

The Maggie Hays and Emily Ann nickel deposits, Western Australia: A geophysical case history

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Key Words: Electromagnetics, Emily Ann, induced polarisation, Maggie Hays, magnetics, nickel sulphides

ABSTRACT

Geophysical techniques played a significant role in the discovery of the Emily Ann massive nickel-sulphide deposit and extensions to the Maggie Hays deposit, which are associated with komatiitic olivine cumulate ultramafic rocks, in an Archaean greenstone belt located about 500 km east of Perth, Western Australia.

Detailed aeromagnetic surveys were used to outline komatiitic rocks and structures. Physical property measurements on drill core showed the mineralisation to be highly conductive and magnetic. Trial induced polarisation, audio magnetotelluric and time-domain electromagnetic (TEM) surveys indicated that the latter had the most potential for detecting the nickel-sulphide mineralisation.

The Maggie Hays deposit comprises both disseminated and massive nickel-sulphides concentrated at the base of an ultramafic unit 200-500 m below the surface. A limited moving-loop TEM survey in 1992 located an anomaly immediately north of the main part of the deposit. Diamond drilling of this anomaly failed to discover extensions to the deposit or explain its source. In 1995, a fixed-loop TEM survey delineated an excellent response confirming the earlier moving-loop anomaly, which when drilled, resulted in the discovery of the Maggie Hays North zone 100 m below the surface.

A moving-loop TEM survey resulted in the discovery of the blind, high-grade Emily Ann nickel-sulphide deposit 3 km north of the Maggie Hays deposit, at a depth of 120 m. Downhole TEM surveys aided delineation diamond drilling of the deposits with the location of extensions of mineralisation.

High-powered, late-time moving-loop TEM, with fixed-loop TEM follow up, is currently being used routinely to explore for additional deposits. However, the highly conductive overburden response obscures the signal from bedrock conductors, which are often represented only as low-amplitude, late-time anomalies. Geophysical targeting is further complicated by the close proximity of highly conductive barren banded iron formation-hosted massive sulphides. Trial airborne EM surveys have detected Maggie Hays North, but not Emily Ann and probably not the Maggie Hays main zone.

INTRODUCTION

The Lake Johnston nickel-sulphide deposits are located 500 km east of Perth, Western Australia at 32°15'S, 120°30'E on the Lake Johnston (SI51-1) 1:250 000 scale map sheet (Figure 1). LionOre Australia (Nickel) Pty Ltd (LionOre) and QNI Limited (QNI), who have been exploring the belt as a joint venture since mid-1994, jointly own the deposits. Exploration has located two main deposits. The Maggie Hays deposit contains inferred and indicated resources of 11.9 Mt at 1.47% Ni, comprising a main disseminated and massive-sulphide zone and a northern massive-sulphide-stringer zone. The Emily Ann deposit contains inferred and indicated resources of 2.17 Mt at 3.71% Ni and is predominantly massive sulphides.

EXPLORATION HISTORY

Nickel exploration at Lake Johnston from 1966 to 1971 involving Laporte Mining (Laporte) and Union Miniere located near-surface anomalous nickel and copper in the weathered zone at Maggie Hays. Follow-up of anomalous nickel assays in soil samples and shallow drill holes, by Amoco in 1981, intersected nickel-sulphide mineralisation at Maggie Hays with at least one hole intersecting the margin of the main zone. Time-domain electromagnetic (TEM) surveys located an anomaly over Maggie Hays North. However, no follow-up drilling was undertaken due to the prevailing low nickel price.

In 1991 and 1992, Forrestania Gold NL (Forrestania) carried out further exploration at Maggie Hays including surface and downhole TEM (DHEM) surveys. The TEM anomaly at Maggie Hays North was confirmed, but the follow-up drill hole stopped about 20 m short of mineralisation. In 1993, deeper drilling at Maggie Hays finally succeeded in locating the main zone of disseminated mineralisation.

In 1994, Forrestania, through its fully owned subsidiary Maggie Hays Nickel NL, entered into joint venture agreement with Gencor Limited (Gencor) to explore the Lake Johnston belt. In late 1995 additional diamond drilling of the Maggie Hays North conductor finally succeeded in locating the Maggie Hays North massive-stringer sulphide zone. In 1996, extensive TEM surveys to the north and south of the Maggie Hays deposit commenced, and in early 1997, drilling of a TEM anomaly resulted in the discovery of the Emily Ann deposit.

In 1997, there were a series of corporate changes whereby Forrestania was taken over by LionOre International Mining Limited and Gencor's interest was transferred to QNI.

GEOLOGY

Regional Setting

The deposits occur within an Archaean greenstone belt approximately 100 km in length and comprising a series of cusped to linear volcano-sedimentary blocks separated by granitoid batholiths (Gower and Bunting, 1976). The simplified stratigraphy

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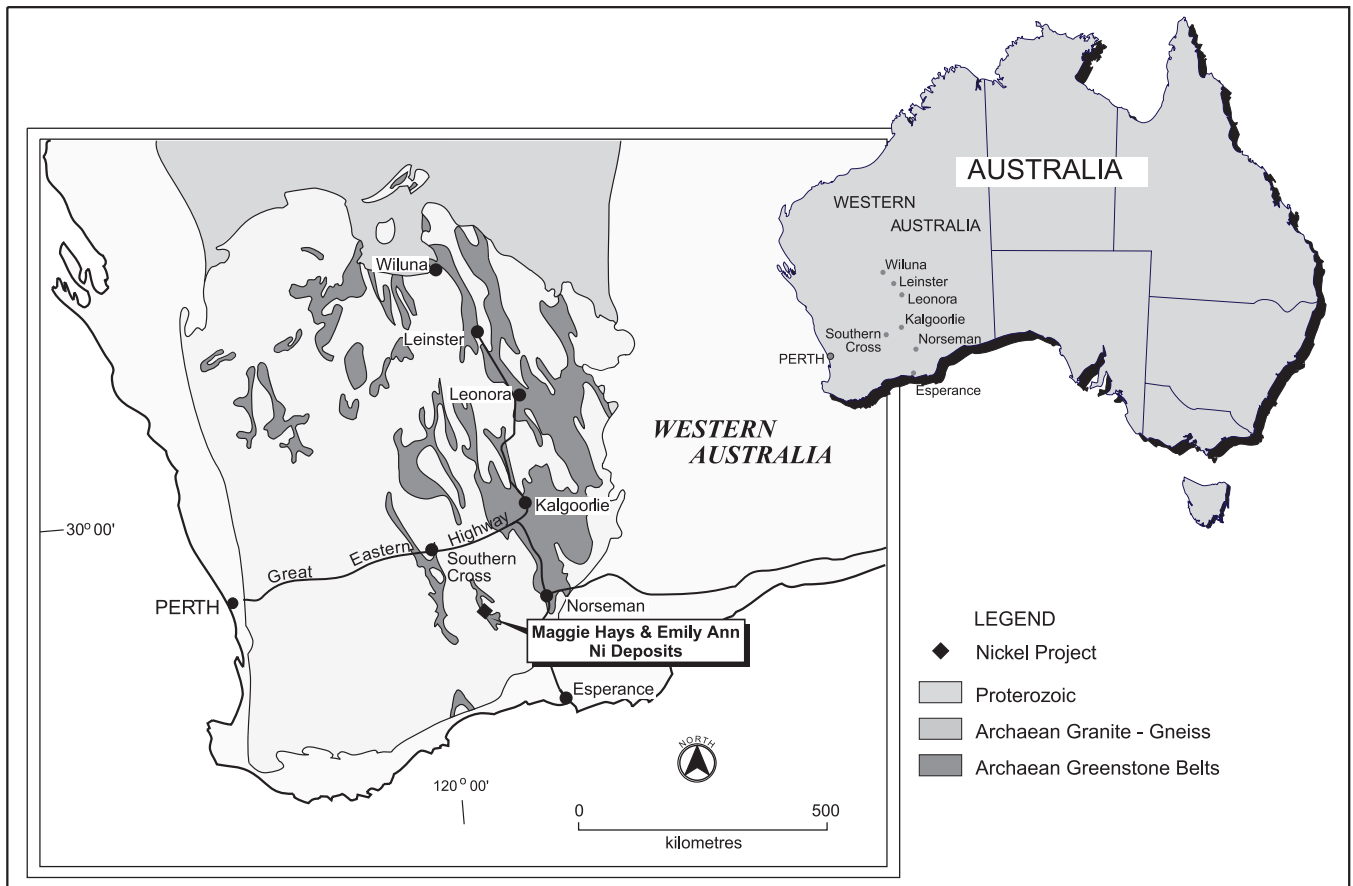


Fig. 1. Location of the Emily Ann and Maggie Hays nickel deposits, Western Australia.

of the greenstone belt can be summarised, from east to west, as follows (Buck et al. 1996):

- Mafic volcanics and intrusions with minor ultramafics
- Eastern ultramafic unit (EUU)
- Felsic to mafic volcanics
- Central ultramafic unit (CUU)
- Banded iron formation (BIF)
- Western ultramafic unit (WUU)
- Mafic to felsic volcanics

The stratigraphy strikes northwest-southeast and has variable dips ranging from flat to steeply inclined to both the east and west. Northwesterly and easterly trending Proterozoic dykes, such as the Jimberlana Dyke, cut across the stratigraphy at various locations.

The bedrock geology is obscured by deep, widespread, lateritic weathering and transported overburden. Weathering of ultramafic rocks is particularly intense. A ferruginous duricrust and underlying saprolite extend to depths of up to 80 m. Another factor, which also complicates the application of electrical and electromagnetic geophysics in the area, is the occurrence of substantial saline groundwater.

The Maggie Hays and Emily Ann Deposits, along with a series of smaller nickel-sulphide deposits, occur along a total strike distance of 12 km (Figure 2). The nickel-sulphide deposits are closely associated with the CUU, which regionally comprises the thickest occurrences of least fractionated, magnesium-rich olivine cumulate lithologies.

The ultramafic stratigraphy is complicated by a series of early strike-parallel thrust faults, which disrupt the continuity of faults

and can cause repetition of geological units. Thrusting is interpreted to be responsible for shallow dips at a number of locations. These thrusts are important controls at the Emily Ann and Maggie Hays North deposits.

The stratigraphy has been metamorphosed to amphibolite grade (Perring, 1995a, 1995b; Perring and Hill 1995; Perring et al., 1994; Buck et al. 1996). The more magnesium-rich ultramafic cumulates consist of varying proportions of serpentine and metamorphic olivine and lesser anthophyllite and talc amphibole and chlorite. Less magnesium-rich ultramafics consist dominantly of tremolite and chlorite.

Maggie Hays

The Maggie Hays deposit is blind, with the top of the main disseminated sulphide zone commencing at a depth of about 200 m beneath the surface and the massive sulphides at a depth of about 350 m beneath the surface, as shown in the cross section along 82700N (Figure 3).

The main zone of the deposit is located at the base of the CUU in association with olivine orthocumulate and mesocumulate lithologies that have subvertical dips to the east and west. Structurally, the zone occurs at a local pinch-out in the CUU against stratigraphically overlying BIF (to the west) and underlying felsic volcanics (to the east). The structural termination is controlled by an early thrust, which dips at about 50° to the east and plunges at about 45° to the south, thereby terminating the main zone of the deposit at depth. A second lower grade portion of the deposit, known as the southern zone, occurs several hundred metres to the south. The Maggie Hays North zone of the deposit is controlled by the same thrust, with the mineralisation totally hosted

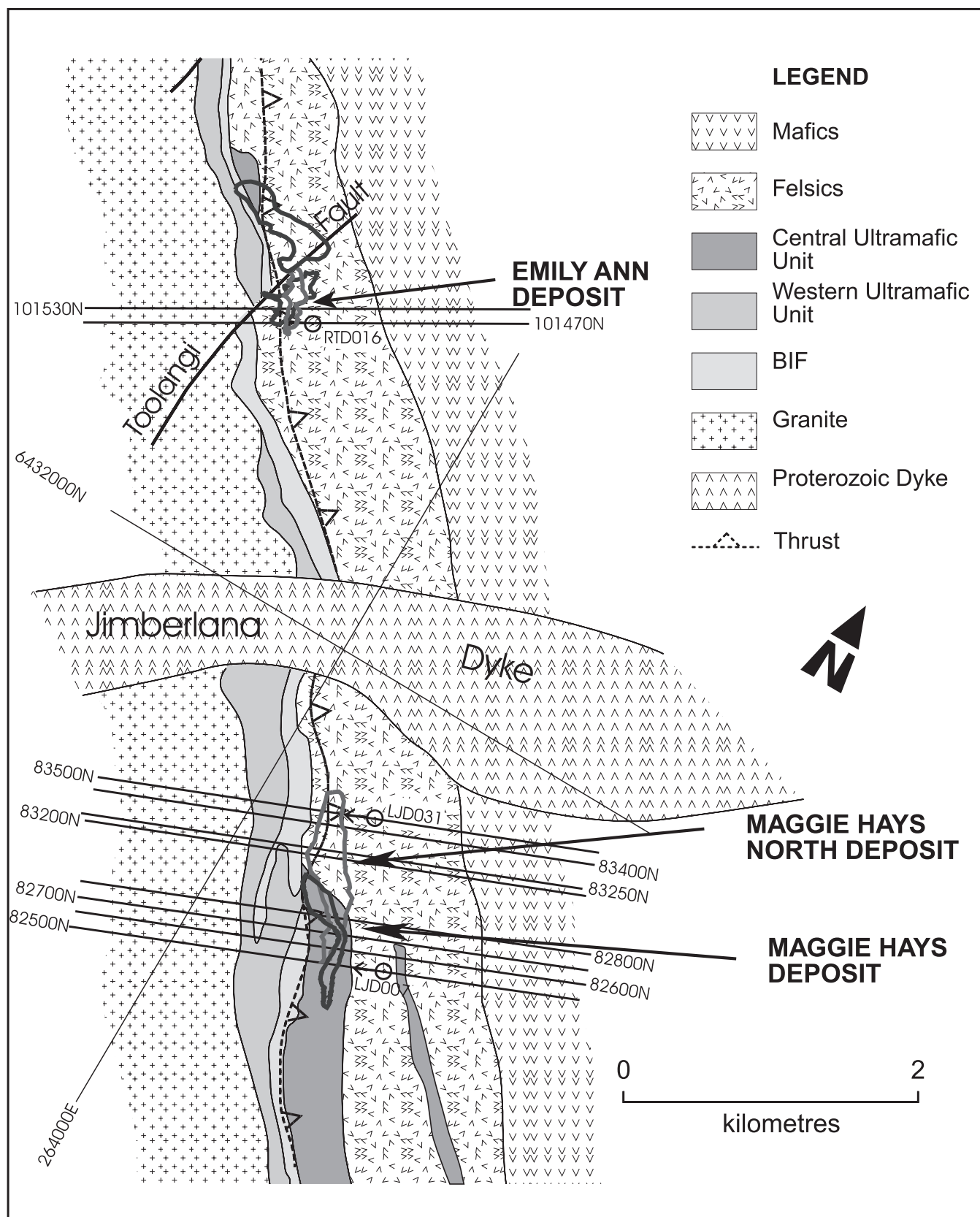


Fig. 2. Geological setting of the Emily Ann and Maggie Hays nickel deposits. Note that the Maggie Hays deposits and the Emily Ann deposit are on different grid systems. (Geology by LionOre, unpubl)

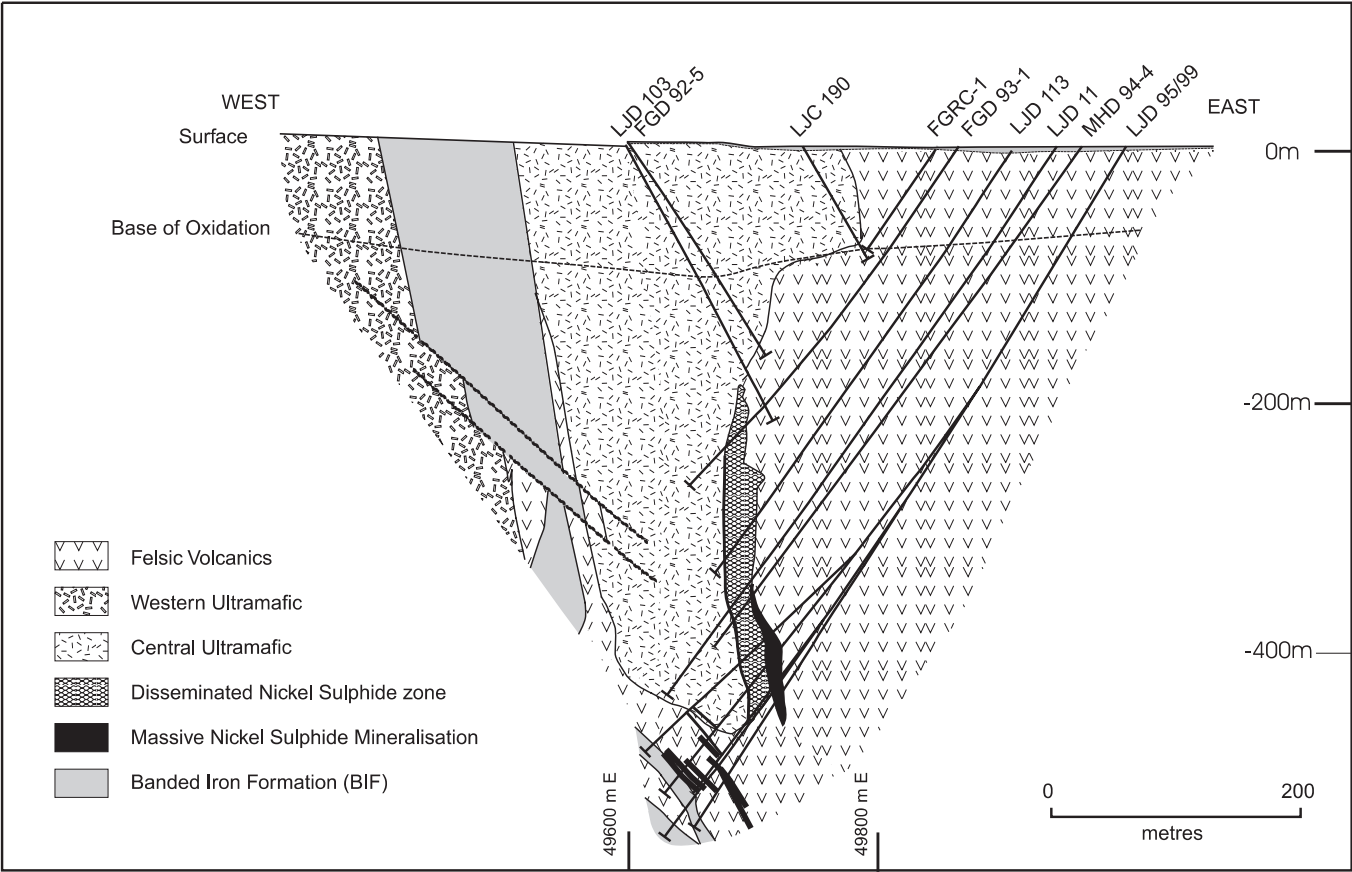


Fig. 3. Maggie Hays cross section 82700N. See Figure 2 for location.

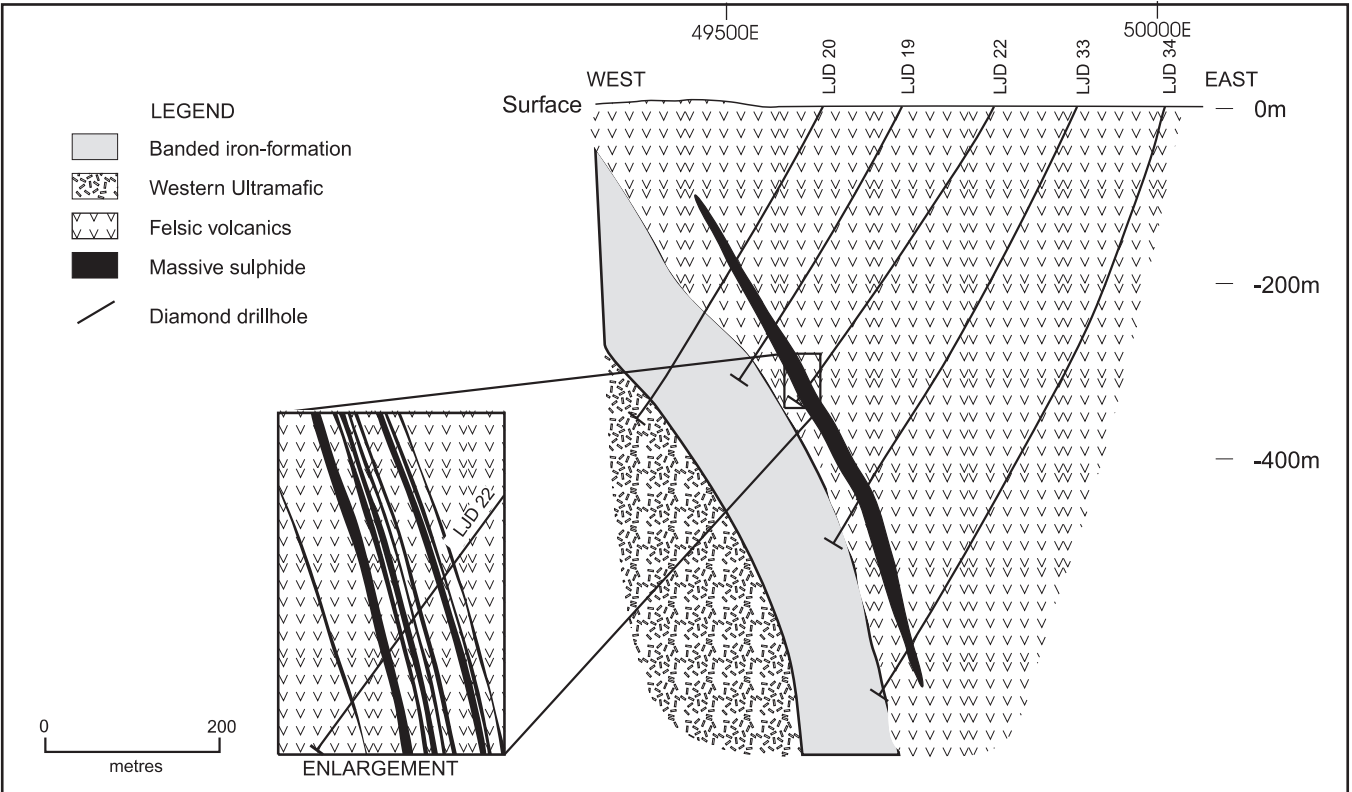


Fig. 4. Maggie Hays North cross section 83200N. See Figure 2 for location.

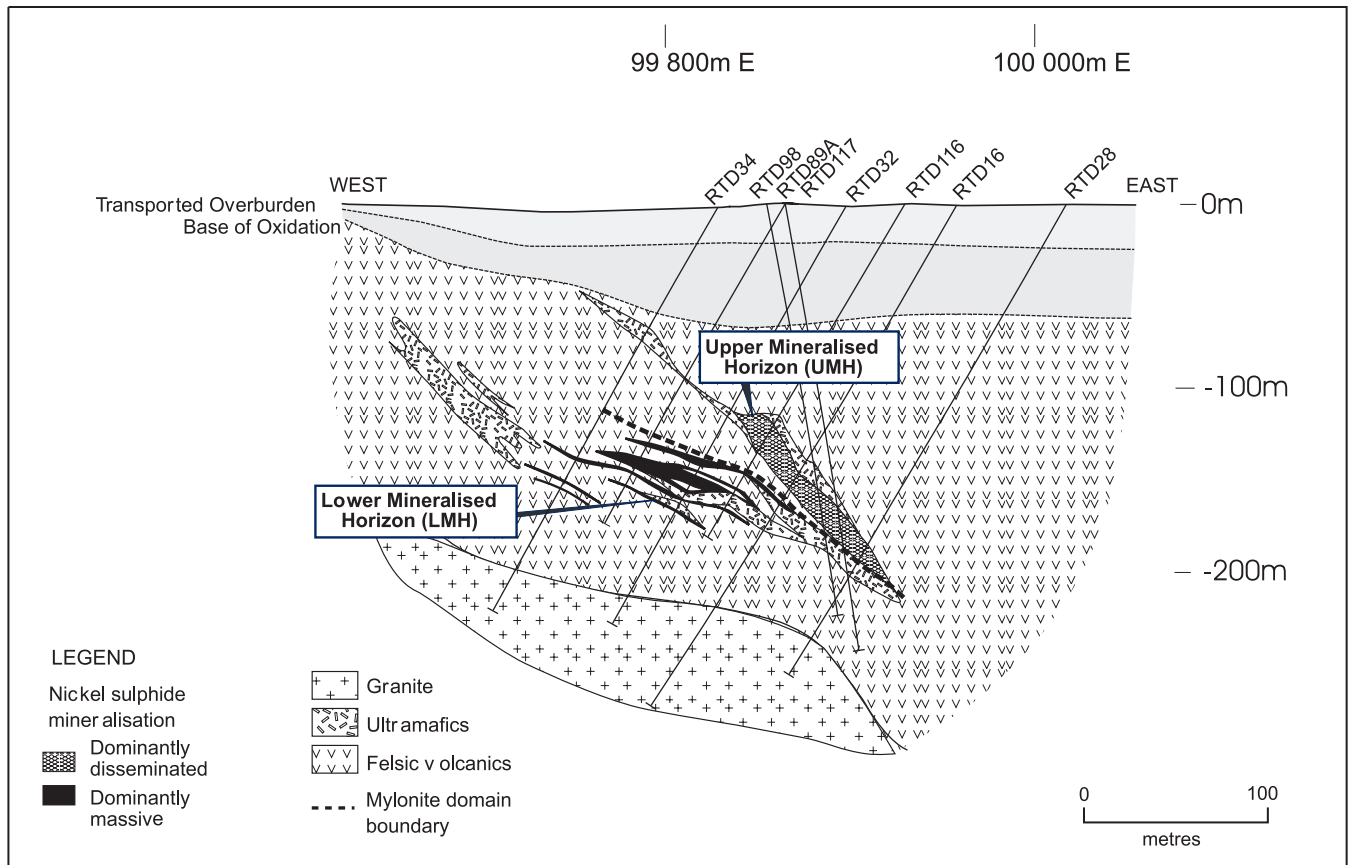


Fig. 5. Emily Ann cross section 101470N. See Figure 2 for location.

by felsic volcanics, as shown in the cross section along 83200N (Figure 4). The deposit, which consists dominantly of pyrrhotite, pentlandite and pyrite and minor chalcopyrite and violarite, can be subdivided into the following styles of mineralisation:

Main Zone:

- Located at the base of the CUU with the bulk of the deposit located between 200 and 500 vertical metres beneath the surface and over a strike extent of 600 m.
- Basal massive sulphide zone of 4-6% Ni, located towards the lower (down-dip) margin of the disseminated zone and the northern structural termination of the ultramafic.
- Upper disseminated zone of 0.3-2.0% Ni, comprising up to 40% disseminated sulphides hosted by olivine ortho- mesocumulate ultramafic serpentinised to varying mixtures of serpentine, metamorphic olivine, anthophyllite and talc.

Northern Zone:

- Hosted entirely by felsic volcanics with the mineralisation controlled by an early thrust fault. The zone dips at about 50° to the east and has a strike extent of about 800 m.
- Massive, stringers and breccia sulphides. The sulphides form as a matrix to felsic clasts.

Southern Zone:

- Located several hundreds of metres to the south of the main deposit in high-magnesium ultramafics.
- Up to 10% disseminated sulphides, similar to the main disseminated zone.

Emily Ann

The surface geology at Emily Ann is totally obscured by transported sediments and a thick saprolite profile extends down to about 80 m below the surface.

The deposit occurs in a complex geological setting, consisting dominantly of felsic volcanoclastics hosting subordinate discontinuous lenses of mineralised and barren ultramafics, which dip at between 40° and 60° to the east in the vicinity of the deposit. The ultramafics and associated nickel-sulphide mineralisation do not extend to the bedrock surface and are therefore totally blind. The deposit has been subdivided into two main mineralised structural domains, termed the upper mineralised horizon (UMH) and lower mineralised horizon (LMH), separated by an east-dipping mylonitic thrust surface as shown in the section along 101470N (Figure 5).

The UMH has a strike extent of about 520 m and down-dip extent of up to 150 m. The mineralisation is highly variable and consists dominantly of disseminated to matrix pyrrhotite-pentlandite and lesser stringer and massive sulphides. The proportion of massive sulphides increases downwards towards the boundary mylonite. The mineralisation in the LMH is of greater economic significance and consists of lenses of high tenor (8-14% Ni) massive nickel sulphides (pyrrhotite-pentlandite) distributed over a strike length of about 520 m and with a down-dip extent of about 270 m.

The main portion of the deposit is truncated to the north by the northeast-trending Toolangi fault (Figure 2). Wide-spaced diamond drilling has traced the LMH, as a narrow zone commonly less than 1 m in thickness, for a further 600 m north of the fault.

Rock Type	Massive Nickel-Sulphides	Disseminated Nickel-Sulphides	BIF-Hosted Barren Sulphides	Banded Iron Formation	Barren Ultramafic Rock	Felsic Volcanic Rock
Magnetic Susceptibility (SI x 10 ⁻⁵)	50200	21400	69000	69000	9400	40
Inductive Conductivity (S/m)	40000	300	130	~0	~0	~0
Galvanic Resistivity (ohm-m.)	0.000016	0.0029	.0087	2.8	206	827
Chargeability (mV-s/V)	166 (unreliable)	140 (unreliable)	211	4	6	2
Dry Density (g/cm ³)	4.59	3.54	3.50	3.05	2.64	2.69

Table 1. Maggie Hays Deposit: Physical property measurements on core.

The reader is referred to Buck et al. (1998) for more details of the geology of the Maggie Hays deposits.

PHYSICAL PROPERTIES

The results of physical property tests carried out by Systems Exploration (NSW) Pty Ltd (Emerson, 1995) on core from the main Maggie Hays deposit are shown in Table 1. The massive nickel sulphides and the nearby BIF are both extremely magnetic, with magnetic susceptibilities ranging from 0.5 to 0.69 SI units, and are essentially magnetically indistinguishable. The ultramafic host rocks are highly magnetic (0.094 SI units) and easily distinguished from the virtually non-magnetic felsic volcanics (0.0004 SI units). The massive nickel sulphides are extremely conductive (40,000 S/m). The disseminated nickel sulphides and barren sulphides are much less conductive than the massive sulphides, but at 300 S/m are still highly conductive. The remaining rock types are relatively non-conductive. All of the sulphide-bearing rocks appear to be highly polarisable, but only the response from the BIF-hosted sulphides (211 mV-s/V) is considered reliable because massive electrode effects and consequent termination impedances in the water bath for the nickel-sulphide samples prevented reliable measurements. It was thought that the internal intrinsic IP of these very conductive sulphidic rocks would be low (Emerson, 1995). The ultramafic rocks are marginally more polarisable than the other host rocks, possibly due to the presence of disseminated magnetite. All of the sulphide-bearing rocks are dense (3.54 to 4.59 g/cm³), particularly the massive sulphides (4.59 g/cm³). The density of the serpentinised ultramafic rock (2.64 g/cm³) is very similar to that of the felsic volcanic rock (2.69 g/cm³). These densities are also similar to that of typical granite (2.67 g/cm³), thus raising doubts about the use of gravity for discriminating between these rock types. The results confirm the applicability of electromagnetic methods for direct sulphide detection and magnetic methods for lithological mapping.

AEROMAGNETICS

Contours of total magnetic intensity from the study area are shown in Figure 6. These data show magnetic responses of 2,000-20,000 nT due to BIF and ultramafic sequences, occurring within a quieter background due to area of non-magnetic felsic and mafic volcanic rocks. The Jimberlana dyke, and particularly its metamorphosed margins, form a prominent east-northeast-striking positive magnetic anomaly which interrupts the greenstone stratigraphy. The main Maggie Hays mineralisation is located over

the eastern margin of a broad, complex, magnetic response related to the CUU sequence. Two-dimensional modelling of the narrow, linear magnetic anomaly above the mineralisation indicates a very shallow source at 10-30 m depth and this is interpreted to be a magnetite accumulation in the regolith. The Maggie Hays North zone occurs within a magnetically quiet area of felsic volcanic rocks, east of a highly magnetic BIF unit (20,000 nT). Neither of the Maggie Hays mineralised zones produce a recognisable magnetic anomaly. The Emily Ann mineralisation occurs in a magnetically quiet area of felsic volcanic rocks, east of a highly magnetic BIF unit. Like Maggie Hays, this mineralisation also does not produce a recognisable magnetic anomaly.

MOVING-LOOP TEM

Moving-loop TEM (MLTEM) has been the main geophysical exploration method used, and was responsible for the discovery of both the Maggie Hays North mineralisation and the Emily Ann deposit. The surveys have been a mixture of 100 x 100 m single-turn loop/14 A and 100 x 100 m twin-turn loop/28 A configurations. A contour plan of the late-time (35 ms) data shows prominent responses due to various sulphide bodies including the nickel-sulphide deposits (Figure 7). BIF-hosted barren sulphides are the source of most of the anomalous responses and it is not easy to discriminate between these responses and the nickel-sulphide responses.

Interpretation of the MLTEM data was initially largely qualitative and based mainly on anomaly shape combined with the use of nomograms. More recently, forward and inverse modelling has been carried out, where appropriate, with Multiloop and Maxwell, (Ribbon-based plate modelling programs produced by Lamontagne Geophysics and ElectroMagnetic Imaging Technology Pty Ltd respectively).

At Maggie Hays the MLTEM has been relatively unsuccessful. A recent trial survey along 82700N, using 200 x 200 m twin-turn transmitter loops, produced relatively uninteresting profile data (Figure 8a), although there are vague indications of a slightly longer decay for the eastern part of the section. A conductivity-depth section (CDS) calculated using the 'Spiker' process (Smith and Buselli, 1991) shows correlation of a very weakly conductive zone with the mineralisation (Figure 8b). A highly conductive zone well below the mineralisation is of interest, although it may possibly be the CDS transformation of a very low-amplitude twin-peaked response from the mineralisation.

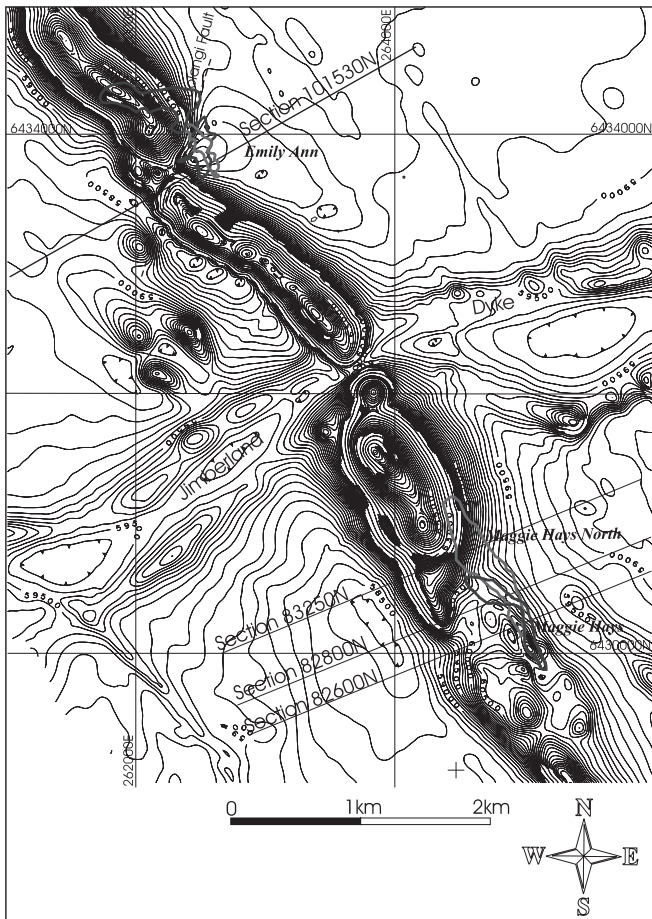


Fig. 6. Aeromagnetic TMI contour plan showing location of nickel deposits and various traverses and cross sections. The data were collected at a line spacing of 50 m and a flight height of 40 m. The contour interval is 100 nT. The thick lines show the surface projection of the nickel deposits.

There are two probable reasons for the poor detectability of Maggie Hays. Firstly, the massive sulphides only appear at a depth of about 350 m. Forward modelling using Maxwell has shown that the MLTEM response from such a body would be very low. Secondly, if the extremely high conductivity in Table 1 is representative, then a conductance of greater than 200,000 S is indicated. This conductance is well beyond the inductive limit of a normal off-time impulse TEM system and would thus give a very poor response. It should respond better to a system capable of measuring on-time or magnetic (B) field information. Measurements of the conductivity of core and surface and downhole TEM surveys at the Silver Swan massive nickel-sulphide deposit have produced strikingly similar responses (Amann and Pietila, 1998).

At Maggie Hays North, the MLTEM profile along 83250N shows three prominent late-time anomalous peaks (Figure 9a). These are a combination of twin-peaked anomalies from the east-dipping BIF-hosted barren sulphides and the nickel-sulphides. The up-dip minor peak from the nickel-sulphide response is superimposed on the major peak from the BIF sulphides. A CDS (Figure 9b) shows that the anomalies are due to highly conductive zones occurring at shallow depth (60 m). The nickel-sulphide conductor has a time constant of 52 ms.

At Emily Ann, the MLTEM profile along 101530N (Figure 10a) shows a low amplitude, but well-defined, single-peak late-time

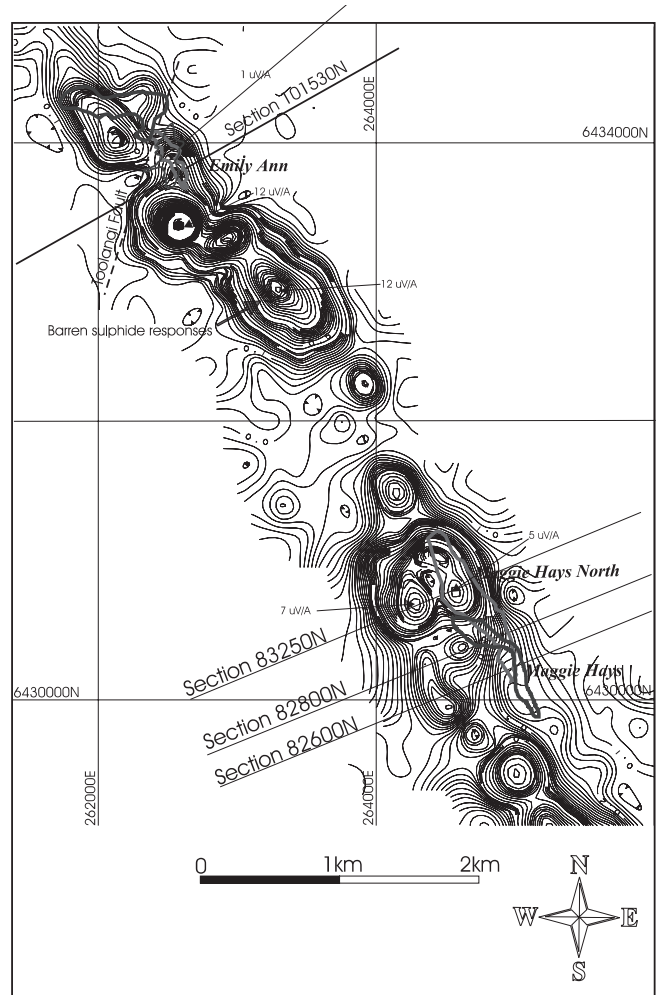


Fig. 7. Moving-loop TEM: Contour plan of the ch.30 (35 ms) response showing the location of nickel deposits and various traverses and cross sections. The contour interval is 0.025 mV/A. The thick lines show the surface projection of the nickel deposits.

anomaly over the mineralisation. The time constant of this conductor is 71 ms. The CDS (Figure 10b) shows that the anomaly is due to a highly conductive zone at a depth of about 150 m, which coincides with the mineralisation. The shallow-dipping nature of the mineralisation, its massive sulphide composition and the relatively resistive felsic volcanic host rocks provide ideal conditions for detection by MLTEM.

FIXED-LOOP TEM

Fixed-loop TEM (FLTEM) surveys have commonly been used to detail MLTEM anomalies, rather than as a primary exploration technique. This approach has been applied because the unpredictable geometry and stratigraphic location of the nickel deposits increase the risk of poor primary-field coupling with a deposit. Most FLTEM surveys used 300 x 600 m loops with 20 A of current and measured three orthogonal secondary field components. However, recent surveys used smaller multi-turn loops to try and minimise overburden response.

At Maggie Hays several FLTEM surveys have been undertaken in an attempt to obtain a recognisable response from the deposit, but with little success. In contrast, FLTEM surveys have been very successful at Maggie Hays North in accurately delineating the extent and geometry of the deposit. The asymmetric Z-component anomaly on profile 83250N, shown in Figure 9c, clearly indicates the east-dipping nature of the mineralisation. Inverse modelling of

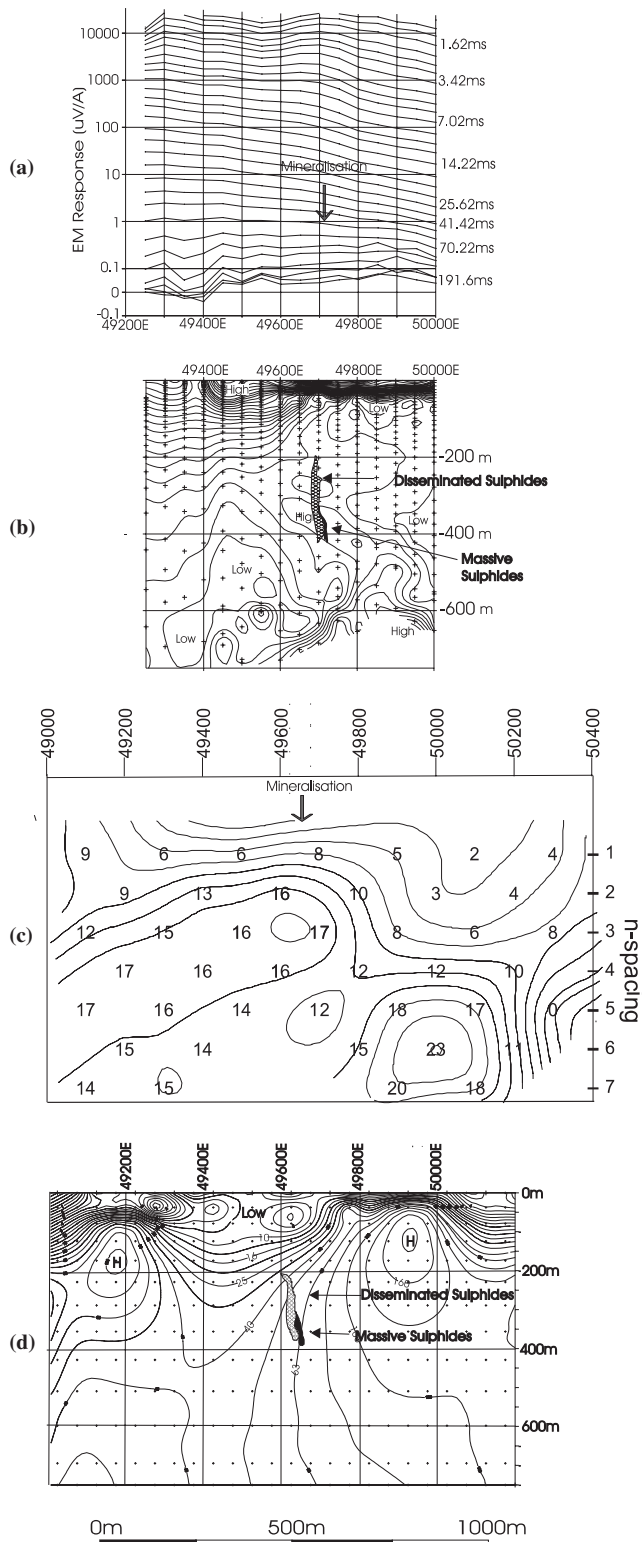


Fig. 8. Maggie Hays Deposit - TEM, IP and AMT responses showing correlation with mineralisation. See Figure 2 for locations of profiles. The arrows indicate the surface projection of mineralisation. a). Line 82700N: Coincident moving-loop TEM (200 x 200 m twin-turn loops) response profiles. b). Line 82700N: Coincident moving-loop TEM (200 x 200 m twin-turn loops) - conductivity depth section. Units are S/m and the contour interval is 0.01 S/m. The indicated conductivity in the vicinity of mineralisation is 0.05 S/m. The surface conductivities are about 1 S/m. c). Line 82800N: Induced polarisation: Dipole-dipole (a = 200 m) - decoupled-phase pseudosection. Units are milliradians and contour interval is 25 mrad. (d). Line 82800N: AMT resistivity inversion section. Units are ohm-m and the contour interval is logarithmic. The indicated resistivity in the vicinity of mineralisation is 50 ohm-m. The surface resistivity is about 5 ohm-m.

these data using Filament, (a current filament based program produced by ElectroMagnetic Imaging Technology Pty Ltd), produced a conductor dipping at 45° to the east at a depth of 120 m beneath 49450E on line 83200N (Figure 9b). This model is consistent with the located mineralisation with the exception of the slightly shallower dip of the model, which is probably due to some residual half-space response in the modelled data.

No FLTEM surveys were done over Emily Ann because resource drilling and DHEM surveys proceeded so quickly that it became superfluous.

SLINGRAM TEM

The Slingram (or separated horizontal loop) TEM array was trialed as a possible means to better detect the response from steeply dipping conductors relative to that from the horizontal conductive overburden. The Emily Ann deposit, which is unfortunately the least suited of the deposits to the Slingram array because of its sub-horizontal nature, was chosen for the trial survey prior to knowledge of its geometry. The resulting anomaly (Figure 10c) is distinct, but much lower in amplitude than the comparable MLTEM anomaly (Figure 10a). The shape of the anomaly is diagnostic and consistent with the shallowly east-dipping conductor.

INDUCED POLARISATION

In light of the large disseminated-sulphide component of the Maggie Hays deposit, a trial dipole-dipole IP survey were carried out over several lines using both 100 m and 200 m dipoles. The decoupled phase pseudo-section from the 200 m-dipole survey along 82800N is shown in Figure 8c. The highly anomalous broad phase response is interpreted to be from a combination of both barren BIF-hosted sulphides to the west and the upper disseminated nickel-sulphides. The low resolution and uncertainty of how much of the response is from the nickel-sulphides makes it a difficult technique to use for targeting drill holes.

The IP survey also found that the regolith zone has an apparent resistivity of 2-10 ohm-m. No IP surveys were conducted over Maggie Hays North and Emily Ann.

AUDIO MAGNETOTELLURIC SURVEY

A trial magnetotelluric survey was carried out to see if the method could locate deep, steeply dipping, massive-sulphide conductors. The natural source AMT method was chosen rather than the controlled source method because of the conductive nature of the overburden and the consequent problem of trying to obtain 'far field' data. Several lines were surveyed at Maggie Hays, but considerable effort was required to try and obtain valid, repeatable, data.

The AMT Cagniard resistivity inversion section for 82800N (Figure 8d) shows a broad, low resistivity zone, mainly to the west of the mineralisation, and is possibly due to a combination of the barren BIF-hosted sulphides and the more deeply weathered ultramafic rocks.

DOWNHOLE TEM

Numerous holes were surveyed with three-component DHTEM (Crone PEM) to search for off-hole conductors and to guide step-out drilling. Inverse modelling using Filament, where appropriate, followed qualitative interpretation. This modelling was found to be very reliable for off-hole conductors, but less so for the complex responses from intersected conductors. The qualitative

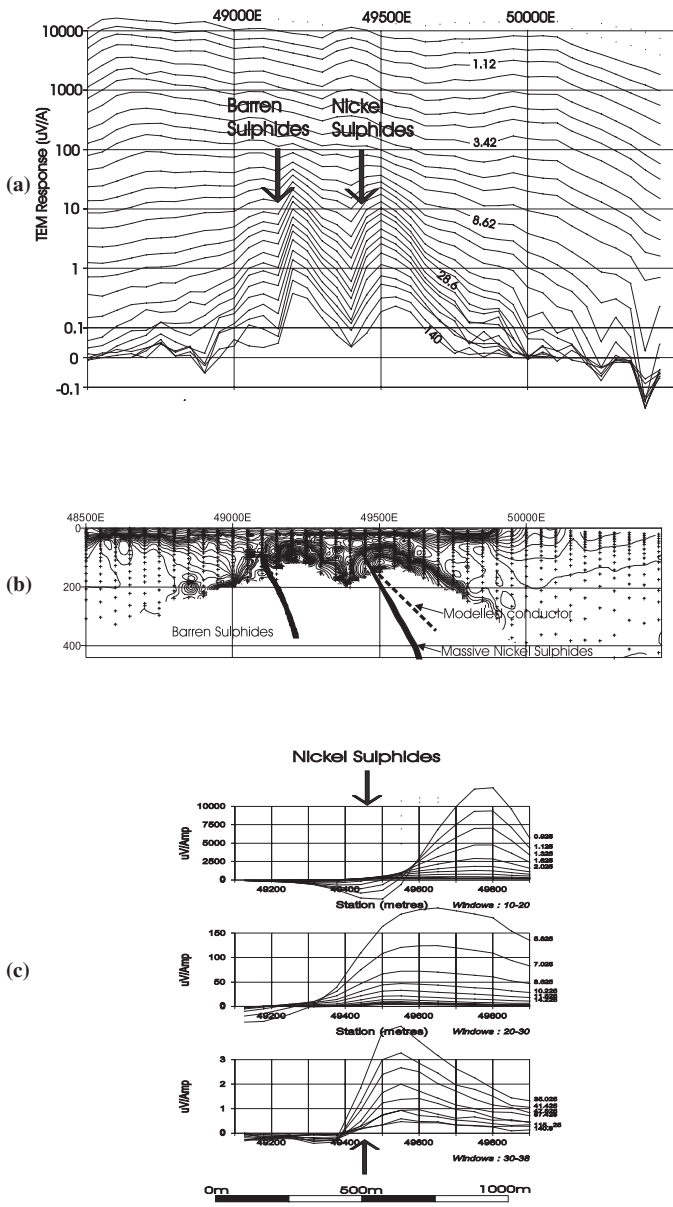


Fig. 9. Maggie Hays North - TEM responses showing similar anomalies from barren and nickel-sulphides. See Figure 2 for location of profiles. The arrows indicate the surface projection of mineralisation. a). Line 83250N: Coincident moving-loop TEM (100 x 100 m twin-turn loops) response profiles. b). Line 83250N: Coincident moving-loop TEM (100 x 100 m twin-turn loops) - conductivity depth section. Units are S/m and the contour interval is 0.02 S/m. The indicated conductivity in the vicinity of the sulphide bodies is 4 S/m. The surface conductivities are about 1 S/m. c). Line 83250N: Fixed-loop TEM: Vertical (Z) component response profiles.

interpretations based on the anomaly polarities of the various components and anomaly widths were shown to be substantially correct. The massive nickel sulphides and the barren BIF-hosted sulphides both produced excellent down-hole anomalies with long time constants. At Maggie Hays, DHTEM produced time constants of up to 24 ms for the massive nickel sulphides, which although indicating a good conductance, is considerably lower than for the other two deposits. It is possible that the extremely high conductance is producing a diminished response in the time range measured. Due to instrument limitations most of the earlier holes were logged with a time base too short to measure the full late-time response. This was subsequently improved in more recent logging.

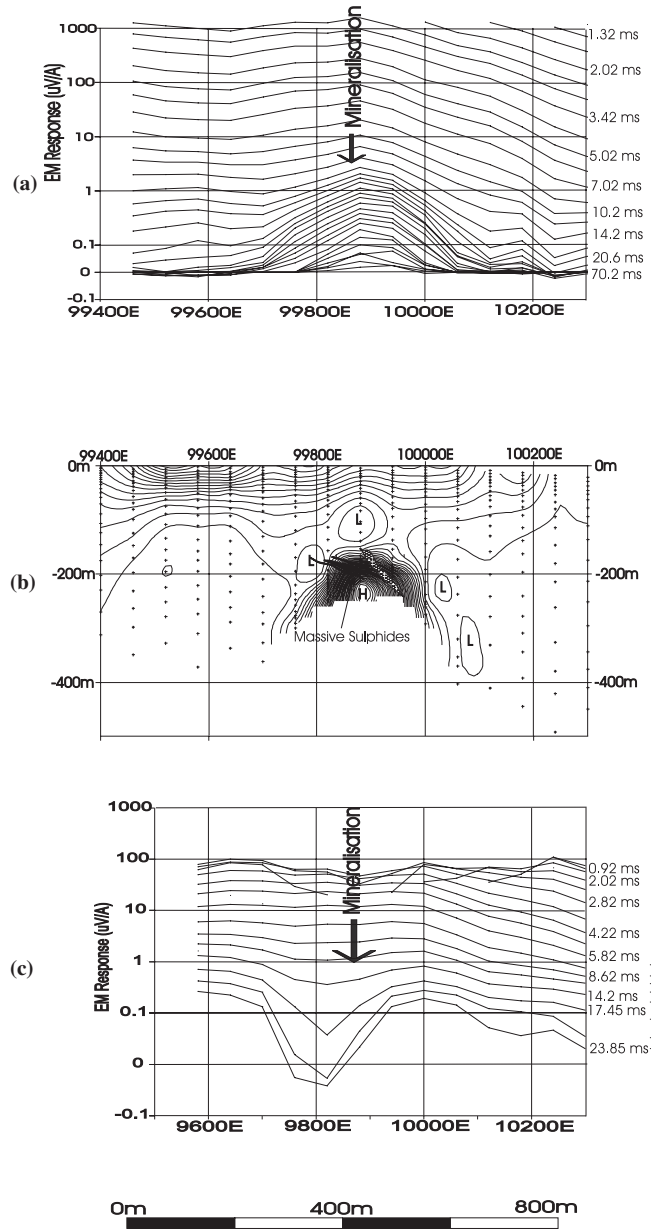


Fig. 10. Emily Ann - TEM responses showing correlation with mineralisation. See Figure 2 for location of profile. The arrows indicate the surface projection of mineralisation. a). Line 101530N: Coincident moving-loop TEM (120 x 120 m twin-turn loops) response profiles. b). Line 101530N: Coincident moving-loop TEM (120 x 120 m twin-turn loops) - conductivity depth section. Units are S/m and the contour interval is 0.02 S/m. The indicated conductivity in the vicinity of the sulphide bodies is 1 S/m. The surface conductivities are about 0.2 S/m. c). Line 101530N: Slingram TEM: (120 x 120 m twin-turn loops); Receiver - transmitter separation 240 m; Vertical (Z) component response profiles.

Axial (Z) component responses from typical holes from the three deposits are shown in Figures 11. The locations of these holes are shown in Figure 2. The response from hole LJD007 at Maggie Hays (Figure 11a) shows a prominent, complex, intersection anomaly from a wide nickel-sulphide zone at 550 m, a narrow nickel-sulphide intersection anomaly at 640 m and an equally prominent anomaly from barren BIF-hosted sulphides intersected towards the end of the hole. The response from hole LJD031 at Maggie Hays North (Figure 11b) shows a broad negative anomaly at 370 m caused by massive nickel sulphides south of the hole. A prominent intersection anomaly at the end of this hole is due to barren BIF-hosted sulphides. At Emily Ann, the response in the

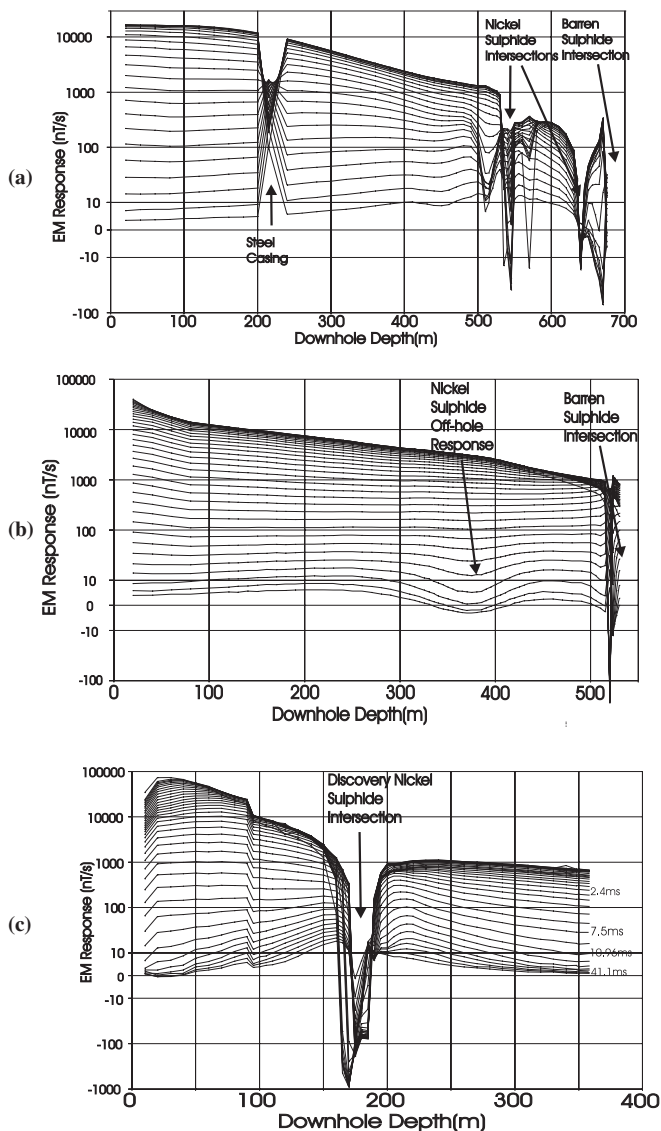


Fig. 11. Downhole TEM axial (Z) component responses showing correlations with mineralisation. Hole locations shown in Figure 2. a) Maggie Hays: Hole LJD007 (Section 82500N). b), Maggie Hays North: Hole LJD031 (Section 83500N). c) Emily Ann: Hole RTD016 (Section 101470N - see Figure 5).

discovery hole RTD016 shows a prominent intersection anomaly at 180 m due to the massive nickel-sulphides (Figure 11c).

AIRBORNE EM

GEOTEM Deep, QUESTEM 450, and TEMPEST systems (all 25 Hz) were flown over various deposits at Lake Johnston. The QUESTEM data were collected in windy conditions and were too noisy to interpret. The TEMPEST data, which have only recently been received, have not been fully analysed, but appear to show similar responses to the GEOTEM (see below).

The GEOTEM X-component profiles and CDS sections (calculated with EM Flow, an AMIRA-based software product of Encom Technology Pty. Limited) for lines 82615N and 82815N at Maggie Hays are presented in Figure 12. Most of the response is

from the thick, saline, regolith and the response from bedrock sulphide conductors would be in the near noise level late-time data.

The profiles for line 82815N, flown west to east, shows a bunching of the late-time channels over the mineralisation, suggesting a possible deep conductor, but the data are affected by noise at these late delay times (Figure 12a). The CDS for this line shows a remarkably good correlation between a conductive zone and the mineralisation, but a second conductive zone further to the east remains unexplained by any known geological features (Figure 12b). The profiles from line 82615N, flown east to west, do not show any late time anomaly over the mineralisation (Figure 12c), and this is confirmed by the CDS (Figure 12d). The conductive features to the east on the CDS are again unexplained by known geology.

Despite the good correlation of the CDS anomaly with the nickel sulphides on the west to east line, it is not certain that the mineralisation has been detected. A possible explanation for the better response on the line flown towards the east is that in this configuration the transmitter is above more resistive rocks during the measurement and more signal could get to the sulphides. Alternatively, and more likely, the CDS sections could be showing the typical 'tail' artefacts expected at the eastern edge of the broad conductive regolith zone over the ultramafic sequence. It is hard to visualise how the airborne EM could detect the mineralisation when the ground TEM failed.

At Maggie Hays North, the results are more convincing. The profiles and CDS sections for lines 83225N and 83400N are shown in Figure 13. There are reasonably distinct anomalies on the profiles over both the nickel sulphides and the barren sulphides to the west. The CDS sections for both lines show good correlation of easterly dipping conductive zones with the sulphides. There is the possibility of edge artefacts, but the correlation of the conductive zones with the mineralisation is remarkably good.

Emily Ann was not flown with GEOTEM and does not appear at this stage to have been detected by the TEMPEST survey.

DISCUSSION AND CONCLUSIONS

The initial discovery of Maggie Hays was not due to geophysics, however, the subsequent discovery of Maggie Hays North and Emily Ann was substantially due to the use of modern TEM surveys. Table 2 summarises the responses of the three deposits to the various geophysical methods used.

The aeromagnetic surveys were fundamental in locating ultramafic and BIF sequences and interpreting the structure of the area. The magnetic data do not define the nickel deposits nor do they indicate any consistent structural or volcanological signatures associated with the deposits. This is consistent with conclusions drawn by McCall et al. (1995) in their study of the magnetic responses of several nickel deposits at Widgiemooltha, Western Australia.

Limited physical property tests show that both the massive nickel-sulphide and the barren BIF-hosted sulphide mineralisation are highly conductive, highly magnetic, dense and probably highly polarisable. Consequently, both form ideal, but indistinguishable, geophysical targets. The extreme conductivity of the massive nickel sulphides raises the possibility of poor detectability by off-time impulse TEM systems.

Ground TEM surveys, using high-powered MLTEM modes followed by FLTEM follow-up surveys, successfully discovered the Maggie Hays North and Emily Ann deposits. The long time

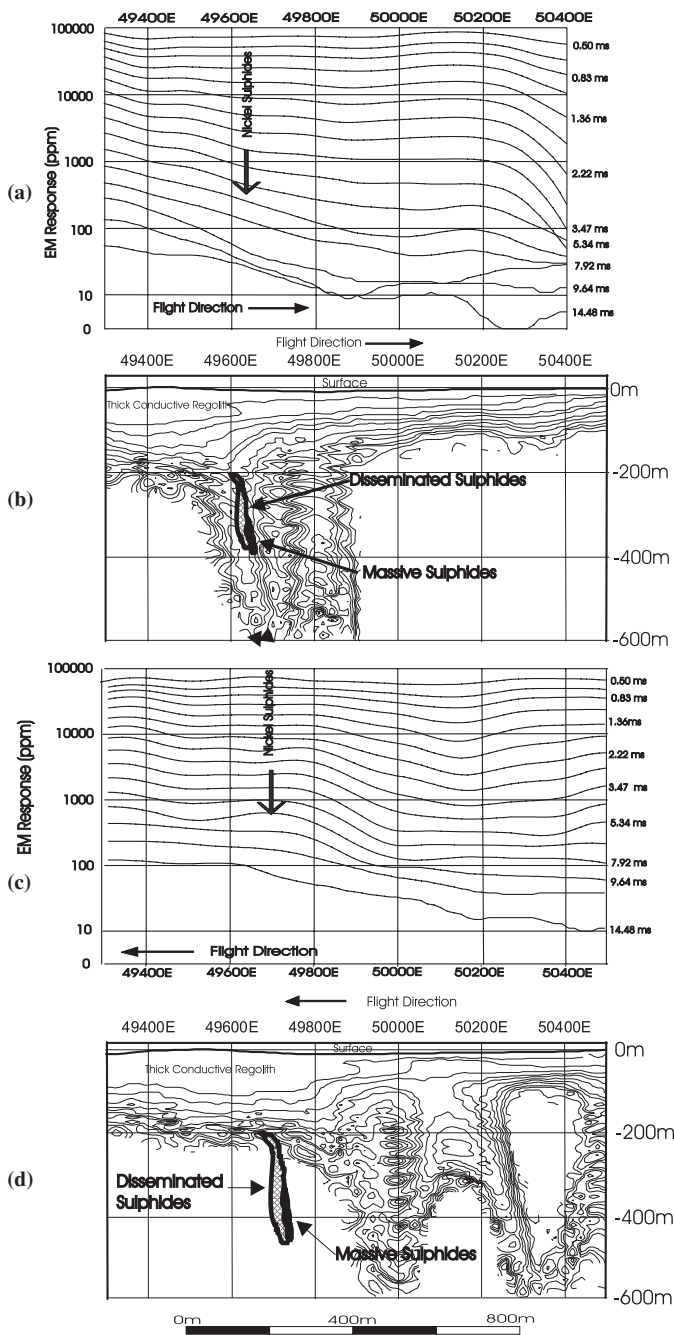


Fig. 12. Maggie Hays Deposit: Airborne EM responses showing correlation with mineralisation. See Figure 2 for approximate location of profiles. Arrows indicate surface projection of nickel-sulphides. a), Line 82815N: GEOTEM (flown west to east) - X component response profiles. b) Line 82815N: GEOTEM (flown west to east) - conductivity depth section. Units are S/m and the contour interval is 0.01 S/m. The indicated conductivity in the vicinity of the mineralisation is 0.01 S/m. The surface conductivity is about 0.2 S/m. c) Line 82615N: GEOTEM (flown east to west) - X component response profiles. d) Line 82615N: GEOTEM (flown east to west) - conductivity depth section. Units are S/m and the contour interval is 0.01 S/m. There is no anomalous zone in the vicinity of the mineralisation. The surface conductivity is about 0.2 S/m.

constants of 52 ms and 71 ms for these two deposits explain their excellent TEM responses. In contrast, the Maggie Hays main zone is not convincingly detected by surface TEM surveys, possibly due to its deeper depth, and perhaps its extremely conductive nature.

The three-component DHTM surveys produced excellent anomalies from both nickel sulphides and barren sulphides.

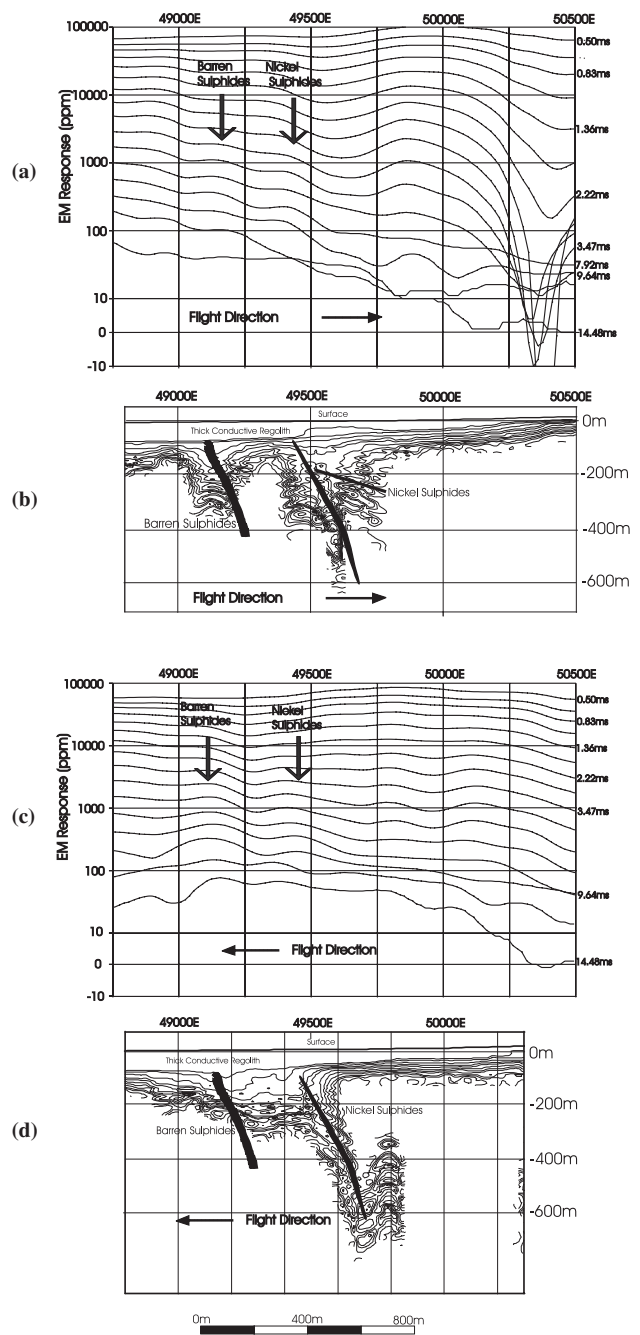


Fig. 13. Maggie Hays North deposit: Airborne EM responses showing correlation with mineralisation. See Figure 2 for approximate location of profiles. Arrows indicate surface projection of nickel-sulphides. a) Line 83225N: GEOTEM (flown west to east) - X component profiles. b) Line 83225N: GEOTEM (flown west to east) - conductivity depth section. Units are S/m and the contour interval is 0.01 S/m. The indicated conductivity in the vicinity of the nickel mineralisation is 0.06 S/m. The surface conductivity is about 0.2 S/m. c) Line 83400N: GEOTEM (flown east to west) - X component profiles. d) Line 83400N: GEOTEM (flown east to west) - conductivity depth section. Units are S/m and the contour interval is 0.01 S/m. The indicated conductivity in the vicinity of the nickel mineralisation is 0.02 S/m. The surface conductivity is about 0.2 S/m.

The prominent broad IP anomaly at Maggie Hays is interpreted as due to a combination of responses from both barren BIF-hosted sulphides and disseminated nickel-sulphides. The method could be considered for trying to locate disseminated nickel sulphides, but its low resolution and response to adjacent barren sulphides argue against its routine application.

Deposit	Surface TEM	DHTEM	AEM	Magnetics	IP	AMT
Maggie Hays	No response	Good response	Probably not detected	No recognisable anomaly	Uncertain	Probably not detected
Maggie Hays North	Good late-time response	Good response	Weak but recognisable response	No recognisable anomaly	Not surveyed	Not surveyed
Emily Ann	Good late-time response	Good response	Not flown	No recognisable anomaly	Not surveyed	Not surveyed

Table 2. All Deposits: Response to geophysical methods used.

The AMT survey at Maggie Hays does not convincingly delineate the nickel-sulphides. This is not surprising considering the similar poor response from the TEM surveys.

The GEOTEM survey has probably detected Maggie Hays North, but its detection of Maggie Hays is very doubtful. Airborne EM shows some potential for rapid exploration for shallow massive sulphide deposits in more resistive parts of the project area, but suffers from ambiguous responses and artefacts in CDS processing.

ACKNOWLEDGEMENTS

This paper is published with the permission of Lionore Australia Pty Ltd and QNI Ltd. The authors acknowledge the many exploration staff that contributed to the discovery of the Lake Johnston deposits. Various contractors such as Tesla-10, OuterRim Exploration Services, Zonge Geophysics, Geoterrex and World Geoscience Corporation have worked diligently to collect the data and are thanked. Don Emerson of Systems Exploration carried out the core tests.

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