CSIRO PUBLISHING
www.publish.csiro.au/journals/eg *Exploration Geophysics*, 2007, **38**, 200–207

The contribution of magnetite to the induced polarization response of the Centenary orebody*

Karen Pittard[1,2] Barry Bourne[1]

[1]Barrick Gold of Australia, 2 Mill St, Perth, WA 6000, Australia.
[2]Email: kpittard@barrick.com.au

Abstract. The Centenary gold deposit is a concealed ore body located 110 km north of Leonora, Western Australia. The orebody is associated with sulphides and is hosted in the magnetic portion of the Mount Pickering Dolerite. Due to its sulphidic nature, both gravity and induced polarization (IP) were trialled soon after discovery.

The gravity survey showed major structures and delineated the host magnetic dolerite, and a trial dipole–dipole IP and resistivity survey detected a significant chargeability anomaly over Centenary. Interestingly, both forward and inverse models showed an IP anomaly that was broader than, and displaced from, mineralisation. Down hole IP and resistivity surveys also showed an elevated chargeability response shallower and broader than the intersected mineralised zone. Pyrite is the main sulphide associated with Centenary and is spatially related to gold mineralisation. These data therefore suggested that pyrite was not the sole contributor to the chargeability response of Centenary.

Petrophysical results, integrated with examination of thin sections, found that the five samples giving the highest chargeability response contained at least 5% pyrite and 5% magnetite, and at least 15% magnetite and pyrite combined. Samples with comparable amounts of pyrite, but less magnetite, gave a lower chargeability response. This supports a hypothesis that rocks containing both magnetite and pyrite at Centenary can generate a larger IP response than rocks containing pyrite or magnetite alone.

Key words: Centenary, greenstone, geophysics, induced polarization, magnetics, gravity, pyrite, magnetite.

Introduction

The Centenary gold deposit is located 80 km east of Leinster within the Yilgarn Block, Western Australia (Figure 1). The deposit was discovered in 1996 during a 320 m by 320 m step-out diamond-drilling program. The discovery hole intersected 33 m at 8 g/t Au.

The orebody is associated with sulphides (mainly pyrite), and a trial IP survey detected a significant chargeability response over the deposit. Interestingly, this response was broader than, and slightly displaced from, mineralisation. This fact, combined with petrophysical measurements, suggested that magnetite may be contributing to the IP response of the Centenary orebody.

These observations formed the impetus for a research project, which included acquiring a new suite of petrophysical measurements of the host lithology, and quantifying the amount of magnetite and pyrite in each of the petrophysical samples through thin section analysis (Pittard, 2001). Results of the study showed that magnetite combined with pyrite may give a larger chargeability response than similar quantities of pyrite alone. Results also showed that magnetite alone may give a small chargeability response.

Geology and mineralisation

The Centenary gold deposit is located at the southern end of the Yandal greenstone belt, which is a north-north-westerly trending, fault bounded greenstone sequence, situated east of Leinster in the northern part of the Eastern Goldfields Province, Western Australia (Figure 1). Rock assemblages are typical of granite-greenstones in the Eastern Goldfields Province. Metabasalt and metamorphosed felsic volcanic and sedimentary rocks dominate the greenstones, and these have been intruded by a variety of granitoid rocks (Krcmarov et al., 2000).

Locally, the rock package comprises a volcano-sedimentary succession, which has been intruded by the Mount Pickering Dolerite. Granitoid intrusions lie to the east. The Mount Pickering Dolerite sill is part of the folded sequence of the Darlot Syncline, which is a north-west-trending, north-west-plunging, upright, open fold. Interpreted geology and airborne magnetic data are shown in Figure 2. As can be seen in the airborne magnetics, the Centenary orebody is predominantly hosted in the magnetic dolerite sub-unit of the Mount Pickering Dolerite sill (Krcmarov et al., 2000).

Centenary is a concealed orebody, open at depth, containing reserves of 5.86 Mt @ 5.1 g/t (957 000 ounces) and resources of 630 Kt @ 5.4 g/t (265 000 ounces) (resources exclusive of reserves) as at 30th June, 2005. The mineralised system lies on the western limb of the Darlot Syncline, within the upper, relatively competent, strongly magnetic portion of the Mount Pickering Dolerite. Gold mineralisation is mostly contained in silicic alteration zones surrounding en echelon, extensional quartz veins that dip shallowly to the SW. These zones also contain cubic, 1–40 mm diameter pyrite crystals. The Centenary orebody also contains a mineralised quartz reef, which is a more common mineralisation style (Krcmarov et al., 2000).

*Presented at the Australian Earth Sciences Convention, June 2006, Melbourne.

© ASEG 2007 10.1071/EG07020 0812-3985/07/030200

Fig. 1. Location of the Centenary Deposit, Western Australia.

A late tectonic timing of mineralisation is indicated by textural and structural relationships, but the absolute age of the deposit is not known. The gold, which is free milling, has strong spatial (and probably genetic) association with the pyrite. The amount of gold in Centenary is directly proportional to the amount of pyrite. The gold occurs as free particles on grain boundaries, or within fractures in sulphide grains (Krcmarov et al., 2000).

Geophysical surveys

Geophysical surveys over the Centenary deposit have included airborne magnetics, ground gravity, and dipole–dipole induced polarization. Results of these surveys are presented below to give the reader a feel for the geophysical response and setting of the Centenary orebody. A following section on petrophysics links survey data to rock properties.

Airborne magnetics/radiometrics

A detailed magnetic survey was flown by UTS Geophysics in 1999, with a flying height of 20 m and line spacing of 25 m. The aim of the survey was to map mineralising structures and host lithologies. Magnetic data shown in Figure 2 have been reduced to the pole. The surface projection of the Centenary orebody is given in white. The magnetic marker within the Mount Pickering Dolerite, which hosts the Centenary orebody, can be seen to be continuous and regionally extensive. East–west trending Proterozoic dolerite dykes are evident to the south. Regional magnetic lows are attributed to non-magnetic dolerites and felsic volcanics, and major faults are visible in the magnetic

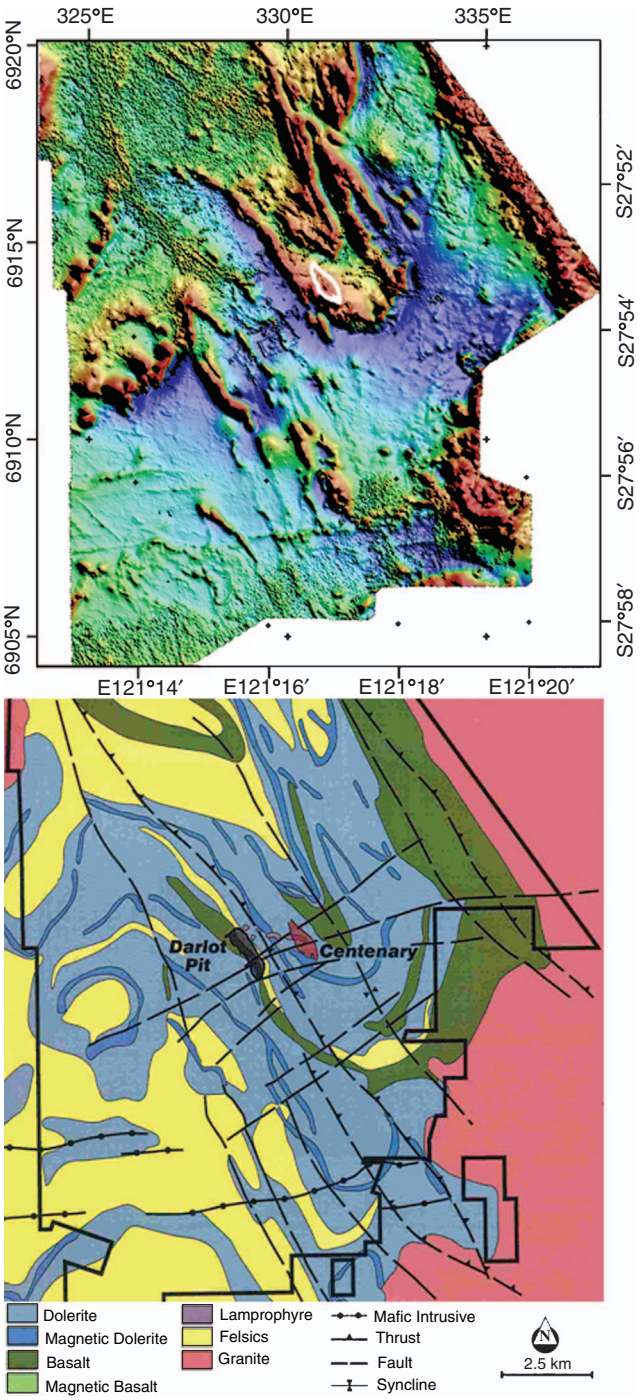

Fig. 2. Aeromagnetic data over the Centenary orebody. Total magnetic intensity reduced to the pole (above) with simplified interpreted geology over the same area (below). The surface projection of Centenary is shown in white.

data. High frequency 'noise' is explained by surface maghemite. The magnetic data do not delineate the Centenary orebody, however they do show structural controls to mineralisation.

Gravity

A gravity survey over Centenary was conducted by Haines Surveys in 1997, employing a line spacing of 160 m and a station spacing of 40 m. Lines were oriented north-east, perpendicular to geology. Gravity data are shown in Figure 3 with the surface projection of the Centenary orebody. A gravity response from the

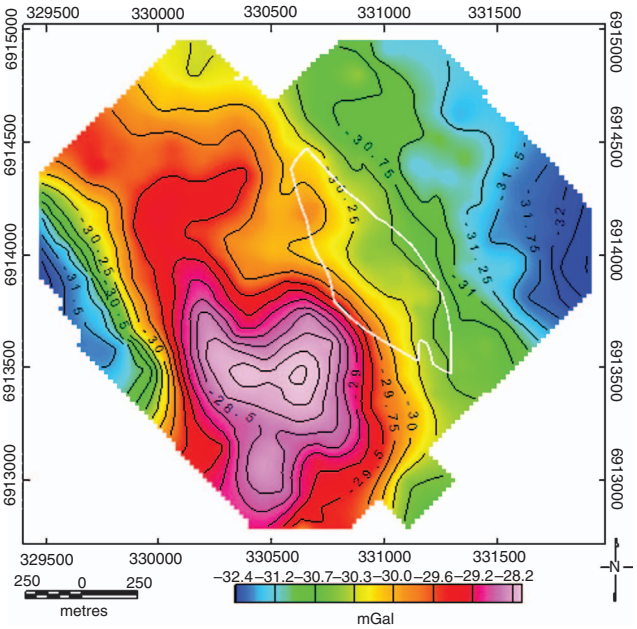

Fig. 3. Bouguer gravity reduced at a density of 2.67 t/m^3 over the Centenary orebody. The surface projection of Centenary is shown in white.

Centenary orebody is not visible in the data. The gravity high coincides with outcropping magnetic dolerite. This dolerite is resistant to weathering, and as a result has a thinner weathering profile: typically 10–20 m to the base of complete oxidation (BOCO) in contrast to deeper weathering over felsics and basalts: 40–50 m to BOCO. This variable weathering profile, combined with a slight density contrast between the magnetic dolerite and the surrounding lithologies, accounts for the gravity high (Bourne, 1999).

Induced polarization and resistivity

A dipole–dipole induced polarization and resistivity survey acquired by Zonge Engineering in 2000, utilising 100 m dipole spacing, showed a chargeable response over mineralisation. Figure 4 shows the location of the dipole line relative to the surface projection of the Centenary orebody, and Figures 5 and 6 show IP and resistivity field data. Resistivity data show a conductive overburden and a zone of low resistivity positioned above the chargeable body. Faults extend from the surface

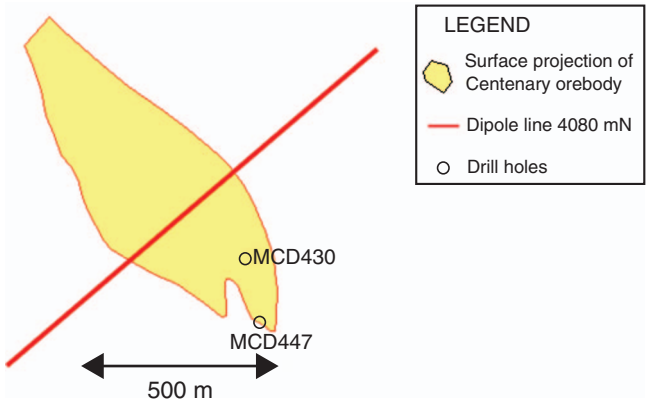

Fig. 4. Location of dipole–dipole IP and resistivity line 4080 mN and drillholes MCD430 and MCD447 relative to the surface projection of the Centenary orebody.

through the orebody and such faults may act as conduits to fluids, lowering the resistivity in the area.

Petrophysics

Petrophysics has played, and will continue to play, an essential role in characterising the induced polarization response of the Centenary orebody. Petrophysical data over Centenary include laboratory measurements and down hole surveys. These datasets are discussed below.

Laboratory measurements

Quantec, a geophysical contracting firm, made laboratory measurements on core samples from various lithological groups, and these gave the first indication that the magnetic and mineralised portion of the Mount Pickering Dolerite was chargeable. A second round of petrophysics was conducted as part of an honours project (Pittard, 2001), where 35 rock samples were selected from the magnetic portion of the Mount Pickering Dolerite. All samples had magnetic susceptibility, density, resistivity, and chargeability determined. Combined petrophysical data from both studies are contained in Table 1.

The mineralised dolerite is a subset of the magnetic dolerite. Note that the chargeability response for the mineralised dolerite is anomalously high. No other physical property seems to distinguish the mineralised dolerite from its surrounding lithologies as strongly as chargeability. This observation is supported by geophysical survey data, where airborne magnetics

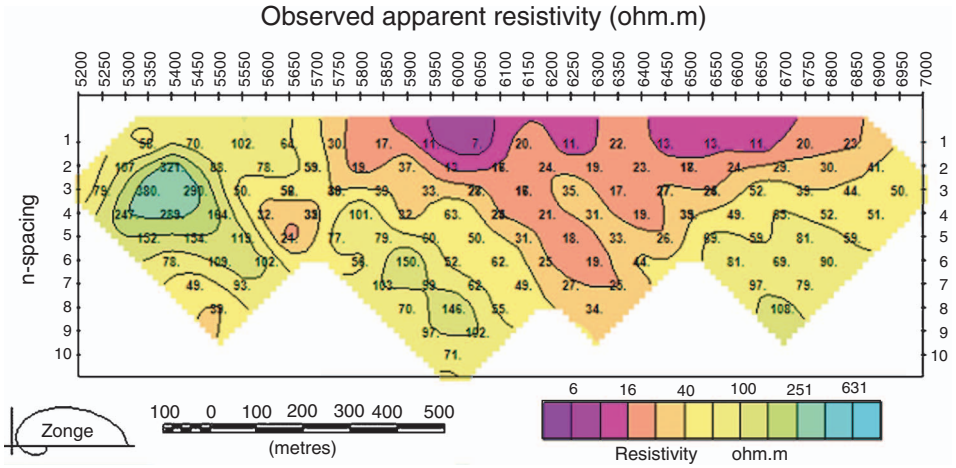

Fig. 5. Field resistivity data on line 4080 mN.

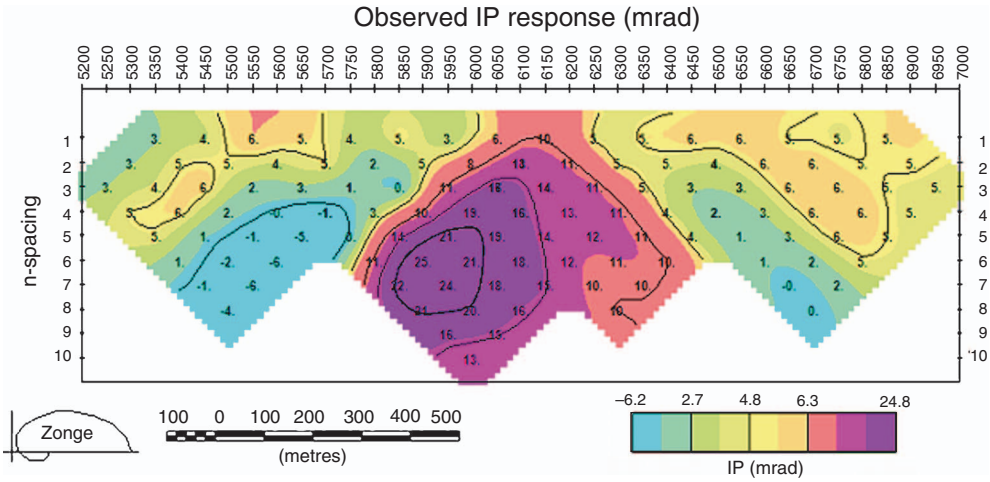

Fig. 6. Field chargeability data on line 4080 mN.

Table 1. Average petrophysical results obtained from measurements made on core and underground rock samples of mineralisation and surrounding country rocks.

Lithology	IP (mV/V)	Resistivity (Ω.m)	Density (t/m^3)	Magnetic susceptibility (SI × 10^{-3})	Number of samples
Tertiary hardpan	5.1	34.0	1.94		1
Pisolitic laterite	14.5	22	2.73	13.80	1
Residual clay saprolite	6.9	110	1.75		2
Felsic volcanic	2.3	5513.3	2.74		3
Basalt	1.7	5006.7	2.91		3
Dolerite	3.3	3988	2.91	1.36	5
Magnetic dolerite	17.0	3886.8	2.94	68.62	13
Non-magnetic regional pyritic dolerite	4.6	3660	3.08	0.60	1
Magnetic local mineralised dolerite	34.7	3129.5	2.99	64.71	27
Lamprophyre	3.6	3600	2.81	3.05	3

and gravity do not directly map the orebody (Figures 2 and 3), however there is a chargeability high over the deposit (Figure 6). The magnetic susceptibility of the mineralised dolerite is marginally lower than its host magnetic dolerite, due to pyrite replacing magnetite grains. Pyrite replacement of magnetite would also contribute to a higher average density of mineralised dolerite, compared with host dolerite.

Thin sections were made from the 35 samples of magnetic dolerite. These were examined primarily to estimate the proportion and grain size of magnetite and pyrite within the sample. Table 2 summarises the petrophysical and mineralogy of samples taken locally and regionally to mineralisation.

The chargeability of samples taken close to the orebody is significantly higher than in samples regional to the orebody. There is minimal difference in density, magnetic susceptibility, and resistivity between the two groups, which suggests IP as the most diagnostic geophysical tool to explore for deposits similar to Centenary. Finally, pyrite percentages are significantly less in samples regional to the orebody. Magnetite is, in the mean statistics, the same for both local and regional samples.

Figure 7 shows a graph of magnetite content as estimated from thin sections, magnetic susceptibility measured from hand samples, and IP. While one may reasonably expect a linear relationship between magnetite and magnetic susceptibility, the result is actually quite scattered. One possibility is that the thin sections are not representative of the hand samples. The Centenary deposit was found in a highly altered environment, with alteration zones extending only very short distances (often around 5 cm) from mineralisation. As a result magnetite content is often highly variable throughout a hand sample.

Figure 8 shows magnetic susceptibility of the 35 samples plotted against induced polarization, with size of magnetite grains shown in colour. Grain size is an important variable when looking at IP effects, as smaller grain sizes equate to a larger surface (if volume is kept constant), which is known to increase chargeability (Wong, 1979; Clark et al., 1992). The high

Table 2. Mean petrophysical properties of magnetic dolerite samples local to (within 200 m) and regional to (beyond 500 m) mineralisation.
Percentage magnetite and pyrite included from petrography.

Location	IP (mV/V)	Density (t/m^3)	Magnetic susceptibility (SI × 10^{-3})	Resistivity (Ω.m)	Percent magnetite	Percent pyrite
Local (24)	26.77	2.98	69.09	3431	10	7
Regional (11)	17.23	2.93	71.87	3448	10	0

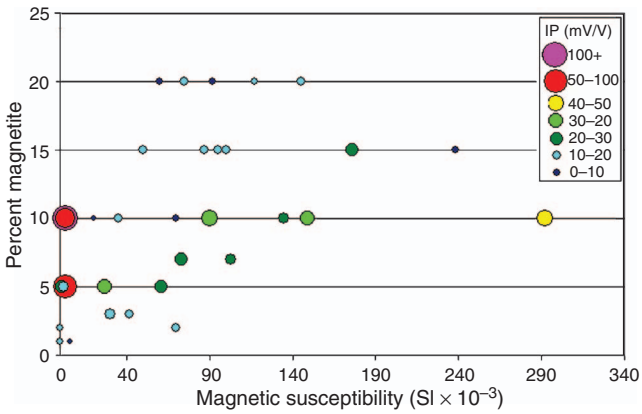

Fig. 7. Ternary image of percent magnetite, estimated from thin sections, plotted against magnetic susceptibilities, obtained from hand samples. Induced polarization is shown in colour.

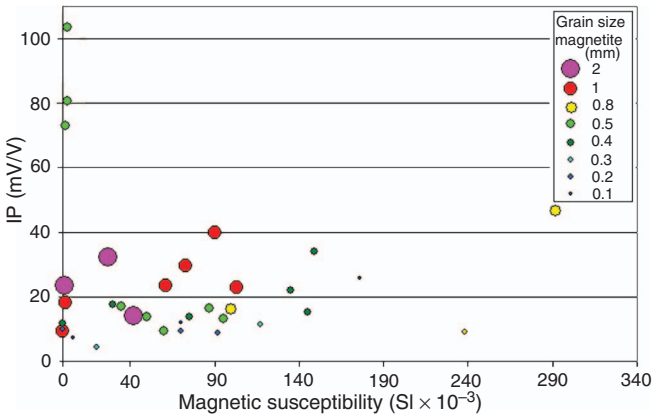

Fig. 8. Ternary image of induced polarization, magnetic susceptibility, and grain size of magnetite.

degree of scatter in Figure 8 shows that magnetic susceptibility is not strongly related to the induced polarization results. The grain size of the magnetite also does not look strongly related to either the chargeability or the magnetic susceptibility of the sample.

Figure 9 shows percentage pyrite (estimated from thin sections) plotted against chargeability (measured in hand samples), with grain size shown in colour. Perhaps surprisingly, there is no correlation seen between IP and percentage pyrite. The grain size of the pyrite does not appear strongly related to either the chargeability or the magnetic susceptibility of the sample. Forsyth (1999) also found that in rocks containing magnetite, no correlation could be found between an elevated IP response and increased pyrite content; decreasing sulphide percentages were, in fact, associated with larger IP values in samples containing magnetite.

Figure 10 shows a crossplot image of percentage magnetite and pyrite, displayed with chargeability. The five samples that give the highest chargeability response all have at least 5% magnetite and 5% pyrite, and at least 15% magnetite and pyrite combined. This region within Figure 10 is circled in red.

There is one sample, with 5% magnetite and 20% pyrite, which fails to give a large chargeability response. Forsyth (1999) reviewed a large IP response obtained from the Purple Haze prospect in the Forrestania greenstone belt, Western Australia. His conclusion was that the IP response could be attributed to bands of massive magnetite coupled with very minor sulphides.

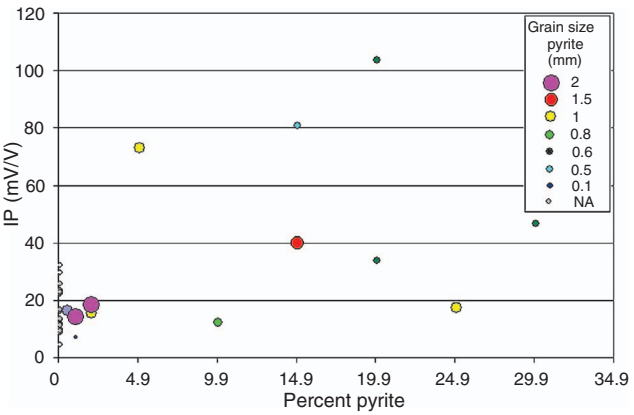

Fig. 9. Ternary image of induced polarization, percentage pyrite and grain size of pyrite.

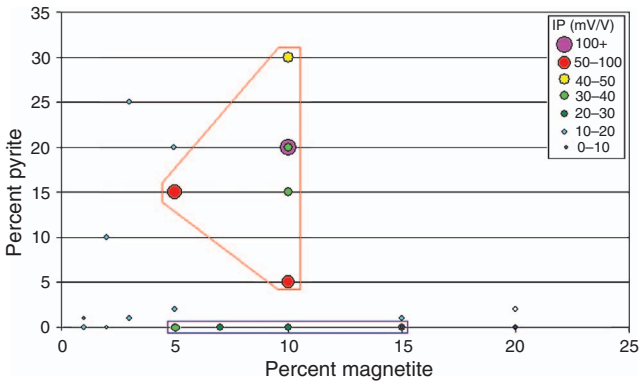

Fig. 10. Ternary image of percentage pyrite, percentage magnetite and induced polarization.

It may be that the magnetite : pyrite ratio needs to be at least 1 : 4 to give an elevated IP response.

There are seven samples that do not contain pyrite, yet produce an IP response greater than 20 mV/V. These samples are circled in blue. Three samples within this region contain 5% magnetite, two samples contain 7% magnetite, and one sample each contains 10% and 15% magnetite, as estimated by thin section analysis. There are also 9 samples that overlap on this graph within the blue circle which have IP responses less than 20 mV/V (between 4.4 mV/V and 16.87 mV/V). Examination of hand samples confirms that the seven chargeable samples contain little to no pyrite. There is nothing exceptional about these samples in terms of any other physical properties measured, and all except one sample have magnetic susceptibilities of greater than 60×10^{-3} SI. Thin section analysis cannot suggest any reason why these four chargeable samples differ from non-chargeable samples containing no pyrite and similar amounts of magnetite. Three of these samples were taken local, and four regional, to the orebody. This result may have an important implication for exploration: in searching for sulphide associated mineralisation in host rocks containing magnetite, rocks containing both magnetite and sulphides may produce very strong IP responses, while lesser IP anomalies may possibly be sourced by magnetite alone. The Centenary orebody gave a highly chargeable response in data collected by Zonge Engineering along line 4080 mN.

Down hole induced polarization and resistivity

A down hole pole-dipole induced polarization survey was acquired by Scintrex in 1997. Holes MCD430 and MCD447

within the deposit were logged using dipole spacings of 5 m. The locations of these holes relative to the surface projection of the Centenary orebody are shown in Figure 4. Down hole plots of these data are shown in Figures 11 and 12 along with magnetic susceptibility, lithology and gold grade.

Notice a proximal relationship between elevated levels of chargeability and mineralisation. Chargeability is typically a little offset from (shallower), and broader than, mineralisation. Hole MCD447 illustrates this well: gold mineralisation occurs between depths of 193.5 m and 198.5 m (>2 ppm) while the elevated IP is observed between depths of 155 m and 185 m (>30 mV/V). If one assumes that pyrite content is proportional and spatially related to gold content (Krcmarov et al., 2000), then one would expect a deeper and narrower IP response in the down hole logging data.

Low magnetic susceptibility values where gold is present suggest that mineralisation caused local magnetite destruction.

Modelling

Petrophysical data show the Centenary mineralisation should provide an induced polarization anomaly. Field data confirmed this via a dipole–dipole IP and resistivity survey. Forward modelling was used to quantitatively link laboratory measurements, field data, and geology. Modelling attempted to replicate field dipole–dipole induced polarization and resistivity data. Based on a comparison of frequency and time domain data over the same line, an empirical factor of 1.6 was applied to convert from mV/V (petrophysical data and down hole surveys) to mrad (Zonge frequency domain data).

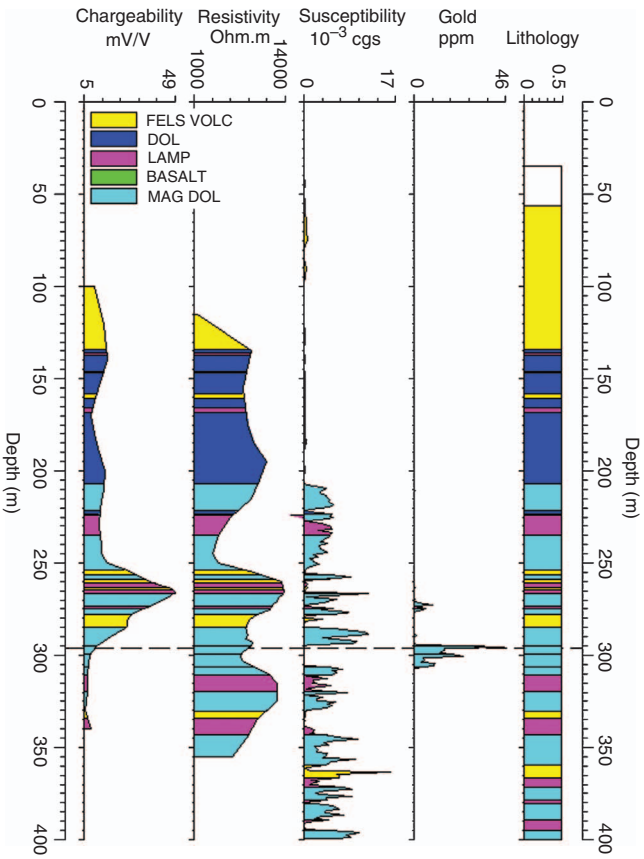

Fig. 11. Scintrex pole-dipole DHIP and resistivity data displayed with magnetic susceptibility and lithology for hole MCD430. Dipole spacing was 5 m.

Forward model

A forward model of the IP response of line 4080 mN (Figures 13 and 14) was constructed using PCIP forward modelling software. Table 3 shows chargeability and resistivity of modelled geologic units in the forward model. A resistivity of 4000 Ω.m and a chargeability of 16 mV/V were attributed to the host rock. These values are very close to the petrophysical results shown for the host magnetic dolerite in Table 2.

A property of 100 mV/V attributed to the chargeable body falls at the top end of the range of petrophysical measurements for mineralised dolerite. The body is modelled shallower than

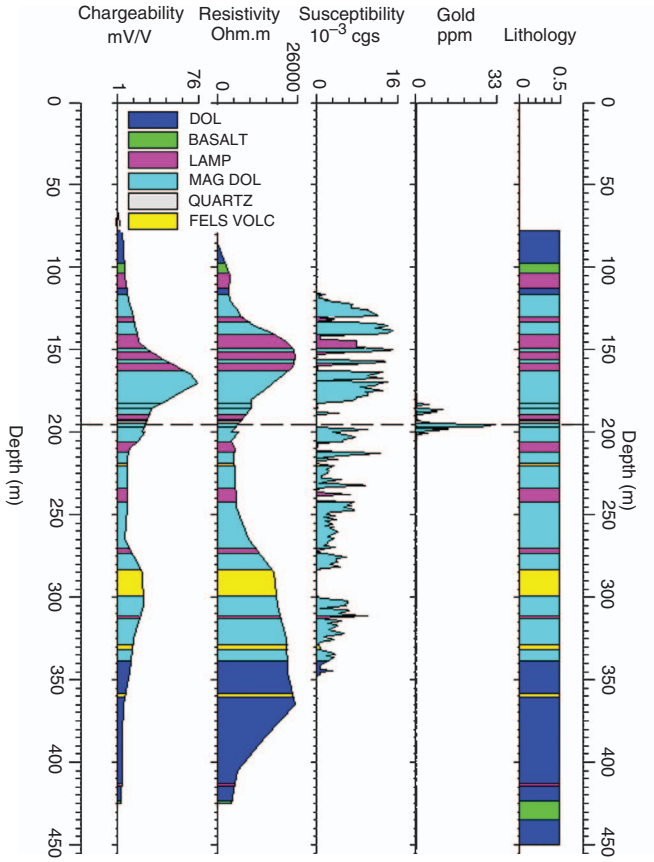

Fig. 12. Scintrex pole-dipole DHIP and resistivity data displayed with magnetic susceptibility and lithology for hole MCD447. Dipole spacing was 5 m.

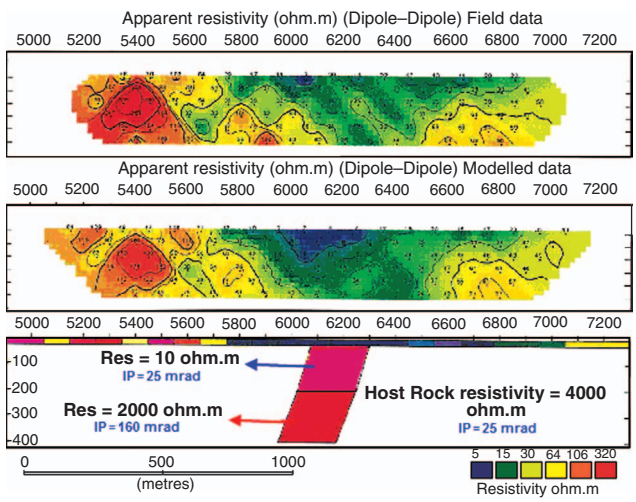

Fig. 13. Forward model for resistivity data on line 4080 mN.

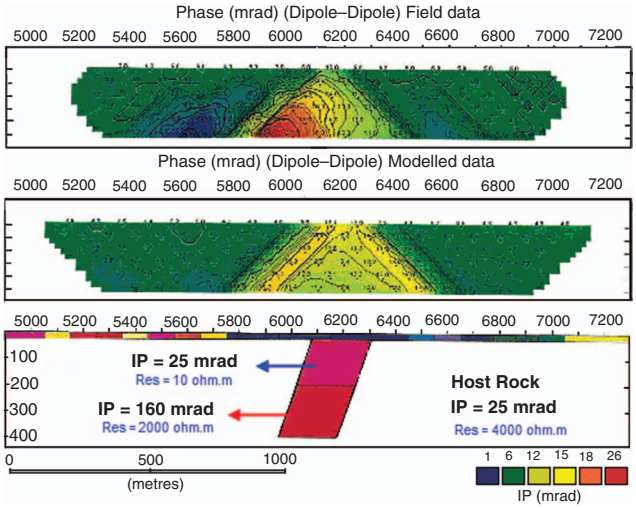

Fig. 14. Forward model for chargeability data on line 4080 mN.

Table 3. Chargeability and resistivity attributed to modelled geologic units in the forward model.

	Resistivity (Ω.m)	Chargeability (mV/V)	Chargeability (mrad)
Overburden	3 to 50	3	5
Host rock	4000	16	25
Body	2000	100	160
Weathering and/or alteration	10	16	25

mineralisation: a depth of 200 m as opposed to a known depth of ~300 m. Note that the notion of an IP source shallower than mineralisation is supported by the down hole logging data shown previously – the offset between gold mineralisation and chargeability shown in MCD430 in Figure 11 and MCD447 in Figure 12.

Figure 13 shows a zone of low resistivity (10 Ω.m) positioned above the chargeable body in the forward model. Faults extend from the surface through the orebody and such faults may act as conduits to fluids, lowering the resistivity in the area. Figures 13 and 14 show the model and the model response, with field data, for resistivity and chargeability respectively. The bulk of the resistivity data has been modelled by near surface features.

Inverse model

An unconstrained inversion of the three-point decoupled field data over line 4800 mN is shown in Figures 15 and 16. This inversion was performed using Zonge TS2DIP software. These figures show, from top to bottom: results of an unconstrained inversion of three-point decoupled data; forward modelled data; and field data. Note that the overburden resistivity varies between 6 and 20 Ω.m, and that the host rock resistivity averages around 60 Ω.m. The latter is much lower than that used in the forward model, and is not supported by the petrophysics. Being an unconstrained inversion, this parameter is poorly resolved, and probably reflects an initial starting value. Also note that some near surface resistivity features have probably been modelled at unrealistic depths, for example the 251 Ω.m anomaly at 200 m depth seen in Figure 15 is possibly sourced by a near surface resistor.

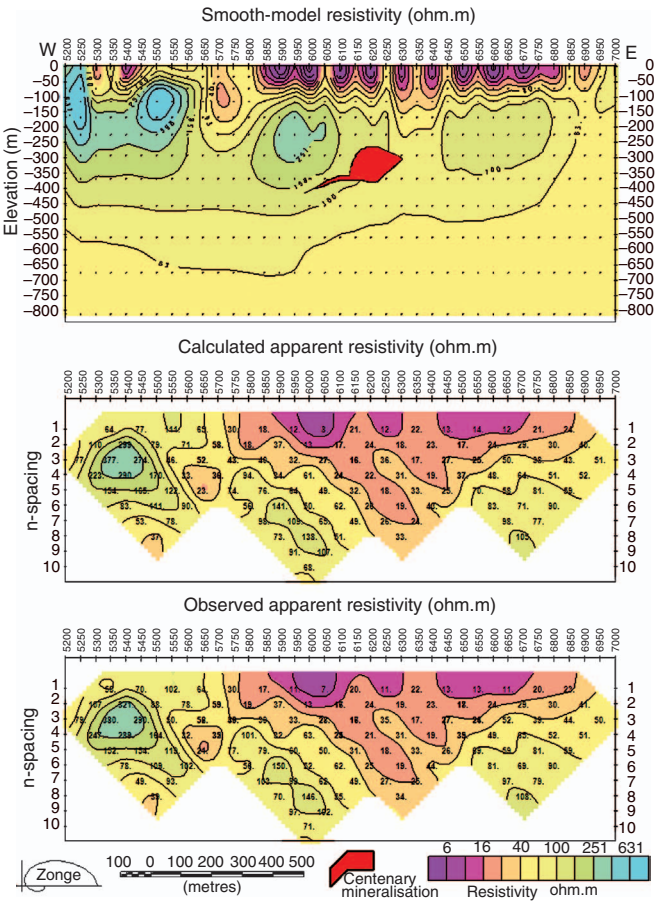

Fig. 15. Inversion of resistivity data on line 4080 mN.

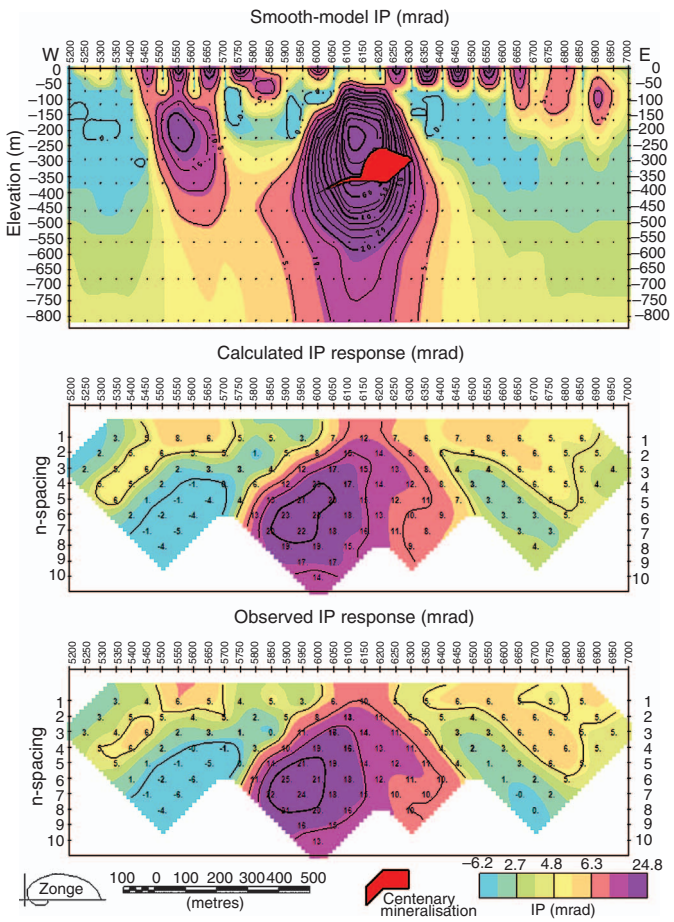

Fig. 16. Inversion of IP data on line 4080 mN.

Figure 16 shows a chargeable body of 40 mrad extending between ~100 m and 375 m depth, with a maximum IP response of 80 mrad at 225 m depth. This is shallower and less chargeable than the body used in the forward model, and certainly shallower than the known mineralisation depth of 300 m. This once again supports the notion of an IP source shallower than mineralisation, supported by down hole logging data in drill holes MCD430 (Figure 11) and MCD447 (Figure 12).

Finally, it is worth mentioning that when a second, smaller, and weaker chargeable body generated at 110 m depth below 5500 mE was drilled, non-sulphidic magnetic dolerite was intersected.

Conclusions

Petrophysical data and thin section analysis showed that on average, chargeable samples local to the orebody contained higher percentages of pyrite, but not necessarily more magnetite, than less chargeable samples further from the orebody (Table 1). This observation alone suggests that pyrite is the variable controlling the IP response. It is therefore surprising that a straightforward correlation was not seen between the amount of pyrite in each sample and the IP response of that sample. It was only when both the percentage of pyrite and the percentage of magnetite in each sample was considered that a relationship with induced polarization (albeit based on a very small sample size) emerged.

Downhole logging data show a chargeability response that is shallower and broader than the intersected pyrite associated mineralisation. Additionally, forward and inverse modelling of surface data also suggest a chargeable body shallower than known mineralisation. An anomaly due solely to pyrite-associated mineralisation should be narrower and deeper, based upon the known position of the Centenary orebody. Down hole and surface IP datasets therefore support the hypothesis that pyrite alone does not explain the IP anomaly seen over Centenary, and that magnetite may be a contributing factor to this anomaly.

A less intense chargeable body to the west of the mineralisation was seen in unconstrained inversions performed on data collected over the Centenary orebody. When this anomaly was drilled, non-sulphidic magnetitic dolerite was intersected. It is proposed that while non-sulphidic magnetite may give an IP effect, anomalies produced by such rocks will be less intense than those seen in rocks containing a combination of magnetite and pyrite.

Acknowledgments

The paper is published with the permission of Barrick Gold of Australia Limited. The authors thank reviewers Todd Grant and Phil Hawke for comments on the paper.

References

Bourne, B., 1999, *Darlot/Centenary Geophysical Summary and Follow-up Proposal*: Homestake Internal Memorandum (unpublished).

Clark, D. A., French, H. H., Lackie, M. A., and Schmidt, P. W., 1992, *Rock Magnetism and Magnetic Petrology Applied to Geological Interpretation of Magnetic Surveys*: Division of Exploration Geoscience, Inst. Minerals, Energy and Construction, Restricted Report 303R.

Forsyth, A., 1999, *Petrophysical analysis of nickeliferous rocks at the Forrestania greenstone belt, Western Australia*: B.Sc.(Honours) thesis (unpublished), Curtin University.

Krcmarov, R., Beardsmore, T. J., King, J., Kellett, R., and Hay, R., 2000, Geology, regolith, mineralisation and mining of the Darlot-Centenary gold deposit, Yandal belt: in Phillips, G.N., and Anand, R. R., (Eds). *Yandal greenstone belt*: *Aust. Inst. of Geoscientists Bulletin* **32**, 351–373.

Pittard, K., 2001, *The Contribution of Magnetite to the Induced Polarisation Response of the Centenary Orebody*: B.Sc.(Honours) thesis (unpublished), Curtin University.

Wong, J., 1979, An electrochemical model of the induced-polarization phenomenon in disseminated sulfide ores: *Geophysics* **44**, 1245–1265. doi: 10.1190/1.1441005

Manuscript received 1 August 2006; accepted 18 June 2007.