configuration include initial equipment costs that are considerably higher than those for the configurations previously described, relatively inflexible arrangement and spacing of measurement stations, and the difficulty of measuring initial and final electrode polarization values for correction of polarization errors.

Once the configuration for a given survey is chosen, it is necessary to select survey line orientation and spacing and to determine the spacing of measurement stations along the survey lines. As for any other geophysical technique, if elongated anomalies are expected the survey line orientation should be perpendicular to the anticipated anomaly orientation. Because signal-to-noise ratios for environmental or engineering SP surveys often are low, it usually is preferable to conduct closely-spaced measurements along widely-spaced survey lines rather than the converse (Semenov, 1974).

Measurement station spacing depends on the anticipated anomaly wavelength. As for other geophysical potential fields, anomaly wavelength depends on the configuration, size, and depth of burial of the source of the anomaly. Techniques for modeling of SP anomalies generated by simple geometric sources, described in a later section, can be used to estimate expected anomaly wavelengths.

As there is no universal zero potential reference level for SP measurements, selection of the zero potential point for a given data set is arbitrary. Usually, a station remote from expected or observed anomalous activity is assumed to be at zero potential. Locating the survey base station in such a quiet area and assuming the base station potential to be zero facilitates computation and may improve data reproducibility (Corry, 1985). On the other hand, locating base stations centrally within the survey area reduces required wire lengths, and running survey lines outward from anomalous areas makes it easier to determine when anomalous activity has ended and sufficient background has been measured. However, a central base location may result in higher noise levels if time-varying potentials are present in the central area.

In some cases it is desirable to obtain SP data in water-covered areas such as the upstream face of a dam or the floor of a reservoir. Using submersible nonpolarizing electrodes, data can be obtained successfully in either fresh or salt water with either gradient or fixed-base configurations (Corwin, 1976). Because of the continuous contact between the electrodes and the water, continuous data profiles can be recorded on a strip chart recorder or other data acquisition system. This recording allows very rapid coverage as well as infinite lateral resolution. Although offshore SP signal amplitudes are reduced by the relatively low resistivity of the water (especially salt water), noise and error levels also are lower, and signal-to-noise ratios for offshore SP data usually are equal to or greater than those for onshore data.

Equipment

Equipment required to obtain SP measurements using the gradient configuration includes electrodes, connecting wire, a measuring meter, and a tool for digging electrode holes to an appropriate depth (as discussed later, hole depth can be an important consideration for data quality). For the fixed-base configuration, additional equipment includes a much greater length of connecting wire (up to several thousand meters) and a reel to hold the wire. As previously discussed, the multi-electrode array requires additional electrodes (equal to the expected number of measurement stations), and possibly a multiconductor cable and data acquisition system.

Unlike most other geophysical equipment, complete SP equipment sets are not readily available from commercial sources and must be assembled by the user. The following sections discuss data quality considerations for SP equipment components including electrodes, measuring meters, connecting wire, and auxiliary components such as wire reels and telluric monitors.

Electrode performance depends on the polarization and drift characteristics of the electrode pair. "Polarization" is defined as the potential measured at a given time between an electrode pair in the absence of external electric fields, and "drift" refers to time variation of the polarization value.

Although electrodes of stainless steel (Parasnis, 1966) and copper-clad steel (Koester et al., 1984) have been used for SP field measurements, nonpolarizing electrodes have been found to give much more reproducible data (Parasnis, 1966; Corwin and Butler, 1989). Such electrodes consist of a metal element immersed in a solution of a salt of the metal, with a porous junction forming the boundary between the solution and the soil (Ives and Janz, 1961). Although such electrodes are not truly nonpolarizing and are more accurately called liquid junction electrodes, the "nonpolarizing" label is commonly employed and will be used for this discussion.

High-frequency electrode noise levels in the microvolt range are an important consideration for other geophysical applications such as magnetotelluric measurements (Petiau and Dupis, 1980). For SP measurements, however, electrode polarization and drift response to variation in environmental parameters such as temperature and soil moisture content and chemistry is of greater interest. Laboratory and field measurements of such responses have been performed for a variety of nonpolarizing electrode types, including copper-copper sulfate, silver-silver chloride, lead-lead chloride, zinc-zinc sulfate, and cadmium-cadmium chloride (Ewing, 1939; Semenov, 1974; Morrison et al., 1979a, 1979b).

Results of these measurements indicate that although these different electrode types respond in varying degree to changes in the environmental parameters listed, under most conditions these differing responses do not seem to affect significantly the error and noise level of field SP measurements (Morrison et al., 1979b). For severe conditions such as extreme variations in temperature or soil chemistry it may be worthwhile to use commercially available reference electrodes with a dual electrolyte chamber for increased soil isolation or to install thermometers directly into the electrolyte solution to monitor electrode temperatures.

For most applications, commercially available copper-copper sulfate electrodes, sold for use in pipeline corrosion surveys, have been found to give SP field data of acceptable quality if drift and polarization effects are monitored and corrected as discussed later. Commercially available silver-silver chloride electrodes, sold as reference electrodes for pH and other electrochemical measurements, are similarly acceptable for offshore SP measurements. To minimize leakage, electrolyte solutions can be gelled if desired (Semenov, 1974).

The response of copper-copper sulfate and silver-silver chloride electrodes to environmental variations is well documented (Ewing, 1939; Ives and Janz, 1961; Corwin and Conti, 1973; Morrison et al., 1979a, 1979b; Petiau and Dupis, 1980). Because the liquid-junction construction of nonpolarizing electrodes tends to suppress response to electrochemical variations, temperature and soil moisture content differences tend to produce the largest electrode effects.

For copper-copper sulfate and silver-silver chloride electrodes, response to changes in soil moisture content is of the order of about $+0.3$ to $+1$ mV per percent moisture content increase, depending on soil type and electrode construction. Other measurements (Morrison et al., 1979b) have shown a maximum response of about 70 mV for a copper-copper sulfate electrode pair connected between saturated and very dry desert clay soil.

Thus soil moisture variations can represent a significant noise source when signal levels are a few tens of mV. Careful field notes documenting observed soil moisture levels can be helpful in distinguishing between anomalies caused by sources of interest and those related to soil moisture variations. This is especially important in seepage investigations, where positive SP readings caused by wet soil must be separated from those caused by the upward movement of subsurface water. In such cases, it may be worthwhile to construct a simple test cell to measure the moisture effect directly (Morrison et al., 1978; Corwin and Butler, 1989).

The temperature response of copper-copper sulfate and silver-silver chloride electrodes given in the preceding references is of the order of +0.5 to +1 mV per degree C. Note that this refers to the temperature difference between the electrolytes of the electrodes rather than that between the soils at the measuring stations, so the effect of a change in soil temperature will not be seen until the electrolyte temperature begins to change. As temperature changes are the major cause of electrode potential drift, and as temperature polarization values can reach levels of 10 to 20 mV under severe conditions, care should be taken to minimize electrode temperature changes. Procedures for this are discussed later.

Important considerations for the voltmeter used for SP field measurements include resolution, range, input impedance, ac interference rejection, and suitability for field use. Also, as discussed later, it is desirable to have the capability of measuring electrode contact resistance.

Resolution of 1 mV is sufficient for SP field measurements, and a range of +/− 10 VDC will cover even very large anomalies generated by dc current grounds. As noise in the 10 to 100 Hz range is common in developed areas, inclusion of low-pass filtering in the voltmeter is necessary. Electrode contact resistance ranges from a few hundred ohms in water or very conductive soil to several megohms in snow, frozen soil, or very dry or rocky soil. In most areas, contact resistance will be of the order of a few thousands of ohms to a few tens of thousands of ohms. Thus a voltmeter input impedance of ten megohms generally will be sufficient, but several hundred megohms or more may be required for high-resistance conditions.

It is important to measure and record electrode contact resistance at each station. This measurement ensures that there are no breaks in the connecting wire, that contact resistance is low enough to avoid loading the measuring circuit, and that ground contact conditions are relatively uniform from station to station. If the measured SP voltage is relatively large, currents generated by the ground circuit may be great enough to bias significantly the resistance measurement and sometimes may even result in negative resistance readings. In such cases an additional resistance reading should be made with the meter leads reversed, and the true resistance then will be approximately the average of the two readings.

Fortunately, most of the requirements listed are met by inexpensive, commercially available digital multimeters (DMM's). Resolution typically is 1.0 or 0.1 mV, maximum range is +/− 500 Vdc or more, ac interference rejection usually is sufficient, resistance measurement capability is built in, and input impedance typically is 10 m · Ω or more. In areas where ac noise levels are very large, additional low-pass filtering may be required. Ground contact resistance values exceeding about 100 k · Ω may require use of a high-impedance instrument such as a portable pH meter with a voltage display or a battery-operated electrometer, both of which are commercially available.

Because most of the resistance in the measuring circuit is in the electrode-to-soil contact, the resistance and gauge of the connecting wire usually are not important, and wire of small diameter or high-strength, high-resistance conductors such as cadmium bronze can be used to minimize weight and bulk. As a section of exposed wire in contact with wet soil can generate error potentials of hundreds of millivolts, maintenance of insulation integrity is critical.

Insulation damage can be minimized by careful wire deployment and by the use of abrasion-resistant materials such as polypropylene, polyethylene, or premium-grade polyvinyl chloride (PVC). Standard-grade PVC has poor abrasion resistance, and may crack at cold temperatures. The use of thick-wall insulation increases both damage resistance and wire bulk and weight. To avoid ground loops it is important to insulate the wire conductor from the body of the reel on which the wire is carried.

A telluric monitor is used to record time-varying potentials in the earth that could be mistaken in the survey data for spatial variations. Instrumentation for such a monitor consists of a recorder (usually a battery-operated strip chart recorder), electrodes, and connecting wire. For optimum definition of telluric current directions, it is desirable to use an orthogonal electrode array and a two-channel recorder. Previous comments regarding electrodes and instrument specifications also apply to the telluric monitor. Deployment of the monitor and use of the monitor record for data correction are discussed later.

Measurement Procedures

Selection and implementation of appropriate survey field procedures are critical for maintenance of SP data quality. Appropriate field procedures are those which eliminate or minimize errors related to data acquisition, and which provide methods for recognition of errors and their removal, to as great a degree as possible, from the field data. Because little has been published regarding SP field procedures, they are discussed in some detail in the following sections.

The apparent "geologic noise" level of SP data at station spacings from a few centimeters to tens or hundreds of meters ranges from almost zero to tens or hundreds of millivolts. This geologic noise includes measurement errors caused by electrode polarization and drift, changing soil contact conditions, and time-varying potentials as well as noise related to changing soil conditions and other natural and artificial sources. Much of this noise can be eliminated or reduced, leaving only variations that are unavoidable or uncorrectable to be filtered or smoothed.

Electrode Polarization and Drift.—Electrode polarization and drift are a major component of SP measurement error. For a survey conducted from a single base station, the first field reading will be in error by the initial polarization potential between the base and measuring electrodes and the last field reading will be in error by the final polarization value. Therefore measurement of these polarization values in a bath of electrolyte solution immediately before installation and after removal of the base electrode will allow subtraction of these polarization errors from the measured values, with corrections for intermediate measurements obtained by interpolation (Corwin and Butler, 1989).

For situations in which the base electrode is in the soil for long periods of time (more than about one hour), intermediate drift correction values can be obtained by periodically reading the potential between the measuring electrode and an auxiliary ("portable reference") electrode carried in a container of electrolyte solution. By assuming that the potential between the base and auxiliary electrodes remains constant, drift of the measuring electrode with respect to the base electrode can be determined and removed. These procedures apply specifically to the fixed-base configuration, but the general concepts are equally applicable to other configurations.

Although this assumption is not always valid (sometimes the auxiliary electrode drifts significantly with respect to the base electrode), the preceding procedures have been found empirically to improve SP data reproducibility. Even in cases where the corrections are incomplete (for example, where the potential at the base station has changed due to drying of the soil or other factors) these procedures at least allow recognition of drift and polarization errors and estimation of their magnitude.

Electrode drift and polarization can be reduced by minimizing exposure of the electrodes to temperature and chemical variations. The ideal is to maintain the base and measuring electrodes at the same temperature (or at a constant temperature difference) and at a constant electrochemical state. Temperature variations can be reduced by keeping electrodes out of the sun and by minimizing exposure to hot or cold soil (note also that some electrodes with a clear housing may exhibit a photoelectric effect). Electrochemical drift can be reduced by minimizing the time the measuring electrode is in the soil (especially if the composition of the soil is different from that of the base station) and by cleaning the porous junctions of the electrodes between measurements.

There is some controversy as to whether readings should be made quickly, before significant drift has occurred, or after the readings have stabilized. In most cases, readings become essentially constant (drift of less than a few tenths of millivolt per minute) within a few seconds after the electrode is installed in the soil, and observation time will be determined by the need to detect time variations due to tellurics or artificial sources.

In some cases, however, readings are observed to drift significantly (more than about 1 mV per minute) for several minutes or even hours. In such cases the question is whether the initial or the final reading represents the desired value. If the source itself is changing with time (for example, a variation in the rate of underground seepage flow), then both readings will of course be of interest. However, if the drift is due to electrode response to changing soil conditions such as moisture content, temperature, or pore fluid chemistry, the "correct" reading should be that obtained before the measuring electrode is significantly polarized by reaction to the new soil parameters. Further research is needed to determine the origins and effects of such drift.

Electrode performance also depends on the condition of the electrodes. The electrolyte solution should be kept saturated (i.e., with excess crystals in the solution) to avoid polarization potentials related to concentration changes. Leaking junctions should be repaired or replaced to avoid electrolyte contamination by groundwater solutions. Although copper-copper sulfate electrodes are electrochemically robust and generally show little response to visible contamination of the electrolyte, the electrolyte should be renewed when polarization of an electrode pair at equilibrium in a bath of electrolyte solution exceeds several millivolts. In some cases, it may be necessary to clean the metallic element or to replace the porous junction (if it is removable) to achieve acceptable polarization values.

Electrodes filled with electrolyte should not be stored with their junctions exposed to the air, as this exposure results in rapid leakage and deterioration of the junction material. Draining of the electrodes and dry storage will maximize junction life, but storage with the junctions tightly capped or immersed in a bath of electrolyte solution (or sand or soil saturated with electrolyte solution) will help retard junction deterioration.

The process of measuring contact resistance forces current to flow through the electrodes, resulting in temporary electrode polarization. Therefore, the contact resistance measurement should be made after the SP measurement and the resistance reading time should be as brief as possible to minimize this polarization. Because the exact value of the resistance is not important, the resistance should be measured only for a second or two even though the resistance reading may not completely stabilize in this time.

Occasionally an unusual condition is seen when observed contact resistance values, even when measured by a very high-impedance instrument, become very high or apparently infinite although soil conditions do not appear to change, SP readings are stable, and no evidence of measurement circuit loading is seen. In many cases this condition is associated with crossing of a fault or vertical contact. Although the SP readings obtained under these conditions appear to be valid, more study of this phenomenon is needed.

Electrode-to-Soil Contact.—When an electrode is removed from and replaced in the same location, the SP reading will almost always change. For moist, conductive, compact soils this change may be only a few millivolts, and generally is less than 5 or 10 mV for most soils. However, for dry, resistive, loose soil it may amount to several tens of millivolts or more. This uncertainty represents an important component of irreproducible reading error. As previously discussed, this error may accumulate rapidly for measurements made using the gradient configuration and will accumulate to a lesser degree through tie-in points with the fixed-base configuration. Even when the values do not accumulate, they contribute to the noise level of the data. Therefore, it is important to attempt to minimize this error.

To obtain the most consistent readings, the electrode holes must be dug deep enough to penetrate dry (or rain-saturated) surface soil so as to encounter vadose soil moisture and to minimize surface temperature variations. In compact soils this depth may be only a few centimeters, but dry, loose, or rocky soils may require 50 cm or more. Installation of the electrode in compact, undisturbed soil is desirable if at all possible, but may be difficult for very rocky soils. In such cases adding a few centimeters of removed fines to the bottom of the hole may be helpful. For extreme conditions, such as pavement, exposed rock, or soil with no fines (e.g., riprap on the upstream face of a dam), usable data usually can be obtained by placing a sponge saturated with electrolyte solution between the junction and the ground.

Because the temperature and moisture content of soil exposed to air will change, the electrode hole should be refilled with soil and flagged if the station is to be reoccupied or used as a tie point. Remeasurement then can be made for depth and soil conditions as close as possible to original, even days or weeks later.

For very dry soil conditions, or conditions where soil moisture changes considerably from station to station, watering of the electrode holes may help improve contact consistency (Semenov, 1974). However, because measured potentials will drift strongly while free water is diffusing from the holes, it is necessary to wait several hours or more after watering to take the measurements (Corwin and Hoover, 1979). Therefore, electrode holes should be watered only under exceptional conditions, where the additional survey time is justified.

A technique for statistical reduction of the effects of both contact potentials and soil property variations is to use multiple electrode holes at each station (Sill and Johng, 1979). The holes are placed in some consistent geometric pattern around the station location, within a radius of a few meters or less. The recorded value then is the average of the measurements, and the deviation provides an estimate of the noise and error level. The added time and cost of the additional measurements must be compared with the expected improvement in data quality. However, whenever measured values change suddenly along a profile, additional nearby measurements should be made to verify the new value and to determine the spatial wavelength of the variation.

Often, both signal amplitudes and levels of noise and error are seen to be strongly related to near-surface soil resistivity. Thus signal-to-noise levels and the ratio of tie-in error to signal amplitude generally are roughly similar for widely varying soil conditions. The main exceptions to this are found in developed areas, where soil disturbance and artificial noise sources tend to reduce data quality levels relative to those seen in undeveloped areas.

Time-varying Effects

In addition to the electrode drift effects discussed, time variations of SP readings may be caused by changing site conditions such as soil properties or subsurface resistivity variations due to changing saturation levels; or by electric fields generated by natural or artificial sources (Ernstson and Scherer, 1986). It is important that these variations be recognized and removed from the data to avoid measurement errors and misinterpretation of time variations as spatial anomalies. As mentioned, for engineering surveys the magnitude of the source of an anomaly of interest also may change with time (e.g., the rate of subsurface seepage flow).

Time variations may be divided into those which would be expected to be recognized during the course of an individual measurement and those which occur too slowly or too infrequently to be so recognized. Because telluric activity (discussed later) exhibits a spectral peak around periods of about 20 to 30 s, a similar reading time often is used to help detect such activity. Thus time variations may be arbitrarily divided into those between about a 1 and 30 s period, which would be detected during the course of a measurement (if of large enough amplitude), and those of more than about a 30 s period which usually must be detected by other methods to recognize them and to differentiate them from electrode drift.

Changing site conditions can generate SP variations over periods ranging from minutes to months or longer. Thus some of these variations will be significant over the course of a survey lasting several hours or days, while others will be seen only if an area is resurveyed. Such variations can be generated by changes in soil properties due to temperature variations, rainfall, or construction activity; changes in topographic effects due to rainfall; varying water table depth; and changes in corrosion fields due to changing soil conditions.

As discussed in a later section, streaming potentials are generated by the flow of fluids through porous media. Because the magnitude of streaming potentials generated by subsurface water flow is related both to pore water resistivity and to the resistivity of the surrounding medium, changes in these parameters will affect observed SP values. The depth of the water table, the degree of soil saturation, or the temperature or ionic composition of the pore water all may be affected by rainfall, seasonal variations, or the elevation of water behind a dam or other impoundment structure. Thus potentials related to subsurface water flow may change following rainfall or changes in impoundment levels even if the flow rates remain constant. Resistivity measurements can be helpful in detecting such effects (Corwin and Butler, 1989).

Significant time variations of SP readings also may be caused by vertical movement of near-surface vadose water. Such movement may be related to evapotranspiration by vegetation (Ernstson and Scherer, 1986) or response to solar heating of near-surface soil (Semenov, 1974). Under some conditions such variations may reach several tens or hundreds of millivolts and may be a significant source of noise and error. These variations often are characterized by a strong vertical dependence of SP values within the hole dug for electrode emplacement.

The second category of time-varying noise is generated by natural telluric currents caused by time variations of the Earth's magnetic field or by artificial sources (stray currents).

Natural telluric current variations have periods ranging from milliseconds to hours (Keller and Frischknecht, 1966; Kaufman and Keller, 1981). For SP surveys, the most significant periods are those in the 20–30 s range and those of about 0.1 s, which sometimes appear as high-frequency noise on DMM voltage readings. Amplitudes of potential variations generated by telluric currents usually are of the order of several millivolts per kilometer, so they usually do not exceed a few millivolts for surveys conducted over areas of less than one kilometer. For variations of this magnitude, a reasonable approximation of the steady-state value usually can be obtained by averaging over a few cycles.

Telluric variations may be tens or even hundreds of millivolts per kilometer in some areas of high resistivity, in conductive zones where current channeling occurs, or during magnetic storms. Under such conditions it is difficult to obtain usable data unless the described correction procedures which follow are employed. Lightning strikes generate voltage spikes of very high amplitude and very short duration. These spikes usually are easily recognized and generally are not a major source of error.

Time-varying stray currents are generated by grounded electrical machinery and are very common in developed areas in which environmental and engineering SP surveys usually are conducted (Figure 1). Stray currents generated by corrosion processes also may change with time, but these changes are of much longer period than those associated with electrical machinery. High-frequency (50 or 60 Hz) noise may be generated by overhead or buried powerlines, but such noise usually is well suppressed by filters in the dc measuring circuits of most DMM's. In severe cases, additional low-pass filtering may be needed to suppress reading fluctuations caused by such high-frequency noise.

Lower-frequency stray currents may have periods ranging from a few tenths of a second to hours, days, or longer; and may have amplitudes of hundreds or even thousands of millivolts per kilometer (Frohlich, 1971; Hoogervorst, 1975). An example of noise generated by stray dc currents is shown on Figure 1. The source of the noise was the electrically operated San Francisco Bay Area Rapid Transit System, California, and the measurements were made across an 8.5 m dipole oriented perpendicular to the tracks and about 1 km to the east. Even at this distance, the observed noise of about +/− 5 mV extrapolates to a level of about +/− 600 mV/km.

Obviously, it is very difficult to obtain usable SP data in the presence of such noise. One method of avoiding stray current noise is indicated by the lower portion of Figure 1. As for many sources of industrial noise, operation is curtailed during evening hours and weekends, so SP readings sometimes may be made during these periods.

If measurements must be made during periods of significant natural or artificial time-varying noise, tech-

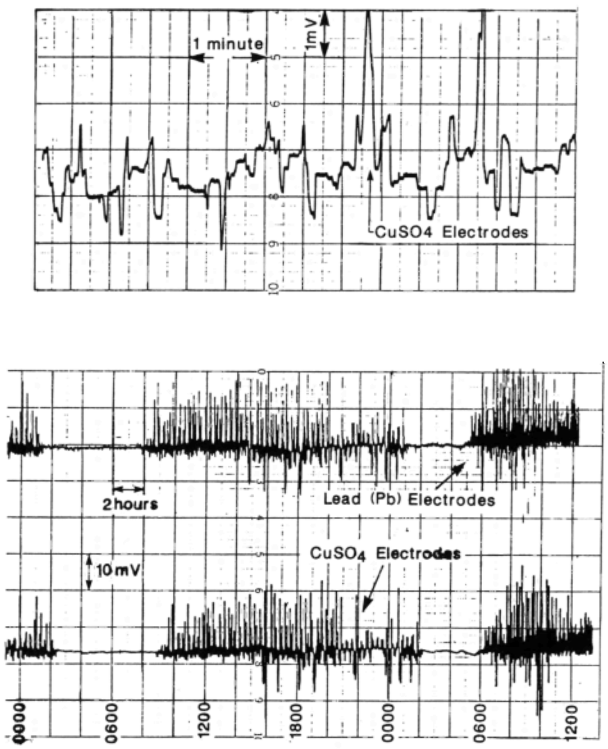

FIG. 1. Potentials generated by stray currents from electrically operated transit system, San Francisco Bay area, California. Dipole separation was 8.5 m, located about 1 km east and oriented perpendicular to the tracks. Quiet intervals on lower figure correspond to night and weekend periods. Upper figure shows detail of the time variations. Apparent time shift of lower record is due to chart recorder pen offset.

niques to reduce the effects of such noise may be used. One such method is to use the multielectrode configuration. The readings from the electrode array may be stacked or filtered until satisfactory data quality is obtained. Care must be taken to differentiate between telluric and other distant-source fields, which increase in amplitude with increasing electrode separation, and fields from nearby artificial sources, which decrease away from the source.

For a fixed-base configuration, a procedure based on a technique described in Frohlich (1971) for reduction of time-varying noise on dc electrical resistivity measurements may be used. A stationary electrode dipole of length comparable to that of the survey line is installed along or parallel to the survey line, and the signal from this dipole is brought to each measurement station by appropriate connecting wires. This signal is recorded for a period of a few hours to a day to estimate an approximate zero potential level for the variations.

Once this level is determined, SP readings at each measuring station are made at the instant that a zero potential reading is seen on the monitoring dipole. If superimposed long-period variations prevent the measured values from crossing the zero potential level during the measurement interval, SP readings can be made at a number of different noise potential values and the readings can be linearly extrapolated back to the zero level (Figure 2). Because this procedure does not account for resistivity variations along the survey line, and because the true dc potential across the monitoring dipole generally is not exactly zero, corrections will not be exact. Nevertheless, the procedure can result in very significant noise reduction and allow data to be taken under otherwise impossible conditions.

Figure 3 shows SP variations recorded across a 155 m dipole at a site in northern Canada, and Figure 4 shows an SP profile obtained in the presence of these very large

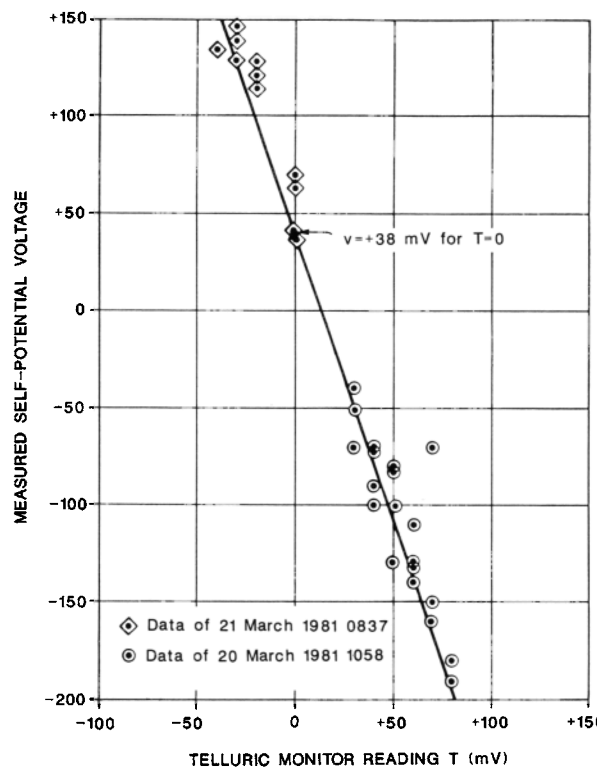

FIG. 2. Plot of measured SP values at Station 22+00 (Figure 4) versus readings on telluric monitor, northern Canada. Measurements were taken at approximate 10 s intervals, beginning at the indicated time. SP value at measurement station 22+00 was about +38 mV for zero telluric current flow. Respective negative and positive polarities of 20 and 21 March data were due to long-period telluric variations superimposed on the short-period readings (see Figure 3).

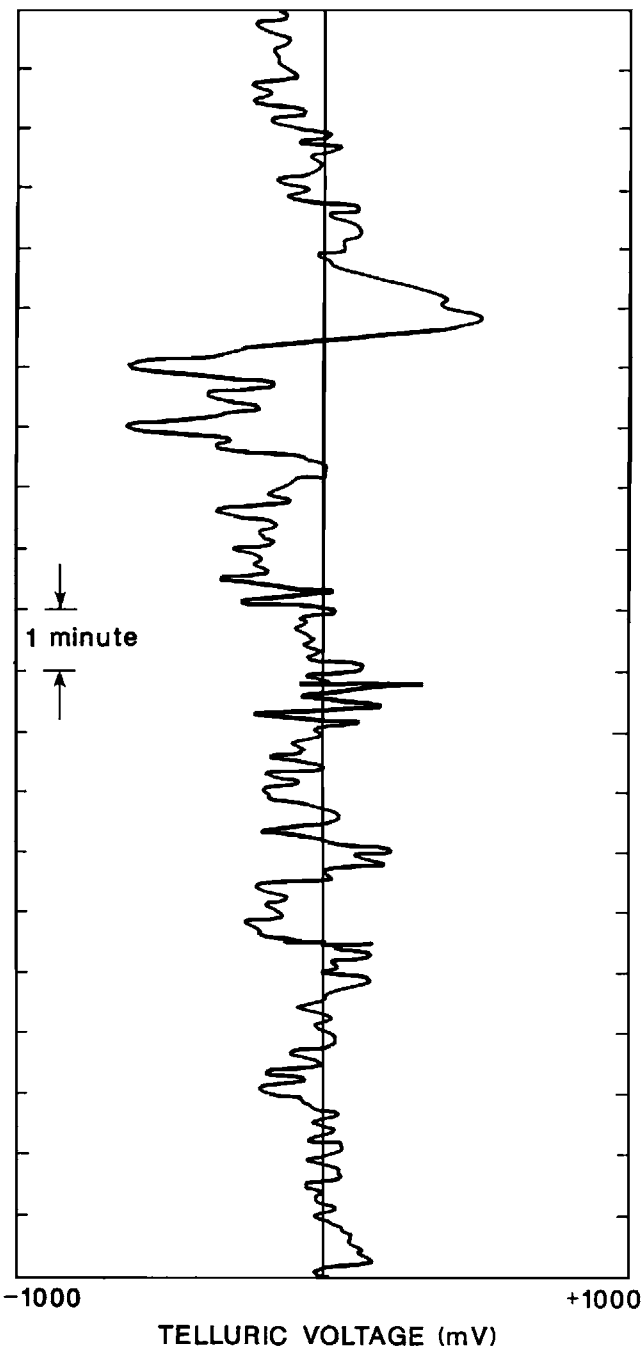

FIG. 3. Typical telluric potential variations recorded across monitoring dipole referenced in Figure 2. Electrode separation was 155 m.

variations, using the described technique (the examples of Figures 2 and 6 also are from this site). Further examples of noise reduction using a similar technique are given in Frohlich (1971).

The routine use of a telluric monitor to record time-varying potentials in the survey area is recommended. Without such a record it is difficult to detect long-period variations, and potentials generated by such variations can be mistaken for spatial anomalies. Even if the recorded data are not used for quantitative corrections, periods of significant noise can be recognized and values measured during these periods can be rechecked. This procedure necessitates recording the time at which each field SP measurement is made.

Other Sources of Noise

In addition to the electrode and time-varying effects discussed, SP data are subject to a number of noise sources that generally are stable or change relatively slowly with time. These include topographic effects, grounds of electrical equipment, corrosion of buried metal, corrosion protection systems, electrochemical potentials, unwanted streaming potentials, distorting effects of terrain or lateral resistivity variations, conductive mineral deposits, and geothermal activity. Recognition of such noise sources, and removal of their effects from the field data if possible, will improve data quality and assist in the separation of desired signals from unwanted noise.

Topographic potentials generally tend to become more negative with increasing elevation (the "negative summit" phenomenon) and are thought to be caused by the downslope movement of subsurface water. These potentials are not seen consistently, but when present may be of large amplitude, up to a few millivolts per meter of elevation (Poldini, 1938, 1939; Zablocki, 1976; Corwin and Hoover, 1979; Nayak, 1981). Topographic effects usually are largest in areas having volcanic geology, porous near-surface soil or rocks, large elevation changes, and high precipitation producing an abundant supply of fresh near-surface ground water. In some cases topographic potential gradients are easily recognized and are consistent enough to permit their removal from field data, but these gradients may vary considerably within a given survey area and may change following rainfall. [Ed Note: Up to 3000 mV change have been observed in Zambia in quartzitic terrain].

Grounds of direct-current electrical equipment may generate relatively constant potential fields in the earth if the equipment is in operation during the entire period of the field survey. As these fields may be of very large amplitude, it is important to record the location and operating period of such equipment in the survey field notes.

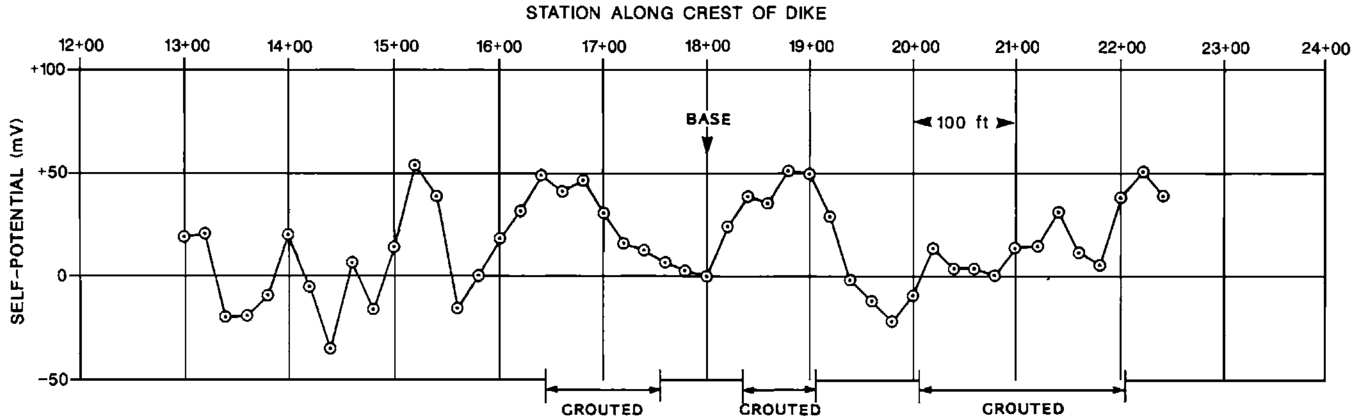

FIG. 4. Corrected SP data taken along an impoundment dike, in the presence of the noise shown on Figures 2 and 3. Note negative SP readings corresponding to uniform seepage between grouted areas.

These grounds often are equivalent to line or point sources of current, so their fields sometimes can be calculated and removed from the measured data.

Corrosion of buried metal such as well casings, pipelines, culverts, debris, and reinforcing rods in concrete can generate large potential fields. Vertical well casings often exhibit negative SP anomalies around the top of the casing (Figure 5), generated by an oxidation-reduction mechanism similar to that for conductive mineral deposits (Sato and Mooney, 1960). Reservoir outlet tunnels or spillways of reinforced concrete often show a negative anomaly at the onshore end of the structure and a positive anomaly over the submerged offshore end, generated by a similar mechanism. Buried unprotected pipelines and grounded elevated pipelines are characterized by alternating positive and negative potentials (Uhlig, 1963). By design, active and passive corrosion protection systems generate very large potentials (Uhlig, 1963).

Because such buried metal sources are very common in the developed areas where environmental and engineering SP surveys are conducted, it is important to record their presence in the field survey data. Inspection of site plans and the use of magnetic and electromagnetic techniques can help disclose buried metal sources that are not visible from the surface. In some cases corrosion fields can be modeled as generated by point or line current sources and, to some extent, removed from the data.

Electrochemical potentials can be generated across boundaries separating formations with differing pore water composition (Heiland, 1940; Nourbehecht, 1963; Semenov, 1974; Sill, 1982). Such potentials sometimes are observed when crossing faults or contacts. In some cases these potentials may be the desired signal (e.g., for geologic mapping or contaminant detection); otherwise, they contribute to geologic noise.

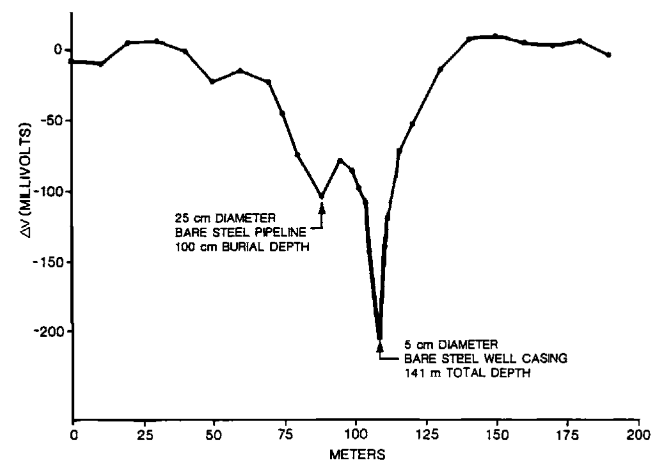

FIG. 5. Self-potential anomalies generated by buried metal pipelines and well casings at East Mesa, California.

Changes in vegetation patterns sometimes correlate with SP variations. In some cases this correlation is caused by corresponding changes in soil properties such as moisture content or pore water chemistry, but SP variations also may be caused directly by the vegetation. Examples include bioelectric effects (Scott, 1962) and streaming potentials generated by near-surface water flow related to plant evapotranspiration. Therefore, changes in vegetation patterns should be recorded in the field notes.

Streaming potentials that are not the desired survey target also can contribute to noise. Examples include the topographic effects previously discussed; movement of subsurface water along faults, fractures, or stratigraphic boundaries; and downward diffusion of surface water. For seepage investigations, it sometimes is difficult to separate streaming potentials generated by these sources from anomalies of interest related to the seepage flow.

Lateral resistivity variations and topography will distort SP fields generated by subsurface sources. If resistivity data are available, the effects of lateral resistivity variations can be calculated using dc potential field theory (Cull, 1985). Terrain effects can be estimated qualitatively (Kunetz, 1966) or modeled mathematically (Xu et al., 1988).

Finally, SP anomalies related to conductive mineral deposits (Sato and Mooney, 1960) or geothermal activity (Corwin and Hoover, 1979) may constitute noise for engineering SP investigations. If surveys are conducted in areas of known geothermal or mining activity (e.g., seepage investigations for tailings ponds or heap leach sites) the possibility of such anomalies should be considered.

For many of these stationary noise sources, it often is helpful to make additional readings while approaching the suspected source. Additional readings can both confirm the presence of the source and give a better indication of the nature of the potential field generated by the source.

Interpretation of Self-Potential Data

This section summarizes available techniques for interpretation of SP data. Field data are assumed to be of good quality, and the effects of geologic, topographic, time-varying, and other noise sources are assumed to have been removed or minimized.

SP anomalies may be generated by gradients of pressure, temperature, or chemical concentration in the earth. The anomaly amplitude depends on the products of the gradients and the cross-coupling coefficients that relate the flow of fluid, heat, or matter to the generated potential; and on the electrical resistivity structure of the earth. Voltages generated by fluid flow are called electrokinetic or streaming potentials, and those related to heat or ionic flow are called thermoelectric and electrochemical potentials, respectively. The process of SP anomaly generation is discussed in detail in the references given in the section on analytical modeling techniques.

SP data may be interpreted qualitatively, geometrically, or analytically. The interpretation procedure selected will depend on the desired goals of the investigation, the quality of the field data, the amount of available additional geological, geophysical, and hydrologic data, and the time and computer resources available for the interpretation phase of the investigation.

Qualitative Interpretation

Qualitative interpretation involves preparation of data profiles and contours and visual inspection of these to look for patterns known or thought to be characteristic of desired sources. For example, the results of many previous investigations indicate that negative SP anomalies often are seen at areas where seepage flow is entering a dam or other containment structure (e.g., Figures 4 and 6) and that positive anomalies often are seen above areas where flow is ascending toward the surface or where surface seepage is occurring.

Such qualitative interpretation has proven useful in many cases where the SP data were used primarily to indicate locations for more detailed geotechnical or geophysical investigations. However, use of the geometric interpretation techniques described, which require minimal additional effort, can help provide information about the depth and configuration of anomaly sources as well as their location.

Geometric Source Models

Geometric interpretation involves use of calculated curves and contours generated by relatively simple SP source models to match the observed field data. Available models include polarized points, lines, cylinders, spheres, sheets, and other geometric forms. Matching of field data to the curves generated by these sources can provide useful preliminary information about the form, depth, and orientation of inferred anomaly sources.

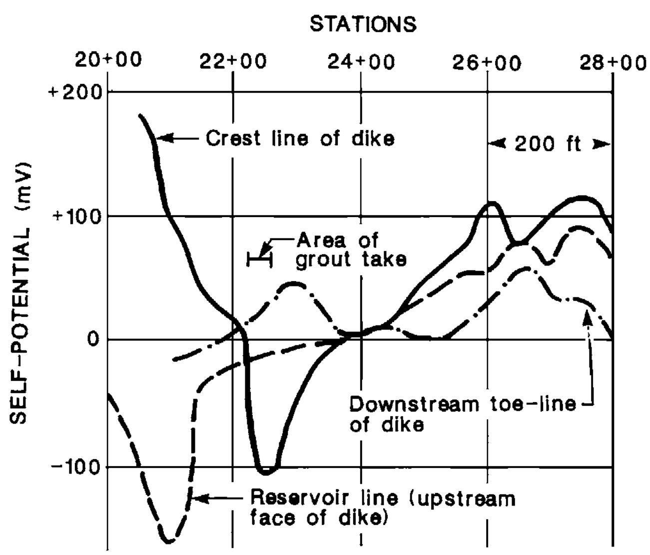

FIG. 6. SP data along an impoundment dike, northern Canada (from Godfrey, 1984). Area is same as illustrated in Figures 2, 3, and 4.)

Although no quantitative information about flow rates or source types is provided by these techniques, they are useful not only for the source parameters they provide but also for helping to eliminate SP anomalies caused by sources for which depth or configuration are inconsistent with known geologic or engineering information. Also, the preliminary models derived from these techniques are useful as input to the analytical modeling programs discussed.

The following paragraphs briefly summarize a number of geometric SP source models. Because most of the algorithms are relatively simple, they may be programmed on a calculator or personal computer. Corwin and Butler (1989) describe a computer program written for an IBM-PC and compatible computers for the calculation of anomalies generated by several geometric source models.

The references cited usually include not only derivations and equations for calculating model curves, but also interpretation schemes based on the use of anomaly wavelengths and shapes, characteristic curves, nomograms, and a variety of other methods. Often, use of these interpretation schemes prior to computer curve matching can save considerable time by providing reasonable first estimates of source parameters; and in some cases these easily obtained estimates may be sufficient for the degree of interpretation desired. In addition to the references given, Semenov (1974) presents an extensive discussion of geometric SP source modeling, and Agarwal (1984) summarizes modeling equations and describes a transform approach to anomaly interpretation.

Point-current Sources.—A point-current source or sink (Stern, 1945; Telford et al., 1976) or multiple combinations of point sources and sinks provide a powerful and flexible geometry for modeling of SP anomalies. Any arbitrary source configuration, with any arbitrary charge distribution, can be expressed as an appropriate spatial distribution of point sources and sinks.

A particularly useful application of a single point source or sink model is to provide a first estimate of the depth to the source of a circular or nearly circular SP anomaly. Because a point source represents the minimum possible source size, the source depth of the anomaly can be no greater than that which provides a reasonable fit to a point source model. Thus fitting a point source to the observed data can quickly indicate the maximum source depth. The size of the source region then must increase as its depth decreases from this maximum value.

The half-wavelength XH (the distance from the origin at which the anomaly is one-half of its maximum value) of an anomaly generated by a point current source buried at depth d in a uniform half-space is given by

$$XH = \sqrt{3}\, d.$$

This equation is helpful for quickly estimating the depth of a point source.

As numerous analytical equations have been developed for calculating the fields generated by point sources in inhomogeneous media, the use of single- or multiple-point sources allows relatively simple calculation of SP fields in the presence of geologic structure such as layers, contacts, faults, and dikes. More complex two- or three-dimensional structure may be modeled using algorithms developed for resistivity interpretation.

Examples of the use of multiple-point sources to model complex source geometry are given in DeMoully and Corwin (1980) and in Corwin et al. (1981). Morrison et al. (1978) present a computer program for calculating the SP field generated by an arbitrary array of point sources and sinks in the presence of a vertical resistivity contact.

Horizontal Line Sources.—A line source (Rao et al., 1970) represents the simplest geometry for modeling elongated SP anomalies. As for a point source, the depth to a line source that fits the field data represents the maximum possible source depth for an elongated anomaly.

More complex elongated source geometries may be modeled as distributions of multiple line sources and sinks. In the literature, many models described as sheet sources actually are dipolar line pairs located along the top and bottom edges of the "sheet." Such models are widely used for interpreting SP fields generated by thin, elongated mineral deposits. The sheet model discussed next is considered as one having uniform charge on the faces of the sheet rather than charge concentrated along the upper and lower edges.

Spherical Sources.—A polarized sphere model (Petrowsky, 1928; Bhattacharya and Roy, 1981) can be used to interpret SP data for sources that have similar dimensions along all three axes. The sphere model also can be used for initial interpretation of approximately circular field anomalies, to check whether the shapes of the model curves are more characteristic of a point source (indicative of a large ratio of source depth to source size) or a spherical source (indicative of shallower burial depth).

Cylindrical Sources.—The relation of the polarized cylindrical model of infinite length (Murty and Haricharan, 1985) to the line source is analogous to that of the sphere to the point source. Complex cylindrical models may be approximated by a series of line sources placed around a cylindrical circumference, and line sources also can be used to approximate a cylinder of finite length. At burial depths that are large relative to the radius of the cylinder, the SP field of the polarized cylinder approaches that of a line dipole having the same inclination as the angle of polarization of the cylinder and a separation equal to the diameter of the cylinder.

Vertical Dipolar Sheet Source.—A model consisting of a vertical sheet of dipolar charge (Fitterman, 1979) has proven particularly useful for SP modeling because flow in the vicinity of vertical discontinuities of resistivity and/or coupling coefficient often has been observed to generate dipolar charge distributions of this type, and anomalies fitting this model have been observed in a number of field studies. Although most of these anomalies were related to the movement of geothermal fluids in the vicinity of fault or fracture zones, similar anomalies also have been observed above vertical or nearly vertical geologic features in the vicinity of flows of nonthermal ground water. Fitterman and Corwin (1982) describe the use of an inversion routine to interpret SP data related to geothermal activity in the vicinity of a vertical contact.

More complex sheet sources can be modeled using techniques discussed in Fitterman (1979, 1982, 1983a) or by approximating the sheet with a distribution of point or line sources and sinks (Corwin et al., 1981). Sheets that are not vertical also can be modeled using either numerical techniques or approximations with point or line sources.

Analytical Modeling Techniques.—Analytical SP modeling techniques are based on concepts of irreversible thermodynamics and coupled flows of fluids, heat, electrical current, and chemical diffusion as described in Onsager (1931), Pourbaix (1949), Denbigh (1951), Prigogine (1955), and others. Application of these concepts to flow in soils is discussed in Mitchell (1976).

Study of the specific application of these concepts to interpretation of SP data was first reported in Nourbehecht (1963), followed by the work of Hulse (1978), Fitterman (1978, 1979, 1984), Ishido and Mizutani (1981), Sill (1983), and others. Sill (1983) summarizes previous work, presents a number of useful type curves, and shows a field example for which analytical techniques were used to interpret SP data for a geothermal area in terms of heat and fluid flow. Sill and Killpack (1982) describe a computer program (SPXCPL) for analytical two-dimensional modeling of SP data generated by the flow of fluid and/or heat in the earth. Wilt and Corwin (1988) discuss the use of analytical modeling of SP data for dam seepage investigations, using program SPXCPL.

Input to SP modeling programs such as SPXCPL include the electrical resistivity structure of the region to be modeled, values of cross-coupling coefficients and earth material conductivities (hydraulic, thermal, or electrochemical, depending on the source type), and the location and intensity of pressure, heat, or electrochemical sources and sinks.

Measurement of electrokinetic cross-coupling coefficients for earth materials have been reported in Rao (1953), Kermabon (1956), Schriever and Bleil (1957), Tuman (1963), Ahmad (1964), Abaza and Clyde (1969), Bogoslovsky and Ogilvy (1972), Ishido and Mizutani (1981), and Johnson (1983). Measurements of thermoelectric cross-coupling coefficients are reported in Nourbehecht (1963), Dorfman et al. (1977), and Fitterman and Corwin (1982) lists measured electrokinetic, thermoelectric, and electrochemical coefficients. Note that all these values were measured in the laboratory, and there is a need for field measurement of cross-coupling coefficients under in-situ conditions.

The analytical computer programs described are complex to use and require considerable memory and execution time compared to the relatively simple geometric source models. In many cases resistivity, cross-coupling coefficient, source strength, or material conductivity values may not be available and must be estimated. Even when these parameters must be estimated, experience indicates that these analytical techniques can provide a very useful tool for interpretation of SP data (Wilt and Corwin, 1988). Unlike the geometric techniques, they can account for complex structure; can distinguish among pressure, temperature, and electrochemical sources and sinks; and can provide quantitative estimates of flow rates.

Applications

Most published SP case histories are examples of mineral or geothermal exploration (Sato and Mooney, 1960; Corwin and Hoover, 1979). However, results of SP investigations for a variety of engineering and environmental applications also have been published. Some examples of such studies are listed. More extensive bibliographies are given in Semenov (1974) and Corwin and Butler (1989).

Few published SP case histories (for any application) include geometric or analytical interpretation of measured anomalies. Because such interpretation contributes strongly to the effectiveness of field studies, it is hoped that wider knowledge of the availability of these techniques will lead to their more extensive use for future investigations.

The majority of SP surveys conducted for engineering or environmental applications involved studies of groundwater movement related to leakage of dams, dikes, canals, reservoir floors, and other containment structures; location of faults, voids, sinkholes, rubble zones, archaeological remains, and other subsurface features that affect groundwater flow patterns; delineation of flow in the vicinity of landslides, wells, drainage structures, and springs; and regional groundwater flow.

The U.S. Army Corps of Engineers Waterways Experiment Station has conducted and published a considerable number of SP investigations of dam seepage. Examples include Cooper et al. (1982), Butler (1984), Koester et al. (1984), Yale et al. (1985), Llopis (1987), and Corwin and Butler (1989). Other examples of dam seepage investigations are given in Bogoslovsky and Ogilvy (1970a, 1970b, 1973), Semenov (1974), Nelson and Black (1977), Haines (1978), Bogoslovsky et al. (1979), Gex (1980), Fitterman (1983b), Godfrey (1984), and Wilt and Corwin (1988). Drainage systems associated with dams and other water containment structures also may generate characteristic SP fields (Bogoslovsky and Ogilvy, 1973; Ogilvy and Bogoslovsky, 1979).

The dam seepage investigation described in Godfrey (1984) is of particular interest because it includes results of a remedial grouting program conducted following the SP survey. SP data profiles for this survey (measured before grouting) are shown on Figure 6. As described in Fox and Jones (1982), twelve grout holes were drilled in the interval between Stations 21 + 80 and 22 + 60. Two holes within the large negative anomaly on the crest line accepted a total of 926 sacks of grout; the remaining nine holes accepted a total of only eleven sacks. Seepage flow before grouting was 1.64 to 2.13 cubic meters/min, and dropped to 0.05 to 0.06 cubic meters/min after completion of the grouting. Unfortunately no follow-up SP survey was conducted to determine whether the SP anomaly disappeared after grouting.

Seepage through embankments also has been studied using SP methods. Published examples include Davenport et al. (1983), Hadley (1983) and Black and Corwin (1984). Examples of SP studies of seepage through reservoir floors are given in Ogilvy et al. (1969) and Bogoslovsky and Ogilvy (1970a). As mentioned previously, SP measurements conducted over water-covered areas are particularly fast and cost-effective, and many successful (but unpublished) surveys of this type have been performed.

SP measurements have been used to map the configuration of the flow field around producing water wells. Published examples of this application are given in Gorelik and Nesterenko (1956), Bogoslovsky and Ogilvy (1973), and Semenov (1974). Typically, positive SP contours centered around the producing well tend to mirror-image the configuration of the water table depression cone.

Faults and contacts may exhibit SP anomalies if they affect groundwater flow or if they separate regions of differing soil chemistry (Bogoslovsky and Ogilvy, 1974; Semenov, 1974). An example of the SP field associated with a shallow fault in the Livermore Valley of central California is shown on Figure 7. The location of the fault trace was established by a trenching investigation, and

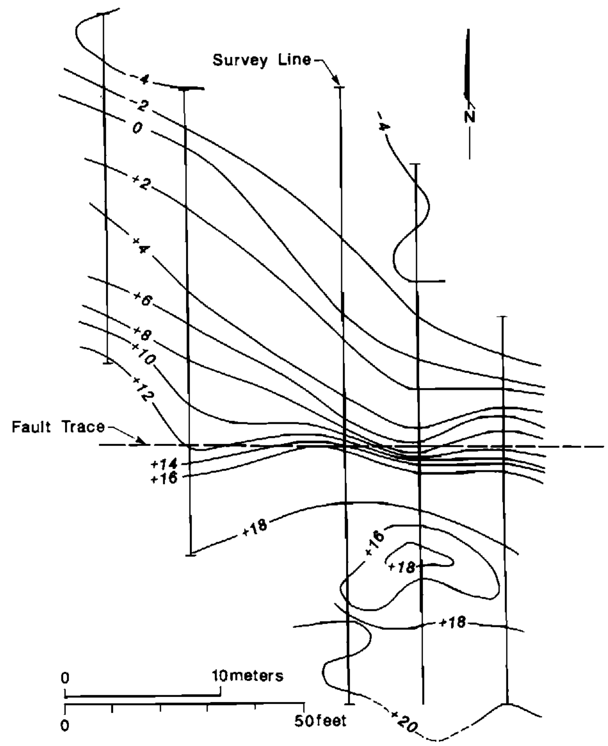

FIG. 7. SP data in the vicinity of a shallow fault, Livermore Valley, central California. Contour interval is 2 mV. Fault was acting as barrier to southward movement of shallow ground water.

evidence that the fault served as a barrier to lateral groundwater movement was furnished by the presence of moist soil and green surface vegetation to the north of the fault and dry soil and parched vegetation to the south.

Examples of SP anomalies related to regional groundwater flow are given in Rao (1953), Semenov (1974), and Schiavone and Quarto (1984). Other SP applications related to subsurface water flow include landslides (Bogoslovsky and Ogilvy, 1977; Bogoslovsky et al., 1977), sinkholes (Erchul, 1987), archaeological investigations (Wynn and Sherwood, 1984), and earthquake prediction (Corwin and Morrison, 1977; Fitterman, 1978; Morrison et al., 1979c).

Although the SP method has been used extensively to explore for areas of elevated heat flow associated with geothermal activity, there are few published examples of engineering or environmental applications of the method for detection of subsurface thermal anomalies. As elevated temperatures often produce groundwater movement and geochemical changes, it may be more difficult to interpret SP data for thermal sources than for relatively simpler flow sources.

Corwin and Hoover (1979) and Rodriguez (1983, 1984) show examples of SP investigations of subsurface coal mine fires, and Dorfman et al. (1977) show SP contours associated with a steam flood conducted for secondary petroleum recovery. SP measurements conducted over a controlled underground coal gasification project in Hanna, Wyoming (R. F. Corwin, unpublished data) indicated that the burn front generated measurable SP anomalies, but that care had to be taken to separate well casing effects from thermal anomalies.

Despite the possibility that SP data could be used to map subsurface geochemical variations such as contaminant plumes, there appears to be no published example of such an application. Theoretical studies are reported in Nourbehecht (1963) and Sill (1982) that indicate most such anomalies probably would not exceed a few tens of millivolts in amplitude, but under favorable conditions such anomalies could be detectable. SP anomalies that appear to be related to electrochemical diffusion-adsorption processes have proven useful in geologic mapping applications. Semenov (1974) gives examples of SP anomalies associated with pegmatite veins. Additional research is needed to determine whether SP techniques could be helpful in delineating subsurface geochemical anomalies.

References

Abaza, M. M. I., and Clyde, C. G., 1969, Evaluation of the rate of flow through porous media using electrokinetic phenomena: Water Resources Res., **5,** 470–483.

Agarwal, B. N. P., 1984, Quantitative interpretation of self-potential anomalies: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 154–157.

Ahmad, M. U., 1964, A laboratory study of streaming potentials: Geophys. Prosp., **12,** 49–54.

Bhattacharya, B. B., and Roy, N., 1981, A note on the use of a nomogram for self-potential anomalies: Geophys. Prosp., **29,** 102–107.

Black, W. E., and Corwin, R. F., 1984, Application of self-potential measurements to the delineation of groundwater seepage in earth-fill embankments: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 162–164.

Bogoslovsky, V. A., and Ogilvy, A. A., 1970a, Natural potential anomalies as a quantitative index of the rate of water seepage from reservoirs: Geophys. Prosp., **18,** 261–268.

——— 1970b, Application of geophysical methods for studying the technical status of earth dams: Geophys. Prosp., **18,** 758–773.

——— 1972, The study of streaming potentials on fissured media models: Geophys. Prosp., **20,** 109–117.

——— 1973, Deformations of natural electric fields near drainage structures: Geophys. Prosp., **21,** 716–723.

——— 1974, Detailed electrometric and thermometric observations in offshore areas: Geophys. Prosp., **22,** 381–392.

——— 1977, Geophysical methods for the investigation of landslides: Geophysics, **42,** 562–571.

Bogoslovsky, V. A., Ogilvy, A. A., and Strakhova, N. A., 1977, Magnetometric and electrometric methods for the investigation of the dynamics of landslide processes: Geophys. Prosp., **25,** 280–291.

Bogoslovsky, V. A., Kuzmina, E. N., Ogilvy, A. A., and Strakhova, N. A., 1979, Geophysical methods for controlling the seepage regime in earth dams: Bull. Internat. Assn. Eng. Geol., **20,** 249–251.

Butler, D. K., 1984, Geophysical methods for seepage detection, mapping, and monitoring: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 157–160.

Cooper, S. S., Koester, J. P., and Franklin, A. G., 1982, Geophysical investigation at Gathright Dam: U.S. Army Corps of Engrs., Misc. Paper GL-82-2.

Corry, C. E., 1985, Spontaneous polarization associated with porphyry sulfide mineralization: Geophysics, **50,** 1020–1034.

Corwin, R. F., 1976, Offshore use of the self-potential method: Geophys. Prosp., **24,** 79–90.

Corwin, R. F., and Conti, U., 1973, A rugged silver-silver chloride electrode for field use: Rev. Sci. Instrum., **44,** 708–711.

Corwin, R. F., and Morrison, H. F., 1977, Self-potential variations preceding earthquakes in central California: Geophys. Rev. Lett., **4,** 171–174.

Corwin, R. F., and Hoover, D. B., 1979, The self-potential method in geothermal exploration: Geophysics, **44,** 226–245.

Corwin, R. F., DeMoully, G. T., and Morrison, H. F., 1981, Interpretation of self-potential survey results from the East Mesa geothermal field: J. Geophys. Res., **86,** B3, 1841–1848.

Corwin, R. F., and Butler, D. K., 1989, Geotechnical applications of the self-potential method; Rept 3: Development of self-potential interpretation techniques for seepage detection: Tech. Rep. REMR-GT-6, U.S. Army Corps of Engineers, Washington DC.

Cull, J. P., 1985, Self potential and current channelling: Geophys. Prosp., **33,** 460–467.

Davenport, G. C., Hadley, L. M., and Randall, J. A., 1983, The use of seismic refraction and self-potential surveys to evaluate existing embankments: Rocky Mt. Regional Mtg., Am. Inst. Min., Metallurg., Petr. Eng.

DeMoully, G. T., and Corwin, R. F., 1980, Self-potential survey results from the Beowawe KGRA, Nevada: Trans. Geotherm. Resources Council, **4,** 33–36.

Denbigh, K. G., 1951, The thermodynamics of the steady state: John Wiley & Sons, Inc.

Dorfman, M. H., Oskay, M. M., and Gaddis, M. P., 1977, Self-potential profiling—a new technique for determination of heat movement in a thermal oil recovery flood: Preprints, 52nd Ann. Mtg., Soc. Petr. Eng., Am. Inst. Min., Metallurg., Petr. Eng.

Erchul, R. A., 1987, Geotechnical applications of the self-potential (SP) method, Report 1, The use of self-potential in the detection of subsurface flow patterns in and around sinkholes: Tech. Rep. REMR-GT-6, U.S. Army Corps of Engrs.

Ernstson, K., and Scherer, H. U., 1986, Self-potential variations with time and their relation to hydrogeologic and meteorological parameters: Geophysics, **51,** 1967–1977.

Ewing, S., 1939, The copper-copper sulfate half-cell for

measuring potentials in the earth: Tech. Section, Amer. Gas Assn. Distribution Conferences.
Feller, W., 1957, An introduction to probability theory and its applications, Volume 1: John Wiley & Sons, Inc.
Fitterman, D. V., 1978, Electrokinetic and magnetic anomalies associated with dilatant regions in a layered earth: J. Geophys. Res., **83,** B12, 5923–5928.
——— 1979, Calculations of self-potential anomalies near vertical contacts: Geophysics, **44,** 195–205.
——— 1982, Computer program SPDIKE for calculation of self-potential anomalies near vertical dikes: U.S. Geol. Surv. open-file rept. 82-470.
——— 1983a, Modeling of self-potential anomalies near vertical dikes: Geophysics, **48,** 171–180.
——— 1983b, Self-potential surveys near several Denver Water Department dams: U.S. Geol. Surv. open-file rept. 83-302.
——— 1984, Thermoelectrical self-potential anomalies and their relationship to the solid angle subtended by the source region: Geophysics, **49,** 165–170.
Fitterman, D. V., and Corwin, R. F., 1982, Inversion of self-potential data from the Cerro Prieto geothermal field, Mexico: Geophysics, **47,** 938–945.
Fox, R. C., and Jones, M. C., 1982, Remedial drilling and grouting of two rockfill dams: Proc., Conf. on Grouting in Geotechnical Eng., Am. Soc. Civ. Eng., 136–151.
Frohlich, R. K., 1971, The influence of industrial stray currents on the measurement of earth potentials and their elimination: Geophys. Prosp., **19,** 118–132.
Gex, P., 1980, Phenomenes d'electrofiltration lies a quelques sites de barrages [Electrofiltration phenomena associated with several dam sites] (in French): Bull. Soc. Vaud Sc. Nat. no. 357, **75,** 39–50.
Godfrey, K. A., 1984, New tools help find flaws: Civil Engineering/ASCE, Sept. 1984, 39–42.
Gorelik, A. M., and Nesterenko, I. P., 1956, Electrofiltration potential method in the determination of the radius of the depression hollow during a pumping test from a bore hole (in Russian): Izv. Akad. Nauk SSSR, Ser. Geofiz., **11,** 1361–1363.
Hadley, L. M., 1983, A geophysical method of evaluating existing earth embankments: Bull. Assn. Eng. Geol., **20,** 289–295.
Haines, B. M., 1978, The detection of water leakage from dams using streaming potentials: Soc. Prof. Well Log Analysts 19th Ann. Logging Sympos.
Heiland, C. A., 1940, Geophysical exploration: Prentice-Hall, Inc.
Hoogervorst, G. H. T. C., 1975, Fundamental noise affecting signal-to-noise ratio of resistivity surveys: Geophys. Prosp., **23,** 380–390.
Hulse, S. E., 1978, An investigation into the causes of steady state electrical potential differences occurring naturally on the surface of the earth: M.S. thesis, Univ. of Ariz.
Ishido, T., and Mizutani, H., 1981, Experimental and theoretical basis of electrokinetic phenomena in rock-water systems and its applications to geophysics: J. Geophys. Res., **86,** B3, 1763–1775.
Ives, D. J. G., and Janz, G. J., 1961, Reference electrodes: Academic Press Inc.
Johnson, G. R., 1983, Rock property measurements and analysis of selected igneous, sedimentary, and metamorphic rocks from worldwide localities: U.S. Geol. Surv. open-file rep. 83-736.
Kaufman, A. A., and Keller, G. V., 1981, The magnetotelluric sounding method: Elsevier Sci. Publ. Co., Inc.
Keller, G. V., and Frischknecht, F. C., 1966, Electrical methods in geophysical prospecting: Pergamon Press, Inc.
Kermabon, A. J., 1956, A study of some electro-kinetic properties of rocks: M.S. thesis, Mass. Inst. Technol.
Koester, J. P., Butler, D. K., Cooper, S. S., and Llopis, J. L., 1984, Geophysical investigations in support of Clearwater Dam comprehensive seepage analysis: U.S. Army Corps of Engrs. Waterways Experiment Station Misc. Paper GL-84-3.
Kunetz, G., 1966, Principles of direct current resistivity prospecting: Gebruder-Borntraeger.
Llopis, J. L., 1987, Geophysical investigation in support of Beaver Dam comprehensive seepage investigation: M.S. thesis, Miss. State Univ.
Mitchell, J. K., 1976, Fundamentals of soil behavior: John Wiley and Sons, Inc.
Morrison, H. F., Corwin, R. F., DeMoully, G. T., and Durand, D., 1978, Interpretation of self-potential data from geothermal areas: Semi-annual technical progress rep., USGS contract #14-08-0001-10545, Univ. of Calif., Berkeley.
Morrison, H. F., Corwin, R. F., Harding, R., and de Moully, G., 1979a, Interpretation of self-potential data from geothermal areas: Semi-annual technical progress rep., April 30, USGS contract #14-08-0001-16546, Univ. of Calif., Berkeley.
——— 1979b, Interpretation of self-potential data from geothermal areas: Semi-annual technical progress rep., Sept. 30, USGS contract #14-08-0001-16546, Univ. of Calif., Berkeley.
Morrison, H. F., Fernandez, R., and Corwin, R. F., 1979c, Earth resistivity, self potential variations, and earthquakes: a negative result for M = 4.0: Geophys. Res. Lett., **6,** 139–142.
Murty, B. V. S., and Haricharan, P., 1985, Nomogram for the complete interpretation of spontaneous polarization profiles over sheet-like and cylindrical two-dimensional sources: Geophysics, **50,** 1127–1135.
Nayak, P. N., 1981, Electromechanical potential in surveys for sulphides: Geoexploration, **18,** 311–320.
Nelson, J. S., and Black, W. E., 1977, Streaming potential (SP) techniques applied to seepage investigation, Colstrip Dam, Montana: Ann. Mtg., Assn. Eng. Geol.
Nourbehecht, B., 1963, Irreversible thermodynamic effects in inhomogeneous media and their applications in certain geoelectric problems: Ph.D. thesis, Mass. Inst. Technol.
Ogilvy, A. A., Ayed, M. A., and Bogoslovsky, V. A., 1969, Geophysical studies of water leakages from reservoirs: Geophys. Prosp., **17,** 36–62.
Ogilvy, A. A., and Bogoslovsky, V. A., 1979, The possibilities of geophysical methods applied for investigating the impact of man on the geological medium: Geophys. Prosp., **27,** 775–789.
Onsager, L., 1931, Reciprocal relations in irreversible processes I: Phys. Rev., **37,** 405–426.
Parasnis, D. S., 1966, Mining Geophysics: Elsevier Science Publ. Co., Inc.
Petiau, G., and Dupis, A., 1980, Noise, temperature coefficient, and long-time stability of electrodes for telluric observations: Geophys. Prosp., **28,** 792–804.
Petrowsky, A., 1928, The problem of a hidden polarized sphere: Philos. Mag., **5,** 334–353; 914–933.
Poldini, E., 1938, Geophysical exploration by spontaneous polarization methods: The Mining Magazine, **59,** 278–282; 347–352.
——— 1939, Geophysical exploration by spontaneous polarization methods: The Mining Magazine, **60,** 22–27; 90–94.
Pourbaix, M. J. N., 1949, Thermodynamics of dilute

aqueous solutions: E. Arnold and Co.
Prigogine, I., 1955, Thermodynamics of irreversible processes: Charles C. Thomas, Publisher.
Rao, M. B. R., 1953, Self-potential anomalies due to subsurface water flow at Garimenapenta, Madras State, India: Trans. Am. Inst. Min., Metallurg., Petr. Eng., Min. Eng., 400–403.
Rao, B. S. R., Murthy, I. V. R., and Reddy, S. J., 1970, Interpretation of self-potential anomalies of some geometric bodies: Pure Appl. Geophys., **78,** 66–77.
Rodriguez, B. D., 1983, A self-potential investigation of a coal mine fire: M.S. thesis, Colo. Schl. of Mines.
——— 1984, A self-potential investigation of a coal mine fire: 54th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 165–168.
Sato, M., and Mooney, H. M., 1960, The electrochemical mechanism of sulfide self-potentials: Geophysics, **25,** 226–249.
Schiavone, D., and Quarto, R., 1984, Self-potential prospecting in the study of water movements: Geoexploration, **22,** 47–58.
Schriever, W., and Bleil, C. E., 1957, Streaming potentials in spherical-grained sands: J. Electrochem. Soc., **104,** 170–176.
Scott, B. I. H., 1962, Electricity in plants: Sci. Am., Oct. 1962, 107–117.
Semenov, A. S., 1974, Electrical prospecting with the natural electric field method (in Russian): Nedra, Leningrad.
Sill, W. R., and Johng, D. S., 1979, Self-potential survey, Roosevelt Hot Springs, Utah: DOE rep. IDO/78-1701.a.2.3, Dept. of Geol. and Geophys., Univ. of Utah.
Sill, W. R., and Killpack, T. J., 1982, SPXCPL: Two-dimensional modeling program of self-potential effects from cross-coupled fluid and heat flow (user's guide and documentation for version 1.0): DOE/DGE rep. DOE/ID/12079-60, ESL-74, Earth Sci. Lab., Univ. of Utah Res. Inst.
Sill, W. R., 1982, Diffusion coupled (electrochemical) self-potential effects in geothermal areas: DOE/DGE rep. DOE/ID/12079-73, Dept. of Geol. and Geophys., Univ. of Utah.
——— 1983, Self-potential modeling from primary flows: Geophysics, **48,** 76–86.
Stern, W., 1945, Relation between spontaneous polarization curves and depth, size, and dip of ore bodies: Trans. Am. Inst. Min., Metallurg., Petr. Eng., **164,** 189–196.
Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1976, Applied geophysics: Cambridge Univ. Press.
Tuman, V. S., 1963, Thermo-telluric currents generated by an underground explosion and other geological phenomena: Geophysics, **28,** 91–98.
Uhlig, H. H., 1963, Corrosion and corrosion control: John Wiley & Sons, Inc.
Van Nostrand, R. G., and Cook, K. L., 1966, Interpretation of resistivity data: U.S. Geol. Surv. Prof. Paper 499.
Wilt, M. J., and Corwin, R. F., 1988, Numerical modeling of self potential anomalies due to leaky dams: model and field examples: Presented at the Internatl. Sympos., Detection of Subsurface Flow Phenomena by Self-Potential/Geoelectrical and Thermometrical Methods, Univ. of Karlsruhe, Fed. Rep. of Germany.
Wynn, J. C., and Sherwood, S. I., 1984, The self-potential (SP) method: an inexpensive reconnaissance and archaeological mapping tool: J. Field Archaeology, **11,** 195–204.
Xu, S., Gao, Z., and Zhao, S., 1988, An integral formulation for three-dimensional terrain modeling for resistivity surveys: Geophysics, **53,** 546–552.
Yale, D. E., Llopis, J. L., and Sharp, M. K., 1985, Geophysical seepage studies at Center Hill Dam, Tenn.: U.S. Army Corps of Engrs. Waterways Experiment Station Misc. Paper GL-85-29.
Zablocki, C. J., 1976, Mapping thermal anomalies on an active volcano by the self-potential method, Kilauea, Hawaii: Proc., 2nd Sympos. on the development and use of geothermal resources, San Francisco, CA, U.S. Govt. Printing Office, Washington, DC, vol. 2, 1299–1309.