Geophysics of the Honeymoon Well Nickel Deposits, Western Australia

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ABSTRACT

The Honeymoon Well nickel sulphide deposits are located in the Agnew-Wiluna greenstone belt, about 45 km south of Wiluna. Both disseminated and massive sulphide nickel deposits are hosted by komatiitic rocks within the deformed and metamorphosed Honeymoon Well ultramafic complex. Fresh ultramafic bedrock is covered by up to 50 m of highly conductive transported material which greatly hampers both exploration and understanding of the bedrock geology.

In the early-1970s, mineralisation was discovered by diamond drilling geochemical anomalies defined by wide-spaced percussion drilling over ultramafics that had been outlined by ground magnetics. Subsequent drilling has defined a resource of 158 Mt at 0.71 per cent nickel (based on 0.4 per cent nickel cut-off, 300 m below surface, December 1995) in four deposits.

Over the life of the project a wide range of geophysical techniques have been used including airborne and ground magnetics, time domain electromagnetics (EM), induced polarisation (IP)/resistivity, gravity and downhole techniques including EM, IP and physical property measurements.

Detailed magnetics and gravity were most useful in mapping lithological and structural boundaries within the ultramafic complex whereas electrical techniques helped to define the limits of sulphide mineralisation and locate new targets for exploratory drilling. Strong IP responses were recorded over each of the known deposits with a distinct EM response over the massive sulphides at Wedgetail. Downhole geophysics was used to constrain modelling of surface responses and to help confirm that targets had been intersected by drilling.

The presence of highly saline ground water (up to 200 000 ppm total dissolved salts) within the cover sequence and weathered profile, greatly hampered the use of electrical methods, with careful monitoring of signals and some improvement in technologies required to provide effective coverage.

INTRODUCTION

The Honeymoon Well nickel deposits are located about 45 km south of Wiluna within the northern part of the Agnew-Wiluna greenstone belt (Figure 1). The project area is covered by up to 50 m of transported material which greatly hampers both exploration and an understanding of the bedrock geology.

Mineralisation was first discovered at Honeymoon Well in the early-1970s by diamond drilling lateritic geochemical anomalies defined by wide-spaced percussion drilling over the ultramafic rocks that had been outlined by ground magnetics. Since 1989 intense exploration has discovered two additional deposits and increased resources in the previously known deposits. As a result the overall resource has increased from 10 Mt at one per cent nickel in 1989 to currently 158 Mt at 0.71 per cent nickel (0.4 per cent nickel cut-off, above 200 RL) in four deposits.

This paper summarises the geophysical characteristics of the Honeymoon Well nickel mineralisation with particular emphasis on the massive sulphide Wedgetail deposit and the disseminated sulphide Corella deposit.

GEOLOGY AND MINERALISATION

The Honeymoon Well greenstone belt is 6 - 7 km wide and composed of a regional west-younging sequence of a lower basalt/gabbro unit, including a laterally persistent basaltic

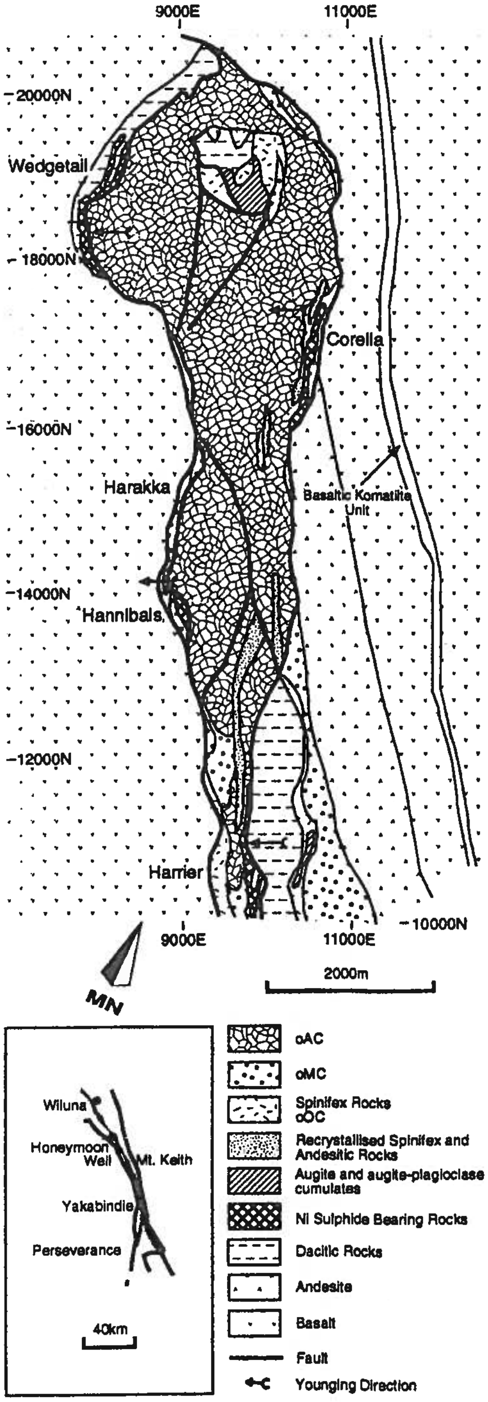

FIG 1 - Honeymoon Well locality and geological plan at 100 m below surface (after Gole *et al*,1996b).

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komatiite flow, felsic volcanic and volcaniclastic rocks, a heterogeneous komatiite sequence and a western felsic/basalt sequence (Gole *et al,* 1996). The basaltic komatiite flow or Unit D, as described by Liu *et al* (1995), is the host of the Honeymoon Well nickel mineralisation.

The ultramafic sequence varies from 1.5 to 3 km in width and consists of a diverse suite of komatiite lithologies including spinifex-textured rocks, olivine orthocumulates, mesocumulates and adcumulates (oOC, oMC and oAC) (Figure 1). The ultramafic sequence occurs below a thick cover of variably indurated sands and gravels (5 - 25 m), transported clays (0 - 40 m) and an *in situ* weathered profile (30 - 60 m).

The Honeymoon Well deposits can be split into two types: disseminated sulphides (trace to five modal percent) in olivine rich cumulates (Hannibals, Harrier and Corella) and sulphide-rich rocks (massive sulphide, sulphide breccia and olivine-sulphide cumulates) in spinifex textured flows (Wedgetail) (Gole *et al,* 1996). The disseminated deposits have generally similar host lithologies, ore compositions and sulphide assemblages.

The Corella deposit is located along the eastern contact of the Honeymoon Well ultramafic complex. The deposit has a strike length of 1.5 km and occurs within a deformed heterogeneous sequence of oAC and minor oOC and oMC. The attitude of the eastern fault contact between oAC and metabasalt varies along strike from east dipping to west dipping (Figure 2). Lithological units within the mineralised sequence are sub-vertical except in the south where units dip shallowly westwards at depth (Figure 3). The mineralisation consists of disseminated sulphides containing trace to approximately three per cent modal per cent sulphides. Most sulphides typically occur as scattered lobate to blebby aggregates intergrown with magnetite, carbonate and other gangue minerals.

The Wedgetail deposit is located along the northwestern margin of the ultramafic complex. The deposit has a strike length of 1.7 km and varies in width from ten to 80 m (Figures 1 and 4). The deposit comprises disseminated and massive sulphides hosted by a steep easterly dipping sequence of oOC and spinifex textured rocks. The massive and brecciated massive sulphides contain 30 - 90 per cent sulphide and vary in thickness from a few centimetres to several metres. Primary massive sulphides consist of pyrrhotite, pentlandite, pyrite and minor chalcopyrite (Gole *et al,* 1996).

PHYSICAL PROPERTIES

Density

Density measurements have been made on drillcore using the displacement of water method as part of the routine resource estimation process. Density data along with other physical property measurements are presented in Table 1 for the major rock types. As expected the strongest density contrast (>1 g/cc) occurs between massive sulphide and all other units. The disseminated mineralisation does not provide a measurable contrast to the unmineralised ultramafic host rocks, however there is a contrast between the more mafic rock units and the surrounding granites.

Electrical properties

The majority of the electrical properties have been determined by borehole logging. Several samples were also processed under laboratory conditions but because of difficulties in finding representative samples and replicating the highly saline *in situ* conditions, the downhole logging data were considered more representative of the rock types.

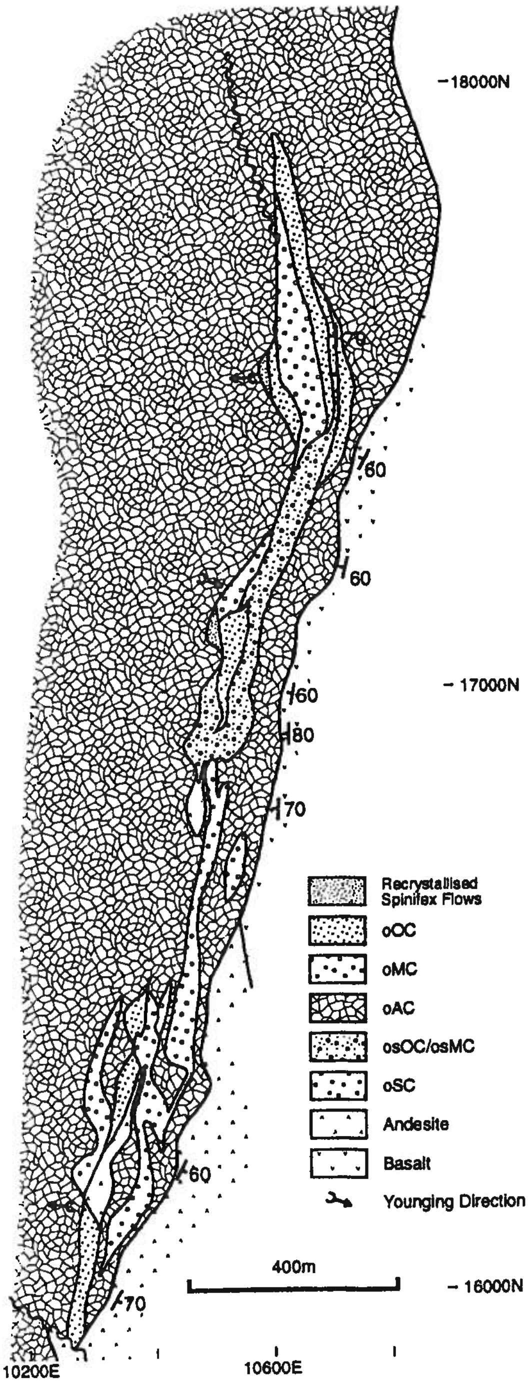


FIG 2 - Geological plan of Corella at 100 m below surface.

Apparent conductivity was calculated from quadrature phase measurements collected using a frequency domain Geonics EM39 inductive conductivity tool. Conductivities were calculated using the low induction approximation (assuming conductivity < 12 S/m) (McNeil, 1986) at a frequency of 39 200 Hz and a transmitter-receiver coil spacing of 0.5 m. Table 1 clearly shows the conductive nature of the overburden and the massive sulphides. In places the disseminated sulphides are also quite conductive.

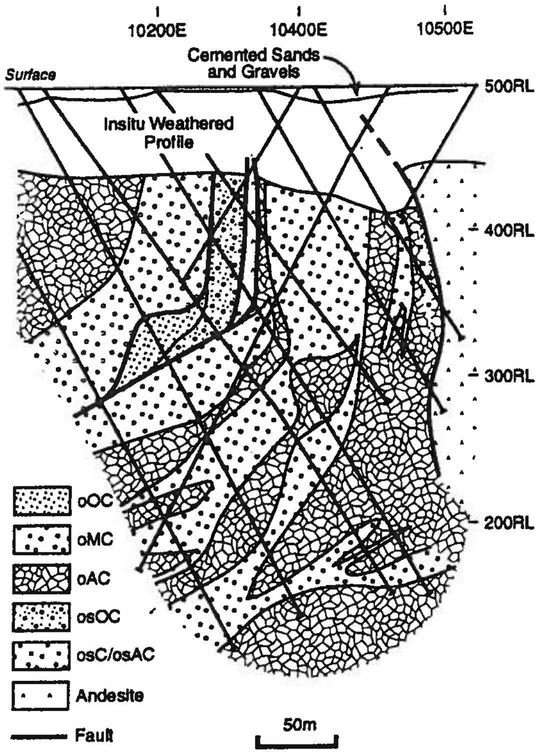


FIG 3 - Interpreted geological cross-section of Corella along line 16 300 mN.

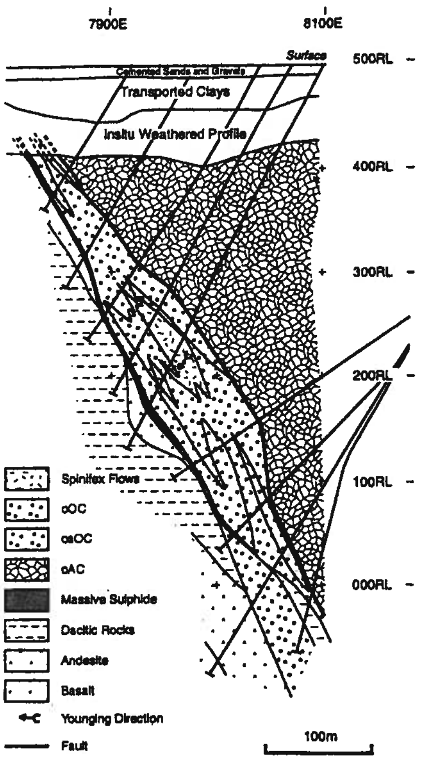


FIG 4 - Interpreted geological cross-section of Wedgetail along 18 200 mN (after Gole *et al*,1996b).

TABLE 1

Summary of physical properties of rock types and mineralisation at Honeymoon Well.

Rock Type	Density (g/cc)	Conductivity (mS/m)	Chargeability (msec)	Magnetic Susceptibility (SI x 10^{-5})	Remanent Magnetism (Qn)
Quarternary Sands	~2.1	~200	n/a	10 - 10 000	n/a
Lake Clays	~1.8	~500	n/a	0 - 50	n/a
Main Regolith Profile	~2.4	300 - 2000	0 - 10	0 - 50	0.1 - 0.5
Metasediments	~2.75	<10	0 - 10	0 - 100	0.1 - 0.7
Metabasalt	~2.8	<10	0 - 10	0 - 100	n/a
Ultramafics (Lizardite-Antigorite Rich)	2.6 - 2.65	30 - 60	10 - 150	250 - 20 000	0.1 - 5
Ultramafics (Talc-Carbonate Rich)	2.85 - 2.9	30 - 60	5 - 50	50 - 4500	0.1 - 1
Disseminated Sulphides (> 0.4%)	*2.6 - 2.85	30 - 3000	50 - 250	80 - 20 000	0.5 - 9
Massive Sulphides	3.5 - 4.5	>3000	10 - 350	7000 - 15 000	0.1 - 42

* Density independent of sulphide content for disseminated mineralisation.

Down hole IP measurements were recorded using a Scintrex time domain IPR-12 receiver and TSQ-3 transmitter. The pole-dipole electrode configuration was used with an a-spacing of 1 m and a frequency of 0.125 Hz. Table 1 summarises the chargeability results from window 12 (820 - 1050 msec). As expected there is a strong chargeability contrast between the sulphide mineralisation and the surrounding rocks. Downhole logging has also highlighted elevated chargeability zones within nonmineralised ultramafics. Investigations have shown that appreciable IP effects can be attributed to magnetite concentrations (5000 x 10^{-5} SI) (Aravanis, 1995), especially where it is finely disseminated throughout the ultramafics.

Magnetic properties

Susceptibility measurements were routinely collected on core using a Geoinstruments JH-8 hand-held magnetic susceptibility meter and/or provided by downhole logging using a Bartington magnetic susceptibility probe. Susceptibility ranges for the various rock types are summarised in Table 1. While the ultramafics are significantly more magnetic than the metasediment/basalt units there is no clear differentiation between mineralised and unmineralised ultramafics. There is a tendency however, for the talc carbonate and oAC ultramafics to be less magnetic than the oMC and oOC units.

Selected core samples were sent to D Emerson of Systems Exploration Pty Ltd for remanent magnetisation measurements. Strong remanence was recorded for the massive sulphide samples (pyrrhotite) but generally much weaker for all other rock types. Koenisberger ratios (Qn) varied from 0.1 to 42.

GEOPHYSICAL SURVEYS

Geophysical techniques have been applied at Honeymoon Well to map lithologic boundaries and structure, help define the limits of mineralisation, and to evaluate the effectiveness of geophysical techniques in areas of thick conductive cover. Methods used include airborne and ground magnetics, surface time domain electromagnetics, surface induced polarisation/resistivity, gravity and downhole geophysical logging.

Airborne magnetics

An airborne survey covering the full length of the Honeymoon Well ultramafic complex was flown in 1990 by Kevron Pty Ltd with a flight line spacing of 50 m and a nominal height of 40 m. Figure 5 shows a first vertical derivative image of the airborne magnetic data. The main magnetic feature observed in the image is the outline of the Honeymoon Well ultramafic complex. As highlighted in Table 1 the ultramafic units have typically ten times the susceptibility of the metasedimentary and metabasalt units.

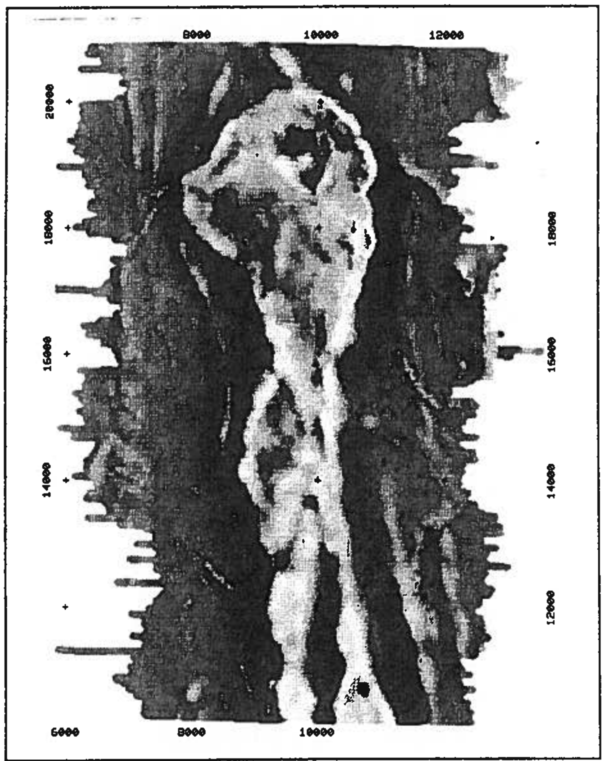


FIG 5 - First vertical derivative image of the airborne magnetic data from Honeymoon Well.

The presence or absence of magnetite within the ultramafic rocks is primarily due to differences in metamorphic fluid compositions both during the initial serpentinisation (magnetite constructive) and later talc-carbonate (magnetite destructive) alteration (see Bourne *et al,* 1993). Magnetite destructive alteration is prevalent along the contact between ultramafics and the surrounding rock types and along fault surfaces within and cross-cutting the ultramafics. This often results in the ultramafics being wider than inferred from the airborne magnetics. The first vertical derivative image reflects a complex history of fluid movement, serpentinisation and talc carbonate alteration.

The nickel mineralisation occurs marginal to north-south trending talc-carbonate zones near the contact between the ultramafic and metabasalts and/or metasedimentary units. The host rocks in the vicinity of mineralisation are often associated with zones of increased magnetite concentration reflecting alteration.

Time domain electromagnetics

In 1986 a moving loop SIROTEM survey using 200 x 200 m transmitter loops was carried out over the Honeymoon Well ultramafic sequence to target massive sulphide mineralisation. Unfortunately the technique was unable to penetrate the conductive surface material that blankets most of the prospective ultramafic. In 1993 a trial transient EM survey using a CRA developed receiver coil successfully detected a dipping bedrock conductor coincident with the massive sulphides at the Wedgetail deposit. Survey specifications include a 200 x 200 m double turn transmitter loop, a frequency of 0.25 Hz and a Zonge transmitter (GGT-30) and receiver (GDP-16) with the CRA receiver coil.

Figure 6 shows transient responses comparing the CRA receiver coil with the standard Zonge TEM/3 antenna for a central east-west profile over the mineralisation (18 500 mN). A dual peaked anomaly centred over 7850 mE is evident in late times (>150 msec) for the CRA coil but there is no discernible response from the standard antenna. The decay curve for the station with peak response (8000 mE) is shown in Figure 7 highlighting a straight line late time response (>300 msec) with a time constant of 247 msec, characteristic of an extremely good conductor.

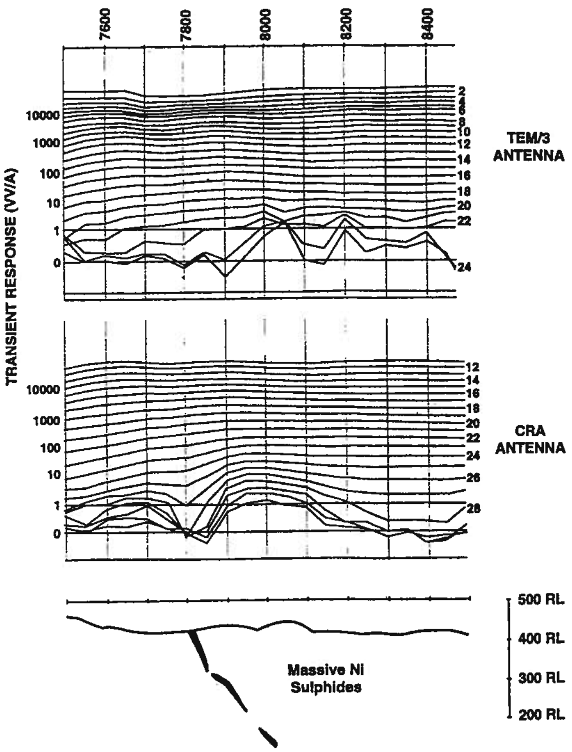


FIG 6 - Time-domain EM (200 x 200 m moving loop) results for Wegetail along line 18500 mN. A conventional TEM/3 antenna response is shown as a comparison to the CRA antenna.

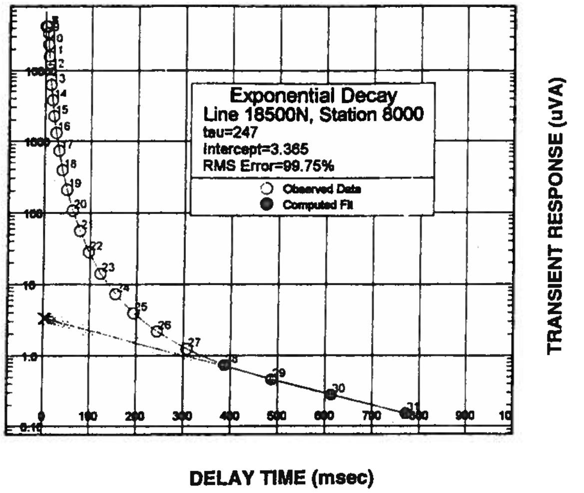


FIG 7 - Decay curve analysis from a log-linear curve of time verses transient response for station 8000 mE of line 18500 mN.

Downhole conductivity logs from borehole 93HWD276 (Figure 8) confirmed the Wedgetail mineralisation is strongly conductive, and highlighted increased conductivity over the disseminated mineralisation immediately above the massive mineralisation.

EM surveys over the rest of the prospect failed to locate additional conductors even though thin massive sulphides were intersected in several drillholes elsewhere in the prospect. In the Honeymoon Well area strong continuous conductors are required before a measurable EM response is obtained.

Downhole time domain electromagnetics

Downhole SIROTEM surveys, using fixed-surface transmitter loops (300 x 500 m) and downhole receiver profiling, were completed in several holes at the Wedgetail deposit. The transient response (axial component) was measured for standard 2 Hz delay times using a GDP-16 receiver and GGT-25 transmitter at 10 m downhole intervals. Anomalous responses attributable to the conductive mineralisation were detected as in-hole and off-hole responses. An example of an in-hole response of the Wedgetail mineralisation can been seen in Figure 9.

Hole 92HWD157 intersected patchy disseminated mineralisation (<2 per cent sulphides) from 200 to 248 m. The massive mineralisation (70 per cent sulphides) occurs as a thin narrow band (0.3 m) beneath the disseminated mineralisation. The down hole EM response at 240 m correlates with the thin

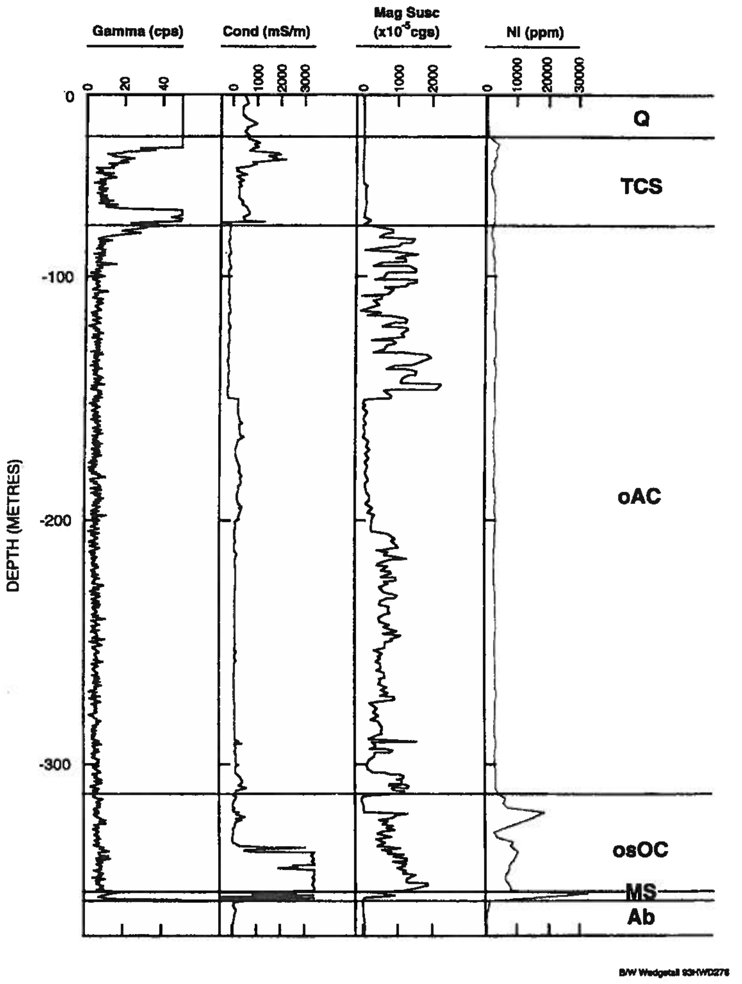


FIG 8 - Gamma, magnetic susceptibility and conductivity logs at Wedgetail for drillhole 93HWD276.

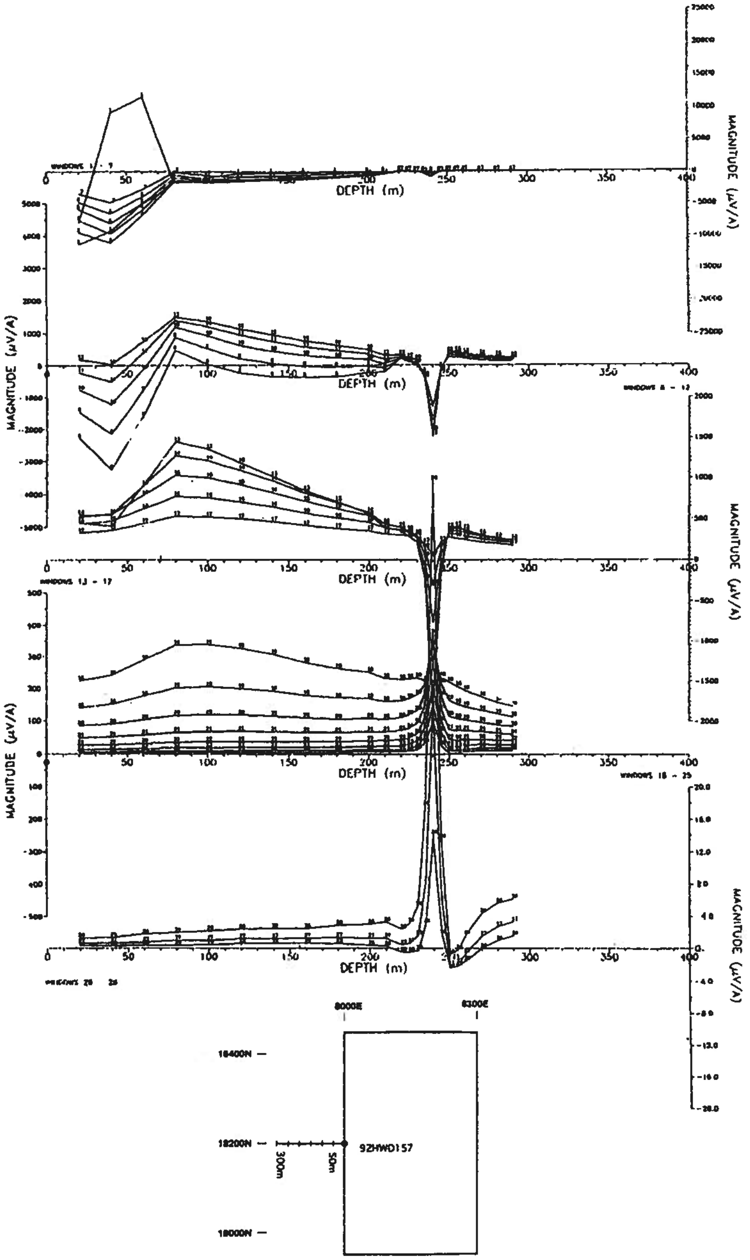


FIG 9 - Down hole EM results at Wedgetail for hole 92HWD157.

TABLE 2

Theoretical IP response from a layered conductive half space using a fundamental frequency of 0.125 Hz.

Induced Polarisation (mrad)

N-spacing	0.125 Hz	0.375 Hz	0.625 Hz	0.875 Hz	1.125 Hz	Three-point decoupled phase
1	5	14	23	31	40	0.50
2	9	26	42	58	73	0.13
3	12	37	60	82	103	-1.25
4	16	47	77	105	132	0.13
5	20	57	93	127	159	1.13
6	23	68	109	148	185	-1.00

massive sulphide zone. The observed sign reversal from mid- to late-times are related to the expansion and contraction of eddy currents within the sulphide zone across the position of the drillhole (see Macnae and Staltari, 1987; Lane, 1987). An early time response due to the conductive overburden is also present from 0 to 80 m.

Induced polarisation/resistivity

In 1981 a time domain IP survey using a 100 m dipole-dipole array was carried out over the Honeymoon Well ultramafic sequence to target disseminated sulphide mineralisation. Unfortunately the conductive surface material and the low powered transmitter caused low signal to noise ratios adversely effecting data quality and production deeming the technique impractical for the area.

In 1994 the complex resistivity method was trialed using a Zonge receiver (GDP-16) and high-powered transmitter (GGT-25) with a dipole-dipole array and an electrode spacing of 100 m. In order to gain effective coverage additional steps were taken to help negate the masking effects of the cover sequence. Careful signal monitoring, high transmitter currents and three-point decoupling (see Zonge, 1994) enabled the separation of the apparent IP from inductive coupling effects.

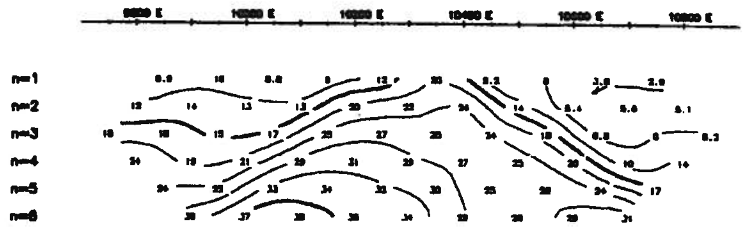
To test how effective the three-point decoupling algorithm was in Honeymoon Well environment the theoretical EM coupling response was calculated using the program IPEM3D (see Newman *et al*, 1986). The chargeability effect from a layered half space (75 m of one ohm-m material over a 600 ohm-m basement) with zero IP response was calculated from a 100 m grounded wire using frequencies which approximate those collected in the field. These results (Table 2) show that significant EM coupling effects (23 mrad at 0.125 Hz and n = 6) can be effectively removed using the three-point decoupling algorithm. This confirmed that the decoupled phase is a good approximation of the true IP response at Honeymoon Well.

Complex resistivity dipole-dipole induced polarisation data from Honeymoon Well has mapped out numerous zones of elevated chargeability. These zones are due to either fine grained sulphides (low grade), disseminated magnetite or nickel mineralisation. All of the known nickel deposits are associated with an induced polarisation response. The decoupled responses are typically 15 - 25 mrad. Downhole induced polarisation has confirmed that the nickel mineralisation is chargeable (>50 mrad). Survey results from the Corella deposit are presented as pseudosections of apparent resistivity, raw phase (0.125 Hz) and the three-point decoupled phase in Figure 10, and downhole logs of IP, conductivity, magnetic susceptibility and natural gamma in Figure 11.

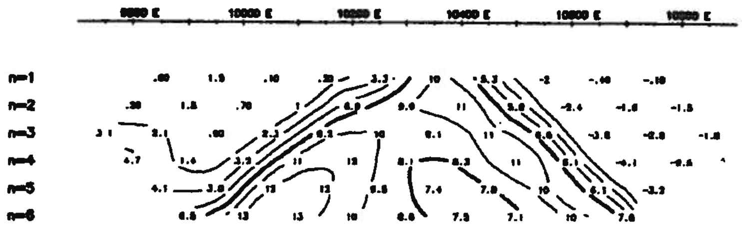
CONCLUSIONS

The Honeymoon Well nickel deposits, particularly those composed of disseminated sulphides, represent a challenging target for most geophysical techniques because of the conductive overburden material, depth of weathering and the subtle physical property contrasts between barren and sulphide-bearing rocks. The combination of detailed airborne magnetics, surface IP/resistivity and surface time domain EM have proven to be the most effective geophysical methods in locating mineralisation at Honeymoon Well.

RAW PHASE 0.125 HZ (milliradians)



3-POINT DECOUPLED PHASE (milliradians)



APPARENT RESISTIVITY (ohm metres)

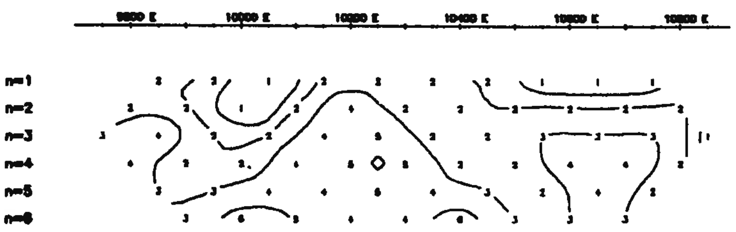


Fig 10 - Complex resistivity IP (100 m dipole-dipole) results at Corella for line 16 200 mN. The interpreted geological section for this line is shown in Figure 3.

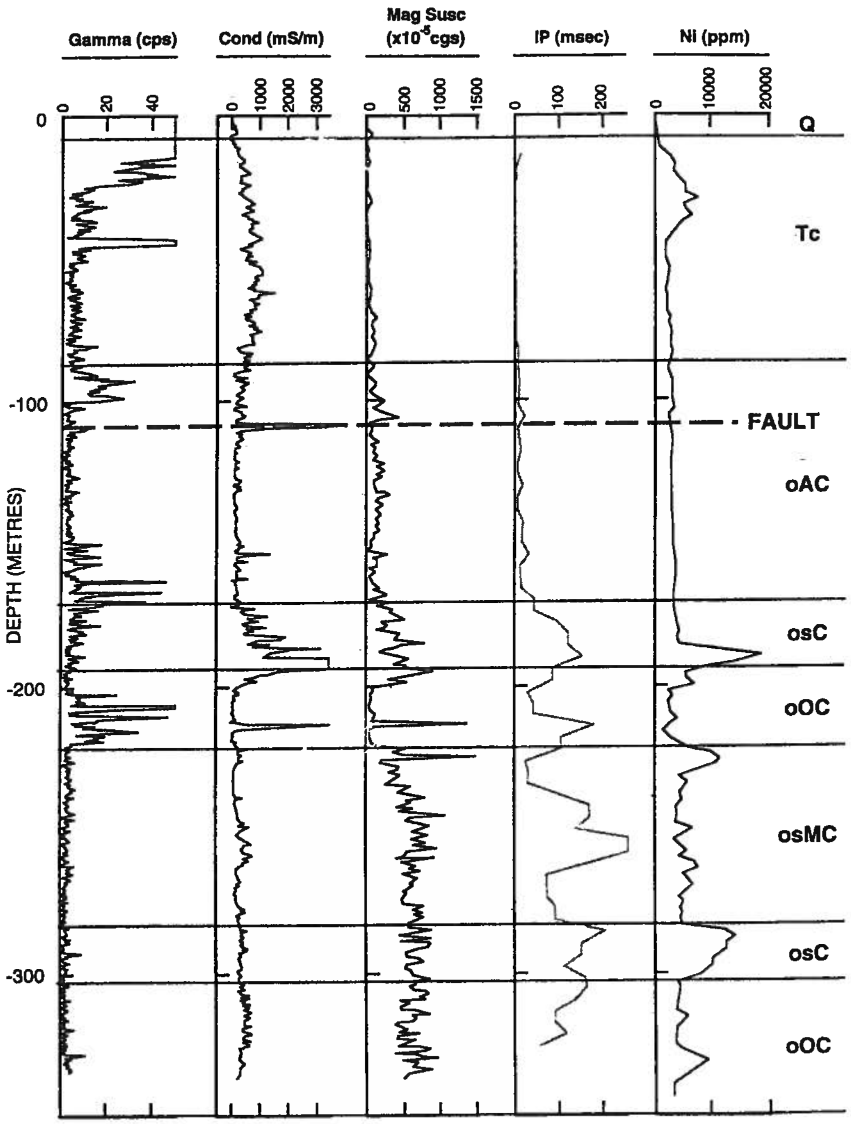


FIG 11 - Gamma, magnetic susceptibility, conductivity and IP logs at Corella for drillhole 95HWD703.

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