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Magnetic petrology: Application of integrated rock magnetic and petrological techniques to geological interpretation of magnetic surveys

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Abstract

Interpretation of magnetic surveys in terms of geology is hampered by poor correspondence between broad lithological categories and magnetic properties, and by lack of knowledge of the geological factors that influence the magnetisation of rocks. Magnetic petrology is the integrated application of rock magnetic and conventional petrologic techniques to identify and characterise the magnetic minerals in rocks. This information elucidates the factors that produce, alter and destroy magnetic minerals and thereby influence the bulk magnetic properties of the rocks and their associated magnetic anomalies. Improved understanding of magnetic petrology is therefore essential for maximising the geological information that can be obtained from magnetic anomaly patterns.

Key words: Magnetic petrology, rock magnetism, magnetic surveys, magnetic interpretation, geological interpretation.

Introduction

Magnetic interpretation is essentially an inversion process, whereby magnetic anomaly patterns are analysed to produce an interpreted source distribution, and the sources in turn are interpreted in terms of geological entities, such as rock units, alteration zones and structures. The fundamental problem of magnetic interpretation arises because this inversion of magnetics to geology is highly ambiguous. The non-uniqueness of source geometry associated with a given anomaly is a well known problem of magnetic modelling (quantitative interpretation), which can be ameliorated by constraining the class of possible models. Constraints can be imposed *a priori*, on the basis of geological plausibility for example, or, preferably, can rely on additional information from drilling, other geophysical methods, or from magnetic property measurements. Similarly, the ambiguity in inferring the geological nature of the sources (qualitative interpretation) can be reduced by a better understanding of the relationships between magnetic properties of rocks and geology.

Magnetic petrology is the integrated application of rock magnetic and conventional petrologic techniques to identify and characterise the magnetic minerals in rocks. This paper discusses the application of magnetic petrology to improving geological interpretation of magnetic surveys and illustrates some general findings with case studies.

Geological Controls on Magnetic Properties

There are many geological factors that influence magnetic properties, directly or indirectly, including: lithology, depositional environment, tectonic setting, geochemical affinities, hydrothermal alteration, metamorphic grade, structure and rock age. For this reason, there is only a weak correlation between magnetic properties and broad rock

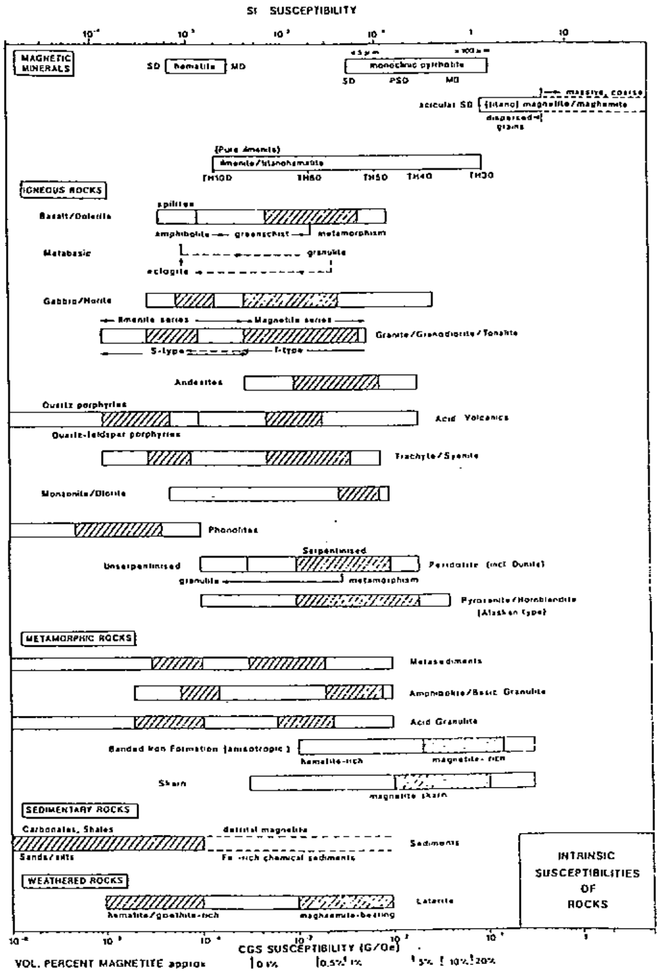

FIGURE 1
Susceptibilities of common rock types and magnetic minerals. The bars represent total observed ranges and the hatched areas represent usual ranges. SD = single domain, MD = multidomain, PSD = pseudosingle domain, THx = ilmenite-hematite solid solution containing 100x mole per cent ilmenite.

names, such as 'granite', 'basalt' or 'pelitic metasediment'. Figure 1 shows the total range and common range of susceptibilities found for a number of rock types.

From Fig. 1 it is evident that most rock types are associated with a broad range of possible susceptibilities. Moreover, the distribution of susceptibilities within the total range is often strongly bimodal, reflecting the existence of distinct paramagnetic and ferromagnetic subpopulations within each rock type. The subdivision of felsic plutonic rocks into paramagnetic ilmenite-series granitoids and ferromagnetic magnetite-series granitoids typifies this phenomenon. The total iron content of the paramagnetic and ferromagnetic representatives is generally comparable, but the iron is partitioned primarily into paramagnetic silicate minerals (mainly as ferrous iron) in the former. The magnetic properties of the ferromagnetic rocks are usually dominated by magnetite, reflecting the presence of ferric iron exceeding the amount that can readily be incorporated into the major and varietal minerals.

When rocks are classified more specifically, as to varietal mineralogy, metamorphic grade etc., the range of magnetic properties exhibited by each category is greatly reduced. For example, a hornblende-biotite granodiorite is likely to be ferromagnetic, with a moderate susceptibility (typically ~ 0.01 SI), whereas muscovite-biotite granodiorites are generally paramagnetic, with susceptibilities less than ~ 0.001 SI. As another example, fresh young basalts are almost invariably ferromagnetic, with moderate to high susceptibilities, whereas metabasalts in the greenschist or amphibolite facies are usually paramagnetic.

Metamorphism of Ultramafic and Mafic Rocks

The primary oxide phase in alpine-type peridotites and peridotitic komatiites is paramagnetic chrome-spinel. Therefore these ultramafic rocks are only weakly magnetic, provided they remain unaltered. This applies to the unserpentinised cores of some thick olivine adcumulate lenses, for instance. However, peridotites are usually serpentinised, and contain secondary magnetite, in the form of discrete grains of nearly pure magnetite, plus rims of Cr-magnetite around cores of primary Cr-spinel. The amount of secondary magnetite depends on the degree of serpentinisation and is inversely correlated with the rock density (Toft *et al.*, 1990). Fully serpentinised ultramafics have high susceptibilities (0.01-0.1 SI), augmented by viscous remanence parallel to the present field with a typical Q value of ~0.2, and are associated with prominent magnetic anomalies.

Moderate carbonate alteration of serpentinised ultramafics redistributes the magnetite, but does not greatly affect the susceptibility, on average. However, intense talc-carbonate alteration demagnetises the serpentinites, with iron from magnetite going into carbonate. Prograde metamorphism of serpentinised peridotites changes the composition of the ferromagnetic spinels, with initial incorporation of Cr, followed by Mg and Al, reducing the susceptibility progressively until the rocks become essentially paramagnetic at granulite grade (Evans and Frost, 1975; Shive *et al.*, 1988).

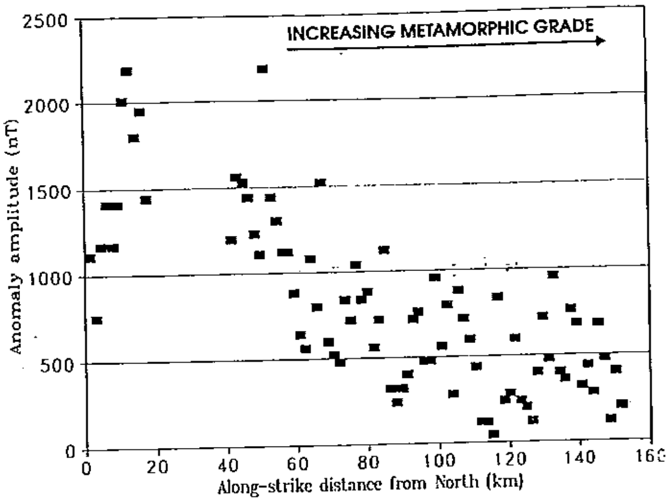

FIGURE 2
Along-strike variation of the magnetic anomaly over the nickel deposit-hosting ultramafic unit of the Agnew-Wiluna Greenstone Belt. Note the decrease in anomaly amplitude with increasing metamorphic grade from north (prehnite-pumpellyite facies) to south (mid-upper amphibolite facies).

Figure 2 shows the amplitude of the magnetic anomaly associated with the major ultramafic unit of the Agnew-Wiluna Greenstone Belt of the Yilgarn Block, on succesive profiles from north to south. This unit hosts a number of nickel deposits, including Honeymoon Well, Mount Keith and the Leinster Nickel Operations. The metamorphic grade along the belt increases from prehnite-pumpellyite facies around Wiluna, in the north, to upper amphibolite facies around Leinster Nickel Operations in the south. There is a decrease in the magnetic anomaly amplitude, by a factor of three, associated with the increasing metamorphic grade and the concomitant change in spinel compositions.

Mafic rocks are generally weakly magnetic throughout most of this belt. This is attributed to the effects of metamorphism, because basalts and gabbros from greenschist and amphibolite grade areas almost invariably have low susceptibilities, whereas subgreenschist grade equivalents are often ferromagnetic. Figure 3 shows the distribution of susceptibilities of mafic rocks according to metamorphic grade. In greenschist and higher grade metabasites the titanomagnetite originally present has been replaced by sphene, hematite and rutile, greatly reducing the susceptibility.

Magnetic Signature of a Porphyry Copper System

Ishihara (1981) recognised the association between oxidised magnetite-series granitoids, which are moderately to strongly magnetic, and porphyry copper mineralisation, contrasted with the relatively reduced tin granites, which belong to the paramagnetic ilmenite-series. Sillitoe (1979) has pointed out the particular association between Au-rich porphyry copper systems, magnetite-bearing granitoids and magnetite-rich potassic alteration zones. This relationship is explicable in terms of the model of Cameron and Hattori (1987), which was developed in the context of Archaean gold mineralisation.

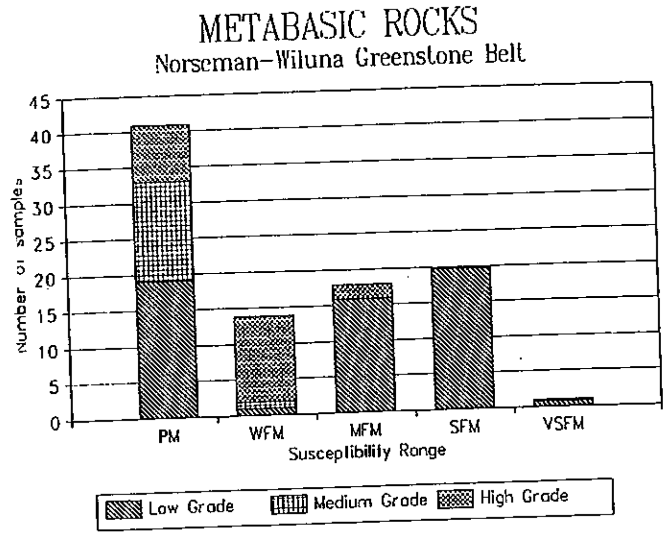

FIGURE 3
Frequency histogram of susceptibilities of metamorphosed basalts, dolerites and gabbros from the Norseman-Wiluna Greenstone Belt. Note the generally low susceptibilities of medium and high-grade (mid-greenschist to upper amphibolite) metabasites, contrasting with the wide range of susceptibilities, with many high values, for the low-grade (prehnite-pumpellyite to lower greenschist facies) metabasites. PM = paramagnetic ($k<100$ μG/Oe = 0.0013 SI), WFM = weakly ferromagnetic (k = 100-300 μG/Oe = 0.0013-0.0038 SI), MFM = moderately ferromagnetic (k = 300-3000 μG/Oe = 0.0038-0.038 SI), SFM = strongly ferromagnetic (k = 3000-10 000 μG/Oe = 0.038-0.13 SI), VSFM = very strongly ferromagnetic (k > 10 000 μG/Oe = 0.13 SI).

The magnetic signature of an idealised porphyry copper system is shown in Fig. 4. The anomaly is reduced to the pole to eliminate dependence of anomaly form on geomagnetic field direction. Away from the system the magnetic anomaly pattern is "busy", reflecting the typically inhomogeneous magnetisation of magnetic volcanics. Destruction of magnetite within the extensive propylitic and phyllic alteration zones produces a magnetic low, with a central smooth, flat zone. This response resembles the signature commonly associated with epithermal systems within volcanics, such as the Conway and Bimurra prospects in north Queensland (Irvine and Smith, 1990). There is a magnetic high within the "alteration low" due to the magnetic felsic porphyry that is the source of the mineralising fluids. This local high may be quite pronounced for a gold-rich system with a well-developed magnetite-bearing potassic zone.

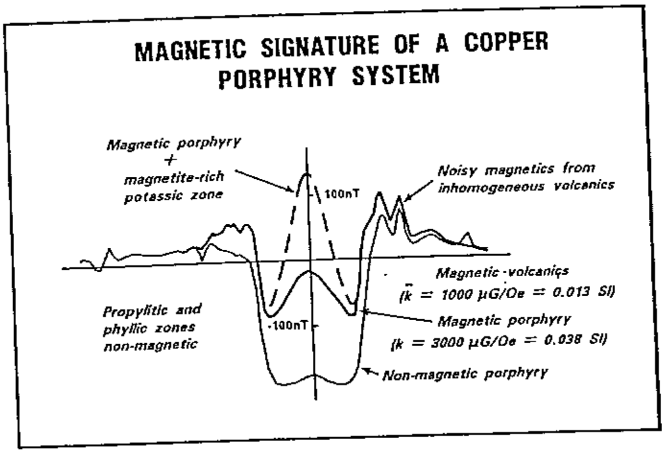

FIGURE 4
Idealised magnetic anomaly associated with a porphyry copper system, showing the noisy background associated with magnetic volcanics, the 'alteration low' associated with the propylitic and phyllic alteration zones, the high arising from the magnetic porphyry plus, in the case of gold-rich copper mineralisation, the magnetite-bearing potassic alteration zone.

Magnetic Signatures of Layered Mafic/Ultramafic Complexes

The phase petrology, mineralisation and magnetite distribution within layered mafic/ultramafic complexes, such as the Bushveld, Stillwater and Skaergaard intrusions, arise from differentiation of tholeiitic magma. The tholeiitic differentiation trend is characterised by pronounced iron enrichment, reflecting early crystallisation of Mg-rich silicates. Ultramafic cumulates at the base of such intrusions contain chromite as the only primary spinel phase, but are usually serpentinised, with abundant secondary magnetite. Cumulus chromite bands within the ultramafic zone may represent economic Cr and PGE mineralisation. Nickel, copper and gold mineralisation are also associated with the uppermost chromite band in the Bushveld Complex. The lower norites, gabbros and anorthosites crystallised under reducing conditions, with iron predominantly in the ferrous state, and contain virtually no magnetite. As the magma evolves and ferrous iron is increasingly removed into anhydrous silicates, the ferric/ferrous ratio increases to the point where titanomagnetite can start to precipitate, initially as a minor intercumulus phase, and then in abundance as a cumulus phase in the upper ferrogabbros and ferrodiorites. This zone often contains thick cumulus layers of V-Ti-magnetite mineralisation.

The Bushveld Complex can be regarded as a 'type example' of these large intrusions that is particularly interesting from the exploration viewpoint, because of the variety and abundance of associated mineralisation. Information on the

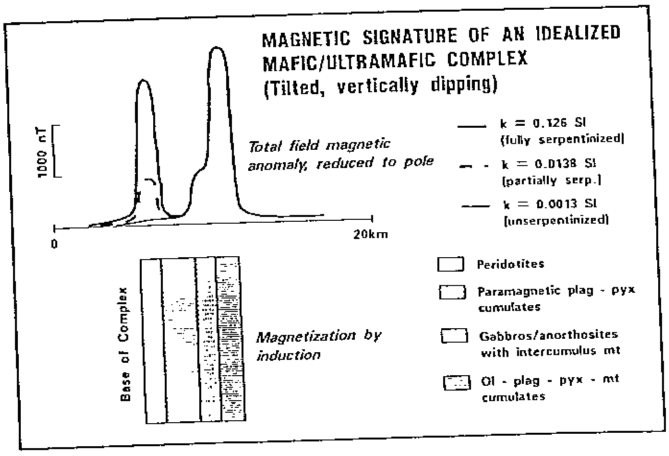

FIGURE 5
Idealised magnetic anomaly associated with a large layered mafic/ultramafic intrusion that has been tilted on its side. Most commonly, the ultramafic basal zone with cumulus magnesian olivine is highly serpentinised and is strongly magnetic. Susceptibility values in the figure refer to the basal peridotites, according to the degree of serpentinisation. Also shown are the paramagnetic lower gabbros, norites and anorthosites (plagioclase-pyroxene cumulates), with assumed susceptibility 0.0013 SI; the moderately magnetic gabbros and anorthosites containing intercumulus magnetite, with assumed susceptibility 0.038 SI; and the magnetite-rich upper ferrogabbros and ferrodiorites (Fe-olivine + plagioclase + pyroxene + magnetite cumulates), with an average assumed susceptibility of 0.151 SI. The geomagnetic field is 50 000 nT.

phase petrology of the Bushveld Complex (Wager and Brown, 1967) has been used to produce an inferred gross magnetic stratigraphy and an idealised magnetic signature over such an intrusion (see Fig. 5). Because of the well-developed layering exhibited by these intrusions, detailed magnetics can also be used to trace individual thin horizons within them.

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