The role of geophysics in the discovery and delineation of the Cosmos Nickel Sulphide Deposit, Leinster area, Western Australia

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INTRODUCTION

The Cosmos nickel deposit is located approximately 40 km south of the Mt. Keith nickel mine in the Kathleen Valley portion of the Norseman-Wiluna greenstone belt, in the northeast of the Yilgarn Craton of Western Australia (Figure 1a). Jubilee Gold Mines NL intersected massive nickel sulphides in the predicted position in the first diamond hole drilled to test the conductor. The limited depth extent of the conductor suggested by the modelling was confirmed by subsequent drilling and downhole TEM surveys. Detailed ground and aeromagnetic data subsequently collected over the deposit defined the host ultramafic well, but did not clearly distinguish the magnetic massive sulphide zone. The significance of the Cosmos TEM surveys was their ability to quickly and accurately focus drilling on the small but high-grade massive sulphide lens within the much larger mineralised halo.

The Cosmos mineralisation has a strike length of approximately 260 m, a depth extent of up to 140 m in fresh rock and an average true width of 7 m (maximum 20 m). It consists of lenses of massive felsic volcanics and volcaniclastics forms the footwall to the ultramafic varying in thickness from about 150 m at the southern tenement boundary to pinching out to the north of the deposit. A thick sequence of relatively massive felsic volcanics and volcanics forms the footwall to the Cosmos deposit. Traces of pyrite, sphalerite, chalcopyrite, pyrrhotite and galena occur in the upper part of this felsic unit.

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EXPLORATION HISTORY

Prior to Jubilee’s 1997 exploration programme, a number of other companies had evaluated the nickel potential of the Kathleen Valley area. Several holes were drilled in the vicinity of Cosmos during the nickel boom of the late 1960s and early 1970s. A diamond drill hole was collared in the felsic footwall near the southern end of the Cosmos deposit and drilled towards the southeast into the mineralised ultramafic. This hole tested the...
Fig. 1a. Regional geology of the Kathleen Valley area of the Norseman-Wiluna greenstone belt, showing the location of the Cosmos nickel-sulphide deposit.

Fig. 1b. Geology of the Cosmos area, showing the location of the Cosmos deposit and the location of the transmitter loop used for DHEM surveys. The Cosmos ultramafic referred to in the text is the southern mineralised portion of the eastern ultramafic.
Cosmos ultramafic sequence about 150 m south of the deposit, but failed to intersect significant nickel-sulphide mineralisation.

During their extended involvement in the region (1987-present), Jubilee's exploration activities were primarily focused on gold, resulting in the delineation of several, currently sub-economic, gold deposits located in the central part of the Kathleen Valley project area. Surface mapping and interpretation of an aeromagnetic survey flown during 1995 identified the presence of substantial thicknesses of ultramafic rocks in the southern part of the project area. However, this work stopped about 400 m north of Cosmos.

In early 1997, the company decided to focus on nickel, based on modern geological models, e.g., Hill and Gole (1990). Exploration commenced in the southern ultramafic sequence, using a combination of surface prospecting and reconnaissance RAB drilling. Drill lines located immediately south of the Cosmos deposit confirmed the presence of ultramafic rocks and returned geochemical analyses strongly anomalous in elements indicative of nickel-sulphide mineralisation. Follow-up RC drilling intersected several wide zones of disseminated nickel-sulphide mineralisation.

Jubilee decided to undertake a moving-loop TEM survey with the objective of detecting massive nickel sulphide zones along the ultramafics. The Cosmos conductor was detected on the second line (6944550N) of the survey (Figure 2). A line of RAB holes was drilled along line 6944550N to investigate the peak of the EM response. One of the holes on this traverse intersected a gossan developed above the massive sulphide body. Samples from this hole returned strongly anomalous nickel, copper and platinum-group elements. The prospective geology and highly anomalous geochemistry supported diamond drilling to test the strong bedrock conductor. The design of the initial core holes was based on the conductor location as determined by quantitative modelling of the late delay time response from a subsequent fixed-loop TEM survey.

The first diamond drill hole, JCD-001, on line 6944580N (Figure 4), intersected about 9 m of massive and disseminated pyrrhotite-pentlandite mineralisation, including 3 m grading 7.5% Ni, close to the target depth predicted by the TEM modelling. The second diamond hole, JCD-002, drilled on line 6944540N (Figure 5), encountered over 22 m of massive nickeliferous sulphides, including an intersection of 18 m at 10.67% Ni.

During the detailed surface inspections that followed the initial drilling success, two small subcrops of gossan were recognised as the weathered surface expressions of the Cosmos massive sulphide body on line 260600E at 6944580N and 6944520N.

SURFACE TRANSIENT ELECTROMAGNETIC SURVEYS

Cosmos moving-loop survey

The 1997 moving-loop TEM survey employed a standard, single turn, medium power, 100 m x 100 m in-loop configuration, with data collected at 50 m intervals on lines mostly 200 m apart. In the prevailing moderate background conductivity conditions, transient decays were normally read to delay times of about 17 ms, with the signal typically decaying into noise levels by 5 ms.

A distinct, well-defined mid- to late-time anomaly was detected on the second line (6944550N) of the planned survey (Figure 2). A slightly weaker, less well defined anomaly was detected on the adjacent line to the north (6944700N; Figure 3). On line 6944550N, the anomalous profile shows a possible double-peak anomaly, centred at 260600E, with a magnitude of about 5 μV/A on the latest delay channel collected (channel 26 - 17.4 ms delay). The double-peak character of the anomaly, with a slightly higher eastern peak, suggested a steep, easterly dip for the source conductor. The estimated depth to the top of the conductor was approximately 50 m, the likely depth of oxidation. No quantitative modelling was attempted to confirm these visual estimates. Analysis of the anomalous decay curves, e.g., 260650E, 6944550N, indicated a time constant of the order of about 14 ms (Figure 6). The decays do not display a classical, distinctly linear late-time pattern on the log-linear plot, possibly because the field data were not collected to late enough delay times.
Fig. 4. Geological cross section along line 6944580N showing the surface fixed-loop TEM FILAMENT model of the Cosmos conductor, and the late-time DHEM data and modelled conductor from the discovery drill hole, JCD-001.

Fig. 5. Geological cross section along line 6944540N, showing the surface fixed-loop TEM FILAMENT model of the Cosmos conductor, and the late-time DHEM data and modelled conductor from drill hole JCD-004.
TEM data from lines 6944350N and 6944900N, to the immediate south and north of the Cosmos massive sulphide, did not contain recognisable anomalous responses along strike from the Cosmos conductor. Contours of the moving-loop TEM amplitude data for the Cosmos area are included as Figure 7.

In summary, the anomalies on lines 6944550N and 6944700N display characteristics consistent with a shallow to moderate depth, short strike length conductor. The location of the conductor, or near, the ultramafic contact confirmed it as a high priority nickel-sulphide exploration target warranting immediate follow-up.

Cosmos fixed-loop survey

A large, fixed transmitter loop TEM survey was used to confirm and detail the Cosmos moving-loop TEM anomaly, with X-, Y- and Z-component data collected at 50 m intervals on six 100 m spaced lines over the Cosmos anomaly. Figures 8a and 8b show the Z- and X-component profiles for line 6944600N over the centre of the orebody and Figure 9 shows the late-time amplitude contour plan for the X-component channel 20 (5.8 ms).

The results of the fixed-loop survey confirmed the position and orientation of the conductor interpreted from the moving-loop data. Ideally the transients should have been read to later delay times, but the strength of the conductor and the relatively large conductivity contrasts meant there were no significant interpretation problems using this mid decay range data. The fixed-loop data indicate time constants of about 12.5 ms, similar to those obtained from the moving-loop survey (Figure 6). The absence of classical, linear decay in the fixed-loop data indicates that true, late-time behaviour (confined secondary current) was not achieved in the time range measured.

After initial visual interpretation, forward and inverse modelling of the fixed-loop TEM data was undertaken, using the FILAMENT program. This software package uses elliptical or rectangular current loops to approximate the induced EM fields in a target conductor. Modelling concentrated on the channel 20 (5.8 ms) data, using the three-component information from all six profiles simultaneously. Channel 20 data were used because the majority of the responses attributable to surficial and background conductivity had decayed, but the strong signal from the Cosmos conductor remained. In retrospect, a model using the channel 26 data would have been preferable as it would better display the high conductance of the Cosmos ore body.

Modelling of the fixed-loop data provided clear indications of the dip and depth of the conductor and some idea of its limited depth extent. Several starting models were evaluated with the best fit to the field data obtained using a steep, east-dipping source. The model indicated that the strongly conductive source was a north-striking, east-dipping (approximately 65°), tabular body, about 150 m long, with a depth extent in the 150-300 m range. The depth to the top of the conductor was estimated at about 50 m, the anticipated depth of oxidation. The depth extent of the conductor was difficult to resolve. Models using extents in the 150-400 m range produced similar fits.

The initial diamond drill holes (JCD-001, JCD-002) testing the Cosmos target were designed to intersect the simple, 'best fit', plate-like conductor at about 100 m below surface (~125 m downhole). This hole design catered for reasonable variations in the modelled dip and depth of the target. Diamond drill hole JCD-001, collared at 260675E on line 6944580N and inclined at 60° to the west, intersected massive and disseminated pyrrhotite-pentlandite mineralisation at the contact between the host ultramafic and underlying felsic volcanics (Figure 4). Massive sulphides were encountered at about 120 m downhole (approximately 105 m below ground level) which correlated well with the position of the easterly dipping conductor predicted by the channel 20 FILAMENT modelling.

Upon the successful completion of JCD-001, a second diamond hole (JCD-002) was collared 40 m to the south on line 6944540N (Figure 5). This hole intersected massive nickeliferous sulphides from about 115 m downhole (100 m below surface), which also correlated well with the predicted conductor location. The correlations between the modelled conductor and the massive sulphides on the discovery lines 6944580N and 6944540N, are shown on Figures 4 and 5. Subsequent drilling and downhole EM (DHEM) surveys confirmed that this thick sulphide zone forms the core of the Cosmos conductor.

DOWNHOLE ELECTROMAGNETIC SURVEYS

Encouraged by the results of the two diamond drill holes, an intensive drilling programme was undertaken to evaluate the dimensions of the Cosmos sulphide body. The results of some holes in this programme were disappointing, with the next two holes failing to intersect substantial sulphide zones. The size and geological complexities of the Cosmos sulphide body were becoming apparent.

DHEM surveys were employed to help clarify the geometry of the sulphide zone and to expand the effective search radius of the drilling. Crone Pulse EM equipment was used to collect three-component (axial Z and radial X+Y) DHEM data in several campaigns during the Cosmos evaluation drilling. Readings, normally to delay times of about 40 ms after turn off, were...
collected at 10 m intervals downhole, with the reading interval reduced to 5 m through complex anomalous zones. Holes JCD-001 to JCD-012, from the initial phase of diamond drilling, were surveyed using a single 300 m x 300 m transmitter loop located in the hanging wall of the mineralised ultramafic, to optimise coupling with the massive sulphide zone (Figure 1b). Subsequent DHEM campaigns employed large (up to 600 m x 300 m), well-coupled transmitter loops rather than multiple, smaller, variably coupled transmitter loops. The DHEM data were interpreted using a combination of standard visual techniques and FILAMENT modelling of selected (mostly late) time channels.

As expected, the highly conductive Cosmos sulphide body proved to be ideal for mapping with DHEM. Numerous classical intersection, near-miss and off-hole responses were obtained during the course of the campaigns. The nature of these responses was similar to those observed from other nickeliferous massive sulphides in the Yilgarn Craton, e.g., Amann and Pietilä (1998), Trench and Williams (1994).

DHEM data from the JCD-001 (Figure 4) and JCD-002 (Figures 5 and 10) holes display typical, complex, short-wavelength responses coincident with the sulphide intersections obtained in these holes. By comparison, the DHEM from holes drilled below, along strike or into the footwall and hanging wall of the Cosmos deposit, e.g., JCD-004, (Figure 5) displayed classical, longer wavelength responses typical of a high conductance, off-hole source. Modelling of the late-time (30-40 ms) DHEM data showed consistent correlation between simple plate conductors and the drill-defined massive-sulphide body. The positions of the modelled conductors on the discovery sections are shown on Figures 4 and 5.

A major exploration objective of the DHEM programme was to identify deep or lateral repetitions of the massive sulphide that had not been recognised in the surface EM surveys. Of particular interest in the early stages of the drilling programme was the clarification of the down-dip extent of the sulphide zone. During the delineation drilling it had quickly become evident that the southern part of the main sulphide body was restricted at relatively shallow depths by what appeared to be a late dolerite intrusive. At the time, the thickness and orientation of the dolerite was unknown.

DHEM was used in the search for the down-dip continuations of the Cosmos mineralisation below the dolerite body. Strong, well-defined, late-time responses indicative of a substantial off-hole conductor were present in most of the logs from drill holes that had not intersected the orebody. Unfortunately, all of these responses were clearly from a strongly conductive body above the drill holes, i.e., the Cosmos massive-sulphide body.

The results of the DHEM surveys indicated that the dolerite had restricted the down-dip extent of the southern part of the orebody. However, the emplacement of this intrusive had probably caused substantial thickening of the southern portion of the sulphide lens. This thickened zone contributes substantially to the effective conductance of the orebody.

DHEM data from holes drilled through the sulphide body provided useful semi-quantitative information on the local geometry, continuity and extent of the conductive mineralisation. The DHEM data confirmed the dimensions and orientation of the Cosmos massive-sulphide body. Quantitative interpretation of long-wavelength, late-time, off-hole DHEM anomalies showed that the Cosmos conductor was recognisable in holes 150-200 m from the core of the sulphide body. This confirms the high conductance of the conductor and the potential of the method as an exploration tool for blind massive-sulphide bodies.

Fig. 7. Moving-loop TEM Z-component contours for Channel 23 (10.2 ms) showing the short strike length Cosmos conductor at the southern end of the survey. Anomaly amplitude is 8 µV/A.
MAGNETICS

Prior to the discovery, Jubilee did not have detailed magnetic data over the Cosmos area. The 1995 Kathleen Valley aeromagnetic survey (40 m spaced east-west lines, ground clearance 40 m) stopped about 400 m to the north of the orebody. This survey had mapped a strike extensive ultramafic unit about 500 m to the northwest of Cosmos (the ‘western ultramafic’ in Figure 1b), but its relationship to the Cosmos ultramafic was unclear. After the discovery, detailed ground and aeromagnetic data were collected over the deposit and the surrounding area.

To date, no systematic magnetic susceptibility measurements have been made on either the Cosmos mineralisation or the major lithologies intersected during drilling. However, the pyrrhotite-rich sulphide assemblage is distinctly magnetic, as are the host ultramafics, which may contain in excess of 5% magnetite.

In the initial ground magnetic survey, data was collected at a 5 m station spacing on 25 m spaced lines (Figure 11). As is common in the Yilgarn Craton, this dataset contained substantial high-frequency ‘noise’ from near-surface alluvial and lateritic magnetic material. However, the survey clearly defined the strongly magnetic host ultramafic, which produced a peak anomaly of about 2000 nT, contrasting strongly with the virtually non-magnetic footwall and hangingwall lithologies. The response from the distinctly magnetic, pyrrhotite-rich sulphide body is not distinguishable from that of the ultramafic host unit, which includes a significant high-frequency component resulting from the thick, near-surface ironstone cap (Figure 12). This inability to discriminate the ore and host magnetic responses is not unusual for this style of deposit, e.g., McCull et al. (1995).

Contours of the ground magnetic data (Figure 11) demonstrate that the Cosmos ultramafic pinches out at surface to the north of the Cosmos conductor. However, reliable interpretation of the magnetic data is severely hindered by the near-surface noise. The current geological interpretation (Figure 1b), from drilling and surface mapping, has the Cosmos ultramafic terminated by the felsic porphyry intrusive crosscutting the sequence from the hanging wall. The magnetic data clearly demonstrate that there is no direct, near surface connection between the Cosmos ultramafic and the western ultramafic that extends more or less continuously over 15 km to the northern end of Jubilee’s Kathleen Valley project area (Figure 1a).

A detailed aeromagnetic survey was flown on 25 m spaced lines, with a nominal sensor height of 25 m above ground level and an along-line reading interval of about 6 m. The objectives of this survey were to extend the detailed coverage obtained via the ground magnetics and to obtain data over Cosmos that was less affected by near-surface magnetic material. These objectives were achieved, however, the Cosmos orebody is not recognisable in this better quality magnetic data.

To the west and north of Cosmos, the magnetics suggest that relatively low-angle thrust (?) faults (mostly northeast-trending), may be superimposed upon a regional, north-trending, strike-slip fault system. The significant disruption and rotation of ultramafic fault blocks evident in the magnetics could be generated by the interaction between the northeast- and north-trending fault sets. These interpreted low-angle structures are difficult to confirm geologically or geophysically, but are consistent with the structural regime recognised in the Yakabindie deposits further to the north along the ultramafic belt (Figure 1a; Hill, 1982).

Fig. 8. Fixed-Loop TEM data along line 6944500N. (a) Z-component, (b) X-component.
Fig. 9. Fixed-loop TEM data X-component contours for Channel 20 (5.8 ms) showing the short strike length Cosmos conductor. Contour interval is 0.2 $\mu$V/A.

Fig. 10. DHEM data from drill hole JCD-002 showing complex intersection responses from upper and lower massive sulphide zones.

Fig. 11. Total field magnetic contours (nT) for the Cosmos detailed ground magnetic survey.
Geophysics of the Cosmos nickel sulphide deposit

The Cosmos deposit is by no means a difficult exploration target for currently available exploration technology. It is a subcropping massive-sulphide body in a strongly nickel-mineralised ultramafic province which contains two major producing nickel mines (Mt. Keith to the north and Leinster to the south) and several undeveloped nickel deposits (Hill and Gole, 1990). The effect of near-surface conductivity on electromagnetic responses is relatively benign. Yet this relatively small but very valuable resource remained undiscovered despite recognition of the potential of the area and drill testing by several proficient exploration groups. This is an indication of the inherent difficulties involved in accurately locating a relatively small nickel-sulphide body within deeply weathered terrain and the value and effectiveness of TEM in such exploration.

The geophysical character of the deposit is consistent with that reported for similar nickelliferous massive-sulphide deposits in the Yilgarn Craton (Trench and Williams, 1994; Mutton and Williams, 1994). No new or innovative geophysical approaches were employed at Cosmos, but the careful application of established geophysical methodology, particularly TEM, had a significant impact on the exploration programme.

The major contribution of the initial TEM survey to the Cosmos discovery was its ability to focus exploration quickly and accurately on the high value, massive-sulphide orebody contained within the much larger mineralised halo. The initial (pre-discovery) interpretation of the position, orientation and extent of the conductor, based on simple, quantitative modelling of the fixed-loop TEM corresponds very well with the actual distribution of the Cosmos orebody. The horizontal dimensions of Cosmos are not atypical for this type of deposit. There are no convincing indications of the conductor on the moving-loop TEM traverses 200 m to the north and south of the original anomalous traverses. Thus, detailed geophysical surveys are required to ensure its recognition.

Conversely, because the volume of magnetic sulphide in the orebody is relatively minor compared with the volume of strongly magnetic host rock, there is insufficient contrast between the magnetic response of the pyrrhotitic sulphides and the magnetite-rich ultramafic to enable the orebody to be recognised and targeted from detailed, high-precision magnetic surveys.

The discovery of the Cosmos orebody emphasises that an integrated approach to exploration utilising all available information and techniques maximises the chances of exploration success.

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Fig. 12. Profile of detailed ground magnetic data along line 6944500N with modelled geology. The Cosmos massive sulphide is located at 260600E at the base of the Cosmos ultramafic.

DISCUSSION AND CONCLUSIONS

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