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Preliminary interpretation of density and magnetic properties of rocks from Leinster

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Introduction

A synthesis of new detailed laboratory physical property analysis of samples collected in this study from the Leinster area will provide the basis for correlating the subsurface geology with geophysical inversions and interpretations at regional, district, and deposit scales. I collected 300 drill core and surface samples from the Leinster area, and have analysed 160 of them for a suite of magnetic properties at the Australian National University paleomagnetic laboratory. The magnetic properties analysed were: induced susceptibility (κ), natural remanent magnetisation (NRM) intensity and direction (declination and inclination), Koenigsberger (Q) ratios, NRM components (using progressive demagnetisation), and susceptibility versus temperature relationships. Density analysis of the samples was performed at Geoscience Australia. The samples will be further described with selected thin section petrography, and possibly XRD mineralogy estimation. This information will help identify trends in physical properties related to rock types, mineralogy, and primary and secondary processes.

Background

The critical link between geological and geophysical interpretation is an understanding of the physical properties of the rocks and minerals involved. For nickel exploration in Archean greenstone belts this is complicated by complex changes in density and magnetic properties associated with serpentinisation and metamorphism of ultramafic rocks, but aided by strong physical property contrasts between sedimentary or felsic rocks and mafic or ultramafic rocks, and between host rocks and sulphide mineralisation.

Geophysical interpretation and modelling commonly uses standard or textbook physical property values due to a lack of actual measurements, especially in new or poorly explored areas. However ancient rocks can have complex histories and standard values may not be representative. Figure 1 shows textbook physical property values for various common minerals in Archean greenstone belts, and the effects of some of the geological processes acting upon them. Serpentinisation replaces olivine with serpentine and magnetite. Both may be replaced during carbonatisation by carbonate and Ca-amphiboles. Metamorphism may create new olivine and form a suite of new silicate minerals (Hill et al., 1990). Further serpentinisation creates more magnetite and serpentine at the

expense of olivine. The physical properties of the ultramafic rocks will therefore be controlled by the primary geochemistry of the rocks (and therefore igneous processes), alteration fluid chemistry, water rock ratios, strain, and metamorphic pressure, temperature, and duration. It is unlikely that a standard set of properties will be accurate. Sterritt (2006) has laid the groundwork for understanding how some of these processes, and their affect on mineralogy, relate to the observed physical properties of ultramafic rocks associated with nickel sulphide deposits. Depending on their histories, other rock types in the belt, such as the felsic and mafic volcanics and intrusives, and sedimentary rocks, might have escaped such dramatic changes, but metamorphism, deformation and fluid flow may still have an effect.

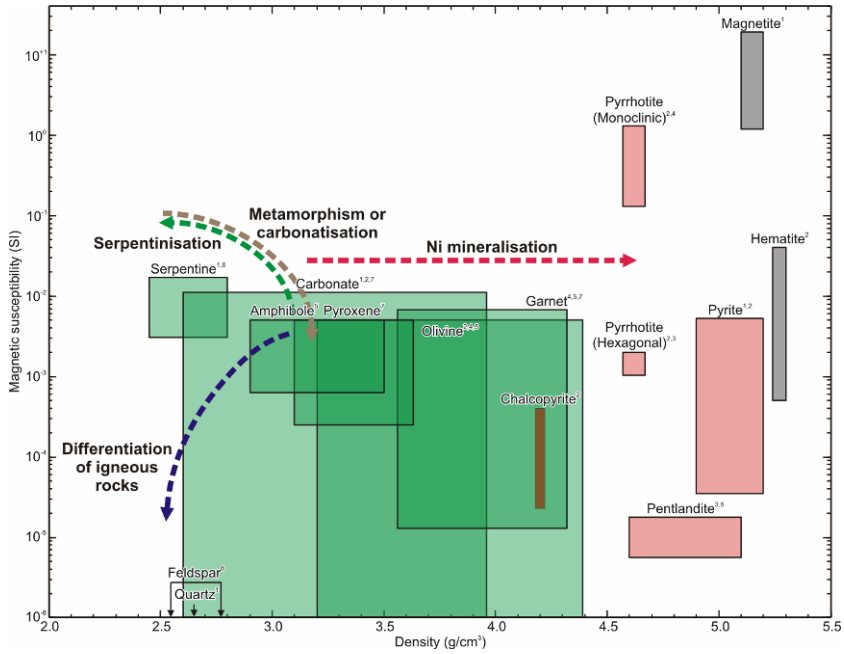

Figure 1. Physical properties of common silicate (green), sulphide (red) and oxide (grey) minerals associated with Archean greenstone-hosted nickel deposits, and trends of various geological processes acting upon them. Igneous processes lead to a trend from high density and susceptibility ultramafic and mafic rocks through to low density and susceptibility felsic rocks (Henkel, 1991). Serpentinisation replaces ultramafic olivine with serpentine and magnetite (Henkel, 1991). Carbonatisation is magnetite-destructive and will anneal any primary or secondary porosity. Metamorphism also removes porosity and at amphibolite grades can produce abundant metamorphic olivine. The impact of nickel sulphide mineralisation will depend on the host rock and the ore mineralogy (commonly monoclinic and hexagonal pyrrhotite, plus Ni-bearing pentlandite). Feldspar, quartz, and other non-iron-bearing minerals are diamagnetic with slight negative susceptibilities that plot off the diagram as indicated by arrows. Numbered sources are: 1 – Telford et al. (1990); 2 – Hunt et al. (1995); 3 – Emerson et al. (1999); 4 – Clark (1997); 5 – Chesterman and Lowe (1979); 6 – Bleil and Petersen (1982); and 7 – Schön (2004).

By way of example Table 1 shows typical text book magnetic susceptibilities for some rock types expected at Leinster, compared to ranges of laboratory magnetic susceptibilities measured in this study. It is clear that the standard text book values are poor predictors of actual magnetic susceptibility measurements, and are often off by several orders of magnitude. Where no physical property measurements are available, measurements from adjacent or related areas would be more useful, but text book values must suffice if there is no other information available.

Table 1. Comparison of standard text book susceptibility estimates versus actual measurements on Perseverance rocks in this study showing the poor correlation.

Rock type	Text book mag. sus. range (10^{-3} SI; Telford et al., 1990)	Leinster measured mag. sus. range (10^{-3} SI; this study)
Peridotite (i.e., dunite)	96-200	2.7-86
Granite	0-50	0.1-9.8
Porphyry	0.25-210	0-0.3
Average metamorphic rocks	0-73	0.04-4.6

Geophysical inversions require input of physical property knowledge at two stages of the process. Physical property information is required when defining a constraining reference model or bounds and using more realistic properties will result in more reliable inversion results. But even in greenfields exploration where there is no prior geological knowledge, an understanding of physical properties is required to interpret inversion results. Without an expectation of what the physical properties should be it is difficult to assess the validity of recovered physical property models. A lack of physical property knowledge also hinders assessment of which features and physical property contrasts may represent prospective horizons or target regions. Fortunately, in established projects and mines, companies commonly have large databases of physical properties. Densities are required for ore reserve estimates, and magnetic susceptibilities are regularly gathered during exploration as an aid for mapping and logging. Knowledge of physical properties in near-mine environments may be useful in constraining and interpreting inversions in similar data-poor greenfields areas.

The magnetic response of a rock is derived from two main constituents, the magnetic response induced by the earth's present magnetic field, and an intrinsic remanent magnetisation component that reflects the rock's history. Magnetic surveys measure the component of the sum of the two constituents that lies in the direction of the earth's magnetic field, but the current UBC–GIF magnetic inversion code assumes that induced magnetisation is dominant. Where the remanent magnetisation component is in the direction of the earth's field, the observed magnetic response, and therefore recovered susceptibilities, may be greater than measured susceptibilities. If the remanent magnetisation component is in the opposite direction to the earth's field, then the observed magnetic response and recovered susceptibilities will be less than measured induced susceptibilities. The remanent component will have little affect on recovered susceptibilities if it were oriented perpendicular to the earth's field. Remanent magnetisation can only be effectively measured in a laboratory, so there is little information of the relative importance of the remanent magnetisation component in magnetic interpretations in the Yilgarn Craton. It is important to test if remanent magnetisation may cause problems for inversions in particular areas, and to take its effects into account during interpretation.

Data collection

In November 2005 I spent a week at Leinster collecting samples and making magnetic susceptibility measurements. I collected 32 variously weathered surface samples from a variety of common rock types in 27 locations around the district where outcrop had been mapped by previous workers (Liu et al., 1996; Stewart, 2001). In addition, I collected 88 samples from three drill holes from the Perseverance deposit targeting footwall felsic and mafic rocks, the Perseverance dunite lens, and the granites east of Perseverance Fault. Time constraints prevented me from sampling mineralised zones. Follow-up work by BHP Billiton staff (R. Brabham, written commun., 2006) collected an additional 150 samples from 25 drill holes throughout the district, covering a range of nickel sulphide mineralisation styles (disseminated to massive sulphides, low grade to high grade nickel) and some footwall mafic rocks.

For three weeks in July 2006, I prepared and analysed magnetic properties on 31 of the surface samples and 127 of the drill core samples at the Australian National University paleomagnetic laboratory. I cut half core and quarter core samples into four to five 22 mm × 22 mm × 22 mm cubes; from full core and surface samples I cored four to five 22 mm long 25 mm diameter cylinders. For each sample the most representative three specimens were selected for analysis. The intensity and direction of NRM was measured on either a Molspin spinner magnetometer or a more sensitive semi-automated 2-axis cryogenic ScT magnetometer. The induced susceptibility of the specimens was measured either on a Digico susceptibility bridge (for lower susceptibilities) or an

AGICO KLY-3 kappabridge (for higher susceptibilities). All instruments are cross-calibrated to ensure consistent results between instruments (C. Klootwijk, written commun., 2006). Samples from drill core were axially oriented by marking the down-hole direction on each specimen. Surface samples were unoriented, but the relative orientation of each specimen within a sample was maintained and all specimens from a rock sample were measured in the same orientation. As such, for core samples the measured inclinations and declinations of NRM do not represent a discrete vector but define a small circle with axis of rotation along the direction of the drill hole, for surface samples the inclinations and declinations are arbitrary.

Ninety-nine specimens from representative samples were further analysed for their NRM components using fully automated alternating field (AF) demagnetisation on a 2G cryogenic magnetometer. This involved progressive step-wise demagnetisation of specimens with increasing AF strengths up to 140 mT, with measurement of the NRM components and intensity remaining after each step (after Giddings et al., 1997). Small additional rock chips were extracted from 65 samples and crushed to <150 µm using a hand crusher and sieve for thermomagnetic analysis. About 1 cm^3 of each sample powder was subjected to continuous induced susceptibility measurement on an AGICO KLY-3 kappabridge with CS-3 furnace and CS-L cryostat over a range of temperatures. Each powder was cooled to -196.4 °C in the cryostat with liquid nitrogen then slowly heated to room temperature while measuring susceptibility. The furnace was then used to slowly heat the same powder to 700 °C in argon gas before slowly cooling, while again measuring susceptibility. Density analysis of the samples was performed at Geoscience Australia where the samples were dried for two days at 110 °C, weighed, soaked in water for two days, weighed, and then weighed suspended in water.

Understanding physical properties

Interpretation of the physical property measurements is ongoing; however, basic plots have been prepared (attached) and some initial observations have been made. These include:

- Only ultramafic rocks (mean 36×10^{-3} SI) and massive sulphides (mean 110×10^{-3} SI) have susceptibilities greater than 10×10^{-3} SI. Granites are the next most magnetic rocks (mean 3.5×10^{-3} SI).
- Only sulphide-rich rocks have densities greater than 3.4 g/cm^3 (mean 3.8 g/cm^3). Unserpentinised ultramafic rocks, and mafic rocks have the next highest densities > 2.7 g/cm^3.
- Cross plots of density versus magnetic susceptibility show a number of trends that can be directly correlated with geological processes. Increasing sulphide abundance is associated with a strong increase in density but only a slight increase in susceptibilities. Serpentinisation of ultramafic rocks is associated with a strong decrease in density and a slight increase in susceptibilities. There is a clear trend of decreasing density and susceptibility with igneous differentiation from ultramafic to mafic to felsic volcanic rocks; relative to this trend the granitoid rocks have anomalously high susceptibilities. Weathering strongly decreases density and may decrease susceptibility slightly.
- Thermomagnetic analysis is a reliable method for identifying specific minerals in a sample (Hunt et al., 1995; Clark, 1997). It is particularly useful for identifying extremely fine-grained magnetic phases (< 10 µm) that can't be readily identified by thin section petrography, yet may contribute significantly to the magnetic properties (magnetic grains between 0.03-30 µm account for most remanent magnetisation: Hunt et al., 1995; Clark, 1997; Schön, 2004). As expected, this study identified multidomain and single domain magnetite and pyrrhotite as being the dominant magnetic phases. In addition, titanomagnetite and perhaps ilmenite are indicated in several samples. Massive sulphide samples show the possible presence of either goethite (especially in shallow weathered samples) or troilite (pure FeS hexagonal pyrrhotite).

- NRM is common, especially in the ultramafic rocks and sulphidic rocks. Out of 461 specimen measurements, 64 % have Koenigsberger ratios (ratio of remanent to induced magnetisation: Q = NRM / κH) > 1.0 (equal contributions from remanent and induced magnetisation), but 78 % of those specimens are from ultramafic or massive sulphide samples. Q ratios > 10.0 (remanent magnetisation 10 times stronger than induced) are observed in 17 % of all specimens and 94 % of those are from ultramafic or massive sulphide samples.
- The lack of fully oriented samples prevents quantitative directional analysis of NRM; however the axially-oriented drill core samples can be assessed in terms of the inclination and total horizontal component of NRM relative to the sample (not relative to the earth). The NRM directions almost entirely point up the core axis. When rotated into earth coordinates using the drill hole orientations, samples from steeper holes commonly retain normal polarities (upward directions), however samples from shallowly plunging holes may show either normal or reverse polarities depending on the axial rotation of the sample (which defines a small circle on a stereonet). There is major scatter of NRM directions and intensities, even within rock types. This could reflect true geological heterogeneity or complex NRM overprints.
- Some specimens show an overprinting NRM component consistent with the present-day earth's magnetic field at the lab in Canberra. This component is likely to represent a viscous remanent magnetisation (VRM). The rapid acquisition of such VRM, after only days in a particular orientation relative to the earth's field, suggests that the samples may also have acquired an overprint parallel to the earth's field while still in the ground. The net effect of such VRM is that the measured NRM intensities and Koenigsberger ratios will be overestimated, since VRM is effectively indistinguishable from induced susceptibility (Musgrave et al., 2006).
- An additional upwards vertical NRM overprint is observed in some samples from drill core. Such strong vertical overprints are commonly encountered in drill core samples due to the acquisition of isothermal remanent magnetisation (IRM) from magnetised core barrels (Pinto and McWilliams, 1990). This drilling overprint would have replaced any geological NRM components as well as any in situ VRM again resulting in overestimation of NRM intensities and Koenigsberger ratios.
- Principal component analysis (Kirschvink, 1980) was used to identify discrete NRM components where present. The possible orientations of each component can be plotted as small circles on a stereonet, in geographic coordinates for drill core samples, and sample coordinates for surface samples. This analysis is also consistent with overprints associated with drilling induced IRM and VRM acquired in the present day magnetic field, either in the lab or in the ground. In most samples these components dominate the measured NRM and in nearly all samples the NRM is completely reset at low AF strengths (< 10 mT).
- Semi-automated AF demagnetisation was not possible on sulphide-rich samples, and time-consuming manual AF demagnetisation was only performed on one sample. That sample showed a strong intrinsic remanent magnetisation with no evidence of either IRM or VRM overprinting, despite having a low coercivity. The high Koenigsberger ratio (22) and extreme NRM intensity (92,000 mA/m) of the massive sulphide sample indicate that remanence must be considered when modelling sulphide bodies, however the sample comes from a shallowly dipping hole and it is not clear whether the NRM is of normal or reverse polarity; further analysis using oriented samples would be required. The sulphide bodies are volumetrically insignificant at larger scales of observation and may be ignored in district and regional geophysical interpretations.

Attached files

- Poster
    - This is a poster I wish to present at the Mineral Exploration Roundup 2007 conference in Vancouver on January 29.

- It provides a graphical summary of the physical property measurements and interpretations I have made based on data I have acquired in this study.
- In particular these show the main cross-plots I have used, and their correlation with geological processes as observed in the rocks.

- Data
  - This Excel spreadsheet and tab-delimited text file contains all the physical property data (except AF demagnetisation and thermomagnetic analyses) acquired during this study. The fields are:

COLUMN	FIELD	DESCRIPTION
1	SPECID	My lab ID number (D = Drill core, S = surface)
2	HOLE ID	BHPB/WMC drill hole ID
3	AREA/100k SHEET	Location
4	CORE SIZE	Core diameter
5	FROM	Depth from
6	TO	Depth to
7	SAMPLE NO (BHPB)	BHPB/WMC sample ID
8	EASTING (MGA94)	Surface sample location, easting in MGA94 Zone 51. Obtained using GPS.
9	NORTHING (MGA94)	Surface sample location, northing in MGA94 Zone 51. Obtained using GPS.
10	ELEVATION (m AHD)	Surface sample location, elevation in meters obtained using GPS.
11	Field SG g/cm3 (BHPB)	BHPB/WMC density measurement (g/cm^3)
12	Field MagSus 1e-3 SI (NW)	My KT-9 field measurement of susceptibility (average of > 5 repeats) 1e-3 SI
13	NUM SPECIMENS	Number of specimens (cubes or cylinders) that I analysed per sample
14	GEOLOGY	Geology rock code, either LNO 1999 or GA/GSWA 100k map sheet
15	DESCRIPTION	Simple sample description
16	MEANDEC	Vector mean NRM declination (degrees)
17	MEANINC	Vector mean NRM inclination (degrees)
18	K	Precision parameter, a measure of dispersion of the vector measurements
19	DELTA	Angular standard deviation of dispersion of vector measurements
20	ALPHA95	0.95 confidence limit on the mean direction, equivalent to 2 standard deviations from the mean (degrees)
21	NRM (mA/m)	Geometric mean NRM intensity (mA/m)
22	NRMSTD	NRM intensity standard deviation (mA/m)
23	SUS(1e-3)	Geometric mean magnetic susceptibility (1e-3 SI)
24	SUSSTD	Magnetic susceptibility standard deviation (1e-3 SI)
25	Q	Koenigsberger ratio, Q = NRM/κH (unitless). H = 46.41 mT is the earth's field

		intensity
26	DBDEN(g/cm3)	Mean dry bulk density (g/cm3)
27	DBDENSTD	Dry bulk density standard deviation (g/cm3)
28	GRAINDEN(g/cm3)	Mean grain density (g/cm3)
29	GRAINDENSTD	Grain density standard deviation (g/cm3)
30	POROSITY(%)	Mean porosity (%)
31	POROSITYSTD	Porosity standard deviation (%)
32	THERMOMAGNETIC MINERALS	The major magnetic minerals as determined by identification of Curie points during thermomagnetic analysis. MD = multidomain; SD = single-domain. In some samples there is a curie Where interpretation is unclear, the approximate Curie temperature is indicated.
33	AF DEMAG NOTES	Indicates AF demag steps at which different NRM components are observed with an interpretation of their origin. IRM = isothermal remanent magnetisation; VRM = viscous remanent magnetisation; ChRM = characteristic remanent magnetisation, the intrinsic remanence in the sample. Soft and Hard refer to the coercivity of the ChRM.
34	OTHER NOTES	Other comments regarding the sample.

- Field versus lab plots
  - These two plots show the good correlation between field and lab measurements for the samples. The field density measurements were obtained by BHPB/WMC and come without error estimates. The field susceptibility measurements were obtained by me with repeat (> 5) measurements using a KT-9 susceptibility meter on whole core with correct core diameter corrections applied.
- Histogram plots
  - These plots my (NW) physical property measurements are broken down according to logged geology by extracting data for different rock code groups as indicated in the filenames.
  - For my measurements I overlay a line plot of normalised frequencies for each group in the BHPB dataset as a comparison. If both datasets are representative the line should trace the same shape as the histograms.
  - The vertical red bar in each plot represents the arithmetic mean for density, and the geometric mean for susceptibility, NRM intensity, and Koenigsberger ratio (Q).
  - For the ultramafic rocks which commonly show abundant sulphides, I show stacked bar graphs based on the logged sulphide abundance.
- AF demagnetisation plots
  - These technical plots summarise the results of alternating field (AF) demagnetisation to identify the components of NRM present in each sample. For an introductory explanation of paleomagnetic plots and techniques I recommend Butler (1992, available online at http://www.geo.arizona.edu/Paleomag/book/). The file naming scheme is: SPECID_ROCKCODE_R/I (where R indicates remanence is dominant with Q > 1 and NRM > 500 mA/m, and I indicates induced magnetisation is dominant).
  - TOP LEFT: The Zijderveld plot (Zijderveld, 1967) shows horizontal (map view) and vertical (cross section view) projections of the x and y (arbitrary), and up-down components of the NRM vector at each step of demagnetisation. The directions are

shown relative to sample coordinates with up-hole pointing vertically up. A single NRM component will be shown by a straight line pointing towards the origin (zero magnetisation). Multiple components may show up as bends in the line, with each straight segment representing a single component.

- TOP RIGHT: Modified Zijderveld plot where the total horizontal component (sqrt(x^2 + y^2)) is plotted instead of the arbitrary x and y in axially-oriented or unoriented samples. The directions are shown relative to sample coordinates with up-hole pointing vertically up. Where the specimen line plots parallel to either the earth's field in the lab or the earth's field in the ground (which has been rotated from geographic to sample coordinates) that component may lie in the direction of the earth's field.
- LOWER LEFT: Intensity spectrum during demagnetisation showing the NRM intensity (normalised by the initial NRM intensity) as demagnetisation progresses. The red line shows the coercivity spectrum which is just the slope, or intensity change, at each step. Most samples show soft NRM which is easily reset at low AF strengths (< 10 mT).
- LOWER RIGHT: NRM component plot in geographic coordinates (for core samples) or sample coordinates (for surface samples) on an equal angle stereonet. Solid lines and symbols are lower hemisphere projections; dashed lines and open symbols are upper hemisphere projections. Black line shows orientation of drill core with down (solid square) and up (open square) directions marked. Blue star shows orientation of present earth's magnetic at Perseverance. Blue circle shows orientation of earth's magnetic field in the lab in Canberra, rotated into geographic coordinates based on the drill core orientation. Red small circle shows the hardest NRM component (and usually the only component) observed during demagnetisation. Blue and green small circles show softer components (if present). Numbers in the top right indicate the AF strengths at which the component is observed. If a small circle passes through either of the earth's field symbols (eg. specimen D0403.1), that component is consistent with a VRM obtained under the present day earth's field either in the ground or in the lab. These samples will have NRM intensities and Koenigsberger ratios that are overestimated. Samples where the small circle is tightly centered on the sample up direction (open square; eg. specimen D2003.1) the specimen is likely showing a drilling imposed IRM, and measured NRM intensities and Koenigsberger ratios will be meaningless.

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