The Geo-Physical Continuum:
An Introduction to Mineral Exploration Geophysics for Geologists

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Geologists describe rocks using lithology, alteration, color, texture, and structure, among other things. Geological observations are limited to the earth's surface and drill holes. Interpretations of geology far from these observation areas are necessarily speculative. Geophysical techniques can observe areas within the earth far from the surface and between drill holes, but do not detect these same geological characteristics. They can "see" only bulk physical properties, such as density, electrical resistivity, seismic velocity, and others. Geophysical techniques are also limited by "poor vision", including limited detection distance, sensitivity, resolution, and masking of deeper physical properties. Geophysical surveys are not a substitute for a good geologic map or model, but can be useful to extend and confirm geologic interpretations.

Density:

Density is the most easily understood physical property. It is controlled primarily by mineralogy, pore space, and pore fluid. Dense minerals, less pore space, and existence of a pore fluid all contribute to higher earth density. Figure 1 shows some relationships of density to geology. Density is detectable using gravity surveys, in which minute variations in Earth's force of gravity are measured at the earth's surface, in drill holes, or from aircraft, and interpreted to estimate density in 2 or 3 dimensions over a limited region. Gravity survey measurements are expressed in milligals (mg), and usually initially presented as contour maps. Gravity surveys are typically used to estimate sedimentary basin thickness, or detect the presence of large masses of differing density. Local gravity surveys can detect the presence of volcanogenic massive sulfide (VMS) deposits due to the higher density of sulfide minerals relative to host rocks. Density is measured in units of g/cm^3 or equivalent. Specific gravity is the ratio of the density of a sample to the density of water and has no units. Specific gravity of rock samples can be measured by geochemical laboratories.

Electrical Resistivity:

Electrical resistivity is the resistance of earth materials to the flow of electricity, principally alternating current. Resistivity is controlled by mineralogy, mineral spatial relationships, porosity, and pore fluid types. Metallic-luster minerals, clay minerals, increased pore space, and conductive (salty) pore fluids decrease resistivity. Figure 2 shows some relationships of resistivity to geology. Resistivity surveys can detect massive sulfide deposits and graphite concentrations, and can also be used to map a wide range of resistivity in three dimensions over entire project areas. Resistivity is detectable using several different geophysical survey techniques. Magneto-Tellurics (MT) measures resistivity with depth over a point on the earth by measuring time-variations in both the magnetic and electrical fields at very low frequencies (<1Hz). Audio Magneto-Tellurics (AMT) extends the frequency range into the audio spectrum (10-15,000 Hz), The energy source for these techniques are natural electrical currents, including distant lightning. Controlled-Source Audio Magneto-Tellurics (CSAMT) improves on AMT by adding a local source of magnetic and electrical energy. Resistivity is also measured in an Induced polarization (IP) survey (see next paragraph). Resistivity units are ohm-meters (Ω-m).

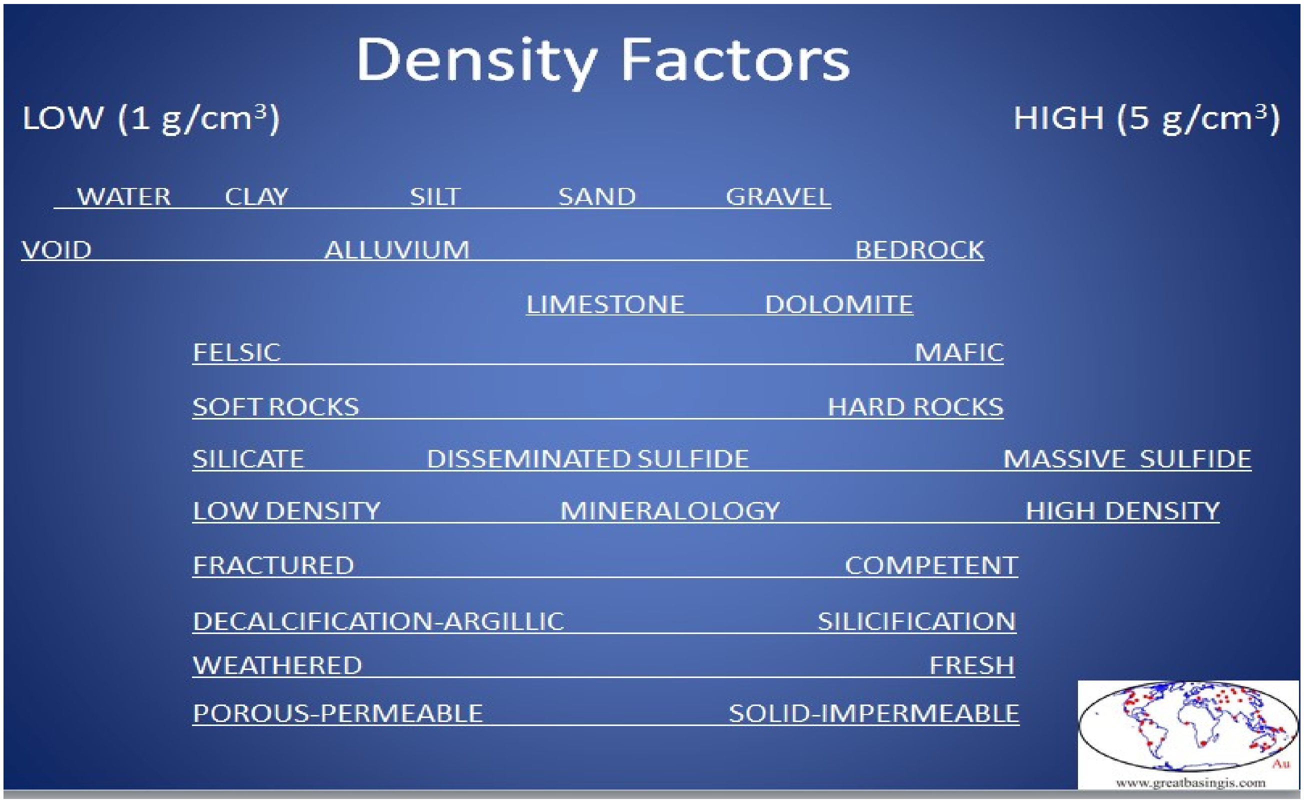

Figure 1: Relationships of density to geologic factors. This is a series of 1-D graphs, not a 2-D graph. The central part of the graph is where much of the density is controlled by pore space and moderate density variations in silicate rocks. On the right edge, unusually high densities are related to concentrations of high-density minerals, typically sulfides, and on the left edge very low densities are related to lack of rock material.

Chargeability (IP Effect):

Chargeability is the ability of the earth to briefly store an electrical charge. This physical property is caused by the interaction of disseminated metallic-luster minerals with pore or capillary water. The magnitude of this effect is more-or-less proportional to surface area, thus finer grain size tends to maximize the effect for a given metallic-luster mineral percentage. Chargeability is detectable using “Induced Polarization” (IP) surveys that inject electrical current into the earth. IP surveys are most commonly used in the exploration for porphyry copper deposits, but can also used in other settings where finer-grained sulfides are important. IP effect, phase lag, and frequency effect are near synonyms for chargeability, resulting from several different geophysical techniques in use. IP results are usually expressed as percentages. For example percent frequency effect (PFE), Metal factor (MF), IP surveys also measure resistivity.

Magnetic Susceptibility and Magnetic Remanence:

Earth possesses a “dipole” magnetic field, with north and south poles near the geographic poles. The strength of Earth’s magnetic field at any given point is measured in nano-Teslas (nT). The strength of the earth’s field is approximately 50,000 nT at high latitudes and 30,000 nT near the magnetic equator. Earth’s magnetic vector lines of force are steeply dipping near the poles and vary to nearly horizontal near the magnetic equator. Earth’s magnetic field is typically slightly modified locally by two separate physical properties of nearby rocks: magnetic susceptibility and magnetic remanence.

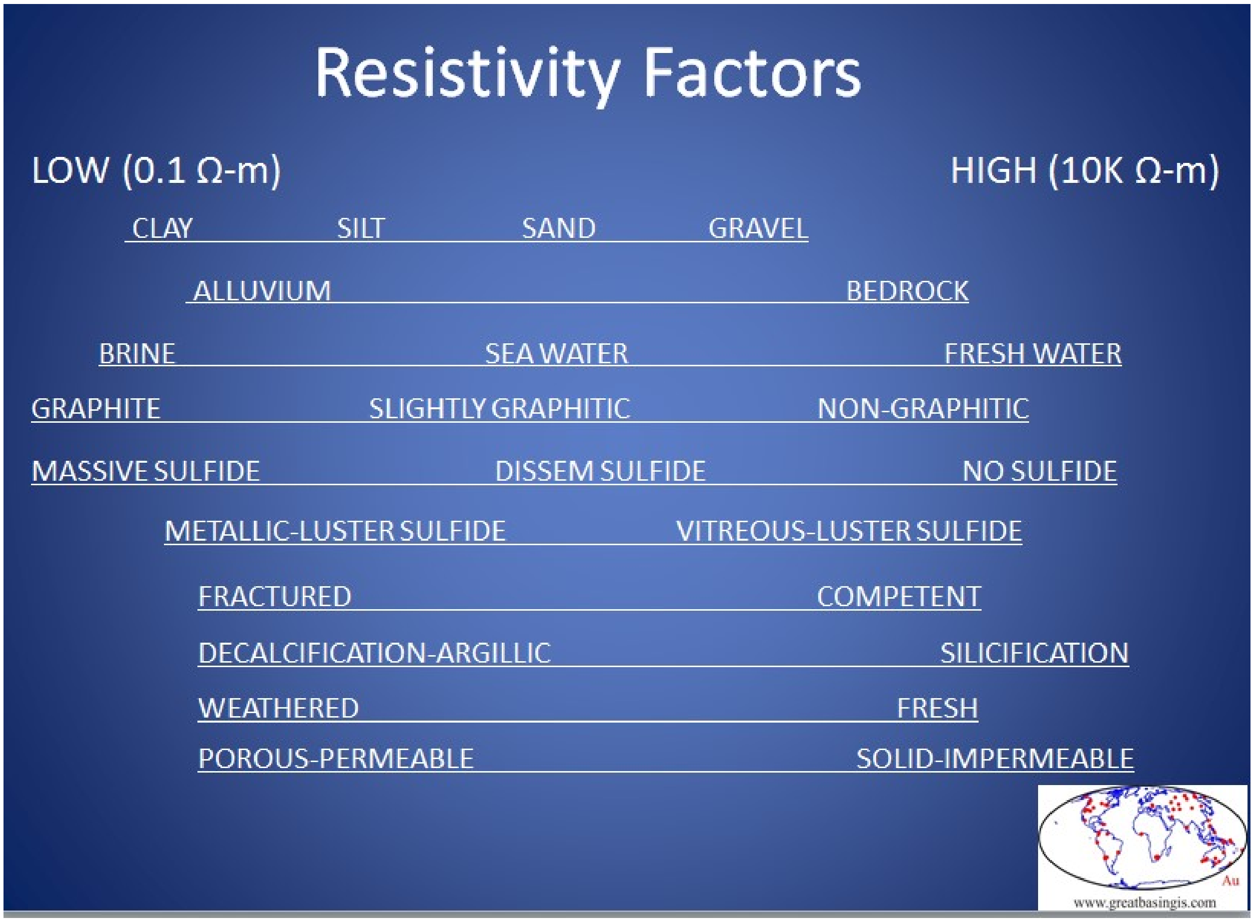

Figure 2: Relationships of resistivity to geologic factors. This is a series of 1-D graphs, not a 2-D graph. The central part of the graph is where much of the resistivity is controlled by pore space in silicate rocks. On the right edge, unusually high resistivities are related to pure pore water or massive silicate rocks with few grain boundaries and little pore space. On the left edge low resistivities are typically related to concentrated, grain-connected bodies of metallic-luster minerals, wet phyllosilicates, or very salty pore water.

Magnetic susceptibility is a property whereby a non-magnetic material can locally modify a vector magnetic field (normally Earth's field) in which it is immersed. The susceptible material becomes temporarily magnetized. This has the effect of causing local variations in Earth's dipole magnetic field. Magnetite is the primary mineral that shows this effect. Pyrrhotite also possesses a weaker version of this physical property. Susceptibility units are usually referred to as “cgs units”. Rock sample susceptibility can be measured in the field using hand-held instruments.

Magnetic remanence is a physical property whereby minerals are naturally magnetic and possess a local magnetic field, with north and south poles, the same as a household bar magnet, but usually much weaker. This local magnetic field combines with (adds to or subtracts from) Earth's dipole vector field creating local variations. These local effects can add to or subtract from the anomalies created by magnetic susceptibility. Both magnetite and pyrrhotite can possess magnetic remanence, but it can be strong, weak, or undetectable.

The combined effect of both magnetic susceptibility and remanence modifications on Earth's dipole magnetic field can be measured using hand-held or airborne magnetometers. Magnetic surveys are extremely useful in the search for magnetic iron ore, and also for general geological mapping in rocks that have contrasting concentrations of magnetite. Magnetic survey maps can be simple to interpret in areas where magnetic rocks are overlain by thin or no non-magnetic cover, such as Precambrian shield areas. Interpretation can be difficult in areas such as the Great Basin, where the bedrock of interest is usually non-magnetic, and can be covered by magnetic volcanic rocks or very thick non-magnetic alluvial basins. Magnetic survey units are expressed as nano-Teslas (nT). In older data they may be expressed as gammas (γ), which have the same value.

Magnetics and gravity are "potential field" methods. Because of this, survey results can be recalculated to represent different survey parameters. For instance, a magnetic survey flown at one elevation can be recalculated to match one flown at a higher elevation. There are many other useful calculations possible on potential fields. Very commonly, a function or large number is subtracted from the survey results to reduce the values from the 50,000 range to smaller, more easily comprehended numbers.

Seismic:

Seismic velocity is the speed of sound within the earth. While the speed can be measured directly, discontinuities and boundaries between layers of differing seismic velocity are more commonly detectable. The seismic technique sequentially injects sound energy into the earth in an array of locations, and detects the response at the earth's surface at many other points in their vicinity. Seismic surveys are highly developed in the petroleum industry, but are less common in mineral exploration, due to high cost and other factors. Unlike most other geophysical techniques, seismic surveys can have good resolution at large depths. Survey results give a "time" section, where the vertical axis is time. To convert to depth, some geologic input is required, either down-hole velocity measurements or velocity estimates.

Radiometrics:

The earth's surface emits natural gamma rays due to the presence of uranium, thorium and potassium. Each element (daughter products for U and Th) emit gamma rays of different energies. These can be detected and differentiated by gamma-ray spectrometers, some of which are small hand-held instruments, or larger more sensitive systems for airborne surveys. The most common use is as down-hole gamma-ray probes used in uranium exploration and development. Natural gamma rays penetrate only a very short distance (several feet) in soil, less in rock, severely limiting their 3-D utility. Radiometric maps can be considered similar to remote sensing surveys; inversions are not possible. Survey units are usually expressed as counts per second (cps), or after data reduction as percentage or ppm U, Th, and K. When these elements are determined using gamma rays, they are usually expressed as eU, eTh, or eK to distinguish from those determined by chemical methods. Very small hand-held scintillometers can be used for prospecting. These detect a wider energy range of gamma rays, and thus are more sensitive than larger spectrometers, but do not differentiate U, Th, or K.

Inversion:

In a manner analogus to geology/orebody modelling, geophysical survey results can be used to calculate a 2-D or 3-D earth model of a physical property. These can be represented by cross-sections, depth maps, level maps, or 3D models. In geophysics, this procedure is called the "inverse calculation" or "inverse problem". The resultant earth model is known as an "inversion". For many geophysical techniques, the results are non-unique. Many different earth models can be calculated from the same survey results. The opposite procedure, calculating synthetic survey results from a given earth model is known as the "forward calculation". The forward calculation is unique; a single earth model will always result in the same synthetic survey results. Addition of geologic constraints, such as in-situ measured physical properties, or

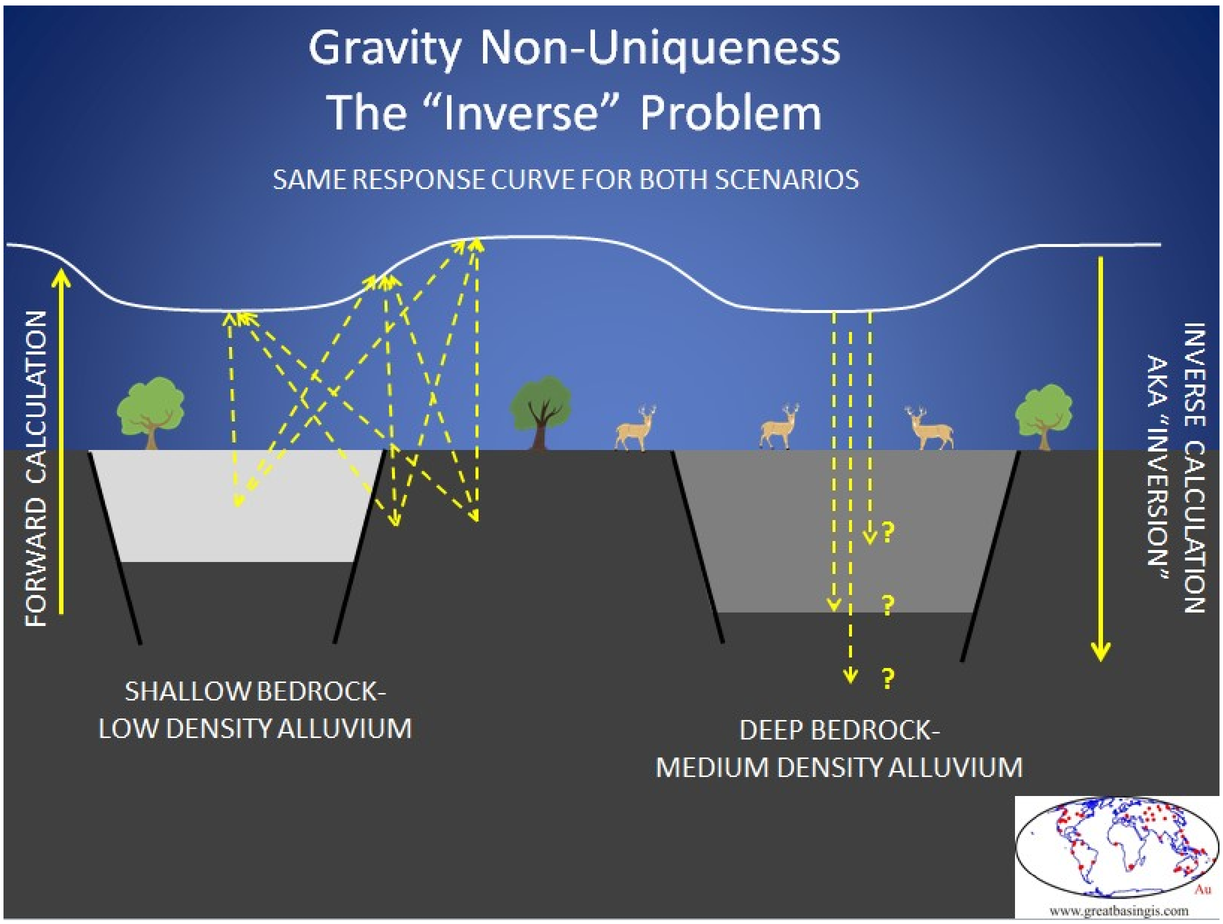

Figure 3: The "inverse problem". Survey results are the same on the left and right, but the geology is different. There is a trade-off between bedrock depth and physical property. A larger physical property contrast will require a shallower bedrock depth. On the right side, calculations from the survey results can result in many different bedrock depths, depending on the physical property contrast between alluvium and bedrock. On the left, the dotted arrows show the forward calculation, how the physical property at 3 points result in synthetic survey results at those 3 points. These calculations always result in the same synthetic survey value.

some known positions of geologic boundaries can be used to mitigate the inverse problem. Figure 3 shows an example of the "inversion problem", in which two 2-D earth models result from the same survey results.

Summary:

Geophysical techniques measure only physical properties, have optical limitations, and are subject to non-uniqueness in earth model (inversion) calculation. Geophysical surveys are not a substitute for geologic mapping, but can be used to enhance and extend geologic understanding. Therefore it is important to understand the geology of your project area as much as possible before interpreting any geophysical survey. Have a good geologic map of your area, integrated with any available drilling. Get representative physical property measurements using field instruments or estimates for your various geologic map units, lithologies and altered areas. From this data, you should be able to at least partially understand your exploration area in terms of physical properties. Look at case histories to help determine the applicability of the various geophysical survey types in your area. Use a reputable geophysical contractor and geophysicist to perform and help interpret your survey, and provide them with your estimates of the geology and physical properties that are present.

Lastly, beware of ineffective (scam) proposals. Some “red flags” include no publications or degrees, unusually useful performance (detects orebody outline and/or detects one or more elements), and no explanation (or a questionable explanation) of how the technique works. If you see any of these red flags, contact a reputable geophysicist, they probably will already have some knowledge of the proposed technique and would likely be pleased to advise you.