

Induced Polarization Survey of Sulfide-Bearing Rocks in Eastern Tennessee and Western North Carolina

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Iron pyrite in minute crystal form occurs extensively in the Anakeesta Shale formations in the Appalachian Mountains and can cause serious environmental problems when exposed in highway cuts and embankments. Many remote sensing techniques were evaluated in an effort to find a means of economically, accurately, and expeditiously locating these low-grade sulfide mineral deposits and to establish their vertical and longitudinal boundaries along a proposed highway corridor. Other benefits also are discussed. Good results were achieved by using induced polarization techniques along a route in the Tellico Mountains of eastern Tennessee and western North Carolina.

Low concentrations of sulfide minerals are a serious cause for concern when they occur in the path of proposed highway construction. The Appalachian Mountains of eastern Tennessee and western North Carolina are noted for deposits of both rich and low-grade ores of iron pyrite. The Anakeesta shale formation, which occurs extensively in the Tellico Mountains between Tellico Plains, Tennessee, and Robbinsville, North Carolina, contains low-grade deposits of iron pyrite or iron sulfide (FeS_2) with crystals often too small to detect with the unaided eye. When exposed to the elements and permitted to weather, the minute crystals oxidize quickly to form a weak solution of sulfuric acid (H_2SO_4) and probably iron oxide (Fe_3O_4), both of which are damaging to aquatic life. In an area experiencing occurrences of acid rain and the natural production of tannic acid through the decomposition of certain organic materials, the addition of even a weak solution of sulfuric acid can severely upset the balance. Many natural trout streams occur in the rather scenic area, which attracts many avid trout fishermen and protectors of the environment. Acid runoff strong enough to corrode asphalt-coated corrugated metal pipe is a cause of concern to environmentalists, judges sympathetic to environmental concerns, governmental officials, and professional highway engineers.

Acid drainage and its adverse environmental impact are very familiar to residents and researchers of Appalachia from Maine to Georgia, especially to those from the coal-mining regions and the mining operations of the Copper Basin, which is in the vicinity of this project. The environmental problem resulting from the construction of the highway project discussed in this paper may have occurred on many projects but could have gone unnoticed or ignored because of the need for highways. Many of the problems that did occur with acid leaching have stabilized over many years or are overshadowed by mining or other such disturbances. The seriousness of the problem was highlighted recently when acid drainage occurred during construction of a proposed highway connecting Tellico Plains, Tennessee, to Robbinsville, North Carolina.

Once sulfide minerals are disturbed by highway construction and leaching begins, remedial measures can be very expensive compared with incorporating appropriate protective measures during the design stage. Detection of the deposits and the use of design procedures incorporating a combination of measures to avoid the deposits and remedial measures may be the most economical and expedient approach.

Detection or location of the sulfide mineral deposits prior to the final design and before disturbance during construction is crucial to the

adequate protection of the environment. To be effective and acceptable, detection must be both accurate and economical. Any detection method used in the Appalachian region also must be adaptable to rough mountainous terrain characterized by fairly complicated geology and dense forest vegetation. Under these difficulties the induced polarization and resistivity detection method was tested for the first time in highway work in a successful effort to find low-grade iron pyrite deposits located along a proposed continuation of a route where previous highway construction had caused pollution problems.

ENVIRONMENTAL PROBLEMS ASSOCIATED WITH SULFIDE MINERALS

Acid mine drainage and acid rain are problems familiar to many, but acid drainage from highways has not been considered a widespread problem, although problems have been experienced at some locations, especially in the Appalachian Mountain range. The most common source of acid drainage is the leaching of compounds containing sulfur of which iron pyrite is the main contributor in the Appalachian Mountains. The problems occur generally when widely disseminated, minute crystals of iron pyrite contained in somewhat porous rock are disturbed and left exposed to weathering. Highway cuts and embankments, if not protected by blankets of impermeable materials, create such exposure to weathering and resultant leaching. The telltale signatures of the presence of iron pyrite are rust-colored stains on cut slopes and on exposed broken rocks in fills, the deterioration of pipe culvert inverts, the deposition of iron oxide in streams or ditches, the dying of aquatic plants and animals, and the appearance of certain algae. In some locations such as the Copper Basin, galvanizing on steel guard rails has a life span of only two to five years as a result of acid rain and splashing of acid drainage generated through the processing of sulfide minerals.

The need to locate and deal with sulfide minerals effectively is certainly a matter of concern for highway planners and designers. Although environmental problems have only recently been considered important by many, they now must be handled effectively. The expertise of geologists is essential not only to the corridor and route selection process but also in the construction and operational phases. Geologists should conduct preliminary investigations during the conceptual stage. If pyrite deposits are obvious, they can be avoided. The obscured disseminated deposits can cause problems, but they can be located during the preliminary design stages immediately after preliminary center lines and profiles have been developed. If communications are good among planners, environmental sections, location sections, and geologists, suspect areas can be delineated in the early stages and can receive proper attention as the proposed route is developed more fully.

Once iron-pyrite-bearing formations have been exposed in highway cut sections and in embankments, the process that breaks down the pyrite into the environmentally damaging iron oxide and sulfuric acid is difficult and expensive to control. Usually

a combination of remedial measures is necessary. The increased acidity of streams must be lowered to ambient levels. For best trout survival and reproduction, particularly in a natural habitat, the pH level must be kept between about 6.5 and 8.5. A pH level of 5 can be tolerated to some extent by the trout of the Appalachian range where streams tend to be acidic. At intolerable pH ranges, expensive treatment facilities and monitoring stations may be required for lowering the acid levels. Sodium hydroxide (NaOH) or lime, quick lime (CaCO₃), or hydrated lime [Ca(OH)₂] may be used as the neutralizing agent (1). When these compounds are dissolved in water, heat is generated. Thus temperature monitoring may be required also, especially in trout streams of marginal quality. For trout reproduction, stream temperatures must range from 40°F to 50°F (4.44°C to 10°C) for a few months, and for continued healthy survival, stream temperatures must not exceed about 70°F (21.11°C). The same chemical compounds used to neutralize the generated sulfuric acid will cause the precipitation of iron oxide as the pH level rises. In order to control appearance and to remove the solids at the point of neutralization as required by the U.S. Environmental Protection Agency, the water may have to be passed through a retention pond capable of maintaining a detention time of about 30 min. The location of such a treatment facility is critical, especially if a retention pond is necessary. Aeration may also be necessary to provide free oxygen in the outfall, to provide for mixing, and to provide for complete oxidation. Such facilities do not blend well aesthetically.

Massive doses of lime applied to the cut and fill slopes will provide some short-term neutralization. If the cut slopes are near vertical, little else can be done except to direct the drainage to the treatment facilities. Fill slopes may cause the most serious leaching problems if the fills are constructed with pyritic rock without choking the voids and sealing the slopes with an impervious material. An embankment of large rock containing large voids will allow rain water to run freely through the fill, dissolving the pyrite in massive quantities. A fair remedial measure may be to work in as much limestone dust as possible and envelope the embankment section in a thick, impervious layer of clay.

The deterioration of pipe inverts caused by acid drainage is very difficult to remedy. About the only solution is to reline the deteriorating pipe culverts with vitrified clay or plastic pipe. This effectively reduces the original pipe size, which, in turn, may cause ponding at the inlet end. The resulting overflow around the culvert and through the fill will dissolve iron pyrite in the embankment material and further defeat efforts to limit acid water generation. If ponding occurs, protection must be provided against seepage through the fill. Inlet structures must be constructed carefully to direct all drainage into the vitrified or plastic liner. The outlet end may require an anchoring device and a paved ditch if it emerges up in the side of the fill.

Remedial measures always seem to leave something to be desired, usually are expensive, and usually require constant maintenance and monitoring. A better approach is to try to avoid the pyrite deposits that can cause problems or to incorporate protective measures into the original design. In many cases, troublesome deposits if adequately located, can be avoided by slight line shifts or by changes in the profile grade line to avoid cutting into the deposit. It may not always be feasible or practical to avoid the deposits. Then economics and design problems may necessitate other considerations

such as designing the cut slopes so they will support a thick blanket of impervious clay at least over the pyrite zone. Rock containing the pyrite may have to be disposed of either in embankments or waste areas where the materials can be enveloped on the top, bottom, ends, and sides with an impervious clay layer. Usually if handled in the design phase, treatment facilities can be avoided, and the cost will be considerably less.

TECHNOLOGY TRANSFER OF INDUCED POLARIZATION TO THE HIGHWAY FIELD

The problems with water quality encountered when highway cuts penetrated rock strata that contain widely disseminated minute crystals of iron pyrite were causes for serious concern. With many miles of highways still needed in the Appalachian region and with some highways nearing the final design stage, an accurate, economical, and expedient means of locating the worrisome, low-grade sulfide mineral deposits was very much in demand. The use of core drilling rigs in the area is very expensive, is disruptive to a sensitive environment, and might cause public concern.

Many miles (kilometers) of the Tellico-Robbinsville project were virtually inaccessible to drill rigs. At accessible points, the drill rigs would have had to be moved in on skids with tracked vehicles or cables or set with helicopters. Tracked vehicles would have had to haul in water for the drills or water would have had to be pumped for about two miles up 45- to 60-degree slopes. Skidding in the equipment would have required a great deal of clearing, and some clearing would have been required even if drills were set by helicopter. Every possible cut section would have had to be cored, and even then some deposits could have been missed. Recognizing these problems, some type of remote sensing methods seemed to be needed. Consideration was given to the various types available.

The photographic and nonphotographic imaging techniques of remote sensing can be used in mineral exploration and detection, but these methods are keyed entirely to interpretive methods that rely on surface indicators. These techniques also must be coordinated with seasons due to the dense foliage, although vegetation types are sometimes indicators of soil condition and minerals present. Some types of remote imaging techniques are good for determining soil types and plotting geologic formations. However, anything that lies below the surface does not lend itself very well to detection by these methods.

Electrical and magnetic geophysical exploration and prospecting methods were considered next. Almost all of these techniques can be used in either a movable surface mode or in aircraft. These methods are used extensively in the search for oil and minerals, and the electromagnetic techniques are known to be very good for locating iron pyrite. Consideration was given to the possible use of aircraft to search for the scattered, low-grade iron pyrite deposits plaguing the completion of the forest road across the Tellico Mountains just south of the Great Smokey Mountains. The method employs either airplanes or helicopters usually towing a bird trailing about 200-500 ft (60-150 m) below and behind the aircraft containing all or part of the signal transmitting and receiving equipment. The aircraft must also fly from 200 to 400 ft (60 to 120 m) above the ground. The terrain, weather conditions, and forest types common to this area present problems in the use of such airborne systems. Because of the rough, steep terrain, associated severe air currents, rapidly occurring thunderstorms, and

tall, dense vegetation, the movable surface surveying mode was considered most practical.

The remaining practical choices of conducting a surface mineral survey seemed to be either electromagnetic or induced polarization methods. Both methods are good for finding sulfide mineral deposits and for defining geologic features. However, electromagnetic methods are mostly limited to locating massive sulfide deposits of about 15 percent by volume or above. The induced polarization technique is sensitive enough to locate deposits of approximately 1 percent concentration. Although the induced polarization technique has a number of favorable attributes, it became apparent, after helping carry the equipment over 17 miles (27 km) of rough mountainous terrain between 3000 and 5000 ft (900 and 1500 m) in elevation, that the method involved considerable effort. The favorable final results, however, made the effort worthwhile.

Although no reference could be found to the use of induced polarization in the highway field prior to this undertaking, the method seemed appropriate for the need. Induced polarization methods are widely recognized in geophysical exploration and are known to be capable of delineating anomalies indicative of low-grade iron pyrite deposits. To test the applicability of the method for the sulfide concentrations occurring along the proposed highway route, a small demonstration project was set up along a 2-mile (3.22-km) section of the centerline. Core samples had been taken, and geological maps and profiles had been prepared for this area by capable geologists. A reconnaissance line was run using an electrode configuration with 200-ft (60.96-m) spacing and dipole-dipole array (see Figure 1). At locations where anomalies indicative of iron pyrite were detected, a detailed survey was made using a 25-ft (7.62-m) spacing and dipole-dipole array at 25-ft intervals along the centerline. Both the lateral and vertical limits of a sulfide deposit can be defined by a detailed survey.

Detailing is the most expensive and time-consuming part of the survey, but the need for such detailing is greatly reduced by the reconnaissance survey. The exact location and horizontal limits of the areas needing detail work will be defined by the reconnaissance survey. In addition, if a preliminary profile of the proposed line is available, then any deposits falling entirely within embankment sections can be eliminated from the full detailed survey and possibly skipped in the reconnaissance survey.

Absolutely essential to the use of induced polarization techniques is the use of qualified personnel. The interpreter or geophysicist must be knowledgeable by education and experience in the areas of geophysical exploration and geology, must be capable of comprehending the area being surveyed, and must have a complete understanding of the induced polarization equipment being used. The survey team must be chosen on the basis of proven experience and ability.

INDUCED POLARIZATION EQUIPMENT AND METHOD OF USE

Polarization refers to the phenomenon that occurs when current that is applied to moist soil just below the ground surface is blocked at the interface of a metallic surface by an opposing current (see Figure 2). The mode of conduction of the current applied to the moist soil is ionic in nature. This applied current flows through the solutions in the pore spaces of rocks. When this current reaches the face of the pyritic mineral, the ionic current is converted to electronic current or is blocked until it builds up sufficiently to give up or receive the electrons contained in the crystal lattice of the metallic particles in the pyrite bearing formation. The blocking action, or the resistance to the flow of current, increases with the time that the induced direct current is allowed to flow through the conducting medium. This results in the build up of ions at the metallic interface. Eventually, an excess of ions builds up at the interface, which appreciably reduces the amount of current flow through the metallic particles. The electromotive (coulomb) forces between the charged ions at the polarization zone force the ions to return to their normal position when the induced flow of direct current is cut off. This reversal of charge or

Figure 2. Diagrammatic sketch of induced polarization process.

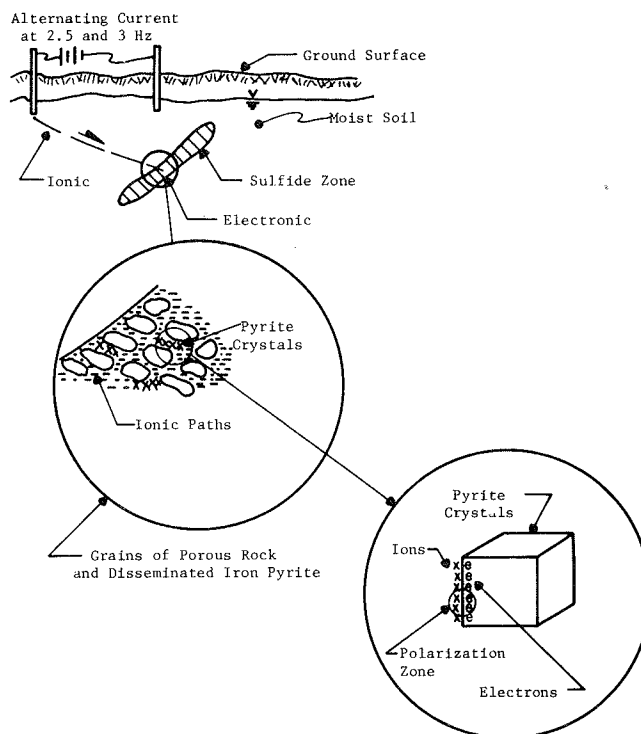
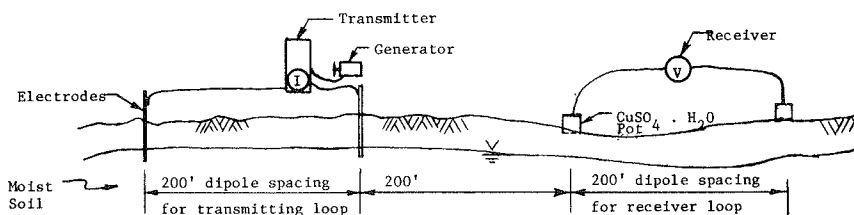


Figure 1. Electrode configuration with dipole-dipole array; constant spacing of 200 ft was used on reconnaissance survey.



transient flow of charged particles creates a small current flow that can be measured as a voltage at the ground surface as a decaying potential difference. This "pulse transient" induction method of detecting polarization can be achieved either by applying the current for a period of time and measuring the decay after cut off or by averaging several decays by applying the current in alternate directions in a series of pulses. These measurements are taken in the "time domain." The geophysicists look for areas where current flow is maintained for a short time after the applied current is terminated. By reversing or alternating the flow of current repeatedly at frequencies of from direct current to a few cycles per second before the polarization occurs, the effective resistivity of the system will change as the frequency of the switching occurs, thus permitting measurements to be made in the "frequency domain." The apparent resistivity value is measured as the frequency of the applied current is altered. The presence of metallic minerals is indicated by changes in the apparent resistivity. A correlation can be developed between the type of material present below the ground surface and the recorded data, which include measured resistivities, frequencies, and applied voltage (2-5).

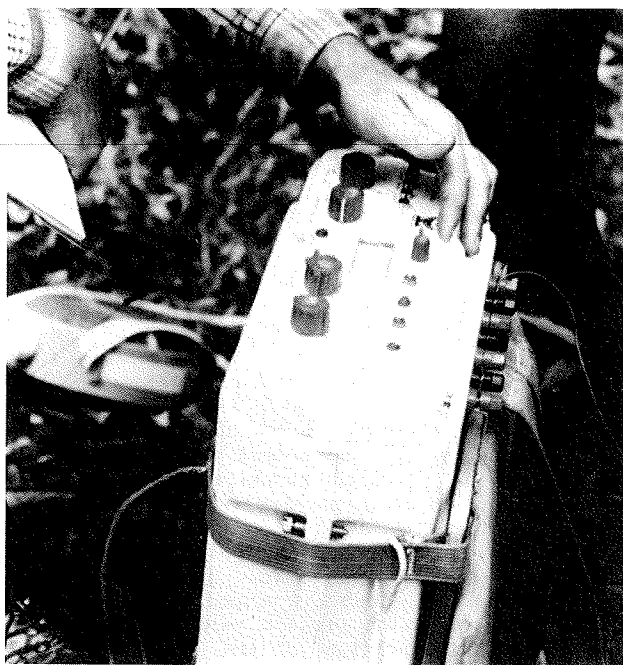
The resistivity of the material encountered or its ability to conduct electrical current is the key to the interpretative process. Since graphite, for example, is an excellent conductor, this property allows easy detection of graphitic shales into which the current seems to disappear. Some graphitic shale was encountered on the project and provided a good demonstration of this characteristic. Decreased or low resistivity and increased polarization are indicative of contact with a pyrite deposit.

The induced polarization technique functions in accordance with Ohm's Law, i.e., voltage equals current times resistance ($V = IR$). Current is passed into the ground by the transmitter at specific preset frequencies, and the receiver measures the output voltage. Since the earth is not really a true resistor, inductance and capacitance are present, and impedance is referred to as the apparent resistivity. Capacitance and inductance are frequency dependent. Voltage measurements are actually taken at the higher frequency; then the frequency is lowered to obtain a frequency effect measurement that is related to the polarization of the subsurfaces.

Figure 1 illustrates the configuration of the equipment and the spacing of the dipole-dipole array used in the reconnaissance survey made along the center line of the proposed highway. The equipment used to conduct the survey was divided into two categories—one for the transmitting electrodes and one for the receiving electrodes. A number of hollow, steel stakes about 30 in (75 cm) long to provide for maximum contact were used as the electrodes and were equipped with quick-connection alligator clips. The electrode conductors were heavy-gauge, insulated copper wire. Additional items used consisted of a small sledge hammer, an axe, a small supply of water for occasionally wetting the soil around the electrodes, an extra supply of wire, a tool kit for adjusting the equipment, and walkie-talkies.

There are two distinct circuits in the system—the transmitting circuit and the receiving circuit. In the transmitting circuit, the transmitter (see Figure 3) is equipped for varying the frequency of the applied current while maintaining a constant voltage through the electrode to the moist soil. The transmitter was very sensitive to moisture and condensation caused by frequent showers, high humidity, and condensation caused by extreme changes in

Figure 3. Induced polarization transmitter with frequency control and alternating input current regulator.



temperature. (This problem was solved by the use of a desiccant.) The transmitter, weighing about 40 lb (18 kg), could not be left in the field overnight because of the moisture problem and possible damage by the wild hogs in the area. The geology of the area, rough terrain, soil conditions, soil moisture, and high currents required by the high resistance to current flow in the area prevented the use of a battery-pack-powered transmitter, thus necessitating the use of a gasoline-operated generator weighing about 50 lb (23 kg). About 2 gal (7.5 L) of gasoline had to be carried in for about a 10-h operating period.

The receiving circuit consisted of the receiver (see Figure 4) for measuring the voltage, two copper sulfate pots that acted as the receiver dipole electrodes, and the connecting wire. Water was added to the soil beneath the copper sulfate pots to provide the necessary moisture, and the copper sulfate level was checked daily.

A four-person crew was probably optimum with everyone taking turns carrying the equipment. However, a larger crew seemed desirable at the end of a 10-h day when the vehicle was more than 5 miles away, over a ridge, and about 1000 ft (300 m) higher or lower in elevation. The day always began with a rough ride, usually a long hike into the line, and a careful calibration of the receiver to the transmitter while the first station setup was under way.

INTERPRETATION OF DATA

The reconnaissance survey procedure used is described as a surface mode, moving set-up, induced polarization and resistivity survey that uses the frequency domain. The transmitting and receiving dipoles were spaced 200 ft (60.96 m) apart to obtain only the $N = 1$ induced polarization and resistivity measurements (see Figure 5). Both sets of dipoles were moved continually along the survey line at 200-ft (60.96-m) intervals that provided a measurement of resistivity and polarizability within a half sphere with a radius of 100 ft (30.48 m) or to a

depth of 100 ft. When areas of decreased resistivity and increased polarizability were located, detail work was recommended or conducted to more accurately determine the boundaries and depth to the anomalous source. The detail survey employed 25-ft (7.62-m) or 50-ft (15.24-m) dipole settings for determining the width and depth of the sulfide mineral deposits. As the data were interpreted, profile maps were developed showing the location of definite, probable, and possible induced polarization anomalies. The occurrence of anomalies is indicated by bars as illustrated in the lower part of Figure 6. The bars represent the surface projec-

tion of the anomalous zones as interpreted from the location of the transmitter and receiver electrodes when the anomalous values were measured.

Since the induced polarization measurement is essentially an averaging process, as are all potential methods, it is frequently difficult to pinpoint the source of an anomaly. No anomaly can be located with more accuracy than the electrode interval length. Using 200-ft (60.96-m) electrode intervals, the position of a narrow sulfide body can be determined only to lie between two stations 200 ft apart and 100 ft deep. In order to locate sources at some depth, longer electrode intervals must be used, with a corresponding increase in the uncertainties of location. Therefore, while the center of the indicated anomaly probably corresponds fairly well with the location of the source, the length of the indicated anomaly along the line should not be taken to represent the exact edges of the anomalous material since the exact edges will lie somewhere between the dipole spacing used and the set-ups that incorporate the first and last readings indicating an anomaly.

Metal factor (MF) anomalies, percent frequency effect (PFE), and resistivity are shown on detail data plots, but only resistivity and PFE anomalies are shown on reconnaissance plots. The PFE results indicate polarizable areas without taking into account the resistivity of the areas. The MF or "metallic conduction factor" is obtained by combining the PFE and the resistivity data.

The PFE is a ratio of the apparent resistivity (ρ) at the low frequency (f_1) or switching cycle

Figure 4. Induced polarization receiver for measuring output voltage for calculating resistivities ranging from 20 ohm meters to greater than 80 000 ohm meters at frequencies of 2.5 and 3 Hz.

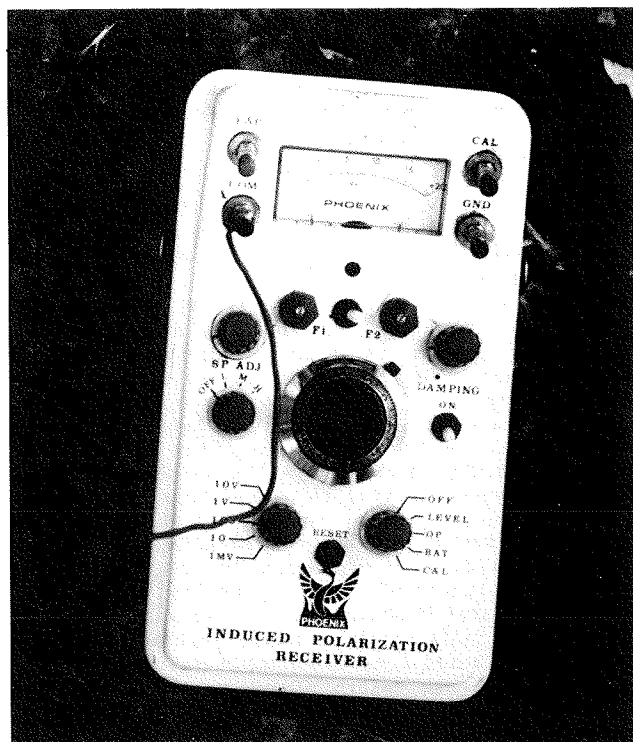


Figure 5. Electrode configuration with 200-ft dipole array; $X = 200$ ft and $N = 1$ for reconnaissance work; $X = 25$ ft or 50 ft and $N = 1, 2, 3$, and 4 for detail work.

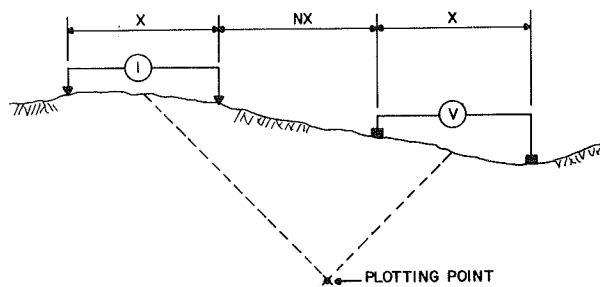
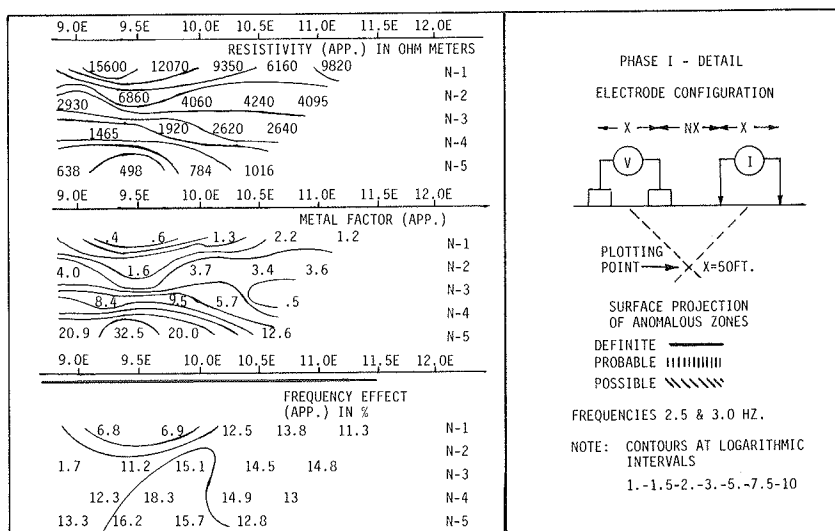


Figure 6. Typical output plot of induced polarization data showing resistivity plot, percent frequency effect, and metal factor plot, with symbols for indicating location of pyrite deposits.



and the apparent resistivity at the higher frequency (f_2) (5).

$$\text{Apparent resistivity at low frequency at station } a = [\rho(f_1)/2\pi] a \quad (1)$$

$$\text{Apparent resistivity at high frequency at station } a = [\rho(f_2)/2\pi] a \quad (2)$$

$$\text{Apparent frequency effect} = (fe)_a = \left\{ [\rho_a(f_1)/\rho_a(f_2)] - 1 \right\} a \quad (3)$$

The MF is obtained by combining the PFE and the resistivity.

$$\begin{aligned} \text{MF} = (fe \times 100)/[\rho(f_1)/2\pi] \times 1000 &= \left\{ [\rho_a(f_1)/\rho_a(f_2)] - 1 \right\} \times 100 \\ &\div [\rho_a(f_1)/2\pi] \times 1000 = \left\{ [1/\rho_a(f_2)] - [1/\rho_a(f_1)] \right\} \\ &\times 2\pi \times 10^5 \end{aligned} \quad (4)$$

A good conductor (low resistivity) that is strongly polarizable (high PFE) will give a well-defined or "definite" MF anomaly. Less-well-defined MF anomalies are designated as probable or possible. The PFE and MF parameters are complementary. The relative importance of each type of information depends on the particular geophysical environment encountered and the type of target expected. For example, a mineralized silicified zone will give a "definite" MF anomaly. Alternatively, an oxidized ore zone may only give a "weak" PFE anomaly but a "definite" MF anomaly.

The plot of the reconnaissance data usually shows only the apparent resistivity and PFE. The variation in resistivity is related to the variation in rock units. Low resistivity indicates conductive material and/or highly permeable rock, such as carbonaceous slates or phyllites. High resistivity indicates tightly compacted rocks such as quartzite or sandstones. A high PFE response of 10 or above suggests a very high concentration of sulfides or polarizable material; conversely, a low PFE response indicates low or nonexistent sulfide content. A combination of low resistivity and high PFE can be assumed to represent areas where sulfide mineralization would readily dissolve if exposed in a road cut or fill.

RESULTS OF STUDY

On this project, a section of low resistivities was encountered in the first 2000 ft (610 m), but the PFE response was not continuous, indicating some points of high sulfide content. The PFE response dropped dramatically at some locations, and the resistivity remained low, which led to the conclusion that the rock units in these areas were very permeable but contained very little sulfide mineralization. At several other locations, the apparent resistivity was moderately high, approximately 5000 ohm meters, and the PFE was anomalous. These areas probably contained several narrow massive sulfide veins or disseminated sulfide mineralization zones across most of the 200-ft (60.96-m) intervals. Only a detailed survey of these locations would validate the interpretation. The detailed survey or shorter interval profiling conducted in the demonstration phase proved the importance of conducting detail work at locations where the reconnaissance survey indicated high sulfide content or anomalous response.

High PFE readings were received along the entire line but at varying depths, with some areas exhibiting highly polarizable material at or near the surface. Near the central portion of the line, a high PFE response was recorded at depths greater than 50 ft (15 m). Road cuts in the areas of shallow response would undoubtedly expose the pyritic material, but probably no significant amount of pyrite would be encountered in the central portion.

There was a wide variation in apparent resistiv-

ity for the entire proposed highway center line, ranging from 20 ohm meters to greater than 80 000 ohm meters. The areas of low resistivity and high PFE were symbolized on the data plots by solid bars above and below the line respectively (see Figure 6). Where these bars coincide, sulfide mineralization occurs in conductive and/or extremely permeable rock and most likely would present problems if disturbed by cutting or if the material were used unprotected in embankments. The depth and width of these areas could not be determined with any precision by use of the reconnaissance data alone. Detailed surveys in these areas would be required if they appeared to fall within cut sections where the profile grade would penetrate the pyrite deposit. Several areas were located that exhibited a high sulfide content as symbolized by a solid bar below the line and indicated by moderate to high resistivity readings. The high resistivity indicates a less permeable, more dense rock unit that, if exposed to weathering, may not be subject to serious leaching or release of sulfides into solution. Additional insight is provided elsewhere (9,10) into the physics involved in the induced polarization process and discusses applications through a case study.

OTHER POSSIBLE BENEFITS

The benefits derived from the use of induced polarization and resistivity surveys for locating troublesome deposits of sulfide minerals as applied to route location have been demonstrated. Other benefits that may be of use in highway construction include the potential for locating areas of very sound rock, which is structurally and environmentally acceptable for use in roadway work for rock blankets, riprap, fills, or aggregates. Very dense, compact rock with good structural characteristics are indicated by apparent resistivity measurements above 10 000 ohm meters and a PFE response of less than 2 percent occurring through several continuous dipole intervals. The induced polarization and resistivity technique will give readings to depths of about 600 ft (180 m), which is well within the penetration range of most quarrying operations. Faults and large fractures are detectable by using the induced polarization survey method, as are cavities and voids containing moisture. Faults may be indicated by no return signal or by no readings at the receiver if all the equipment is operating properly. Under certain conditions negative readings can be obtained, indicating that the circuit may be broken between the transmitter and the receiver. This might be indicative of faulting, fracturing, or some strong discontinuity. A force field in the underlying strata strong enough to overcome the applied current and to reverse the flow may be indicative of some geologic phenomenon.

It was realized early in the project that good geologists who are fully knowledgeable of the induced polarization equipment and its capabilities could determine a great deal about the geologic formations occurring below the surface and could determine approximate depths of formations fairly well. This knowledge would be very useful in preliminary design work and should be considered if the induced polarization equipment is used for locating iron pyrite deposits in the early stages of design considerations. Another potential use is for locating natural sand-gravel deposits in areas where they may be present.

SUMMARY AND CONCLUSIONS

Sulfide minerals, even in low concentrations, particularly iron pyrite, can cause some serious prob-

lems when deposits of minute mineral crystals contained in rather porous rock are disturbed in highway construction and subjected to weathering (11). Remedial measures, after the weathering and breakdown of iron sulfide begins, can be expensive and difficult to accomplish. Locating the troublesome deposits and avoiding them or incorporating methods of dealing with them into the design seems to be the most logical, economical, and practical means of avoiding later problems.

The feasibility of locating troublesome iron pyrite deposits using induced polarization and resistivity surveys was well-demonstrated on the proposed forest highway connecting Tellico Plains, Tennessee, and Robbinsville, North Carolina. This was the first time that induced polarization techniques had been applied to highway work, although the technology for such use had been proven and in existence for mining surveys since the early 1950s. Excellent results were obtained in this demonstration, and induced polarization surveys have been conducted for other highway projects since. Other benefits of induced polarization surveys in highway work were also demonstrated to be feasible. However, some research into interpretative techniques and correlations between data generated and geologic formations indicated should be conducted before actual field applications are made.

The data obtained from an induced polarization and resistivity survey must be interpreted. Although one can determine with almost absolute certainty that a potentially troublesome iron pyrite deposit exists, one cannot determine directly that the formation in which the deposit occurs will or will not neutralize the sulfuric acid formed by the dissolving pyrite. Just as qualified geologists must carefully examine core samples and personally visit the site where core samples are taken, so must they review the data obtained from induced polarization and resistivity surveys and conduct their own personal field investigation. Nor can geologists and soils engineers make absolute determinations about subsurface conditions without additional information gained by core drilling, petrographic analysis, and induced polarization. Good usable results are obtained by diligent qualified personnel by using appropriate methods and procedures while recognizing limitations. Used appropriately, an induced polarization and resistivity survey can produce information that will help locate points strategically for core sampling resulting in possible substantial savings of many thousands of dollars and considerable time.

Induced polarization surveys may be conducted most profitably after good preliminary center lines and profile grade lines have been developed but before lines and grades are committed to such a stage that only costly shifts and adjustments can be made. If some preliminary geological studies have been conducted, including some on-site reconnaissance, the survey time required may be kept to a minimum and having to recall the induced polarization survey team may be avoided--an important factor when using private firms located in distant states. In this concept, the induced polarization process shows good promise as a planning, location, and design tool in the highway field. As with any technique, the capability of the process must not be exceeded, and the value of a qualified geologist operator and interpreter must not be minimized. Induced polarization is no genie, although it will find gold.

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