APPLICATIONS OF THE SELF-POTENTIAL METHOD FOR ENGINEERING AND ENVIRONMENTAL INVESTIGATIONS

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ABSTRACT

Self-potential (SP) surveys detect surface voltage variations caused by subsurface flows of fluid, heat, and ions. Therefore the SP method can be useful in applications where such flows are related to subsurface targets of engineering or environmental interest. Examples of engineering and environmental applications of the SP method discussed in this paper include studies of fluid flow in the vicinity of dams, reservoirs, wells, and faults; investigations of coal mine fires, steam injection, and nuclear tests; and surveys for environmental contaminants.

Although the equipment and field procedures used for SP surveys are relatively simple, considerable care must be taken to ensure that data are reproducible, that sources of noise are recognized, and that appropriate data reduction techniques are used to correct for electrode drift and polarization. Interpretation of SP data then may be carried out using qualitative, geometric, or analytic methods. Qualitative recognition of typical anomaly patterns is helpful for determining source locations and selection of more quantitative interpretation methods. Geometric source modeling, similar to that done for other potential field methods such as gravity and magnetics, is used to estimate source configuration and depth. Analytical modeling, based on concepts of irreversible thermodynamics and coupled flows, can provide information about the nature, location, and intensity of SP anomaly sources.

INTRODUCTION

This paper is not intended to be a tutorial on the self-potential (SP) method, but rather to provide a brief overview of the use of the method for engineering and environmental applications. However, extensive reference is made to three publications that do provide considerable detail on SP field data acquisition and processing, interpretation of SP data, and examples of engineering and environmental applications of the method. Corwin and Butler (1989), a report issued by the U.S. Army Corps of Engineers Waterways Experiment Station, includes information on SP electrodes, field procedures, and interpretation techniques; a detailed case history of a dam seepage investigation; and a bibliography and data base of references related to the acquisition and interpretation of seepage-related SP data. Corwin (1990a), published by the Society of Exploration Geophysicists (SEG), provides a general tutorial on the SP method; and Corwin (1990b), published in the proceedings of a symposium on detection of subsurface flow phenomena, provides a detailed discussion of equipment, field procedures, noise sources, and data processing techniques.

The major previous applications of the SP method have been for mineral and geothermal exploration, but recently it has found increasing use in engineering and environmental investigations. This paper begins with a brief review of the mechanisms by which subsurface flows of fluid, heat, or ions may generate surface SP anomalies. Because the equipment and field procedures used for SP surveys have not been documented as thoroughly for the SP method as for other geophysical techniques, references to sources of information on these subjects are given.

Although interpretation of SP survey results generally has been qualitative, geometric and analytical modeling techniques similar to those used for other potential field geophysical methods such as gravity and magnetics are available for interpretation of SP data. These techniques are discussed briefly and references describing published SP modeling methods are given. The paper concludes with examples of applications of the SP method for studies of fluid flow sources (dam seepage and flow around a well and a vertical fissure zone); heat flow sources (a secondary recovery steam flood); and ionic flow (exploration for pyrite deposits in proposed road cuts).

SOURCES OF SP FIELDS

Electric self-potential fields may be generated by flows of fluid, heat, or ions through a porous medium such as rock or soil. Fields generated by fluid, heat, and ionic flow are known as electrokinetic (or streaming), thermoelectric, and electrochemical potentials, respectively. Because such flows often are related to sources of engineering or environmental interest, measurement of the surface component of SP fields generated by these flows can be helpful in determining the location, magnitude, and configuration of the source of the flow (for example, a zone of seepage beneath a dam; a localized heat source such as a coal mine fire; or ionic gradients related to a subsurface contaminant plume).

The source mechanisms by which these fields are generated are treated in detail in physical chemistry texts such as MacInnes (1961) and Glasstone and Lewis (1960). A brief summary of geologic electrokinetic and thermoelectric source mechanisms is given in Corwin and Hoover (1979), and Sill (1983) describes the calculation of surface SP fields from given subsurface flows.

Theoretical considerations and results of many field investigations indicate that surface SP fields generated by subsurface fluid flows of engineering interest may exceed 1000 millivolts (mV) in amplitude, although field magnitudes of tens to hundreds of mV are more common. The magnitudes of SP fields generated by heat flows related to sources of engineering interest tend to be somewhat smaller than those related to fluid flow. SP fields generated by ionic flow related to conductive minerals or artificial sources such as buried metal well casings or pipelines tend to be relatively large and easy to detect, but theoretical calculations and field experience indicate that ionic flows related to electrochemical concentration gradients such as contaminant plumes tend to generate small SP fields that may be difficult to detect.

Note that these SP fields have not been described as "anomalies". To be considered anomalous, an observed SP variation must be based on reproducible data and must be distinguishable from background noise. Data quality and noise sources for SP investigations are discussed briefly in the following sections.

EQUIPMENT, FIELD PROCEDURES, AND NOISE SOURCES

Equipment and field procedures for conducting SP surveys for mineral exploration are discussed in standard texts such as Parasnis (1966) and Telford et al. (1976). Because anomaly amplitudes generally are lower and noise levels generally are higher for SP surveys conducted for engineering and environmental studies compared with those typically seen for mineral exploration, considerable care is needed to assure that data are reproducible and that SP variations due to noise sources are distinguished from anomalies of interest.

Sources of SP noise and error include time variations of measured values (caused by natural telluric currents or grounded electrical machinery), electrode drift and polarization, topographic effects, buried metal, electrical grounds, and changes in soil properties. Recognition of such sources avoids their being interpreted as related to the desired target of the investigation, and in some cases the noise effects can be calculated and removed from the field data.

Because its data quality usually is better than that of a gradient measurement, the fixed-base survey configuration generally should be used for field SP data acquisition. Also, the use of magnetic and/or electromagnetic (EM) measurements in conjunction with SP data is very helpful in recognizing sources of SP noise due to buried metallic objects. Detailed discussions of SP equipment, field procedures, and noise sources for engineering and environmental surveys are given in Corwin and Butler (1989) and Corwin (1990a, 1990b).

INTERPRETATION OF SP DATA

Most interpretation of SP data is performed qualitatively, by preparing profiles and contours of the field data and inspecting these for obvious "anomalies" in expected target areas. This type of interpretation is useful for determining areas for follow-up investigations with other methods, but considerably more information about the depth, configuration, and nature of the source of an SP anomaly can be obtained using the geometric and analytical SP modeling techniques discussed briefly below.

Geometric modeling techniques similar to those used for other potential field geophysical methods such as magnetics and gravity also have been developed for SP interpretation. Source configurations for which analytical models have been published include points (Stern, 1945), lines (Rao et al., 1970), spheres (Petrowsky, 1928), cylinders (Bhattacharya and Roy, 1981), and sheets (Broughton Edge and Laby, 1931; Fitterman, 1979). These geometric models can provide useful estimates of the configuration, depth, and lateral extent of the sources of SP anomalies. A computer program (SP1) for calculation of the SP fields generated by the source configurations listed above is included in Corwin and Butler (1989). An example of the use of this program for a dam seepage investigation is shown on Figure 1 and is discussed in a later section.

Analytical modeling methods for SP data can be used to determine the geometric parameters described above, and also can be used to help define the nature of the source (i.e., to determine whether a given anomaly is caused by fluid, heat, or ionic flow) and to model the flow rates and associated driving potentials (pressure, temperature, or electrochemical gradients) in the earth. These analytical methods are based on concepts of irreversible thermodynamics and coupled flows of fluids, heat, chemical diffusion, and electrical current. Application of these methods to geologic investigations are discussed by Nourbehecht (1963), Hulse (1978), Fitterman (1979), Sill (1983), Wilt and Corwin (1990), and others. Sill and Killpack (1982) describe a computer program for analytical two-dimensional modeling of SP data, and the U.S. Army Corps of Engineers is expected to publish a PC version of this program in 1990.

APPLICATION EXAMPLES

Many examples of the use of the SP method for mineral exploration have been published. Hulse (1978) and Sato and Mooney (1960) include extensive bibliographies of such publications.

Because of its direct response to heat and fluid flow, the method also has been widely used for geothermal exploration (Corwin and Hoover, 1979). A selection of references for this application (and for the seepage investigations mentioned below) is included in Corwin and Butler (1989).

For engineering and environmental applications, most published case histories have been studies of subsurface water movement for seepage investigations, with a smaller number of examples of heat and ionic flow studies. Expanded abstracts from a 1984 SEG technical program session entitled "Engineering and Groundwater Applications of the Self-Potential Method" present a variety of case histories (see Rodriguez, 1984 for reference). About 30 references to engineering SP case histories are included in Corwin (1990a), and the proceedings of a 1988 symposium on the use of geophysical methods for subsurface flow detection (see Wilt and Corwin, 1990 for reference) include a considerable number of application examples.

The SP method has been widely used for both mining and engineering investigations in the Soviet Union, and numerous case histories have been published. The textbook (in Russian) by Semenov (1974) provides many field examples of engineering SP measurements, and other Soviet investigators have published a number of case histories in western journals (e.g., Bogoslovsky and Ogilvy, 1973; Ogilvy et al., 1969).

As for most geophysical methods, results of the great majority of engineering and environmental SP investigations are presented only as internal, unpublished reports. However, enough representative case histories have been published in the open literature, or released from internal reports, to provide an idea of the range of engineering and environmental applications of the SP method. The following sections present brief summaries of examples of such applications.

Subsurface Water Flow

DAM SEEPAGE INVESTIGATION

An example of an SP profile measured along the downstream toe of a leaking dam, along with a model curve generated by the program SP1 mentioned above, is shown on Figure 1 (Corwin and Butler, 1989). This reference also presents results of a study based on the analytical program described by Sill and Killpack (1982) that indicates the origin of the negative SP anomalies often seen above seepage paths and the positive anomalies associated with areas of upwelling. A more detailed description of this study is given by Wilt and Corwin (1990).

The relatively negative portions of the profile were

LINE SOURCE MODEL PARAMETERS

SOURCE NO.	X SOURCE (ft)	Y SOURCE (ft)	Z SOURCE (ft)	CURRENT (Amps)	LENGTH (ft)
1	6398	2840	2	-0.070	50
2	6900	2950	50	-0.100	50
3	7250	2850	50	-0.200	50
4	7650	2780	50	-0.200	50
5	7458	2816	40	+0.100	50

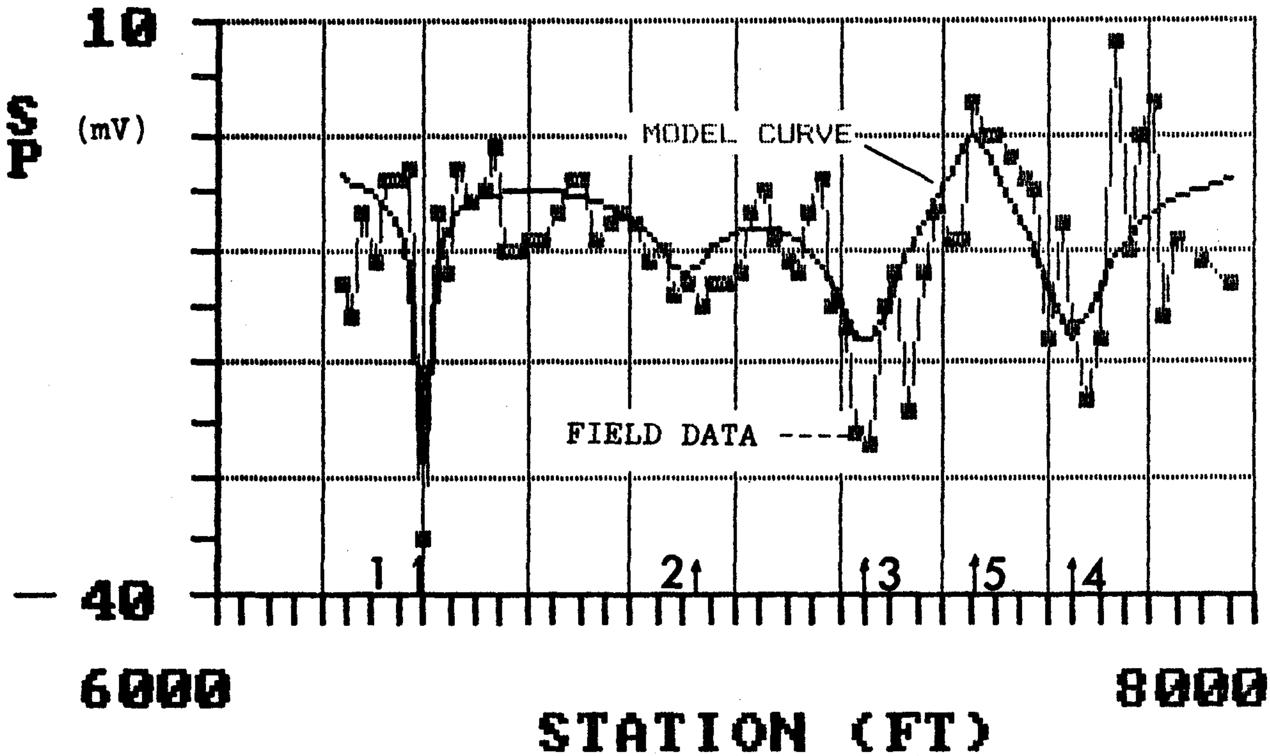

Figure 1. SP profile measured along the downstream toe of a leaking dam (from Corwin and Butler, 1989). Stations were along X-axis, parallel to dam crest; Z indicates depth below surface. Computer screen display was generated by program SP1 using horizontal line sources perpendicular to dam axis to represent paths of seepage flow (negative current) and upwelling (positive current). Note typical high level of point-to-point geologic noise relative to amplitude of anomalies.

interpreted to be related to subsurface seepage paths (the high point-to-point noise level of the profile data, comparable to the amplitude of anomalies interpreted as due to seepage flow, is typical). To investigate the depth of these seepage paths, they were modeled as negative line sources of current using program SP1. The three negative sources at a depth of 50 ft (a reasonable depth for seepage flow at this location) corresponded to seepage paths indicated by other techniques. The source at 2 ft depth was above the impounded water level and so could not be seepage-related. The positive source at Station 7458 corresponded to an observed area of upwelling of seepage flow.

Many other examples of SP surveys for investigation of dam seepage and drainage structure flow are given in the references cited in the publications listed above. In addition to onshore measurements, SP surveys also can be conducted within a reservoir or other water-covered area by towing electrodes behind a small boat or from onshore cable reels. These offshore surveys are particularly useful for locating areas of seepage of reservoir floors or locations where seepage flow is entering the upstream face of a dam or other containment structure.

OTHER SUBSURFACE WATER FLOW APPLICATIONS

Figure 2 shows SP contours around a producing well (Semenov, 1974). The positive SP gradient toward the well would be reversed for a well that was pumping fluid into the earth. The elongation of the contours indicates the preferential flow direction. Figure 3 (Ogilvy and Bogoslovsky, 1979) shows SP and resistivity profiles over a subsurface fissure zone that channels groundwater flow downward from the surface soil layer. Location of such fissure zones is important for environmental studies of contaminant migration. Additional subsurface flow applications of the SP method include studies of landslides, drainage structures, springs, sinkholes and cavities, archaeological features, and regional groundwater flow. SP variations also have been associated with faults that affect groundwater movement.

Thermal Sources

References to SP investigations of thermal sources of engineering and environmental interest are much less common than those for subsurface water flow. Because thermal SP anomalies often are of relatively low amplitude and may be difficult to separate from those generated by groundwater movement associated with the thermal source, interpretation of thermal SP data requires considerable care.

An example of SP variations thought to be associated with a steam flood for secondary petroleum recovery is shown on Figure 4 (Dorfman et al., 1977). The SP contours appear to follow the

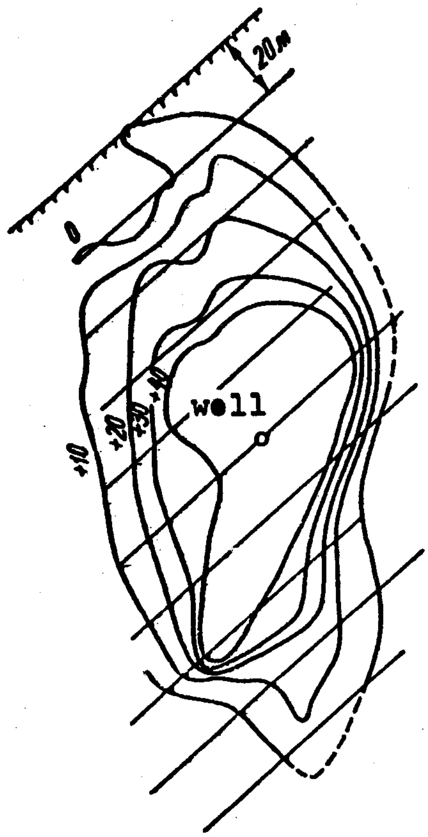

Figure 2. SP contours around a producing well (from Semenov, 1974). Contour interval is 10 millivolts.

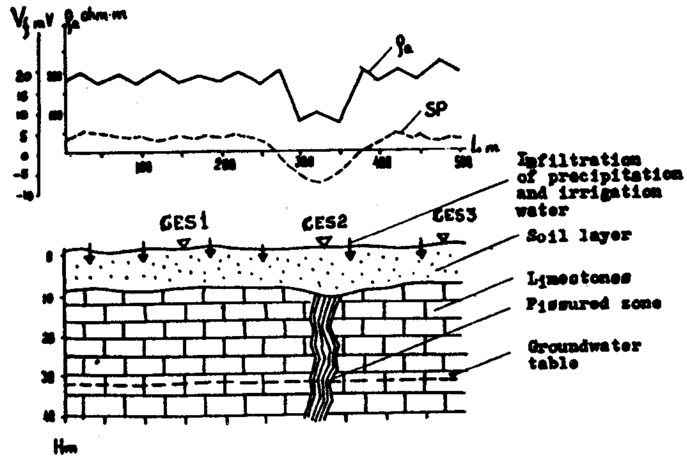

Figure 3. SP and resistivity profiles above a fissure zone serving as a conduit for downward groundwater flow (from Ogilvy and Bogoslovsky, 1979).

thermal front of the steam flood as indicated by the wellhead temperatures. Other examples of thermal SP investigations include underground coal gasification, coal mine fires (Rodriguez, 1984), and remnant heat flow around underground nuclear test sites (Corwin, 1989). This last reference also contains examples of analytical modeling of thermal and fluid flow SP data using the program developed by Sill and Killpack (1982).

Ionic Flow Sources

Ionic flows generated by electrochemical interaction between the natural oxidation-reduction gradient in the earth and electronically conductive minerals are the source of the SP fields used for mineral exploration (Sato and Mooney, 1960). A similar mechanism is responsible for the SP fields associated with buried metal objects such as well casings, pipelines, rebar-reinforced concrete, debris, etc.

There appear to be few documented examples of electrochemical reactions that generate SP anomalies associated with sources of engineering and environmental interest. Theoretical studies by Nourbehecht (1963) and Sill (1982) indicate that SP anomalies of up to a few tens of millivolts could be associated with large changes in groundwater ionic composition.

Semenov (1974) and Heiland (1940) show examples of SP variations associated with changes in subsurface mineralogy and groundwater composition, suggesting that SP data could be helpful for mapping geologic boundaries or for detecting electrochemical potentials caused by subsurface contaminants. An unpublished survey over a gasoline plume at a depth of about 5 m showed an SP anomaly of about 15 millivolt amplitude that appeared to correlate with the location of the plume. SP variations over archaeological sites reported by Wynn and Sherwood (1984) may have been caused in part by geochemical changes. However, considerably more investigation is needed to determine the utility of the SP method for such electrochemical applications.

An example of the use of SP measurements for an application combining mineral exploration and environmental considerations is furnished by an investigation for sources of disseminated pyrite along proposed highway alignments (Hopkins and Corwin, 1989). Because weathering products of pyrite exposed by road cuts in this area can cause severe environmental contamination, it was necessary to locate buried pyrite deposits along the proposed alignments to allow planning of mitigation measures. As time and budget constraints did not allow for the use of induced polarization (IP) methods along the entire 38 km length of the proposed alignments, SP was used for initial reconnaissance of the alignments and IP for more detailed follow-up studies.

The profile shown on Figure 5 illustrates some general aspects of SP measurements as well as the application for this specific purpose. Three geologic formations were present along the

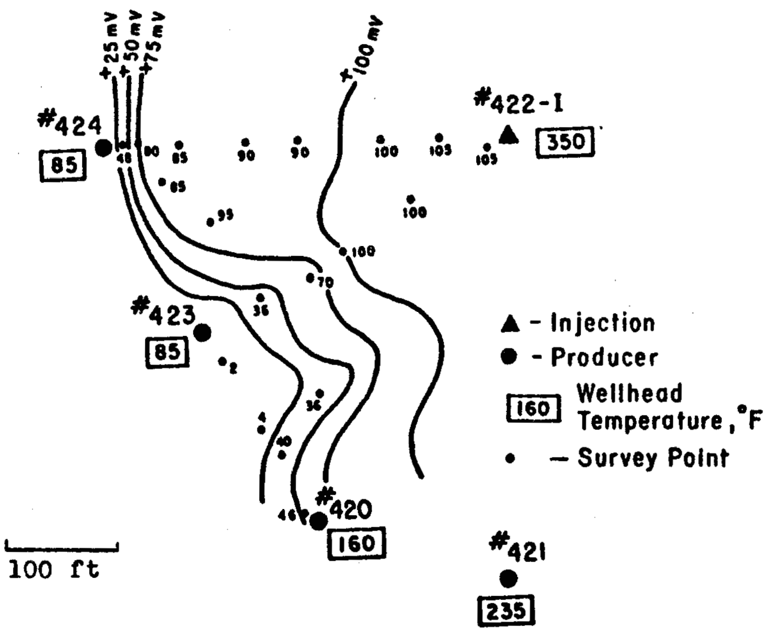

Figure 4. SP contours above a steam flood for secondary recovery of petroleum, Slocum Field, Texas (from Dorfman et al., 1977). Injection was at a depth of 500 - 600 ft.

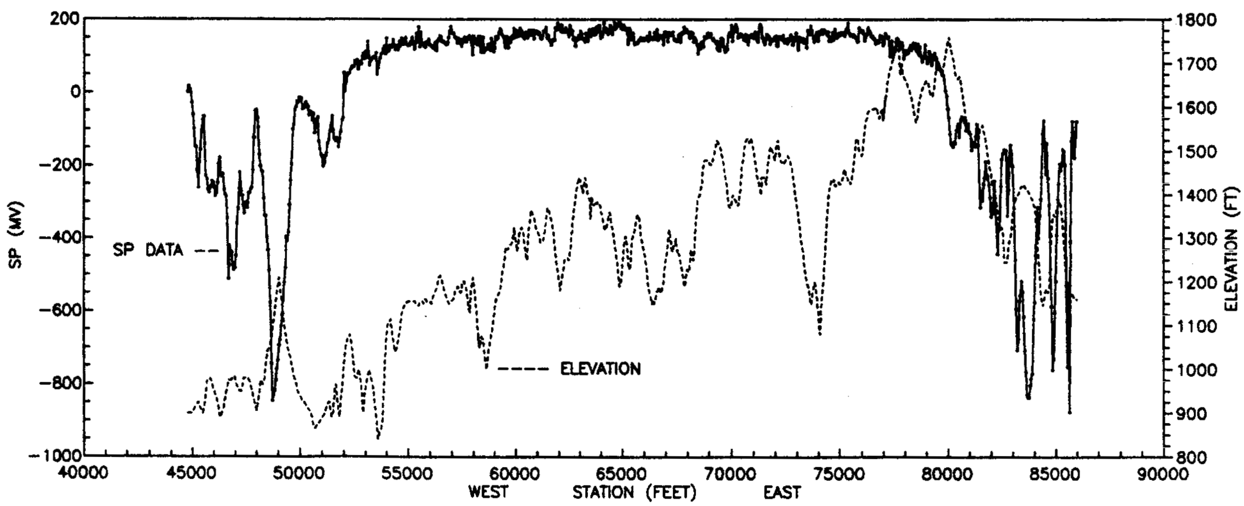

Figure 5. SP profile conducted for pyrite reconnaissance along proposed highway alignment (from Hopkins and Corwin, 1989). See text for explanation.

profile, with contacts located at about stations 54000 and 79000. SP activity in these three formations was very different in nature. To the west of station 54000 the SP profile strongly "mirror-imaged" the topography, which is typical of a topographic SP effect when it is present. Between stations 54000 and 79000 SP activity is at a much lower level than to the east or west, and virtually no topographic effects are seen. Small negative SP variations in this central formation correlated with highly disseminated pyrite deposits confirmed by IP measurements. To the east of station 79000, the large negative SP variations did not correlate with topography, but were associated with major pyrite deposits confirmed by borehole data and strong IP anomalies.

CONCLUSIONS

Because of the low signal-to-noise ratio of most SP data taken in the developed areas where many engineering and environmental studies are conducted, care must be taken to obtain reproducible data and to recognize noise sources unrelated to desired targets. Experience indicates that, if these criteria are met, it is possible to reliably acquire SP data of quality high enough to be useful for engineering and environmental purposes. The increasing use of geometric and analytical techniques for modeling SP data is extending the utility of the method to include not only locating anomalies related to fluid flow, thermal, and geochemical sources, but also to help determine the nature, strength, depth, and configuration of the sources.

The SP method has found widespread application for subsurface fluid flow investigations, where its unique ability to respond directly to the movement of fluid allows mapping of seepage and groundwater movement. Engineering and environmental sources of heat flow are less common than those for fluid flow, but a number of successful applications indicate that the method can be useful for investigations of subsurface thermal sources. Theoretical studies indicate that subsurface geochemical variations may generate measurable SP anomalies, but aside from mineral location applications such as that discussed above, the utility of the SP method for engineering and environmental investigations of geochemical sources remains to be established.

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