A Sub-Audio Magnetics case study: 
Flying Doctor Pb-Zn-Ag Deposit, Broken Hill, Australia

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ABSTRACT

The Flying Doctor Deposit is located approximately 5 km north-east of Broken Hill, NSW. The area lies along strike from the main Broken Hill ore bodies and is considered highly prospective for the development of base-metal sulphide mineralisation. The deposit was originally detected by induced polarization profiling techniques. Subsequent drilling in 1965 led to the discovery of a massive sulphide body. Over the last 20 years, comprehensive geological and geophysical data have been acquired at the site and consequently, the Flying Doctor Deposit has become an important test site for the evaluation of new geophysical techniques in the Broken Hill region.

One of the first Sub-Audio Magnetics (SAM) trials was conducted at the Flying Doctor deposit in late 1992 to test the feasibility of acquiring total field magnetometric resistivity (TFMMR) data simultaneously with high definition total magnetic intensity (TMI) data. Subsequent trials in 1995 focused on acquiring total field magnetometric induced polarization (TFMMIP) and total field electromagnetic (TFEM) parameters. It was found that the Flying Doctor Deposit exhibited no magnetic susceptibility contrast but that the mineralisation was readily detected by both the TFMMR and TFMMIP parameters. This paper describes the results of the TFMMR/TFMMIP surveys and compares them with results obtained with prior surveys including gradient-array induced polarization (IP), dipole-dipole array induced polarization and magnetic induced polarization (MIP) surveys.

The SAM trials demonstrated that it is possible to map several geophysical properties simultaneously with a single instrument, and confirmed that SAM is capable of acquiring data cost-effectively at spatial resolutions equivalent to high definition magnetics. An important conclusion from the surveys was that much greater interpretative power can be derived from having multiple data sets which reflect independent physical properties.

INTRODUCTION

The Flying Doctor Pb-Zn-Ag Deposit, named for its proximity to the old Royal Flying Doctor Radio Control Centre, is located approximately 5 km north-east of Broken Hill. The Control Centre has since moved to the local airport and the favoured name for the location is currently “Barrier main lode, Northern Leases”. The name “Flying Doctor” is retained here because of its more popular and historical usage. The area lies along strike from the main Broken Hill ore bodies and is considered highly prospective for the development of sulphide mineralisation. A locality and regional geology map of the area is shown in Figure 1.

The deposit was originally detected by induced polarization profiling techniques as a zone of intense chargeability anomalies. Subsequent drilling in 1965 led to the discovery of a massive Pb-Zn-Ag sulphide ore body. The most recent drilling in 1980 delineated what has until recently been described as sub-economic mineralisation, with reserves of 300 000 tonnes averaging 5.7% Pb, 59 g/t Ag and 3.0% Zn (Widdop et al., 1983). Over the last 20 years, comprehensive geological and geophysical data have been acquired at the site and as a result, the Flying Doctor Deposit has become an important test site for the evaluation of new geophysical techniques in the Broken Hill region. The SAM surveys described in this paper were conducted as part of the initial research into the SAM technique and are described in detail by Cattach (1996) and Boggs (1999).

GEOLOGICAL SETTING

The geology of the Flying Doctor Deposit has been comprehensively described in reports by Stevens et al. (1980) and Widdop et al. (1983). The majority of the known stratiform and

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strata-bound base-metal mineralisation in the Broken Hill Block occurs in two metamorphic rock suites. These are the Thackaringa Group and the overlying Broken Hill Group, both of which are part of the Willyama Supergroup (Stevens et al., 1980). Widdop et al. (1983, p 5) state that

“...The known Broken Hill type Pb-Ag-Zn mineralisation occurs within the Broken Hill group which consists of a variable sequence of metasedimentary gneisses, quartzo-feldspathic gneisses, pegmatites, amphibolites, iron formations and the so-called ‘lode-horizon’ rocks.”

At the Flying Doctor Deposit, two separate lode horizons have been delineated: the upper lode horizon (ULH), and the main lode horizon (MLH). The MLH is the direct extension of the lode horizon containing the main Broken Hill ore bodies. The ULH is most likely a structural repetition of the MLH. There is an intimate association between the lode horizon rocks (commonly quartz gahnite, garnet quartzite, and garnet sandstone) and the development of Pb-Ag-Zn sulphide mineralisation, and the lode horizon rocks are generally interpreted to be metamorphosed, locally remobilised, chemical sediments, deposited together with the stratiform sulphides.

A geological map of the Flying Doctor Deposit is included as Figure 2. Much of the early exploration work conducted in the area was based on the imperial grid system shown in Figures 2 to 6. Three principal survey lines with a separation of 750 ft (228.6 m) were established at the site and are shown as Lines 24.50, 25.25, and 26.00. Geological cross sections along these lines are shown in Figure 3. Tyne (1987, p287) states that

“...The major sulphide intersections occur near the boundary between a quartzitic gneiss and the retrograde shear zone and are equivalent to the ULH. ... Although the sulphide body is generally tabular and dips steeply to the west, it shows a considerable variation in cross-sectional shape over the 450 m strike length between Lines 24.50 and 26.00. The narrow sulphide intersections within the shear zone are equivalents of the MLH. This mineralisation appears to have been remobilised during the development of the Globe Vauxhall retrograde shear, and as a result is conformable with the shear zone boundaries.”

The host rocks are sillimanite and quartzitic gneiss. Some surface traces of lode horizon rocks can be observed at about 6 W on the imperial grid lines. However, there is no gossanous outcrop to indicate the presence of buried sulphide concentrations. The Globe Vauxhall Shear Zone parallels the surface projection of the ULH and the MLH.

Form of the Mineralisation

The character of the mineralisation at the Flying Doctor Deposit has been summarised by Widdop et al. (1983, p14) as follows:

“The Pb-Ag-Zn mineralisation consists predominantly of coarse metamorphic intergrowths of galena and sphalerite (marmatite) together with microscopic inclusions of native silver and silver bearing minerals. Although the intersections of higher grade sulphides generally consist of medium to coarse grained stratiform and locally remobilised sulphides, fine-grained disseminated stratiform sulphides are also common and occur together with

Fig. 2. Flying Doctor geological plan (adapted from Larsen, 1993). East-west lines show the locations of cross sections in Figure 3 and the dipole-dipole IP pseudosections shown in Figure 5. Station spacings are in 100 ft intervals.

Fig. 3. Flying Doctor geological cross sections (adapted from Tyne, 1985). Vertical exaggeration is 1:1.
coarse sulphides... Sulphides are most commonly hosted by the lode types but occur in a wide range of rock types. Both stratiform and remobilised stratabound sulphides occur within the lode horizon rock types ... The sulphide mineralisation consists predominantly of: galena sphalerite (var. marmatite), minor pyrrhotite, chalcopyrite and pyrite + accessory arsenopyrite, foel lingite and rare accessories ... Common gangue mineralogies in intersections are, in general order of abundance; quartz, gahnite, f.g. muscovite, biotite, chlorite, K-feldspar, sericite altered sillimanite.”

Widdop et al. (1983, p14) describe extensive development of the Globe Vauxhall and Western retrograde schist or shear zones within the area as representing “… ductile shear deformation within which the original mineralogies of the prograde metamorphic gneisses appear to have been altered, overprinted and recrystallised resulting in the formation of retrograde schists consisting of quartz + sericite ± chlorite ± biotite ± accessory staurolite, chlorotoid.”

EXISTING GEOPHYSICAL DATA PRIOR TO SAM SURVEYING

An evaluation of geophysical techniques with respect to their effectiveness for exploring for deposits similar to Flying Doctor has been compiled by Bishop (1989). Of the techniques discussed in that report, electromagnetic (EM) techniques were considered the most successful, followed by induced polarization (IP). Magnetics and radiometrics failed to detect the deposit. The techniques relevant for comparison with SAM are IP and magnetic induced polarization (MIP).

Induced Polarization Surveys

A gradient-array induced polarization survey over Flying Doctor is described by Tyne (1987). The results of the survey are shown in Figure 4. The survey was conducted with a current-dipole spacing of 3600 ft (1100 m), and a potential-dipole spacing of 100 ft (30.5 m). The distance between survey lines was 250 ft (76 m). The results indicate a region of low resistivity and low chargeability responses in the south-western corner of the grid. According to Tyne (1987), this appears to be related to a conductive layer of soil cover in the area and the data generally reflects the thickness of soil. There is no localised resistivity or chargeability anomaly which could be attributed to the Flying Doctor mineralisation. Tyne (1987) suggests that the large potential dipole spacing may have resulted in serious loss of resolution of the anomaly.

Dipole-dipole IP surveys also described by Tyne (1987) were more successful in defining the Flying Doctor mineralisation at depth. Representative pseudosections from Line 25.25S are depicted in Figure 5 and can be compared to the geological cross section in Figure 3. The resistivity pseudosection shows a strong conductor at about -600 flanked by a resistive unit on the east and a thin conductive surface layer overlying resistive host rock on the west. The chargeability and phase pseudosections both show distinct anomalies over -600. Another significant anomaly situated at about -1400 is attributed to pyrite mineralisation within the Western Shear Zone. Of interest is that the western IP anomaly at -1400 is not associated with an appreciable resistivity low.
Magnetic Induced Polarization

The magnetic induced polarization (MIP) method uses a single-component magnetometer to measure chargeability and resistivity effects, as opposed to SAM which uses a total-field magnetometer to detect the responses. The techniques are otherwise very similar in field practice in that the two techniques are detecting current channelling in the sub-surface. Test MIP surveys were conducted by Scintrex over Lines 25.25 S, 25.75 S, and 26 S (Howland-Rose, 1978). Both frequency-domain and time-domain measurements were made during the survey. Time-domain profiles recorded on Line 25.25 S are shown in Figure 6. The survey resulted in a strong chargeability response over the mineralisation. The normalised magnetic field response (HN) indicated a broad conductive zone with peaks occurring at 700 W and 800 W. The frequency domain parameters provided similar results as shown in Figure 7. The parameters relative phase shift (RPS) and percent frequency effect (PFE) are also measures of the IP response, and correlate well with the time-domain parameter. The MIP technique showed promise in detecting the mineralisation. However, as pointed out by Bishop (1989), the lack of coverage with magnetic induced polarization meant that the superiority of the technique over electrical induced polarization was not established at Flying Doctor.

SAM FIELD PROCEDURE

In more recent years, a local metric coordinate system has been established at the Flying Doctor site (see Figure 2). All SAM surveys were conducted with reference to the metric grid. Grid north was orientated at 50° from magnetic north. The magnetic inclination, I, was approximately -64.3°.

The SAM field procedure is described in an initial concept paper by Cattach et al. (1993). The two current electrodes C1 and C2 were embedded at (4800 mE, 19800 mN) and (4800 mE, 20800 mN) respectively. The survey area was located within the boundaries 4500 mE to 5100 mE and 20000 mN to 20600 mN (600 m × 600 m). However, a small part of the survey area in the east could not be surveyed because of the existence of buildings. The wire feeding the electrodes was laid out in a U-shape to the west of the centre line (4800 mE). Coordinates defining the location of the wire are as follows: (4800 mE, 19800 mN) (C1); (4200 mE, 19800 mN); (4200 mE, 20800 mN); (4800 mE, 20800 mN) (C2). The layout of the SAM survey is shown in Figure 8. Traverses were surveyed on foot in an east-west (local) direction. The line interval was 10 m. An 8 Hz, 50% duty cycle transmitter signal was used to acquire the total field magnetometric resistivity data. The survey was repeated at a later date with a transmitter frequency of 4 Hz in order to acquire the total field magnetometric induced polarization data (Boggs, 1999). Both surveys used a Geophysical Technology TM-4 Cs vapour magnetometer, sampling at nominally 200 samples per second, as the SAM receiver.

SAM SURVEY RESULTS

SAM Total Magnetic Intensity (TMI)

The spatially-varying total magnetic intensity (TMI) field data were extracted from the combined SAM signal data set by low pass filtering and were then resampled at 0.5 m intervals. After correcting for diurnal variation, the data were gridded and imaged. The image is shown in Figure 9 with the geology overlay from Figure 2. In all the following images, the colour assignment ranges from purple for low amplitudes to red for high amplitudes. There is a magnetic gradient increasing to the north-east corner of the survey area. The deposit has been extensively drilled and the discrete dipolar anomalies aligned along the axis of the mineralisation are caused by steel drill-hole collars. The linear features to the south and east of the image are due to fences. There are subtle linear features aligned south-west to north-east which cross the mineralisation. However, there is no distinct magnetic signature from the mineralisation itself.
Total Field Magnetometric Resistivity (TFMMR)

Standard corrections were applied to the TFMMR data for removing the effect of the primary and normal fields. The data were then converted to equivalent MMR (EQMMR, Boggs, 1999). The EQMMR data were imaged as shown in Figure 10. The exceptional detail possible with the EQMMR data is best demonstrated though the calculation of the first vertical derivative, also included here in Figure 11. There is a significant north-south tending linear “high” that may be coincident with the Globe Vauxhall Shear Zone. In addition, there are a number of well-defined linear features, some of which run parallel to the strike of the mineralisation and some which cut obliquely across strike. The stippled linear features on the eastern margin of the survey area are due to grounded steel picket fences that have channelled the current.

Total Field Magnetometric Induced Polarization (TFMMIP)

TFMMIP data was determined by integrating under the decay curve during the transmitter Off time. The weak TFMMIP signal is due to the induced polarization response, and signal stacking procedures are adopted to improve the signal-to-noise ratio. One result of this, for data that are continuously acquired, is that the spatial resolution of the data is reduced compared to the TFMMR.
data (typically 10 m sample interval compared with 2 m for TFMMR). The TFMMIP signal is due to return current and is therefore opposite in sign to the TFMMR response. The data has been inverted here for purposes of comparison with the TFMMR, and then converted to equivalent MIP response (EQMMIP, Boggs, 1999). The EQMMIP anomalies therefore appear as highs in the middle of the survey area in Figure 12. That is, the EQMMIP anomalies due to sulphides in the shear zone are represented by the distinct, broad highs coinciding with the shear.

In order to facilitate comparison of the EQMMR and EQMMIP data, contours of the EQMMIP were overlain on the colour image of the EQMMR as shown in Figure 13. It is interesting to note that the EQMMIP anomalies on the Globe Vauxhall Shear coincide with EQMMR (conductivity) highs. However, another distinct EQMMIP anomaly was detected on the Western Shear which in contrast corresponds with an EQMMR low. This feature was also detected by the dipole-dipole IP surveys as shown in the pseudosections in Figure 5.

CONCLUSIONS

Magnetics is one of the most commonly used and probably one of the most valuable geophysical methods available to the mineral explorer. Recent developments in instrumentation and survey procedures have made high-quality data even more accessible and cost-effective and will ensure a vital role for the technique in the future. Magnetics is very accessible and inexpensive and therefore it is extremely widely used. Consequently, a great deal of reliance is often placed on the technique. However, other geophysical techniques are required to map subsurface structure and mineralisation where there is little to no magnetic susceptibility contrast. It has been demonstrated that SAM can fill this gap.

A great benefit of SAM is that it provides multiple data sets which reflect independent physical properties. Simultaneous data acquisition of multiple independent data sets using SAM provides a cost-effective means by which successful exploration may be achieved.

The Flying Doctor Case Study serves to illustrate that:

1. It is possible to map several geophysical properties simultaneously with a single instrument.
2. The acquired TFMMR data is of equivalent resolution to high-definition TMI, and provides a great deal of new information in magnetically quiet zones.
3. The TFMMIP data, although acquired at lower resolution than TFMMR because of the signal stacking processes, are still of much higher resolution than conventional electrical/ electromagnetic techniques, and were useful for identifying the Globe Vauxhall Shear Zone.
4. Much greater interpretative power can be derived from having multiple data sets from SAM surveying which reflect independent physical properties.

REFERENCES


