Exploration Geophysics (2005) ***36****, 133–139*

The SAM EQMMR response of the regolith at East Victory, St Ives Gold Mine, Western Australia

Michael Whitford[1] **Jayson Meyers**[2] **Ned Stolz**[3]

Key Words: Sub-Audio Magnetics (SAM), equivalent magnetometric resistivity (EQMMR), regolith, East Victory, electrical resistivity imagining (ERI), HeliSAM

ABSTRACT

The Sub-Audio Magnetics (SAM) equivalent magnetometric resistivity (EQMMR) response has been investigated along a single 2.2 km long transect in the East Victory area at the St Ives Gold mine near Kambalda. The integration of a number of high-definition geophysical surveys, including electrical resistivity imaging (ERI), high-resolution gravity surveying, HeliSAM surveying, drill testing, and downhole logging along the same 2.2 km transect has shown the SAM EQMMR response here is due to variations in the regolith.

The thickness of the regolith, predominantly the depth to fresh rock, was accurately determined by inversion of apparent resistivity from the ERI survey. The depth of the regolith along the transect was later confirmed by drilling at six locations, with the base of saprock found to be within 5 m of predicted depth from the ERI profile.

From the high-resolution gravity surveying at 10 m station spacing, a residual was created to highlight the contribution of the low-density regolith to the gravity response. This gravity residual was found to have an excellent inverse correlation with the SAM EQMMR anomaly data. The high-amplitude, positive SAM EQMMR responses also show excellent correlation with the depth of regolith interpreted from the ERI profile. HeliSAM showed the same broad EQMMR anomalies as ground-based SAM, but the resolution and amplitude was much lower because of detector height, fewer along-line readings, and helicopter noise.

Gravity data were successfully modelled in 2.5D using the ERI inversion to constrain the depth of polygons. Using the gravity model, the SAM EQMMR response along the transect was also successfully modelled by assigning relative current densities to the polygons, as opposed to absolute density values. The SAM EQMMR response was also inverted in 3D from gridded data using the UBC Grav3D program with some degree of success, with the depth of the main conductor in the inversion in agreement with drilling information.

Downhole conductivity logging along the East Victory transect shows that the regolith is highly conductive, with peak conductivities ranging from 1200–2700 mS/m. It can be shown that the lateral differences in regolith conductivity do not play a major role in defining the SAM EQMMR response in this environment. The regolith produces SAM EQMMR anomalies that reflect wide zones of deeper weathering, where the conductive regolith contained higher current density compared to the underlying fresh bedrock. It is demonstrated that high-amplitude SAM EQMMR anomalies map out geological structures and rock units that have been preferentially weathered and have both high current densities and large geometric size.

INTRODUCTION

A detailed study of the geophysical responses of the regolith using a number of high-resolution geophysical systems has been conducted along a single 2.2 km long transect within Goldfields, St Ives Gold Mining Company's Kambalda leases. The geophysical responses from electrical resistivity imaging (ERI), sub-audio magnetics (SAM) equivalent magnetometric resistivity (EQMMR), and a detailed gravity survey have been inverted and modelled to show their respective contributions in relation to imaging the subsurface regolith. HeliSAM data is also compared to ground SAM data in the East Victory area.

An objective of this study is the investigation of the regolith controls on the SAM EQMMR response. The SAM technique is a relatively new, high-definition geophysical mapping method that is becoming increasingly popular for exploration in the eastern goldfields of Western Australia. Though this method is being used to map current channelling over mineral prospects, the nature of the response is still relatively poorly understood because there are few case studies of its application (e.g., Cantwell, 2003; Meyers et al., 2004). The total-field magnetometric resistivity (TFMMR) is the main data component that is acquired and processed to produce the EQMMR anomaly. The total magnetic intensity (TMI) is also simultaneously collected.

It has been shown that for a grounded transmitter electrode spacing of 2000 m over a 50 m thick overburden layer with a resistivity of 10 Ω.m, approximately 80% of the current remains in the overburden (Edwards and Howell, 1976). Street (1989) suggested that in such a conductive environment, the magnetometric resistivity (MMR) response would be dominated by changes in the conductivity and thickness of the regolith overburden.

The East Victory area is located in a hypersaline environment on the south shore of Lake Lefroy, and as such it is expected that a higher percentage of the current will be confined to the regolith, comprised of saprolite and transported overburden on top of greenstone and granite bedrock.

STUDY AREA LOCATION AND GEOLOGY

Location

The study transect lies within the St Ives Gold Mine leases at Kambalda, in the Eastern Goldfield province of Western Australia.

[1] *Resource Potentials Pty Ltd*
PO Box 1457
West Perth WA 6872
Australia
Phone: 61-8-94869299
Facsimile: 61-8-92899189
Email: mikew@respot.com.au

[2] *Curtin University of Technology and CRC-LEME*

[3] *St. Ives Gold Mining Company, Goldfields Limited*

Manuscript received 24 December, 2004. Revised manuscript received 13 April, 2005.

The transect is located within 1 km of Lake Lefroy, and has very low topographic relief (Figure 1).

Geology

The study transect lies on the southern end of the Norseman-Wiluna Greenstone belt within the Archaean Yilgarn Craton. Mineralisation at St Ives lies within a corridor of mafic to ultramafic rocks, bounded by the Boulder-Lefroy Fault to the east, and the Merougil Fault to the west. Rocks hosting mineralisation at St Ives are the Kambalda Komatiite, Devon Consols Basalt, Kapai Slate, Defiance Dolerite, Paringa Basalt, and unnamed intermediate to felsic intrusive rocks (Nguyen et al., 1998). Mineralisation in Kambalda is known to occur within several kilometres of the Boulder Lefroy Fault (Witt, 1992), along structures that are interpreted to be splays of this fault.

Regolith at St Ives

The greenstone-granite bedrock geology of St Ives is overlain by regolith cover of varying thickness and composition. The primary regolith units in the area are lake and palaeochannel sediments, colluvium, hardpan, and thick saprolite from weathering of the bedrock. Regolith over the lake areas on St Ives leases consists more of lacustrine clays, with lenses and horizons of spongolite and lignite in the palaeochannels. Palaeochannels that lie within the St Ives mining leases contain up to 70 m of transported sediments (Lintern and Gray, 1996).

Anand and Paine (2002) describe a typical weathering profile as having a lateritic residuum at the surface. The regolith along the East Victory transect has no well-developed lateritic top, and as such, can be said to be partially truncated (Madden, 2004). The top regolith layer along the East Victory transect is hardpanised aeolian sands and sandy clays. Six holes were drilled along the this transect at shallow and deep weathering zones, with regolith units logged as colluvium, palaeochannel clays, upper saprolite, lower saprolite, and saprock. The regolith profile is affected by basement rock type, shear structures, and erosional-depositional history. The regolith profile is shallow over the Paringa Basalt, and slightly deeper over the Black Flag Beds, which are comprised of clastic and volcaniclastics sediments. The depth of the regolith profile

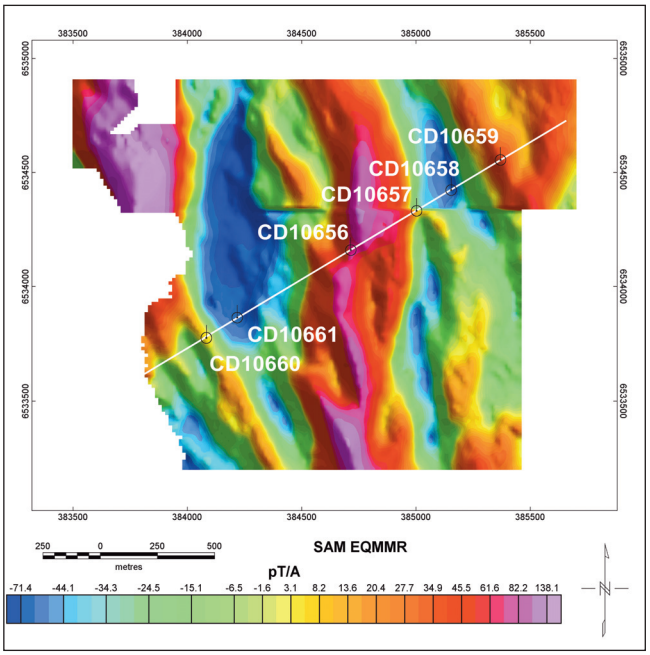

Fig. 2. SAM EQMMR image of East Victory area showing the transect in white, with location of six air core drillholes.

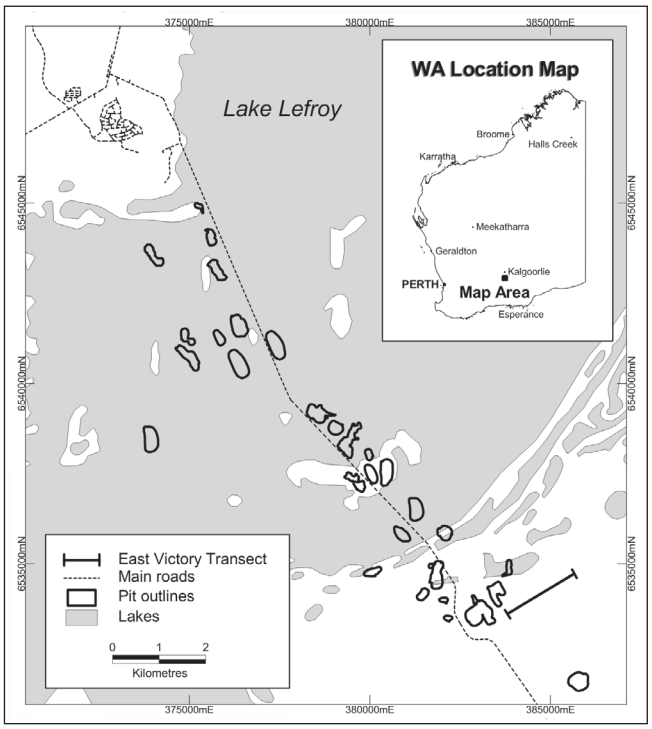

Fig. 1. Location of East Victory study transect in relation to local topographic features.

increases over zones of structural complexity, because of increased porosity in sheared and brecciated rocks (Madden, 2004).

METHODS

The East Victory transect crosses two SAM survey grids that have been stitched together to produce the EQMMR image shown in Figure 2. These two survey grids were collected using east-west traverses with 50 m line spacing. The EQMMR data points are nominally spaced at 2 m along transect lines. The transmitter current was about 8 amperes for both grids.

The HeliSAM survey, shown in Figure 3, covers a larger area as a single grid in comparison to the ground SAM. For the airborne

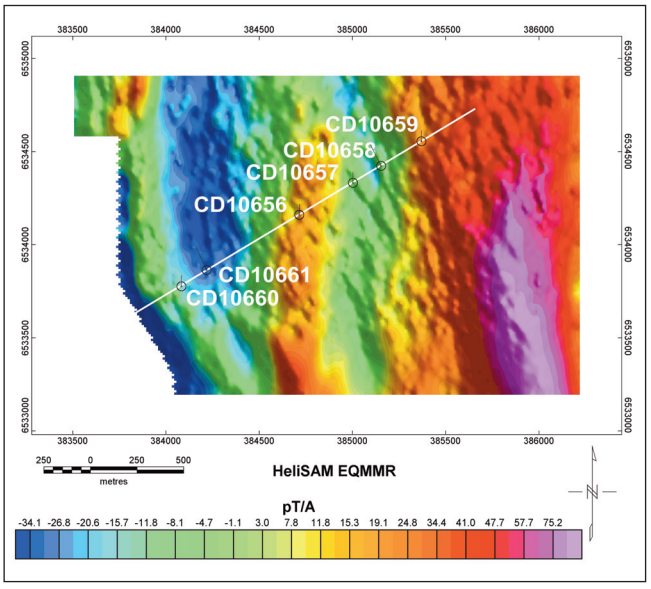

Fig. 3. East Victory HeliSAM EQMMR image with transect highlighted in white. The same broad wavelength features are present when compared with Figure 2.

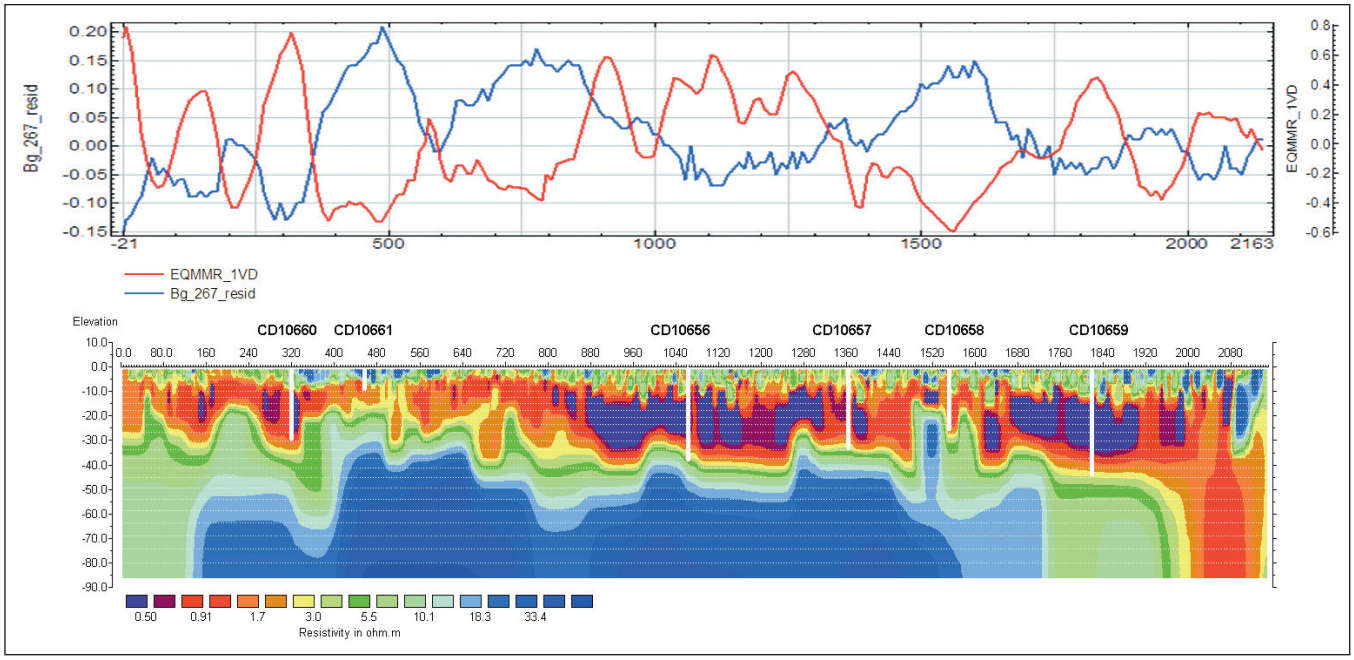

Fig. 4. Profiles of SAM EQMMR first vertical derivative (red line) and gravity residual (blue line) along the East Victory transect (top) showing the inverse correlation between gravity lows and SAM EQMMR highs. Below is the ERI inversion and drillhole locations illustrating the depth to resistive basement.

survey, a transmitter current of approximately 8 amperes was used, with 50 m, east-west orientated flight lines. The terrain clearance for the HeliSAM survey was approximately 25 m.

The ERI survey electrodes were spaced at 10 m, with 24 electrodes used on each cable. A total of 9 cables were used to cover 2.16 km. The ERI transmitter is capable of output currents of 2.5 A, output power of up to 250 W, and an output voltage of 1000 V. An inverted section of apparent resistivity, shown in Figure 4B, was generated to provide depth estimates of the conductive regolith.

High-resolution gravity data were acquired along the East Victory transect at 10 m station intervals for a total of 212 stations. The Bouguer gravity anomaly was calculated using a density of 2.67 t/m^3. More widely spaced gravity data over the East Victory area were also supplied by St Ives Gold Mining Company. The station separation for this data varied from 100 m to 200 m. A gravity residual was created by upward-continuing Bouguer gravity data to 60 m above the observation datum and subtracting this from the original Bouguer gravity data. Gravity residuals for the transect and the East Victory area are presented in Figures 4 and 5, respectively.

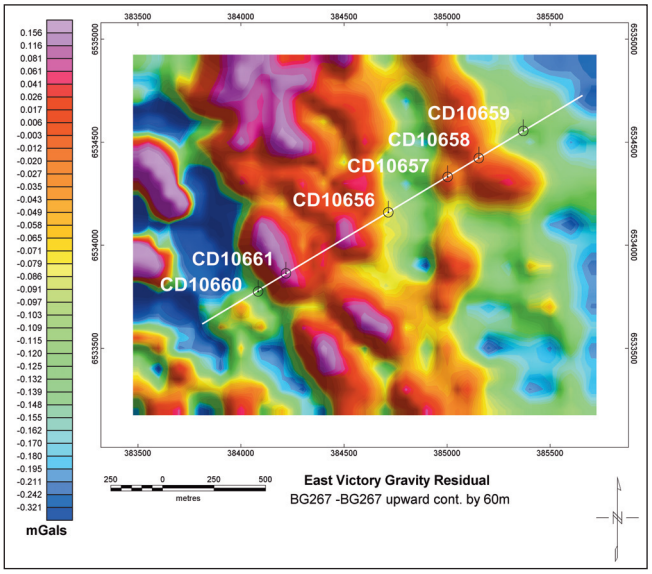

Fig. 5. Residual gravity anomaly image created over the East Victory area, with the transect highlighted in white. Comparing this with Figure 2, the central SAM EQMMR anomaly corresponds to the residual gravity low.

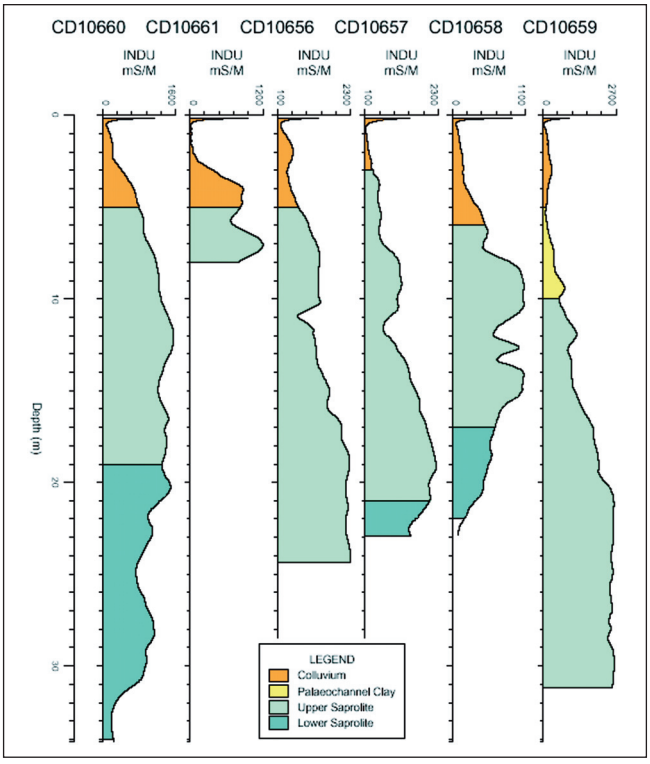

Fig. 6. Downhole conductivity of the six drillholes along the East Victory transect showing sources of SAM EQMMR and ERI conductors and resistors along the transect. Drillhole locations are shown in Figure 2.

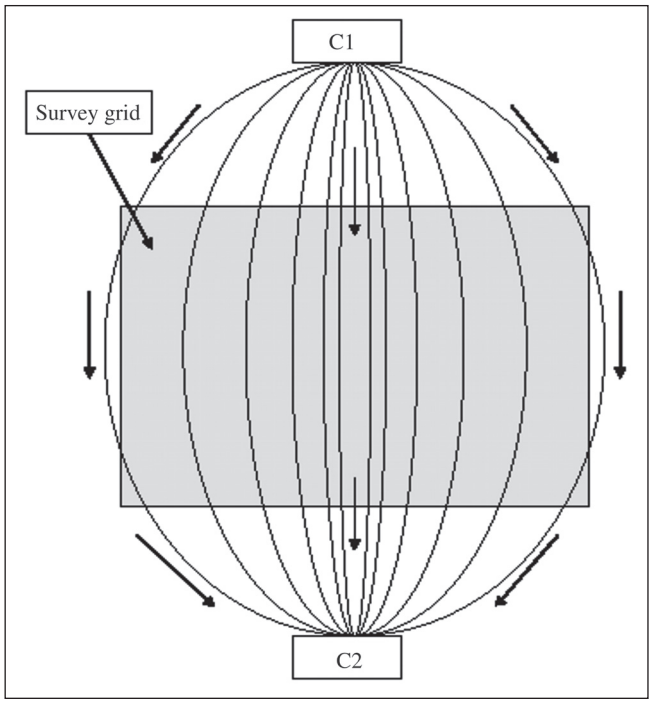

Fig. 7. Current channelling representation through a SAM survey grid with arrows representing current flow direction in a uniform half space. There is a directional bias to detect conductive features in the direction of current flow, and there will be a bias towards higher amplitude anomalies occurring in the centre of the survey grid due to higher transmitter current density. Figure modified after Telford et al., (1990).

Six air core drillholes were drilled into SAM anomaly highs and lows along the East Victory Transect until they hit fresh bedrock and were stopped. The drillholes were logged for regolith conductivity using an Auslog A634 inductive conductivity tool. Conductivity logs are shown in Figure 6. Drill chips were logged for geology, and an ASD spectral analyser was used to log kaolinite crystallinity.

RESULTS

Data Interpretation

The resistivity profile inverted from the ERI survey provided an excellent image of conductive regolith thickness (Figure 4). The drilled depth of the base of the regolith correlates to within 5 m of the depth interpreted from the inverted resistivity profile. The ERI delineated conductive zones within the regolith, and defined a resistive surface layer overlying the more conductive saprolite (Figure 4). This resistive surface layer corresponds to the colluvium layer at the top of the regolith, and is confirmed by the conductivity logging (Figure 6).

The SAM method relies on current channelling through the subsurface between two electrodes. A schematic of current flow for a SAM survey is shown in Figure 7, and this shows that there is a distinct bias towards channelling currents along structures with a similar orientation to the current electrodes. Data are also processed to obtain the horizontal EQMMR response between the transmitter electrodes (Cattach et al., 1993). The highest current densities lie along the central axis of the survey grid. The SAM method also gives slightly higher amplitude anomalies along the central axis of the survey grid, even after a uniform half space anomaly from the transmitter wire and electrodes is removed during data reduction (Cattach et al., 1993). This is also evident in the EQMMR image at East Victory (Figure 2), where the highest amplitude anomalies occur in the centre of the grids.

A SAM anomaly high is expected to correlate with features having increased conductivity and current density. The integration of the ERI and gravity with the SAM data indicates that where the conductivity within the regolith is relatively uniform, the depth of weathering and width of the deeply weathered zones play a major role in generating SAM anomalies. The anomaly profile in Figure 4 shows an excellent inverse correlation between the SAM EQMMR first vertical derivative (1VD) and the Bouguer gravity residual. The SAM 1VD highs and gravity residual lows correspond with the deeper regolith profile, as mapped by the ERI image. The Bouguer gravity residuals highlight variation in density within the regolith that is independent of conductivity, and also reflect the density contrast between saprolite (1.8–2.2 t/m^3) and fresh bedrock (2.5–3.1 t/m^3).

By comparing the gravity and ERI data to the SAM data it can be seen that the SAM response is mainly controlled by the width and thickness of the deeper weathered zones in the regolith. This is most evident at 320 m along the transect in Figure 4. Comparing the SAM EQMMR at this location with the broader central conductor it is seen that the amplitude is much smaller at 320 m. The width of the deeply weathered zone also is a controlling factor in the SAM EQMMR response, as the geometrical size of the zones with increased relative current density plays an important role.

Downhole conductivity logging of six air core drillholes along the transect was also used to determine controlling factors in the SAM EQMMR response. Conductivity logging shows that the regolith is highly conductive, with peak conductivities ranging from 1200 to 2700 mS/m (Figure 6). Comparison of all the peak conductivities with the SAM EQMMR response demonstrates that the strongest SAM EQMMR anomaly does not correspond to the highest downhole conductivity, but instead corresponds with the deepest regolith. The main factor controlling the EQMMR response at east Victory is the depth and width of regolith, and not variations in regolith conductivity.

Comparison of the gravity residual map (Figure 5) with the SAM EQMMR map over the East Victory area (Figure 2) shows that most of the SAM EQMMR anomalies can also be identified

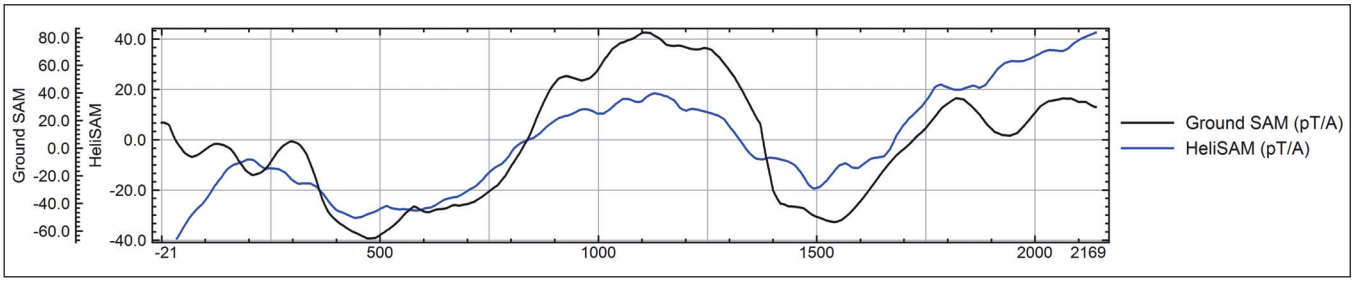

Fig. 8. HeliSAM EQMMR (blue line) along the East Victory transect, compared with the ground SAM EQMMR (black line). The same broad features seen in the ground Sam results can be seen in the HeliSAM results, but the detail is lost and the amplitude is lower in the HeliSAM.

in the gravity data, although at a lower resolution due to the wide gravity station spacing. The gravity data also identifies east-west oriented features that are not present in the SAM EQMMR, because the north-south dipole orientation does not channel current into east-west features.

Comparison of SAM and HeliSAM

The HeliSAM method of acquiring EQMMR data is very similar to the ground-based method. HeliSAM uses a caesium vapour sensor to measure the magnetic field, and the sensor is mounted in a bird slung below a low-flying helicopter. This HeliSAM method is still in development.

The resultant HeliSAM EQMMR survey results are shown in Figure 3. The East Victory transect from the HeliSAM data is shown in profile in Figure 8, with comparison to the ground SAM results. The HeliSAM anomaly resolution is much lower than the ground survey, and the data is much noisier than the ground data. Loss of resolution is expected, because the sensor is 25 m above the ground, along-line sampling is 12 m compared with 2 m for the ground SAM, and the airborne sensor is subject to severe noise from bird movement and the vicinity of the helicopter. Some of the noise in the data is attributed to static electricity generated by the bird moving through the air (Cattach, 2003). Despite the high noise levels, the same broad anomalies are present in the HeliSAM as in the ground SAM survey. HeliSAM has merit for covering large areas quickly, where precise resolution is not a major issue.

Data Modelling

Integration of all geophysical data has provided a reasonable understanding of the subsurface regolith, and modelling of the gravity and SAM EQMMR data further support the inverse relationship between gravity and EQMMR anomalies at East Victory.

The gravity data along the transect have been modelled using a density contrast method to represent the regolith (Figure 9). The regolith model was created by using the ERI resistivity inversion to obtain depths of weathering. The regolith is modelled in 2.5D using a series of polygons with different thicknesses and densities to represent variations in the regolith. The discrete polygons allowed for lateral variations in density contrast between the basement and the overlying regolith. This allowed for more variation within the regolith and is an excellent approach for modelling the regolith using gravity data. The majority of the regolith blocks were assigned an average density contrast value of -0.8 t/m^3 relative to the underlying fresh bedrock; although values of -0.6 and -0.7 t/m^3 were also used. This equates to a regolith density of 1.8 to 2.1 t/m^3. The long wavelength regional was defined by St Ives regional gravity data, and was removed. A good fit to the high-resolution field data along the East Victory transect has been achieved using the 2.5D model.

Following the gravity modelling, the SAM EQMMR was modelled using the same gravity modelling software. Szarka (1987) describes how a simple relationship exists between the horizontal component of the MMR field associated with the current density of a one-dimensional current flow and the Bouguer gravity anomaly, this relationship justifies the use of the same modelling software. The regolith model generated to model the gravity data was exported for use with the SAM EQMMR data, and the input densities were modified in order to reflect the relative current density. Using this method, a representation of current density across the transect was generated and has a good fit to the observed SAM EQMMR data (Figure 10).

The SAM data in the East Victory area was inverted using the UBC Grav3D software (Li and Oldenberg, 1998). The mesh that was used in the inversion consisted of 10 m cell sizes along line, by 20 m across line, by 5 m deep. The inversion was constrained with relative density limits of 0 t/m^3 as the lower limit and 50 t/m^3 as

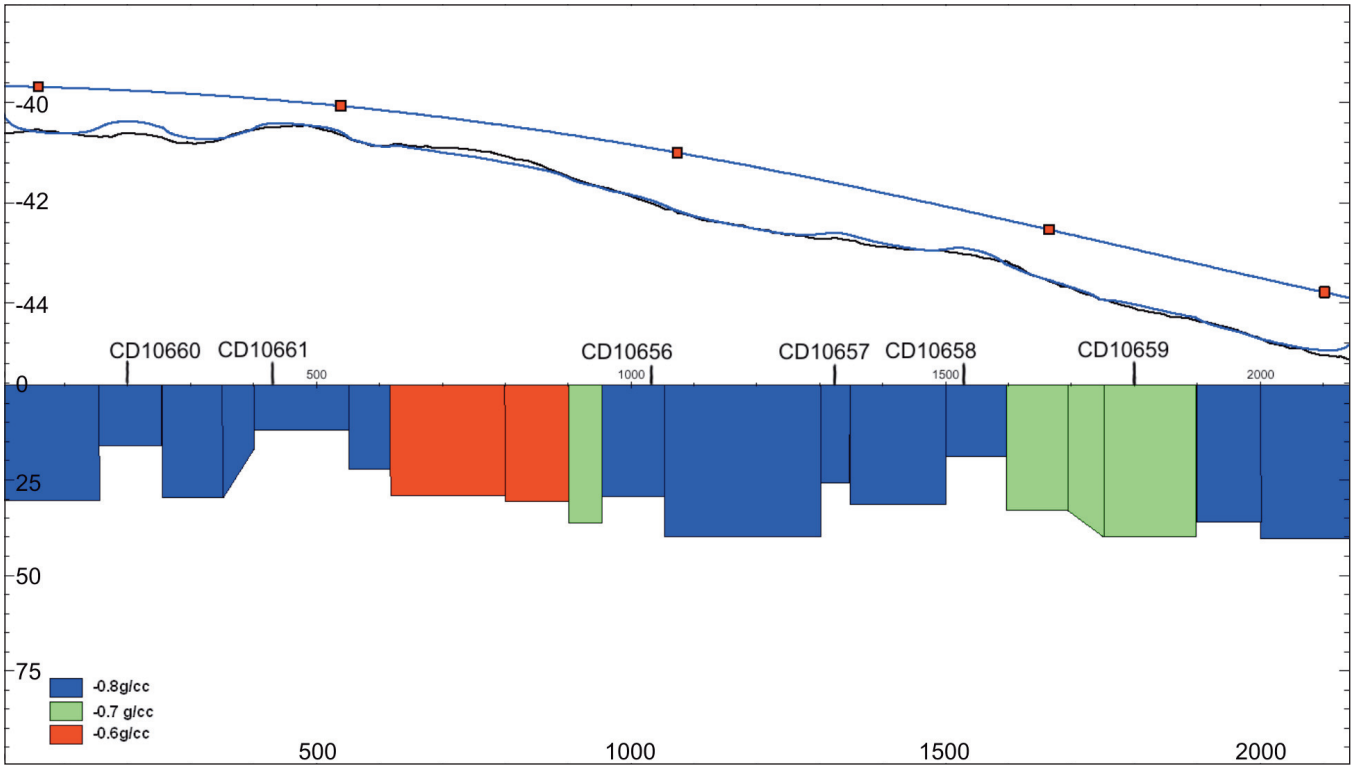

Fig. 9. Regolith model created to model the regolith contribution to the gravity response. A regional trend has been defined and removed. The model depths and shapes were created from the ERI inversion. Blue polygons represent a density contrast of -0.8 t/m^3 with the basement. Red polygons correspond to a contrast of -0.6 t/m^3, and green corresponds to a contrast of -0.7 t/m^3.

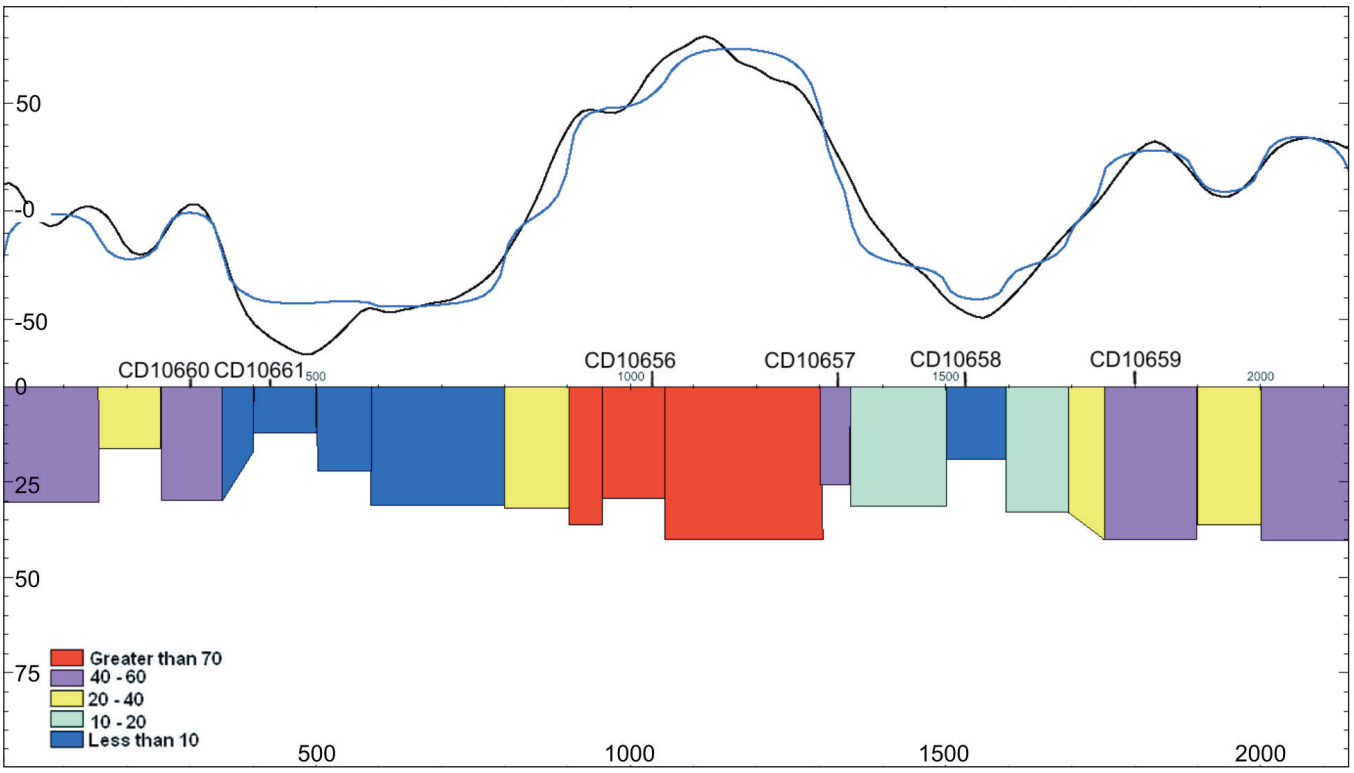

Fig. 10. SAM EQMMR response modelled using the same model used for the gravity data. The density – current density relationship described by Szarka (1987) allows the current density to be modelled using potential field modelling software. The values used in the SAM EQMMR models represent relative current density as opposed to density for the gravity data. It can be seen that a good fit is achieved with higher relative current densities being assigned to the deeper and broader regolith features.

the upper limit. The resulting model is presented in Figure 11. This model indicates the SAM response source to be in the near surface, corresponding to the conductive regolith. Some of the smaller conductors do not appear in the inversion. The central conductor in the inversion is at depths between 40–45 m, and this is in agreement with depths of regolith indicated by the ERI inversion and results from drillhole CD10656. The fact that only the major conductors have been represented in the inversion suggests that the smaller conductors have only a negligible amount of current flow, leading to a low current density, and also that the cell size used in the inversion was too coarse to successfully resolve narrow anomalies.

The conductor to the east of the main conductor, located at drillhole CD106559, is present in the inversion model, though it does not agree with the drilled depth of regolith. This conductor disappears at about 20 m depth, but the drilled depth of regolith is 48 m. This conductor does not appear to be as deep as the central feature in the 3D model, possibly because it has a much smaller EQMMR amplitude and the width of the weathered zone is much less.

CONCLUSIONS

The ERI method is able to collect large quantities of data along a transect at close electrode spacings in a relatively short amount of time. This data can then be quickly and easily inverted to provide a high-resolution profile of the transect, in this case down to approximately 80 m depth. The ERI inversion provided the most direct and easily interpretable results showing detail in the regolith along the transect. This method gave accurate depth estimates of the conductive regolith that correlated well with those from drilling. The ERI was also able to detect the resistive surface

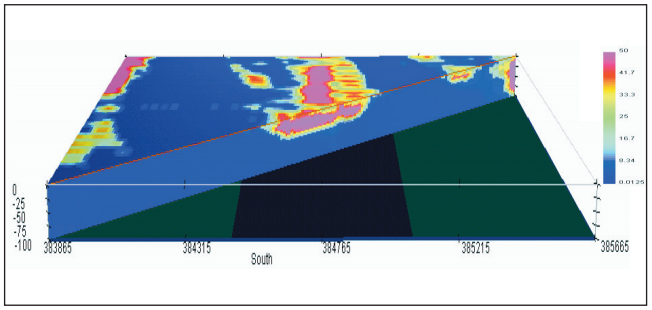

Fig. 11. SAM EQMMR UBC Grav 3D inversion with a cut away through the East Victory transect. The central SAM conductor has been inverted to a depth in agreement with the drilled depth of regolith. The smaller amplitude conductors that lay either side of the central conductor were not able to be inverted, possibly due to the model voxel size used.

layer of colluvium to a depth that correlated well with geological logging from the six drill holes along the transect.

The residual gravity data along the transect showed high-frequency anomalies, and was found to have a good inverse correlation with the SAM EQMMR and the SAM EQMMR 1VD. The good inverse correlation between these two data sets is primarily controlled by the depth of weathering, and the width of the weathered zones along the transect. In areas that have electrically resistive regolith, gravity would be able to detect the preferential weathering when SAM and ERI would not be as effective.

The regolith along the transect was successfully modelled using the gravity data and a density contrast method, and then removing

a regional effect. Discrete blocks were used to model the density contrasts along the transect. The discrete blocks allowed for lateral variations in density contrast between the basement and the overlying regolith. This allowed for more variation within the regolith and is an excellent approach for modelling the regolith using gravity data.

An approximation of the SAM current density response over the transect was also successfully modelled using the regolith polygons constructed to model the gravity data. This model shows that the greatest current density occurs along the deeper and wider regolith features, with the highest relative current density assigned to the deep, central conductor. Modelling of the SAM data using the gravity regolith polygons highlights how the SAM response is confined to the regolith at St Ives, and also provides information on the subsurface current flow related to differential weathering of rock units and shear zones.

A 3D inversion of the SAM data using the UBC gravity inversion software showed the central SAM conductor to have a modelled depth to basement in agreement with the ERI and drilling. However, this inversion was not able to provide depth estimates of the smaller, edge conductors. Further experimentation with the parameters used in the inversion, including the model voxel size, may help to provide better results. Until a fully successful inversion of the SAM response is achieved, the ERI will still provide the most reliable and detailed information on the depth of the conductive regolith.

Integration of all the methods used in the study provided a detailed knowledge about the geophysical responses of the regolith along the transect. It is proven for the first time that SAM maps out geological structures primarily coincident with deeper and wider zones of weathering. The ERI provided detailed information about depth of weathering along the transect, and provided the most reliable results for subsurface mapping of conductive regolith. This method is much more expensive than the SAM method when it comes to acquiring data over a survey area. If detailed information were only required over several lines, such as in this study, the ERI provides the best results for money. For subsurface regolith mapping in detail over larger areas, the SAM method provides the most cost-effective results.

Gravity information is very useful, but at 10 m along line sampling it would cost much more than SAM surveying. Perhaps the best exploration procedure would be to integrate a number of these methods, specifically SAM survey results with one or more lines of ERI to provide depth information along lines within the SAM survey area. The integration of these two methods would provide the best results and also represent a reasonable expenditure for exploration and regolith studies in areas containing electrically conductive regolith.

ACKNOWLEDGMENTS

CRC LEME and Gold Fields, St Ives Gold Mining Company, are gratefully thanked for providing funding and data for this research. The authors also thank G-Tek Pty Ltd , Geoforce Pty Ltd, and Daishsat for assistance in data collection.

REFERENCES

Anand, R.R., and Paine, M., 2002, Regolith geology of the Yilgarn Craton, Western Australia–implications for exploration: *Australian Journal of Earth Sciences*, **49**, 3–162.

Cantwell, N.A., 2003, *High resolution geophysical methods for gold exploration under regolith cover, Songvang Prospect, Western Australia*: B.Sc. (Honours) thesis (unpublished), Curtin University of Technology.

Cattach, M.K., 2003, *Research update to assess the feasibility of HeliSAM, a helicopter-bourne sub-audio magnetics survey system*: G-Tek Australia Pty. Ltd. (Unpublished Report), 28 pp.

Cattach, M.K., Stanley, J.M., Lee, S.J., and Boyd, G.W., 1993, Sub-Audio Magnetics (SAM) – A high resolution technique for simultaneously mapping electrical and magnetic properties: *Exploration Geophysics*, **24**, 387–400.

Edwards, R.N., and Howell, E.C., 1976, A field test of the magnetometric resistivity (MMR) method: *Geophysics*, **41**, 1170–1183.

Li, Y., and Oldenburg, D.W., 1998, 3-D inversion of gravity data: *Geophysics*, **63,** 109–119.

Lintern, M.J., and Gray, D.J., 1996, The Argo Gold Deposit, Western Australia: in *Eastern Goldfields Field Excursion Field Guide*, CRC LEME Open File Report 109, 34–48.

Madden, J., 2004, *East Victory aircore orientation drilling targeting SAM highs and lows*: Goldfields, St Ives Gold Mine (Unpublished report).

Meyers, J.,Cantwell, N.,Nguyen, P., and Donaldson, M., 2004, Sub-audio magnetic survey experiments for high-resolution, subsurface mapping of regolith and mineralisation over a blind gold discovery near Agnew in Western Australia: *17th Geophysical Conference and Exhibition, Australian Society of Exploration Geophysicists, Extended Abstracts*.

Nguyen, P.T., Donaldson, J.S., and Ellery, S.G., 1998 Revenge gold deposit, Kambalda: in Berkman, D.A., and Mackenzie, D.H., (eds.), *Geology of Australia and Papua New Guinean Mineral Deposits*: The Australasian Institute of Mining and Metallurgy, Monograph 22, 233–238.

Street, G. J., 1989, MMR surveys for the location of palaeochannels in the Eastern Goldfields, Western Australia: *Exploration Geophysics*, **20**, 123–126.

Szarka, L., 1987, Geophysical mapping by stationary electric and magnetic field components–a combination of potential gradient mapping and magnetometric resistivity (MMR) methods: *Geophysical Prospecting*, **35**, 424–444.

Telford W.M., Geldardt, L.P. and Sheriff, R.E., 1990, *Applied Geophysics*, Second Edition: Cambridge University Press.

Witt, W.K., 1992, *Gold deposits of the Kalgoorlie-Kambalda-St Ives area, Western Australia, part 3 of a systematic study of gold mines of the Menzies-Kambalda region*: Geological Survey of Western Australia Record 1992/15, 108 pp.