

The Use of Sub-Audio Magnetics (SAM) in Gold Exploration – Examples from the Yilgarn Craton, WA

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ABSTRACT

The results of Sub-Audio Magnetic (SAM) surveys and the relationship to other geophysical datasets and geological information are presented for three different styles of gold mineralisation within the Archaean Yilgarn Craton, W.A.

The Jericho prospect is located to the north of the Butcher Well deposit in the Laverton area and is hosted within a mafic unit consisting of predominately high-magnesium basalt. The source of a broad SAM total field magnetometric resistivity (TFMMR) response initially could not be identified as it did not appear related to the depth of cover or weathering from shallow drilling. Further analysis of the SAM result, following additional drilling and a dipole-dipole induced polarization (IP) survey, indicated that the source of the SAM TFMMR response in the southern portion of the survey area is due to a combination of variation in depth of the regolith and a number of narrow potassic alteration zones within the basaltic unit.

The objective of the SAM survey at the Bronco prospect in the Southern Cross region was to map perturbations within the massive pyrrhotite-pyrite horizon that hosts gold mineralisation. In order to maximise current flow within the sulphide horizon, the electrodes were placed within the sulphide units at the base of two open pits located along strike. The TFMMR data shows a response having a width that significantly narrows to both the north and south of the survey area and correlates with the width of the primary sulphide. In addition, a number of flexures and offsets have been delineated. High-intensity magnetic responses, due to maghemite in the regolith, have resulted in noise being introduced in the TFMMR data.

Gold mineralisation at the Triple 'O' lode within the Cornishman Deposit is associated with quartz-pyrrhotite-pyrite alteration of banded-iron formation that is located below a thrust in a 'blind' location. The sulphide alteration can be semi-massive and very conductive (up to 3000 S/m), but the use of traditional electromagnetic techniques at similar deposits in the region has not proven particularly successful because of the small spatial footprint of the sulphidic alteration. Hence, the objective of the SAM surveying was to determine whether the technique could successfully map the narrow, sub-horizontal sulphidic alteration zones. The TFMMR data highlighted a broad conductive zone that is comprised of three discrete conductors, two of which have been confirmed by drilling to result from sulphide alteration of the banded-iron formation and to have associated gold mineralisation. The third anomaly is thought to be due to the preferential weathering of a non-mineralised shear zone.

INTRODUCTION

The Sub-Audio Magnetics (SAM) method was developed in the early 1990s for simultaneously mapping the magnetic and electrical characteristics of the Earth (Cattach et al., 1993). The method has been used in mineral exploration (Boggs et al., 1998; Meyers et al., 2004) and for unexploded ordnance detection (Boggs et al., 1998). The SAM method has been applied over a number of Sons of Gwalia gold prospects within the Archaean Yilgarn Craton of Western Australia. In all cases, the aim of the SAM surveys was to map mineralised or potentially mineralised geological features ranging from conductive shear zones to massive sulphide units. However, in terms of understanding the SAM responses and providing geological and exploration information, the results have been mixed. In this case study, the results of three SAM surveys, one from the Laverton region and two from the Southern Cross region, are shown in relation to other geophysical techniques and geological information.

SUBAUDIO MAGNETIC METHOD

The SAM method has been fully described in Cattach et al. (1993) and Boggs et al. (1998) and will only briefly be described here. The SAM method measures the magnetic field induced by a time-varying current applied to the Earth. The applied current is created with a high-power transmitter producing a low-frequency square-wave signal that is introduced into the ground through distant electrodes placed along strike of the structure or lithology under investigation. The transmitter current is preferentially channelled along geological features that are relatively less resistive than their surroundings. The electromagnetic signal from current distribution within the ground is measured simultaneously with the Earth's spatially-varying magnetic field using a total-field magnetometer that samples at a fast enough rate to adequately measure the full spectrum of the artificial waveform. The signals from Earth's magnetic field and the electromagnetic field due to the applied current (including that from the transmitting wire) are spectrally distinct. They may be separated with the aid of digital signal processing techniques and processed to remove these effects and to sample parts of the waveform to produce total-field magnetometric resistivity (TFMMR) and total-field magnetometric induced polarization (TFMMIP), as well as total magnetic intensity (TMI).

The raw TFMMR data is corrected for the theoretical fields produced by the transmitting wire and current flowing through a homogenous half-space, resulting in an anomalous response due to perturbations in current flow caused by lateral conductivity variations. As the TFMMR parameter is a total-field measurement made in the presence of the Earth's magnetic field, its component direction is variable from site to site and grid to grid. The equivalent MMR transform converts the TFMMR data to a horizontal component perpendicular to the axis of the electrode spread used in the survey, known therefore as the equivalent MMR (EQMMR). This transform allows for a standard presentation form in which the data are more readily related to the underlying resistivity, and has been adopted as a standard presentation of the TFMMR data shown in this paper.

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JERICO PROSPECT, LAVERTON

The Jericho prospect is located approximately 4 km north of the Butcher Well Mine and approximately 10 km west of Red October on the western edge of Lake Carey in the Laverton district of the NE Goldfields. The prospect is located within a 500 m wide mafic unit bounded by sediments (Figure 1) and was identified by anomalous gold mineralisation within the regolith detected in rotary air blast (RAB) drilling. However, the primary source of this anomalous gold mineralisation could not be readily identified. It was thought that the alteration of primary structures would have magnetic and electrical property contrasts with respect to the unaltered mafic units and thus geophysical methods could be used to target further drilling. A SAM survey was undertaken as both the magnetic and electrical character of the area could be mapped with the one survey.

SAM Survey

The SAM survey covered an area of 1000 × 600 m with the electrodes placed 400 m to the north and south of the edge of the survey area. The transmitter frequency was 2 Hz with a 50% duty cycle achieving a current of 7 amperes. The data were acquired using a Geometrics G-822A magnetic sensor in conjunction with a Geophysical Technology TM-4 magnetometer controller. In the case of the Jericho survey, the line spacing was 20 m with raw magnetic field data resampled to a 0.5 m interval using the position information from the inbuilt odometer. As the local grid was very close to magnetic grid north, the horizontal component of the TFMMR can be considered to be EQMMR.

SAM Survey Results and Interpretation

The TMI data was subdued, with a small dynamic range of only 70 nT and little coherent character (Figure 2). The most intense anomalies in the south-eastern part of the survey area relate to the presence of maghemite in laterite gravels within the regolith. A number of NW and NNE trends observed from magnetics are interpreted as shears or faults (Figure 2).

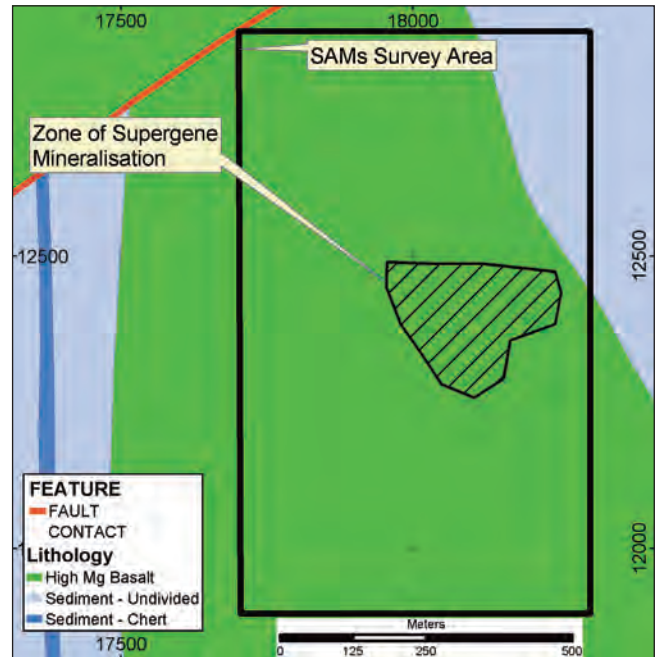


Fig. 1. Jericho Prospect – Simplified Geology and location of SAM survey. The source of the supergene gold mineralisation is in narrow zones of sericite-pyrite alteration within the basaltic unit.

A significant, broad, anomalous conductive zone, trending NNE on the eastern side of the survey area, dominates the equivalent MMR data (Figure 3), with a number of shorter-wavelength anomalies superimposed. This anomaly changes orientation from north-north-east to north-north-west at approximately 12 600 mN, which is close to the location of the north-west trending shear zone interpreted from the magnetics (Figure 2). Because of significant electromagnetic coupling, total-field magnetometric induced polarization (TFMIP) data could not be recovered. The effect of EM coupling on the TFMMR data was reduced by using late-time windows (Cattach, 2000).

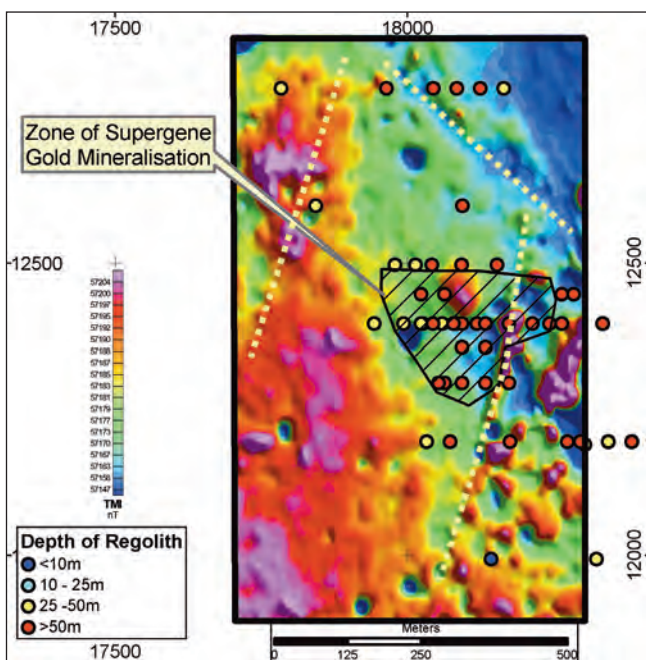


Fig. 2. Jericho Prospect – SAM Total Magnetic Intensity (TMI) and depth of regolith from drilling data as coloured circles, and interpreted shears as yellow dashed lines. The total dynamic range of the TMI is 70 nT.

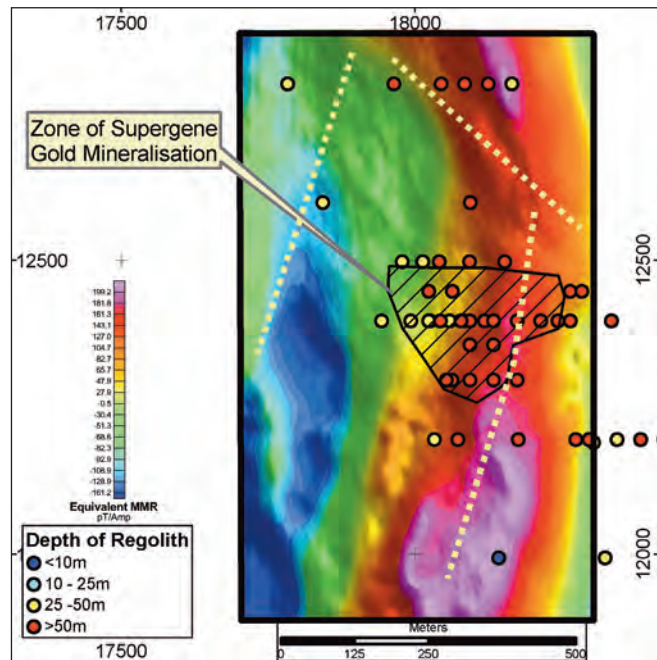


Fig. 3. Jericho Prospect – SAM Equivalent MMR with depth of regolith from drilling data as coloured circles, and interpreted shears as yellow dashed lines.

The sources of the conductive responses were difficult to determine from the drilling data that was available shortly after the survey was completed. The conductive zones did not appear to be related to an obvious stratigraphic unit such as carbonaceous shale, but the SAM response did show a very loose correlation with thickened regolith development, such as would be expected to be associated with a deeply weathered shear zone (Figure 2). However, the thickest and widest regolith development is around the area of the supergene mineralisation, which is not where the MMR response is best developed, either in terms of half-width or amplitude. Hence, the source of the MMR response was interpreted to relate primarily to bedrock features within the mafic package.

Dipole-Dipole IP Survey and Results

A dipole-dipole induced polarization (DDIP) survey carried out over an 800 m strike distance was completed by Zonge Engineering, with the aim of determining whether the broad, conductive zone observed in the MMR data was related to a significant bedrock alteration system at depth. In addition, further drilling was undertaken which included some reverse circulation (RC) and diamond drilling.

The DDIP survey comprised 8 lines, at 100 m spacing, with a dipole spacing of 100 m. The receiver was a Zonge GGT10 transmitter and a GPD32 at a fundamental frequency of 0.125 Hz, with currents of 15–20 amperes. The data were inverted using Zonge’s 2D smooth model inversion. The results of the resistivity inversion in relation to the equivalent MMR and drilling data are shown in Figure 4a and 4b for sections 12090N and 12390N respectively.

The DDIP results show a reasonable relationship in resistivity for both sections between the base of regolith (saprolite) from drilling and the base of the conductive overburden, defined by the resistivity to be <6 Ω.m. A slight increase in thickness from west to east is observed. This supports the original observation that the conductive MMR response did show a loose correlation with thickened regolith development. This increase in the thickness of the conductive regolith may contribute to the broad MMR response but cannot explain the entire anomaly because:

- a) the zone of thickened regolith, in the vicinity of the supergene mineralisation, extends to the east (Figure 2) whereas the MMR response decreases to the east (Figure 3).
- b) The MMR anomaly is developed best, both in terms of amplitude and width, in the south of the survey area (Figure 3) where the regolith, as defined by drilling, is relatively uniform.

The RC and diamond drilling contained a number of zones of potassic (sericite-pyrite) alteration as shown on Section 12390N in Figure 4b. These zones are likely to be more conductive than the adjacent unaltered mafic rocks and thus would be expected to channel current. Although not definitive, the source of the MMR anomaly is thought to be result from the summation of the individual responses from these alteration zones, superimposed on the broad regolith response.

BRONCO PROSPECT, SOUTHERN CROSS

The Bronco Deposit is located 15 km south-west of Marvel Loch Gold Mine, along the western limb of the Mt Caudan massive sulphide horizon, which lies on a sediment-mafic contact

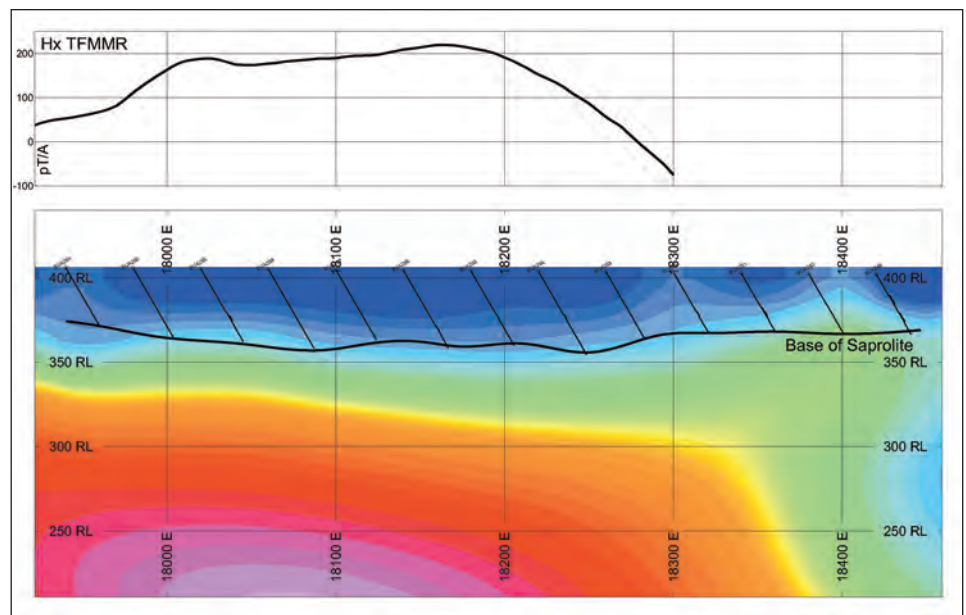


Fig. 4a. Jericho Prospect DDIP Resistivity Inversion – 12090N in relation to drilling, base of the regolith and equivalent (Hx) MMR data. The colour ranges for the inversion model are shown in Fig. 4b with the base of regolith defined by the resistivity of approximately 6 Ω.m.

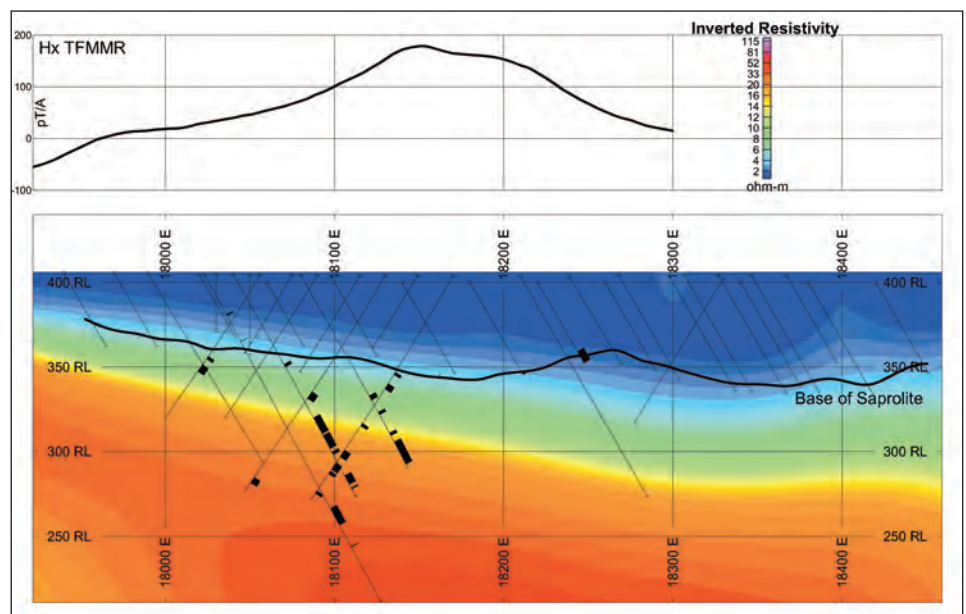


Fig. 4b. Jericho Prospect DDIP Resistivity Inversion – 12390N in relation to drilling and equivalent (Hx) MMR data. The black bar graph down the drillholes show the location of zones of alteration.

(Figure 5). The sulphide unit is comprised of pyrrhotite-pyrite, and its thickness varies from 2 m to more than 50 m in fold closures. A number of small, predominately oxide gold deposits such as Great Victoria, Bronco, Hercules, and Grand National are located along the Mt Caudan horizon, where the massive sulphide unit has been locally thickened by folding and cut by late cross faults. The Bronco SAM survey was located between two old open cuts, Bronco South and Brumby pits, which had been mined to depths of 20 to 50 m below the current surface. Much of the survey area was carried out over the back-filled Bronco open pit, which was oxidised to a depth of around 100 m. The objective of the SAM survey was to assess the effectiveness of the technique in the detailed mapping of flexures, offsets or zones of local thickening along the sulphide horizon. As the sulphide unit was the main target, the effect of the regolith was minimised by placing the electrodes in the base of the pits along strike, and within the sulphide unit, in order to enhance the current flow along the sulphide unit.

SAM Survey and Results

The survey grid had dimensions of 450×400 m with the electrodes located along strike to the north, in the base of the Brumby open pit, and to the south, in the base of the Bronco South open pit. The survey specifications were similar to that used at Jericho, with a transmitter frequency of 2 Hz and a 50% duty cycle achieving a current of 7 amperes. The survey line spacing was 20 m with a final along-line sample interval of ~ 0.5 m and ~ 2.0 m for the TMI and TFMMR, respectively.

Images of the reduced-to-pole magnetics and the EQMMR data are shown in Figures 6 and 7 respectively. A coincident magnetic and EQMMR north-south striking response occurs along the western edge of the survey area, coinciding with the conductive and magnetic massive sulphide horizon. The EQMMR data indicates that the sulphide unit has a number of flexures and offsets along its strike length such as:

- an offset and flexure of the EQMMR response towards the southern end of the survey.
- a widening of the EQMMR response within the northern half of the Bronco pit area.

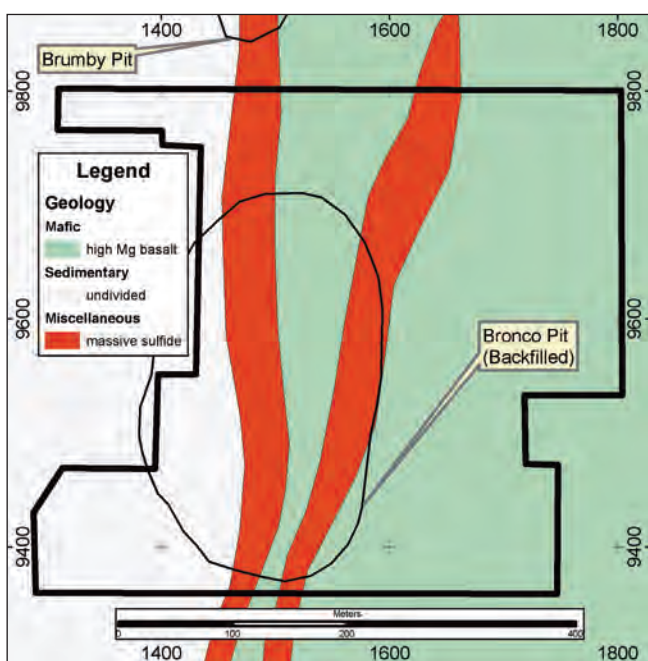


Fig. 5. Bronco Deposit – Simplified bedrock geological interpretation and location of the SAM survey. The massive sulphide units of the Mt Caudan horizon are shown in red.

- a dramatic narrowing of the EQMMR response in the far northern section of the survey.

In conjunction with drilling data, the EQMMR data has improved the geological interpretation of the primary sulphide unit. The magnetic response due to maghemite within the regolith can be observed as the noisy high-amplitude magnetic zone in the north-eastern area of the survey (Figure 6). The large amplitudes and broad frequency content has also affected the MMR data resulting in isolated high-amplitude (the highest of the survey) EQMMR anomalies.

A narrow sulphide unit located just to the east of the main western sulphide unit (Figure 5) has not been detected in the EQMMR response (Figure 7). This is most likely because the electrodes were placed directly in contact with the western unit in the base of pits, so that most current flow was this sulphide unit and there was little to no leakage into the eastern massive sulphide unit.

CORNISHMAN PROJECT, SOUTHERN CROSS

The Cornishman deposit is located 5 km to the south-east of Southern Cross in the Yilgarn Craton of Western Australia. The deposit is within the Frasers Shear Zone and consists of two main types of mineralisation. The Double 'O' lode occurs in quartz-sulphide veins with biotite-diopside-pyrrhotite-pyrite wallrock alteration within a ductile shear zone. The Triple 'O' lode, the main lode of interest here, is hosted within a folded banded-iron formation (BIF) with the mineralisation consisting of calc-silicate veins and alteration (Watkins, 1997). Geological interpretation using detailed aeromagnetic and geological outcrop and drilling data (Figure 8) shows the BIF (in blue) located on the boundary between a basalt sequence and an ultramafic-gabbro sequence. The ultramafics have been thrust over the BIF, with the mineralisation located below the footwall of the ultramafic unit and thus not reaching the surface.

The alteration consists of quartz-grunerite-diopside-pyrrhotite-pyrite with a pyrrhotite content locally up to 30%–50%, but

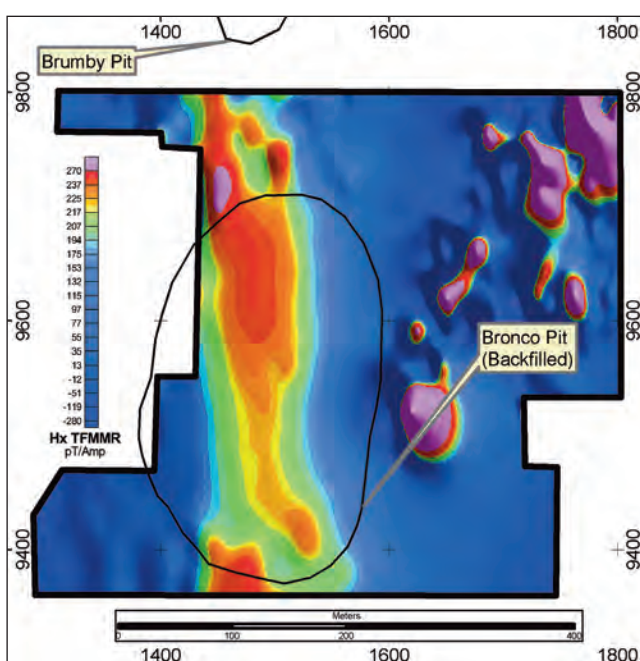


Fig. 6. Bronco Deposit – NE Shaded TMI Reduced-to-Pole magnetics from the SAM survey.

generally ~10%. The gold grades appear to correlate with sulphide abundance (Watkins, 1997). The mineralisation forms narrow, sub-horizontal, high-grade gold shoots. The deposit has a similar mineralisation and structural style to Golden Pig, which is located 5 km to the north-west (Nugus et al., 2002).

The objective of the SAM survey at Cornishman was to determine whether the technique could successfully map the narrow, sub-horizontal sulphidic alteration zones to the south of the pit area. Although the alteration can be very conductive (up to 3000 S/m) the use of traditional electromagnetic techniques at Golden Pig has not proven particularly successful. This is due to the small spatial footprint of the sulphide zone, with a down-dip extent less than 20 m, and hence poor EM coupling.

SAM Survey and Results

The SAM survey was completed in March 2003, covering a 800 × 1200 m area extending south-east from the Cornishman open pit, centred over the postulated continuation of mineralisation along strike (Figure 8).

The transmitter was a Zonge GGT-10, operated at frequency of 4 Hz with a 50% duty cycle and achieved a current of 7.2 amperes. The northern electrode was located in the floor of the pit with the southern electrode located 1.4 km to the south, on the surface. The data were acquired using a Scintrex CS-2 Cs vapour magnetometer in conjunction with a Geophysical Technology TM-4 magnetometer controller synchronised with via GPS. Survey lines were 50 m apart, orientated at 070° (magnetic) running perpendicular to geological strike, and were navigated in real time with hand-held differential GPS. The final along-line sample interval was approximately 0.5 m and 2.0 m for the TMI and TFMMR respectively.

Less emphasis was placed on the TMI data from the SAM survey as the area had been previously surveyed with airborne magnetics in 1997 by UTS, at a line spacing of 20 m and a flight

height of 20 m, prior to the commencement of mining. The reduced-to-pole TMI (RTP) and second vertical derivative (2VD) images from the aeromagnetics, for the prospect area, are shown in Figures 9a and 9b.

The EQMMR data highlights a broad conductive region running through the centre of the survey area, which separates into two conductors towards the south (Figure 10a). This broad response corresponds to the Fraser Shear Zone and is most probably due to preferential weathering of the Fraser Shear Zone. This is supported by the depth of RAB and Aircore drilling (as an indicator of regolith depth) with a concentration of the deeper holes coinciding with the broad MMR response. To enhance conductor edges and delineate discrete bodies within this broad response a first vertical derivative (1VD) image of the EQMMR data was created and used for interpretation (Figure 10b).

Three conductors have been clearly resolved: a discrete western conductor, a central and an eastern conductor (Figures 10a and 10b). The western conductor, whose strike length is ~300 m, is located on the western margin of a BIF and is located along strike from the mineralisation associated with the western BIF at Cornishman. Drilling along this conductor confirmed that the source is mineralised sulphide alteration of BIF. The central and eastern conductors can be traced over most the survey area, being joined in the north of the survey and separating towards the south. The eastern conductor lies to the east of a highly magnetic trend in an essentially magnetically quiet area and coincident with an interpreted shear. Hence the EQMMR response is thought to be due enhanced current flow within locally thicker regolith, developed by preferential weathering of the shear zone. The central EQMMR response is segmented and located on the western edge of a magnetic unit that has been interpreted as the southern extension of the eastern mineralised BIF in the Cornishman Pit. The drilling at the northern end of this response intersected mineralisation, but to the south along this response drilling is wide spaced and predominately shallow RAB drilling with only a few deeper RC holes. One of these RC holes, DH601, had intersected

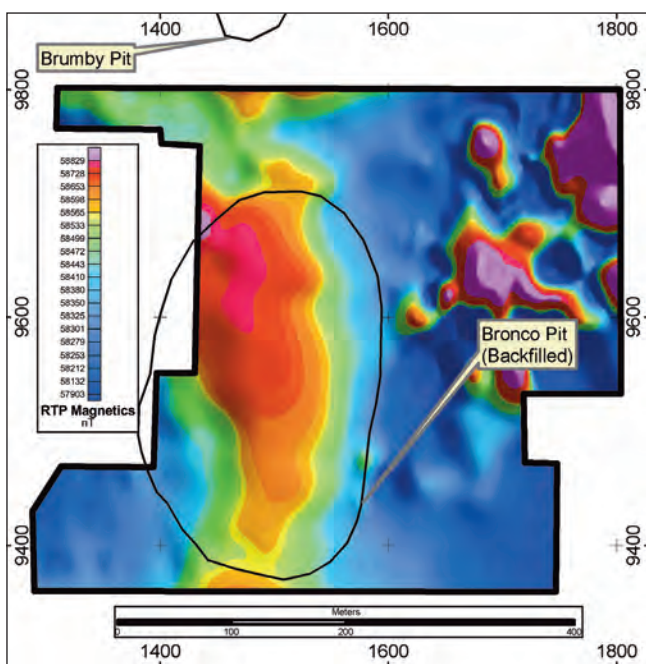


Fig. 7. Bronco Deposit – North-east Shaded Equivalent MMR data.

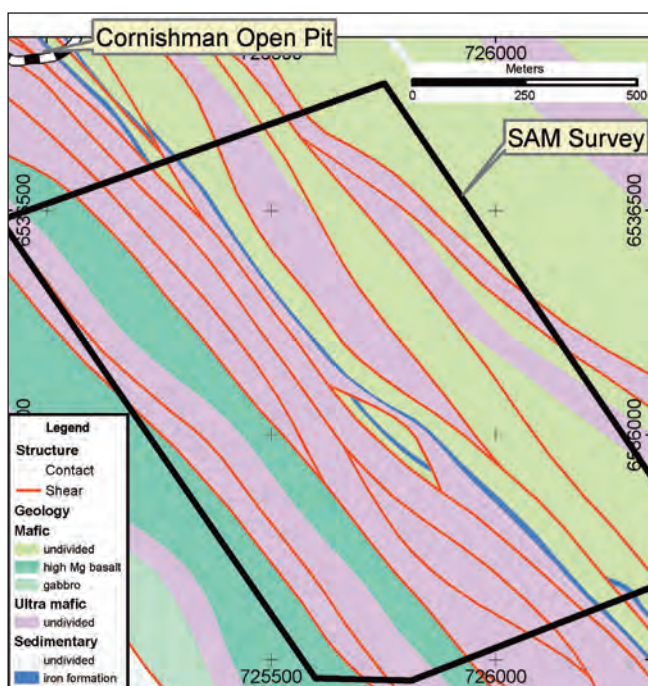


Fig. 8. Cornishman Prospect – Simplified interpreted geology and location of the SAM survey. The BIF units which host Cornishman-style mineralisation, as interpreted from drilling and aeromagnetics, are shown as thin blue units.

pyrrhotite-pyrite altered banded-iron formation with minor gold mineralisation when the hole was abandoned after shanking the bit (Figure 10b). Thus, the cause of the central EQMMR response has been interpreted to be due to sulphide alteration within a BIF unit. The segmented nature of the EQMMR response is thought to be due to cross-faulting of the mineralised zone.

CONCLUSIONS

SAM surveying over gold prospects has provided information on structural trends, the location of massive sulphide, sulphide alteration of BIF, and increased depth of weathering.

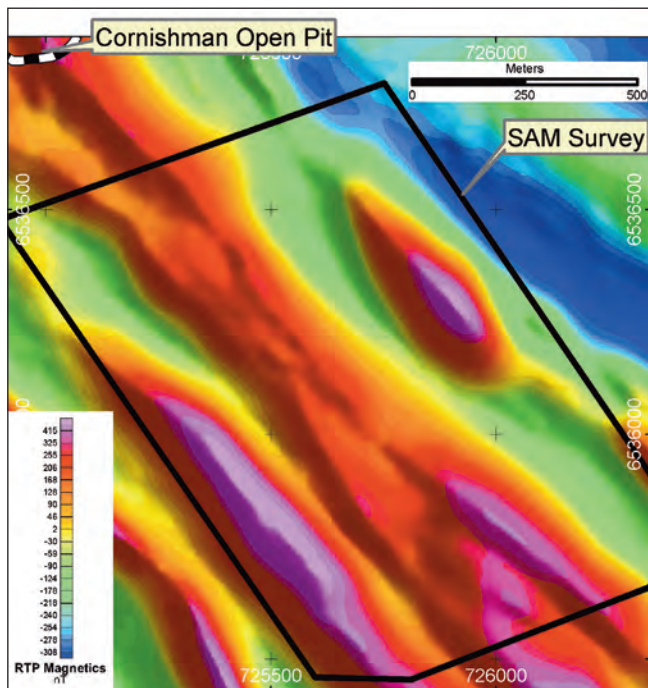


Fig. 9a. Cornishman Prospect –NE Shaded Reduced-to-Pole magnetics from aeromagnetics showing the location of the SAM survey. The dynamic range of the RTP TMI is 1000 nT.

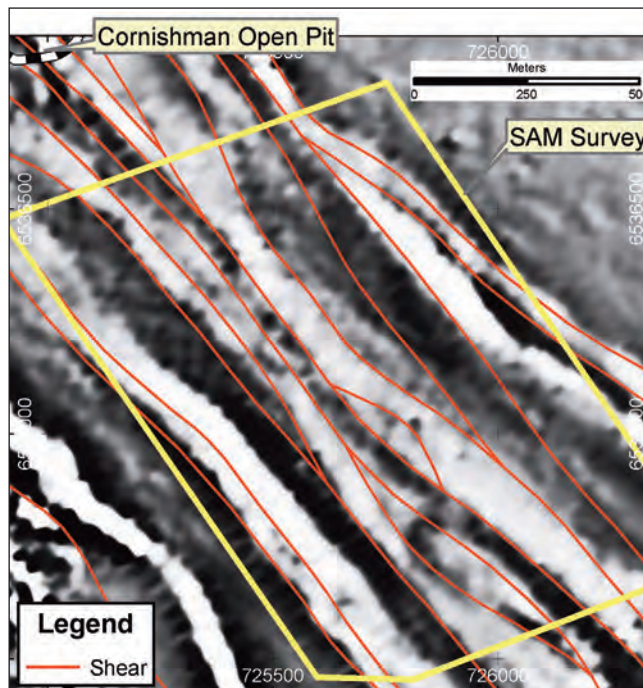


Fig. 9b. Cornishman Prospect – Second Vertical Derivative image from aeromagnetics showing the location of Cornishman Pit, interpreted shears, and the SAM survey.

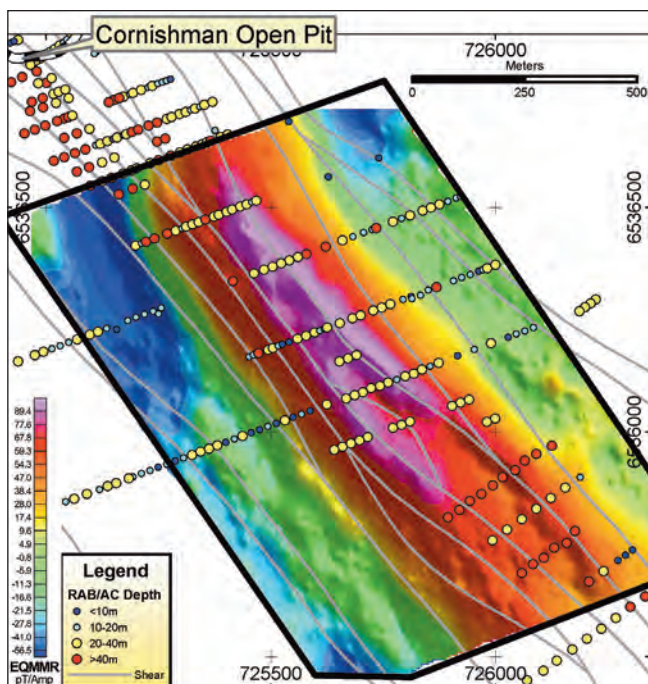


Fig. 10a. Cornishman Prospect – North-east shaded image of SAM Equivalent MMR (Total range is 160 pT/Amp) showing the interpreted shears from aeromagnetics and drilling data and the depth of RAB/Aircore drillholes. The broad MMR is most probably due to preferential weathering of the Fraser Shear Zone.

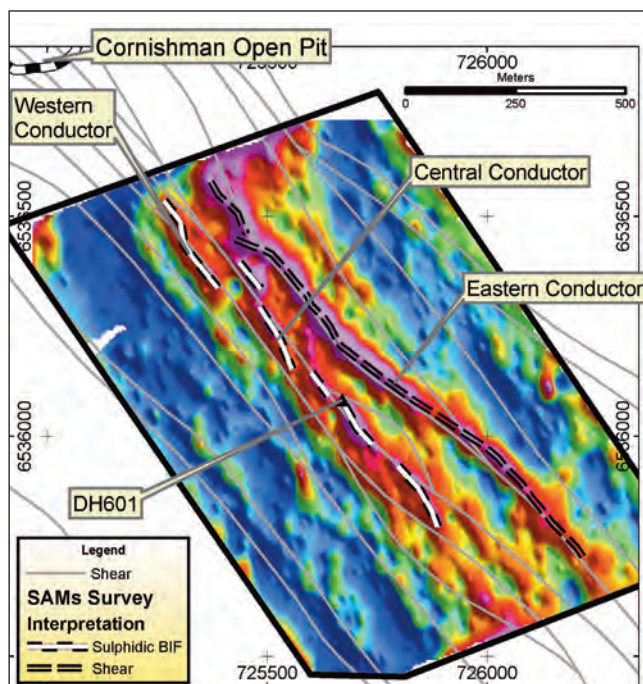


Fig. 10b. Cornishman Prospect – North-east shaded image of First Vertical Derivative of SAM Equivalent MMR data, showing the interpreted shears from aeromagnetics and drilling data. The Western and Central conductive features identified from the SAM MMR data are interpreted to be related to sulphidic alteration of BIF units. The Eastern conductor is interpreted to be due to preferential weathering along a shear.

At Jericho, the source of the MMR anomalies could not be positively resolved despite significant drilling and a dipole-dipole IP survey. A combination of regolith deepening from west to east, and a number of narrow potassic alteration zones within the fresh mafic rocks, is thought to cause the MMR response. A high-resolution resistivity profiling survey such as ERI (Whitford et al., in this volume), detailed petrological examination, and electrical property logging of drill holes within the prospect would be required to conclusively explain the source of the response. Despite a depth of oxidation to 100 m and a backfilled pit at Bronco, flexures, zones of thickening, and faulted offsets of a massive sulphide lens could be mapped in detail using SAM surveying. This was achievable by having current electrodes located towards the base of oxidation, within pits that occurred along strike of the survey area. However, the current was channelled too well within the main sulphide unit to detect a second sulphide unit, which was located to the east.

Following successful surveys at Bronco, the technique was used at Cornishman to map sulphide alteration within BIF. To enhance the current channelling along the conductor of interest, ie the BIF, the northern electrode was located within the altered BIF, below the base of oxidation, in the southern end of the Cornishman pit. The EQMMR shows a broad response, which correlates with preferential weathering of the Fraser Shear Zone. By standard potential field high-pass filtering techniques, such as a first vertical derivative transform, three discrete conductive zones within the broad response were delineated. Drilling on two of these conductive zones has shown the SAM response to be related to sulphide alteration of the BIF with gold mineralisation. Thus, the SAM method provides a high-resolution exploration technique for mapping potential mineralisation along strike and providing drill targets.

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