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Petrophysical Properties of the Goonumbla Volcanic Complex, NSW: Implications for Magnetic and Gravity Signatures of Porphyry Cu-Au Mineralisation

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ABSTRACT

Petrophysical data are important for constraining the geophysical signatures of the Endeavour Cu-Au deposits within the Goonumbla Volcanic Complex (GVC). Susceptibilities vary systematically with lithology and, particularly, with alteration. Remanence tends to be subordinate to induced magnetisation in the GVC. Densities are predictably related to composition, Alteration effects on densities are generally minor, although rocks with particularly strong development of secondary magnetite, hematite or sulphides have higher densities.

Modelling of magnetic and gravity profiles over the Goonumbla volcanic belt and the GVC, constrained by geological information and petrophysical properties, suggests that the GVC is underlain by a large zoned intrusion, representing the parent magma chamber, which has a substantial low density, weakly to moderately magnetic, core of alkali feldspar granite to monzonite composition, enclosed by marginal mafic monzonite and monzodiorite phases. The mafic roof zone and marginal phases of the GVC have high susceptibilities (> 0.08 SI, > 2.5 vol % magnetite).

A prominent ridge of low density material occurs along the eastern margin of the mother intrusion. A zone of lower susceptibility occurs above the felsic ridge, probably representing magnetite-destructive alteration due to fluids emanating from the inferred underlying felsic intrusion. This zone appears to be related to the Endeavour lineament, which is thought to control the emplacement of many of the mineralising intrusions in the GVC. Magnetic signatures of deposits tend to be obscured by the heterogeneous magnetic environment, but reflect variably developed halos of enhanced magnetite content, associated with early potassic alteration, surrounding a core of reduced magnetite content, which represents the combined effect of felsic mineralising intrusives, mineralising phase (K-feldspar dominated) alteration and phyllic overprinting. Different signatures can be expected for lava-dominated wall rock sequences (weak to moderate annular high with well-developed central low) and volcaniclastic-dominated sequences (unimodal weak to moderate high).

INTRODUCTION

The Goonumbla Cu-Au deposits lie within the GVC, which is interpreted to be the volcanic roof zone above a shallow pluton-scale magma chamber. Within the GVC numerous porphyry stocks with finger-like apophyses emanate from the magma chamber (Heithersay and Walshe, 1995; Blevin and Morrison, 1997). The volcanics and intrusions are comagmatic and coeval: the more mafic phases (diorite and monzodiorite) of the underlying pluton are equivalent to the Goonumbla Volcanics and the monzonitic spines and stocks are equivalent to the overlying Wombin Volcanics. The mineralised finger-like porphyry intrusions are tapped off progressively larger zoned intrusions that in turn are tapped off an underlying zoned pluton.

Mineralisation is associated with a small number of spines within the GVC and, in particular, in a cluster around the E31 stock, which is a monzonitic apophysis off the magma chamber. Mineralised spines tend to occur along linear trends that can be related to magnetic lineaments.

Although the Goonumbla deposits lack large, mineral-destructive, pervasive alteration zones, alteration is well developed in and around the mineralised spines and overprints the coarser grained intrusive phases and the host volcanics. The main pluton itself has a hornfels aureole with amphibole, magnetite and biotite, that affects the adjacent volcanics and locally the dioritic marginal phase (Blevin and Morrison, 1997). Prominent red feldspathic alteration forms in and around the mafic monzonite intrusive phase. The peripheral part of this zone has a network of fractures and veinlets with selvages of hematite dusted K feldspar and spots of biotite. The inner part of this zone has pervasive red K feldspar locally with albite.

Pink quartz-K feldspar-albite alteration is associated with quartz monzonite porphyry phases in the spines, closely associated with a combination of hydrothermal breccias, replacement patches and cavity fill. These zones represent the ‘kitchen for mineralisation’ where hydrothermal fluids segregated from partially crystallised magma (Blevin and Morrison, 1997).

Extensive sampling of the volcanic and intrusive rocks of the Goonumbla Volcanic Complex, which hosts the Northparkes Cu-Au deposits, and the Ordovician volcanic and intrusive rocks of the surrounding area was carried out as part of an industry sponsored study of magnetic and radiometric signatures of intrusive-related gold deposits in eastern Australia, AMIRA P426 (Clark and Dickson, 1998). Relationships between magnetic and density properties, lithology and alteration have been used to constrain magnetic and gravity modelling of the GVC as a whole, as well as magnetic models of individual deposits.

The effects of alteration on magnetic properties have implications for use of magnetics in exploration for porphyry copper-gold deposits in the Goonumbla area, as well as in similar geological settings elsewhere.

PETROPHYSICAL PROPERTIES

Average magnetic susceptibilities for each sampled rock type and style of alteration, based on measurements on more than 600 drill core samples, are summarised in Table 1, from which it is evident that the geological environment in and around the Goonumbla deposits, and by inference throughout the GVC, is moderately to highly magnetic overall (mean susceptibility of all drill core samples ~ 30 x 10^{-3} SI.

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Lithology Alteration	Basaltic Andesite (WV)	Trachy-andesite (GV,WV)	Latite (GV,WV)	Trachyte (WV)	Monzo-diorite	Mafic Monz.	Monz-onite	Aplite	Alk Fsp Granite	All
Unaltered		34 (dyke)			66	25	19	1		32
Propylitic	36	61	79	41						63
Weak propylitic	72					21				43
Potassic: KF+B(M)	83 (KF)/BT	104	58		49	46				61
Potassic: BM		63								63
Potassic: KF	95 KF/BM	26	68	5	44	14	10			19
Potassic: KQ/KF		30			39		0.6			33
Strong phyllic	0.7		0.15		20	7	0.4			7
Weak phyllic		82	91		22		0.4		0.04	38
All	66	49	73	23	41	15	4	1	0.04	30

Rock unit: GV = Goonumbla Volcanics, WV = Wombin Volcanics, Alteration:KF = K-feldspar, KQ = K-feldspar + quartz, KQ/KF = KQ overprinting KF, BM = biotite-magnetite, BT = biotite; (Parentheses indicate weak alteration)

Table 1. Magnetic Susceptibility (10^{-3} SI) of Goonumbla Drill Core Samples as a Function of Lithology and Alteration.

Susceptibilities vary systematically with lithology and, particularly, with alteration. Goonumbla Volcanics and Wombin Volcanics, irrespective of composition (basaltic andesite, trachyandesite, latite or trachyte) and facies (lavas, volcaniclastics, epiclastics) are strongly magnetic, except when strongly affected by phyllic alteration. Trachytes tend to have somewhat lower susceptibilities than the more mafic compositions, for equivalent alteration.

Susceptibilities of the intrusive rocks conform to: Monzodiorite > Mafic monzonite > Monzonite >> Aplite > Alkali feldspar granite, for equivalently altered rocks. Overall, propylitic alteration has little effect on susceptibility, whereas early potassic (orthoclase+biotite) alteration is magnetite-producing and can substantially enhance susceptibility. Phyllic alteration is magnetite-destructive and produces very low susceptibilities when intense. The overall effect of alteration on susceptibility is: early potassic phase (biotite+K-feldspar) > fresh > main mineralising phase (K-feldspar; K-feldspar-quartz) > weak phyllic overprint of mineralised rock >> intense phyllic alteration.

Within the above sequence of alteration effects, pronounced decreases in susceptibility occur progressively earlier for more felsic rocks. Mafic volcanics and monzodiorites have high susceptibilities when potassicly or propyliticly altered, moderate susceptibilities when partially overprinted by phyllic alteration and much lower susceptibilities when completely overprinted by phyllic alteration. Monzonites are much more susceptible to magnetite destruction during K-feldspar-quartz alteration.

Both polarities of remanence are present, even within adjacent samples, indicating that events spanning at least one geomagnetic reversal are recorded palaeomagnetically. Remanence tends to be subordinate to induced magnetisation for most samples from the Goonumbla area. Furthermore, variability in remanence directions ensures that the bulk magnetisation of large volumes of rock in the GVC is dominantly induced and remanence can be ignored in modelling.

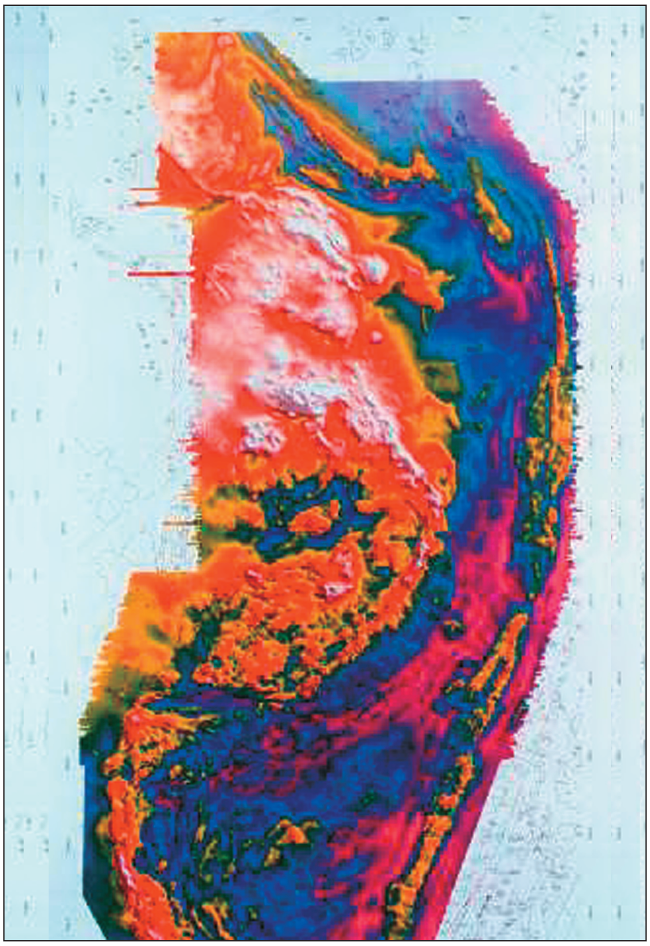

Fig. 1. TMI aeromagnetic image for the Goonumbla Volcanic belt, showing the N-S trending Forbes anticline on the east and the exposed portion of the GVC in the middle-upper west. Flight lines E-W, spacing 100-120 m, sensor height 70 m. Total range of TMI is 3200 nT. Area of image is 30 km x 55 km. Image courtesy of North Ltd.

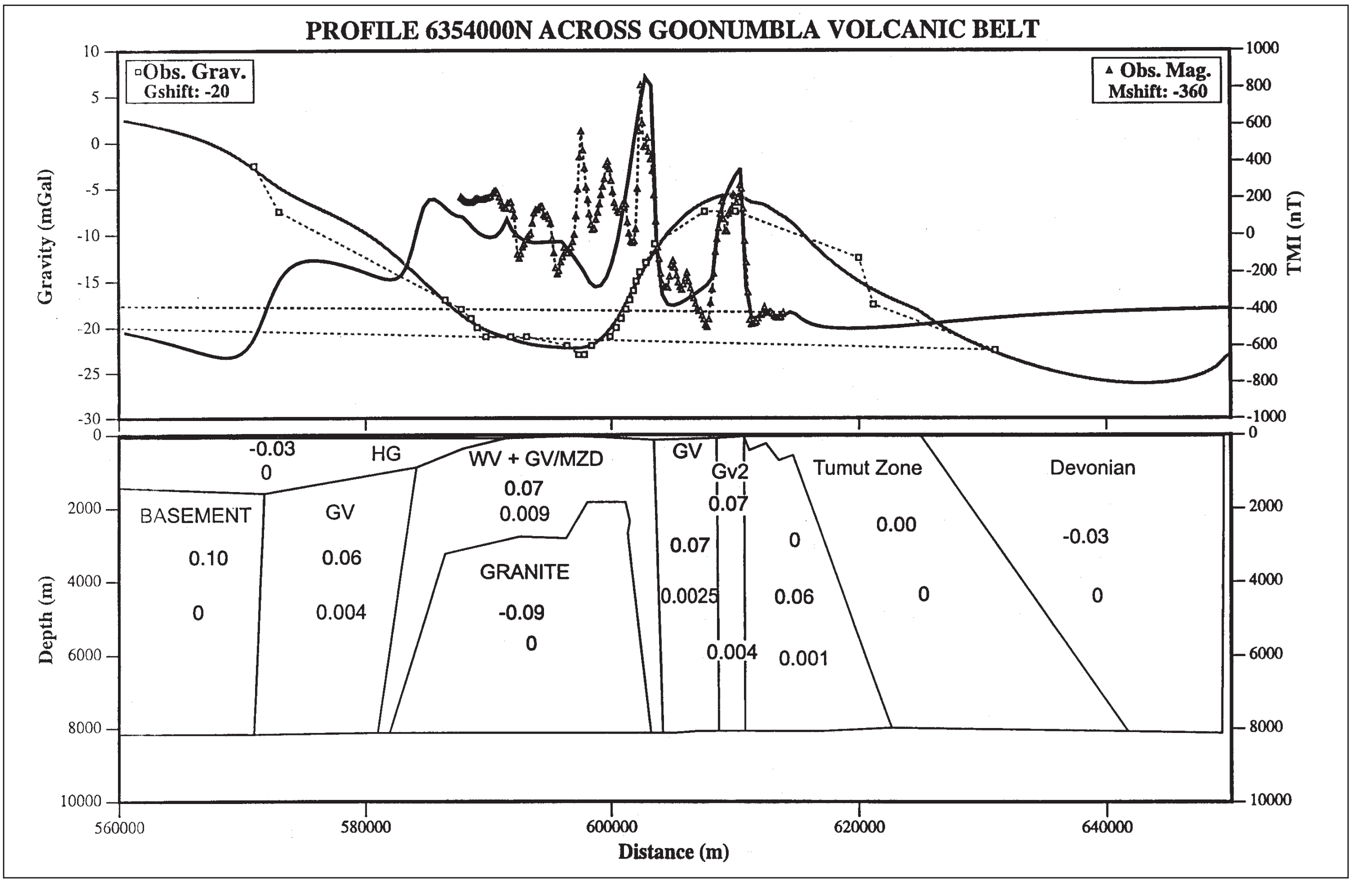

Fig. 2. 2D magnetic and gravity model for line 354000 mN across the GVC and the Goonumbla volcanic belt. Density contrasts in gcm^{-3} (upper annotation) (1 gcm^{-3} = 1000 kgm^{-3}) and susceptibilities in μG/Oe (1 μG/Oe = 4π x 10^{-6} SI) are annotated on the bodies. Squares represent measured gravity values in milligals; triangles indicate measured TMI (nT). WV = Wombin Volcanics, GV + Goonumbla Volcanics, MZD = monzodiorite, HG = Hervey Group. This model fits the gravity data very well and provides a reasonable match to the magnetic profile. A better fit to the magnetics requires a tongue of weakly magnetic material above the felsic ridge, extending to shallow depths.

Densities are predictably related to composition, with densities ranging from 2750 kg/m^3 for the most mafic volcanics to 2670 kg/m^3 for the trachytic volcanics. Similarly the average density of monzodiorite is 2750 kg/m^3, monzonite has a density of ~2620 kg/m^3 and the altered, somewhat porous samples of alkali feldspar granite have a low density of 2530 kg/m^3. Alteration effects on densities are minor, except that rocks with particularly strong development of secondary magnetite, hematite or sulphides have higher densities.

GRAVITY AND MAGNETIC MODELLING

The GVC is associated with a prominent subcircular magnetic high with complex internal structure (Figure 1), and with a prominent gravity low (-12 mGal = -120 μms^{-2}). Modelling of magnetic and gravity profiles over the Goonumbla volcanic belt and the GVC, constrained by geological information and petrophysical properties, suggests that the GVC is underlain by a large zoned intrusion, representing the parent magma chamber, which has a substantial low density, weakly to moderately magnetic, felsic core with marginal mafic monzonite and monzodiorite phases. Although the magnetic and gravity modelling of the GVC cannot constrain the composition and geometry of the subsurface bodies uniquely, certain features are common to all plausible models. These features can therefore be interpreted with reasonable confidence from the potential field data.

The modelling (e.g. Figure 2) indicates that the GVC comprises a relatively mafic shell (volcanics and small intrusions in the roof zone, and a mafic margin to the main intrusion) cored by a felsic intrusion at depth. The mafic roof zone and marginal phases of the GVC have high susceptibilities (> 0.08 SI, > 2.5 vol % magnetite) and moderate to high densities (2.7-2.8 g/cm^3), which imply predominantly monzodioritic (trachyandesitic) bulk composition for the outer shell. The thickness of the magnetic roof zone of the GVC generally exceeds 2 km and may be as thick as 5 km in the west central portion of the complex. The felsic core to the main intrusion has low to moderate susceptibility and appears to have a reasonably flat top in the western portion of the GVC.

A prominent ridge, about 2 km wide, of low density, hence felsic, composition, occurs along the eastern margin of the mother intrusion (see Figure 2). The top of this ridge lies 2-2.5 km below the surface. A zone of lower susceptibility occurs above the felsic ridge, extending to within ~500 m of the surface, and may represent magnetite-destructive alteration due to fluids emanating from the relatively shallow felsic intrusion along the eastern margin of the mother intrusion. This zone appears to be related to the Endeavour lineament, which is thought to control the emplacement of many of the mineralising intrusions in the GVC.

The Goonumbla Volcanic Complex is a noisy magnetic environment, with variable, but generally high, susceptibilities away from the mineralised zones. This tends to produce a large number of 'false orebody' anomalies. The proximity of larger, unmineralised stocks to the narrow mineralised spines also tends to obscure the signatures of the orebodies. Because the mineralising intrusives are comagmatic with the volcanic host rocks, magnetisation contrasts are relatively small and variable.

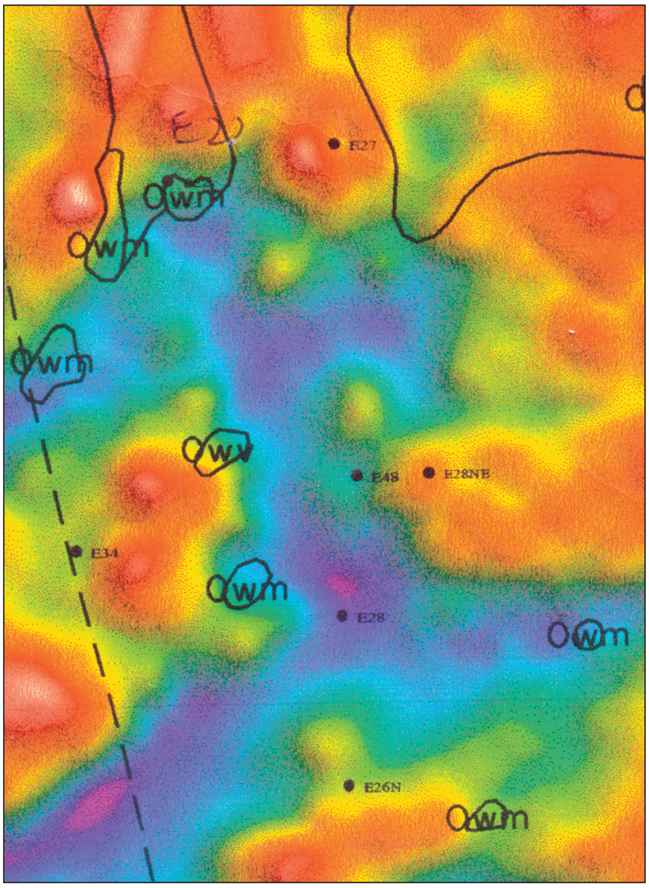

Fig. 3. TMI aeromagnetic image of central portion of the GVC, showing the subtle magnetic signatures of several deposits (deposit locations indicated by dots) that lie along the Endeavour linear. The 'doughnut' anomaly of E27 occurs at the north centre of the image. Magnetic low 'dimples' with subtle surrounding highs are associated with E48 (centre of the image), E26N (south centre) and E22 (west of E27). Area of image is approximately 3 km x 5 km.

The typical deposit signature is localised and subtle on a regional scale, but generally detectable on a prospect scale. A 'doughnut' anomaly signature is recognisable at several of the deposits (Fig.3). This signature arises from a halo of enhanced magnetite content, associated with early potassic alteration, surrounding a core of reduced magnetite content, which represents the combined effect of felsic mineralising intrusives, mineralising phase (K-feldspar dominated) alteration and phyllic overprinting. E27 is associated with the most prominent and best-defined of these doughnut signatures. The magnetite halo signature at E27 is enhanced by a magnetic intrusion SW of the central low. The E48 (Hooper *et al*., 1996), E26N and E22 deposits exhibit central magnetic lows, with less prominent flanking highs. At each of the above-mentioned deposits, modelling of aeromagnetic profiles confirmed that the known geology and magnetic properties could account for the observed signatures.

Different signatures can be expected for lava-dominated wall rock sequences (weak to moderate annular high with well-developed central low) and volcaniclastic-dominated sequences (unimodal weak to moderate high). This arises from the relatively high permeability of potassically altered lavas to hydrothermal fluids associated with phyllic overprinting, compared to potassically altered volcaniclastics, which have much less extensive phyllic zones (Wolfe, 1994). The latter type of signature appears to be rarer - of the deposits sampled for this study, only the E37 and E37W deposits are associated with magnetic highs. Furthermore this difference probably reflects the style of alteration at those deposits, which conforms more closely to the classic porphyry copper model, with a potassic core surrounded by a phyllic zone, and therefore differs from that of the deposits that are associated with the Endeavour linear and the E31 stock. The phyllic zones at E37 and E37W are not highly developed, due to the low sulphidation nature of the Goonumbla-style mineralisation.

Many unmineralised stocks of comparable dimensions to the mineralising intrusions appear to be associated with strong bullseye magnetic highs, due to their relatively mafic composition (possibly with enhanced magnetite in a hornfels aureole) and the absence of magnetite-destructive alteration in the core of the system. Much larger unmineralised intrusions, such as the E31 stock, may be recognisable by sizeable zones of somewhat lower and smoother magnetic field within the generally busy pattern of the GVC.

Due to the deposit style in the GVC (relatively shallow, areally restricted), the magnetic signatures are enhanced by high pass filtering, such as vertical derivative images. However, this filtering also emphasises local variability within volcanics and shallow intrusions, and tends to distort the residual signature of the deposit. High pass filtering can, however, help to define structures that may control emplacement of mineralising intrusions. In particular, suitable enhancements are useful for defining linear structures that appear to control emplacement of mineralising intrusions and for detection of late fracture-controlled alteration.

Linear filtering (i.e. convolution filtering in the space domain or, equivalently, wavelength filtering in the frequency domain), designed to suppress 'regional' effects that obscure the deposit signature, produces results that depend critically on the form of the regional and invariably distorts the residual signature of the deposit. However, visual or automated recognition of possible deposit signatures requires clean regional-residual separation by non-linear filtering. An approach that uses nested moving windows, with dimensions tailored to the sizes of the targets and the characteristic scale of regional effects, is suggested. This automated procedure mimics graphical methods of regional-residual separation. When coupled with pattern recognition (either human or computer-based), this approach, or other non-linear filtering approaches to regional-residual separation, appear to offer the best hope for defining magnetic targets in the environment of the GVC.

CONCLUSIONS

Gravity and magnetic modelling provides insight into the gross structure of the GVC. Most mineralisation appears to occur above a relatively shallow ridge of felsic composition, which represents an extension of the underlying core of the GVC magma chamber.

The Cu-Au deposits of the GVC, which occur at depth as narrow mineralised spines, represent difficult geophysical targets. Magnetic properties of the mineralising intrusions and the comagmatic host rocks are systematically affected by alteration, with magnetite halos produced during early potassic alteration (immediately pre-mineralisation) and subsequent partial magnetite destruction during the main mineralising phase (K-feldspar-quartz alteration), followed by total magnetite destruction within core zones that have strong phyllic alteration. This zoning is 'inside-out' with respect to the classic Lowell-Guilbert porphyry copper model. The amplitude of the annular magnetic high associated with the magnetite halo reflects the facies (lava versus volcaniclastic sandstone) of the host rocks into which the orebody is emplaced. Understanding of the effects of primary lithology and alteration on the magnetic properties are essential for generating predictive models of orebody signatures. Recognition of these signatures amidst the clutter of a very noisy magnetic environment requires innovative data processing approaches, as a naïve search for 'look-alike' signatures will in most cases be thwarted by the distortion of steep magnetic gradients and overlapping anomalies.

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