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GEOPHYSICS OF IRON OXIDE COPPER-GOLD DEPOSITS

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Abstract – Geophysics is an essential part of most modern mineral exploration programs for iron oxide copper-gold deposits. This paper reviews the important physical properties, which are the basis for the application of geophysical methods, and attempts to illustrate and summarise the ways they have been applied with data and images from selected deposits. Some comments are provided on their historical effectiveness and the role of these methods in an overall program, which must use all available data from geology, mineralogy, geochemistry and geophysics.

Introduction

The class of iron oxide-Cu-Au deposits has captured the imagination of many explorers in the last decade. There have been notable successes, and extensive exploration programs continue on most continents. There is however, no universally accepted definition of this class of deposits, no comprehensive genetic model and no simple, unambiguous, geometric or mineralogical description.

This paper attempts to take a pragmatic approach and look for common features and physical properties which may affect the application and interpretation of geophysics in further discoveries. These features may be regional or local, they may target either a prospective setting or direct detection and they will be illustrated with real examples, wherever possible.

Deposit Types

Although the author knows no universally accepted and unambiguous definition of iron oxide-Cu-Au deposits, there are certainly common characteristics of many deposits that are commonly included in this class.

Perhaps the primary mineralogical characteristic of all deposits in this class is the abundance of magmatically sourced iron oxide, either magnetite or hematite (including specularite), often, but not always, accompanied by a relative lack of iron sulphides. Hitzman (Hitzman, 2000) considers that magnetite-apatite ("Kiruna-type") deposits are closely related and usually occur as precursors to the introduction of copper and gold. The addition of copper and gold, while economically critical may not always occur, leading to many "barren" magnetite-apatite deposits closely related to this class. Uranium may also be present (eg Olympic Dam) and potassic alteration often accompanies the introduction of copper and gold.

In practise, magnetite is almost always present, although variably abundant, both within the deposit itself and in the surrounding rocks. The presence of magnetite-apatite systems is generally considered to be a favourable indicator of the right tectonic setting. Although some deposits occur close to iron rich BIF's, this is considered an element of structural control and not a primary characteristic of the deposit type (Andrew R.L., pers. comm.).

The presence of copper, as chalcopyrite, sometimes accompanied by variable concentrations of pyrite, is a primary economic characteristic. Gold may also be present, but although it is an important economic feature, it is unlikely to occur in sufficient concentration to affect the physical properties and hence it has little direct relevance to geophysical considerations.

The geometry of these deposits seems to be extremely variable and complex. Apart from size, which is also an economic criterion, there seems little which can be said about the geometry that might affect geophysical targeting. Due largely to the influence of structural control, deposits of this type occur in many shapes, sizes and attitudes, so that any attempt to restrict the geometry may excessively limit the target description. The combination of size and location will ultimately limit the economic potential of most deposits, but that is outside the scope of this paper.
Hitzman (Hitzman, 2000) considers that deposits of this class usually occur in post-Archaean rocks from early Proterozoic to Pliocene. They occur in a range of tectonic environments associated with significant igneous activity, and possibly close to volcanic centres, but generally do not appear to be associated with specific intrusions. They are often localised along fault splays off major, crustal–scale extensional faults, but are located in diverse rock types, resulting in a wide variety of deposit styles and mineralogies. This structural control and diverse nature of the resulting styles of mineralisation results in a high degree of complexity in the final deposits.

Physical Properties

Magnetic Properties *(ref. Clarke, 1997)*

Magnetite is classed as *ferrimagnetic*. On an atomic scale, magnetic moments are antiparallel, but tend to cancel out imperfectly resulting in an appreciable magnetisation. At normal temperatures it exhibits strong magnetic susceptibilities (the susceptibility of 100% massive magnetite ranges from ~ 10 to 150 SI) and often also has significant remanent magnetisation.

Hematite (including specularite) is usually described as *anti-ferromagnetic*. At normal temperatures the antiparallel magnetic moments are deflected from the anti-ferromagnetic plane, resulting in a weak or "parasitic" magnetism. Susceptibilities are typically $6x10^{-4}$ to $2x10^{-3}$ SI. There may also be significant remanent magnetisation, a point that is often forgotten.

Figure 1 illustrates the expected range of magnetic susceptibilities for a number of common rock types and minerals, taken from Clark and Emerson (1991).

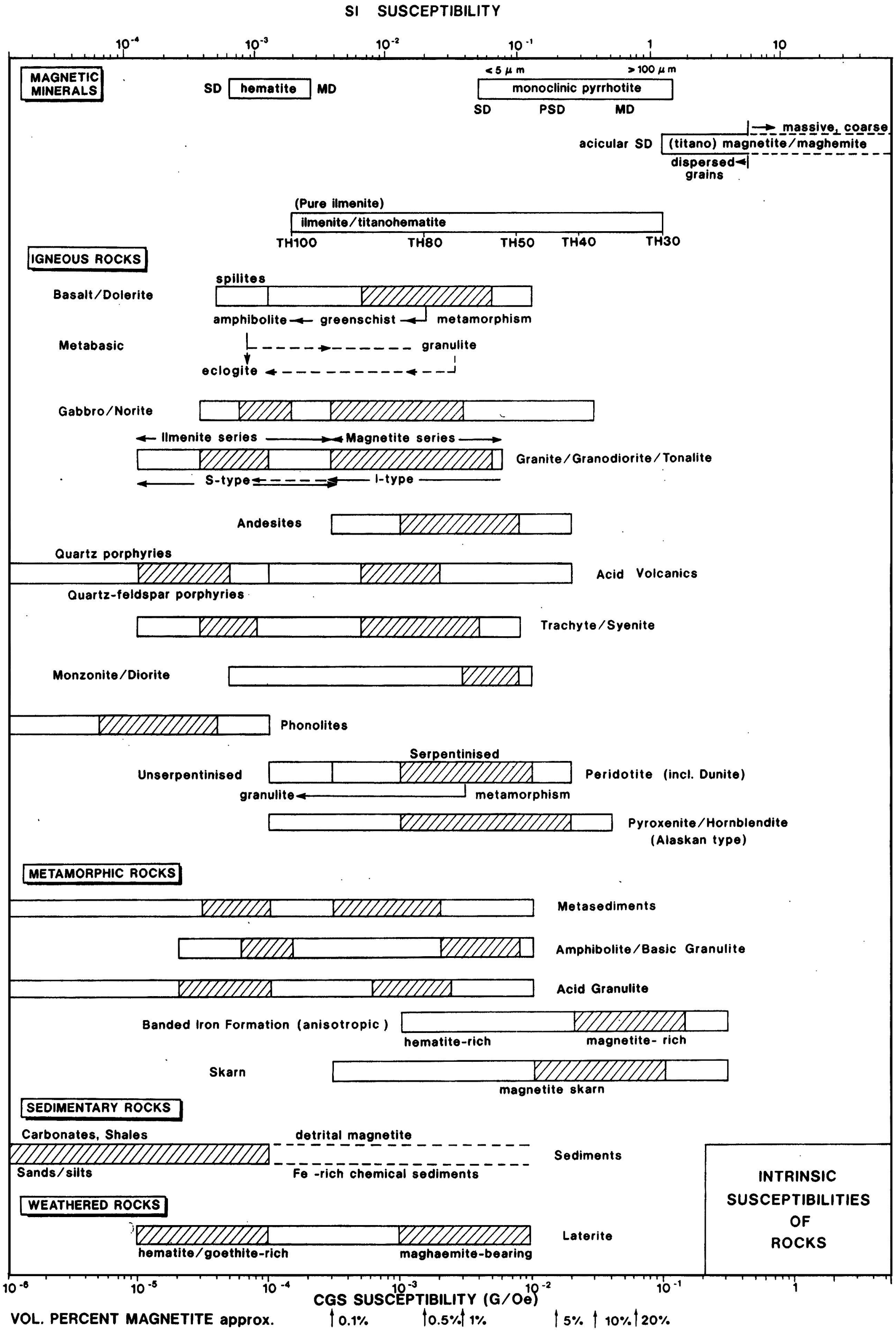


Figure 1: The expected range of magnetic susceptibilities for a number of common rock types and minerals, taken from Clark and Emerson (1991).

In practic, magnetite is usually associated with pronounced magnetic responses or "anomalies" and hematite is not, but this can sometimes be misleading.

Since magnetite is a common rock forming mineral, it occurs in many rocks in varying concentrations and grain sizes. The grain size affects the intrinsic magnetic properties of the mineral. In addition, when disseminated, the effective magnetic properties are diluted and self-demagnetisation effects become important. Dilute dispersions of magnetite grains (f<0.1) give susceptibilities of ~3.5f (SI), where f is the volume fraction of magnetite (Clark, pers. comm.). The presence of remanence may either reduce or enhance the effective magnetisation.

The dominant magnetic phase in many rocks is fine grained, magnetically soft multi-domain magnetite, which mainly exhibits viscous remanent magnetisation. This remanence is frequently sub-parallel to the present field and hence it tends to enhance the effective susceptibility without changing the resultant direction of magnetisation. Iron oxide copper-gold deposits are often associated with more coarse-grained magnetite, which tends to retain an ancient remanent direction. It may add to or subtract from the induced magnetisation, or simply skew the resultant magnetisation vector. This would affect quantitative interpretation. Nevertheless, the presence of significant magnetite is usually easily recognised by pronounced magnetic "anomalies".

Hematite, particularly if coarse grained, can sometimes exhibit significant remanent magnetisation resulting in magnetic "anomalies", but this is relatively rare. When it does occur it is generally not aligned with the present field and hence it can distort the resultant direction of magnetisation. This can seriously affect the quantitative interpretation of magnetic sources, where typically only induced magnetisation is considered.

The ratio of remanent to induced magnetisation is termed the Koenigsberger ratio (Q) and some typical values of Q for a number of common rocks are summarised in Figure 2, taken from Clark and Emerson (1991).

In the deposits of interest in this paper, hematite (and maghemite) may result from the partial (or as at Olympic Dam, the almost complete) destruction of magnetite by alteration processes, and hence the two often occur either together or in close proximity. In these cases strong remanent magnetisation is common.

The only common sulphide mineral, which exhibits significant magnetisation at normal temperatures, is pyrrhotite, whose magnetic properties vary from anti-ferromagnetic (hexagonal), with low susceptibility (~1.5×10^{-3} SI) and no remanence, to ferrimagnetic (monoclinic) which has a much higher susceptibility. Monoclinic pyrrhotite has a susceptibility ranging from 0.04 SI for fine grains (<5µm) up to ~10 SI for coarse grained (>100µm) massive monoclinic pyrrhotite. It usually also exhibits strong remanence (Q ranges from 1-10 for coarse (>100µm) grains to >100 for fine grains) which is often quite oblique to the present field (Clark, pers. comm., Clark, 1997). Pyrrhotite is not common in iron oxide copper-gold deposits and hence the magnetic properties of pyrrhotite are not of primary consequence.

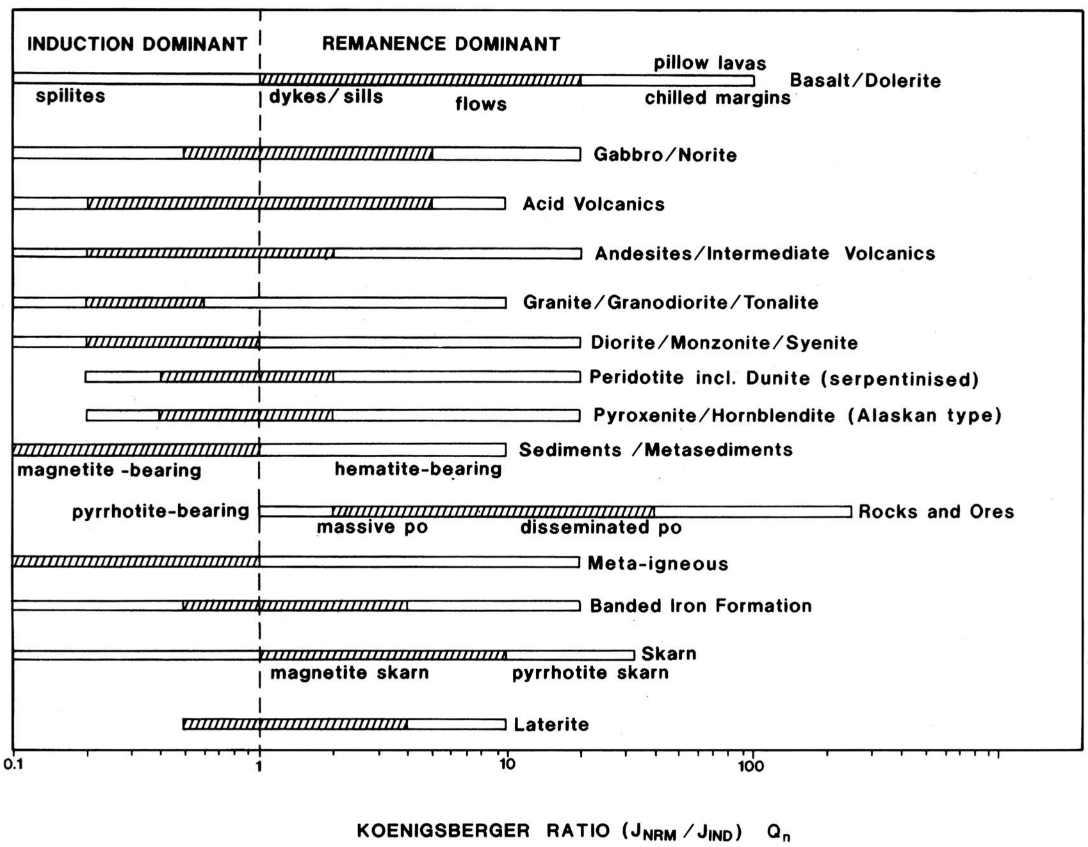


Figure 2: Typical Koenigsberger ratios for common rocks.

Chalcopyrite is paramagnetic and has a typical susceptibility of 30 to 40x10^{-5} SI. It does not contribute significantly to any magnetic response.

Gold is weakly diamagnetic and generally occurs in very low concentrations. It does not contribute significantly to any magnetic response.

Most other rock forming minerals are either weakly paramagnetic or diamagnetic and most observed magnetic responses can be attributed to the presence of magnetite, maghemite and, to a lesser extent, hematite.

Specific Gravity

Most rock forming minerals have a well-documented density or specific gravity. The specific gravity of commonly occurring rocks can be estimated from the mineral composition. In real rocks, impurities and other factors result in much more variability. Nevertheless average dry bulk densities for most rock types are generally close to or in the range 2.5 to 3.0 gm/cm^3 as listed below:

Acid igneous (Av.) ……...	2.30 – 3.11 gm/cm^3
Basic igneous (Av.) ……...	2.09 – 3.17 gm/cm^3
Metamorphic (Av.) ……...	2.4 – 3.1 gm/cm^3

(Ref. Tables 2.3 and 2.4 in Telford et. al. 1976)
(Ref. Table 5, Olhoeft G.R. and Johnson G.R. 1989).

By contrast, most ore forming minerals have much higher densities. Olhoeft and Johnson (1989) list the following values for the minerals of interest in this study.

Chalcopyrite …………...	3.6 gm/cm^3
Gold ……..……………..	3.6 gm/cm^3
Maghemite ………….....	4.9 gm/cm^3
Magnetite ………..…….	5.2 gm/cm^3

In all cases they are likely to be much more dense than their host and consequently, if large enough, will result in significant gravity "anomalies". In particular, large hematite associated deposits (eg. Olympic Dam) may be difficult to detect by any other geophysical method.

Electrical Resistivity/Conductivity

The electrical resistivity or conductivity of most minerals is reasonably well documented, however in real rocks there can be significant variations due to impurities, dilution, pore fluids and mode of occurrence. The values quoted generally refer to the properties of a relatively pure mineral specimen. In rocks the inherent variations due to impurities are likely to be minor compared with dilution, due to low concentrations or the presence of saline pore fluids in the overburden or in fractures. In addition there will be major differences between rocks where the conductive mineral particles are either evenly disseminated or interconnected by a network of veinlets.

Nevertheless, the electrical properties of magnetite, hematite (including specularite), chalcopyrite, pyrite and perhaps even gold are of interest.

Most rock forming minerals have very high electrical resistivities and consequently the rocks formed from them are resistive also. Some examples are listed below (taken from Tables 5.4 & 5.5, in Telford et al, 1976). These are typical examples, but there can be wide variations due to weathering, fracturing and other mechanical factors.

Sandstones ………………	(1-6.4)x10^8 (Ωm)
Limestones ……………...	50 - 10^7 (Ωm)
Dolomite ………………...	3.5x10^2 - 5x10^3 (Ωm)
Andesite …………………	4.5x10^4-1.7x10^2 (Ωm)
Granite …………………..	3x10^2 - 10^6 (Ωm)
Basalt ……………………	10 - 1.3x10^7 (Ωm)

By contrast, magnetite, hematite, chalcopyrite and (gold) are usually several orders of magnitude more conductive, as listed below (from Table 5.2, in Telford et al, 1976):

Magnetite …………....…	5x10^{-5} - 5.7x10^3(Ωm)
Hematite ………………....	3.5x10^{-3} - 10^7(Ωm)
Specularite (Av.) …..……	6x10^{-3}(Ωm)
Chalcopyrite …………....	1.2x10^{-5} - 0.3(Ωm)
Chalcocite …………….....	3x10^{-5} - 0.6(Ωm)
Pyrite ………………..……..	2.9x10^{-5} - 1.5(Ωm)
Pyrrhotite ……………..…	6.5x10^{-6} - 5x10^{-2}(Ωm)
Gold ………………..……	2.4x10^{-8}(Ωm)

In practice, most rocks conduct by movement of ions in the pore fluids. If the rocks are porous (as in the weathered zone) and pore fluids are saline, this can greatly enhance the conductivity. It is common, for example, to measure resistivities in the range 1 to 10 (Ωm) in Australia, due primarily to a deep, porous weathered zone and saline ground water. Nevertheless, in most cases the metallic sulphide minerals will still be much more conductive than barren rocks and even rocks containing magnetite and hematite (specularite) are likely to be relatively conductive.

Several methods are available to measure resistivity (or conductivity) and detect major anomalies in rock resistivity. These include primarily induced polarisation (IP) & resistivity, electromagnetics (EM) and magnetotellurics (MT). Within these broad headings there are numerous subdivisions and variations on the specific method of making the measurement. In principle they could all detect magnetite, hematite and chalcopyrite if they occur in sufficient abundance and in a favourable environment. In practice however there are many complications which may favour one method over another.

IP & Resistivity measurements are usually made together and they are very sensitive to large volumes of even low-grade mineralisation. The addition of an IP measurement contributes to this sensitivity, but it can also respond to many non-economic targets.

EM measurements, whether made from the air or on the ground (or even in drill holes) respond best to a high resistivity contrast, even though the target conductor may occupy a small volume. For example a thin sheet of highly conductive mineralisation may be a good EM target but respond poorly to IP & resistivity.

MT, AMT and CSAMT all respond similarly to resistivity, but they do not include an IP measurement. In some cases they can achieve very great depth penetration to large conductors. MT and AMT are passive measurements, which use natural field variations as an energy source, but these can be unreliable. CSAMT uses an artificial source to ensure sufficient energy for a measurement.

Chargeability *(ref. Parkhomenko E.I., 1967 and 1971)*

Although most host rocks conduct electricity by movement of ions through pore fluids, the "metallic minerals" or those with metallic lustre, usually conduct by movement of electrons through the crystal lattice. This includes most of the metallic sulphides and also includes magnetite and hematite (specularite), graphite and, of course, gold. This mixture of ionic and electronic conduction is the basis of the induced polarisation effect, which can be measured in various ways. The basic parameter, which characterises the magnitude of the response of a mineral to induced polarisation, is "chargeability". Since the measured chargeability is extremely dependent on the concentration and mode of occurrence of the metallic particles (eg. disseminated versus interconnected), as well as the conductivity, it is not usual to list intrinsic chargeabilities for various minerals. It is sufficient to say that chalcopyrite, chalcocite, pyrite, pyrrhotite, gold, magnetite and specularite will all increase the chargeability of a rock when they are present. Dr D.W. Emerson (1994) conducted a petrophysical study of the electrical properties of such ores in a recent AMIRA project (P416).

Although details of the induced polarisation mechanism are still debated, the effect has been shown to be reasonably well described by a mathematical model (the Cole-Cole model, ref. Pelton et al, 1978). In this model, another useful parameter is the "time constant" which appears to be related to the average grain size of the metallic particles. There have been a number of attempts to determine the time constant as well as the chargeability, by measuring at a range of frequencies or over a wide time range, and then using these parameters for mineral discrimination. For example, identifying a specific response for magnetite as distinct from a signature for chalcopyrite would obviously be advantageous. Although there have been specific cases where this appears to have been somewhat effective, in general the time constant appears to be mainly dominated by effective grain size.

In summary, it seems enough to say that magnetite, specularite and chalcopyrite (as well as pyrite and pyrrhotite) can all cause IP anomalies and when they occur in close proximity it is often difficult to distinguish between them.

Radiometrics *(ref. Muller D. and Groves D.I. 1995)*

The radiometric method detects gamma radiation, which is emitted by a number of naturally occurring rocks and minerals, that contain specific elements or, more correctly, specific isotopes of these elements. The only naturally occurring elements of interest as gamma emitters are potassium (K40), uranium and thorium (and their daughter products). Modern gamma ray spectrometers, carried in aircraft, are able to distinguish between emissions from these three sources and, if calibrated, provide a quantitative map of their near surface distribution. These can be used to map near surface lithology and often also to detect overprints from alteration. Perhaps the most important of these is the signature of potassic alteration, which has been associated with many copper-gold deposits.

Although magnetite, hematite and chalcopyrite are unlikely to have a direct radiometric signature, the deposits of interest may have a potassic alteration halo, related directly to the copper-gold mineralisation. If so, this could be detected by airborne or ground based radiometric measurements.

The observed radiometric response is often attenuated, to varying degrees, by soil cover but the nature of the source (eg. K, U or Th) may still be apparent. Potassic alteration is often accompanied by depletion in thorium and hence the K/Th ratio is often used to enhance the alteration signature. Various statistical methods (eg. principal components) can also be used to try to separate alteration overprints from the normal responses relating to cover and lithology. Some examples of this approach can be seen in Wellman (1998, 1999) and Shives et al (1997).

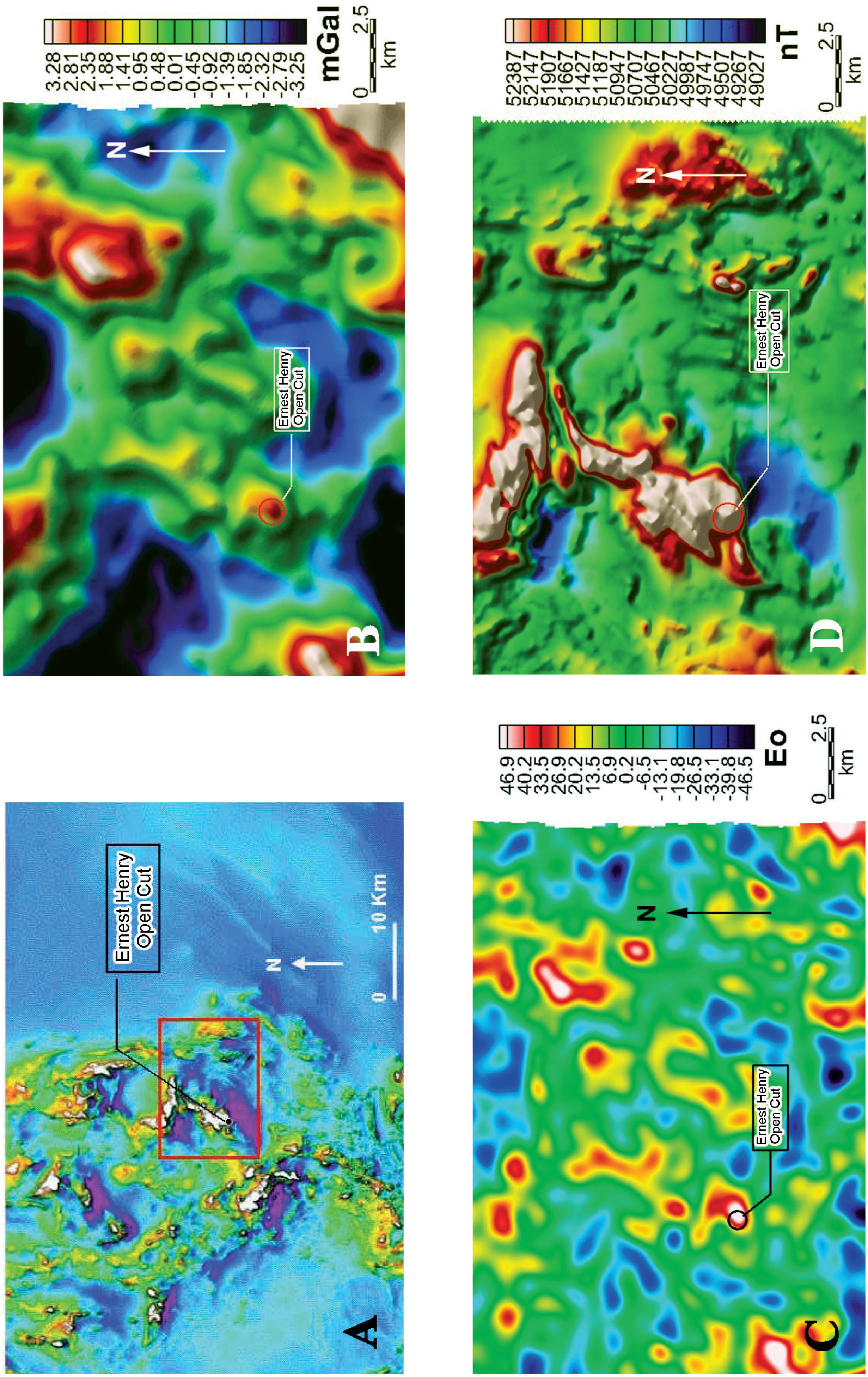
Seismic

Although the acoustic impedance of the ore minerals must increase with increasing specific gravity, the acoustic velocity may compensate due to a decrease caused by faulting and brecciation. In any case, the complex geometry of these deposits is likely to make seismic applications difficult and they are not well documented. Seismic methods do offer high resolution at depth and may find more application in the future.

Regional Responses

Regional geophysical data sets, principally magnetics and gravity, are now becoming readily available in many areas. These data sets are often of high quality and inexpensive, if not free. They are widely used, together with regional geology, as a "first pass" look and as an aid to area selection.

From the discussion of physical properties it should be apparent that iron oxide copper gold deposits are likely to occur in an area of some magnetic activity, although not necessarily coincident with a discrete magnetic anomaly. Haynes (2000) noted this "magnetically active" signature as a characteristic of such mineralised districts at Olympic Dam, Moonta-Wallaroo, Ernest Henry and Candelaria. Plates 1A and 1E show TMI images of the area surrounding Ernest Henry and Olympic Dam. In both cases, there is a notable increase in magnetic activity in the district surrounding the deposits. Numerous possible targets can be easily identified but, in each case, only one has been shown to be associated with economic mineralisation.


A
Ernest Henry Open Cut
N
0 10 Km
B
Ernest Henry Open Cut
N
3.28
2.81
2.35
1.88
1.41
0.95
0.48
0.01
-0.45
-0.92
-1.39
-1.85
-2.32
-2.79
-3.25
mGal
0 2.5 km
C
Ernest Henry Open Cut
N
46.9
40.2
33.5
26.9
20.2
13.5
6.9
0.2
-6.5
-13.1
-19.8
-26.5
-33.1
-39.8
-46.5
Eo
0 2.5 km
D
Ernest Henry Open Cut
N
52387
52147
51907
51667
51427
51187
50947
50707
50467
50227
49987
49747
49507
49267
49027
nT
0 2.5 km

Regional gravity data tends to show similar character but the available data is usually less detailed. The recent development of an airborne gravity gradiometer by BHP (Falcon), and its deployment on mineral exploration projects will undoubtedly change this in the future. A gravity gradiometer measures the gradient of the gravity field, but it can be converted mathematically to produce maps of the gravity field (Gz), which match conventional ground gravity measurements. These airborne measurements can rapidly produce detailed gravity maps over large areas, similar to the airborne magnetic maps, which have been used extensively for many years.

Plates 1B and 1C show images of gravity (Gz) and vertical gravity gradient (Gzz) derived from an airborne survey by Falcon over Ernest Henry.

Radiometric data is generally collected with a gamma ray spectrometer, together with magnetic data, in modern airborne surveys. In recent years there has been a significant improvement in data quality and it is now common to use the data for lithological mapping, in conjunction with magnetics. In some cases it is also possible to recognise an alteration halo as an overprint on the lithology (Shives et al, 1997; Wellman, 1999). At Candelaria, test surveys after the discovery did confirm the value of radiometrics "in determining areas of potassic alteration when it is outcropping or within 10 to 20 cm of the surface" (Matthews and Jenkins, 1997).

Shives et al (1997) described radiometric data from the Lou Lake area, NWT, Canada. In this area, the Sue-Dianne deposit (Goad, et. al., 2000), which has documented similarities with Olympic Dam, was discovered as a result of a radiometric anomaly detected on survey lines 5 km apart. Subsequently, more detailed surveys were flown by the Geological Survey of Canada and this delineated several new targets as well as the existing ones. Plates 2C and 2D show K and Th/K images respectively from this later survey, taken from Shives et al (1997). In this case they used Th/K to enhance the alteration signature. Plate 2B shows the geology. The large area of enriched K, to the south east of Lou Lake, coincides with numerous showings of vein and disseminated Au-Co-Cu-Bi-W-As. There are also coincident magnetic (>2000 nT) and gravity (3 mgal) anomalies not shown here. Although not yet proven to be economic, subsequent drilling has discovered extensive polymetallic sulphide mineralisation within an extensive zone of potassic alteration and iron enrichment.

Figure 3 shows multi-channel profiles along Line 16, which traverses from east to west across the centre of the area shown in Plates 2B, 2C and 2D. The position of the

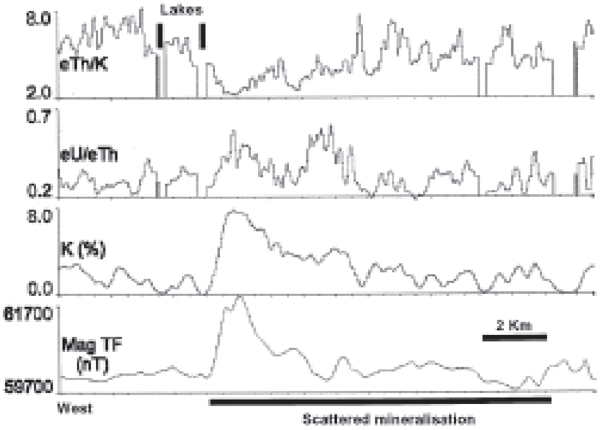


Figure 3 - Multi-channel, partially stacked profiles along Line 16, Lou Lake, NWT, Canada (see Plates 2C & D for location) from a 1993 survey at 500 m line spacing (Shives *et al.*, 1997)

lakes can be clearly seen by a decrease in K response and low values of eTh/K and eU/eTh. Immediately to the east of these lakes there are coincident magnetic and K anomalies which appear to reflect the alteration halo around mineralisation. The alteration zone is also coincident with a zone of increased eU/eTh due to some additional enrichment in U in the mineralised zone. Of course it is well known that there is significant U enrichment in Olympic Dam also, but the depth of cover would mask any similar response to airborne radiometrics.

Deposit Signatures

In detail the geophysical signatures of these deposits are more complex. Although deposits usually occur in an area of significant magnetic relief, they are not always coincident with discrete magnetic anomalies. In the case of the hematite rich Olympic Dam (see Plate 2A) the prominent magnetic anomaly coincident with the deposit appears to come from a deeper source. While it may be genetically related to the mineralisation, it seems unlikely to be directly attributable to it. Plate 1D shows detailed TMI over Ernest Henry. It appears more likely in this case that there is a magnetic response from the mineralisation, but it is only one of many magnetic anomalies in the district and not obviously different from many other possible targets. This is a common feature of these deposits as the related iron oxide is usually much more widespread than the copper sulphide and gold mineralisation.

At Candelaria, in Chile, good quality magnetic data was not obtained until after the initial discovery and earlier

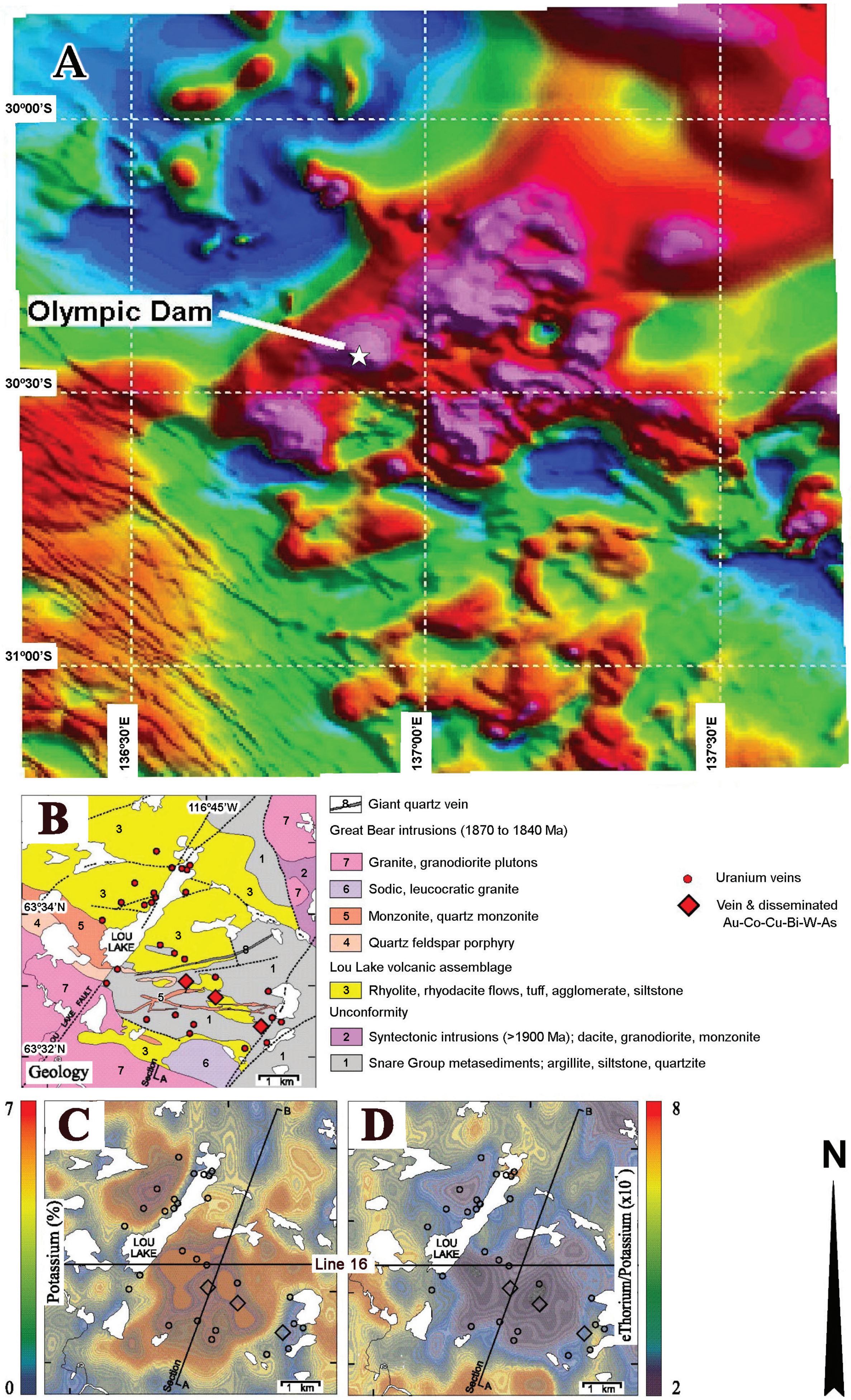
PLATE 1 (see facing page)**:**

A – Shaded TMI Image of Ernest Henry District (courtesy of BHP-Billiton)

B – Shaded Image of Gz over Ernest Henry (courtesy of BHP-Billiton)

C – Image of Gzz over Ernest Henry (courtesy of BHP-Billiton)

D – Detailed TMI over Ernest Henry (courtesy of BHP-Billiton)


A
Olympic Dam
30°00'S
30°30'S
31°00'S
136°30'E
137°00'E
137°30'E
B
116°45'W
63°34'N
63°32'N
LOU LAKE
LOU LAKE FAULT
Section A
1 km
Geology
Giant quartz vein
Great Bear intrusions (1870 to 1840 Ma)
7 Granite, granodiorite plutons
6 Sodic, leucocratic granite
5 Monzonite, quartz monzonite
4 Quartz feldspar porphyry
Lou Lake volcanic assemblage
3 Rhyolite, rhyodacite flows, tuff, agglomerate, siltstone
Unconformity
2 Syntectonic intrusions (>1900 Ma); dacite, granodiorite, monzonite
1 Snare Group metasediments; argillite, siltstone, quartzite
Uranium veins
Vein & disseminated Au-Co-Cu-Bi-W-As
C
D
7
0
Potassium (%)
LOU LAKE
Line 16
Section A
B
1 km
8
2
eThorium/Potassium (x10⁻¹)
N

surveys were of low sensitivity and poorly oriented (Matthews, J.P. and Jenkins, R.A. 1997). Subsequently, high quality data has been obtained. After processing to compensate for the local field inclination (reduction to the pole) an excellent correlation was obtained between the magnetics and mineralisation as shown in Figure 4.

Gravity appears to be more effective in many cases. At Olympic Dam there is also a significant gravity anomaly coincident with the mineralisation which is usually attributed mainly to the ore mineralisation. In fact, early drilling and the discovery hole were sited on the coincident magnetic and gravity anomalies (Rutter, H. and Esdaile, D.J., 1985; Smith, R.J., 1985; Esdaile D.J., et al, 1987).

Similarly, at Ernest Henry, as shown in Plates 1B and 1C, there are both Gz and Gzz anomalies coincident with the deposit. While not unique, they are perhaps more distinctive than the related magnetic features. Detailed ground gravity measurements were used to delineate the deposit and showed good correlation with the mineralisation.

In general one might expect that any significant deposit of the iron oxide copper gold class should have an associated

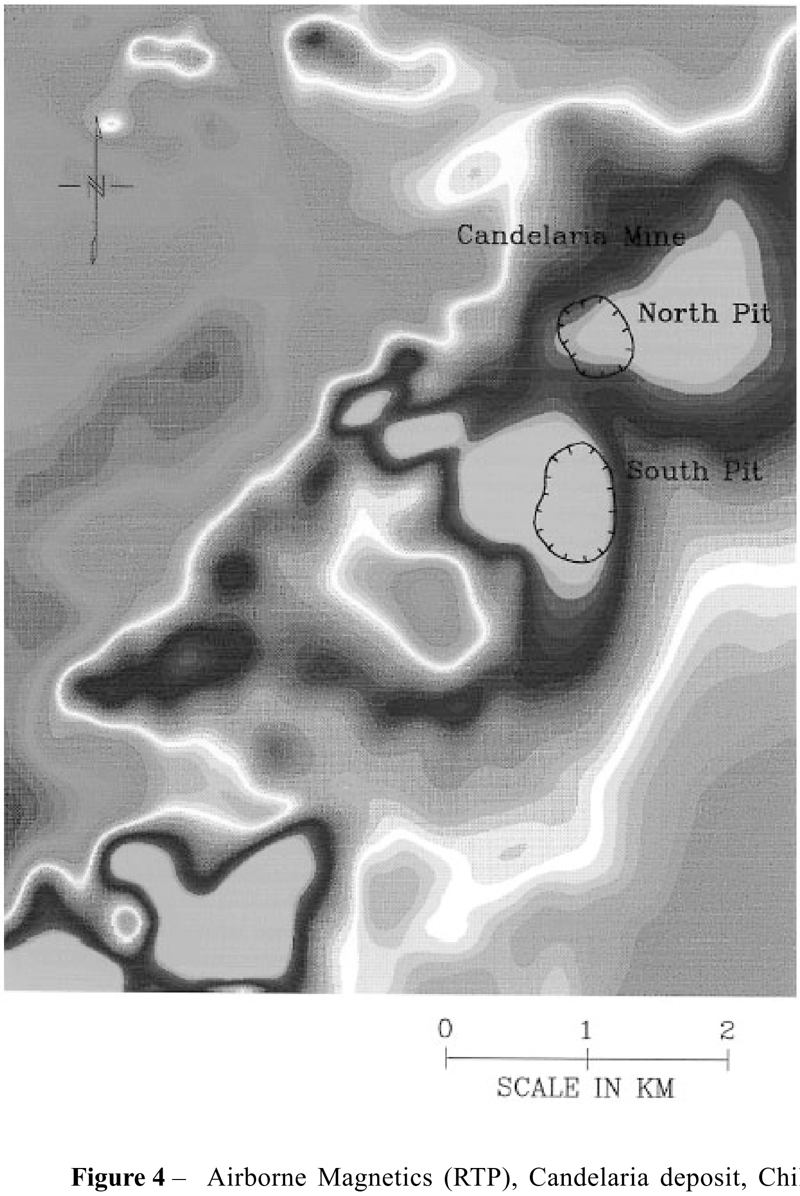


Figure 4 – Airborne Magnetics (RTP), Candelaria deposit, Chile (Matthews and Jenkins 1997).

PLATE 2 (see facing page)**:**

A – Shaded TMI Image of Olympic Dam District (courtesy of PIRSA)

B – Geology and Legend, Lou Lake, NWT, Canada (Shives et al, 1997)

C – K Image, Lou Lake, NWT, Canada (Shives et al, 1997)

D – Th/K Image, Lou Lake, NWT, Canada (Shives et al, 1997) gravity response and may or may not have an associated magnetic response.

Although there is often both associated potassic alteration and uranium enrichment in these deposits, radiometric methods are not widely used for direct detection (as distinct from regional reconnaissance). Thickness of cover often obscures any radiometric signature at the surface but down-hole measurements are often useful for ore delineation. The application of down-hole radiometrics would be dependent on the precise mineralogy of the deposit and will not be reviewed here.

Since magnetite, hematite (specularite) and chalcopyrite (and possibly other sulphide minerals) are all conductive, a range of electrical methods can be used for direct detection of these deposits. Historically IP and resistivity have been widely used and with notable success, but modern EM and MT methods have also been shown to be effective in some cases. They all directly detect the target mineralisation, but unfortunately frequently respond also to the associated magnetite and hematite (and pyrite and pyrrhotite, if present). Since these associated conductors are often more laterally extensive than the target mineralisation they will result in many spurious targets. Nevertheless, several notable discoveries have been attributed to these methods.

Olympic Dam is located beneath approximately 300 metres of relatively conductive cover, which would reduce the effectiveness of electrical methods. Early attempts at detecting the deposit with IP were unsuccessful, due primarily to problems attributable to the deep, conductive cover. Subsequent work with more advanced equipment did give a detectable response (Esdaile D.J., et al, 1987).

At Ernest Henry, the strong magnetic anomalies in the area influenced area selection and ground based TEM surveys were used to "filter" the magnetic targets (Ryan A.J., 1998). Copper and gold mineralisation was discovered in 1991 when drilling a moderate amplitude TEM anomaly. Subsequent down-hole TEM suggested that the initial TEM response was primarily due to a supergene zone rich in native copper. The bulk of the primary mineralisation did not produce a TEM anomaly (Webb, W. and Rowston, P., 1995). Typically, these deposits are not massive and their conductivity is generally not ideal for detection by EM methods. If an enriched supergene zone is present it may present a better target. Subsequently, ground magnetic, gravity and induced polarisation methods were used to delineate the deposit at Ernest Henry. Ground magnetic data showed that the main magnetic response was primarily due to magnetite in shears to the north and south of the main deposit, rather than the ore mineralisation itself. IP is much more sensitive than EM to disseminated mineralisation and both surface and down-hole measurements were used at Ernest Henry. It was shown to respond to both the supergene-enriched zone and to the primary ore, and also to "sparsely mineralised magnetite".

At Candelaria, mineralisation was well known and had been mined intermittently from time to time (Matthews and Jenkins, 1997). Initial IP/resistivity surveys over the known mineralisation revealed extensions both laterally and in depth and these guided early drilling. There is abundant non-economic sulphide mineralisation in the area, which also gave pronounced IP responses. IP and resistivity were primary exploration tools but the success obtained relied heavily on starting in the right place, over known deposits.

In summary, IP and resistivity methods have been generally successful in detecting these deposits but they also respond to both iron oxides and barren sulphides, which are often present. EM methods have not been as successful in general, probably due to the disseminated nature of many targets. EM methods are still developing and they may become more effective in the future.

Conclusions

Regional magnetic, gravity and radiometric data sets are now readily available in many parts of the world. They are valuable tools to assist in locating prospective areas, associated with magmatic intrusions and major structural controls. Radiometric data may also indicate potassic alteration haloes in areas where the signature is not obscured by excessive cover.

Specific deposits themselves may or may not have a magnetic signature although they will almost certainly occur in an area of significant magnetic relief. Almost all known deposits in this class do give a significant gravity response but it may be difficult to recognise in areas of complex tectonics or steep terrain.

IP/resistivity has proven to be the most generally useful of the electrical methods, but it also responds to barren sulphides, if present, and to magnetite and specularite. Consequently it will produce many "spurious" targets. EM methods have been less useful in general, due to the often disseminated nature of the targets, but they should not be ignored. Airborne EM may find more application in the future as new systems develop with improved sensitivity. MT methods should also be applicable, particularly where deep penetration is required, but little data is available.

These deposits are difficult to categorise and hence there is no generally applicable recipe for successful exploration. It is important to use a range of tools and integrate all available geological, mineralogical, geochemical and geophysical data to understand them.

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