Fractional Crystallization, Exsolution, Rapid Uplift and Polar Reversals: Understanding the Complex Magnetic Signatures of Magmatic Ni-PGE systems.

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ABSTRACT

Magmatic Ni-PGE deposits represent some of the most magnetically challenging styles of mineralization. In the past, exploration for magmatic Ni-PGE mineralization has largely been focused on layered mafic to ultramafic intrusions, e.g., the Bushveld Complex in South Africa However, recent advances have shown that Ni-PGE mineralization is typically associated with specific intrusion types, e.g., chonoliths, bladed-dykes and funnels, that acted as high-throughput magma conduits within much larger magmatic provinces. The rocks present within these systems are compositionally diverse, and commonly display strong, stable and often complex remanent magnetization, in association with magnetite, titanomagnetite and pyrrhotite. The objective of this paper is to provide an understanding of the complexities of magnetization in magmatic Ni-PGE systems which will hopefully assist with more effective targeting, particularly in poorly explored, under-cover terrains. Some of the many issues related to magnetization in mafic-ultramafic magmatic systems are examined in this paper. We illustrate how the process of fractional crystallization in large magmatic systems can lead to magnetic zonation. In the case study on Mt Caroline we show that fractional crystallization leads to: magnetite-poor lower pyroxenite units with negligible magnetic signal; alternating Mt-rich anorthosites with strongly induced magnetization and gabbros/ gabbronorites with oppositely oriented remanent magnetisation, in the middle to upper layers. Remanent magnetisation is often not related to cooling of magma but to exsolution, uplift and/or metamorphism. We discuss how the process of exsolution in titanomagnetite can lead to extremely strong and stable remanent magnetization in mafic rocks. Using a case study on Mount Harcus, we demonstrate that an understanding of both the magnetic properties and remanence directions can be used to improve drill targeting in such systems. We explore how the timing of major tectonic uplift episodes and/or metamorphic events can be the main determinant of the remanent magnetisation vectors in many mafic intrusions. Furthermore, we illustrate how contemporaneous rocks can have very different magnetic signatures due to recording similar intensity magnetisations of opposite polarity.

INTRODUCTION

Magmatic Ni-PGE deposits represent some of the more magnetically complex styles of mineralization. In the past, exploration for magmatic Ni-PGE mineralization has largely been focused on layered mafic to ultramafic intrusions, e.g., the Bushveld Complex (Fig 1a) in South Africa or the Skaergaard Intrusion (Greenland). However, recent advances by Barnes et al. (2015), Lightfoot and Evans-Lamswood (2015) and Saumur et al. (2015) have shown that Ni-PGE mineralization is typically associated with specific intrusion types, e.g., chonoliths, bladed-dykes and funnels (Figure 1b-f), that acted as high-throughput magma conduits within much larger magmatic provinces (Le Vaillant et al., 2017). The rocks present within these systems are compositionally diverse, and commonly display strong, stable and often complex remanent magnetization, in association with magnetite, titanomagnetite and pyrrhotite.

In this paper we examine some of the issues related to magnetization in mafic-ultramafic magmatic systems, and explore how magma composition, emplacement mechanics, cooling history, tectonic uplift, and metamorphism can all play a part in the overall magnetic signature of magmatic Ni-PGE systems.

The paper combines insights from a number of case studies from central and NW Australia, and attempts to describe (in simple terms) the processes that control remanent magnetization in magmatic Ni-PGE systems, including:

1. How does the process of fractional crystallization influence magnetic properties in mafic rocks?
2. How is extremely strong and stable remanent magnetization formed in mafic rocks?
3. How can completely different mafic rocks have identical remanence directions?
4. How can almost identical rocks have completely different magnetic signatures?

The goal is to provide an understanding of the complexities of magnetization in magmatic Ni-PGE systems which will hopefully assist with more effective targeting, particularly in poorly explored, under-cover terrains.
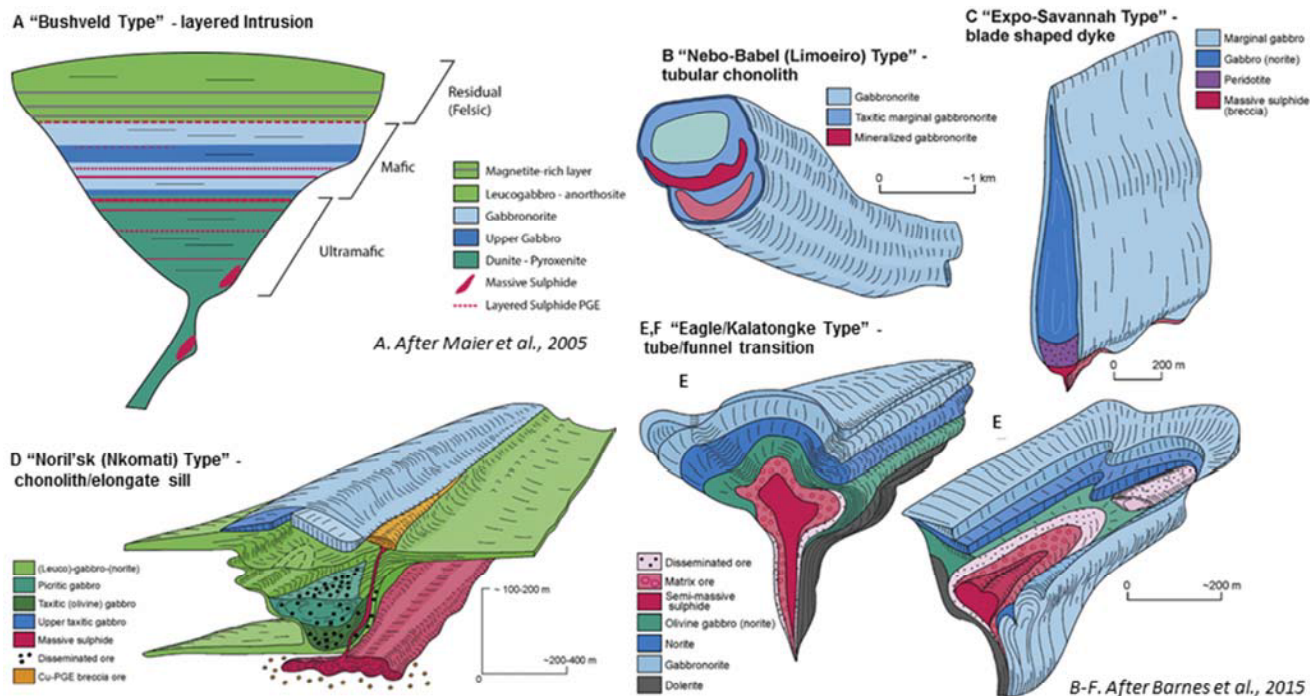
Figure 1: Schematics illustrating the different styles of zonation within sub-types of magmatic Ni±Cu±Cr±PGE systems.

1: FRACTONAL CRYSTALIZATION

Fractional crystallization is (in simple terms) the removal and segregation from a melt of mineral precipitates, i.e., crystals which sink to form a cumulate at the base of the intrusion, thus changing the composition of the magma. The minerals that make up igneous rocks crystallize at a range of different temperatures, so a cooling magma can have some crystals within it and yet remain predominantly liquid. For example, in mafic-ultramafic magmas, orthopyroxene, clinopyroxene and olivine typically crystalize early in the cooling history of an intrusion, and sink to the bottom of the magma chamber to form pyroxenite and dunite. However, the exact species of, and composition of the crystals precipitated varies substantially, based on the composition of the magma, and to some degree the size and architecture of the intrusion and the rate of cooling.

The following is a case study of the magnetic properties of the Mt Caroline Intrusion (Fig 2), Musgrave Block, Central Australia, in which we specifically look at how fractional crystallization influences the layering of different lithologies within an intrusion, and also the associated petrophysical properties (in particular the style of magnetization) within those lithologies. The details may differ from other layered intrusions, but the principles are similar.
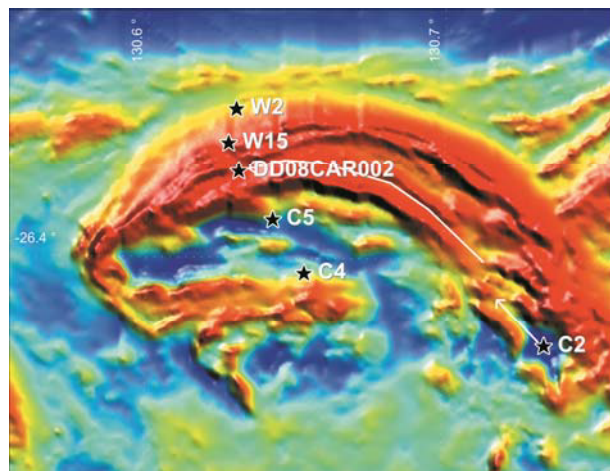

Figure 2: Total magnetic intensity grid over the Mount Caroline layered intrusion in NW South Australia, detailing the positions of drill-holes from which samples were obtained for this study.

A petrophysical study was completed by Austin (2016) and reported in Austin et al. (2016), in which five individual drill holes, forming a fence line across the layering of the Mount Caroline intrusion, were sampled (Fig 2). W2 samples the lowermost basal unit, W15 samples the upper

part of the basal unit, C5 samples the highly magnetic parts of the middle to upper units, whilst C2 and C4 sample the more weakly magnetic parts. The results of the petrophysical analyses are discussed sequentially from the base of the intrusion (the non-weakly magnetic zone in Fig 3) and the middle to upper layers (the moderate-highly magnetic zones in Fig 3).
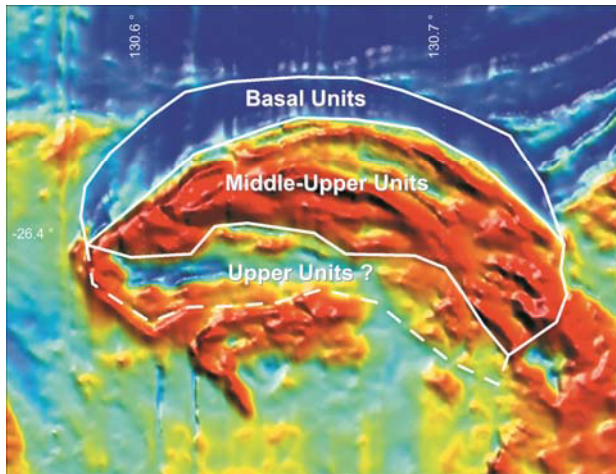
Figure 3: Reduced to pole magnetic grid over the Mount Caroline Layered intrusion in NW South Australia, detailing the approximate positions of the different zones of the intrusion.

Basal Layers

As with many large mafic-ultramafic intrusions, the first minerals precipitated at Mt Caroline were pyroxene-rich cumulates, comprised of orthopyroxene, clinopyroxene and plagioclase. In Mount Caroline, the basal units (sampled by W2 and W15) have bi-modal base density values; some are quite high (~3.3-3-4 g/cc) whereas other are more typical of mafic rocks (~3.0 g/cc) (Fig 4). The higher density values cannot be explained by pyrrhotite which, although present is not present in significant abundance. Based on a basic petrological inspection it would appear that the denser specimens are pyroxenites (made up almost entirely of pyroxene), whereas the lower density samples have significant plagioclase in addition to pyroxene (i.e., are Gabbronorites). Pyroxene minerals commonly have densities of between 3.3 and 3.5, and hence a pyroxene rich rock can easily give rise to densities of 3.3-3.42 g/cc. Any increase in the feldspar content (density ~2.7 g/cc) reduces the bulk rock density substantially, and hence, the density of the basal units are inversely proportional to their plagioclase content.
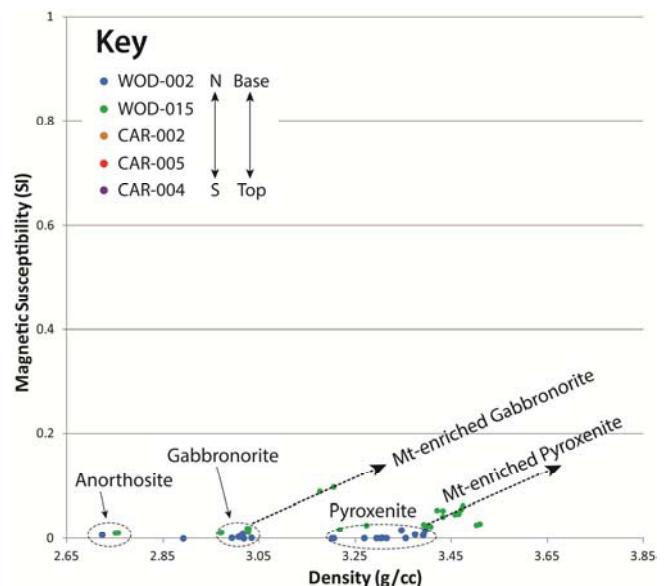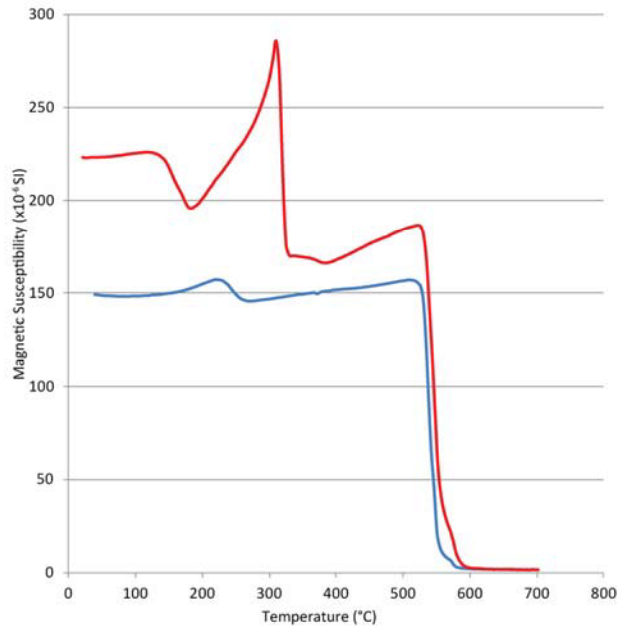

Figure 4: Plot of magnetic susceptibility vs density for the two holes that sampled the lowermost horizons of the Mount Caroline layered intrusion. The rock types are inferred from their base density, i.e., the density of the rocks with ~0 SI susceptibility. Linear trends of increased susceptibility imply magnetite- or pyrrhotite enrichment within that lithology.

The lowermost section of the basal unit sampled by (W2) are for the most part weakly magnetic, with very low susceptibility <0.01 SI, averaging 0.004 SI. Only 2 samples had elevated susceptibility (~0.1 SI) and remanent magnetization (>10 A/m), associated with high Koenigsberger ratios. At least some of the samples near the base of the intrusion contain significant pyrrhotite, along with considerable magnetite as indicated by the sharp susceptibility spike at ~320°C and sharp drop at 560-580°C in the temperature susceptibility curve for sample W2-152 (Fig 5). The primary directions obtained from these samples, and a number of nearby samples are more-or-less consistent, and are oriented shallow up toward the N-NNW. In the majority of other samples, the bulk of the magnetization intensity corresponds to low coercivity (soft) magnetization held in multi-domain (MD) magnetite. These low stability magnetizations are usually fairly conspicuous, commonly oriented anti-parallel to the drilling orientation of the hole (i.e., drilling induced magnetisation; DIM) and/ or parallel to the Earth's magnetic field (i.e., viscous remanent magnetization; VRM).

Samples from the upper part basal unit (W15) are more magnetic than the samples from drill-hole W2. This reflects Mt-enrichment of the magma at stratigraphically higher

positions in the intrusion. They have low to moderate susceptibilities 0.01-0.1 SI, averaging 0.035 SI.

Figure 5: Plots Magnetic Susceptibility vs temperature for sample W2-152A. Red represents the heating cycle and blue the cooling cycle. The heating curve suggests that pyrrhotite and magnetite are both significant magnetic carriers in this sample, as indicate by the sharp spike (associated with pyrrhotite) at ~300°C and the sharp decline in susceptibility at ~580°C indicating magnetite.

Middle to Upper Layers

As the precipitation of pyroxene-rich cumulates continues the magma composition becomes increasingly felsic, and precipitation of pyroxenite becomes less common toward the middle layers of the intrusion. Gabbronorite continues to form, but now it is increasingly interlayered with plagioclase and magnetite-rich units e.g., leucogabbro, leucogabbronorite, and anorthosite. The exact processes by which magnetite-rich horizons are precipitated is poorly understood, but Reynolds (1985), suggests it is triggered by episodic increases in f_{O2} (oxygen fugacity). In the Mt Caroline Layered Intrusion, the magnetite is relatively disseminated, mainly within plagioclase. However, in other layered intrusions magnetite can be semi-massive, e.g., the Bushveld Complex (Fig 6).

For the purpose of simplicity we have divided the upper parts of the intrusion into two broad categories; 1. Mt-rich

horizons; 2. Gabbronorites (Mt-poor horizons), and the two are discussed separately below.
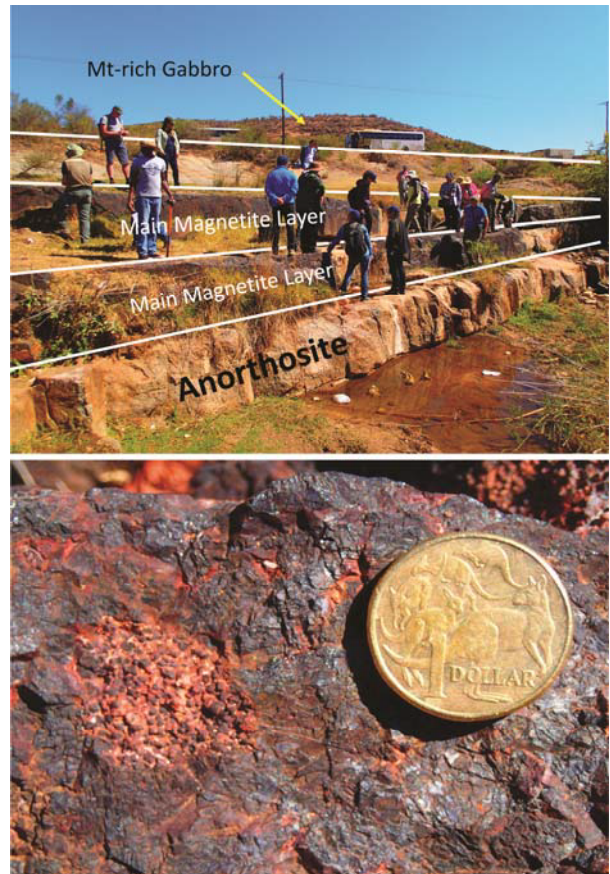
Figure 6: Top. The Main magnetite layer in the upper Bushveld Complex is interlayered with anorthosite and Mt-rich gabbro; Bottom. Magnetite is typically semi-massive, but also forms inclusions in poikilitic plagioclase grains.

Mt-rich layers

Drill hole CAR-005 primarily samples the more magnetite-saturated horizons which are interlayered with magnetite-poorer horizons in the central and upper units (Fig 3). In general the Mt-rich upper layers have high densities (3.2-3.55), high susceptibilities (0.1-0.4 SI) and high NRMs, all indicative of high proportions of magnetite. In this case the main linear trend in the MagSus vs Density plot (Fig 7) intersects the x-axis at ~2.75 g/cc indicating pyroxene-poor lithologies (e.g., anorthosite, leucogabbro and leucogabbronorite,) as noted by Godel et al., (2014). As such, both the density and magnetic susceptibility of this horizon are primarily controlled by magnetite-content.
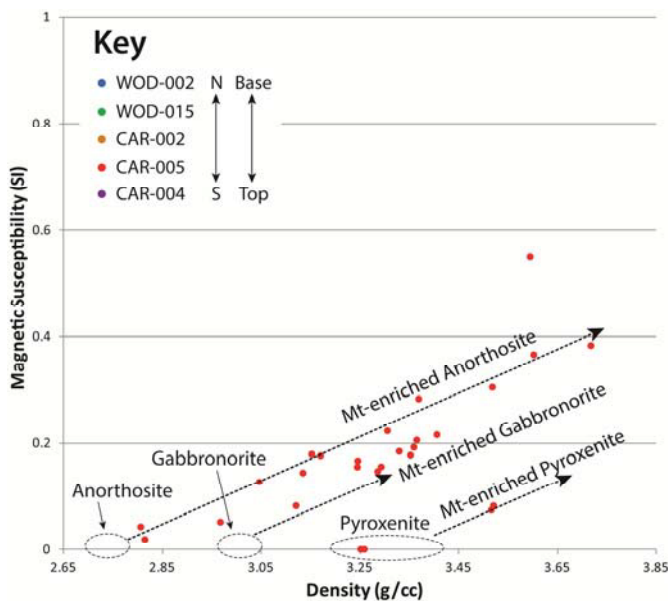
Figure 7: Plot of magnetic susceptibility vs density for drill hole C5 which predominantly samples Mt-rich parts of the middle to upper units of the Mount Caroline intrusion.

The Koenigsberger ratios of the majority of rocks sampled by this drill hole are all relatively low (e.g., 2- 5). However, this number is misleading, because the majority of the magnetization is held in multi-domain (MD) magnetite (see Fig 16). Consequently in the Mt-rich layers:

1. Remanence is very soft (low coercivity), as evidenced by liquid nitrogen cleaning which removes ~80% of the total remanent magnetization.

2. The remanence can be easily reset, and the directions measured are commonly either parallel to the drilling directions, parallel to the Earth's local magnetic field or simply just scattered (palaeomagnetic noise).

3. The *in situ* remanent magnetization would almost certainly have been parallel to the local magnetic field.

4. The remanence and by association the Koenigsberger ratio are in many cases artificially enhanced by ~300% by drilling induced magnetization (DIM; e.g., Austin et al., 2017b).

Together this implies that such rocks can essentially be treated as a purely induced magnetization for modelling purposes. However, magnetization intensities will be substantially (e.g., 1.5 to 3 times) higher than the measured magnetic susceptibility values for this, or similar layers.

Mt-poor Gabbronorite Layers

Drill holes C2 and C4 primarily sample the Mt-poor gabbronorite horizons which are interlayered with Mt-rich anorthosite horizons in the central and upper units (Fig 8). The stratigraphically lower part of the central unit is sampled by drill hole C2, sitting along strike to the SE of its relative position on fencepost line (Fig 2). C4 samples an equivalent but "stratigraphically" higher unit.
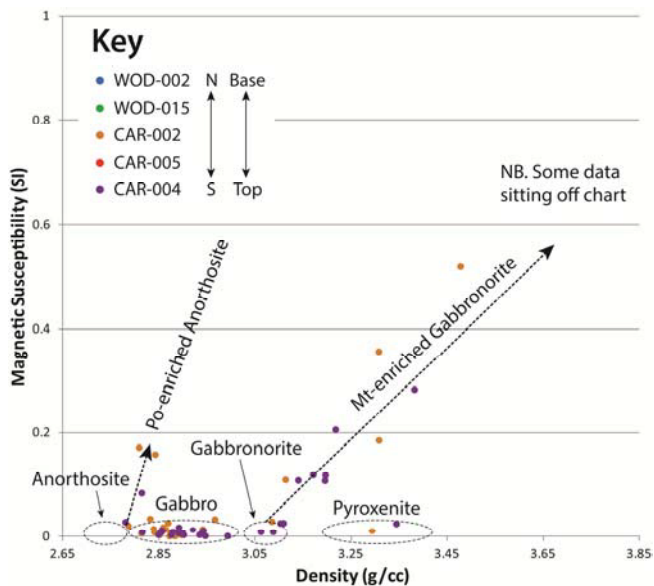
Figure 8: Plot of Magnetic Susceptibility vs density for drill holes C2 and C4 which predominantly sample Mt-poor gabbro and gabbronorite within the middle to upper units of the Mount Caroline intrusion.

The average values for density from these holes are 2.96 and 3.05 g/cc respectively, while the average susceptibilities are 0.07 and 0.09 SI respectively. However, both these units have a bi-modal distribution of properties (MagSus, Density and to some extent NRM). The majority of samples are relatively non-magnetic, with an average susceptibility of ~0.02 SI and densities of 2.91 and 2.95 c/cc respectively. In this case the bi-modal nature does not appear to be related purely to lithological differences, but also to variability in the proportion of magnetite. In these horizons the majority of the base lithologies are gabbros. However, the magnetite-rich samples appear to have a base composition of gabbronorite (based on their densities). This would appear to suggest that magma is fractionating, crystallizing a Mt-poor gabbro/ leuco-gabbronorite and a magnetite-rich gabbronorite.

The remanent magnetization intensity is proportional to susceptibility and density for the most part, and hence is primarily a function of magnetite content. Many of the samples from drill-holes C2 and C4 are overprinted by DIM but to far lesser extent than for samples from drill-hole C5. Where elevated Koenigsberger ratios (e.g., >5) are present they appear to be coincident with visible pyrrhotite.

Other than these Mt+Po enriched samples, which are magnetically soft, the majority of the samples appear to have recorded stable remanent magnetization which is consistent with single domain (SD), or pseudo single-domain magnetite (see Fig 16). Many of the rocks have an initial magnetization that is parallel to the drilling orientation, but during progressive demagnetization, the magnetization directions migrate toward a few distinct orientations, mostly in the lower southern quadrant. In most cases the stepwise demagnetization path of the individual samples are quite different, and the orientation of the pre-existing magnetization is not fully resolved.

A temperature-susceptibility plot of a typical sample (C4-91) indicated that the stable magnetization is associated with magnetite. However, a small bump at around 300°C on the heating curve, implies a small amount of pyrrhotite may also be present. In general the stable magnetizations are oriented moderate down to the SE-SW, i.e., approximately opposite to the inducing field (further discussed in section 4). This is significant though because it essentially means that within the middle to upper layers of the intrusion, the magnetic properties switch, from a strongly induced magnetization (i.e., parallel to the Earth's magnetic field) in Mt-rich anorthosites, to a primarily remanent magnetization in gabbros/ gabbronorites, which, in this case, is typically opposite to the Earth's current magnetic field. Therefore, there are interlayered strongly positive and negative anomalies. These anomalies overlap, and interfere with each other and magnetizations are misrepresented by the measured aeromagnetic data (measured from altitude), making the results of forward modelling and unconstrained inversions misleading.

Conclusions

We have known for a long time that fractional crystallization causes a general decrease in density toward the top of a layered intrusion (i.e., N to S in the density model for Mount Caroline; Fig 9). Fractional crystallization also plays a role in determination of the magnetic properties of a layered intrusion. The exact style of magnetizations will be dependent on a number of factors including: the size and shape of the intrusion; the original magma composition; and the subsequent cooling, uplift and metamorphic history of the intrusion. In the case of Mount Caroline at least there are clear petrophysical distinctions between the basal units and middle to upper units.

The basal units are generally pyroxene-rich and overall relatively dense. They have a bi-modal density distribution, caused by alternating pyroxenite and gabbronorite. They are generally very magnetite-poor, have low magnetic susceptibilities (e.g., Fig 10) and have only a weak magnetic signature (e.g., Fig 2). As fractional

crystallization continues, the precipitated lithologies become increasingly plagioclase-rich toward the top of the intrusion (e.g., anorthosites, present at the top of the Bushveld Complex). Anorthosites typically have low magnetic susceptibility and density, unless they contain significant proportions of magnetite.
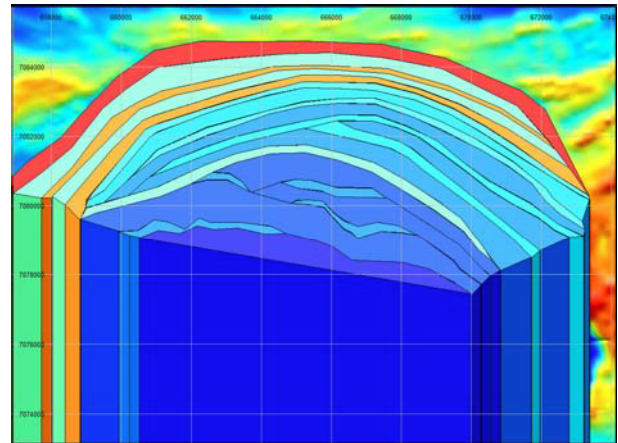
Figure 9: A schematic density model of the Mount Caroline Intrusion, was generated by constrained magnetic modelling, and subsequent populated with measured densities from the same lithology. NB. It could not be derived from gravity modelling mainly due to the lack of detailed data. Warmer colors= higher densities, blue=lower (max=3.4, Min 2.7).
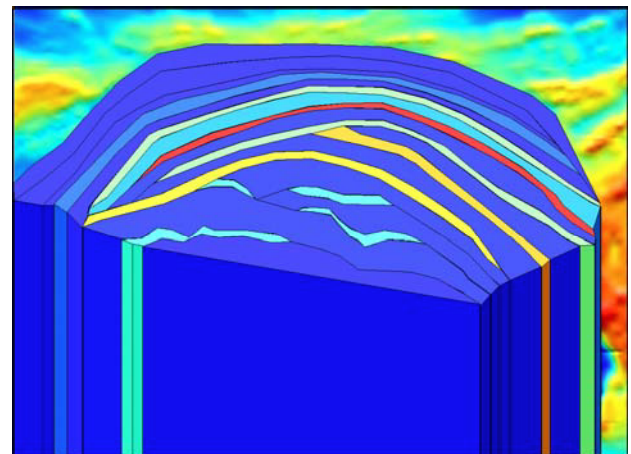
Figure 10: A schematic magnetic model of the Mount Caroline intrusion, was generated by constrained magnetic modelling in ModelVisionPro™. Whilst both magnetic susceptibility and remanent magnetization were used to constrain the model, only modelled magnetic susceptibilities are shown. However, the lows in the middle part of the intrusion actually corresponds to moderate remanet magnetization oriented oppositely to the inducing field. Warmer colours=higher susceptibilities, blue=lower (max=0.5, Min 0.0).

The middle to upper units typically contain pyroxene, plagioclase and magnetite. They have a spread of densities, mainly as a result of variation in magnetite content. There are two main alternating lithologies in the middle part of the intrusion: Mt-rich plagioclase-rich rocks (e.g., anorthosite, leucogabbro and leucogabbronorite); and Mt-poor rocks which contain pyroxene and plagioclase (gabbro and gabbronorite). These two rock types have markedly different magnetic properties. The former has a strong induced magnetization as indicated by the high susceptibility layers in Fig 10). The latter have weaker susceptibility, but moderate oppositely oriented remanent magnetization (represented as blue zones in the susceptibility model, Fig 9). Such interlayered strongly positive and weakly negative anomalies overlap and consequently misrepresent the in situ magnetization of the rocks, making forward modelling and inversions very problematic.

2. EXSOLUTION

Introduction

It is commonly assumed that igneous rocks, acquire remanent magnetization when they crystallize. Whilst this might be more-or-less true for volcanic rocks, it is definitely not true of all rocks. For example, large volumes of very hot (~1300°C) magma, which crystallize very slowly, deep in the crust (e.g., mafic to-ultramafic intrusions which give rise the magmatic Ni-PGE mineralization) may take many millions of years to cool through the Curie point. However, there are other factors that control not only the magnetization vectors imparted to the rocks (as will be discussed in sections 3 and 4), but also the style of the magnetization imparted, i.e., its strength (intensity) and stability (coercivity).

In this case study we examine another intrusion from the Musgrave Block in NW South Australia, known as the Mount Harcus intrusion. Mount Harcus is of approximately the same age at the Mount Caroline intrusion (*ca* 1070 Ma*;* the Giles Event) but has a very different style of magnetic anomaly. It is associated with a large negative magnetic anomaly (Fig 11) that is clearly caused by strong, downward oriented remanent magnetization. Unconstrained modelling of the intrusion suggested that the causative source was a N-S elongate, moderately east-dipping tabular body (Fig 12).

A palaeomagnetic study on Mount Harcus was undertaken by Austin et al. (2014), who sampled 5 drill holes into the Mount Harcus intrusion and one into a similar body to the NNW (Fig 11). Measurements of density and magnetic susceptibility were made on all 556 specimen from some 186 samples, and one specimen from each samples was subjected to AF demagnetization and thermal demagnetization respectively.

The magnetic susceptibility and density results from Mt Harcus are subtly different to those from Mt Caroline (Fig 13). At Mount Harcus petrophysical properties are much more homogeneous, and the lithologies are dominated by Mt-rich gabbros and Mt-poor gabbronorites. Whilst there are some pyroxenites and Mt-rich anorthosites present these are minor. The styles of mineralogy are consistent with lithologies expected toward the top of a layered intrusion. However the shape of the anomaly, and by association the intrusion, is not consistent with a typical layered intrusion (i.e., it is more consistent with a dyke), and the magnetic anomaly observed is very different to that at Mt Caroline. Clearly very different processes controlled both cooling/ crystallization and the acquisition of magnetization at the two intrusions.
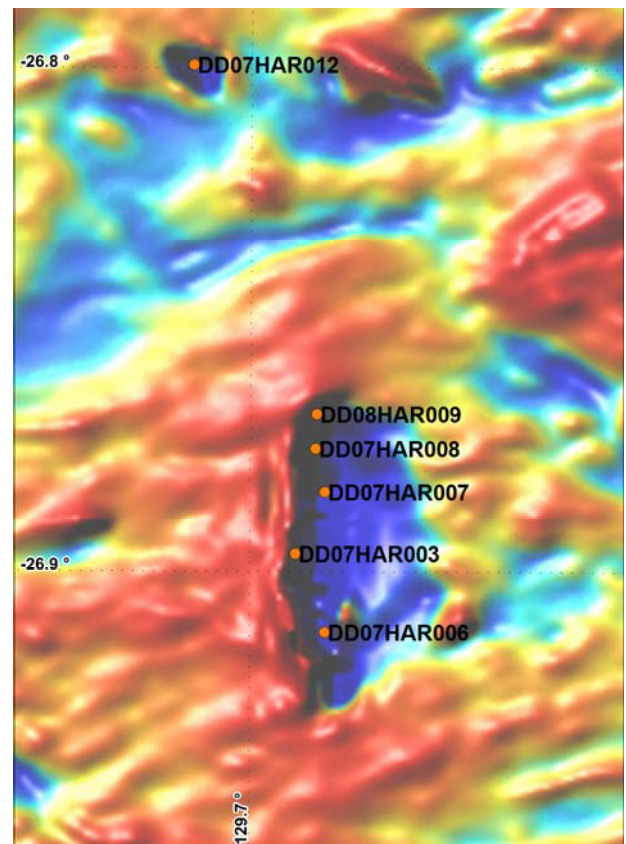
Figure 11: Total magnetic intensity grid over the Mt Harcus Intrusion, and the 6 drill holes from which samples were obtained for this study.
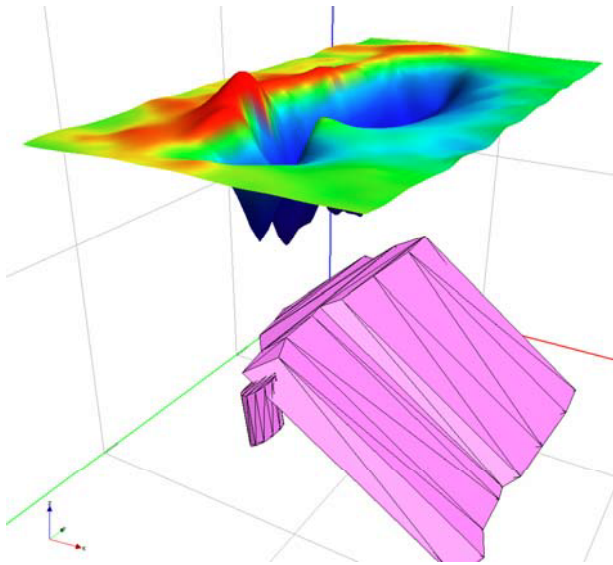
Figure 12: An unconstrained inversion of TMI data over Mount Harcus

Remanent Magnetization

Both alternating field and thermal demagnetization studies revealed that the remanent magnetization at Mount Harcus was very stable. In many cases there was no significant loss of remanent magnetisation intensity until the Curie point of magnetite, as shown in Fig 14. This style of remanence is very stable (i.e., it has a high coercivity). Magnetite is present as discrete large grains, however, the demagnetization behavior is clearly indicative of single domain grains. A parallel study by McEnroe et al., (2015) demonstrated that the large magnetite grains contain microstructures, reduction exsolution lamellae of magnetite in ilmenite (Fig 15), and fine-grained magnetite inclusions in silicate phases. So in this case the extremely stable (high coercivity) magnetization present in the majority of samples from Mount Harcus is due to the style of the grains. In general the style of magnetic grain, exercises a large control over both the magnetic stability of the grain, and to some extent the intensity of the magnetization within that grain.

Multidomain (MD) magnetite is coarse-grained (>10µm), and it cannot retain remanent magnetization over long time periods. Because the grains are so large, the internal structure tends to form magnetic sub-domains (e.g., Fig 16a). These domain walls can move easily under low temperature and pressure to reduce magnetostatic energy in the grain, and re-align the magnetization with any change in the external magnetic field.

Single domain magnetite is fine-grained, and has the ability to carry very stable remanent magnetization. Because the grains are small they cannot form internal walls in order to form the self-cancelling domains found in MD magnetite (e.g., Fig 16b). This means that the magnetization direction present can only be changed by exposure to high temperatures, or to extreme electromagnetic fields (e.g., from lightning strikes).
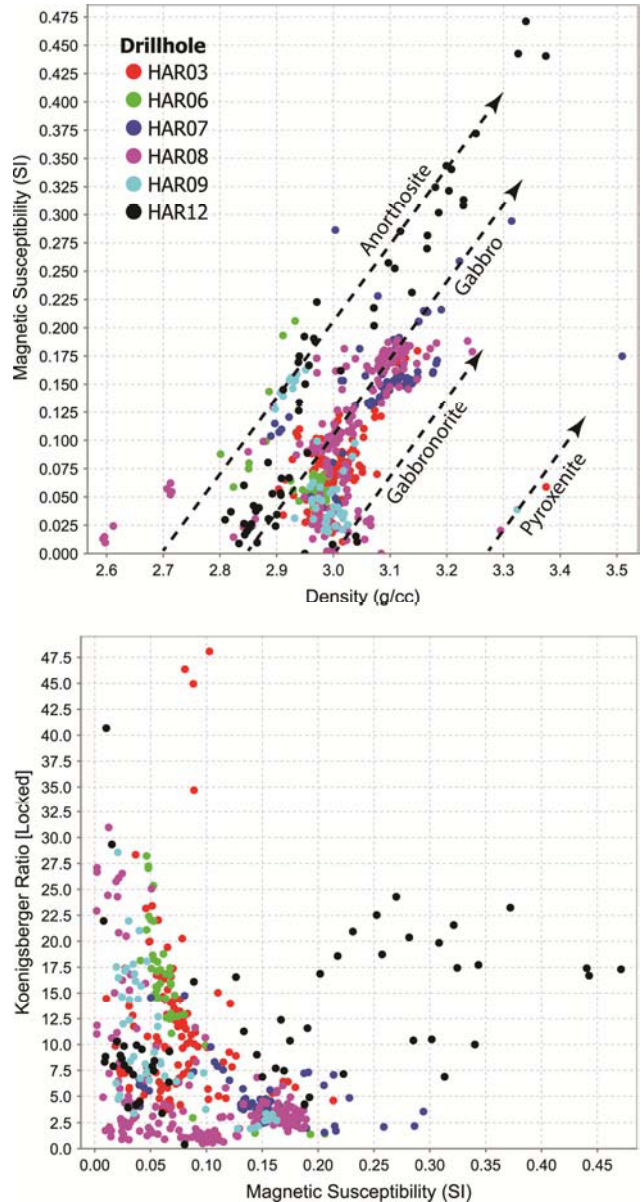
Figure 13: (Top) Plot of magnetic susceptibility vs density for the Mount Harcus intrusion. (Below). Plot of Koenigsberger ratio vs magnetic susceptibility.
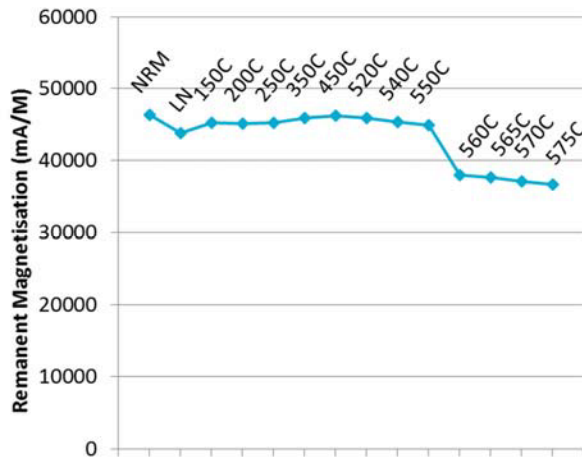
Figure 14: A plot of remanent magnetization intensity with successive thermal demagnetization for sample HAR008-142, illustrates that the magnetization is very stable up to the Curie point of magnetite. This is consistent with single domain magnetite.

Exsolution textures are common in mafic to ultramafic magmatic rocks. They form long after titanomagnetite crystallization, which occurs at high temperatures (~1200°C), occurring at approximately 580-600°C. At this time the titanomagnetite grains exsolve into magnetite and ilmenite, and typically form intergrowths with elongate, blade-like textures (e.g., Fig 15). Whilst the ilmenite is less magnetic, the resulting partitioning of the magnetite grains can lead to more extreme remanence in the rock. Platy grains such as exsolution lamellae can carry extreme remanence, typically 2-3 times higher than for equivalent volumes of more equant grains. This is because they carry a large amount of charge relative to their size (i.e., they have a large surface to volume ratio) as illustrated by Figure 16c. Furthermore, because of their complex shape, they are highly resistant to overprinting by other magnetizations (e.g., subsequent metamorphic events).
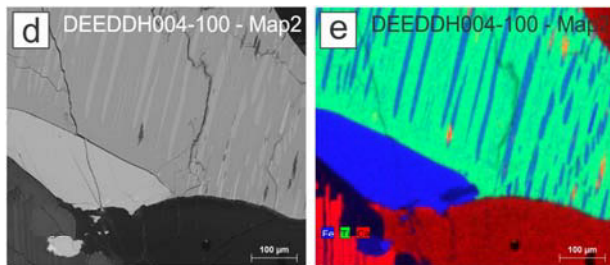

Figure 15: Mineralogy of sample DEEDDH004-100 (from a nearby intrusion) as determined by scanning electron microscopy. The left image is greyscale whereas the right image is coloured to show the chemistry of the grains. In this case the green grain in ilmenite and the blue grains are magnetite (From Godel et al., 2016).
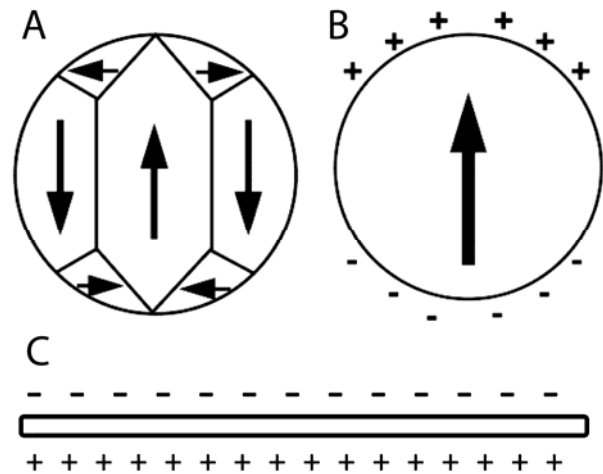

Figure 16: Illustrations of the way in which charge is carried in different types of magnetic grains. A. Multidomain (MD) grain, B. Single-domain (SD) grain, and; C. a platy single-domain grain (e.g., exsolution texture). After Butler, 1998.

Magnetization directions for Mt Harcus were determined by conducting principal component analyses on the results of both AF and thermal demagnetization studies. The resultant magnetization directions are typical of lithologies in which magnetization is held in exsolution lamellae. There is relatively little scatter in the resultant magnetizations and overall the data form a tight cluster (in this case moderate down to the NW remanent magnetization direction) for the entire intrusion. These relatively consistent directions can be used to constrain modelling of the intrusion, and can also be used to deduce information about the time at which the exsolution occurred (by calculating a palaeomagnetic pole).
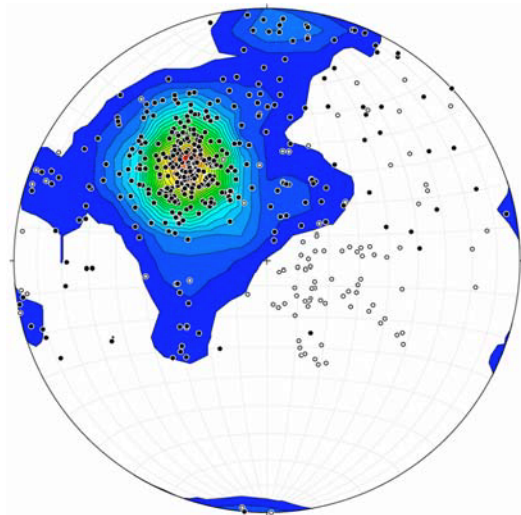

Figure 17: Stereonet showing the resultant magnetization directions for Mount Harcus, determined from principle component analyses of demagnetization data.

Modelling and Implications

The previous un-constrained model of Mt Harcus consisted of a reasonably homogeneous body which was dipping moderately to the east (Fig 12). However, the dip of a body and the magnetization of a body can trade-off against each other, particularly for tabular bodies. The petrophysical data obtained in this study allowed us to constrain the magnetization vector in the modelling procedure and this forces the body to become sub-vertical in order to fit the aeromagnetic data sufficiently (as shown in Fig 18).
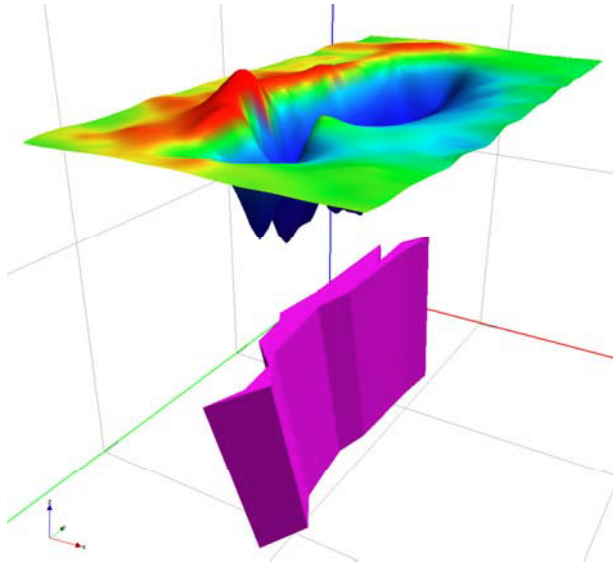

Figure 18: A constrained inversion of TMI data over Mount Harcus indicated that the body is sub-vertical.

Given that we now know that the body is sub-vertical, and that we have likely intersected lithologies consistent with the upper part of a layered system, it is hence likely that Mount Harcus is a bladed dyke style intrusion, and that the best potential for mineralization would be toward the base. In hindsight then it would have been optimal to drill through the middle of the intrusion to test for mineralization at the base (Fig 19).
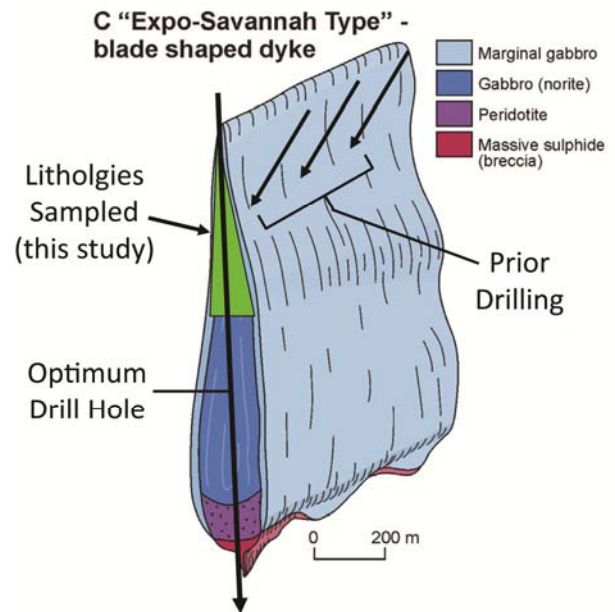

Figure 19: Our petrophysical data and constrained modelling for Mount Harcus suggest it is a bladed dyke

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UPLIFT AND METAMORPHISM

Rocks can record a number of different magnetizations, and these can be related to a number of different events, including cooling and/ or exsolution reactions. However, we often fail to consider that the most critical factor that controls the magnetization direction is when the rock cools through the Curie point. The Curie point is different in different types of minerals as shown in Table 1, but in the case of magnetite it is approximately the same temperature at which titanomagnetite exsolves. For pyrrhotite the Curie point is much lower, and this is significant for metamorphic events in particular.

Generally, we assume that rocks will cool through the Curie point very soon after crystallization. Whilst this is usually true for volcanic rocks and near surface intrusions, if rocks are intruded deep in the crust (e.g., >20km), or if they are subsequently tectonically moved into the mid-lower crust, it may take hundreds of millions of years for the dominant magnetization(s) to be imparted.

Table 1: Common magnetic minerals, and their typical susceptibilities, Koenigsberger ratios (Q) and Curie points.

Mineral	Formula	Mag Sus (SI)	Q	Curie point
Magnetite (MD)	$Fe^{3+}_2Fe^{2+}O_4$	3.8-10.0	0.05-0.5	580°C
Maghemite	Fe2O3	variable	0.05-0.5	545-675°C
Ilmenite	Fe_2TiO_3	0.03 - 3.5	?	50-300°C
Pyrrhotite (m-clin)	Fe_7S_8	variable	1-500	320°C
Hematite	$Fe^{3+}_2O_3$	0.0005 - 0.01	30-1000	685°C

Here we present some results from the several palaeomagnetic studies on mafic rock from both the

Musgrave (Godel et al., 2014; Austin, 2016) and the Arunta (Austin, 2014, Austin and Crawford, in prep) in Central Australia. We evaluate the magnetic signatures deduced in the context of the tectonic development of central Australia. All magnetizations are presented as poles and are visualized on apparent polar wander paths (Figs 20)

The Musgrave Block

A regional study (Godel et al., 2014) took field samples of mafic rocks and sampled drill core from mafic rocks across the Musgrave Block, in central Australia. The samples come from a number of regions within the Musgrave and occur within different structural domains that have different thermal and tectonic histories. The main areas in which surface drilling was undertaken are the Mimili Area (SE) and the Deering Hills (NW). Samples were extracted from numerous drill-holes, including from the Kalka Intrusion, Mount Harcus (discussed earlier), Na Toth, Pallatu and Vaylen Prospects. The magnetizations in the surface drilled samples were commonly effected by lightning induced magnetization (LIM), whereas the samples from drill-core are typically affected by drilling induced magnetization (DIM; see Austin et al., 2017b). In some cases (e.g., surface samples immediately adjacent to a lighting strike) only LIM was present and other cases (e.g., diamond drilled Mt-rich samples) only DIM was present. However, more commonly, LIM and DIM mainly affect the low coercivity components and were removed using low temperature demagnetization ± low intensity alternating fields.

After removal of the low coercivity components, there are several main directions present in the palaeomagnetic data. However, the main directions revealed by principal component analyses were sub-horizontal, SW, WNW and ESE magnetizations. Apparent poles generated from these data are shown in Fig 20. These data show that despite the ~1070 Ma age of the mafic intrusions in the Musgrave, the magnetizations are consistent with much later events, in particular, the Petermann Orogeny and the initial stages of the Alice Springs Orogeny.

Mt Caroline

The samples obtained from Mt Caroline (discussed previously) are better spatially clustered than those from the previous regional dataset. Nevertheless, these samples also display a number of different magnetization directions, particularly in the Mt-poor gabbro and gabbronorite from the middle to upper layers. Many of the rocks have initial magnetization directions that are parallel to the drilling orientation, but during progressive demagnetization, the directions migrate toward a few distinct orientations, mostly in the lower southern quadrant. In most cases the migration paths of the individual samples

are quite different, and the orientation of the pre-existing magnetization is not fully resolved in many instances (*cf.* C4-91A). However, we can infer the original magnetization by tracing the migration paths to the points where the paths of the individual samples would intersect. We can infer that the point(s) of intersection of all the individual paths are the point(s) from which all the magnetization(s) migrated toward the drilling orientation, and hence that it is a primary, or at least significant secondary magnetization directions. Unfortunately in this case, the different demagnetization trends present in the rocks from CAR-002 and CAR-004 illustrate that more than one final direction is present. Hence, there are a few ways to interpret the results.

The demagnetization path of many samples appear to be trending toward a sub-horizontal WSW orientation. Such orientations have been measured elsewhere in the Musgrave (e.g., Godel et al., 2014), and the directions obtained are consistent with a timing of about 445 Ma (Fig 21), i.e., consistent with the Petermann Orogeny. Another direction indicated by many of the samples from CAR-002 and CAR-004 appears to be a moderate - steep, downward oriented magnetization plotting in the SE quadrant. These are consistent with the early- to middle- Alice Springs Orogeny (Fig 21) and similar magnetizations have been measured elsewhere, particularly in the Arunta (Austin, 2014). The steep SSE- directions correspond with the latest Alice Springs Orogeny, at about 330-300 Ma and are consistent with magnetisations measured in both the Arunta and Amadeus Basin (Austin, 2014).

Several of the demagnetization paths also appear to be migrating toward a moderate down to the NW magnetization direction, which is consistent with magnetizations measured at Mount Harcus by Austin et al. (2014). These are likely to be the oldest magnetizations. However, it is unlikely that they are significantly older than 445 Ma. These magnetizations likely correspond to the exhumation of the then lower crustal rocks by ~30-40 km (Edgoose et al., 2004) during the Petermann Orogeny. Even assuming a fairly modest thermal gradient of 30°C/km, these rocks would have been well in excess of the temperatures at which rocks acquire magnetization. Furthermore, at temperatures beyond ~600°C the titanomagnetite, in which the most stable magnetizations are held, would not yet have had an opportunity to exsolve into magnetite and ilmenite. Hence, the carrier mineral of the stable magnetization (i.e., the exsolved magnetite lamellae) could not have existed at such depths and temperatures, let alone cooled through the Curie point prior to exhumation in the Petermann Orogeny.

These rocks do display remanence, and they may preserve a number of different remanent magnetization directions.

However, none of those directions are consistent with the age of initial cooling of the magma. They were acquired during different thermal events. The primary event would have been during the Petermann Orogeny, and the second two are simply low(er) temperature overprints, which would mostly affect softer (lower coercivity) magnetizations. Hence, the magnetization directions recorded in each of the rocks studied are mainly a function of the mineralogy and coercivity (grainsize) of the carrier minerals. Exsolution lamellae may be more likely to retain older magnetisations, but very few if any appear to be consistent with the crystallization age. We cannot use these observations to determine a specific magnetization direction for Giles-aged intrusions. All we can really deduce is that any post-Petermann magnetisations are possible in Giles-aged intrusions in the Musgrave.
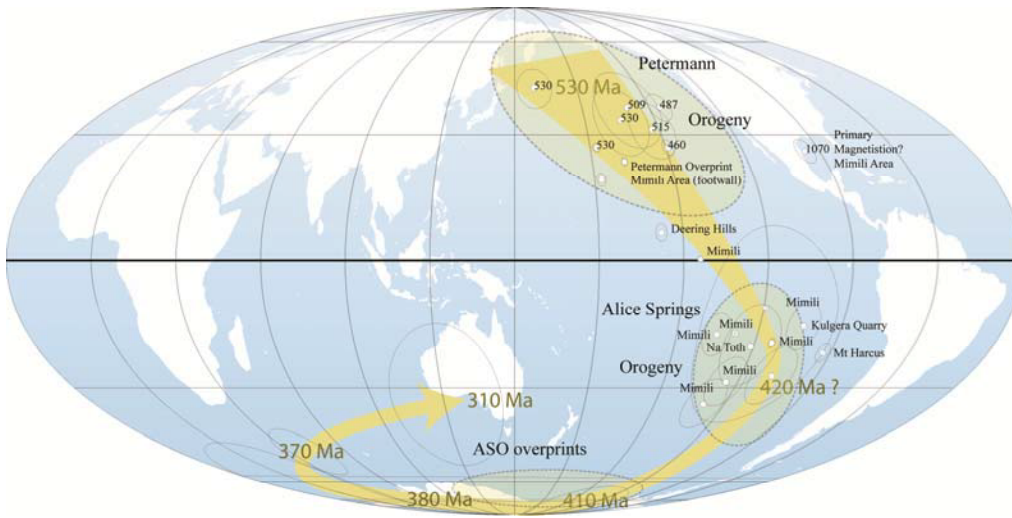
Figure 20: Palaeomagnetic results from a number of intrusions primarily Mimili in the SE and Deering Hills in the NW of the Musgrave Block, plotted against the apparent polar wander path of Li et al., (1990).
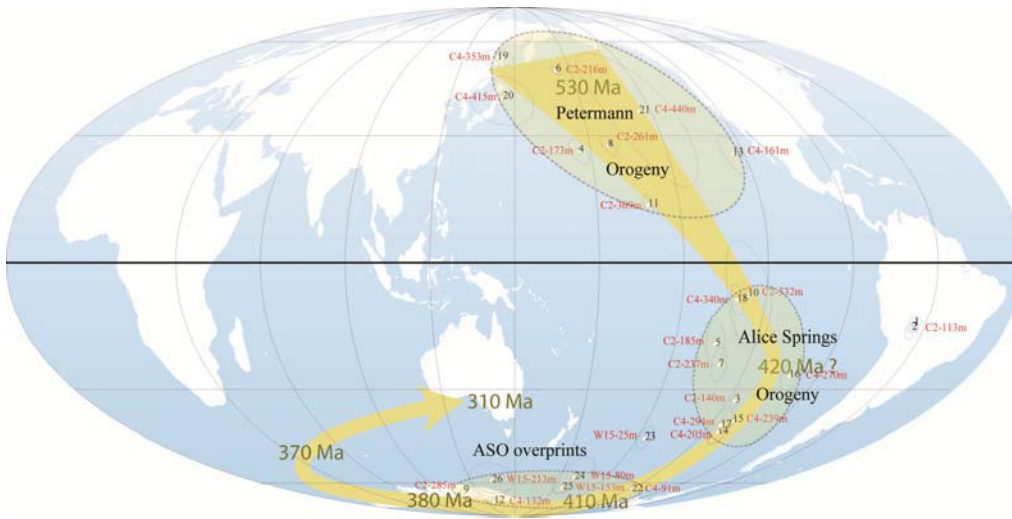
Figure 21: Palaeomagnetic results Mount Caroline Intrusion in the central Musgrave Block, plotted against the apparent polar wander path of Li et al., (1990). Red text indicates drill-hole number and depth.

The Arunta

A similar study was undertaken in the Arunta by Austin, 2014). Surface drilling was used to sample 66 separate cores from 8 different field sites that correspond with three different magmatic suites. The Lloyd suite (~405 Ma) includes the Blackadder, Baldrick, Lloyd 1 and 2 sites; The Kalkarinji suite (~530 Ma; equivalent to Riddoch) is sampled at Kalkarinji 1 and 2, and the Warakurna suite (~1070 Ma; equivalent to Giles) is sampled at Warakurna 1 and 2. The aim of the study was to determine whether magnetization directions could be used to discriminate three different mafic rock types from aeromagnetic data in the Huckittta area.

The remanent magnetization recorded in the lithologies analysed in this study were complex, consisting of

numerous magnetizations. The main magnetizations, in terms of intensity and preservation in most rocks, appear to be steep downward oriented magnetizations that plunge to the SE and SW, and whose mean magnetization overall is Inc: 76°, Dec: 207° (e.g., Figure 7). An apparent pole generated from these data plots very close to the apparent polar wander path at ca 330-300 Ma and to known magnetizations from the Amadeus Basin (Austin et al., 2017a). In many cases these magnetizations are very stable up to an alternating field of 140 mT, and in some cases up to the Curie point of magnetite during thermal demagnetization. However, it is unlikely that these were acquired during cooling of their parent magmas. For the majority of intrusions of interest (i.e., Lloyd Suite) the post-intrusion cooling period would have been *ca* 405 Ma.

We have observed that the primary magnetizations (most stable) are overprinted in the low coercivity magnetic carriers (i.e., soft magnetic components) by a number of magnetizations that plot on the Apparent Polar Wander path at *ca*. 330, 360, 380 and 400-460 Ma. The interpretation of several discrete metamorphic peaks throughout the Alice Springs Orogeny is consistent with previous work by Buick et al. (2008).

Essentially the results show that although these suites intruded at different times, they were sitting deep in the crust at temperatures >580°C prior to the Alice Springs Orogeny and only started acquiring their magnetizations at

that time. Subsequently, several discrete metamorphic Events have overprinted the rocks but only to a very limited degree.
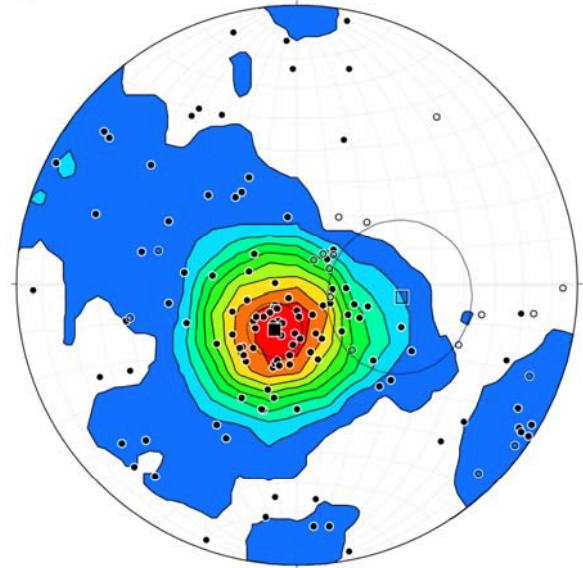
Figure 22: Results of principal component analyses for samples for the Huckitta area in the Arunta, show a clear steep, down to the SSW magnetization. This magnetization directions is consistent with our modelling of the majority of the anomalies in the area.
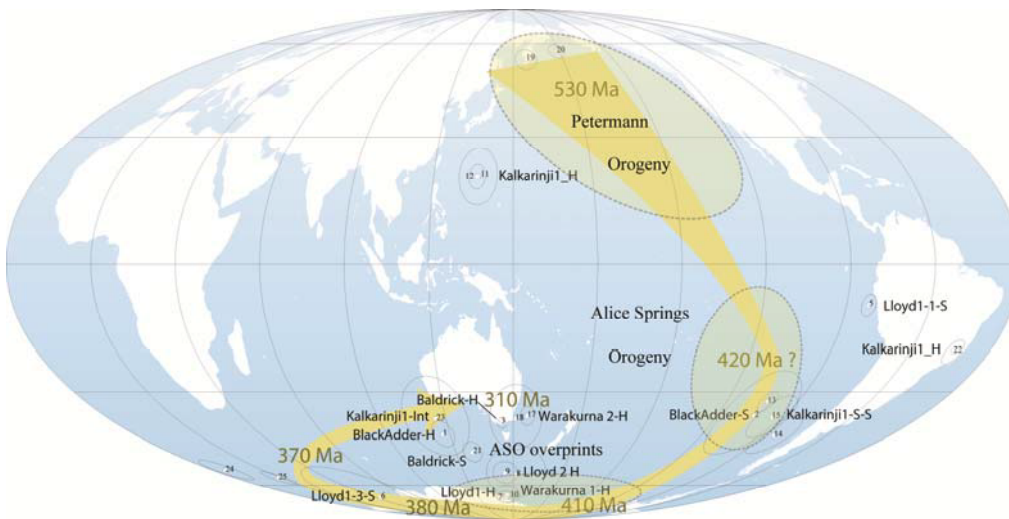
Figure 23: Palaeomagnetic results from surface drilling of 8 individual intrusions in the Huckitta Area of the Arunta Block, plotted against the apparent polar wander path of Li et al., (1990).

MULTIPLE MAGNETIZATIONS

There are many conundrums that potentially face explorers searching for Magmatic Ni-PGE mineralization. We've seen how rocks can accommodate multiple magnetisations from different events. However, one of the most perplexing

situations is when magnetic signatures related to the same event are completely different. In this section we look at the palaeomagnetic results from two adjacent, temporally equivalent intrusions and pose the question. "How can rocks of the same age have different magnetizations?".

Dave Hill Petrophysics

The Dave Hill Intrusion was sampled by drill hole SMD165 (Fig 24, 25). The majority of samples recorded strong remanent magnetization that was persistent up to very strong alternating fields. In many cases these samples did not begin to demagnetize until the 20-30 mT step, and furthermore, in many samples were not fully demagnetised in a field of 140 mT (the maximum field achievable using the 2G magnetometer). This indicates that the magnetic grains are of high coercivity (i.e., resistant to overprinting).
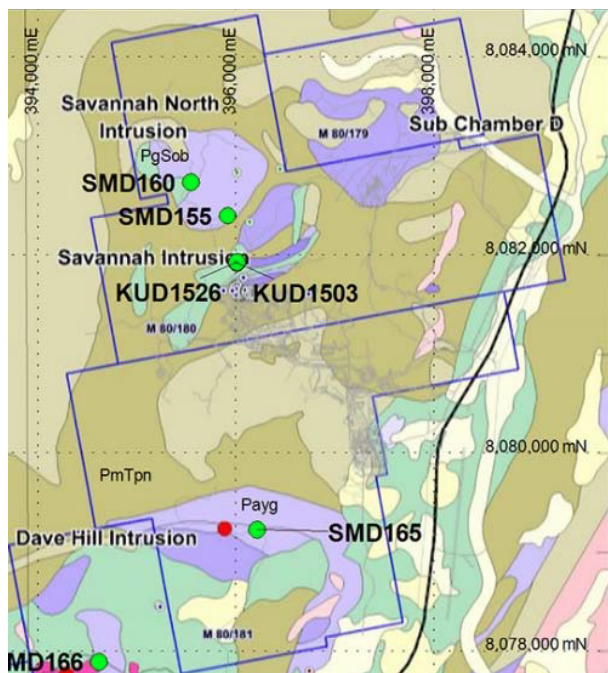
Figure 24: Geological map that has been rectified in MapInfo. Sampled drill holes are in green, and the studied intrusive centres are labelled. Purple units are Sally Malay intrusions (lighter = felsic, darker = ultramafic). Dark blue-green = Sally Downs Supersuite (biotite-norite, olivine- gabbronorite (PgSob/Sog). Brown=Tickalara Metamorphics (mafic granulite (PmTon) and migmatitic gneinss (PmTpn)). Pink = felsic intrusive rocks, e.g., the Mabel Downs Tonalite located in the SE corner. Units are based on Tyler et al. (1998).

The samples have a major component of magnetization with a southerly declination, and steep to moderate downward inclination. The results of the principal component analysis (PCA), summarized in Fig 26, provides a mean remanent magnetization direction of Dec: 182.5° and Inc: 61.3°. In calculating a mean magnetization orientation for Dave Hill, samples with drilling induced magnetizations were excluded. The magnetization were given equal weighting, but a superior result may have been achieved by weighting magnetization intensity.
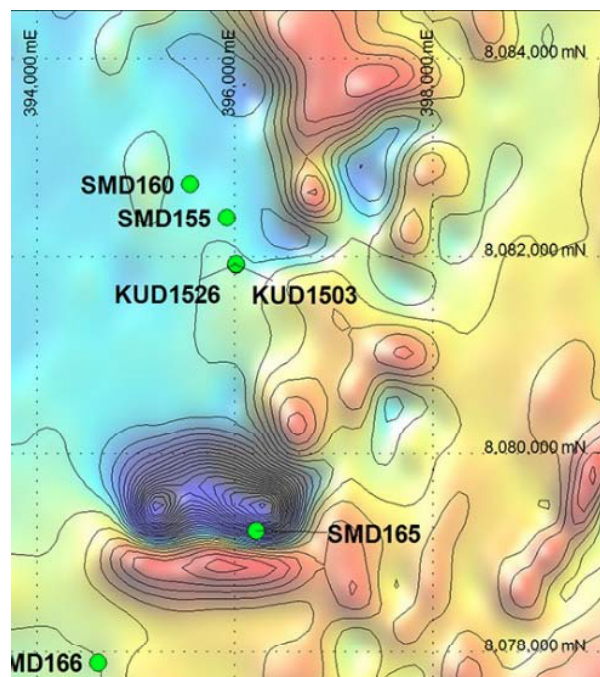

Figure 25: Total magnetic intensity grid, with 50nT contouring. Note the strong negative magnetic anomaly associated with the Dave Hill Intrusion.

As shown by the 1% contour applied to the data (Figure 26) there are two sub-parallel clusters of data. However, both of these are recorded in at least one sample and it is therefore likely that these represent two distinct, but temporally close periods of acquisition of remanence, rather than modification of the remanence direction by subsequent folding. These results are consistent with the pronounced negative magnetic anomaly at Dave Hill. There are several different overprints observed, but these for the most part only constitute a very minor component of the total magnetization, and hence for the purposes of magnetic modelling are insignificant.
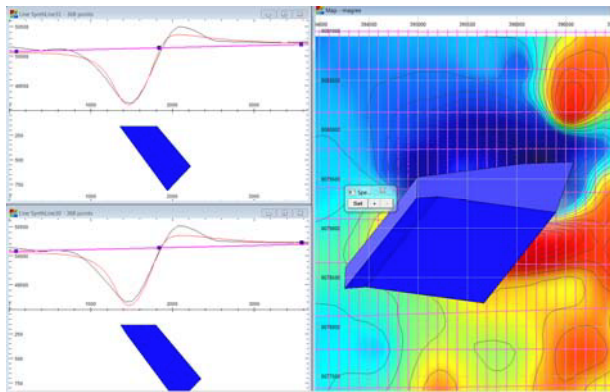
Dave Hill Magnetic Modelling

Based on the palaeomagnetic results for Dave Hill, a simple modelling exercise was undertaken, to confirm the results. A model was generated in ModelVisionPro™, whereby the petrophysical properties were constrained using the mean measured susceptibility, and NRM. Using this approach it was possible to match the anomaly to ~6% r.m.s. (Fig 27). Several aspects of the morphology of the modelled anomaly were not adequately similar to the actual magnetic anomaly, suggesting either the body shape or magnetization used were not appropriate. However, in general the modelling supports the observation that the body is dominated by remanence, and that the measured remanence explains the anomaly.
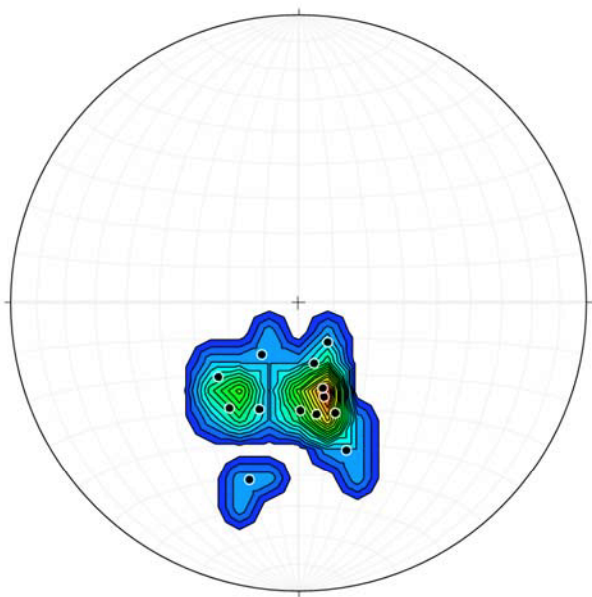
Figure 26: Palaeomagnetic results from Dave Hill, showing remanent magnetization directions for the majority of samples with a 1% contour underlain.


Figure 27: An Initial magnetic model for Dave Hill, shown with TMI grid. The model was constrained by the AMS fabric for the body dip, the measured remanence and magnetic susceptibility was assumed to be negligible.

Savannah Petrophysics

The Savannah Intrusion was sampled by drill hole KUD1503 and 1526 (Fig 24, 25). As is clear from Fig 25, the Savannah intrusion is not associated with a strong downward oriented remanence as is the case at Dave Hill, even though the two intrusions are contemporaneous. The majority of samples display weak natural remanent magnetization values. However, upon demagnetisation, the remanent magnetisation intensity in many of the samples started to increase (e.g., SAV062; Fig 28). Sample SAV062A (Figure 28) had an initial NRM of ~25 mA/m,

but as the sample was progressively degaussed, the intensity increased up to ~200mA/m (8x higher than the NRM). This demagnetisation behavior is indicative a pair of antiparallel magnetizations, with the weaker being preferentially removed to leave a progressively stronger resultant. In many cases the magnetisations are so stable that the highest remanent magnetisation intensity occurs on the last step. Hence the most stable component is almost totally unresolved, and furthermore the remanence direction is extremely stable. In such cases we have just assumed the directions based on the last two degaussing stages (i.e. 130 mT and 140 mT), because thermal demagnetisation could not further clarify the directions.
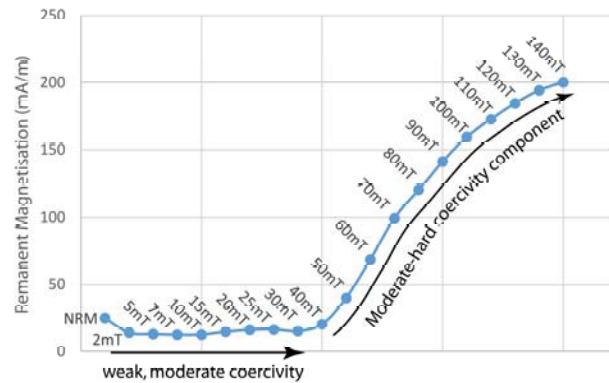
Figure 28: Plot of remanent magnetization intensity with increasing demagnetisation for sample SAV062A

Principal component analyses confirmed that these samples contained two high coercivity palaeomagnetic components with opposite polarity. Typically opposite polarity results are only present in the most stable magnetisations, which commonly account for only the last ~10% of total magnetization. However, in these cases the two components account for the majority of the palaeomagnetic signal and have approximately equal intensity, which effectively cancel each other out. As a consequence the Koenigsberger ratios of many of the Savannah samples are misleading in terms of providing a measure of the strength of the remanence, because the Koenigsberger ratio is calculated using NRM (which is the sum of the remanent magnetisation vectors) not scalar sum of remanent intensities.

When the Koenigsberger ratio is calculated for SAV062A based on the latter preposition, the total intensity of remanence would be ~375 mA/m (15x higher than the NRM), and the associated Koenigsberger ratio would be 4.2. These results are more consistent with a results from the nearby Dave Hill intrusion. Savannah is a rare case in which the lithologies locally have strong remanence and relatively weak susceptibility, but because the remanence is largely self-cancelling, the anomaly at Savannah is subtle to non-existent.

CONCLUSIONS

Magmatic Ni-PGE deposits represent some of the more magnetically complex styles of mineralization. In this paper we examined some of the issues related to magnetization in mafic-ultramafic magmatic systems. We have illustrated how the process of fractional crystallization leads to: magnetite-poor lower pyroxenite units with negligible magnetic signal; alternating Mt-rich anorthosites (with strongly induced magnetization) and gabbros and gabbronorites with oppositely oriented remanent magnetization in the Mount Caroline Layered Intrusive complex.

We discuss that remanent magnetisation is often not related to cooling of magmas and discussed how the process of exsolution in titanomagnetite can lead to extremely strong and stable remanent magnetization in mafic rocks. Using a case study on Mt Harcus, we have demonstrated that an understanding of both the magnetic properties and remanence directions can be used to improve drill targeting in such systems. We've explored how the timing of major tectonic uplift episodes and or metamorphic events can be the main determinant of the remanent magnetisation vectors in mafic intrusions. Furthermore, we have illustrated how contemporaneous rocks can have very different magnetic signatures due to recording equal intensity magnetisations of opposing polarity.

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