Site characterization techniques

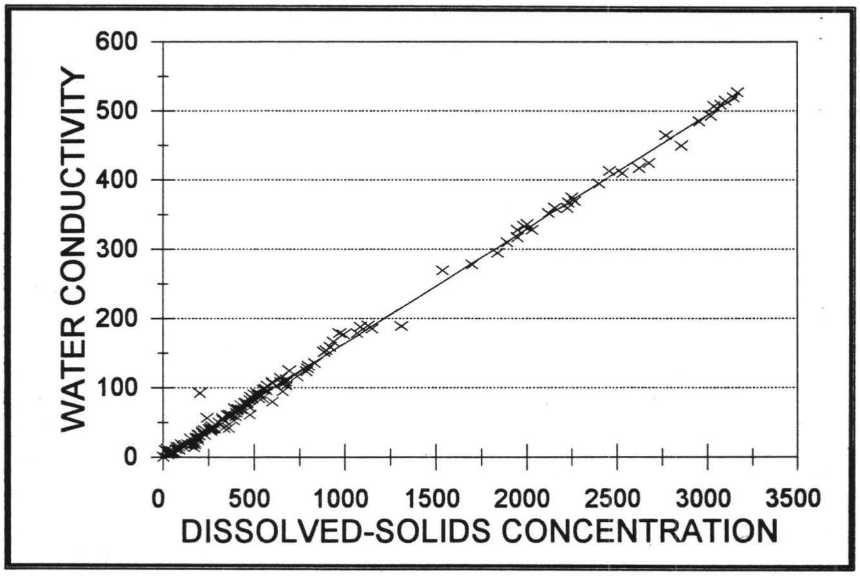
Use of Electrical Conductivity

Geoelectrical methods have been used since the 1920's to search for metallic ore deposits. During the last decade, traditional mining geophysical techniques have been adapted for environmental site characterization. Geoelectrical geophysics is now a well developed engineering specialty, with different methods to focus both on a range of targets and on depths below the surface. Most methods have also been adapted to borehole measurements.

Particular geoelectrical methods respond to at least one of three basic physical properties:

- Electrical conductivity (the ability to conduct electric currents)
- Dielectric permittivity (the ability to hold a charge, as in a capacitor)
- Magnetic permeability (the ability to become magnetized when put in an external magnetic field)

Of these, electrical conductivity is central to most geoelectric methods. Dielectric permittivity is important for **ground-penetrating radar** methods, whereas magnetic permeability is important for targets that contain ferrous metal or that are buried in magnetic soils.



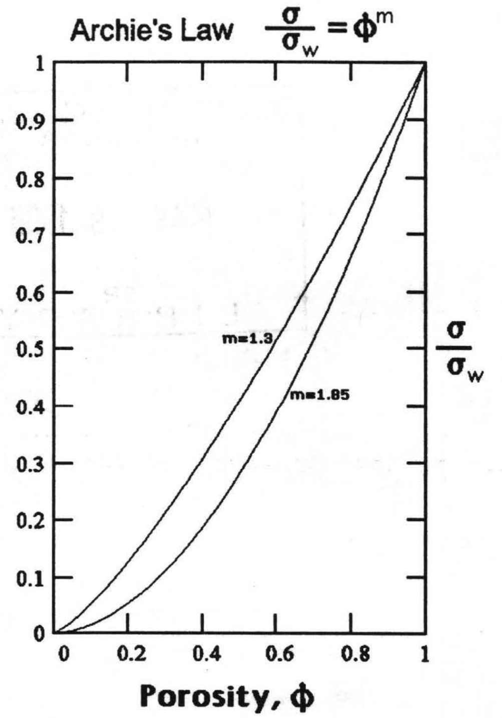
Empirical correlation between dissolved-solids concentration, in milligrams per liter (mg/L), and electrical conductivity, in milliSiemens per meter (mS/m), of ground-water samples. Most water samples with low dissolved-solids (< about 1,000 mg/L) came from the Eastern United States, whereas those with higher concentrations of dissolved solids were from the more arid Southwest. This graph does not distinguish between particular species of dissolved solid.

Electrical Conductivity of Aquifers

The electrical conductivity of a typical water sample reflects the amount of dissolved solids it contains. Distilled water at room temperature and pressure has a conductivity of about 0.01mS/m, whereas that of sea water is about 4,000 mS/m. This means that the potability of a water sample often can be inferred by measuring its electrical conductivity.

Sand or gravel aquifers that are fairly "clean" (not muddy) have a formation conductivity that reflects that of the water in them. Depending on details, the formation conductivity of an aquifer is usually between 5 percent and 25 percent that of the water in it (Archie's Law). Consequently, geoelectrical methods often can detect, within a given aquifer, a plume of brackish water or acidic water contaminated by heavy metal ions or salts.

Archie's Law holds best for aquifers consisting of clean sands and gravels or fissured bedrock; it supposes that the matrix material has a conductivity that is far less than that of the contained ground water. The contribution of the pore water's conductivity will be masked, however, if the matrix material is itself conductive. This commonly happens for geologic units containing **mineralogical clays**. Therefore, conductivity alone cannot distinguish between aquifers and clays (or other conducting units). Usually, though, additional information can be



Clean sand or gravel aquifers have a formation conductivity σ that reflects both their ***porosity***, *ϕ—the proportion of volume containing water-filled voids, and the conductivity of the water in those voids, σ_W. This relationship is expressed by "Archie's Law," an empirical rule graphed here for different values of exponent, m. Parameter m has been measured for marine aquifers to range from about 1.3 for aquifers with a matrix consisting of very rounded particles (typical sand or gravel aquifers) to about 1.85 for those with extremely angular particles (such as shell fragments).*

found to help choose between such alternate interpretations.

Detecting Particular Contaminants

Because many **organic contaminants** do not have high or unusual electrical conductivity, not all plumes of organic contaminants can be traced by their conductivity. Such plumes, however, can sometimes be detected using alternate geoelectrical techniques like **ground-penetrating radar (GPR)** or **induced polarization (IP)**.

The choice of a geoelectric method for detecting particular contaminants depends on several factors:

- Do the physical properties of the contaminant contrast with those of nearby rocks?
- Does the contaminant readily dissolve in ground water?
- Does it float on or sink through the ground water?
- Does it react chemically with rocks or other fluids at the site?

Answers to questions like these have been compiled for several chemical contaminants and incorporated in the DOS computer program "Geophysics Advisor Expert System, Version 2.0," USGS Open-File Report 92-526. The program asks the name of the contaminant and what you know about the geology of the spill site, and then recommends geophysical strategies for detecting the contaminant plume.

Some Ways to Describe Different Geoelectrical Methods

The variety of available geoelectrical methods can be bewildering. Some ways to distinguish between them are:

- **Sounding or profiling methods.** Sounding methods typically make measurements at **fixed sites** to help distinguish geoelectric horizons at different depths under the site; that is, they "see vertically." Profiling methods typically **move** along the surface so as to distinguish edges of geoelectric features that they pass over; they "see horizontally."

- **Controlled or uncontrolled source.** For controlled-source systems, the operator transmits a signal into the ground and then measures the response. For uncontrolled-source systems, the operator measures fields due to sources such as communications broadcasts, lightning strikes, or solar flares. Uncontrolled source systems tend to be cheaper (no transmitter units) but less reliable (because of unsure or weak signals) than controlled-source systems.

- **Galvanic or inductive systems.** Galvanic systems use electrodes inserted in the ground. Inductive systems use antennas (typically consisting of loops of wire) and so may be either ground-based or airborne. Either receiver (Rx) or (for controlled-source systems) transmitter (Tx) may be involved.

- **Deployment geometry.** Both galvanic and inductive systems are further described by specifying the geometry of Tx and Rx deployment. Inductive systems, for example, may use loops that **horizontal** or **vertical**. The (center points of the) loops may be **coincident** or **separated**. Further, the loops may be **coplanar, coaxial,** or **perpendicular**. Similarly, galvanic systems may have all electrodes **in line** or otherwise; the distances between the two electrodes making up each Tx or Rx may be **equal** or **unequal**; and the electrode pairs may be **nested** or **separated**. Each of the various geometries are particularly sensitive to certain target geometries (and insensitive to others), and each have operational advantages and disadvantages. Usually, a particular deployment geometry also affects the depth to which targets can be detected. A geoelectrical system with Rx and Tx separated by 40 m, for example, may not be able to detect targets buried much deeper than about 40 m.

- **Frequency domain or time domain.**

Frequency domain systems measure signals that are pure sinusoids, and both Tx and Rx operate simultaneously. Time domain systems, by contrast, use non-sinusoidal signals, and they have a duty cycle with an "on" time, when the Tx sends out its signal but the Rx is idle, and an "off" time, during which there is no transmission and the Rx works to pick up signals.

Cultural Noise

Modern culture uses many devices that put out electrical and electromagnetic signals that can interfere with geoelectrical work. Power lines, radio and TV transmitters, wire fences, railroad tracks, and buried pipes are examples of such devices—if they are in or near a study area, geoelectrical methods might be unsuccessful. An experienced geophysicist can perform on-site tests to estimate how much of a problem cultural sources are likely to be.

Electromagnetic Systems and Skin Depths

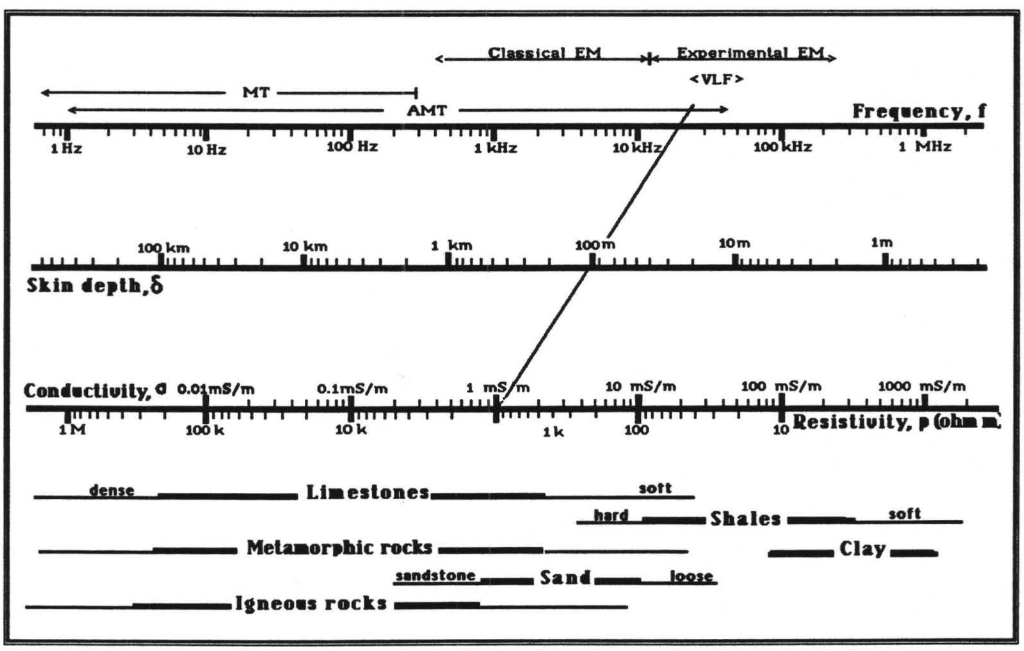
All electromagnetic (EM) systems employ signals composed of coupled magnetic and electrical fields. These fields decay exponentially with depth in the ground. A measure of the decay is the **skin depth**, the depth at which the amplitude of the magnetic or electric field has decreased to 1/e (about 37 percent) of its surface value. Skin depth decreases with frequency and with conductivity of the ground (figure). Most EM systems cannot distinguish targets deeper than about one skin depth.

It is advantageous to use several frequencies in a frequency-domain EM survey; this allows one to distinguish between shallower and deeper targets, as well as to estimate the depth of particular targets. This advantage is inherent in a time-domain system, because a time-domain signal contains multiple imposed frequencies.

Other Geoelectrical Systems

The skin-depth chart is not applicable to geoelectrical methods such as DC, ground-penetrating radar (GPR), induced polarization (IP), and self-potential (SP). The depth reached by DC methods is governed by the geometry of the Rx-Tx electrodes and is typically a fraction (such as 1/3 or 1/2) of the maximum electrode separation. GPR methods have a different skin-depth function, which depends on dielectric permittiv-

Nomogram to calculate planewave EM skin depth from frequency and formation conductivity. To use the nomogram, lay a straightedge between the frequency of the EM device (top bar) and expected formation conductivity (bottom bar), and read off the skin depth on the middle bar. The example shows that VLF equipment—20-kHz frequency—employed in a limestone terrane—1 mS/m conductivity—will have an associated skin depth of about 100 m.



ity in addition to electrical conductivity. GPR methods can give high-resolution details on subsurface structure, but they have shallow exploration depths—typically less than about 30 m. They work optimally in very low conductivity settings (sand or crystalline rock) and have trouble sensing beneath clays. SP measures natural electrical potentials in the ground created by movement of conducting fluids or by electrochemical reactions, such as oxidation and reduction. IP measures the effects of electrical charges built up by chemical or physical reactions on the surface of dispersed, high-conductivity particles.

Results of a geoelectrical survey can be displayed in a number of ways, depending on its intended use. Airborne or ground EM data collected on a grid of lines can be processed to show a contour map of electrical conductivity. If a number of frequencies were used, several such conductivity contour maps may result, each pertaining to a particular depth in the subsurface. Ground-penetrating radar and induced polarization surveys are usually taken along discrete survey lines, so their results are plotted as section views beneath the lines. Vertical electric soundings and time-domain EM soundings usually detect a number of layers immediately under each sounding site—by stringing together results from several such sites, a section view can similarly be constructed. If survey lines are closely spaced, it may be possible to construct a volume model of conductivity.

To find out more:

- **about Archie's Law—**

Jackson, P.D., Smith, T.D., and Stanford, P.N., 1978, Resistivity-porosity-particle shape relationships for marine sands: Geophysics, v. 43, p. 1250-1268.

- **about ground-water conductivity—**

Hem, John D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

- **about geophysical methods—**

Ward, Stanley H., 1990, Geotechnical and Environmental Geophysics, volume I—Review and Tutorial: P.O. Box 702740, Tulsa, OK 74170-2740, Society of Exploration Geophysicists, 387 p.

To order Geophysics Advisor Expert System:

Send $6.00 for Open-File Report 92-526A (DOS disk) or $3.25 for Open-File Report 92-526B (documentation on paper) to: USGS Earth Sciences Information Center Open-File Services Section, Federal Center Box 25286, MS 517 Denver, CO 80225-0046 (303) 236-7476

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Geoelectrical Methods—Some General Terminology

(Trade names are not included here)

AMT	Audiofrequency Magnetotellurics
DC	Direct Current (profiles or soundings)
VES	Vertical Electric Sounding (particular DC method)
EM	Electromagnetics (especially, two-loop methods)
VLF	Very Low Frequency EM (uses ~20-KHz signals)
IP	Induced Polarization, either time- or frequency-domain (also called complex resistivity)
SP	Self-Potential
GPR	Ground-Penetrating Radar
MT	Magnetotelluric (uses lower frequencies than AMT)
TEM	Time-domain EM (also as abbreviated TDEM)

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