Mineralogical, lithological, and alteration sources of geophysical anomalies

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ABSTRACT

Knowledge of physical rock properties are used when processing various geophysical data sets and when attempting to construct 3D geological models. Measurement of physical rock properties are made in the laboratory, in-situ on outcrops, on bore core and by logging of boreholes. Variations in physical properties are controlled by parameters such a mineralogy, grain size, and rock texture. Each of these parameters relates in different ways to geological processes. Examples of physical property variations associated with lithologic, metamorphic, and hydrothermal processes are reported from a number of different mineral deposit settings including; the Bathurst Mining Camp, New Brunswick and the Highland Valley Copper deposit, British Columbia.

INTRODUCTION

Processing and interpretation of geophysical anomalies detected by ground and airborne surveys require some knowledge of physical property variations. For example, calculation of a Bouguer anomaly in a gravity survey necessitates a density value. Unconstrained inversion of an aeromagnetic data set can produce a result which has little geological significance. With some prior knowledge of the appropriate magnetic susceptibility then the constrained inversion will be more geologically appropriate.

It has been widespread practice to think of physical property variations as being predominantly controlled by variations in the mineral content of a rock. This in turn has lead to a "lithology" centred approach to rock property assessment. There are two issues with this approach. First, many physical rock properties are not controlled by the bulk mineral content (magnetite for susceptibility), and other factors such as texture and grain geometry control physical properties (e.g. porosity and electrical conductivity). Second, mineral deposit systems comprise a suite of processes which have lead to a concentration of some specific element. And it is the coherence of these processes which help develop a mineral deposit "footprint". As demonstrated by the CMIC – NSERC Footprints project it is often possible to map a zonation of geological, geochemical and geophysical zones around a deposit. Physical rock properties are the key that links the geophysical anomalies to the observed geochemical and geological variations.

In this note, we report results from many studies where physical rock properties have been used as a proxy for mapping lithological and alteration processes. We specifically focus on magnetic and density variations at many mine settings. We examine the importance and use of magnetic remanence in magnetic anomaly modeling. Finally, we review the status of rock property assessment and make some suggestions for future investigation

PETROPHYSICAL STUDIES

Reference charts

Magnetic anomalies arise from spatial variations in the mineralogical composition of rocks. Magnetic susceptibility then is a critical parameter that we need to understand when we discuss magnetic anomaly patterns. Magnetic susceptibility variations are defined in terms of contributions from three classes of mineral: ferromagnetic, paramagnetic and diamagnetic minerals. Distinguishing between contributions from ferromagnetic minerals such as magnetite, and pyrrhotite and paramagnetic minerals such as biotite and other clay minerals has major implications for the interpretation of geological processes.

Induced magnetic field signals are the consequence of the interaction between magnetic susceptibility and the Present Earth's field. The morphology of the resulting magnetic anomaly is a convolution of the spatial distribution of magnetic minerals and the orientation and magnitude of the local magnetic field vector. Some ferromagnetic minerals are also capable of retaining a magnetic remanence signal. Unlike induced field anomalies remanence related anomalies are independent of the Present Earth's field direction at the time of anomaly observation. Their remanence was acquired at some instant in the past when minerals in that rock unit cooled through Curie point threshold, or grew above a critical grain size.

Recognising the importance of the discrimination of paramagnetic and ferromagnetic sources Henkel (1994) introduced a series of "standard diagrams", or templates for the "understanding of magnetic petrology". As shown in figure 1 these templates include cross plots of magnetic susceptibility versus density and magnetic susceptibility versus Q (Koenigsberger Ratio, Remanence intensity/ Induced intensity). Through use of known susceptibility values for specific minerals it is possible to use these templates to develop mixing / mineralogical alteration models which explain the geological model under consideration (figure 1). Magnetic susceptibility then is an important tool for both petrophysical analysis and also as an important constraint for potential field interpretation (Henkel, 1994).

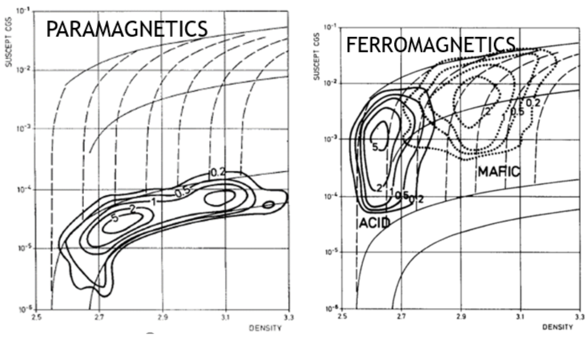

Figure 1a: Henkel (1994) template of susceptibility versus density. Possible mixing lines are defined by dotted lines.

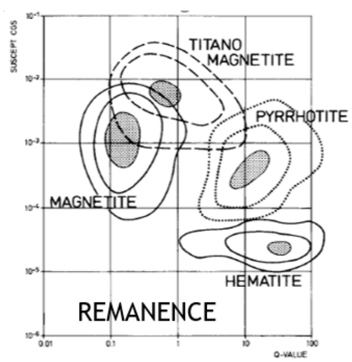

Figure 1b: Henkel (1994) template of Q-Value (Koenigsberger ratio versus susceptibility. Zones for specific mineral species are identified.

Atikokan Susceptibility: Data Presentation and Analysis

Magnetic susceptibility is controlled by the volumetric concentration of specific minerals within a rock sample. As such magnetic susceptibility values must exhibit a log-normal distribution (Latham et al., 1989). Analysis of a susceptibility data set using a log-normal probability plot (Lapointe et al., 1986) provides a mechanism for revealing the presence of mineralogy specific populations of magnetic susceptibility. Lapointe et al., (1984) reported results from a systematic logging of borehole susceptibility variations along a series of boreholes in the Eye – Dashwa Lakes pluton. As shown in figure 2 using the log-normal probability plot method on nearly 2000 measurements from two boreholes it was possible recognise four distinct populations. Two populations represented variations of primary lithology; the high susceptibility diorite unit was only intersected in the ATK5 borehole.

Correlation of the physical property data with detailed petrological studies revealed that the different susceptibility levels corresponded to unaltered granite, intermediate alteration marked by presence of epidote, and advanced alteration where chloride group minerals are present. Extreme alteration levels are associated with presence of clay, iron hydroxides, and carbonate. Confirmation of change in magnetic mineral carrier speciation was achieved through detailed coercivity analysis. As magnetite is progressively eroded more and more hematite becomes present and the coercivity systematically increases.

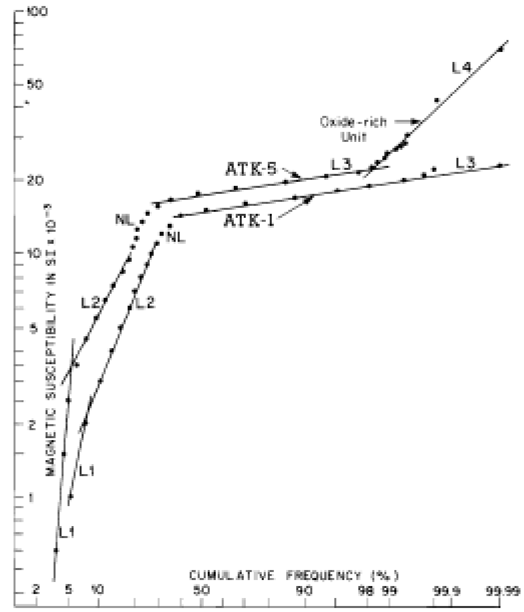

Figure 2: Log-normal probability plot of magnetic susceptibility variations from the Eye-Dashwa Lakes Pluton (from Lapointe et al., 1986).

Highland Valley: Field and Core Measurements

Recent advances in computer technology have led to an increased availability of field portable magnetic susceptibility meters. It is now possible to rapidly obtain susceptibility and density measurements both in the field and in the core shed. This has in turn lead to a dramatic increase in the volume of susceptibility data that has become available. However, there seems to be a limited knowledge of the protocols for the acquisition and then processing of the data. Some suggestions are provided in this submission.

How many magnetic susceptibility measurements should one take? There is no simple direct answer. Much depends on the purpose for which the data is being collected. It is not possible to separate this question from the methodology that is used for analysing the data (see below). Obviously, a fundamental limitation is imposed by the extent and accessibility of outcrops. However, it is recommended that one should make many measurements (>20) on a single outcrop. Individual observations are obtained rapidly and newer instruments digitally record the readings. Ideally measurements are made on near flat, non-lichen covered surfaces. However, attention must be paid to ensuring that all aspects of an outcrop are covered. This includes attempting to obtain measurements in regions of more intense fracturing and alteration. Often these areas are not well preserved in the surface geological record; they are recessive regions covered with overburden. Remember that an in-situ surface will always have some degree of weathering even in Canada.

Lee et al., (2010) present an example of outcrop magnetic susceptibility mapping that was used to locate possible fractures in a large granite pluton. The original susceptibility data for this study which was collected in the 1980's involved acquisition of measurements at points along a series of cut lines. At each site six measurements were obtained and then a simple arithmetic average calculated. A total of 343 site-mean observations were obtained over an approximately 4 sq km area. Gridding of these susceptibility measurements to investigate the distribution of fractures was limited by the irregular distribution and locally sparse data. Only broad scale features could be mapped.

In contrast, Byrne et al (2017) report a study where "ten sets of ten measurements each were completed in each of four zones" (adjacent outcrops), resulting in a total of four hundred magnetic susceptibility measurements". The points were not collected on a systematic grid, rather the measurements were made using an approximate 0.5m spacing. No attention was paid to the presence or absence of vein locations. However, it was known that the density of veins increased as one approached the ore body. By performing this multiple repeat measurement procedure, it was possible to examine the uncertainty and reproducibility of the geometric mean of magnetic susceptibility and to derive a coefficient of variation. The outcome is that it is possible to use the variability of susceptibility within an outcrop as a means of defining the increasing level of alteration.

Fracture Mapping – Alteration, Highland Valley

More recently, in situ surface magnetic susceptibility results reported by the Footprints project from the Highland Valley Copper (HVC) deposit serve to emphasise the importance of the log-normal probability plot for analysing rock property data (Byrne et al., in press). The Guichon Pluton, in which the HVC deposit is located, has a concentric zonation of lithologies progressing from more mafic and more magnetic outer units to more felsic and less magnetic inner units. The outer Guichon and Chataway phases have systematically higher magnetic susceptibility than the inner Bethlehem, Bethsaida and Skeena phases (figure 4a). This plot also serves to accentuate the higher degree of alteration that is present in the inner phases; these change to the alteration populations occurs at a higher percentage of the samples (figure 4b). Finally, like the Atikokan study discussed above, this study also has an alteration population which is not well defined. An intermediate alteration level which is well defined in the outer Guichon and Chataway phases was not recorded by the sampling performed on the inner units.

A more common approach to analysing magnetic susceptibility data is by using box and whisker plots (figure 5). These are especially useful when considering magnetic susceptibility data for use in constraining magnetic inversion models. A magnetic anomaly represents the summation of the contributions from all magnetic sources. Using the log-normal transform serves to dampen the impact of high susceptibility observations. BUT as far as magnetic modeling is concerned it is these high value samples which are contributing most to the observed anomaly patterns. An ideal approach, if possible, would be to use the information provided by the log-probability approach to assign different susceptibility values to geological distinct zones within a given lithological unit in the constrained input model.

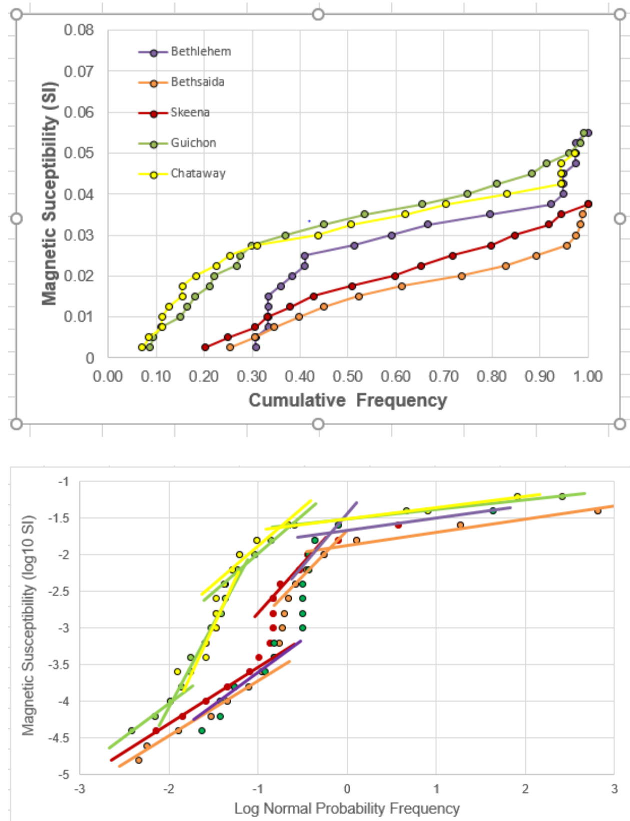

Figure 4 a) Normal probability plot of magnetic susceptibility emphasises variation between lithological units of the Guichon Batholith. **b)** Log-normal probability plot of magnetic susceptibility variations emphasises degree of alteration. More magnetic phases are less altered than younger (later) less magnetic (more felsic units).

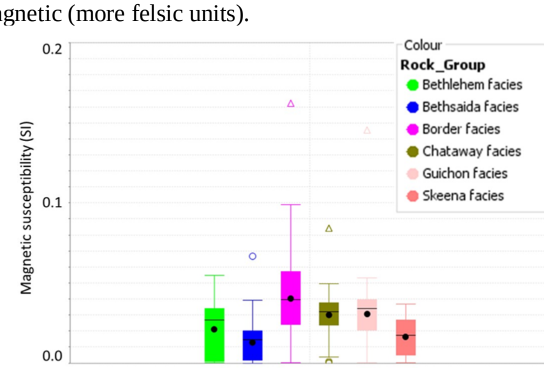

Figure 5: Box-whisker plots of same data from Highland Valley Copper deposit. Box-Whisker plots provide direct information on average rock properties that are appropriate for magnetic anomaly modelling but provide no insight into alteration, or petrogenesis.

In 1977 Henkel and Guzman presented a paper which showed that oxidation alteration associated with increased porosity produced by fracturing within a fault zone is often characterised by the linear reduced magnetic anomaly. Frohlich (1989) and Airo and Wennerstrom (2010) among many others have reported results confirming this original observation. In addition, numerous papers have been published on lineaments: linear topographic features which are formed through increased erosion of fractured rock. Integration of the topographic and magnetic features of lineaments has been used as a means for defining hydrogeological fluid pathways (Rhen et al., 2007).

Using a spatial averaging filter followed by grid differencing Morris et al., (2009) showed that it was possible to define the presence of linear alteration features in both magnetic and topographic data sets. Applying this approach to the Highland Valley site and overlaying the magnetic and topographic grids serves to define the presence of fractures (figure 6a). It is readily apparent that some fractures have more magnetic response than others. This reflects in part the timing of the fracture movement with respect to the fluid systems altering the pluton. Mineralisation related fluids produced a more significant alteration than later post mineralisation fluids.

Magnetic anomalies can be characterised by three parameters: the location of the source body, the geometry of the source body and its physical property. Using a simple parametric modelling routine of a dipping tabular body it is possible to map the geometry of the fracture framework. The location and strike of the fracture is defined by the anomaly pattern. It is known that the fracture outcrops at surface and so the only variables left are the dip and dip direction of the fault. Using this knowledge, one can construct a fracture framework for the pluton (Lesage et al., in press) (Figure 6b).

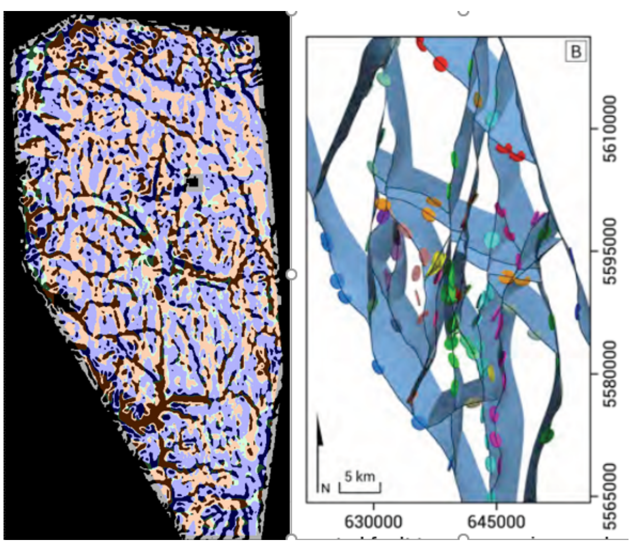

Figure 6: a) Spatial difference plot showing locus of magnetic linear feature (black) over topographic linears (pink). b) Fault geometry framework for HVC computed from magnetic anomaly data using tabular parametric modelling approach (Lesage et al 2017).

Baie Verte, Newfoundland: Constrained Inversion

It is now common practise to invert airborne magnetic data to generate voxel mesh volumes which are then interpreted in terms of a 3D geological model (Li and Oldenburg, 1996). Individual voxels in the mesh are assigned a magnetic susceptibility such that the contribution of all the voxels explains the observed magnetic anomaly pattern and satisfies the mathematical constraints of the model algorithm. As is, well known unconstrained inversions result in models that are non-unique. To closer align the geometric outcome with geological reality recently inversion schemes have taken to including measured magnetic susceptibility constraints (surface, and borehole data) with the input model (Spicer et al., 2011, Tschirhart V., et al., 2013, Vallee et al., in preparation). The output model includes bounds for possible susceptibility variations that are defined by in-situ measurements.

The Rambler deposit located near Baie Verte, Newfoundland is linked to the upper surface of the Rambler Rhyolite part of the Pacquet Harbour Group. “To direct the outcome of the inversion process towards a more geologically reasonable solution” Spicer et al., (2011) included known “geological and geophysical constraints into the input model.” “Reference model constraints included surficial geological contacts as defined by the aeromagnetic data, and subsurface distribution of physical property variations from a series of drill-hole logs” (figure 7). The physical property measurements revealed weak density contrast between the sediments and the mafic volcanic rocks. The magnetic susceptibility data was dominated by the contrast between the gabbro-diorite dykes and the volcanic rocks. The resulting constrained output inversion model closely approximates the model derived from structural data

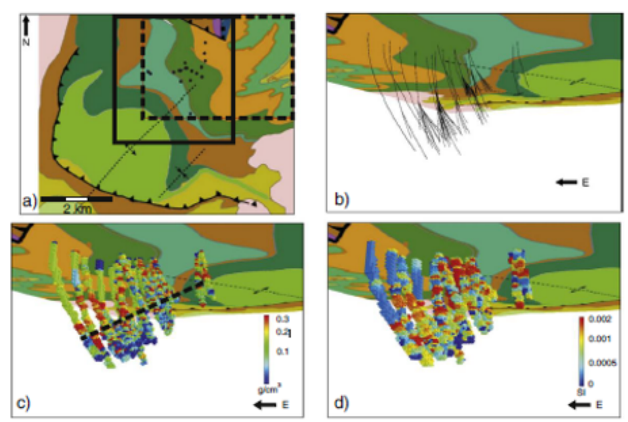

Figure 7: a) Geology of the map area in Baie Verte, Newfoundland, b) Geometry of the boreholes for which physical property variations were measured, c) Block model of density variations relative to base value of 2.67 gm/cc, d) Block model of magnetic susceptibility variations. From Spicer et al., (2011).

Bathurst, New Brunswick: Density

Standard processing of all gravity data requires knowledge of the density of the rocks. A density value is used in Bouguer anomaly corrections for ground gravity surveys, and for the terrain correction in airborne gravity gradiometry. Hinze (2003) suggested that it a density value of 2.67 is the appropriate value to use in most settings. However, using this value for gravity data for the Bathurst Mining Camp, New Brunswick causes topographic artefacts to be carried over into the Bouguer map. The resulting image is then does not provide a true representation of the variation of gravity.

The geology of the Bathurst camp comprises a series of folded overlapping thrust sheets. Using density measurements from both surface and borecore samples Peter Tschirhart (2013) calculated average density values for each of the thrust sheets. Differences between the individual thrust sheets reflected differing content of felsic volcanics and sediments. Using the known surface geology map Tschirhart (2013) developed a spatially variable density correction routine (figure 8). The validity of this approach was tested through a covariance assessment between the topography and the corrected gravity data. The resulting gravity and gravity gradient maps from this variable density correction more accurately reflect regional scale variations of the geology. Some caution is needed when applying this approach since the topography often contains a geological signal.

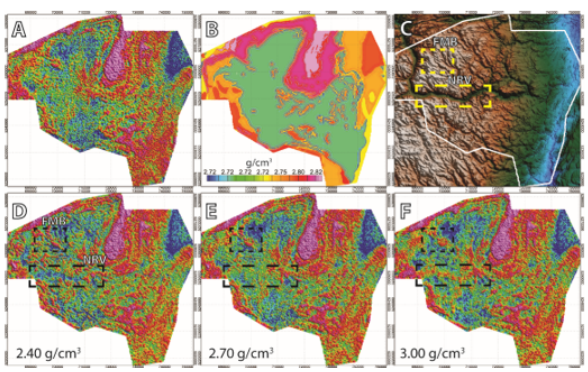

Figure 8: a) Gravity gradiometry Gzz variable density terrain correction, b) Variable density grid, b) Topography, d,e,f) uniform terrain corrections using values on graphs. From Tschirhart, P., (2013).

Malartic, Quebec: Density, Susceptibility, Fabric

Mineralization in the Canadian Malartic deposit is localized primarily along two principal structural trends: an E-W-oriented steeply south-dipping Sladen Fault Zone and NW-SE trending zone located south of the Sladen Fault. Gold is mainly associated with pyrite. Detailed petrological, structural and mineralogical studies have identified a diagnostic footprint zone within which characteristic features outline the presence of a zone of potassic, silicic and carbonate alteration (Perrouty et al., 2017). Genesis of the mineralizing fluids has been attributed to magmatic and also metamorphic processes.

Physical property measurements show that the meta-basic dykes exhibit the largest change in both magnetic susceptibility and density (figure xx). However, these rocks do not have a large spatial extent and therefore the large change in physical property is not reflected in most geophysical surveys. Petrologically, this change is well-defined and can be used to map the spatial extent of the alteration zone. Meta-sediments and felsic intrusives of the Pontiac Group have a complex petrophysical response to alteration. Some of the more strongly magnetic phases appear to be unchanged. There is a significant increase in abundance of less magnetic phases. This suggests that theoretically, it should be possible to locate the alteration zone with a magnetic survey. BUT, the change of susceptibility is from a an already weak magnetic phase to a more weak phase so the resulting anomaly if present would be of very low amplitude. Since magnetic signal varies as a function of the cube of distance it is extremely unlikely that this anomaly could be detected by an airborne survey. To further complicate matters the mineralized zone is located adjacent to Cadillac – Larder lake fault zone and immediately north of the fault are strongly magnetic rocks of the Piche Group which creates a "halo" effect over the low amplitude sediments.

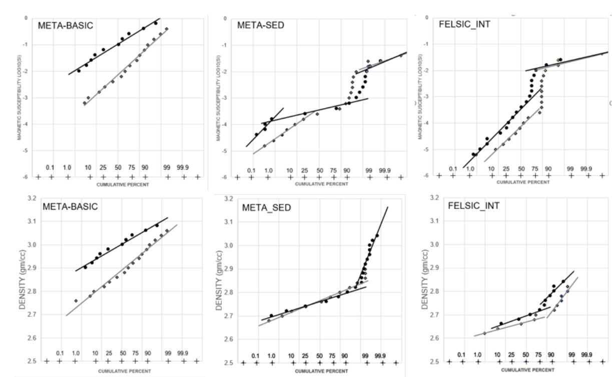

Figure 9: Magnetic susceptibility (upper) and density (lower) variations in meta-basic, meta-sedimentary, and felsic intrusives from the Malartic region. Fresh samples are in black and altered samples in grey.

The mineralizing fluids resulted in the new generation of magnetic mineral species. Closely associated with the pyrite is pyrrhotite and biotite. Both of these phases were deposited after the regional deformation. Anisotropic magnetic susceptibility measurements provide information on the presence of any preferential alignment of magnetic minerals. Such an alignment might represent a preferred crystal alignment, a preferred layering of a given mineral, or inherent crystalline anisotropy. Magnetic fabric measurements on samples from the Malartic area reveal the presence of the alteration zone associated with gold mineralization. Outside the ore zone footprint magnetic fabrics record a well-defined foliation which closely approximates the S2 structural fabric. Within the ore zone footprint foliation is dramatically reduced and the rocks have next to no fabric (Figure 10).

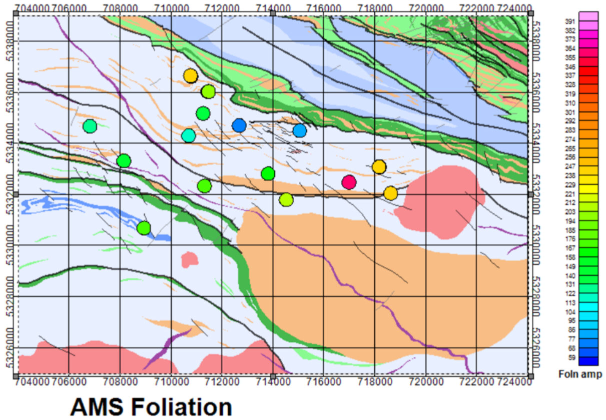

Figure 10: Anisotropic Magnetic Susceptibility (AMS) variations around the Malartic mineralised zone. Late stage mineral alteration has eliminated regional tectonic fabric.

Bathurst, New Brunswick: Remanence

The morphology of any remanent magnetic anomaly is a convolution of the geometry of the geology structure, the orientation of the inherent remanence vector and the vector contribution of the induced magnetic field signal. It is essential to recognise that any remanence contribution cannot have a random orientation. Possible orientations for the remanence vector is controlled by four parameters: the age of the rock and its remanence acquisition; the degree and direction of any post-acquisition tilting; the location of the sample site; and the polarity of the remanence (normal, or reversed). Inverting a magnetic anomaly data from an area in the British Tertiary Igneous Province (c. 60 Ma) and finding an apparently sub-horizontal remanence direction can only be explained in one of two ways; the rock unit has been tectonically rotated (deformed) by over 50 degrees, or the computed (inversion) vector is actually a genuine remanence contribution and some unresolved induced/viscous effect. That is, most magnetic anomalies even those in which remanence is apparently dominant are likely to have some significant induced field component.

The Armstrong B deposit located in the northwest corner of the Bathurst Mining Camp is associated with a distinct magnetic anomaly. Even a preliminary review of the anomaly pattern indicates that magnetic remanence must be significant. The negative portion of the anomaly is located to the south of the positive anomaly. Additional constraints on the geometry of the source body are provided by the numerous borehole intersections. Magnetic susceptibility and density constraints further limit the anomaly model. No direct magnetic remanence measurements were acquired. As demonstrated by Tschirhart, P., et al., (2014) The optimum inversion result which best satisfies the control geology and the magnetic data suggests a remanence direction which has a southerly declination and shallow negative inclination. The inverted result does not fall on the accepted polar wander path for North America. It is too shallow. Comparison with the local bedding strike shows that it is not possible to explain this discrepancy by post emplacement tilting. The only viable explanation is that the anomaly contains some viscous overprint of the Present Earth's Field. The inverted value does fall on the great circle between the PEF and the expected remanence direction. This study shows that it possible to derive meaningful paleomagnetic results from inverting airborne geophysical data.

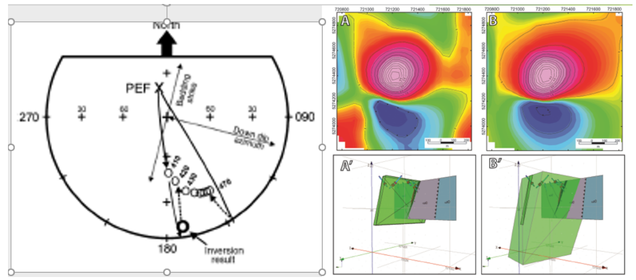

Figure 11: a) Stereonet showing change of effective remanence direction for New Brunswick derived from APWP for North America. Tectonic rotation paths associated with local geology are shown. Great circle link between PEF and remanence directions overlies computed direction. b) Comparison of observed and computed magnetic anomaly patterns and input and out geological models. From Tschirhart, et al., (2013).

DISCUSSION

To date most physical rock properties have been provided as a list with little discussion of the mineralogical, or textural rationale for the observed changes (Grant, 1985, Clark et al., 1992). In part this might be because of the difficulty of obtaining chemical and petrological information on the same samples for which we have petrophysical information. The CMIC-Footprints research program has directly addressed this deficiency and has purposely made samples available to different researchers. The outcome is that we are now starting to see new results in which the mineralogical significance of the petrophysical changes are being discussed.

Further, the advent of new field portable spectrometers capable of yielding mineralogical information and geochemical sensors such as pXRF instruments means that we will soon have access to geochemical and mineralogical data to complement our physical property measurements.

Most often physical property data are used in the context of searching for an anomaly which can be used to characterise a specific mineral deposit. But when considered in the broader context of a mineral system then we must recognise that each system probably comprises a number of geological processes with each one having its own petrophysical component. Surveys have been reported for both porphyry copper and epithermal gold deposits (Hoschke, 2008, Clark, 2014, Airo, 2015). Details of many of the geological processes are still only poorly defined.

Most geophysical models are lithology driven. That is, in construction of an inversion model we emphasise the distribution of different lithological units. We often fail to describe the distribution of geological processes. A common failing is lack of discussion of the alteration associated with fracture systems. Yet in many instances they form a large part of the observed signal.

When considering all physical property variations, we need to look beyond a simplistic mineralogical description. While some physical properties for example paramagnetic susceptibility and seismic velocity that are closely associated with mineralogy other physical properties are controlled by other factors. Grain size shape and volume for example has important ramifications for ferromagnetism: pyrrhotite and titano-magnetite for example exhibit varying response with grain size. Texture and porosity is especially important when considering electrical conductivity since it is often the pore water that dominates the observed signal.

In summary, future studies of petrophysical properties will need to integrate mineralogy, petrology and textural variations. It will be necessary to develop new plots that are capable of revealing these changes in a mineral systems approach.

CONCLUSIONS

1) Physical rock properties genuinely represent the link between geology and geophysical response.
2) Calibration of instruments and cross-laboratory standards are critical.
3) Physical rock properties are essential controls when attempting any type of inversion of geophysical data.
4) Remanence is not random. Whenever remanence is invoked it is essential that the context of the direction be established. Integration with Apparent Polar Wander Path must be tried.
5) We need to develop a better understanding of changes in physical rock properties associated with ALL geological processes.
6) We need to take advantage of new generation of portable mineral mapping and geochemical tools.
7) We need to develop methods for rapidly characterising magnetic mineral carrier, for example coercivity analysis, or multi0frequency susceptibility.
8) We need to develop and use new data interrogation techniques for use with physical property data.

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