Designation: D6639 – 18

Standard Guide for
Using the Frequency Domain Electromagnetic Method for Subsurface Site Characterizations[1]

This standard is issued under the fixed designation D6639; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 *Purpose and Application:*

1.1.1 This guide summarizes the equipment, field procedures, and interpretation methods for the assessment of subsurface conditions using the frequency domain electromagnetic (FDEM) method.

1.1.2 FDEM measurements as described in this standard guide are applicable to mapping subsurface conditions for geologic, geotechnical, hydrologic, environmental, agricultural, archaeological and forensic site characterizations as well as mineral exploration.

1.1.3 The FDEM method is sometimes used to map such diverse geologic conditions as depth to bedrock, fractures and fault zones, voids and sinkholes, soil and rock properties, and saline intrusion as well as man-induced environmental conditions including buried drums, underground storage tanks (USTs), landfill boundaries and conductive groundwater contamination.

1.1.4 The FDEM method utilizes the secondary magnetic field induced in the earth by a time-varying primary magnetic field to explore the subsurface. It measures the amplitude and phase of the induced field at various frequencies. FDEM instruments typically measure two components of the secondary magnetic field: a component in-phase with the primary field and a component 90° out-of-phase (quadrature component) with the primary field (Kearey and Brook 1991). Generally, the in-phase response is more sensitive to metallic items (either above or below the ground surface) while the quadrature response is more sensitive to geologic variations in the subsurface. However, both components are, to some degree, affected by both metallic and geologic features. FDEM measurements therefore are dependent on the electrical properties of the subsurface soil and rock or buried man-made objects as well as the orientation of any subsurface geological features or man-made objects. In many cases, the FDEM measurements can be used to identify the subsurface structure or object. This method is used only when it is expected that the subsurface soil or rock, man-made materials or geologic structure can be characterized by differences in electrical conductivity.

1.1.5 The FDEM method may be used instead of the Direct Current Resistivity method (Guide D6431) when surface soils are excessively insulating (for example, dry or frozen) or a layer of asphalt or plastic or other logistical constraints prevent electrode to soil contact.

1.2 *Limitations:*

1.2.1 This standard guide provides an overview of the FDEM method using coplanar coils at or near ground level and has been referred to by other names including Slingram, HLEM (horizontal loop electromagnetic) and Ground Conductivity methods. This guide does not address the details of the electromagnetic theory, field procedures or interpretation of the data. References are included that cover these aspects in greater detail and are considered an essential part of this guide (Grant and West, 1965; Wait, 1982; Kearey and Brook, 1991; Milsom, 1996; Ward, 1990). It is recommended that the user of the FDEM method review the relevant material pertaining to their particular application. ASTM standards that should also be consulted include Guide D420, Terminology D653, Guide D5730, Guide D5753, Practice D6235, Guide D6429, and Guide D6431.

1.2.2 This guide is limited to frequency domain instruments using a coplanar orientation of the transmitting and receiving coils in either the horizontal dipole (HD) mode with coils vertical, or the vertical dipole (VD) mode with coils horizontal (Fig. 2). It does not include coaxial or asymmetrical coil orientations, which are sometimes used for special applications (Grant and West 1965).

1.2.3 This guide is limited to the use of frequency domain instruments in which the ratio of the induced secondary magnetic field to the primary magnetic field is directly proportional to the ground's bulk or apparent conductivity (see 5.1.4). Instruments that give a direct measurement of the apparent ground conductivity are commonly referred to as Ground Conductivity Meters (GCMs) that are designed to operate within the "low induction number approximation." Multi-frequency instruments operating within and outside the low induction number approximation provide the ratio of the

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***A Summary of Changes section appears at the end of this standard**

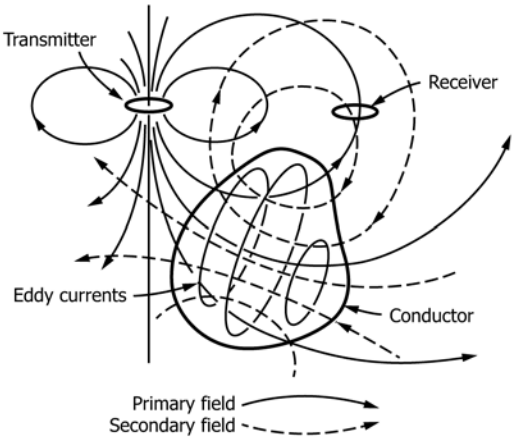
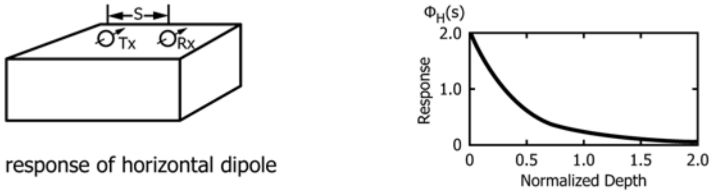


FIG. 1 Principles of Electromagnetic Induction in Ground Conductivity Measurements (Sheriff, 1989)



Relative response of horizontal dipole

Relative response of vertical dipole

FIG. 2 Relative Response of Horizontal and Vertical Dipole Coil Orientations (McNeill, 1980)

secondary to primary magnetic field, which can be used to calculate the ground conductivity.

1.2.4 The FDEM (inductive) method has been adapted for a number of special uses within a borehole, on water, or airborne. Discussions of these adaptations or methods are not included in this guide.

1.2.5 The approaches suggested in this guide for the frequency domain method are the most commonly used, widely accepted and proven; however other lesser-known or specialized techniques may be substituted if technically sound and documented.

1.2.6 Technical limitations and cultural interferences that restrict or limit the use of the frequency domain method are discussed in section 5.4.

1.2.7 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education, experience, and professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged without consideration of a project's many unique aspects. The word standard in the title of this document means that the document has been approved through the ASTM consensus process.*

1.3 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.4 *Precautions:*

1.4.1 If the method is used at sites with hazardous materials, operations, or equipment, it is the responsibility of the user of this guide to establish appropriate safety and health practices and to determine the applicability of regulations prior to use.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the*

Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D420 Guide to Site Characterization for Engineering Design and Construction Purposes

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5730 Guide for Site Characterization for Environmental Purposes With Emphasis on Soil, Rock, the Vadose Zone and Groundwater (Withdrawn 2013)[3]

D5753 Guide for Planning and Conducting Geotechnical Borehole Geophysical Logging

D6235 Practice for Expedited Site Characterization of Vadose Zone and Groundwater Contamination at Hazardous Waste Contaminated Sites

D6429 Guide for Selecting Surface Geophysical Methods

D6431 Guide for Using the Direct Current Resistivity Method for Subsurface Characterization

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms used in this standard, refer to Terminology D653.

3.1.2 The majority of the technical terms used in this document are defined in Sheriff (1991). An additional definition follows:

3.2 *apparent conductivity, σ_a*—The conductivity that would be measured by a GCM when located over a homogeneous isotropic half space that has the same ratio of secondary to primary magnetic fields (Hs/Hp) as measured by other frequency domain instruments over an unknown subsurface. Apparent conductivity is measured in millisiemens per meter (mS/m).

4. Summary of Guide

4.1 *Summary of the Guide*—An alternating current is generated in a transmitter coil producing an alternating primary electromagnetic field, which induces an alternating current in any nearby conductive material. The alternating currents induced in the earth material produce a secondary electromagnetic field, which is sensed by a nearby receiver coil (Fig. 1). Common FDEM instruments operate under the "low induction number approximation", which is a function of the separation between the transmitter and receiver, the electrical permeability and conductivity of the ground, and the frequency of the transmitter signal. Essentially, this means that, in the absence of any metallic objects in the subsurface, the ratio of the magnitude of this secondary magnetic field to the primary magnetic field is directly converted to an apparent conductivity measurement of the earth material in a GCM. The ratio of secondary to primary magnetic fields (Hs/Hp) in other frequency domain instruments can be interpreted in terms of the ground conductivity. When operating under the low induction number approximation, most of the response will be in the quadrature component. When this assumption does not hold, such as in the presence of metal, there will be a significant in-phase component to the response, and the direct correlation of the signal response to apparent conductivity breaks down.

4.1.1 The depth of the site characterization is related to the frequency of the alternating current, the distance between transmitter and receiver coils (intercoil spacing) and coil orientation. For the GCM, the depth of the site characterization is related to the distance between electrodes and the coil orientation.

4.1.2 The apparent conductivity measured by a GCM or calculated from the ratio of the secondary to primary magnetic fields is the conductivity of a homogeneous isotropic half space, as long as the low induction number condition applies and the subsurface is nonmagnetic. If the earth is horizontally layered, the apparent conductivity measured or calculated is the sum of the conductivities of each layer, weighted by its thickness and depth, and is a function of the coil (dipole) orientation (Fig. 2). If the earth is not layered, that is, a homogeneous isotropic half space, both the horizontal and vertical dipole measurements are equal. In either case, if the true conductivities of the layered earth or the homogeneous half space are known, the apparent conductivity that would be measured with a GCM can be calculated with a forward modeling program.

4.1.3 Any variation either in the electrical homogeneity of the half space, or the layers, or a physical deviation from a horizontally layered earth, results in a change in the apparent conductivity measurement from the true conductivity. This characteristic makes it possible to locate and identify many significant geological features, such as buried channels, some fractures or faults (Fig. 3) or buried man-made objects. The signatures of FDEM measurements over troughs and dikes and similar features are well covered in theory (Villegas-Garcia and West, 1983) and in practice.

4.1.4 While many ground conductivity surveys are carried out to determine simple lateral or areal changes in geologic conditions such as the variation in soil salinity or location of a subsurface conductive contaminant plume, measurements made with a GCM with several intercoil spacings or different coil orientations can be used to identify up to two or three horizontal layers, provided there is a sufficient conductivity contrast between the layers (Fig. 4), the layer thicknesses are appreciable, and the depth of the layers falls within the depth range of the instrument used for the measurement.

4.1.5 Similarly, by taking both the horizontal and vertical dipole measurements at several heights above the surface resolved with a rigid fixed transmitter-receiver configuration, two or three layers within the instrument depth of exploration can also sometimes be resolved.

4.2 *Complementary Data*—Other complementary surface (Guide D6429) and borehole (Guide D5753) geophysical data, along with non-geophysical data related to the site, may be

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

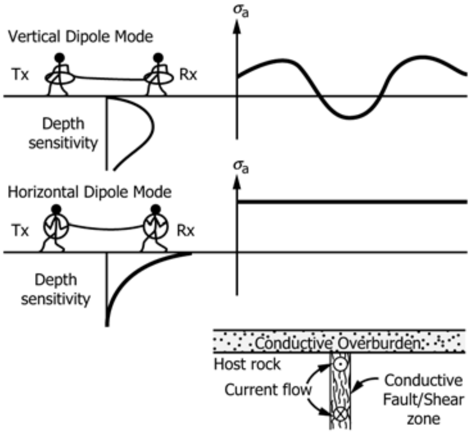

FIG. 3 Typical Vertical and Horizontal Dipole Profiles Over a Fracture Zone (McNeill, 1990)

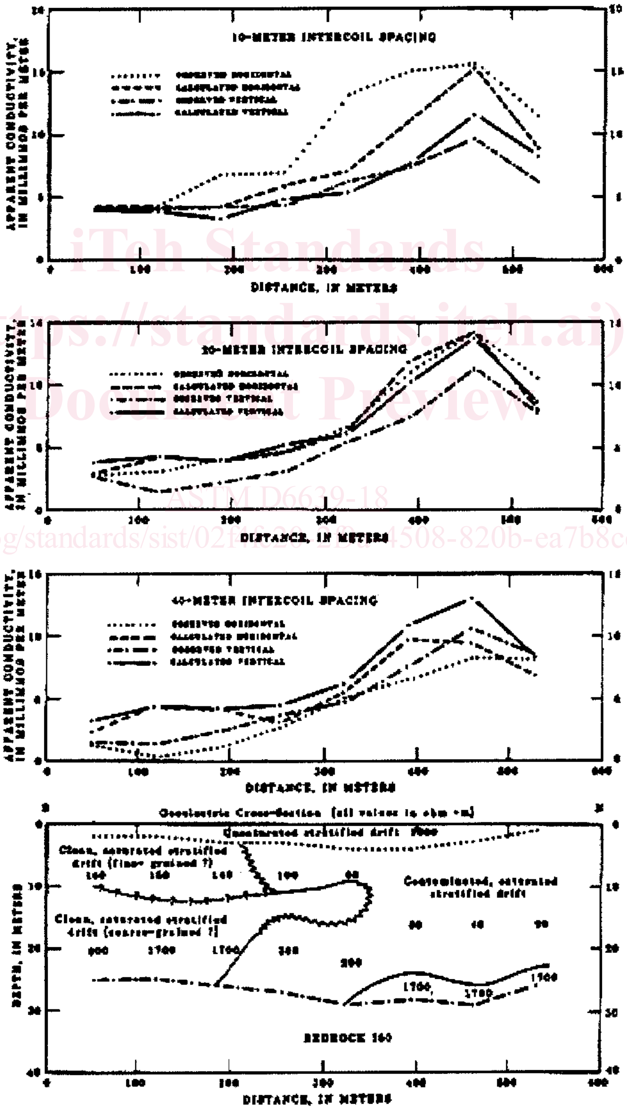

FIG. 4 Cross Section of Frequency Domain Soundings (Grady and Haeni, 1984)

necessary, and are always useful, to properly interpret the subsurface conditions from frequency domain data.

4.2.1 *Frequency Domain as Complementary Method*—In some cases, the frequency domain method is not able to provide results in sufficient detail or resolution to meet the objectives of the site characterization, although for a given depth of investigation, the EM methods usually require less space than linear arrays of the DC method. It is, however, a fast, reliable method to locate the objective of the site characterization, which can then be followed up by a more detailed resistivity or time domain electromagnetic survey (Hoekstra et al, 1992).

5. Significance and Use

5.1 *Concepts:*

5.1.1 This guide summarizes the equipment, field procedures and interpretation methods used for the characterization of subsurface materials and geological structure as based on their properties to conduct, enhance or obstruct the flow of electrical currents as induced in the ground by an alternating electromagnetic field.

5.1.2 The frequency domain method requires a transmitter or energy source, a transmitter coil, receiver electronics, a receiver coil, and interconnect cables (Fig. 5).

5.1.3 The transmitter coil, when placed on or near the earth's surface and energized with an alternating current, induces small currents in the near earth material proportional to the conductivity of the material. These induced alternating currents generate a secondary magnetic field (H_s), which is sensed with the primary field (H_p) by the receiver coil.

5.1.4 Under a constraint known as the "low induction number approximation" (McNeill, 1980) and when the subsurface is nonmagnetic, the secondary magnetic field is fully out-of-phase with the primary field and is given by a function of these variables.

$$\sigma_a = (4/\omega\mu_o s^2)\,(H_s/H_p) \qquad (1)$$

where:

σ_a = apparent conductivity in siemens/meter, S/m,
ω = $2\pi f$ in radians/sec; f = frequency in Hz,
μ_o = permeability of free space in henrys/meter $4\pi \times 10^{-7}$, /m,
s = intercoil spacing in meters, m, and
H_s = the out-of-phase component of the secondary magnetic field, both measured by the receiver coil.
H_p = the out-of-phase component of the primary magnetic field measured by the receiver coil.

Perhaps the most important constraint is that the depth of penetration (skin depth, see section 6.5.3.1) of the electromagnetic wave generated by the transmitter be much greater than the intercoil spacing of the instrument. The depth of penetration is inversely proportional to the ground conductivity and instrument frequency. For example, an instrument with an intercoil spacing of 10 m and a frequency of 6400 Hz, using the vertical dipole, meets the low induction number assumption for earth conductivities less than 200 mS/m.

5.1.5 Multi-frequency domain instruments usually measure the two components of the secondary magnetic field: a component in-phase with the primary field and a component 90° out-of-phase (quadrature component) with the primary field (Kearey and Brook 1991). Generally, instruments do not display either the in-phase or out-of-phase (quadrature) components but do show either the apparent conductivity or the ratio of the secondary to primary magnetic fields.

5.1.6 When ground conditions are such that the low induction number approximation is valid, the in-phase component is much less than the quadrature phase component. If there is a relatively large in-phase component, the low induction number approximation is not valid and there is likely a very conductive buried body or layer, that is, ore body or man-made metal object.

5.1.7 The transmitter and receiver coils are almost always aligned in a plane either parallel to the earth's surface (axis of the coils vertical) and generally called the vertical dipole (VD) mode or aligned in a plane perpendicular to the earth surface (axis of the coils horizontal) generally called the horizontal dipole (HD) mode (Fig. 3).

5.1.8 The vertical and horizontal dipole orientations measure distinctly different responses to the subsurface material (Fig. 2). When these vertical and horizontal dipole mode measurements are made with several intercoil spacings or appropriate frequencies, they can be combined to resolve multiple earth layers of varying conductivities and thicknesses. This FDEM method is generally limited to only 2 or 3 layers with good resolution of depth and conductivity and only if there is a strong conductivity contrast between layers that are relatively thick and relatively shallow (in terms of the intercoil spacing).

5.1.9 The conductivity value obtained in 5.1.4 is referred to as the apparent conductivity σ_a. For a homogeneous and

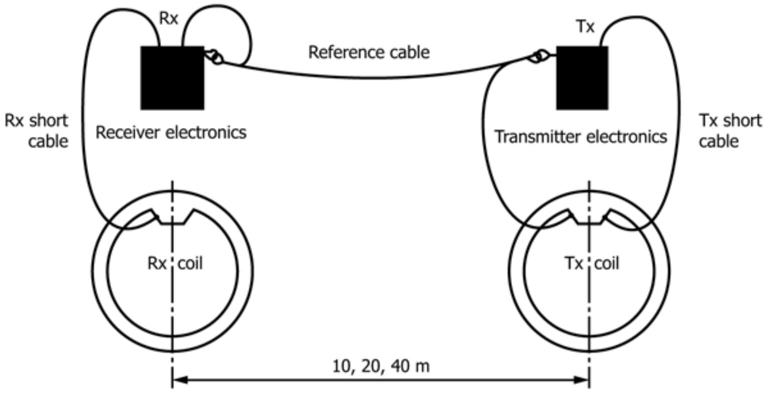

FIG. 5 Schematic of Frequency Domain Electromagnetic Instrument

isotropic earth or half space (in which no layering is present), the apparent conductivity will be the same for both the measurements. Since the horizontal dipole (HD) is more sensitive to the near surface material than the vertical dipole (VD), these two measurements can be used together to tell whether the conductivity is increasing or decreasing with depth.

5.1.10 For instruments referred to as Ground Conductivity Meters (GCMs), the system parameters and constants in 5.1.4 are included in the measurement process, giving a calculated reading of σ_a, usually in mS/m. In some instruments, the ratio of the in-phase components of the secondary to primary magnetic fields (H_s/H_{pp}) is displayed in ppt (parts per thousand).

5.1.11 For other frequency domain instruments, the measurements for both the in-phase and quadrature phase of the secondary magnetic field are given as ratios.

5.1.12 For a homogeneous horizontally layered earth, the measured apparent conductivity calculated by the instrument is the sum of each layer's conductivity weighted by the appropriate HD or VD response function (Fig. 2).

5.1.13 When the subsurface is not homogeneous or horizontally layered (such as when there is a geologic anomaly or man-made object present), the apparent conductivity may not be representative of the bulk conductivity of the subsurface material. Some anomalous features can, because of their orientation relative to the instrument coils, produce a negative apparent conductivity. While this negative value is not valid as a conductivity measurement, it is an indication of the presence of a geologic anomaly or buried object.

5.1.14 Many common geologic features such as fracture zones, buried channels, dikes and faults, and man-made buried objects, can be detected and identified by relatively well-known anomalous survey signatures (Fig. 3).

5.2 *Parameters Measured and Representative Values:*

5.2.1 The FDEM method provides a measure of the apparent electrical conductivity of the subsurface materials. For ground conductivity meters (GCMs), this apparent conductivity is read or recorded directly. For instruments not using the "low induction number approximation" the measurement is given by the ratio of the secondary magnetic field to the primary magnetic field (H_s/H_p).

5.2.2 Some GCMs also give an in-phase measurement corresponding to the in-phase component of the secondary magnetic field in parts per thousand (ppt) of the primary field. The in-phase component is especially useful for mineral exploration, detecting buried man-made metallic objects, or for measuring the soil or rock magnetic susceptibility and verifying the assumption that the subsurface is nonmagnetic (McNeill, 1983).

5.2.3 Fig. 6 shows the electrical conductivities for typical earth materials varying over five decades from 0.01 mS/m to a few thousand mS/m. Even a specific earth material (Fig. 6) can have a large variation in conductivity, which is related to its temperature, particle size, porosity, pore fluid saturation, and pore fluid conductivity. Some of these variations, such as a conductive contaminant pore fluid, may be detected by the FDEM method.

5.3 *Equipment:*

5.3.1 The FDEM equipment consists of a transmitter electronics and transmitter coil, a receiver electronics and receiver coil, and interconnect cables. Generally these vary only from one instrument to another in transmitter power, coil size, intercoil separation and transmitter frequency.

5.3.2 Some instruments are designed with a rigid, fixed intercoil separation usually less than about 4 meters and are used for relatively shallow measurements of less than 6 meters.

5.3.3 For deeper measurements of up to 100 meters, depending on the instrument, the instrument consists of separate coils interconnected by cable, (Fig. 5) and generally operates at several intercoil spacings. Instruments using the "low induction number approximation" usually have a single frequency for each intercoil spacing and are generally referred to as Ground Conductivity Meters (GCMs). Measurements of apparent conductivity, σ_a, are calculated and displayed in millisiemens per meter (mS/m).

5.3.4 FDEM instruments taking multiple frequency measurements at a fixed intercoil separation usually give their

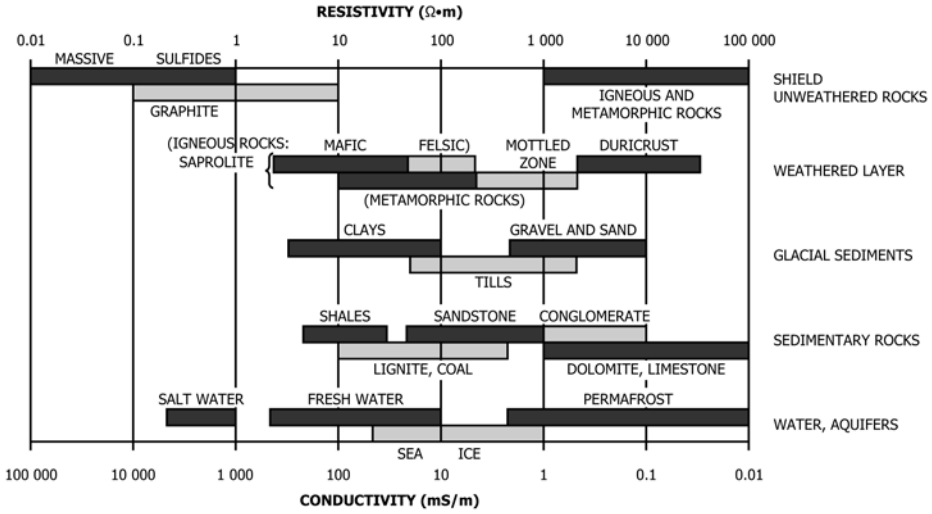

FIG. 6 Earth Material Conductivity Ranges (Sheriff, 1991)