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A geological assessment of airborne electromagnetics for mineral exploration through deeply weathered profiles in the southeast Yilgarn Cratonic margin, Western Australia

I. González-Álvarez *, A.-Y. Ley-Cooper, W. Salama

CSIRO, Mineral Resources, Discovery Program, Kensington 6151, Australia

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ABSTRACT

Mineral exploration in regolith-dominated environments is challenging, requiring the development of new technical tools and approaches. When airborne electromagnetics (AEM) is combined with information on stratigraphy, mineralogy, geochemistry, drilling and landscape observations in a geological context, it becomes a powerful approach to describe the architecture of the regolith cover. This has significant implications for mineral exploration in any regolith-dominated terrain (RDT). This research presents two case studies of AEM data, integrated in a geological context for mineral exploration in the Yilgarn craton margin/Albany–Fraser Orogen (AFO). In one of the study sites presented (study site 1: Neale tenement), the availability of AEM data allowed for lateral and vertical extrapolation of the information contained in datasets at specific locations, thereby creating a 2D architectural model for the regolith cover. In addition, it was determined: (1) the total thickness of the regolith cover and its variability (between 2 m and ~65 m); (2) that low conductivity transported overburden and silcrete units, with a total thickness between ~5 and 45 m, is widely distributed, capping the upper saprolite; and (3) that the silcrete unit varies laterally from being completely cemented to permeable, and that these permeable areas ("windows") coincide vertically with mineralogical/textural/moisture/salt content changes in the underlying saprolite, resulting in increased conductivity. This has been interpreted as resulting from more intense vertical weathering, and consequently a higher vertical geochemical dispersion of the basement signature towards surface. AEM has been used to assist in identifying and describing the lateral continuity of these "windows" in areas with no direct field observations. Surface geochemical sampling above these permeable areas may deliver more reliable geochemical basement signatures.

In the second study site (Silver Lake tenement) the AEM data was strongly influenced by the high conductivity of the hypersaline groundwater. This had a significant effect on the AEM response, resulting in reduced depth penetration and reduced resolution of subtle conductivity contrasts between cover units. Despite this, the AEM data set, combined with geological observations in the area, was able to map the presence and extent of a buried palaeochannel network, the most significant architectural sedimentary feature in the cover. This interpretation allowed for a more efficient drilling campaign to be designed to sample the fresh basement rock suites in the area, by avoiding drilling into palaeochannels.

Integrated and constrained by the geological context, the application of AEM conductivity models by geologists is envisioned as one of the most promising tools within the exploration geologist toolbox to understand the architecture of the cover.

1. Introduction

Regolith-dominated terrains (RDT) are widely recognized as problematic environments for mineral exploration due to their lack of outcrop and deep weathering complexity (e.g., Smith, 1983; Butt, 1985; Anand, 2000; Butt et al., 2000; Vearncombe et al., 2000; Anand and Butt, 2010; Butt, 2016–in this issue; Porto, 2016–in this issue; González-Álvarez et al., in this issue-a; Xueqiu et al., 2016–in this issue). Basement geochemical signatures are masked within the cover due to the geochemical and architectural intricacy of the regolith (e.g., Robertson, 1996; De Broekert and Sandiford, 2005; Anand et al., 2014; Butt, 2016–in this issue; Porto, 2016–in this issue; Xueqiu et al., 2016–in this issue). However, geochemical dispersion processes throughout the regolith units may be locally efficient, producing metal anomalies corresponding to an ore footprint. These geochemical halos may be concentrated in a specific regolith unit, such as laterite or calcrete, and can reach the surface or form supergene ore deposits (e.g., Smith et al., 1987, 1989; Butt et al., 2000; Anand and Butt, 2010; Lintern, 2015). In mineral exploration, linking basement geochemical

* Corresponding author.
E-mail address: Ignacio.gonzalez-alvarez@csiro.au (I. González-Álvarez).

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features with surficial geochemical signatures is critical. To this end, the understanding of the cover architecture and its evolution is essential.

Climatic episodes of intense weathering under humid conditions, coupled with tectonic stability, may lead to large areas of deeply weathered landscapes: up to hundreds of metres in thickness, and therefore limited basement outcrop (e.g., Australia, Brazil, southeast India, southeast China). The chemically altered in situ rock may be covered by transported sediments, which all may be intensely weathered to the extent that the landscape becomes mainly flat and highly complex due to weathering overprinting (e.g., Anand and Butt, 2010).

Geophysical tools and approaches are being developed to assist mineral exploration in a RDT, such as remote sensing, radiometrics and radar, which feature only shallow penetration (<1 μm, <1 m and 1–20 m, respectively). However, technologies such as airborne electromagnetics (AEM) have potential ground penetration of up to >400 m and have been successfully applied in mapping groundwater and fluvial drainage systems (e.g., Reid et al., 2007; Munday et al., 2007), as well as in interpreting the diverse electrical conductivity variability within diverse regolith environments (e.g., Worrall et al., 1999; Munday et al., 2001; Ley-Cooper and González-Álvarez, 2014).

AEM has the potential to develop 3D stratigraphic correlations for the cover, based on the conductivity contrast between transported cover, in situ regolith and fresh basement rocks. This may improve interpretations of landscape evolution in a RDT. AEM can 'map' the surface of the weathering front (Anand and Butt, 2010 and references therein), and define differences in regolith stratigraphy based on properties of the features present that influence conductivity: clay mineralogy, porosity, permeability, and water content and chemistry (e.g., Reid et al., 2007; Ley-Cooper et al., 2008; Munday, 2009).

The southeast of Western Australia is an example of a RDT. It is largely overlain by a thick regolith cover, which extends from the Yilgarn Craton to the coastline, comprising the Albany–Fraser Orogen to the south and the Eucla Basin to the southeast (Fig. 1A and B; González-Álvarez et al., 2016–in this issue). This region contains limited outcrop, and is characterized by deeply weathered cover that evolved mainly during the Cainozoic (Pillans, 2005 and references therein).

This study advocates, from a geologist's point of view, how AEM data can be applied far beyond describing the electrical conductivity of the subsurface and detecting conductors at depth as potential targets for mineral exploration. When AEM is fully integrated in its geological context (geomorphology, stratigraphy, mineralogy, geochemistry, drilling, etc), it becomes a powerful tool to enhance the description of the architecture of the cover. This is exemplified in this research through two case studies of AEM applied to mineral exploration in a RDT in the southeast Yilgarn cratonic margin/Albany–Fraser Orogen.

2. Geological setting

The AFO is a Proterozoic orogenic belt adjacent to the southern and southeastern margins of the Archaean Yilgarn Craton in Western Australia (Fig. 1C). Study site 1 (Neale tenement) is located in the AFO, 60 km northeast of the Tropicana-Havana Au system (Fig. 1A; ~6800000 E, 700000 N UTM, Zone 51). According to Spaggiari et al. (2015) the AFO is the result of the preservation of the southeast Yilgarn Archaean Craton margin that records Proterozoic tectonic changes. These changes were dominated by extensional processes that generated a wide variety of basins and concomitant magmatic activity.

The AFO lithologies are characterized by the Archaean Northern Foreland (metagranitic and metamafic rock suites); the Archaean-Proterozoic Tropicana Zone (with abundant granites); and the Palaeoproterozoic Birunup and Nornalup zones (~1.8–1.6 Ga orthogneiss, metagabbroic and hybrid rocks); the Mesoproterozoic Fraser Zone, and Recherche and Esperance supersuites (~1.3–1.1 Ga metagabbroic and granites rock suites, respectively; Spaggiari et al., 2015 and references therein; Fig. 1C). Eastwards the Phanerozoic sedimentary and volcanic units of the Eucla Basin largely cover the AFO.

The Neale study site is located above the Tropicana Zone, with local outcropping of the Carboniferous-Permian Paterson Formation, Archaean gneiss, the McKay Creek Metasyenogranites and to the east the Palaeoproterozoic Black Dragon gneiss (metagranodiorite and granodiorite; Kirkland et al., 2015; Fig. 1C). The main structural trend in this area is northeast/southwest, which is punctuated by the geometry of the main lithological units (Fig. 1C), together with structural shear zones and magnetic trends (Kirkland et al., 2015).

Study site 2 (Silver Lake tenement; Integra Mining Ltd./Silver Lake Resources) is located in the southeast of the Yilgarn Craton, which is a granitic-greenstone belt characterized by metamorphosed sedimentary–volcanoclastic sequences that reside among large granite-dominated areas. The Yilgarn is dominated by undivided granites to the east (Fig. 1C) and greenstone belt sequences to the southwest (Fig. 1C), together with the Widgiemooltha Dyke suite in the south and north. The most significant geological trend is displayed by elongated domains stretched in the northwest/southeast and southwest-northeast directions (Fig. 1C).

The Silver Lake site is located in the Kurnalpi Terrane (Fig. 1C), which is one of the six terranes of the Yilgarn Craton (Cassidy et al., 2006). The Kurnalpi Terrane is bounded by an interlinked fault system and jointly comprises the Eastern Goldfields Superterrane. It has an estimated age of crustal formation ~3.1–2.8 Ga, with depositional greenstone belts ~2.94–2.66 Ga, coupled with a wide diversity of ages for granite and gneiss emplacement that vary from 2.81–2.62 Ga. The main deformational and metamorphic events identified spanned from 2.67 to 2.63 Ga (Cassidy et al., 2006).

Two relatively recent mineral exploration discoveries have generated interest in the southeast Yilgarn Craton margin-AFO region (Fig. 1): (1) the ~2.52 Ga Tropicana-Havana gold system with 6.41 Moz Au, discovered in 2005 (Doyle et al., 2015); and (2) the Nova-Bollinger Ni–Cu deposit discovered in 2012 in the Fraser Range (ore reserve estimate 13.1 Mt. @ 2.1% Ni, 0.9% Cu and 0.07% Co; IGO website, October 2015).

3. Regolith setting

The weathering framework of the region can be summarized in stages that were initially dominated by fluvial sedimentary systems during the Palaeozoic and Mesozoic. From the Permian to Late Cretaceous humid sub-tropical conditions promoted intense chemical weathering, which shifted in the Late Tertiary to semi-arid conditions (Anand and Butt, 2010 and references therein).

The Neale area is situated on a drainage divide between 300 and 400 m elevation, with the main drainage directed towards the Eucla Basin in the southeast (Fig. 1A and B). Native grasslands dominate this area, with extensive aeolian sand dunes present, characterized by 3300 mm annual potential evaporation and average rainfalls of 200 mm (Fig. 1B and D; Anand and Butt, 2010). The dominance of evaporation has resulted in groundwater salinities of 1000–3000 mg/L TDS (Total Dissolved Salt; Fig. 1D; Commander, 1989). The pH of the groundwater is expected to be low since basement is dominated by granitic gneisses (Gray, 2001). Groundwater salinity, acidity and chemical ligands are key factors that control trace element mobility.

The Silver Lake study site is mainly low relief in the south, with gently undulating and sporadic dissected scarps of granites and greenstone ridges, and primarily high relief in the north. The Digital Elevation Model (DEM) indicates that most of the tenement elevation lies between 150 and 400 m (Fig. 1A). The area is associated with a large palaeodrainage system that drained to the east (Fig. 1D). Numerous saline lakes characterize the drainage system in the central and southern areas (Fig. 1A and D). The vegetation cover is characterized by native grasslands and woodlands. These surficial features reside upon saprolite, as well as colluvial and alluvium sediments, with few outcroppings. The regolith is characterized by residual and calcrete duricrust outcroppings to the south (Fig. 1B).