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Magnetic responses associated with mineral deposits

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Systematic associations of magnetic minerals occur in many mineral deposits and, consequently, the probable presence of mineral deposits can be deduced from anomaly patterns in magnetic data. To be able to successfully apply such an approach an interpreter must understand the range of possibilities for the spatial distribution of magnetic minerals likely to occur in various types of mineral deposits and their host rocks.

Introduction

Significant concentrations of magnetic minerals occur in many mineral deposits and many mineral deposit types are associated with magnetic rock units. However, very few publications have addressed magnetic signatures of ore deposits and their host rocks other than on a deposit by deposit descriptive basis. The object of this paper, which considers mineral deposits in terms of their magnetic mineral associations and their known and expected magnetic responses, is to present an introduction to ways of using magnetic survey data to recognise favourable locations for orebodies and, where possible, to directly detect ore bodies. Ideas from previous works with similar objectives by McIntyre (1980), Webster (1984), Grant (1985), Hoover et al. (1991), Clark et al. (1992) and Gunn (1993) have been incorporated into the paper.

It is generally accepted that many economic mineral deposits have significant similarities in terms of mineral assemblages, geometry, host rocks, and structural and tectonic setting. This has led to the concept of 'deposit types' or 'ore deposit models', which groups deposits in terms of characteristics and origin. Reviews on the concept of ore deposit models have been published by Hodgson (1990), Roberts & Sheahan (1988), and Large (1992a). Cox & Singer (1986), Roberts & Sheahan (1988), Sawkins (1990), Solomon & Groves (1994), and others have produced comprehensive descriptive classifications of deposit types. Various specialist works exist for particular deposit types. The overview presented here of magnetic responses associated with mineral deposits is based on our subdivision of deposit types generalised from these works.

Magnetic minerals

A knowledge of the magnetic properties of minerals is fundamental to understanding the magnetic responses of mineral deposits. Clark (1997) has provided a comprehensive review of this subject in another paper in this volume, so the topic will not be elaborated here. As far as the relevance of magnetic properties to ore deposits is concerned, Clark's paper can be largely summarised by the following facts.

- Two types of magnetisation exist, viz.
  - induced magnetisation, which is proportional to the susceptibility of the material being magnetised and which has the same direction as the Earth's field;
  - remanent (permanent) magnetisation, which can have any direction.
- Induced magnetisation is far more common than remanent magnetisation. However, in certain cases remanent magnetisation can be orders of magnitude greater than induced magnetisation.
- All other factors being constant, the magnetic response of a magnetic body is directly proportional to the magnitude of its magnetisation.
- The magnetisation of a body can be directly related to the volume concentration of magnetic minerals in the body, and this relationship varies according to the magnetic mineral present.
- The only minerals that normally cause observable magnetic effects in the context of magnetic surveys related to mineral deposits are:
  - magnetite, the most magnetic mineral, which generally does not have significance remanence;
  - pyrrhotite, of which only the monoclinic form is magnetic and which frequently has remanent magnetisation an order of magnitude greater than its induced magnetisation—the susceptibility of pyrrhotite is approximately one-tenth the susceptibility of magnetite;
  - hematite, which can exhibit weak magnetic responses due to induced magnetisation and which sometimes has strong remanence;
  - ilmenite/titanohematite, which can give weak but observable magnetic responses;
  - maghemite, a weathering product, which can have strong magnetic responses.
- Pyrite, which is non magnetic, can be metamorphosed to pyrrhotite. This change tends to occur at upper greenschist–lower amphibolite grades. Pyrrhotite can be metamorphosed to magnetite.

Characteristics of magnetic responses

The form and amplitude of the magnetic response of a mineral deposit depend on many other variables in addition to the concentration of magnetic minerals present. Other key factors are the geometry and depth of the deposit, its orientation relative to magnetic north, and the inclination of the Earth's field at its location. These relationships are outside the scope of this paper, but are discussed in all basic texts on magnetic interpretation (e.g. Telford et al. 1990). The net result of these relationships is that there are no fixed anomaly forms that can be regarded as giving standard universal responses for mineral deposits. While this paper is able to describe the typical geometric distribution of magnetic minerals in a variety of mineral deposit types in their original undisturbed forms, the application of this knowledge to the detection of mineralisation requires an appreciation of how such magnetic accumulations will manifest themselves at different localities. The identification process must also account for any deformation, erosion, weathering, metamorphism or remobilisation that may have occurred during the deposit's history. Further complications can be caused by magnetic properties being anisotropic at both crystal grain and bedding scales, and the 'demagnetisation' factor, whereby the effects of extremely strongly magnetic bodies can locally alter the direction of the Earth's magnetic field and thereby influence their own magnetic anomaly. Competent interpreters of magnetic data should be familiar with such complexities.

Massive sulphide deposits

Many economic deposits occur as massive associations of sulphide minerals containing varying amounts of copper, zinc,

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lead, silver and gold. In many of these deposits the sulphide containing the economic mineral is a mass of pyrite and/or pyrrhotite making up 20–50 per cent of the weight of the deposit. Silica is the other main gangue mineral. Chalcopyrite, sphalerite and galena are the main economic minerals with gold and silver being generally subordinate in value. Magnetite may be present in the deposits and in some examples is the dominant gangue mineral. These deposits are referred to as massive sulphide deposits.

Various subdivisions exist for massive sulphide deposits in the published literature, of which by far the best known are the volcanic-hosted massive sulphides (Franklin et al. 1981; Lydon 1984, 1988; Large 1992b), which are hosted by volcanic rocks generally associated with marine sediments, such as shales and greywackes, in various plate-tectonic settings, such as mid-ocean-ridge ophiolites and convergent plate margin back-arc volcanic rifts, and in greenstone belts. Deposits with no obvious volcanic association, but of similar geometry, mineral associations and mineral zonings, occur in rift settings in shale/turbidite host rocks and diverse clastic assemblages identified as being deposited during the earliest (pre-rift) and latest (post-rift or sag phase) stages of rifting.

Disputes exist in the literature as to the relationship between deposits in the various settings. Some authors regard them simply as variations in a common mineralising process, according to tectonic setting and variables such as temperature, oxygen fugacity, salinity and concentration of mineralising solutions. Others invoke different origins for the varyious types. The controversy appears largely irrelevant to the study of the magnetic signatures of these bodies, because the same geometry and zoning of magnetic minerals, albeit with semi-systematic and semi-predictable variation, seem to be manifest in all massive sulphide deposits. The examples presented below support this assertion.

In recognising a common set of associations, it is instructive to use the widely recognised volcanic-hosted massive sulphide deposit type as a starting point. Figure 1, generalised from Lydon (1984) and Large (1992b), shows the idealised vertical cross-section of a volcanic-hosted mineral deposit. The deposit can have circular symmetry, but is commonly elongated in one horizontal direction. Many massive sulphide deposits occur adjacent to major faults, apparently the result of mineralising solutions ascending via the fault plane. Such deposits show the vertical zoning of Figure 1, but their form is equivalent to one side only of the model.

The notable features of typical massive sulphide deposits are:

- The economic minerals chalcopyrite, sphalerite and galena occur together with pyrite and/or pyrrhotite and/or magnetite as a massive tabular/mound-like mass in the upper central part of the deposit. Vertical zoning can occur, with chalcopyrite, magnetite and pyrrhotite tending to occur at the base of the massive sulphides, and sphalerite, galena and pyrite tending to occur in the upper part. The maximum horizontal dimension of the massive mineralisation appears to be of the order of 2000 m and the maximum thickness of the order of tens of metres. Massive sulphide deposits can be significantly smaller than these maximum dimensions.
- The massive sulphides are underlain by a stockwork of veins.
- Deposits are capped by a horizon consisting variably of pyrite, magnetite, pyrrhotite, hematite or silica-rich rocks. This 'ore equivalent horizon' may extend laterally for any distance up to tens of kilometres from the deposit.
- Not all the zones described above are always present.

The stockwork of veins is generally accepted to mark the 'chimney' by which mineralised solutions rose to where the

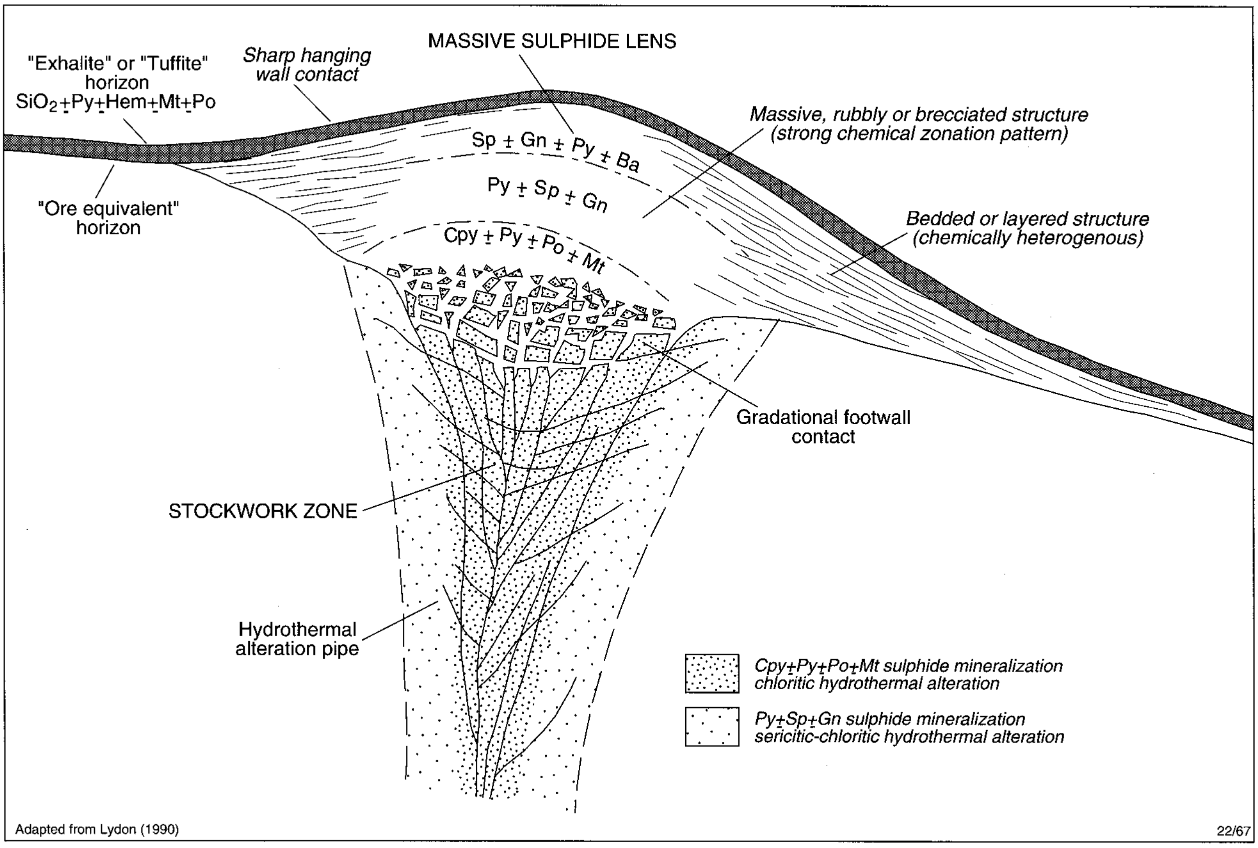

Figure 1. Idealised vertical cross-section of a massive sulphide deposit. Normally, the deposit would have circular symmetry in plan view. If the deposit has been localised by a fault, only one-half of the deposit as shown may occur. Not all the zones illustrated always occur in a single deposit.

massive sulphides were deposited (commonly regarded to be at or near the sea floor). The mineral zoning can be explained by phase diagrams relating the order of mineral precipitation to changes in temperature, oxygen fugacity and salinity as the mineralised solutions ascended. The laterally extensive horizon capping the deposit is variously regarded as a final pulse of an exhalative process associated with the deposit, a cap rock which has blocked vertical migration of mineralised solutions, or a pre-existing formation whose reactive properties have resulted in the precipitation of the massive sulphides from ascending mineralised solutions.

The magnetic response of this idealised model can be appreciated by considering the representations in Figure 2, which show, in diagrammatic form, simplified contours of magnetic fields over massive sulphide bodies with various distributions of magnetic minerals. Figure 2 assumes that the massive sulphides have been tilted on their sides and eroded to expose a plan of a vertical section through the original centre of the deposit and that the deposit is located at a magnetic pole, where there is no asymmetry due to the inclination of the Earth's magnetic field. Although many massive sulphide deposits do occur in situations where they have been tilted on their side, the geometry of the deposits in Figure 2 has been chosen primarily to illustrate that different parts of massive sulphide deposits may have different magnetic responses. If such deposits occur in other orientations, it should be remembered that magnetic responses of different parts of the deposit are likely to be superimposed. The models of Figure 2 assume that the magnetic effects of the lower numbered models are progressively incorporated into those of the higher numbered examples, although this is not always the case in nature.

Figure 2A shows zero response, as some massive sulphide bodies contain no magnetic minerals. The Teutonic Bore (Fritz & Sheehan 1984) and Woodlawn (Whiteley 1981) deposits appear to be examples.

Figure 2B shows a weak magnetic low. This can occur when mineralised solutions moving through the country rock destroy magnetic minerals adjacent to the deposit. Such processes can occur within and adjacent to the feeder pipe below the deposit. The Salt Creek deposit (Gunn & Chisholm 1984) appears to be an example.

Figure 2C shows the situation where magnetic materials such as magnetite or pyrrhotite occur within and/or at the top of the feeder pipe. The Orchan deposit (Hallof 1966; Large 1977) appears to be an example.

Figure 2D includes the responses of Figures 2B and 2C, but also includes the situation where the base of massive mineralisation has a layer of magnetic minerals. The Sullivan deposit of British Colombia (Ethier et al. 1976; Hamilton et al. 1982), which has a massive layer of monoclinic pyrrhotite beneath massive sphalerite and galena mineralisation in a pyrite gangue, accords with this situation.

Figure 2E is an extension of Figure 2D, where magnetic minerals occur throughout the deposit. The Abra deposit (Boddington 1990), which contains a magnetite gangue is an example.

Deposits may also be capped by a laterally extensive horizon containing magnetic minerals which manifests itself as a magnetic ore equivalent horizon (Fig. 2E). The Hope and Gorob deposits of the Matchless Amphibolite Belt in Namibia (Campbell & Mason 1979; Breitkopf & Maiden 1988; Haussinger & Orkrush 1993) and deposits of the Namaqualand Metamorphic Complex in South Africa (Campbell & Mason 1979; Anhaeusser & Maske 1986) appear to be examples. The magnetite and pyrrhotite-rich Cu–Au and Pb–Zn deposits of the Cobar area of New South Wales area (Brooke 1975), which are associated with a magnetic disseminated pyrrhotite horizon (Clark & Tonkin 1994) may be deformed and remobilised variants of this type of deposit.

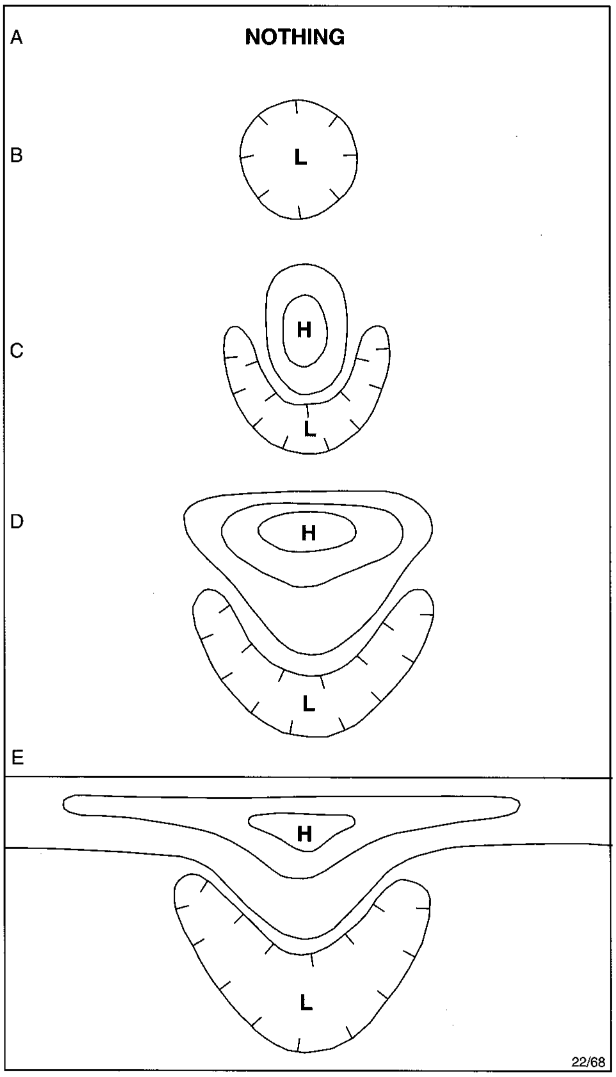

Figure 2. Idealised responses of massive sulphides. The associations with various types of mineral assemblages are given in the text of the paper.

It must be remembered that the ability to detect such anomaly patterns will depend on the magnetic response of the adjacent host rocks.

Figure 3 illustrates the magnetic response of the Gurubang deposit (Aquitaine Australia Minerals 1977), approximately 20 km south of Cooma in New South Wales, in a Palaeozoic volcanic rift. The deposit, a sub-economic pyrrhotite-rich Cu–Zn deposit containing approximately 20 Mt of mineralisation, appears to display zoning consistent with Figure 1, in that the massive mineralisation is underlain by a zone of disseminated mineralisation and appears to be overlain by a magnetic pyrrhotite-rich 'ore equivalent horizon'. The magnetic response of the Gurubang deposit is similar to that illustrated in Figure 2E.

Figure 4 shows the magnetic response of the Rouez deposit, hosted by turbiditic sediments devoid of obvious igneous activity in a Proterozoic sequence in western France (Icart & Safa 1981; Sapin & Babu 1981; Lebouteiller 1981). The deposit contains approximately 100 Mt of sulphides containing Pb (6.3%), Zn (1.5%), Cu (0.6%), Ag (21 g/t) and Au (1.5 g/t). The dominant gangue is remanently magnetised pyrrhotite, which causes the magnetic response. The deposit is concordant with the local geology and occurs as several flat sheets which appear to be underlain by a feeder zone. A laterally equivalent shale unit containing magnetic disseminated pyrrhotite appears to be an 'ore equivalent horizon'. The magnetic response of the Rouez deposit is also similar that illustrated in Figure 2e.

Magnetite-rich Cu–Au deposits of Tennant Creek

The Tennant Creek area of the Northern Territory of Australia contains numerous Cu–Au–Bi deposits. While these have many similarities to massive sulphide deposits, their characteristic differences, such as the subordinate occurrence of Fe sulphides to Fe oxides, vertical elongation as ellipsoid or tabular bodies, cross-cutting relation to host lithology and the presence of economic Bi grades, are sufficient for them to be regarded as a separate deposit type. Tonnages are typically smaller, with the largest deposit containing 7 Mt of ore.

The geology and geophysical responses of the deposits are well documented (Daly 1957; Gunn 1979; Farrar 1979; Hoschke 1985, 1991: Wederkind & Love 1990; Edwards et al. 1990; Hill 1990, Smith & Hall 1995) They are confined to a magnetite-rich unit of the local stratigraphy and appear to be localised by cross-cutting faults, often in fold hinges, near linear hematite shale lenses, which have many of the characteristics of 'ore equivalent horizons'. The mineralisation is significantly zoned.

The deposits have characteristic, easily recognisable, bull's-eye magnetic anomalies caused by high magnetic concentrations associated with the economic minerals (Figure 5). Magnetic data can be used to identify the extent of the favourable host stratigraphy, folds in the stratigraphy, the location of cross-cutting shears that may control the emplacement of the deposits, and the magnetic anomalies caused by magnetite associated with the economic minerals. Over 650 deposits with similar characteristics have been reported, but fewer than 200 of these contain significant economic mineralisation.

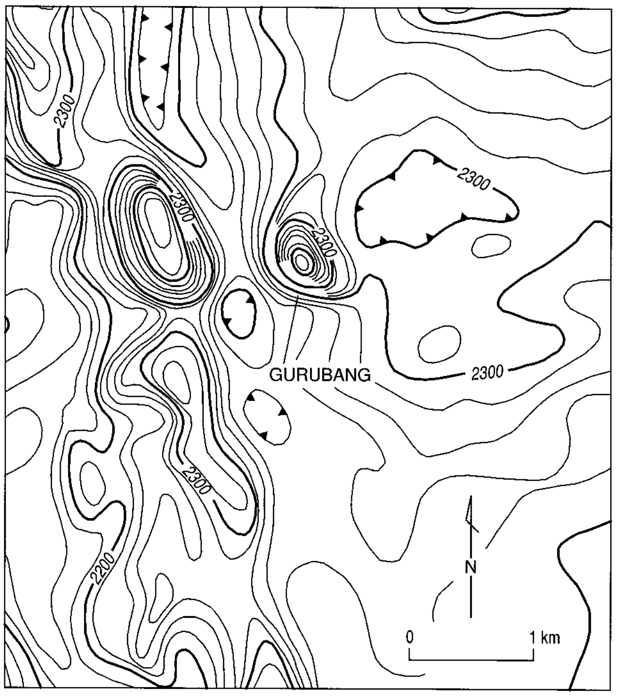

Figure 3. The magnetic response of the Gurubang deposit. The magnetic anomaly associated with the deposit is caused by remanently magnetised massive pyrhhotite. The low to the east of the deposit overlies a stringer zone and may be caused by destruction of magnetic minerals by alteration processes. The 'magnetic ridge' extending laterally from the deposit may be due to disseminated pyrrhotite in an 'ore equivalent horizon'.

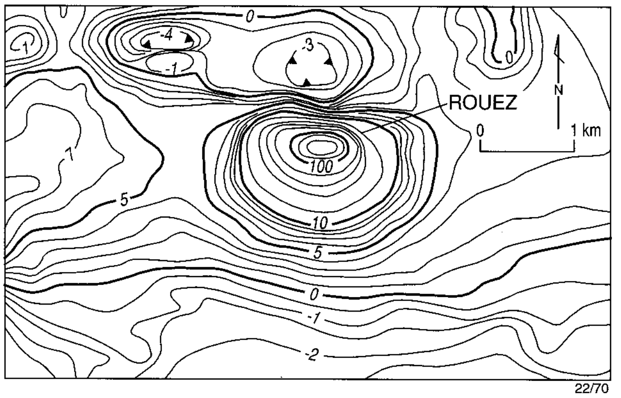

Figure 4. The magnetic response of the Rouez deposit. The main magnetic response is due to remanently magnetised massive pyrrhotite. The deposit is located on a laterally extensive magnetic ridge due to remanently magnetised disseminated pyrrhotite in a shale formation. The minor magnetic lows adjacent to the deposit could be due to destruction of the pyrhhotite by alteration processes.

Porphyry copper deposits

The term porphyry copper deposit encompasses the Cu, Cu–Au and Cu–Mo deposits associated with intrusive stocks of generally felsic and porphyritic nature, emplaced above down-going plates in island arc or Andean settings (Sawkins 1990). The mineralisation occurs as veins and disseminations in country rock above and adjacent to the upper portions of intrusions and in the upper parts of intrusions themselves. Systematic radial zoning of mineralisation and alteration has been identified in the majority of such deposits and a series of models for such zonings have been published (McMillan & Panteleyev 1980). Figure 6 shows a generalised representation of zoning in a porphyry ststem. As discussed by Clark et al. (1992), such intrusive systems have a semi-predictable magnetic response, albeit one related to the depth of erosion of the system. Figure 6 incorporates an idealised magnetic profile for a vertical inducing field (i.e. there is no distortion due to field inclination), reproduced from Clark et al. (1992), for the erosion level indicated in the figure.

Typically, such intrusive systems are emplaced in volcanics or are capped by volcanics associated with the intrusion. The volcanics, which are routinely inhomogeneous in nature, provide an erratic high-level magnetic response to the area. Destruction of magnetite in these volcanics by propylitic and phyllitic alteration can cause a smooth broad magnetic low over the vicinity of the intrusion. The felsic porphyry is generally, but not always, ferromagnetic in nature and, in such cases, a sharp localised magnetic high can occur in the centre of the magnetic low. This model produces a signature of porphyry copper deposits that is not directly related to the mineralisation, but rather to the ensemble of geology and processes associated with the formation of the mineralisation. Brant (1966) has published results of an aeromagnetic survey over the Bagdad porphry copper deposit in Arizona, which appears to fit this model.

Skarn deposits

Skarn deposits (Einaudi et al. 1981) consist of coarse-grained Ca–Fe–Mg–Mn silicates formed by replacement of carbonate rocks during regional or contact metamorphism and metasomatism. Skarn-hosted ore deposits, variably containing Sn, Fe, Cu, W, Zn, Pb and Ag, are commonly found at or near contacts between igneous plutons and sedimentary rocks. There are many variations between sub-classes of skarn deposits and this fact, combined with an apparent lack of definitive geophysical studies of such deposits, prevents more than a cursory overview of their magnetic signatures.

Emerson (1986) measured the magnetic properties of rock

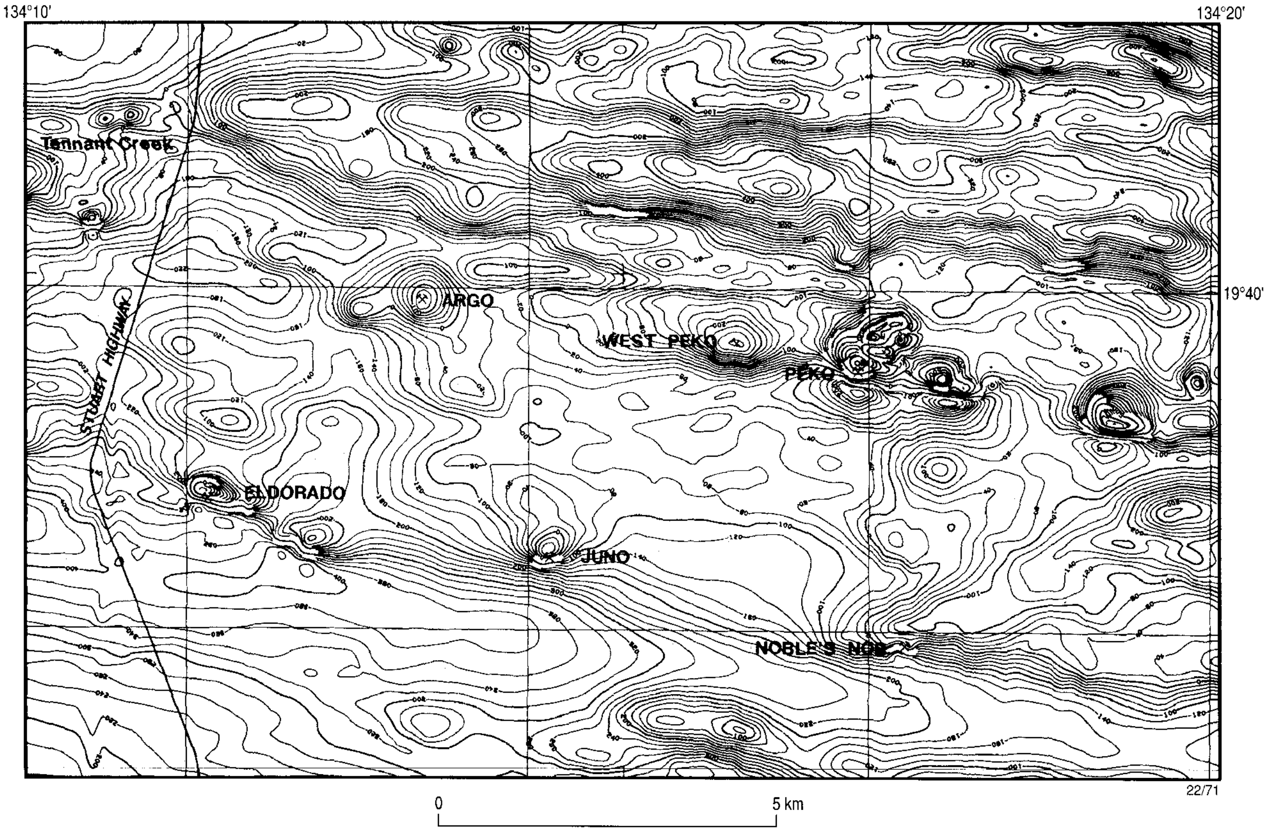

Figure 5. Magnetic responses of several Tennant Creek Cu–Au–Bi deposits (after Hoschke 1991). These manifest themselves as isolated 'bull's-eye' magnetic anomalies.

samples from the King Island W skarn deposit (Brown 1990), the Duckmaloi Bi–W skarn in New South Wales (Weber et al. 1978) and the Mount Moss Cu–Pb–Zn skarn in North Queensland (Manthorpe 1981) and concluded that the magnetisation is complex and variable and, while magnetics can aid skarn recognition, the technique cannot be relied upon for the recognition of skarn-hosted mineral deposits. Emerson did not specifically report on the magnetic responses of mineralised zones in these skarns.

Iron ores associated with igneous rocks include magmatic segregations, contact-metasomatic deposits and hydrothermal replacement deposits. Such deposits constitute only a small proportion of the world's iron production, but represent some of the best magnetic signatures, since they consist predominantly of magnetite. An example of such a deposit is the Marmora magnetite deposit, Ontario, described by Wahl & Lake (1957) as a contact replacement body in Palaeozoic limestones metamorphosed by a syenite intrusion. Metamorphism has altered the originally dolomitic limestone to a garnet, epidote or zoisite skarn. Magnetite occurs in the skarn as disseminated grains or as relatively pure masses. The mineralisation is blind, occurring at a depth of about 30 m. It was discovered through a prominent aeromagnetic anomaly (amplitude ~10 000 nT at a flight height of ~150 m). Two ground vertical magnetic intensity profiles were recorded across the ore body. One was carried out before stripping of the overburden, the second after stripping of around 30 m of cover. The former survey did not outline any zoning in the ore body, although Wahl & Lake stated that a first derivative of the data did. Differences in magnetisation were clear on the second survey and these were found to correlate closely with the grade of mineralisation.

Webster (1984) recognised a spatial association of tin deposits and the periphery of non-magnetic granites. These granites are usually identified with the ilmenite-series granitiods of Ishihara (1978), which have been linked with the S-type

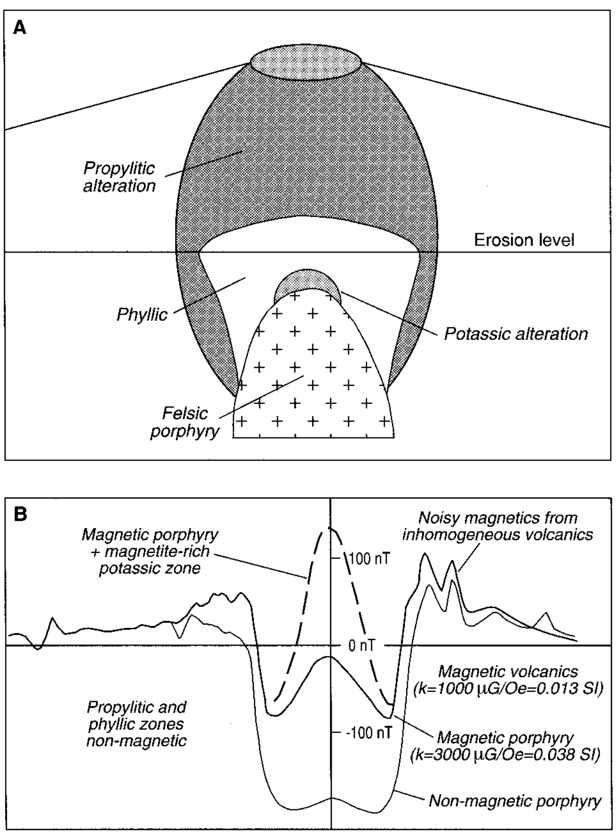

Figure 6. Idealised model for a porphyry copper deposit and associated magnetic responses (after Clarke et al. 1992). Note that the magnetic response of the system varies with depth of erosion.

granitoids of Chappell & White (1974). Tin deposits do not appear to be associated with magnetic granitoids (the magnetite type of Ishihara and the I type of Chappell & White). The tin deposits occur as cassiterite associated with sulphides and silicates in favourable carbonate horizons, breccias and veins. The primary deposits occur around cusps of ilmenite-series granitoids and frequently occur in magnetic aureoles associated with the granites. The aureoles could be due either to contact metamorphic effects or late stage mineralising fluids associated with the intrusions. Webster presented several examples from Tasmania (Cleveland, Renison, Mount Lindsay and Severn) and central New South Wales (Ardlethan and Tallenbung) to support his idea. Several of the Tasmanian deposits, viz. Renison, Mount Bischoff, Zeehan (Severn), Saint Dizier and Cleveland, are directly associated with magnetic anomalies apparently caused by associated pyrrhotite and sometimes magnetite. Large (1989) gave examples of these magnetic anomalies, which are sometimes isolated and clearly evident and sometimes partly obscured by other anomalies in the aureoles surrounding the granites.

The concepts of Webster (1984) appear capable of being generalised to allow the use of magnetics to identify:

- magnetic anomalies indicating the existence of granitic intrusions,
- whether the amplitudes of these anomalies indicate intrusions of the type likely to be associated with a particular type of skarn mineralisation,
- whether contact metamorphism and metasomatism are indicated by magnetic aureoles and,
- whether discrete anomalies likely to be directly associated with mineralisation are present.

Further work remains to be done in this field.

Placer mineral deposits

Placer deposits of minerals, notably gold, but also those of tin, platinum, heavy mineral sands, diamonds and various other minerals can be concentrated in palaeodrainage systems and on shorelines by virtue of having relatively high densities.

Often the channel systems hosting placer deposits are covered by later sediment or volcanics and, thereby, become difficult to delineate. Although the economic content of these channels does not give observable magnetic responses, there are several ways that magnetic data can be used to map the geometry of channels. These are:

- the channels may be eroded into a magnetic substratum, which can create a mappable anomalous response;
- detrital magnetite may be deposited on the floor of channels and the response of this magnetite may be mappable;
- channels may be filled by basalt flows, creating a magnetic anomaly which mirrors the channel geometry;
- maghemite may be formed in channel systems, producing a mappable magnetic pattern—spectacular magnetic images of palaeodrainage systems have been formed by this process in various parts of Australia, e.g. the Cobar area of New South Wales (Sheard et al. 1991).

The total magnetic intensity image of the Bendigo 1:250 000 map sheet (Denham 1997) includes several good examples of the mapping of palaeochannels by aeromagnetic data. These channels are extremely important in the context of gold exploration, as Bendigo has been a major producer of placer gold.

Magnetic data over the offshore area of the Joseph Bonaparte Gulf images a series of palaeochannels that apparently formed during a comparatively recent lowstand episode in the area (Gunn et al. 1995). It is unclear if detrital magnetite or maghemite is causing the anomalies. What is significant is that the clearly defined isolated channel in the west of the area is directly offshore from the mouth of the Ord River, which could be expected to drain erosion products from the diamondiferous Argyle lamproite pipe (Drew & Cowan 1994). This channel system could be prospective for alluvial diamonds.

Mineral sand deposits, concentrated by gravity sorting along beaches, can contain heavy minerals such as rutile, zircon and monazite. The accumulations may be magnetically detectable if they also contain magnetite or ilmenite. Mudge (1994) reported that the mineral sand deposits of Eneabba in Western Australia, which are approximately 50 m below the ground surface and do not contain magnetite, have a weak magnetic response (less than 10 nT in ground survey data) due to their ilmenite content.

Carbonatite-associated mineralisation

Carbonatites (Bell 1989) are alkaline igneous rocks, typically intrusive, but also extrusive, which contain more than 50 per cent by volume of carbonate minerals. They contain exotic mineral assemblages, and a small percentage contain economic mineralisation. The Palabora carbonatite in South Africa contains 300 Mt of copper ore grading 0.69 per cent copper plus important economic grades of apatite and vermiculite, and the Kovodor Complex on the Kola Peninsula of Russia contains 700 Mt of iron ore reserves and 110 Mt of apatite (Sawkins 1990). These mineral concentrations of copper and iron, however, appear to be unique among carbonatites, and the main economic interest in carbonatites is that they are major sources of niobium, phosphate and rare-earth elements and significant sources of titanium, fluorite and vermiculite. Mariano (1989) gives a detailed review of economic mineralisation in carbonatites.

Intrusive carbonatites typically contain concentric zoning of carbonate rocks, which tend to occur in the cores of the intrusions, and alkalic rocks. Variable magnetite concentrations in these zones produce magnetic anomalies, often of the order of several thousand nanoteslas. In ideal circumstances, this magnetic zoning will be concentric, but shape variation in the carbonatite and variation in magnetite concentration may result in magnetic anomalies having oval, elliptical, crescent-shaped or horseshoe-shaped forms. The diameter of intrusive complexes may be of the order of several kilometres. The characteristic concentric zoning in the magnetic pattern, the intense anomaly

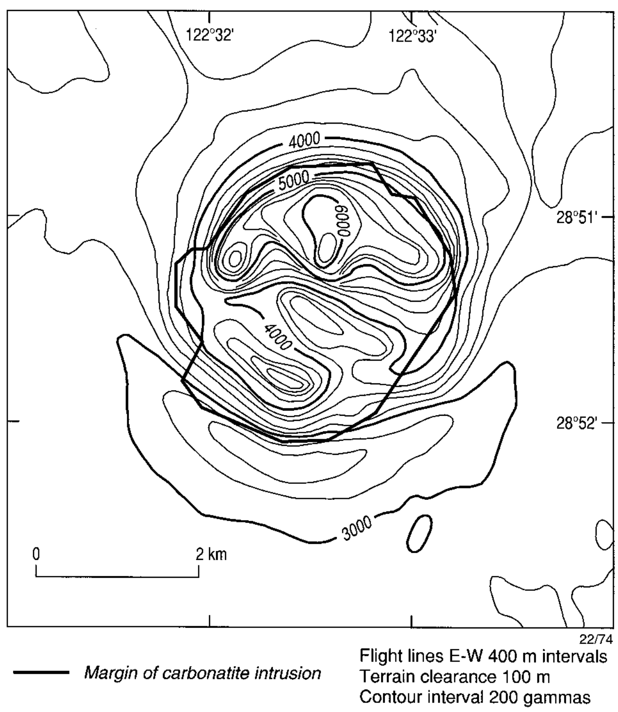

Figure 7. Magnetic response of the Mount Weld carbonatite (after Duncan & Willett 1990).

amplitudes and the tendency for carbonatites to occur in relative isolation allow the use of magnetic responses to target such intrusions. Carbonatites are enriched in uranium and thorium, and elevated radiometric count rates for these elements indicate the presence of a carbonatite rather than another type of concentrically zoned igneous intrusion.

Aeromagnetic surveys have been used successfully to discover carbonatites; approximately fifty were discovered in Ontario and adjacent parts of Quebec in the mid-1960s (Erdosh 1979). Erdosh described this carbonatite province, and gave examples of the deposits and their aeromagnetic responses. Several other examples of aeromagnetic responses have been published by the Ontario Department of Mines (1970).

Despite the widespread occurrence of carbonatites in various continents and their tendency to be geographically concentrated, there is a significant lack of reported carbonatite occurrences in Australia, the Mount Weld Carbonatite in the Archaean Yilgarn Craton (Willett et al. 1986; Duncan & Willett 1990) and the Cummins Range Carbonatite in northern Western Australia, at the junction of the Halls Creek and King Leopold Mobile Zones (Andrew 1990), being some of the few documented examples. These intrusions were discovered through the interpretation of regional aeromagnetic surveys. The Mount Weld Carbonatite has a circular plan and its detailed magnetic expression (Fig. 7) exhibits concentric zoning in accordance with the characteristics described above.

Diamonds

The known economic in-situ accumulations of diamonds occur in a small percentage of kimberlite and lamproite pipes and, although diamonds are known to occur in other igneous rocks and in rocks metamorphosed by high-pressure meteorite impacts, kimberlites and lamproites remain the prime objective of diamond explorers. The geology of these pipes, their mode of occurrence and their magnetic response are well documented, with MacNae (1979, 1995), Gurney (1989), Atkinson (1986), and Jaques (1994) providing sound introductions to these topics.

Kimberlite and lamproite pipes are emplaced as diatremes, originating at upper mantle levels, which rise to the surface with an explosive result that creates an ejecta-filled crater. Before any erosion occurs these craters are underlain by fresh intrusive material, which is approximately elliptical in plan and which tapers with depth. The maximum width of the pipes is of the order of several hundred metres, with examples of approximately 1500 m being known. The pipes can contain both magnetite and ilmenite and these minerals can give rise to observable magnetic responses. Kimberlite material can be serpentinised and this process can enhance the magnetic signature of the pipe. Not all kimberlites and lamproites are magnetic and clusters of intrusions can include magnetic, non-magnetic and reversely magnetised pipes in close proximity. Weathering of the upper parts of the systems can reduce any magnetic response.

Airborne magnetic surveys designed to detect kimberlite and lamproite pipes are typically flown along north–south flight-lines, 50–100 m above the ground with line spacing of the order of 200 m. A magnetic pipe will generally manifest itself as a circular or elliptical bull's-eye anomaly a few hundred metres across. Normally, no characteristic detail is resolvable in airborne anomalies; however, detailed ground magnetic surveys over such pipes frequently show concentric magnetic annuli, which reflect zoning of magnetic minerals in the intrusions (figure 1.16 of Atkinson 1986). The ease of detection of kimberlite and lamproite pipes with magnetic data depends on the magnetic response of the host lithology. A series of isolated, small circular anomalies is easy to detect in non-magnetic sedimentary terranes, but can be extremely hard to identify in areas covered by volcanics or surficial maghemite.

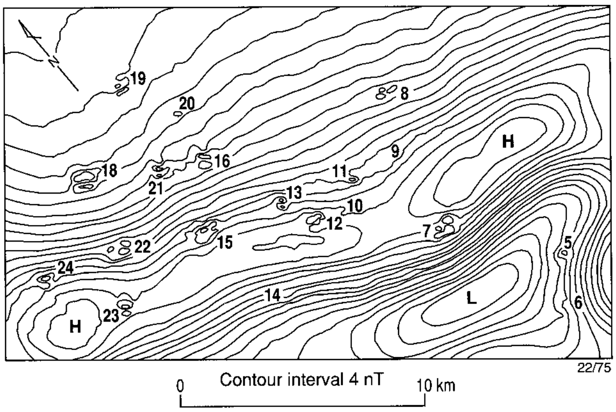

Figure 8. Magnetic responses of lamproites on the Lennard Shelf, Canning Basin, Australia (after Jenke 1983).

Compilations of the magnetic response of kimberlites and lamproites have been published by Gerryts (1970), Macnae (1979) and Atkinson (1986). Published Australian examples include descriptions of the non-economic Ellendale lamproite pipes by Jenke (1983) and Jenke & Cowan (1994). Magnetic contours clearly indicate these pipes relative to the non-magnetic sedimentary host rocks (Fig. 8). Drew & Cowan (1994) have published a description of the diamond-rich Argyle lamproite pipe and, while they conclude that the pipe is probably weakly magnetic, their actual survey results are equivocal as a result of topographic relief and relatively magnetic country rocks.

Chrome platinoids

Economic deposits of chromium, in the form of the mineral chromite, occur in ultramafic intrusions (Stowe 1987). These may be divided into two basic types, stratiform and podiform. The most famous examples of the former are the Bushveld Complex, South Africa and the Great Dyke, Zimbabwe. These layered intrusions are also host to economic platinum and magnetite mineralisation. In areas of poor exposure, magnetic surveys have been used to map the orientation of lithological layering in the Bushveld Complex and also to locate intrusive pipes (Buchanan 1988).

Podiform chromite deposits occur in peridotitic intrusions, often with an ophiolitic affiliation. Examples occur in the Urals, southwestern Europe and the Philippines. Describing deposits in the Urals, Klichnikov & Segalovich (1967) stated that direct search for chromite using the magnetic method is impossible, although zones of higher susceptibility due to serpentinite may occur adjacent to the ore zones. A relationship between magnesium chromite deposits and ultrabasic host rocks with a low iron content and, hence, reduced magnetic anomaly is also mentioned. Yungul (1956), in describing chromite deposits in Turkey, also mentioned that the strongest serpentinisation of the host rocks occurs near chromite bodies. However, the magnetic highs observed over the chromite bodies are attributed to remanent magnetisation of the chromite itself (Figure 9). Bosum (1970) reported on the magnetisation of chromite in deposits in Afghanistan, and also found remanent magnetisation to be important; Koenisberger ratios are generally greater than unity, with a maximum of nine.

Clearly, in exploration for chrome, magnetic surveying can play a role both in locating favourable host rocks and in identifying ore itself. However, mainly because of the magnetic nature of the local geological environment, magnetic data alone are not reliable and gravity data are normally also required.

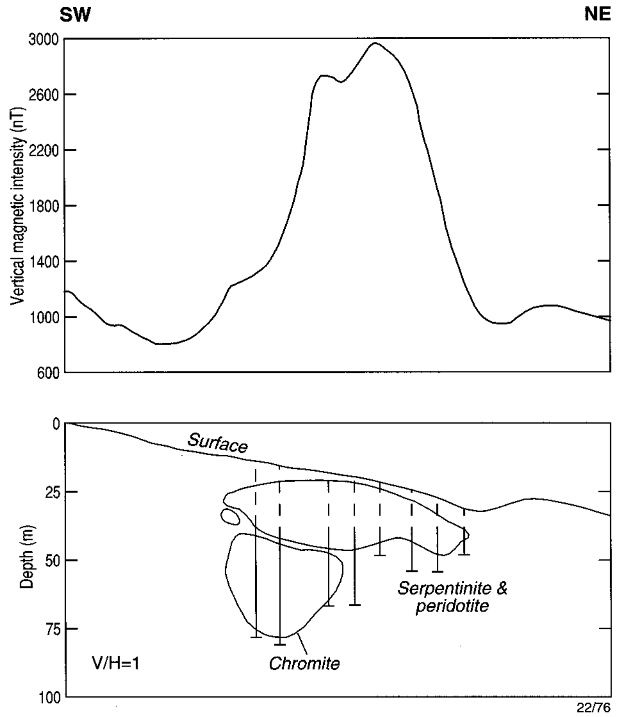

Figure 9. Geological cross-section and magnetic profile across a chromite body in the Guleman area, Turkey. The dashed part of the drill holes indicates the extrapolation to the surface of holes drilled after mining of the shallower ore body. Based on figures in Yungul (1956).

Gold

The low grades of economic gold mineralisation make direct detection using geophysical methods currently impossible (Doyle 1990). For this reason, the main use of magnetic data in exploration for gold is as a mapping tool in conjunction with other exploration methods, particularly geochemistry. The usual aims of such magnetic surveys are to:

- map particular stratigraphic horizons and lithologies which may be mineralised,
- identify structures that may be mineralised,
- detect the presence or absence of magnetic minerals caused by events which may be associated with processes creating gold deposits (e.g. alteration).

These approaches, which are not mutually exclusive, have been used to explore for gold mineralisation ranging in age from Archaean to Recent. As gold occurs in a wide range of geological environments, it is only possible in this review to cite a few examples of the application of magnetic techniques to gold exploration. Probably the best example is the use of high-resolution aeromagnetic data to map Archaean granitoid–greenstone terrains. Such surveys are particularly important in areas of poor outcrop, such as Western Australia (Isles et al. 1989).

In both the Yilgran Craton of Western Australia and the Abitibi region of Canada, gold deposits are spatially associated with large-scale structures defined by regional magnetic datasets (Read 1989; Groves et al. 1990). Once areas considered favourable to mineralisation have been located, surveys of increasing resolution are used to map at local and prospect scales. The value of the data is increased by the fact that gold mineralisation is often structurally controlled and is often found in iron-rich rocks (Groves et al. 1994), which tend to be relatively magnetic. For example, in the differentiated dolerite intrusion that hosts the world-class gold deposits of the Golden Mile at Kalgoorlie, Western Australia, the more magnetic phases of the intrusion are preferentially mineralised, especially where they are cut by faults.

Another example of the use of geophysics for geological mapping is the tracing of magnetic shale horizons in the West Rand Group of the Witwatersrand Basin, South Africa (Roux 1967). In favourable areas, these beds can be detected below several thousand metres of sediment. The gold itself occurs in conglomeratic horizons stratigraphically above these beds. However, the stratigraphic relationship between these units is fairly consistent and hence the location of the shales is a valuable indicator of the gold-bearing strata.

Magnetic anomalies associated with gold mineralisation itself may be due to either magnetite or pyrrhotite. The anomalies may be positive or negative depending on whether the process of mineralisation has deposited or destroyed these minerals. In the Yilgarn Craton the sulphides that may be associated with gold mineralisation depend on the local metamorphic grade. In greenschist facies deposits, pyrite or arsenopyrite are expected. However, at amphibolite facies either pyrite or pyrrhotite may be dominant (Groves et al. 1990). Dockery (1984) describes a positive anomaly due to disseminated pyrrhotite at the Lady Susan prospect in the Archaean of Western Australia.

Hydrothermal alteration associated with gold mineralisation may either create or destroy magnetite. Figure 10 shows a cross-section through the Archaean North Orchin gold deposit, south of Kalgoorlie, Western Australia. Mineralisation is controlled by a thrust, and the deposit is associated with a positive magnetic anomaly of several 100 nT, which has been interpreted as due to a magnetite-stable alteration halo (Williams 1994). Magnetic susceptibility data from drill core show the sub-surface distribution of susceptibility to be complex. Variations are partly due to a fine network of auriferous structures related to the main thrust.

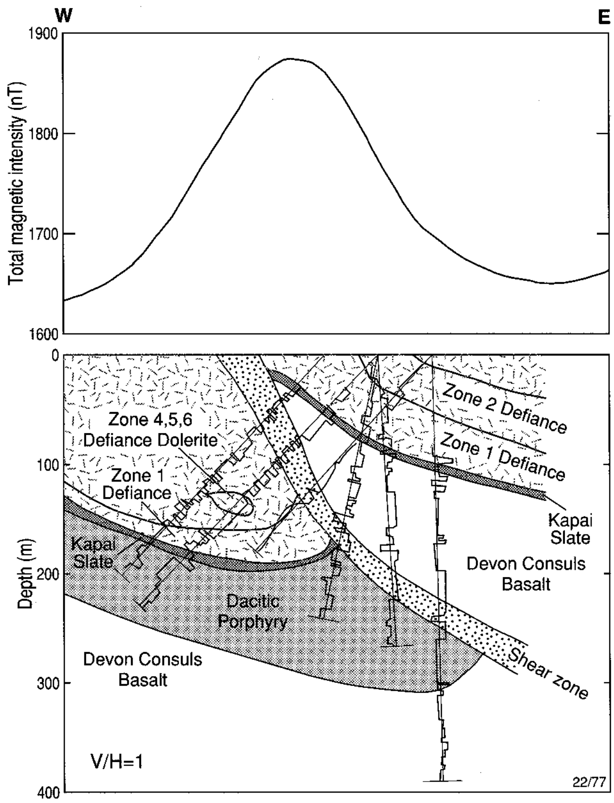

Figure 10. Geological cross-section and magnetic profile across the Orchin gold deposit, Western Australia. The magnetic anomaly is interpreted as due to a magnetite-stable alteration halo. Variations in magnetic susceptibility measured from diamond drill core are also shown. Based on figures in Williams (1994).

Irvine & Smith (1990) gave several examples of hydrothermal destruction of magnetite in the context of epithermal gold deposits. They correlated mineralising processes and zones of flat, smooth magnetic fields surrounding gold deposits.

Clearly, magnetic surveys have a role to play in exploration for gold, particularly when outcrop is poor. However, the responses due to mineralisation itself are diverse and not readily discriminated from anomalies due to other causes. A detailed knowledge of local geology thus appears to be a prerequisite for the successful application of magnetic surveys in gold exploration.

Iron ore

Exploration for iron ore based on its magnetic effects represents the earliest use of geophysics in mineral exploration. According to Espersen (1967), magnetic surveys to locate iron ore were carried out in Sweden as early as the middle of the seventeenth century.

The magnetic signature of iron deposits fundamentally depends on whether the mineralisation is in the form of magnetite or hematite. The majority of the world's iron production comes from ores in banded iron formation (BIF). Important occurrences of such ores are in the Pilbara region of Western Australia and the Lake Superior region of North America. Obviously, such a geological environment gives rise to extremely large and complex magnetic anomalies. The interpretation of data collected from such areas is complicated by the magnitude of the anomalies—which may be significant relative to the geomagnetic field where significant magnetite is present—the presence of strong remanent magnetisation, demagnetisation, and the markedly anisotropic nature of the magnetic properties of the BIFs (Clark & Schmidt 1994).

Kerr et al. (1994) describe the magnetic signatures of BIF-hosted iron ore deposits from the Pilbara region. Structural and stratigraphic control of the mineralisation is important here and the mapping of appropriate stratigraphic horizons and identification of suitable structures, such as faults and folds, are important aspects of the interpretation of magnetic data. The ores themselves form by supergene enrichment of BIF with magnetite being altered to hematite. The ore appears as zones of reduced magnetic intensity within the magnetic BIF horizons. However, this signature is not diagnostic and many similar but unmineralised 'lows' may occur. A similar approach to exploration and ore signature has been reported from Russia (Krutikhovskaya et al. 1967) and North America (Leney 1966).

Hematite iron ore containing approximately 60 per cent iron occurs as localised deposits in extensive quartz magnetite BIF containing approximately 30 per cent iron in the Middleback Ranges of South Australia (Owen & Whitehead 1965). Publications recording the magnetic properties and magnetic responses of these rocks include Taylor (1964), Webb (1966) and Gunn (1975). The hematite ore has a minor magnetic response; however, the BIF is strongly magnetic. Figure 11 shows computer modelling of magnetic profiles across the BIF, reproduced from Gunn (1967), indicating that weathering which converts magnetite to hematite can penetrate to depths of more than 100 m.

The Savage River deposit in northwestern Tasmania is a massive magnetite body that is generally thought to have a magmatic origin (Coleman 1975). The deposit is associated with a magnetic anomaly of more than 10 000 nT, and magnetic surveying, played a major role in the delineation of the deposit (Eadie 1970).

An example of an iron ore replacement deposit was given earlier in the section **Skarn deposits**.

Nickel deposits

Economic deposits of nickel are of two basic types, nickeliferous laterite and nickel sulphides (Knight 1975), and magnetic surveys play a key role in their exploration, for two reasons. Firstly, the deposits occur in association with basic to ultrabasic (meta)igneous rocks, and such rocks tend to have strong magnetic responses. Secondly, the presence of pyrrhotite and magnetite in many nickel sulphide deposits means that the mineralisation itself may be directly detectable by the magnetic method. Nickel-bearing laterites result from the weathering of basic and ultrabasic rocks and, obviously, these source rocks can be readily distinguished, using magnetic surveys, from other less-magnetic rocks.

During exploration, areas likely to contain nickel sulphides are first located with aeromagnetic data. Follow-up ground surveys are then usually required to better delineate prospective areas. An excellent example of the use of aeromagnetic data in this way is in exploration for the komatiitic peridotite-hosted deposits in the Archaean Yilgarn Craton of Western Australia. The geophysical expression of these deposits is described by Mutton (1987), Mutton & Willliams (1994), Pridmore et al. (1984) and Trench & Williams (1994). The deposits occur on or near the contact between komatiitic volcanics and underlying tholeiitic basalts. The sulphides occur in embayments in the contact between the two rock types, interpreted as troughs formed by thermal erosion during eruption of the ultramafics. Later deformation is often concentrated within these troughs. Since the stratigraphy is subvertical, magnetic surveys can be used to map the mafic–ultramafic contact and identify embayments. Subtle changes in thickness and geochemistry of the overlying ultramafics may also be detected.

Many occurrences of nickeliferous sulphides are associated with discrete magnetic anomalies (Dowsett 1967; McCall et al. 1995), some or all of which may be caused by the mineralisation itself. A detailed analysis of the source of magnetic anomalies associated with some Archaean nickel sulphide deposits in the Kambalda area, Western Australia, is described by McCall et al. (1995). Extensive studies of the magnetic properties of both ore and host rocks identified significant variation between individual deposits. The magnetisation of the ore and hanging-wall ultramafic units, the most likely causes of the magnetic anomalies, is affected by their metamorphic/ alteration history. Talc–carbonate alteration reduces the susceptibility of the ultramafics, owing to destruction of magnetite, whilst serpentinisation has the opposite effect. Temperature during metamorphism affects the mineralogy of the ores, with hexagonal pyrrhotite occurring in high-temperature areas. Modelling shows that a shallow magnetic ore body in an area of relatively unmagnetised ultramafics would produce a detectable magnetic anomaly. However, since the metamorphic/alteration environment varies significantly between deposits a few kilometres apart, it is not possible to confidently link any anomaly to previously undiscovered mineralisation.

Figure 12 shows cross-sections and corresponding magnetic profiles across deposits from the Thompson area of Manitoba, Canada. In the case of the Thompson ore body, Dowsett (1967) described pyrrhotite in the ore body as the major cause of the magnetic anomaly, but the nearby 'iron formation' is also a contributor. A peridotite body in the deeper part of the ore body is too deep to be a significant contributor. In contrast, the high-amplitude and longer wavelength magnetic anomaly associated with the Pipe ore body has a significant component originating in the peridotite body that hosts the ore. Also, the ore contains magnetite inclusions as well as pyrrhotite.

Despite the association of magnetic anomalies with many nickel sulphide ore bodies, magnetic data alone are unreliable for locating ore bodies and the use of other geophysical methods, particularly electromagnetics, is essential in target selection.

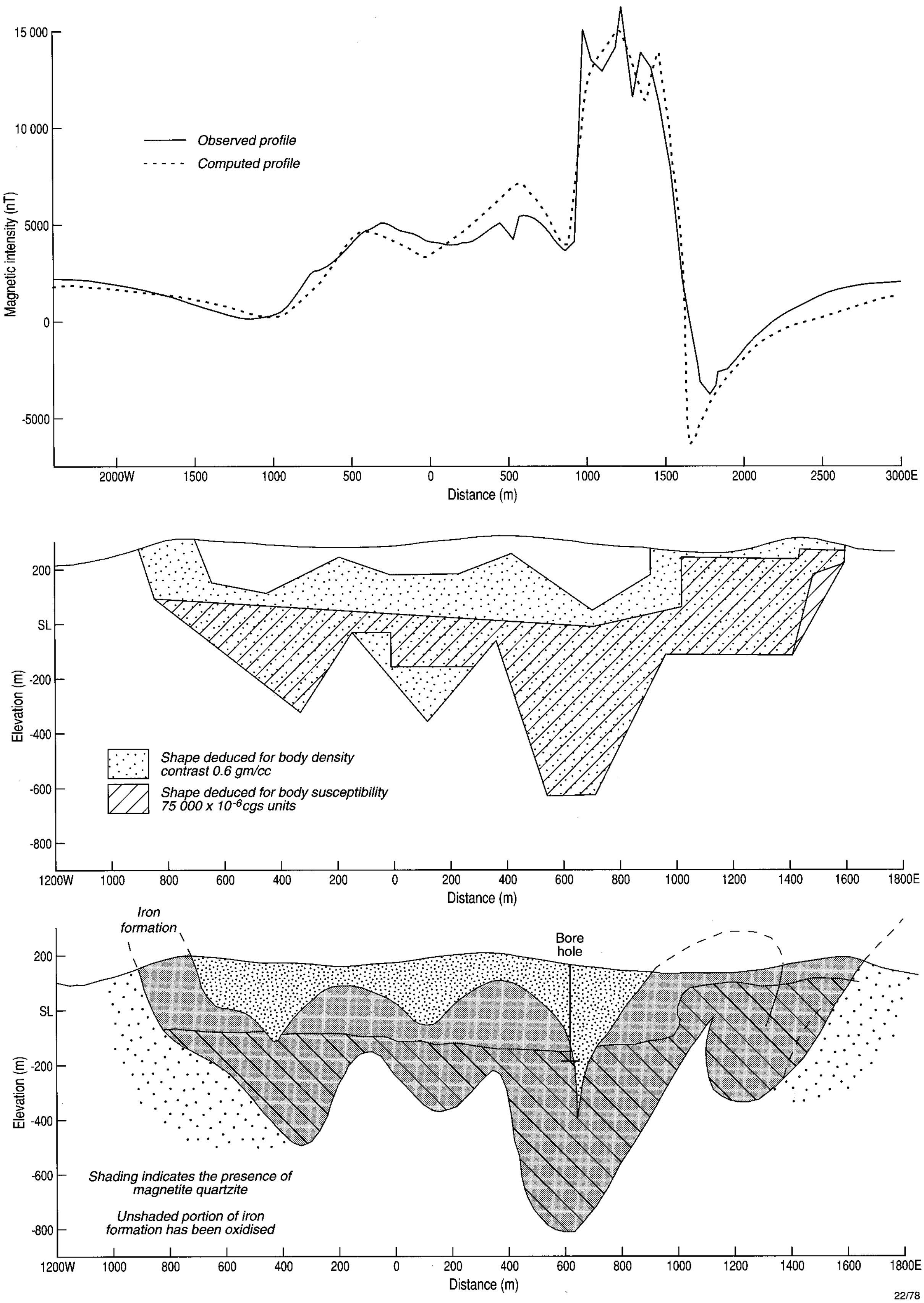

Figure 11. Interpreted magnetic profile over the Middleback Range iron formations, South Australia (after Gunn 1967) The interpretation has been based on detailed rock property measurements and subsequent correction of these values for demagnetisation. The computer program applied a terrain correction for portions of the magnetic mass above observation points. The interpretation indicated a folded layer of magnetite quartzite that has been extensively weathered in its upper levels to hematite. This interpretation is consistent with surface dips and the geometry of the iron formation indicated by gravity modelling.

Concluding remarks

It is apparent, from the examples described above, that the magnetic method can be used as a primary exploration tool for many mineral deposit types. It has not been possible here to exhaustively review studies already existing in the literature. To give a comprehensive coverage of the magnetic response of each of deposit type mentioned in this paper it would be necessary to devote at least a separate paper to each deposit type. What is obvious from the above review is that much more work relating magnetic distribution, magnetic responses and economic mineral accumulations is required. A thorough knowledge of the distribution of magnetic minerals in ore deposits and their host rocks is essential for the successful application of the magnetic method in exploration.

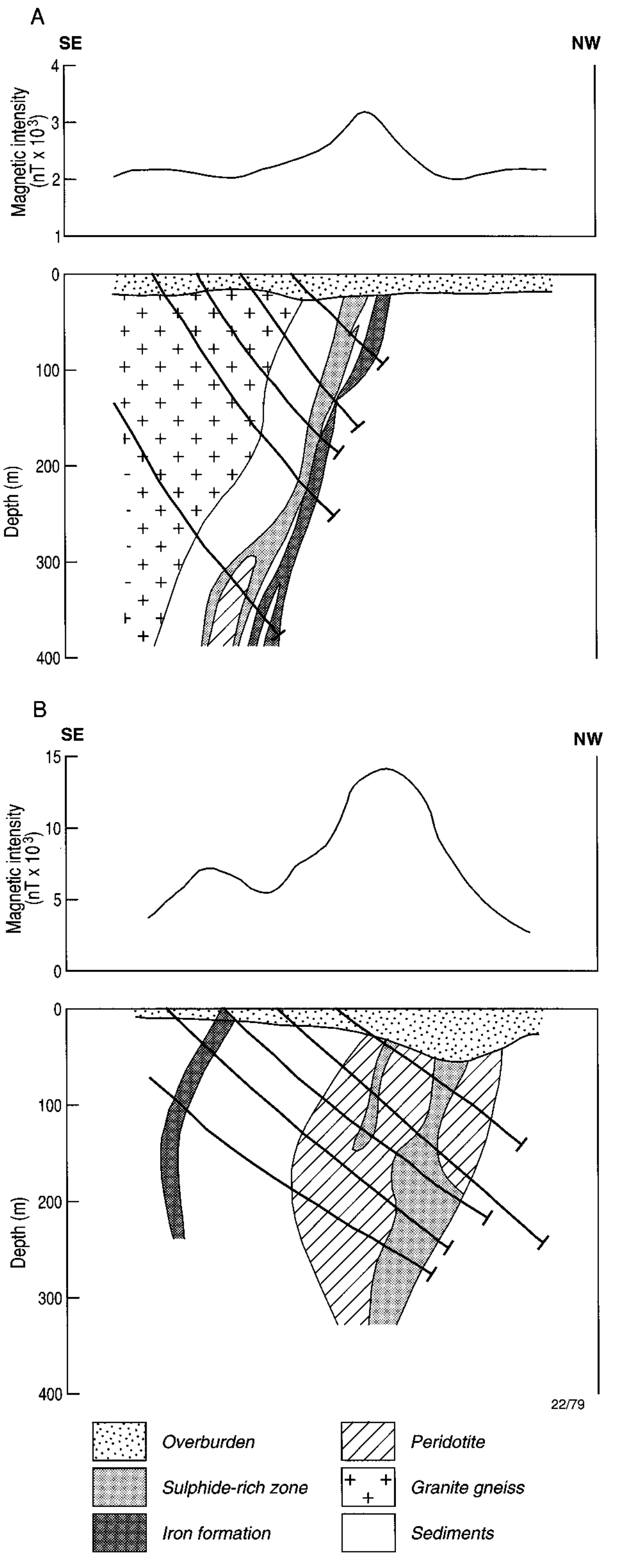

Figure 12. Geological cross-sections and magnetic profile across nickel sulphide deposits in the Thompson area, Manitoba. (A) Thompson mine, (B) Pipe mine. Note the difference in the scales of the magnetic profiles. Redrawn from Dowsett (1967)

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