**Searching for Porphyry Copper Deposits Using Induced Polarization**

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*GOPH 453 Final Project*

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**Introduction**

Copper porphyry deposits are comprised of a complex system of hydrothermal alteration and mineralization. There are multiple economically valuable ore deposit can be found and exploited within these zones. Exploration techniques for these deposits are diverse and involve geochemical and geophysical signatures for defining these deposits. IP exploration is a technique that contributes significantly to this type of exploration and there have been entire deposits have been found using induced polarization without any previous information. Through IP surveying, it is possible to identify the target deposit as well as its constituents.

**Induced Polarization**

Induced polarization is an electromagnetic method that uses a current running through the ground to create a geophysical image. Two electrodes first generate a current; this current enters into the subsurface and is then received by a rock unit that has varying ability to hold onto the supplied current depending on its physical and chemical properties. Two potential electrodes observe the potential difference that is created by the current electrodes and by the substrate material. When the current being supplied is turned off, the potential electrodes still observe a voltage difference for a certain amount of time afterwards instead of instantaneously returning back to zero as one might expect. This voltage decay is a result of the overvoltage effect caused by the storing of charges within mineral grains in the subsurface; this overvoltage is what is responsible for the induced polarization (IP) effect.

**Induced Polarization Arrangement in Field Work**

An induced polarization survey can be conducted using different survey arrays, which are the same ones that are used in DC Resistivity surveys. However, a dipole-dipole arrangement is commonly used as a set up for conducting an IP survey.

The dipole-dipole arrangement consists of two pairs of electrodes: the *current electrodes* and the *potential electrodes*. Each set of electrodes is spaced at the same distance from its pair, and the two pairs are placed at a distance that is some multiple of the spacing between the pairs.

The reason this configuration is used in the field as opposed to a Wenner, Schlumberger or Square array is because it has certain advantages that the other arrays do not. First of all, it exhibits good depth penetration of the current, which means that we can explore for mineralization more thoroughly. It is less labour intensive than some of the other arrays, and since the current and potential pairs of electrodes are not connected to one another this makes it an appropriate choice for utilization in fieldwork.

**Induced Polarization in the Time Domain**

**Summary: How Time Domain IP Works**

1. Current is supplied *(V)* by current electrodes, and is continuously being observed by the potential electrodes
2. Charge builds up on metallic grains
3. Current induces a potential difference in the metallic grains *(Vi) – this is the* ***overvoltage***
4. A voltage (VT) is observed at potential electrodes *(where V + Vi=V****T****)*
5. Current is switched off 🡪 VT – V = Vi
6. Vi decays at a rate depending on the conductivity of the grain and the amount of time the grain was subjected to the current

Induced polarization may be measured in two different ways: with respect to frequency, or with respect to time. In this section, we will observe the IP effect as it occurs with respect to time.

As previously mentioned, induced polarization is a potential difference measurement between the potential electrodes. When the current through the electrodes is turned off (goes to 0 V), the potential difference measurement at the potential electrodes does not instantaneously drop to zero. Instead, the potential difference drops significantly at first (instantaneously, as a result of the current electrodes being switched off) but it then slowly decays to zero after a certain amount of time. The time the voltage takes to decay is the measurement we make during our observations of the IP method in the time domain.

The cause for this phenomenon is the overvoltage effect, which is the observed decay of the potential difference as a function of time. This occurs due to the properties in the subsurface geological units. In the case of ore mineral exploration it can be explained as follows:

Current is supplied to the ground by the current electrodes; these charges move through the substrate and induce a response in chargeable grains in the subsurface. When the current is supplied, a charge builds up outside of the metallic grains. Since the charge is free to move in the metals present in the subsurface (since they are conductors), the electrons will move to the side of the mineral grain where the positive current is present. This positive current will simultaneously repel the protons present in the mineral grain. This current therefore creates a temporary charge separation where the mineral grain acts as a small capacitor, creating a potential difference within itself. When the current is switched off from our current electrodes, the total observed voltage drops instantaneously by the amount of current that was being supplied by the current electrodes (which we will define as *V*) so the remaining voltage is only that of the potential difference that had been induced in the metallic grains by the original current *V.*  It takes a while for this potential difference to disperse leaving us with *Vi*, the overvoltage that decays over time. The decay of voltage over time is what we measure at the potential electrodes. We have previously defined as the “overvoltage effect”, which is the IP response.

**Induced Polarization in the Frequency Domain**

Frequency domain IP methods focus on the effects of using an alternating current to observe an apparent resistivity that is characteristic of underground geological units. This method is used more often than the time domain IP to locate ore bodies.

To conduct this sort of survey, one must apply currents at two different frequencies and then observe the resulting voltage waveform. By comparing the initial current waveform with the voltage waveform, a phase shift can be measured between the two. The phase shift can then be characterized as an apparent resistivity and can be defined as a *frequency effect* by using:

, or (in terms of resistivity) 

These formulas can be multiplied by 100 to give the *percent frequency effect* (PFE) and can also be altered to give the *metal factor* (MF). Results from these calculations can be used to graph pseudosections, as done in lab 4 to locate areas of interest.

**Spectral Induced Polarization**

Spectral induced polarization (SIP) uses the same theory behind the frequency domain IP method, but instead of only applying two different frequencies, it applies a range of frequencies over the subsurface and measures the varying phase angles that are produced. A graphical representation for induced polarization plots the phase angle as a function of the logarithmic value of the applied frequency. This method allows us to see several resistivity measurements at a range of different frequencies.

The purpose of Spectral IP is to distinguish the different material properties that exist in the subsurface. This means that SIP can also be used to separate out zones of primary mineralization, or the areas where the mineralization in a geological formation is the most concentrated.

SIP is especially useful for mineral exploration because it is able to give us a good estimate on the amount of mineralization in the subsurface (both time and frequency domain IP methods are only practical for finding the location of an ore body). The amount of mineralization in the substrate is important to determine for whether or not an ore deposit is economic for a company to produce.

As the SIP method is based on the Cole-Cole relaxation model, it tries to characterize the time constant τ and *c* value to specific types of ore or rock. The time constant, τ, and exponent *c* are measurable physical properties that describe the shape of the decay curve. Studies are underway that give weight to τ being used to discriminate between fine and coarse-grained polarizable mineralization. For a 2-second pulse, it ranges between 0.01 s for fine-grained sulphides, to 100 s for coarse-grained sulphides. As an example to how τ can help locate gold, gold is often associated with fine-grained sulphide mineralization so a τ value of 0.01s can be expected. Spectral τ is a useful parameter for helping correlate anomalies that likely originate from the same geologic source. For example, anomalies with different τ values likely belong to separate zones.

Ongoing research is indicative of exponent *c* being a diagnostic of the uniformity of the grain size of the target. It ranges from 0.1 for non-uniform grain size to 0.8 for uniform grain size. By having a varied large range of frequency values in the case of spectral IP, one can try to correlate the physical parameters *c* and τ to specific types of ore bodies.

**Porphyry Copper Deposits**

Porphyry deposits are large areas of hydrothermal alteration formed primarily by felsic igneous intrusions. These alteration zones assemblages often contain ore deposits; common porphyry deposits include gold, molybdenum, lead, zinc, and, the ore deposit we are most concerned with: copper.

Copper porphyry deposits originate from large igneous intrusions that develop at convergent plate boundaries; therefore these deposits are most common along island arc and continental arc settings. As the intrusion enters into the overlying country rock, it begins to incorporate elements of the country rock into its magma and also begins to cool due to a decrease in pressure and temperature as it rises from within the Earth. As minerals begin to crystallize out of the magma, they separate their constituents from the total chemical make-up of the liquid. Copper is left in the fluid because it is unable to crystallize with these early-forming minerals due to the fact that it is unable to fit itself into their crystal structures; because of this, it remains in solution and therefore increases the concentration of copper within the magma.

The granitic intrusion continues to cool while the copper remains in solution; as the intrusion cools, it alters the rock units around it by contact metamorphism, creating zones of alteration where certain mineral assemblages develop. These zones usually form a dome like structure over the magmatic intrusion and are varying in types and degrees of alteration. The first alteration zone is the potassic zone. This is the hottest zone as it is closest to the magmatic intrusion and hydrothermal fluid continuously passes through. Next, is the phyllic/sericitic zone where the best copper mineralization seems to occur along the margins. The argillic and the prophyllitic zones follow this, and surround the phyllic zone. When the intrusion completely cools, the copper-rich solution is the only thing that remains; it begins to make its way into available fractures, fissures, fault lines or other openings within the rock and crystallizes as a copper-rich ore. This type of hydrothermal interaction can by cyclic, as pulses of magma may continue hydrothermal interaction with these complexes. Hydrothermal fluids will further the stock work of fractures and thus the precipitation of copper.

**Porphyry Copper and Induced Polarization**

Due to the nature of formation of porphyry copper deposits, each alteration zone has characteristic mineral assemblages. Since each zone of mineralization contains different minerals, they will hold on to the induced current differently, varying either on how well they are able to hold charge (their chargeability) or on the amount of time they hold the charge for before the charge disperses. This causes each alteration zone to create a different IP response. Higher chargeabilities often coincide with alteration zones containing pyrite, which can be characteristic of the phyllic zone. The most abundant copper deposits are found usually in or in close proximity to this alteration zone.

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**Case Study: Zoned Deposits in the Philippines**

As mentioned earlier, copper porphyry deposits form by the late cooling of copper-rich fluids after the crystallization of a felsic intrusion. In the Philippines, a fault (the Philippine Fault) exists near a subduction zone. This fault provides available voids into which the copper-rich fluids can crystallize. This zone of porphyry copper deposits is known as the Philippine Copper Belt.

An area for potential porphyry copper deposits in the Philippines was found by noting that there were copper-rich rock units that were occasionally outcropped in the region. This is indicative that the mineral targets are likely shallow; shallow deposits are preferential in mining because it makes for easy prospecting to tell us where to conduct geophysical surveys and it means that we can likely easily conduct extraction of the ore through an open-pit mine, which is cheaper than alternatives.

The zoned deposits in the Philippines were founded through the use of spectral IP surveying with a dipole-dipole array. Through conducting the survey, it was found that there was an anomalous area that responded to the survey with a low frequency effect. This area was interpreted as being the core of the deposit (the igneous intrusion). This would be an appropriate interpretation since the potassic core would be highly resistive, corresponding to a high apparent resistivity therefore giving a low frequency effect.

A high metal factor was observed around the low frequency effect area, which was interpreted to be the pyritic halo (phyllic zone) around the potassic core. The potassic core has little sulfide content, whereas the phyllic zone has high sulfide content due to the pyritization. In referring to models of zoned porphyry deposits, it is likely that the economic ore is deposited between the Potassic and Phyllic zones; this is where drilling was recommended. The deposit was drilled in the recommended zones and had produced around 200 million tons of 0.45% copper.

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­­­­**Case Study: Performing IP in a Lab**

Although in the lectures we covered mostly the theoretical aspect of IP with little emphasis on the physical aspect, we thought it would be interesting to delve into the actual hands on method. By coming across a thesis of a student online, we were able to understand how one would perform the induced polarization effect in a laboratory. With the configuration seen here, there are many components working together.

**Isolation amplifier**: The isolation amplifier eliminates common mode voltage. Common mode voltage creates a noisy signal and by using an isolation amplifier it eases data interpretation.

**Transmitter**: sends series of current signals in square wave which are essential in finding our complex resistivities and phase difference

**Shunt resistor**: The shunt resistor is used when dealing with large currents. The current passes through a small resistive path that is controlled which leads us to measuring our voltage creates a small resistive path to measure the voltage from the transmitter

**Electrodes/Sample:** This is where the rock sample lies, between the two electrodes which pass the current through it, and measure it’s properties.

**GDP-16**: Essentially the heart of the layout, it is what outputs our resulting data in the form of complex/real resistivity, and the phase difference.

**Configuration considerations before data collection**

Before even setting up the equipment, there are preliminary procedures one must follow when beginning data collection. The sample needs to be trimmed to one inch in diameter so that it can fit between the current electrodes properly. The sample then must be soaked in water for approximately three days prior to passing any current through it. This ensures maximum contact and proper flow of the electrolytes through the porous volume of the sample. Finally a rubber band is placed over it so that it can act as an insulator. Prevention of surface current is necessary for accurate readings as we’re primarily interested in the inside composition of the resistivity of the rock.

**Conclusion**

In conclusion, copper porphyry deposits are prolific sources for ore exploration. IP surveys have allowed for identification of the different alteration zones within shallow depths.Using electrical current through two electrodes, voltage can be measured and used to map the subsurface based on its ability to maintain charge. This can be measured with respect to time and frequency, with each response providing information of the physical and chemical properties of the subsurface. This is a useful technique when a model has not yet been developed for a particular area, as it is able to pick up dense clusters of disseminated sulphides. This will allow companies to target these particular zones before wasting resources on blind drilling. It is still a useful tool in later stages of a project as well, for distinguishing alteration zones. After this survey, target zones can be further defined by drilling and geochemical testing. Induced polarization surveys can provide important preliminary information as well as supplementary information to build a solid model for copper deposits.

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