Geophysical exploration techniques used in the Tennant Creek mineral field and Rover field

Angus McCoy [1]

Shortly after the initial Tennant Creek gold rush began, investigations by the Australian Geological and Geophysical Survey of Northern Australia (AGGSNA) led to the realisation that geophysical techniques could play an important role in exploration of the region for economic mineralisation. This paper briefly describes and provides examples of how various geophysical techniques have been applied to exploration of the Tennant Creek mineral field and Rover field.

Magnetic method

The first recorded use of geophysics for exploration in the area was in 1935 when AGGSNA conducted ground magnetic surveys over known gold and gold-copper bearing quartz-hematite ironstone 'lines of lode' to determine if the technique could be used to locate additional concealed ironstones. The magnetic prospecting method had been considered as a possible approach following the realisation that erroneous compass readings around some ironstones was likely caused by the presence of magnetite. The surveys proved very successful with several intensely anomalous magnetic responses, interpreted as being due to deep-seated sources, leading to new discoveries adjacent to the Peko and Eldorado orebodies (Daly 1957). Evidence from later mining operations and deep drilling showed that the steeply plunging, lenticular to pipe-shaped ironstones are predominantly hematite in the oxidized zone to ~100 m depth but become magnetite-dominant below this zone (Donnellan 2011). The characteristic magnetic anomalies caused by the magnetite-rich portion of the ironstones can be directly targeted using magnetic prospecting; this method has become a fundamental exploration tool in the area.

Ivanac (1954) reported that by 1950 all ironstone outcrops had been effectively tested for near-surface mineralisation by pits, costeans or shafts and that further development of the Tennant Creek mineral field would depend on the discovery of concealed deposits. Between 1956 and 1967, the Bureau of Mineral Resources (BMR) flew detailed airborne magnetic surveys over the entire Tennant Region, including very detailed coverage over the highly prospective areas of the Tennant Creek mineral field. The surveys allowed existing ground magnetic anomalies to be interpreted in their regional context; a large number of new ironstone-style magnetic anomalies were detected prompting a resurgence in exploration activity. Over the next 50 years, numerous higher sensitivity and higher resolution airborne magnetic and radiometric surveys were conducted over the area. The Tennant Region has complete magnetic and radiometric data coverage from government-funded 200 m and 400 m line-spaced regional airborne surveys flown in 1998. Industry have acquired more than 200,000 line-km of additional high-resolution airborne data over the Tennant Creek mineral field and Rover field at a line-spacing of between 50 m and 100 m.

The magnetic method, coupled with increasingly sophisticated analysis and interpretation tools, has underpinned many exploration programs and resulted in numerous significant discoveries, including Orlando, Ivanhoe, Juno, Warrego, Golden Forty, K44-Gecko, Argo, and TC8. At the turn of the century, over 700 ironstone bodies had been found, of which 130 were mineralised, with 10 ultimately being mined.

Despite the apparent success, effective drill testing of magnetic targets was often hindered by poor modelling of source geometry due to the effects of self-demagnetisation and remanence (Farrar 1979). To overcome the inherent limitations of traditional magnetic-survey data, Geopeko developed a downhole tri-axial magnetometer technique with which they were able to identify and subsequently target off-hole zones of magnetite enrichment (Smith 1995). The technique was used extensively for both exploration and ore-body modelling; it was particularly helpful at the White Devil mine where it was used to delineate high grade mineralisation in the Deeps Zone. Discovery of the West Peko ironstones at depth demonstrated the value of the technique, and it soon found routine use in exploration drilling campaigns and in mines throughout the Tennant Creek mineral field (Edwards 1990, Hoschke 1991).

Structural geological interpretations based on potential field geophysical data, along with anomaly identification and ranking techniques, have been aided by the development of innovative data processing algorithms, including the analytic signal (Roest 1992), tilt derivatives (Miller 1994) and more recently, vector of residual magnetic intensity (Dransfield 2003). Improvements in modelling programs have included the ability to run forward or inverse processes using geologically and parametrically constrained models, while honouring multiple input data types, to generate either voxel-style or discrete body type representations. This can provide for a much greater confidence in the accuracy of the modelling outputs and subsequent drill targeting. Various workers have applied these techniques to develop 3D solid geology interpretations at the regional scale (Johnstone 2002, Roach 2006), camp scale (Hill 2012) and prospect scale (Osborne 2010).

Gravity method

Early magnetic surveys of the Nobles Nob area recorded only low-order anomalies over the known main lodes and failed to detect extensions at depth (Ivanac 1954). Stackler (1965) undertook a rock-density and theoretical gravity response analysis and proposed that the contrast between the high-density ironstones and the less-dense enclosing slates should produce a strong gravity anomaly over shallow-covered ironstones. Stackler suggested the relative displacement between a gravity anomaly and a

[1] Northern Territory Geological Survey, GPO Box 4550,
Darwin NT 0801, Australia
Email: angus.mccoy@nt.gov.au

corresponding magnetic anomaly could yield information on the plunge and extent of the ironstone as well as geological conditions within and below the oxidised zone. Stackler subsequently conducted the first detailed micro-gravity survey in the Tennant Creek mineral field in a program designed to search the mineralised corridor near Nobles Nob for covered repetitions of the haematite-dominant gold-copper ironstones. Drilling of several styles of gravity anomaly recorded by the survey confirmed that the technique could detect shallow-covered ironstone lodes and could potentially distinguish an underlying mudstone lithology from a porphyry intrusion (Stackler 1965).

The time and cost required to conduct high-resolution, high-precision gravity surveys limited its uptake by industry until the advent of suitable GPS technology and semi-automated gravimeters in the 1990s. Thereafter the technique found regular application in exploration programs as an aid to prioritising magnetic anomaly drill targets and in the search for shallow non-magnetic ironstones.

Walters (2009) noted that the discovery of the Chariot deposit in 1998, followed by similar discoveries at Malbec West, Marathon and Billy Boy, had shown that low-order magnetic anomalies, when coupled with gravity anomalism, could define a new type of haematite-magnetite ironstone target. Osborne (2010) added that analysis of gravity data is helping to develop new geological models for iron-oxide copper-gold (IOCG) style mineralisation in the Tennant Region.

To date, over 130 000 gravity stations have been acquired by industry across the Tennant Creek mineral field and Rover field in numerous detailed surveys that have typically been target-focused along the mineralised corridors. Government-funded regional and semi-regional gravity surveys have contributed approximately 1300 stations at 2 km- or 4 km-spacing across the Tennant Creek mineral field and Rover field; the data generated has provided valuable insights into deep-basement and crustal structures that underpin regional mineral systems.

Electrical methods

Various electrical geophysical techniques including induced polarisation (IP), electromagnetics (EM), sub-audio magnetics (SAM), and magneto-tellurics (MT), have been trialled at numerous prospects with the aim of detecting metallic sulfide accumulations and/or shear-zone alteration-related conductivity contrasts for use as vectors toward mineralisation.

The first IP survey in the Tennant Creek mineral field was over the Nobles Nob area in 1961 where Halloff and Bell (1962) concluded that the technique successfully detected the disseminated pyrite and chalcopyrite mineralisation (known from prior drilling) at depths between 70 m and 100 m. Halloff and Bell (1962) reported that some IP anomalies coincided with magnetic anomalies while others did not, suggesting that the variation was in part due to the presence of different metallic minerals.

Normandy Poseidon were largely responsible for introducing the EM technique to the area. From 1997, they used their proprietary ground-EM system to map deep, conductive responses that the IP technique was unable to resolve due to its limited depth penetration (West 1997). The ground-EM technique was used extensively to map conductive zones as a potential indicator of important structural features within a prospect (Morris 1997). Use of their proprietary heliborne-EM system commenced in 1999 and facilitated faster and more cost-effective deep conductivity mapping (Boyd 2001). Detailed airborne EM surveys now cover many of the significant deposits, including White Devil, Chariot, TC8, Peko, Nobles Nob, Golden Forty, Gecko, Edna Beryl, Rover 1 and Explorer 108.

The discovery of the Goanna and Monitor deposits within the Gecko corridor was the result of a successful application of modern electrical geophysical techniques, in this case, HeliTEM and IP, which helped guide drilling success away from the conventional magnetic and/or gravity anomaly style of target (Osborne 2012). Cuison (2013) noted that the conductive features revealed by the surveys assisted with defining both significant and minor structures that have undergone intense alteration, indicative of shear zones. Combining the various electrical geophysics survey results in an integrated 3D geological model ultimately led to these discoveries.

Cattach (2005) compared results of a SAM survey and a gradient-array IP survey over the Orlando deposit and concluded that the conductivity information provided by both techniques was generally similar, but the SAM technique offered faster rates of coverage and a greater spatial resolution that enabled very subtle features related to both structure and lithology to be revealed. These features are mainly mineralised shear zones and layers in the sedimentary host rocks (Cattach 2005).

At the Rover 4 and Rover 11 deposits in the Rover field, where the cover sequence is over 100 m thick, 3D IP surveys, co-funded by the Northern Territory Government under the Northern Territory Geological Survey (NTGS) Geophysics and Drilling Collaborations (GDC) program, were unsuccessful in detecting the known copper-sulfide mineralisation or in imaging structures from resistivity contrasts. However, they were able to resolve the depth to the resistive basement, as were audio MT surveys conducted as part of the same program (Walters 2017).

Seismic method

Seismic exploration techniques, a traditional tool of the petroleum industry, are now being commonly applied to hard rock environments as the search for economically viable deposits is pushed to greater depths (Eaton 2003). The BMR conducted the first seismic refraction survey in the area in 1979 to determine the vertical thickness of the Warramunga Formation (formerly Warramunga Group). Finlayson (1981) concluded that the package thinned from 2.6 km near Nobles Nob to about 1.2 km near Warrego but noted that these are minimum thickness estimates based on a simplistic interpretation model. Osborne (2016) reported that short seismic reflection surveys had historically been trialled near Orlando and Gecko, but interpretation of the data had proved very challenging in the structurally complex terranes. The most recent seismic reflection surveys were conducted across the Chariot and Gecko corridors and successfully imaged features at 1 km depth. Deep drilling, co-funded by NTGS under the GDC program, intersected an ironstone below a zone of pervasive quartz alteration in the footwall of a major fault at the position of the reflector. This discovery represented the deepest ironstone ever recorded in the region and provided additional evidence to incorporate into evolving ore genesis models (Osborne 2016). Borehole measurements confirmed that the zone of ironstone and alteration provide an acoustic impedance boundary with a contrast and thickness sufficient to produce a strongly anomalous reflectivity response when measured from the surface (Turner 2016). A 60 km seismic reflection line, co-funded by NTGS under the GDC program, was acquired centred about Tennant Creek to improve the understanding of the mineralising systems and underlying structural architecture (Turner 2016). Interpretation of the results revealed deep and shallow northward-verging thrust faults, a known major shear zone, and a possible deep felsic intrusive rock sub-domain. Osborne (2016) reported that the technique has provided a wealth of information and provided new vectors in the search for future orebodies.

NTGS digital information package – Tennant Creek mineral field geophysical data

In covered terranes where orebodies may be found at considerable depth, geophysical datasets are an invaluable aid to explorers. Open-file industry-acquired geophysical data relating to the Tennant Creek mineral field and Rover field, supplied under the statutory reporting process, have been spatially located (**Figure 1**) and compiled into a digital information package (DIP). The DIP contains an attributed GIS of the geophysical surveys with links to the appropriate company report and GEMIS data download page. Company reports that contain related geophysical information, such as interpretations or modelling results, but have no corresponding digital data, are listed and briefly described in a separate non-GIS table. A range of value-added products are provided in the DIP including: seamless-merge high-resolution grids of available magnetic and gravity data of suitable quality, a range of filter-enhanced versions of the grids, and a gravity database of government-acquired and industry-reported gravity stations.

The DIP will be available as DIP021 via the NTGS geoscience exploration and mining information system (GEMIS) https://geoscience.nt.gov.au/gemis

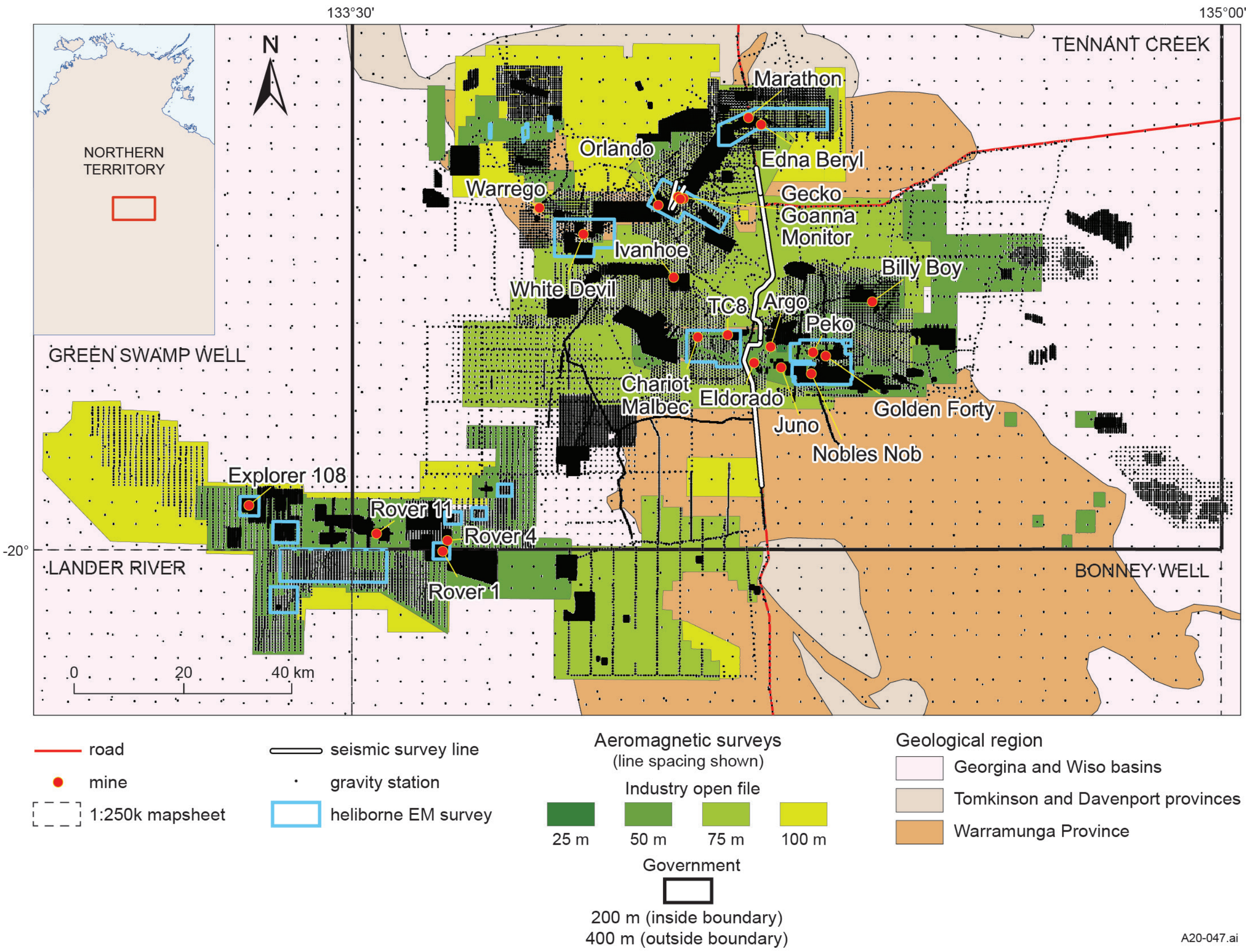

Figure 1. Tennant Creek and Rover fields, open-file industry geophysical survey data coverage. Base is 1:2.5M scale regional geological map. Deposits referenced in text are shown.

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The Rover Mineral Field Deposit Atlas

Rick Valenta[1,2], Jennifer Gunter[1], Karen Connors[1] and Paul Gow[1]

The Rover field, situated to the south and west of Tennant Creek, has long been recognised as showing potential for base metal and precious metals mineralisation. Exploration going as far back as the 1960s has identified mineralisation of the Tennant Creek Cu-Au-Bi style, and more recently, a sediment-hosted Pb-Zn-Ag system at the western end of the area. Exploration in the area has been hampered by pervasive cover of up to 100 m or more, and by the need to base geological understanding of the region on the interpretation of geophysical data and isolated drillholes.

Several prospects have been identified and subjected to more intense drilling in the area, including Rover 1, Explorer 142, and Explorer 108/Curiosity. The Rover area also lies on the margin of the Tennant Creek–Mount Isa focus area of the Australian Government's *Exploring for the Future Program*, and has benefited from insights from some of the regional analyses already carried out as part of that program, including the coverage of the AusAEM airborne electromagnetic survey.

It is well recognised that exploration under thick cover carries significantly more risk than exploration in well-exposed areas. As such, successful exploration requires a combination of conceptual target identification based on rigorous mineral process models, and direct target detection based on the best possible understanding of known and likely deposits, including recognition of halo signatures in common geoscientific datasets.

The aim of this study is to draw together new and existing regional datasets, including geophysics and exploration drilling and other detailed data associated with known mineral occurrences, into a geoscience compilation. The aim of this compilation is to assist future exploration in the region by providing explorers rigorous and comprehensive data, as well as insights into the key geological characteristics related to mineralisation.

The main objectives of the project are:

1. to produce an updated solid geology basement interpretation based on government and open file geophysical data, plus newly compiled open file drilling data, in order to guide further target identification and exploration in the region
2. to produce 3D compilations of the main prospects in the area by pulling together drilling, geophysics, and any other relevant data, to afford explorers the best possible understanding of the characteristics of known mineralisation in the region
3. to produce a regional 3D compilation of geoscientific datasets relevant to exploration over the entire area in order to guide further target identification and exploration in the region.

Collectively, these products will form a basis for future exploration and targeting in the region, highlight areas of prospectivity, and cut short the process of basic compilation and analysis that often forms a barrier to initiation of greenfields exploration programs.

Work commenced in late December on the Rover Mineral Field Deposit Atlas. An initial compilation of drill collars has now been extended to a full drillhole dataset. Work is also progressing on solid geology interpretations, prospect 3D compilations, interpretation and inversion of geophysical data, and incorporation of all other regional precompetitive and exploration datasets.

[1] WH Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, University of Queensland, 40 Isles Rd, Indooroopilly QLD 4068, Australia

[2] Email: r.valenta@uq.edu.au