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Sub-Audio Magnetic survey experiments for high-resolution, subsurface mapping of regolith and mineralisation at the Songvang Gold Mine near Agnew, Western Australia

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ABSTRACT

Experimentation with Sub-Audio Magnetic (SAM) survey parameters over the Songvang mesothermal gold deposit demonstrates that this technology can be effective for identifying conductive, mineralised structures and differential weathering in the regolith at high resolution to a depth of 100 m, as long as the transmitter electrodes are placed sub-parallel to the strike direction of features to be detected. The equivalent magnetometric resistivity (EQMMR) response produced by horizontal current channelling between transmitter electrodes has a very similar pattern to gradient-array apparent resistivity results using a 50 m or less dipole spacing. However, SAM data are recorded using a magnetic sensor, thus avoiding electrical contact with the ground, and the 2 m along-line sample density provides much greater resolution. The same area was surveyed using the same parameters, except that the transmitter electrode directions were at a right angle, and this produced radically different EQMMR results. EQMMR anomaly trends running N–S were found to correspond to gold-mineralised shears, and dips of these shears estimated using gravity modelling methods agree with drilling results. The Songvang main lode is an elongated, shallow plunging, rod-like zone of gold-pyrite ore that is detected by a gradient-array induced polarization survey. SAM equivalent magnetometric induced polarization (EQMMIP) was ineffective at imaging the main lode using surface transmitter electrodes and 1 Hz transmitter frequency. However, the 4 Hz EQMMIP response of the main lode was later imaged in great detail when transmitter electrodes were placed down boreholes into the orebody. The downhole SAM EQMMIP results were very effective at highlighting zones of intense sulphide-related gold mineralisation ahead of drilling. SAM surveying provided EQMMR data that identified shallow, conductive shears that contained economic gold mineralisation, and the EQMMIP data helped to plan resource definition drilling by prioritising chargeable targets related to increased pyrite alteration and gold grade along the Songvang main lode.

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INTRODUCTION

The Sub-Audio Magnetic (SAM) method is a development following the MMR and MIP methods of Seigel and Howland-Rose (1990). Although similar to IP and resistivity, the SAM method allows for greater resolution, and has advantages over the MMR and MIP methods in the speed with which data can be collected. SAM surveying uses a time-varying waveform of current injected into the ground and a roving TM4 or TM6 magnetometer with caesium vapour sensor to measure the total-field magnetometric resistivity (TFMMR) and total-field magnetometric induced polarization (TFMMIP) responses that are induced by horizontal current channelling in the ground. The TFMMR signal is corrected for the local magnetic field to a component parallel to the transmitter electrode direction to produce an equivalent MMR (EQMMR) anomaly map of horizontal current channelling between transmitter electrodes, and in some areas an equivalent MMIP (EQMMIP) anomaly map can also be calculated (Cattach et al., 1993; Boggs et al., 1998; Boggs, 1999). For mineral exploration applications, the SAM surveys cover a square to rectangular prospect area with sides of 1 to 2 km, using traverse spacings of 10–100 m, oriented perpendicular to the transmitter electrode direction. Along-line readings can occur at sub-metre intervals depending on the transmitter frequency, stacking time, and walking speed of the operators. The grounded transmitter electrodes are placed along geological or structural strike, at a distance of 500 m from the edges of the survey areas.

The current transmitter puts out a 50% duty-cycle square-wave of 2–10 A, using frequencies of 1 to 20 Hz depending on the required depth of penetration and spatial resolution. The TM4 uses a recording sample rate of 200 Hz, and is synchronised to the transmitter by GPS timing. The SAM time-variant magnetic signal usually has an amplitude of <5 nT. At transmitter frequencies of 1 to 4 Hz, the horizontal component of the TFMMIP response can also be extracted by stacking the data and integrating the decay signal during the off time. The electromagnetic fields produced by the transmitter electrodes and wires are removed to give residual SAM responses from the survey area, and the induced, modulated magnetic field is removed to obtain total magnetic intensity data (Cattach et al., 1993; Boggs et al., 1998).

Experimentation with SAM surveying parameters has been carried out over a recent gold discovery called “Songvang” (Vietnamese for “River of Gold”) in the Archaean Agnew Greenstone Belt, west of Leinster in Western Australia (Figure 1). Songvang was discovered in 2002, and is a mesothermal gold deposit composed of a rod-like main lode, with a very shallow plunge to the south. The main lode is flanked by two tabular mineralised shears with steep to intermediate dips (Figure 2). The alteration associated with gold mineralisation comprises biotite, pyrite (5–20%), and silica. This reducing and intermediate-temperature alteration assemblage is different from the hightemperature, oxidising alteration assemblage occurring at other Agnew gold deposits (e.g., Broome et al., 1998). The host rock is predominantly basalt, with some gold-pyrite mineralisation also occurring in small granite intrusions within the basalt (Figure 2). The Songvang gold resource exceeds 480 000 ounces, and mining will start in 2005.

The regolith overlying the main orebody is a partially stripped saprolite profile, with a thin saprock layer directly overlain by sand-rich, late-stage alluvial deposits, containing basalt saprock clasts at the base. There is no geochemical anomaly associated with Songvang, because of the thick transported overburden, and previous drilling to fresh bedrock failed to intercept the main lode within the fresh bedrock. The deposit was discovered by deep drilling into fresh bedrock using reverse circulation drilling.

Downhole logging has shown that the regolith cover is only moderately conductive, the crystalline bedrock is highly resistive, and the ore zones are moderate to weakly conductive (Figure 3). Physical property measurements on a few diamond core samples by Systems Exploration (NSW) Pty Ltd showed that the ore zones have weak inductive and galvanic conductivity, and have chargeability of 4–6 times greater than host rocks.

The Songvang prospect was covered by a gradient-array induced polarization (GAIP) survey that helped identify the extent of the main lode at depth. Four different SAM surveys that each utilised different survey parameters were carried out over the same part of Songvang as a baseline study prior to mining, and to assist in planning resource-definition drilling. Other survey methods, such as moving-loop transient electromagnetic transects, dipole-dipole induced polarization, and Geotem airborne electromagnetics, were carried out across the main orebody, as well as high-resolution aeromagnetic and gravity surveying (Cantwell, 2003). This paper compares the SAM survey experiment results with the GAIP results, and discusses the differences between the survey results in terms of current flow through the regolith and underlying mineralised structures.

METHODS AND RESULTS

Gradient Array IP survey

The Songvang main lode correlates with a chargeability anomaly from a GAIP survey that used E–W electrodes, a 0.125 Hz transmitter frequency, 100 m E–W line spacing, and 50 m dipoles spaced at 50 m intervals (Figure 4a). The GAIP chargeability anomaly coincides with a resistive zone in the gradient-array apparent conductivity, reflecting the resistive regolith overlying the Songvang main lode (Figure 4b). The chargeability anomaly correlating with the Songvang main lode is related to the unweathered sulphide minerals and sheared basalt below the regolith and in fresh bedrock.

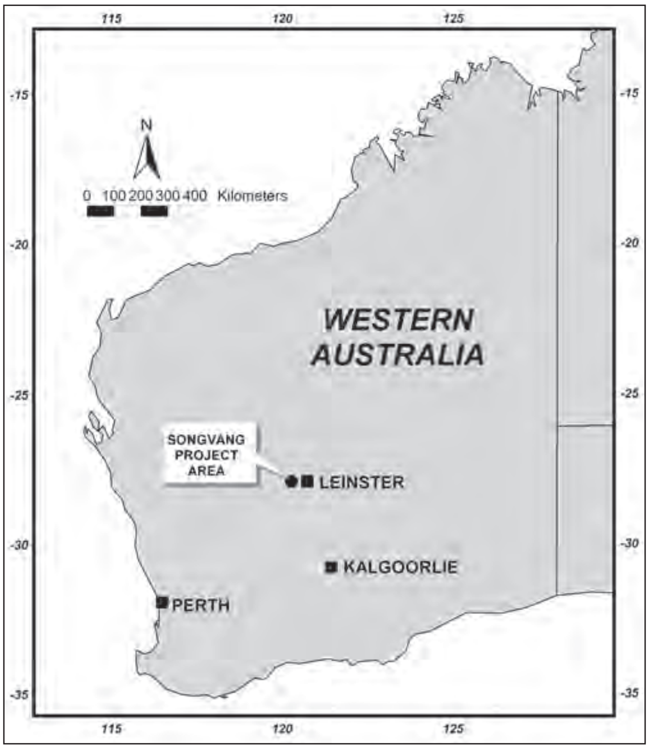


Fig. 1. Location of Songvang study area in Western Australia.

SAM Surveys

Four SAM surveys were carried out over the ore zones to analyse the TFMMR responses in relation to regolith, geology, and mineralisation, and the change in responses using different survey geometries. Experiments were also carried out to detect the TFMMIP response using both surface transmitter electrodes and transmitter electrodes that were placed in drillholes at depths in contact with the shallow and down-plunge ends of the Songvang main lode. The survey parameters for the four overlapping SAM surveys are listed in Table 1. Processed images showing the SAM survey results in relation to the outline of gold mineralisation from drilling are shown in Figures 5 to 7.

Electrodes placed in a N–S direction (survey NS4) provided EQMMR conductivity patterns that are very similar to the gradient-array apparent conductivity (compare Figures 4b and 5a). However, the EQMMR results have much more detail for detecting narrow trends that are aliased by the more widely spaced gradient dipole stations. In addition, one bad reading in the gradient-array survey produces a false low in the eastern side of Figure 4b, whereas the high sample density from SAM surveying avoids this kind of problem. The EQMMR trends correlate with the eastern and western mineralised shears, and deeper weathering along these shears (e.g., Figure 2a). Breaks and offsets in the EQMMR trends

Survey ID	Electrode Direction	Transmitter Frequency (Hz)	Line Direction	Line Spacing (m)	Figure no.
NS4	N–S	4	E–W	50	5a
EW4	E–W	4	N–S	50	5b
NS1	N–S	1	E–W	50	6
DHNS4	N–S	4	E–W	25	7a and b

Table 1. List of the four SAM grids surveyed over the Songvang gold deposit area.

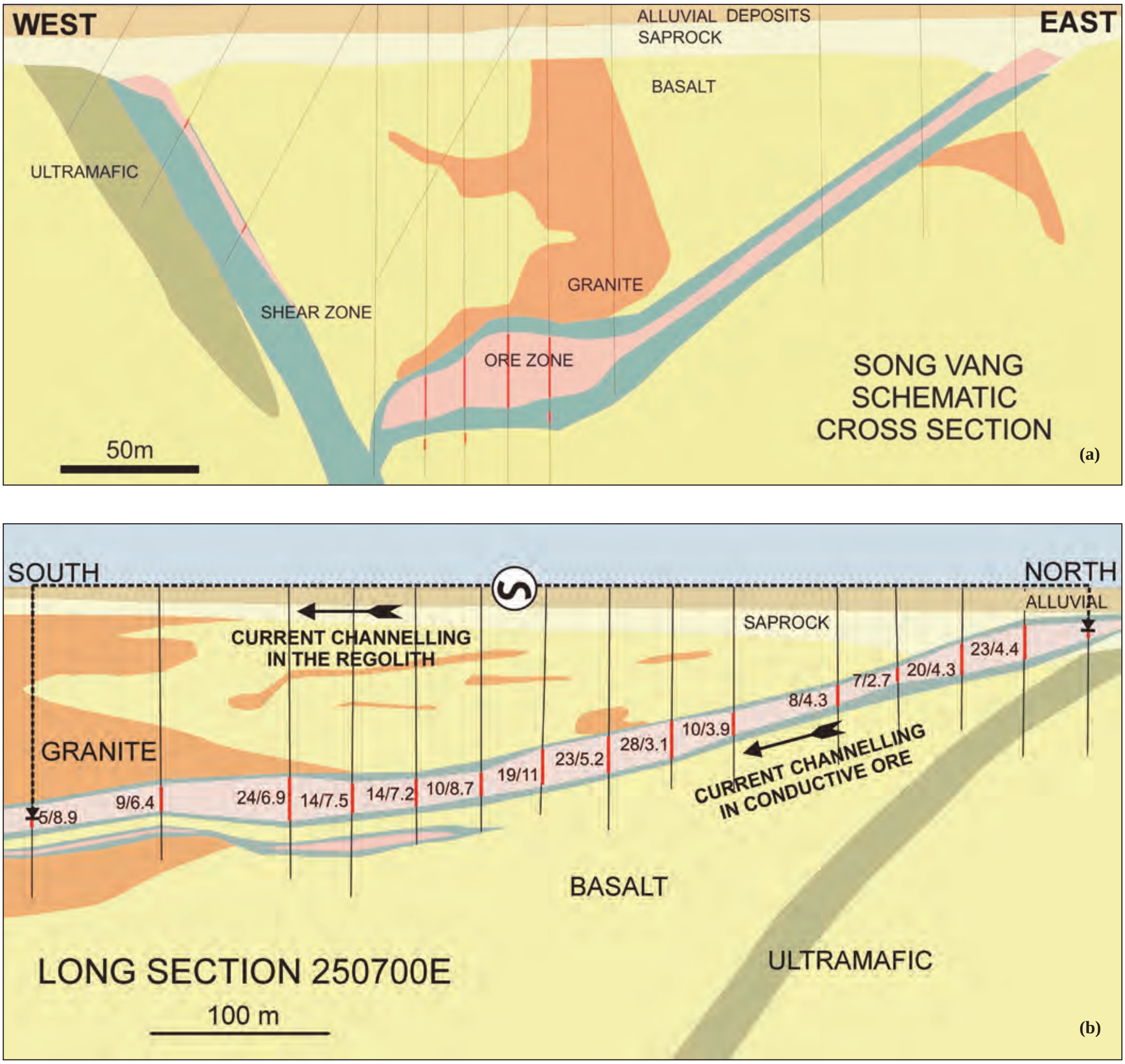


Fig. 2. (a) Interpreted cross section through the central part of the Songvang gold deposit at 6884480mN, showing the main lode sitting in unmineralised fresh rock, flanked by mineralised western and eastern shear zones having deeper weathering at the saprock interface. Thin lines represent drillhole traces; (b) Long section of the Songvang main lode, showing shallow southward plunge and location of downhole electrodes used for surveying grid DHNS4. Thin lines are drillhole locations, and red numbers are intercept thickness in metres over gold grade in g/t that also correlates with the occurrence of pyrite alteration. There is no vertical exaggeration of these sections.

correspond to sub-vertical cross faults that produce minor offsets of the mineralised shears.

Figure 5b shows the EQMMR anomalies detected using E–W transmitter electrodes (survey EW4), which are significantly different from the N–S transmitter electrode grid from survey NS4 (Figure 5a). Current channelling in the E–W direction is weak and EQMMR anomalies occur along interpreted cross faults correlating with the offsets of the eastern and western mineralised shears interpreted from the N–S transmitter electrode EQMMR images. A shallow, E–W trending palaeochannel was detected just north of the Songvang gold deposit in survey EW4, but it was not detected using N–S transmitter electrodes in survey NS4. The gridded data from both surveys were merged, and an image of the merged data set is shown in Figure 5c.

TFMMIP surveys were also run over Songvang to test the ability of this technology to penetrate the regolith and detect the weakly chargeable main lode at depth (survey NS1). Figure 6 shows the EQMMIP results using surface electrodes and a 1 Hz transmitter frequency. There is little similarity to the GAIP chargeability in Figure 4a. The EQMMIP anomaly pattern does not correlate with known regolith or geology, and is considered to be generated by soil responses, unknown E–W trending features, and noise.

Transmitter electrodes were placed down boreholes in order to channel current through the Songvang main lode, with survey line spacing reduced to 25 m (survey DHNS4). Copper rod electrodes (50 cm long and 2.5 cm diameter) were lowered into the shallow part of the main lode at 32 m depth and in the down dip part at 155 m depth, 700 m to the south (Figure 2b). Electrode positions were slightly adjusted up and down the holes to find the lowest resistance and maximum transmitter current through the main lode. The resulting EQMMR anomaly images are similar to the

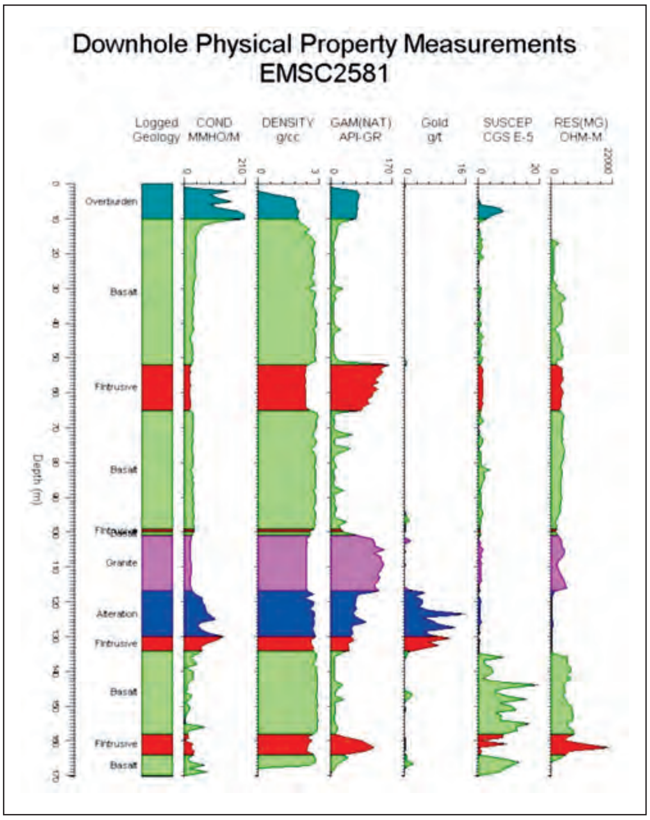


Fig. 3. Downhole logging results for reverse circulation drillhole number EMSC2581, which penetrates the Songvang main lode. The transported overburden and mineralisation is weakly conductive against a very resistive bedrock. High gamma-ray counts in the ore zones are caused by increased potassium levels from biotite alteration.

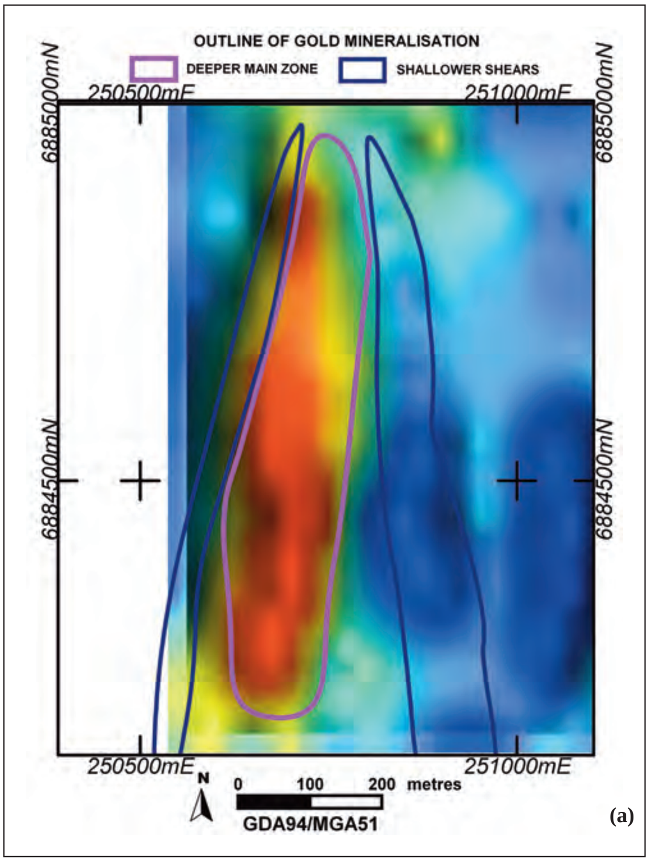
surface electrode surveys, with some distortion occurring around the electrode holes at the North and South edges of the survey area (Figure 7a). This similarity is likely to result from current flow in saline groundwater up the borehole and through the shallow structures and regolith, rather than being focussed into the main lode. The orebody is not very conductive and any response tends to be obscured by current channelling through the regolith.

The downhole, 4 Hz EQMMIP pattern is similar to the GAIP chargeability (compare Figures 4a and 7b). Although, the downhole EQMMIP anomalies show much more structural detail than the GAIP results, and subsequent drilling into the peaks of the anomalies found high gold grades associated with increased pyrite concentration.

The EQMMR, downhole electrode EQMMIP results, and Songvang gold resource wire frames are shown as 3D surfaces in Figure 8 to highlight the good correlation between SAM anomalies and gold-pyrite mineralisation.

Potential Field Modelling of SAM Data

Based on the Poisson-Eötvös relationship, an analogy can be made between vector calculations for gravity fields, as a function of varying density, and the horizontal MMR field, as a function of current density (Szarka, 1987; Boggs, 1999). Current density was successfully modelled using a 3D gravity modelling software package for SAM EQMMR data from the Flying Doctor Pb-Zn deposit Broken Hill (Boggs, 1999), and for estimating depth of conductive regolith over resistive bedrock using MMR data (Street, 1989). Profiles of the EQMMR response



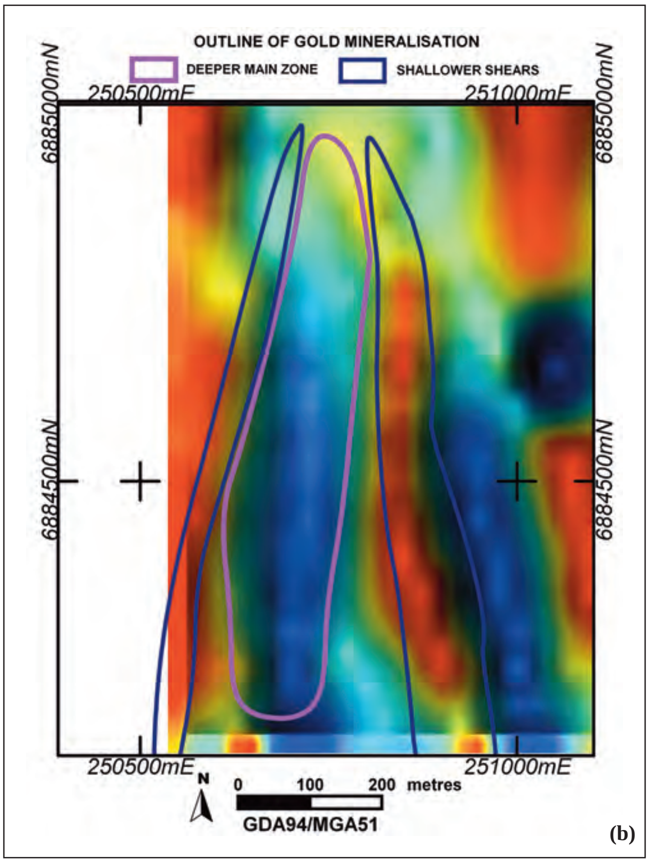
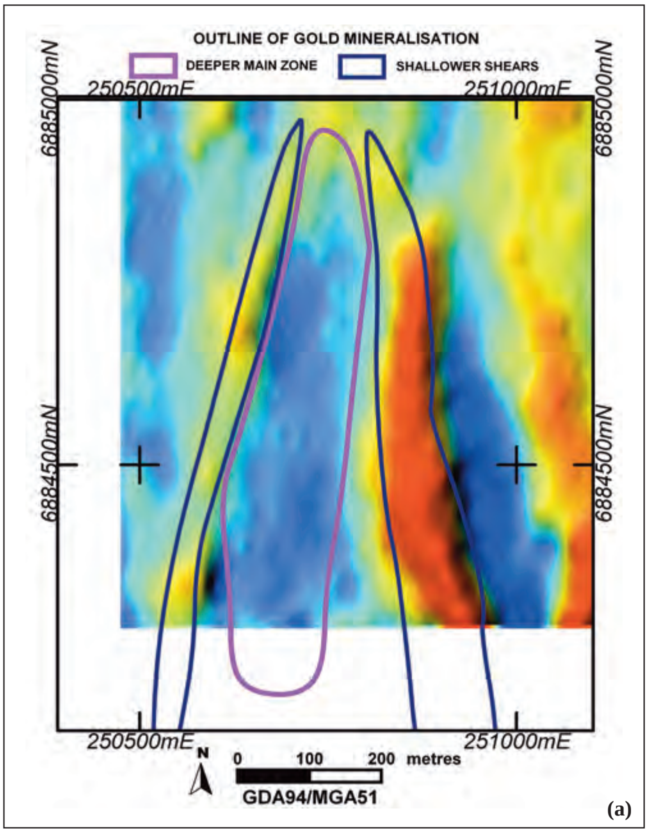
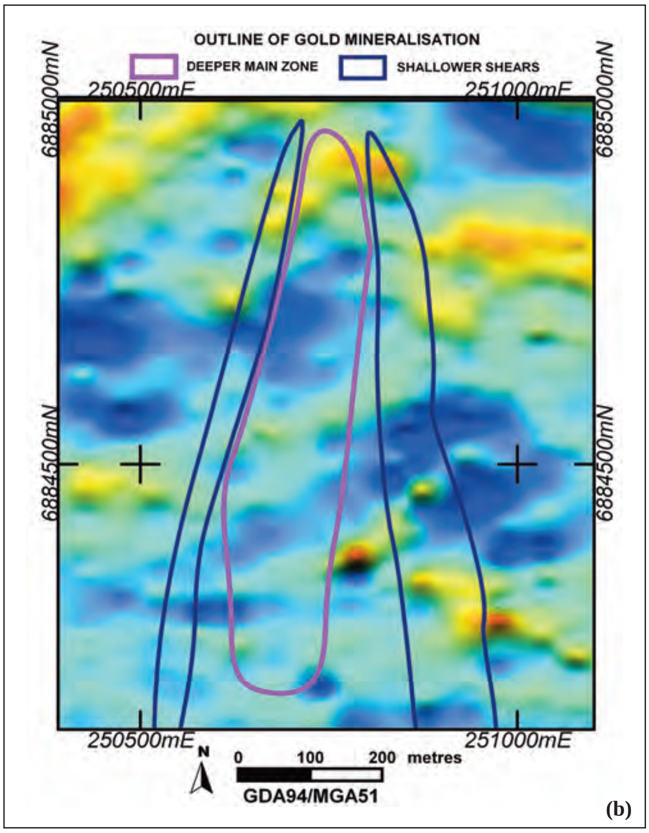


Fig. 4. (a) Gradient array IP response from the Songvang area highlighting the chargeable main lode at depth (dynamic range 0–12 ms); (b) Gradient array apparent conductivity response from the Songvang area, with increased conductivity above the shallow eastern and western shears. Conductor at the eastern side of the image is deeper weathering above an ultramafic unit.





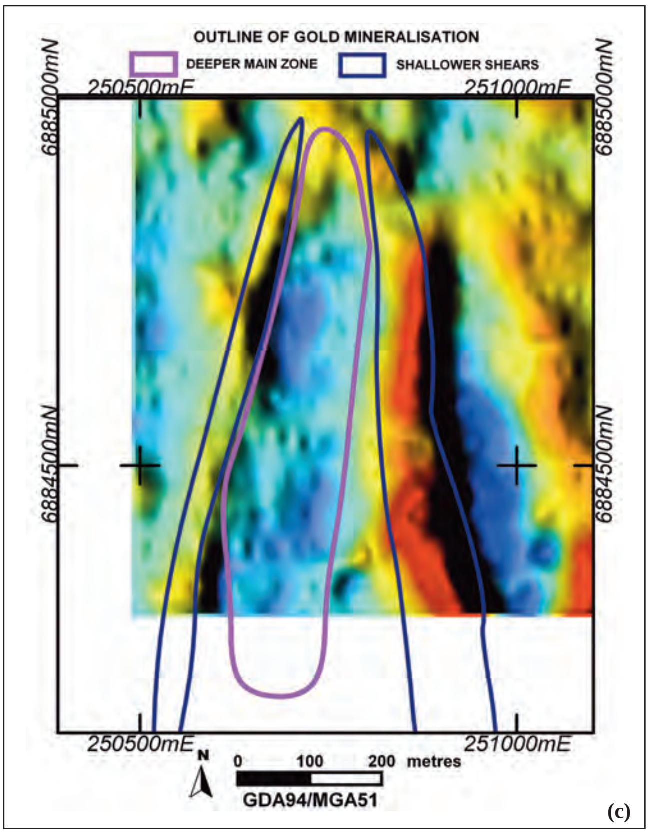


Fig. 5. (a) SAM EQMMR response from survey NS4 with a first vertical derivative filter and West sun shading applied, showing anomalies along the N–S trending shears, similar to the GAIP conductivity in Figure 4b, but at much higher resolution; (b) SAM EQMMR response from survey EW4 with a first vertical derivative filter and North sun angle applied, showing weak current channelling along E–W trending features; (c) SAM EQMMR grids NS4 and EW4 merged into a single grid and with a first vertical derivative filter and West sun angle applied.

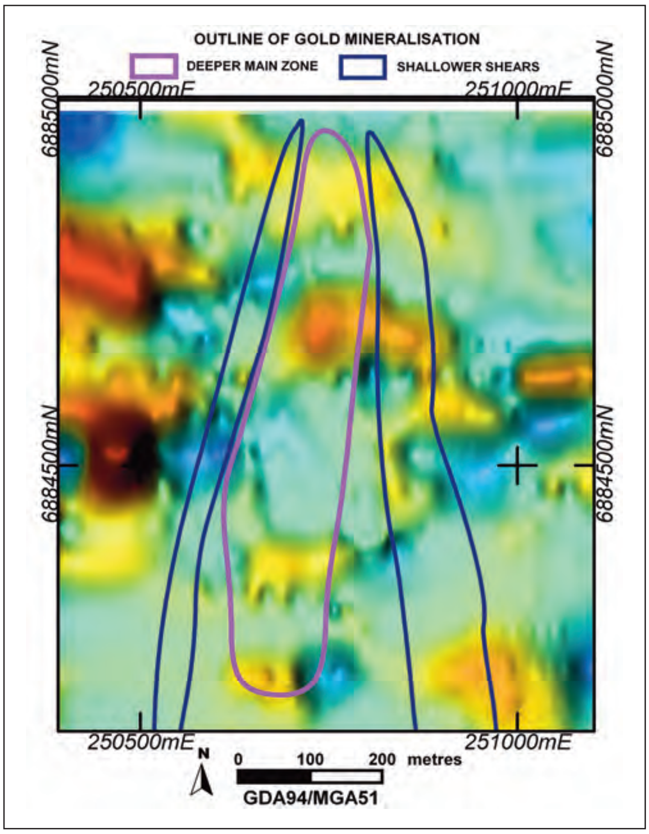
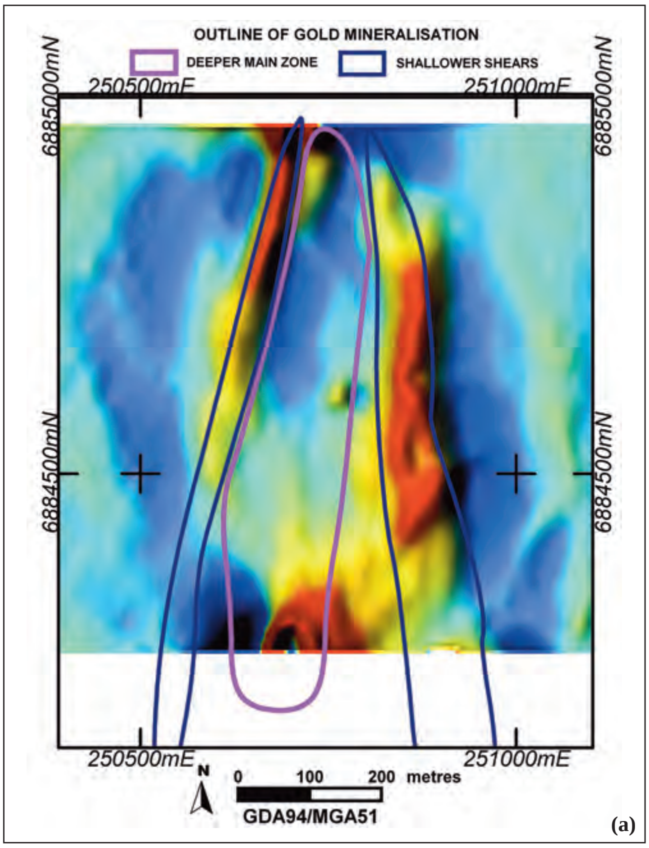


Fig. 6. SAM EQMMIP response from survey NS1 (dynamic range 0–14 ms), showing spotty responses caused by noise and possibly chargeable zones in the regolith. However, the responses in this image do not show any similarity to the GAIP chargeability (Figure 4a) or correlate with known geology or regolith, and are considered to be unreliable data.



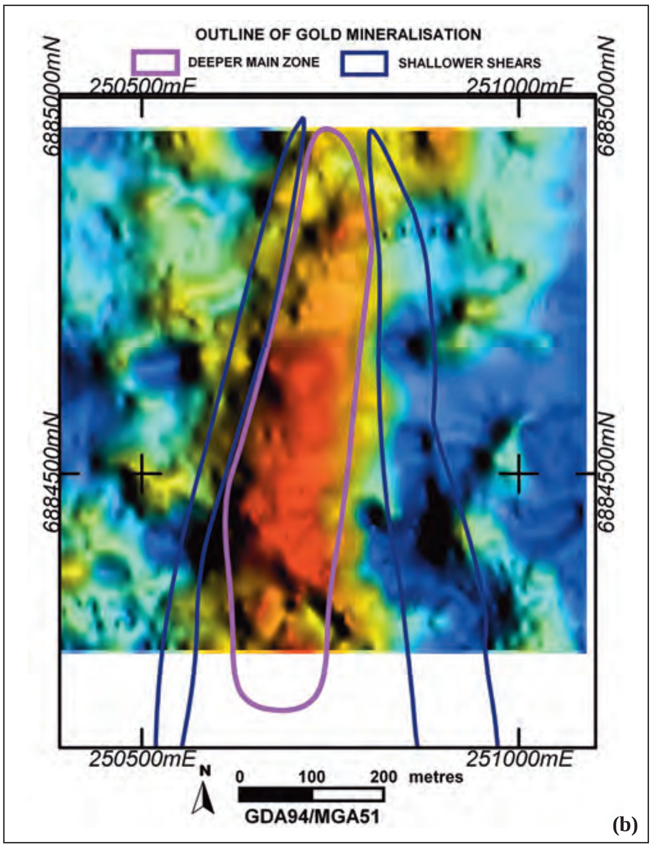


Fig. 7. Downhole electrode survey DHNS4. a) SAM EQMMR response with first vertical derivative filter and West sun angle applied. This image shows similar results to the surface electrode survey in Figure 5a, with some distortion surrounding electrodes near the survey boundary, and this similarity suggests that current channelling up drillholes and into the regolith dominates the signal; (b) SAM EQMMIP response showing excellent correlation with the main lode and GAIP chargeability in Figure 4a, but with much greater anomaly detail that has been used to plan resource definition drilling with great success (dynamic range 0–8 ms).

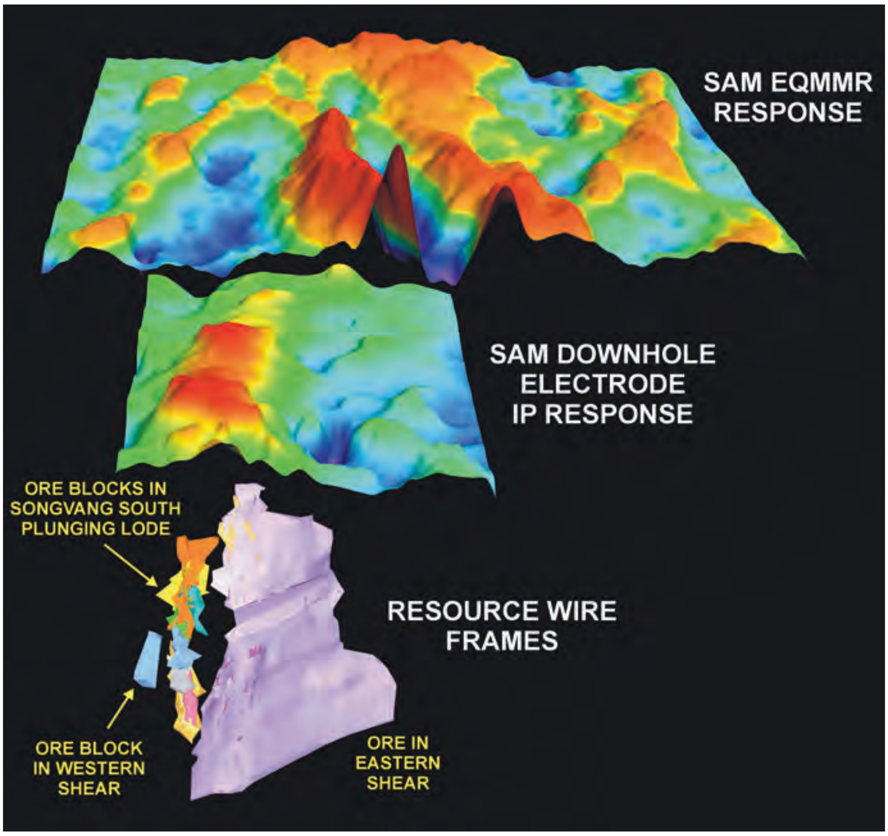


Fig. 8. Three-dimensional surfaces of SAM anomalies in relation to resource wire frames, with view looking to the North.

crossing the Songvang ore zones from survey NS4 have been modelled in 3D using the gravity functions in ModelVision software. Modelling of the EQMMR response from the shallow, mineralised eastern and western shears as dipping polygons with increased relative ‘current density’ values agrees well with the observed data and known structural setting (Figure 9). The main lode below 100 m was not detected in the TFMMR data, as most current channelling occurred in the regolith above this depth.

Unconstrained modelling of the EQMMR data from survey NS4 was also carried out with the UBC Grav3D program (Li and Oldenburg, 1998), and the results are shown in Figure 10. Relative current density is modelled to be greatest in the near surface, along the eastern and western shear zones. The 3D model generates apparent current channelling in the regolith at the top of the shear zones, reflecting deeper zones of weathering rather than dipping plates in the fresh bedrock.

The observed EQMMR response in survey NS4 is probably the product of current channelling in both the conductive minerals in the eastern and western shear zones and along the zones of deeper weathering in the regolith above these shear zones.

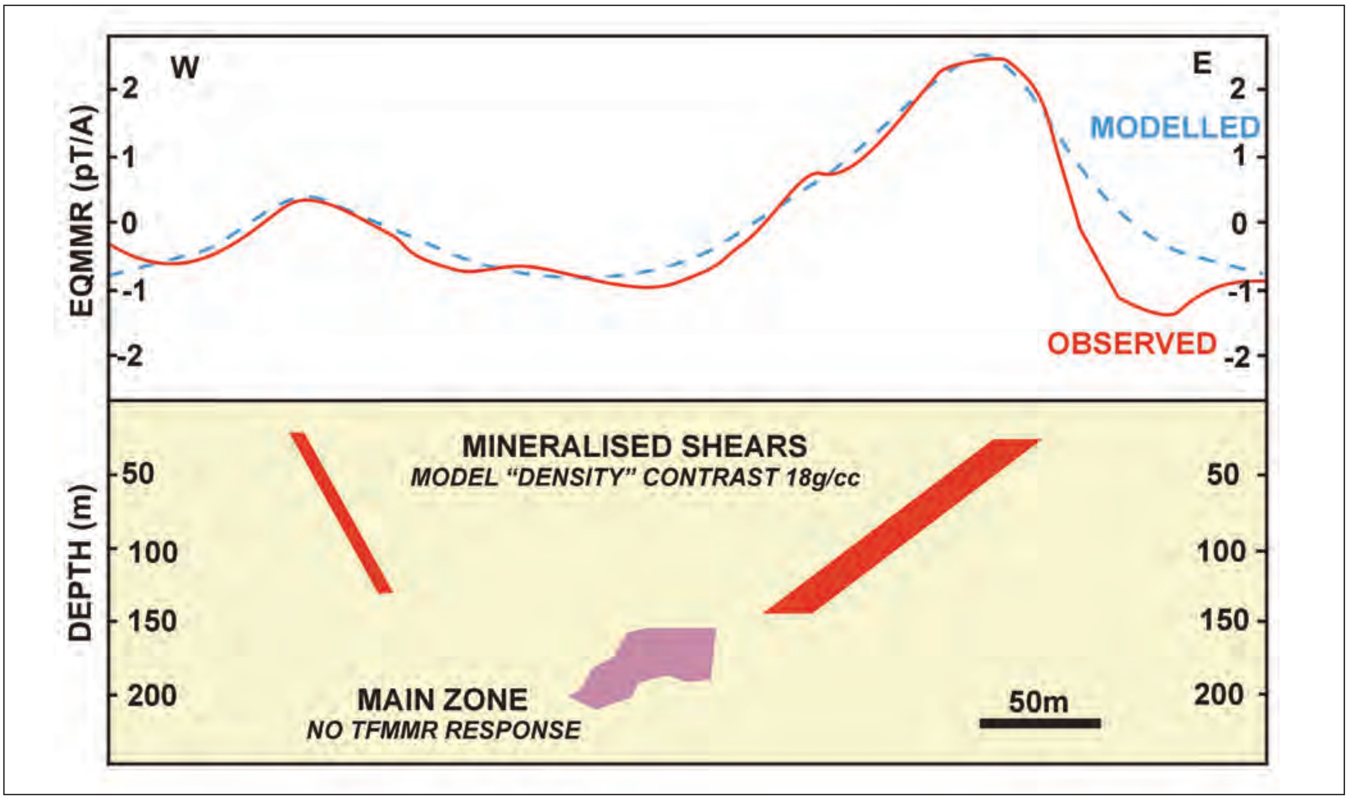


Fig. 9. Gravity modelling of the EQMMR response from survey NS4 data to estimate dips of the eastern and western gold mineralised shears. Same profile location as in Figure 2a.

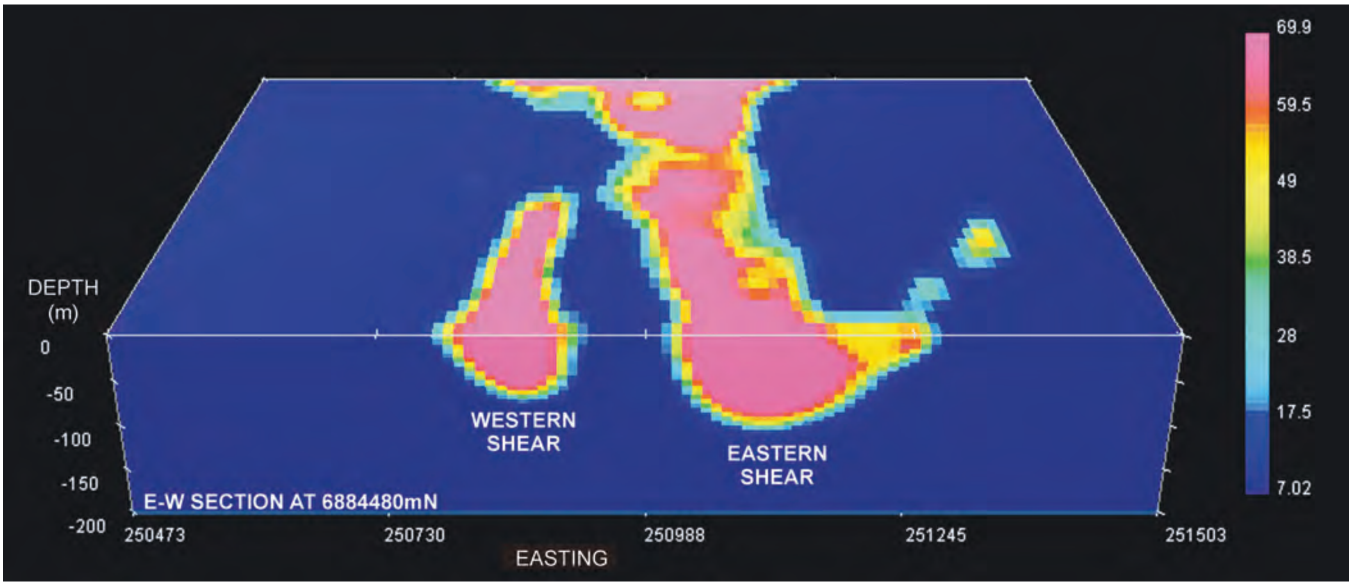


Fig. 10. Three dimensional inversion of the NS4 EQMMR data using the UBC Grav3D program (Li and Oldenburg, 1998), with view looking to the North and cut away section at the same location as in Figures 2a and 9. The inverted current density representation shows the anomalies at the western and eastern shears to be caused by deeper weathering (e.g., Figure 2a), as apposed to conductive sulphide minerals in the shears, as modelled in Figure 9. The current channelling anomalies are thought to be caused by a combination of deep weathering and sulphide minerals in the shears.

Magnetic and Gravity Surveys

The detailed gravity and magnetic data collected over the Songvang gold deposit do not give any direct indication on the location of the mineralisation and related structures, when compared to the SAM results. Figure 11 shows the magnetic pattern over the Songvang gold deposit. The host basalt and granodiorite rocks are non-magnetic, and the magnetic responses are related to N–S trending, serpentinised ultramafic rock units to the west and east of the Songvang deposit. The western ultramafic unit has no corresponding SAM EQMMR response, although deeper weathering along the eastern ultramafic unit corresponds to an anomalous trend of current channelling (Figure 5a). The gravity residual image over the Songvang gold deposit shows a gravity high caused by the bedrock high above the main lode, and two N–S trending gravity lows correlating with the deeper bedrock weathering along the eastern and western shear zones (Figure 12).

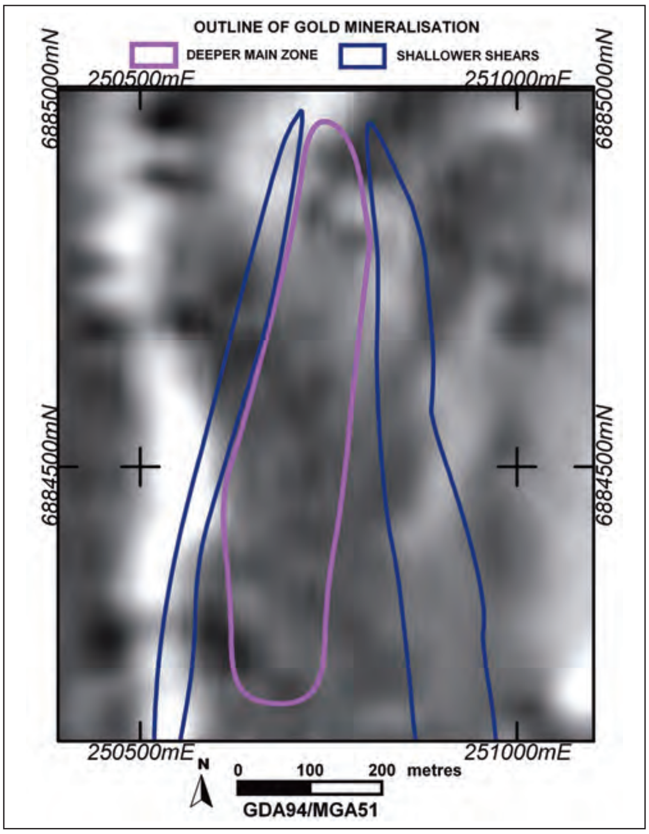


Fig. 11. Aeromagnetic image of the TMI reduced to the pole and with a second vertical derivative filter. Data were collected along 40 m E–W survey lines and at 40 m terrain clearance. Zones of higher derivative magnetic intensity correlate to serpentinised ultramafic units, and there is no useful information for directly targeting Songvang ore zones and structures.

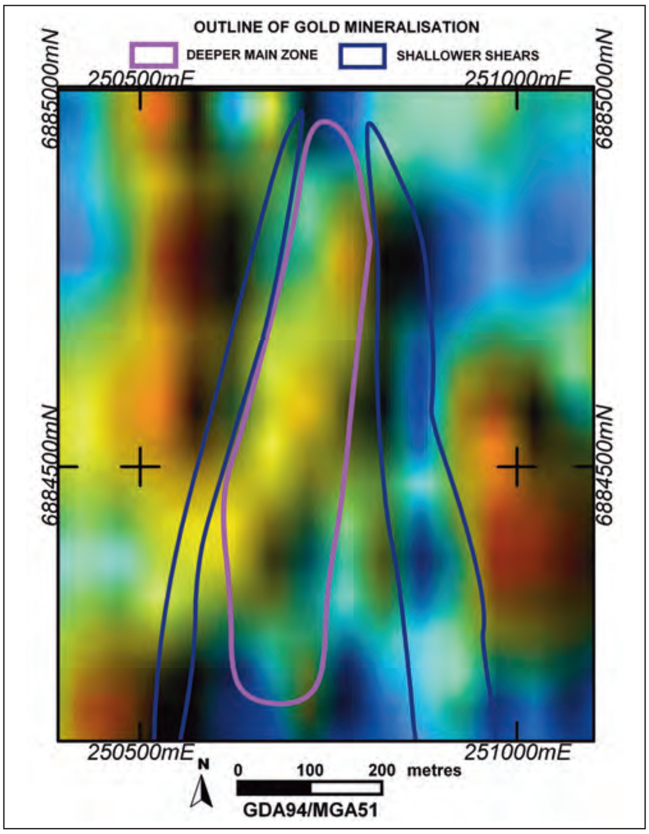


Fig. 12. Gravity residual images with a West sun angle, from a survey with 200 m E–W lines and 50 m station spacing. Gravity lows follow the deeper weathering along the eastern and western shears.

CONCLUSIONS

SAM surveying provides detailed information at prospect scale on current channelling along electrically conductive subsurface features in the regolith and bedrock that are oriented sub-parallel to the transmitter electrode direction. SAM EQMMR anomalies show similar patterns to GAIP apparent resistivity data, despite the different physical approaches to measuring subsurface conductivity between these two methods. However, the SAM EQMMR data provides higher-resolution information for imaging detailed structures and regolith features. SAM surveying is still not ideal for obtaining reliable EQMMIP data using a low frequency 1 Hz transmitter waveform and surface electrodes. However, when transmitter electrodes are placed directly into chargeable ore zones, reliable EQMMIP data can be collected to produce a very detailed image of chargeability anomalies, even at a transmitter frequency of 4 Hz. The level of detail in the EQMMIP data has been useful for planning resource definition drilling to intercept zones of increased pyrite alteration and high-grade gold mineralisation at Songvang.

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