MMI™ GEOCHEMISTRY FOR NICKEL EXPLORATION

INTRODUCTION

The geological understanding of nickel sulphide deposits, particularly those of the komatiite-type, has undergone vast changes in recent years. A summary of the geological understanding, particularly with respect to geochemical implications were presented by Hill (2001). A schematic diagram (Figure 1), based on this article, outlines the challenges for locating such deposits from surface soil geochemistry.

The Ni content of the cumulate facies is commonly 0.1%-1% Ni. Nickel contents of ore can be as low as 2% Ni, so there is often not a great deal of difference in tenor between the Ni sulphide and the hosting silicate rocks. Both the interflow sediments and the basal sulphide complexes are sulphur rich and can accumulate chalcophile elements such as Pd, Co, Cu, Zn, Cd and Pb. (It is now known that the sulphur in the latter is in fact derived from thermal erosion of the former by the lava channel.)

The thickness of the cumulate facies zone is generally of the order of tens to a hundred metres. That of the sulphide ore zone is usually less than ten metres. The lateral extent of the cumulate zone (the channel flow) is tens up to hundreds of metres. Thus, sampling density is of special importance in Ni exploration using any geochemical technique. Techniques such as MMI™ may have an advantage, particularly in the latter stages of exploration because of their superior spatial resolution (due to less extensive surface re-working) compared to conventional techniques.

Figure 1: Schematic Cross-Section of a Komatiite-Type NiS Environment

DETECTION OF ULTRAMAFICS AND CHANNEL FLOWS

The Ni content of soils, as measured by MMI™, is a reliable litho-geochemical indicator of ultramafic rocks. This has been demonstrated in a number of different terrains in the Northern and Eastern Goldfields, and in practice by the successful delineation of over sixty verified channel-flows. The correlation between MMI-Ni and geological mapping was first carried out in 1994 by Gole and Gay at Kangaroo Valley, some twenty kilometres south of Coolgardie. The previously identified komatiite channels are known as Fenion and Tralee.

Two komatiite flows occur within a mafic sequence. Two ultramafic rock types are shown - sheet flow facies rocks, containing spinifex textured and olivine orthocumulate rocks, and channel flow facies rocks. The for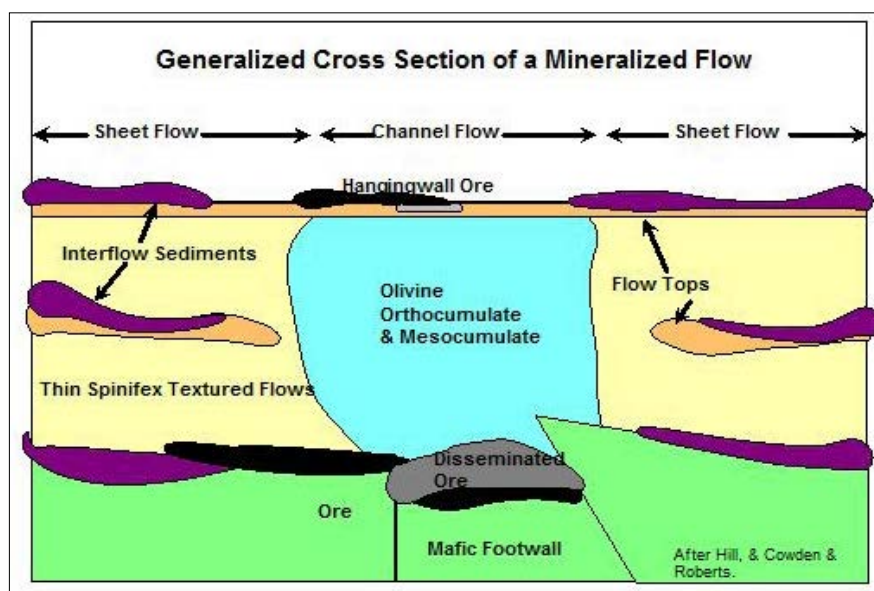mer are delineated from the mafics by the MMI-Ni = 2,000 ppb contour in soils. There are three zones with MMI-Ni > 8,000 ppb. These correspond closely with the areas mapped as silica cap over channel flow facies rocks (Tls/CFR). Not all komatiite channels show this degree of silicification and resistance to weathering. The greatest potential for a soil based technique is in areas of limited outcrop and colluvium, bearing in mind that ultramafics are often the most-easily weathered rocks.

In the Coolgardie area, in excess of thirty other sites with greater than 8,000 ppb Ni in soil (after MMI-B extraction) were examined. All were confirmed as channel-flows. Subsequently similar exercises in the greenstone belts on the western edge of the Yilgarn Block have shown the same characteristics viz MMI-Ni > 2,000 = ultramafic rocks, MMI-Ni > 8,000 ppb = channel-flow ultramafics. These values pertain to residual and erosional terrain. Values will be lower where deposition of foreign material has occurred.

SGS

MMI™ IDENTIFICATION OF NI LATERITES

Using this identical procedure, and the 8,000ppb threshold for Ni, Heron Resources identified the Kalpini Ni laterite resource 65km NE of Kalgoorlie in 1999. The MMI™ image for the discovery area is shown in Figure 3.

Subsequently good correlation was observed between aeromagnetics and the MMI-Ni geochemistry; other Ni laterite areas were identified. By 2004 the combined reserves of the Acra and Wellington areas was 45.7Mt @ 1.03%Ni and 0.07%Co at a cut-off of 0.75%Ni. In 2005 Inco and BHPB took an interest in the project.

RATIOS DISCRIMINATE NI DERIVED FROM SULPHIDES FROM NI DERIVED FROM SILICATE NI SOURCES

Nickel sulphides weather relatively slowly, and this factor combined with the amount of Ni in silicate rocks means that soils near nickel sulphides often contain lower Ni values than soils over channel-flows. Accordingly, other methods must be developed to examine basal contacts for the presence of nickel sulphides. Hill (2001) has shown that both sheet-flow and channel-flow ultramafic rocks contain appreciable Cr (as well as Ni, Mg, etc.). As this element is not partitioned into the sulphide phase it may provide a means of discriminating ore from silicate Ni.

Brand (1999) explored the use of various element ratios for Ni exploration subsequent to both total and partial extractions of surface soils. Several important conclusions emerged. Firstly, whereas Ni alone could not be used as a specific indicator of nickel sulphides, the use of ratios such as Ni/Cr and Cu/Zn could in many cases provide vectors to ore. Secondly it was stated that "weaker acids have been found to be the best for optimizing contrast, because less Cr is extracted relative to Ni, when compared to stronger acids". This is an important conclusion, but the reason is not just the lower extraction of Cr per se. Partial digestions discriminate against mechanically transported forms of many elements, particularly resistates such as Cr. Conventional analysis produces much
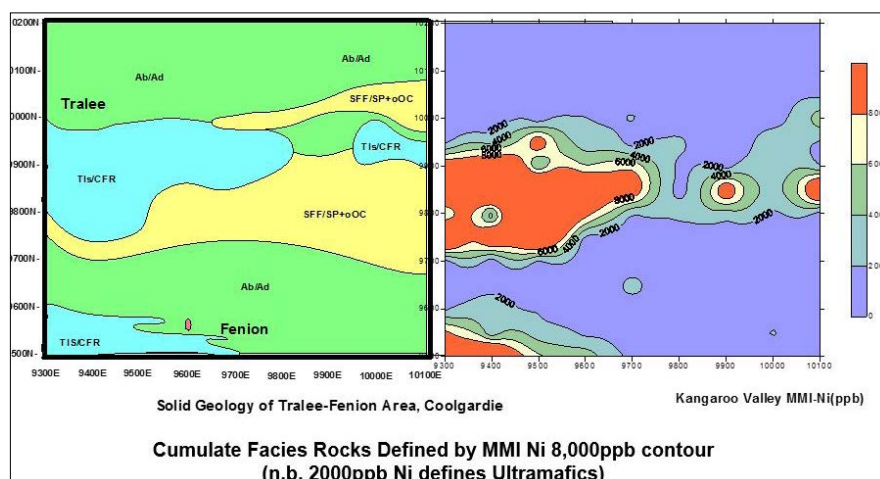

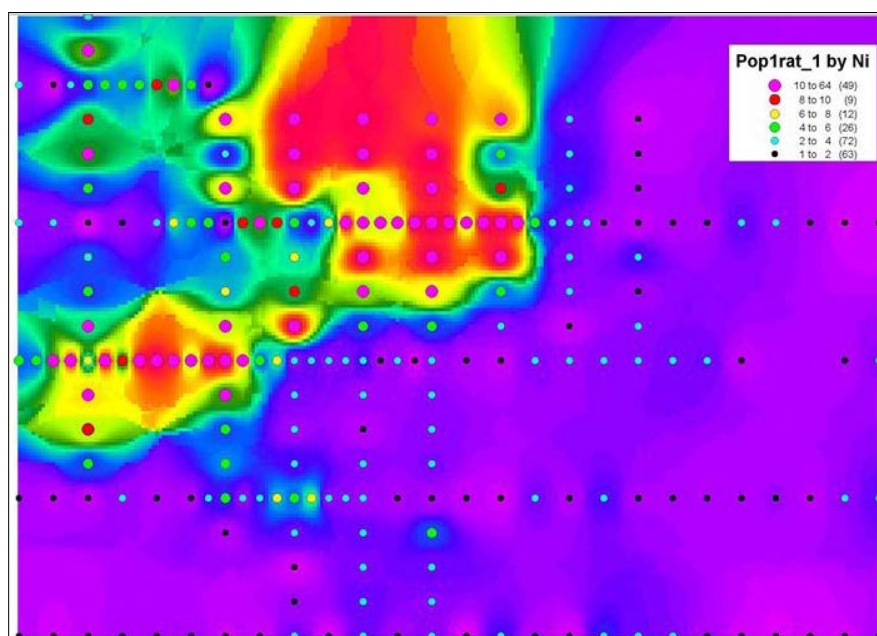Figure 2: Geology and MMI™ of the Kangaroo Valley Area, after Gole and Gay (1995)

Figure 3: Initial MMI™ for the Kalpini Ni Laterite Area, NE Kalgoorlie (Courtesy D. Crook, Heron Resources)

higher "noise" and many false anomalies.

One other advantage of using element ratios is that they can be more readily transferred across different regolith regimes – the absolute analytical values are of lesser importance.

The MMI-M extractant has been developed to provide partial analysis of a wide range of elements in soils including Ni and Cr. Comparison of the Ni & Cr values and the Ni/Cr ratio obtained from soils (with MMI-M) from the North Miitel deposit, in deeply weathered colluvial/alluvial covered terrain, on the east side of the Widgiemooltha Dome is of interest. Figure 4 shows these comparisons (access

courtesy Mincor Resources NL).

At Miitel North, Ni values are evident in soils across the entire transect, but are higher in the west, and lower in the east. Cr is the reverse of this with a distinct low in the centre (note they are lower than equivalent sites in residual/erosional terrain). The Ni/Cr ratio shows a very distinct peak in the centre of the traverse, above mineralization. Several cautionary notes on the use of ratios are required. Firstly, when the denominator in the ratio approaches the detection limit, large but spurious ratios can be generated. In the case of MMI™ and Cr, the lower detection limit is 1ppb. Care is advised in using Ni/Cr ratios when Cr is less than 2ppb. Thus
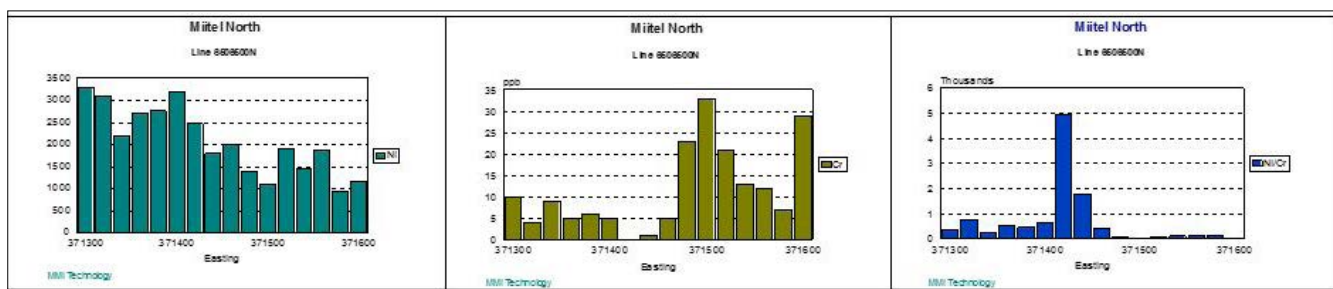
Figure 4: MMI-M Ni, Cr and Ni/Cr Values in Soils from the Miitel North Prospect

a high Ni/Cr ratio (say one thousand) and with Cr>2ppb, also ensures that Ni has a value >2000ppb.

RATIO APPLICATION - LOCATING AND PRIORITIZING BASAL CONTACTS WITH MMI™ IN COLLUVIAL TERRAIN

Ratios provide a geochemical tool which can be used in difficult, covered terrain. What is an appropriate strategy to effectively locate and explore basal contacts to prioritize drilling postions? In areas of subdued outcrop (e.g. colluvium and alluvium) this is not easy, given that ultramafic rocks are generally soft and easily weathered. The sulphide target is usually not wide – often less than 10m. Accordingly, samples 10m- 20m apart are taken across suspected basal contacts, on lines (say) 100m apart. It is important to locate the exact basal contact position not just for drilling, but also to assess the significance of other (anomalous) geochemistry (e.g. Cu, Co, Pd). Mafic and ultramafic rocks contain higher concentrations of Ti than rocks of acid affinities. Hallberg (1982) developed an elegant method to distinguish weathered basalts from andesites, dacites and rhyolites based on the Ti/Zr ratio. With MMI-M leachant, elements such as Ti, Cr and Zr can be extracted and analysed. The basal contact position is identified with Ni/Ti and Ti/Cr ratios which are very sensitive to the change from ultramafic to mafic lithology. Some examples (where reference surface geology is available) are shown in Figure 5 and 6.

Figure 5 shows the changes in MMI™ geochemistry in samples taken every 10m across a mineralized contact identified and made available for this study by Dean Goodwin, 20 km south-west of Coolgardie. The lithologies identified from surface sub-
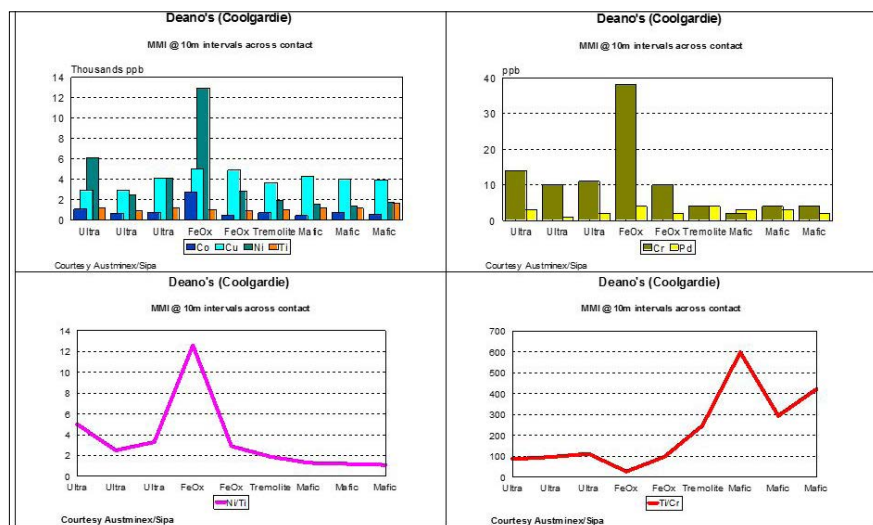
Figure 5: MMI™ Element Concentrations and Ni/Ti and Ti/Cr Ratios Across a Mineralized Contact

Figure 6: Costean at Bill's, South-West of Coolgardie

crop during sampling are marked. Clearly the Ni/Cr and Ti/Cr ratios identify the lithological change from ultramafic (on the left) to mafic. Figure 5 shows a costean across another low angle contact nearby.

Figure 6 shows the typical terrain conditions, and weathered material available from a shallow costean at Bill's 20km south-west of Coolgardie. The base of the ultramafic is in the foreground, and the FeOx material on the contact with mafic rocks is in the background of this photograph. The geochemistry is shown in Figure 7.

In this case the same ratios also define the contact, which is marked by iron oxides, including magnetite. The Ni/Ti ratio shows two peaks, one in the cumulate facies environment and one in the FeOx environment. A plot of the Ni/Cr ratio (Figure 8) shows that the latter is clearly not associated with silicate facies rocks. It is possibly indicative of nickel sulphides at depth.

DELINEATING BARREN FROM FERTILE KOMATIITES – RARE EARTH ELEMENTS

Hill(2001) pointed out that rocks from komatiites which have thermally eroded a suitable substrate such as felsics or black shales, commonly show rare earth signatures. This is because during the assimilation some of the rare earth content of the substrate is transferred. Barren or un-prospective komatiites, having had no such contact are (relatively) rare-earth depleted. Using the MMI-M extractant, and analysis for Ce and Nd (cerium and neodymium) has shown that this phenomenon can be observed in surface soils. Figure 9 shows the Ce and Nd geochemical patterns over the North Miitel transect mentioned earlier.

The modest values of rare earth elements Ce and Nd at 371400E are immediately adjacent to the position for the high Ni/Cr ratio believed to be above the mineralization position. Stratigraphically above (to the east of) the mineralization are komatiite flows. To the east of this (and stratigraphically above) lies the Widgiemooltha Chert. The strong values for the (MMI™) rare earth elements in soils at the eastern end of the line probably reflect this unit.
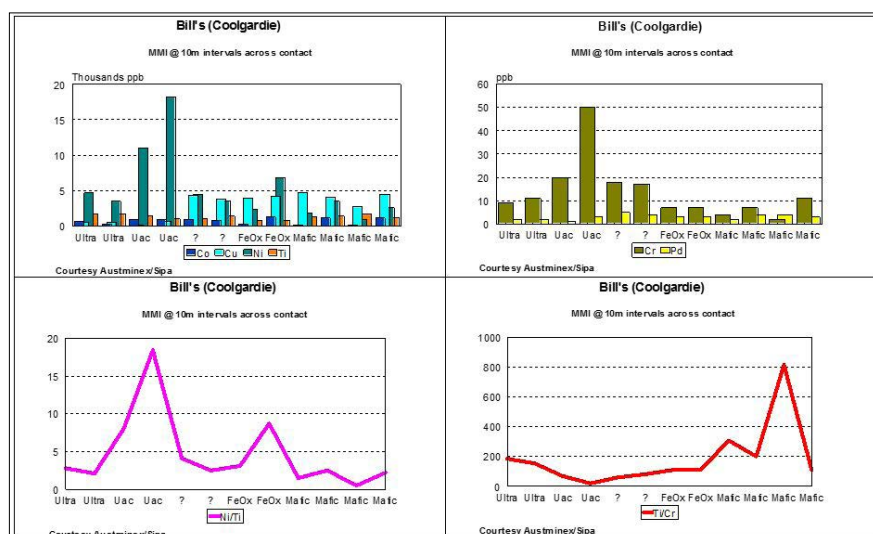

Figure 7: MMI™ Geochemistry Across Bill's, A Mineralized Contact SW of Coolgardie
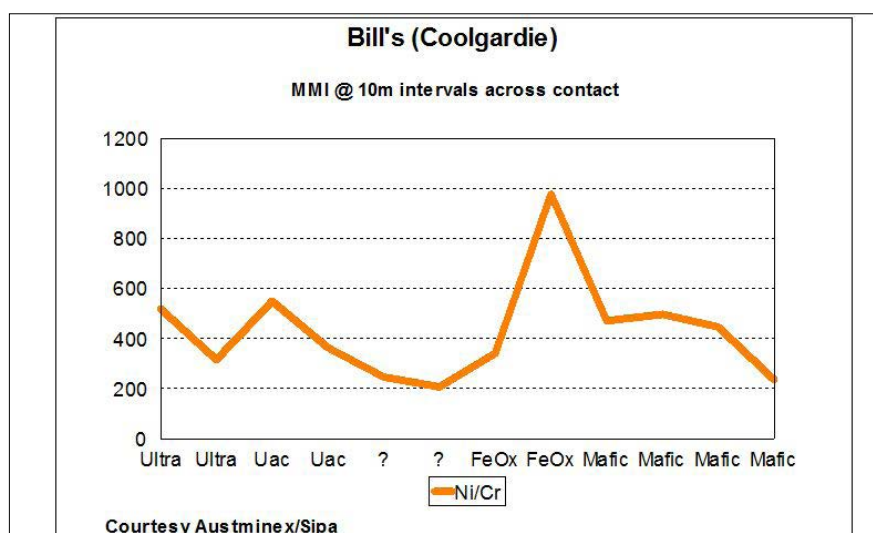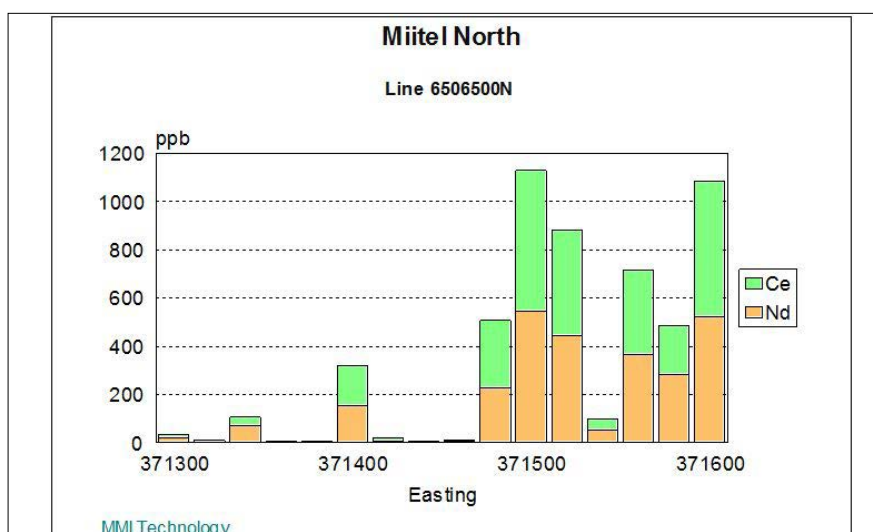

Figure 8: Ni/Cr Ratio at Bill's, SW of Coolgardie

Figure 9: Rare Earth Elements Across the Miitel North Deposit

PRIORITIZING GEOPHYSICS TARGETS

Geophysics, particularly MLTEM, plays a large part in current exploration for Ni. Both airborne and ground techniques such as MLTEM identify anomalously conductive zones in the earth's crust. However, not all conductors owe their conductivity to the presence of nickel sulphides. Geochemistry, and in particular MMI™, is a very useful tool in prioritizing conductors which may be related to Ni.

As well as elements such as Ni, and Pd which have a direct association with ore, other elements such as Cr and the rare earths can be used to infer a potential association with NiS mineralization. The rare earths can also however be diagnostic of black shales. The presence of rare earths in soils can indicate:

(a) (in the absence of high Ni, Cr, Pd) the presence of a black shale or felsic

(b) (in the presence of high Ni & Cr) a komatiite which has thermally eroded a black shale or felsic and acquired S (and rare earths) but has not precipitated Ni sulphide at the base at this position

(c) (in the presence of high Ni, Ni/Cr, Co and Pd) nickel sulphide mineralization.

Figure 10 shows part of a geological map of a prospective Ni exploration area east of the Widgiemooltha Dome (courtesy of Austminex and Dean Goodwin). On it are marked a number of conductive channels obtained from an MLTEM survey undertaken by Southern Geoscience as part of the Larcombe Project.

Some sixteen conductors were identified from the MLTEM survey. MMI™ geochemistry, (at ten or twenty metre intervals) was placed across each of the conductors to obtain a geochemical signature. The elements analysed were Ni, Cr, Pd, Co, Cu, Ce, Nd, Zn. Of the first ten conductors investigated two, MC10 and MC11 indicated the presence of elements related to Ni. The geochemical images for this area are shown in Figure 11.

Figure 11 shows that conductors MC10 and MC13 are geochemically more interesting than MC11 and MC14. The remaining MLTEM geophysical targets showed a lack of rare-earth presence in soils, and also showed low values for Pd and Ni. The area mapped contains
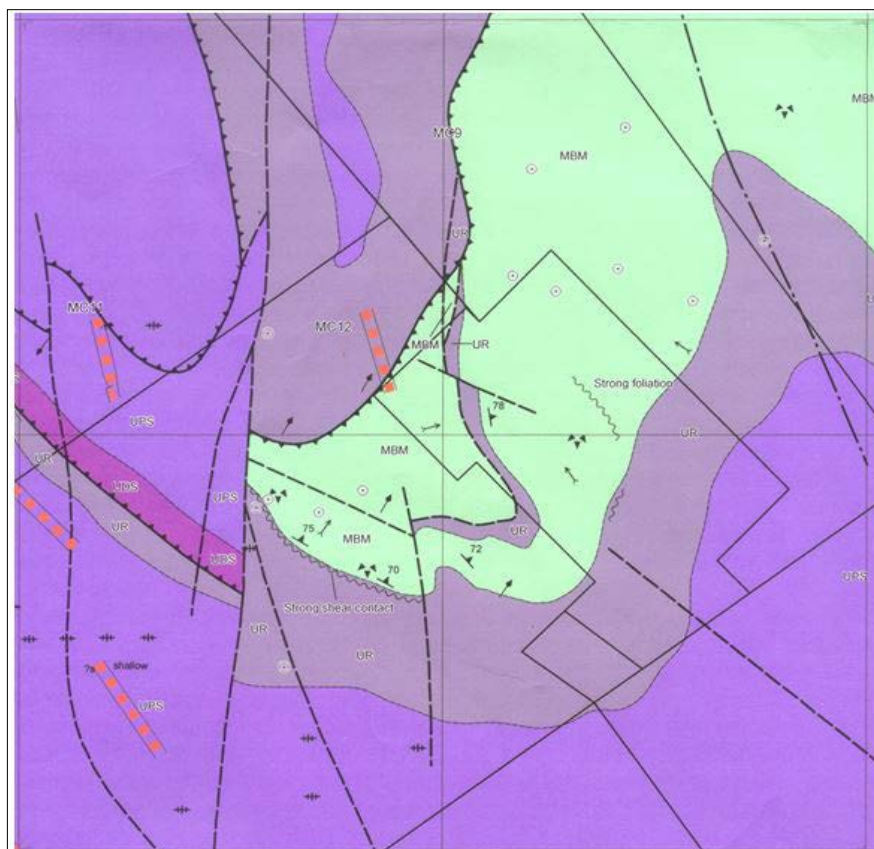
Figure 10: Part of the Geological Map of the Larcombe Project, Showing MLTEM Conductors (In Orange) (Courtesy Austminex & Dean Goodwin)
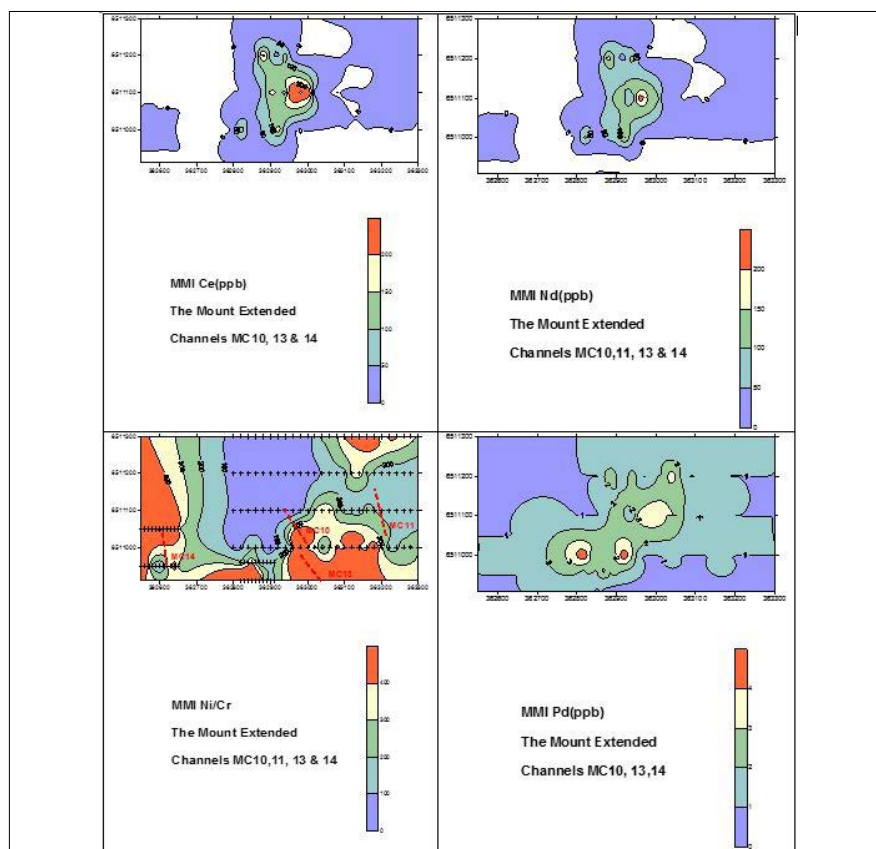
Figure 11: MMI-M Rare Earth, Ni/Cr and Pd Signatures Over Geophysical Conductors, Larcombe Project, Widgiemooltha.

extensive ultramafic rocks, but very little felsic or sulphur-rich rocks. Prioritizing geophysical targets with MMI™ geochemistry is a very useful way to focus drilling programs.

Overlaying the MMI™ geochemistry onto geology can often also be very instructive. For example, the MMI-Ce image from the above project, when overlayed onto the geology of the localized area of channels MC10,11 and 13 provides further vector towards a drilling target.

The highest Ce values (Figure 12) plot on the mapped serpentinite/tremolite contact. Samples were taken at 20m spacings E-W on lines 200m apart. It is interesting that the highest values are from samples directly on the contact.

In Figure 13, the schematic geology of two typical komatiite type 1 deposits is shown.

Plumes of felsic rock, incorporated into the base of the sulphides during the process of thermal erosion, are evident in many deposits of this type. Figure 12 shows this schematically. As shown by the geology of the Larcombe Project area, felsic rocks are conspicuously absent. The existence of high Ce (and Nd) values is therefore very interesting, and probably indicative of either slivers of felsic, or felsic plumes possibly within sulphides near the contact. It should be noted, that in general nickel sulphides of this type will have rare earth signatures near the base – the presence of Ce could be classed as a necessary condition for this type of deposit. But all rare earth signatures do not necessarily imply the presence of nickel sulphides – rare earth anomalies may in fact be also derived from felsics or black shales.
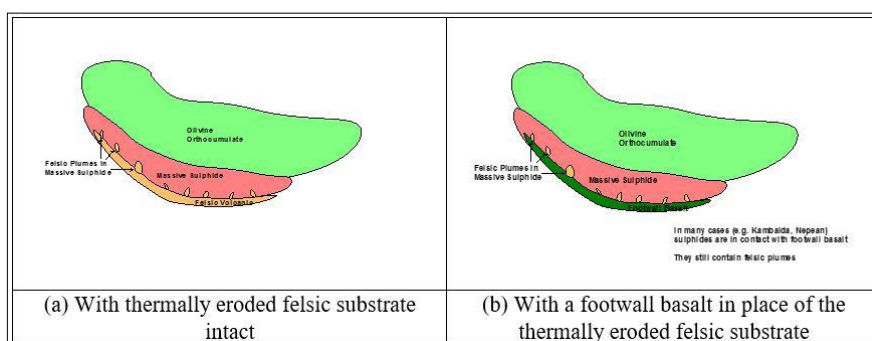
APPLICATION TO A KNOWN NIS DEPOSIT - NEPEAN LINE 4550N

The Nepean deposit occurs at a high angle contact in a structurally modified and metamorphosed environment. It produced approximately 1.1m tonnes of Ni at 2.99% between 1968 and 1987. As shown on Figure 14, a series of strike-slip faults have modified the sulphidized contact which is now evident as a series of "sills" labelled 1, 2 and 3.

Recently, archived samples from Line 4550N at Nepean were accessed, and re-analyzed using the MMI-M technique.
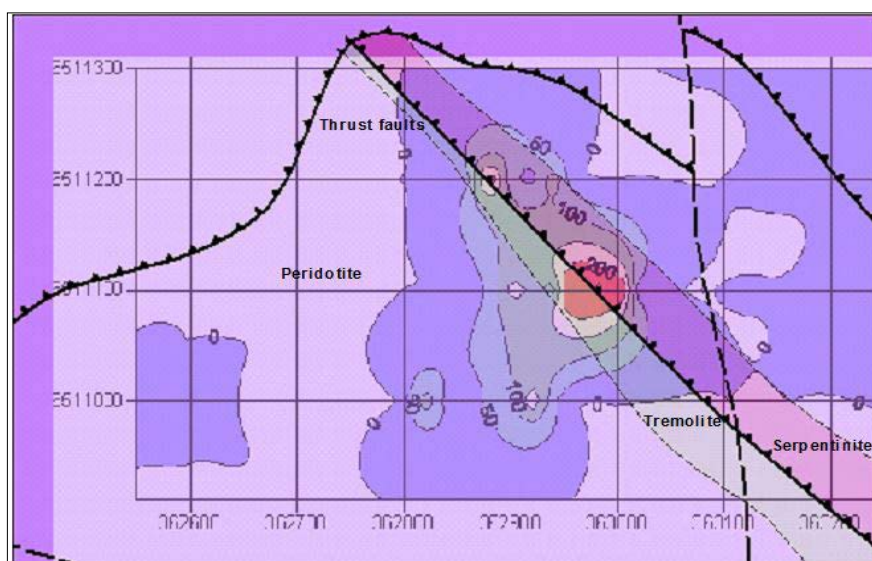
Figure 12: MMI Ce Over Geology, Larcombe Project, Widgiemooltha (after Dean Goodwin, Courtesy Austminex Ltd).

| (a) With thermally eroded felsic substrate intact | (b) With a footwall basalt in place of the thermally eroded felsic substrate |

Figure 13: Annotated Schematic Cross Sections of Typical Type I Nickel Sulphide Deposits Showing Felsic Plumes in the Massive Sulphide at the Base of the Olivine Orthocumulate(After Hill et al, 1999)
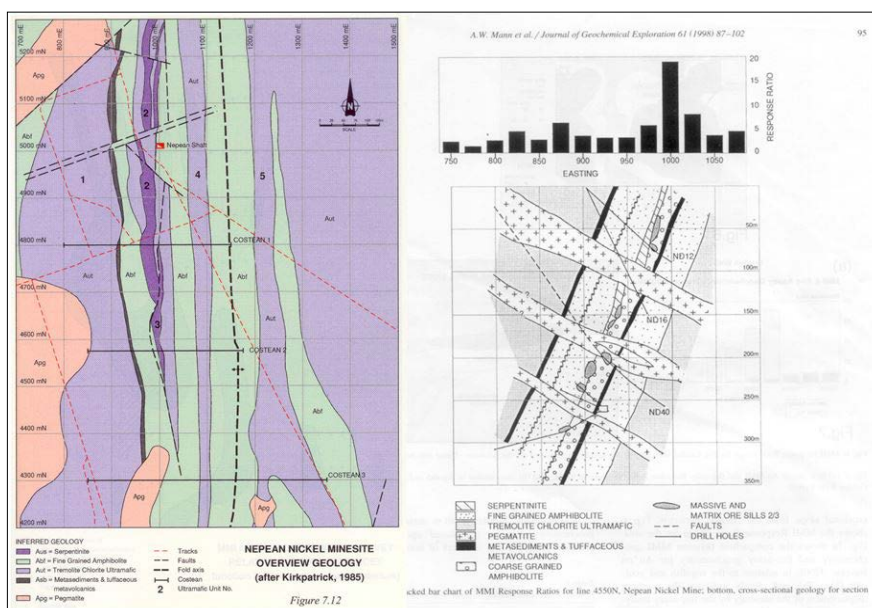
Figure 14: Surface Geology (Left) and a Cross Section at 4550N (right) of the Nepean Ore Body

previous MMI-B extractants along this line as shown in Figure 15.

Note that the sampling interval here is 25 m. The Ni values appear to accurately define the surface projection of ore. Whether or not the signal is derived from ore or some accompanying ultramafic can now be answered by examining the Cr analysis results from the same extraction. Figure 16 shows the Cr values and Ti/Cr ratio from the same MMI-M extraction.

If the high Ni signal in the centre of the line was derived directly from ultramafic, we might expect to also see an increase in Cr signal to over 50 ppb in the centre of the traverse. As shown the Cr values are relatively constant across the traverse, with values of the order of tens of ppb, consistent with the amphibolites noted to be adjacent to ore on this line at Nepean. If anything, Cr values are slightly lower near the ore zone. As a consequence, the Ti/Cr ratio increases and shows the position of the coarse-grained amphibolite footwall. When the Ni/Cr ratio is plotted for this section we see an even better definition of surface projection of ore, as shown in Figure 17.

As can be seen, the Ni/Cr ratio is in excess of a value of 1,000 over the ore zone. The contrast is greater (than the Ni data alone) due to lower background noise. This also indicates there is a greater percentage contribution of Ni in background samples from spurious (e.g. ultramafic) sources than there is (in percentage terms) to the anomalous signal i.e. the Ni signal over ore is derived predominantly from a Ni contribution from the (oxidizing) ore. This is a similar finding to that obtained from Pb isotope studies recently in North America viz. that partial extraction techniques derive a greater percentage of their signal from ore (and less from spurious sources) than do total digestion techniques. The principal reason for this is that they discriminate against lateral transport by accessing only recently adsorbed metal ions. It also establishes that any Ni/Cr ratio in excess of 1,000 is significant as a vector to ore providing the raw Ni is also anomalous, i.e. in excess of (say) 3,000 ppb.

Other elements can and should be used to confirm the likelihood of ore location. Nickel sulphide ores commonly contain appreciable amounts of Cu, Co and Pd.
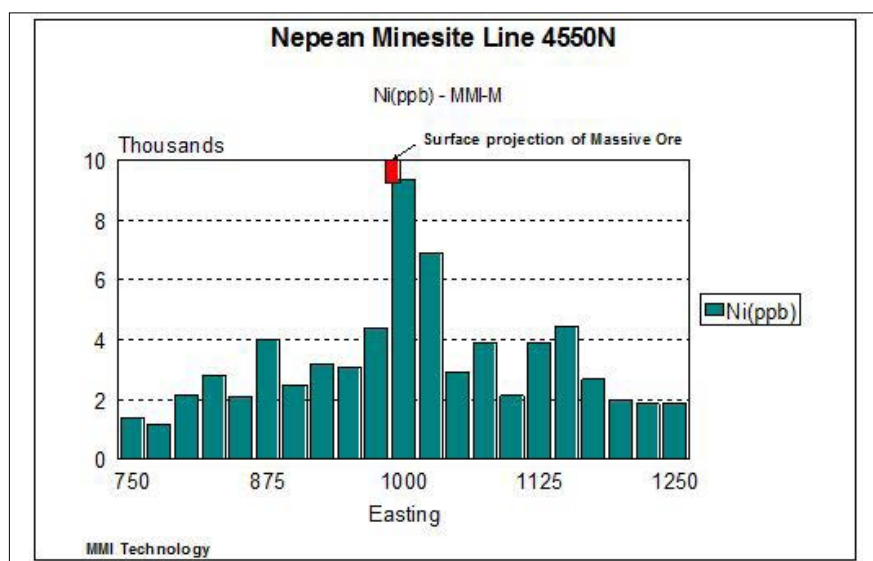

Figure 15: Ni Values in ppb, After MMI-M Extraction of Archived Nepean Samples
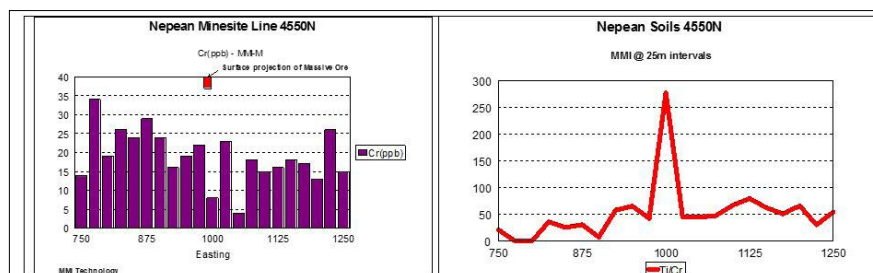

Figure 15: Cr Values and Ti/Cr Ratio After MMI-M Extraction of Archived Nepean Samples
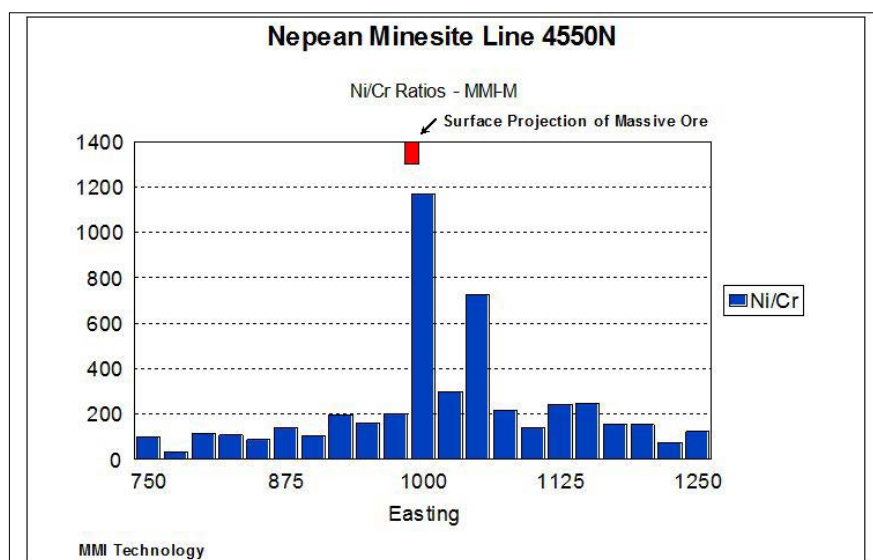

Figure 17: Ni/Cr Ratios After MMI-M Extraction of Archived Nepean Samples

Figure 18 shows that in the case of Nepean, Pd is such an indicator, whilst Cu is not.

As important as the high value of Pd which is observed, is the fact that it is located close to where the Ti/Cr ratio increases, and the Ni/Cr ratio decreases i.e. close to where the geochemistry corresponds with an expected basal contact.

More recently, two other elements have shown an association with the Nepean ore-body. A large number of additional elements were analysed in MMI-M extractions from the samples across Line 4550N. Of these two, cerium and neodymium showed very high responses in soils close to the ore-zone. Figure 19 below shows the results of the analysis for these two rare-earth elements in the Line 4550N soil samples.

As shown Ce and Nd report very strongly in samples adjacent to the sample with very high Ni and Pd. These two elements also report strongly in a separate Ni/Pd anomaly 300m to the south. It is possible they are indicating repeat of the mine sequence which may be structural or a separate concurrent NiS flow or shoot which is part of a braided channel-flow system, and therefore co-genetic with the Nepean sulphides.

PROSPECTIVITY INDICES

As mentioned in the introduction, geochemical exploration for nickel sulphides is difficult, but if applied with thought can also be rewarding as some of the examples presented here have shown. As a summary of the foregoing, and from an MMI perspective, no one element alone is indicative, and it is the combination of a number of soil geochemical factors which gives the best indication of NiS prospectivity. These factors are:

(1)   Moderate to high values Ni.

(2)   High values of Pd.

(3)   High values of Co.

(4)   Moderate to high values of Ce.

(5)   Low values of Cr (i.e. high Ni/Cr).

A multiplicative index of MMI-M analysis values Pd*Ce*Co*Ni/Cr can be used very effectively to highlight those areas with highest prospectivity for NiS, based on the fact that moderate values of all
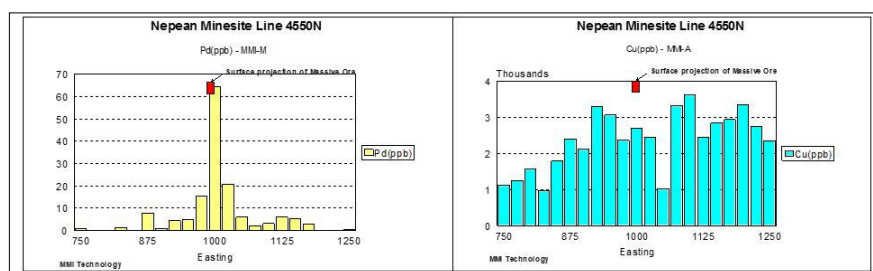

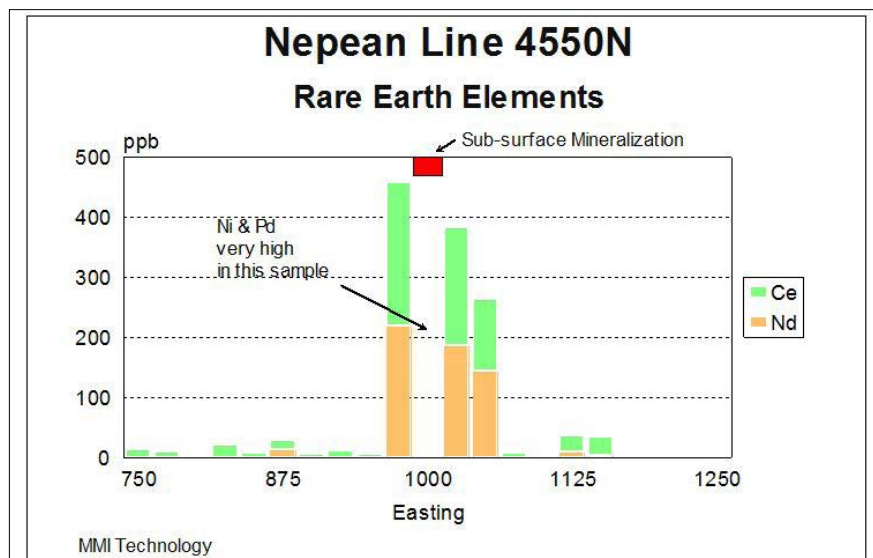Figure 18: Pd and Cu Concentrations in MMI-M Extraction from Soils Across Nepean 4550N

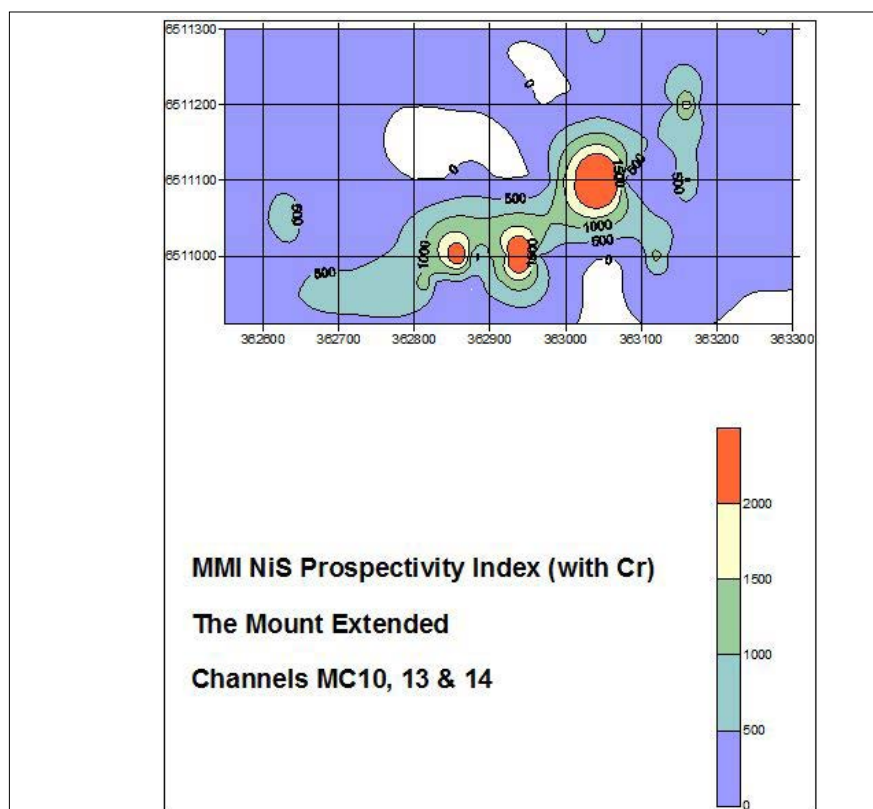Figure 19: Rare Earth Elements Ce and Nd in Soils, Line 4550N at Nepean

Figure 20: NiS Prospectivity Index for the Area of the Larcombe Project Area Referred to in Figure 11

Results for the Ni analysis using this extractant matched Ni analysis after

provide a single parameter for targeting drilling. In Figure 11 above, the individual images for Ni/Cr, Pd, Co and Ce were shown for a potential target. Figure 20 shows the NiS prospectivity index for the same area, derived from the same data.

This index should only be applied in the final stages of interpretation, when it has been established that the individual components e.g. Ni>8000ppb etc pertain.

DISCRIMINATING AGAINST BLACK SHALES

Discriminating a genuine basal contact nickel sulphide from a black shale or sediment by any geochemical method can be very difficult. Since both are chalcophile the chemistries can be very similar. In addition black shales are often intimately and closely associated with the mineralized sequence. The use of zinc (and cadmium) is often recommended as a discriminator, but care has to be taken – some nickel sulphides contain sphalerite, and not all black shales are higher in Zn and Cd. However it is worth testing any prospective Ni, Co, Pd, Ce anomaly for Zn, particularly if a local reference black shale is available.

GRID DENSITIES AND SAMPLING

For locating channel-flow facies rocks, a sampling density of 50 m spacing on lines (say) 100 m apart is commonly used. Sampling needs to be closed up to 10m-20m for follow-up investigation of the basal contacts as the surface projection of

a viable Ni sulphide target is very small.

Soil samples for MMI™ are taken from 10-25 cm below surface, i.e. the surface soil and litter is removed and then a ‚vertical channel' or composite over the next 15 cm is taken. Preferably samples should be coarsely sieved (3-4 mm), but apart from this no other preparation is required. Do not pulverize samples, or dry moist or wet samples. Snap seal plastic bags are used to transport the 300-500 g of sample required to the licensed laboratory (SGS, Perth in Australia and SGS, Toronto in Canada).

APPLICATION TO OTHER ENVIRONMENTS

Much of the above has been carried out on soils taken from residual and erosional environments overlying komatiites or komatiite nickel deposits on the Yilgarn Block, Western Australia. In particular, the absolute magnitude of the elemental values may only be applicable to those environments. Adjustments will have to be made if the technology is transferred to nickel deposits under cover. One of the potential advantages of using elemental ratios such as Ti/Cr and Ni/Cr is that they may be directly transferable to e.g. colluvial and alluvial environments, assuming that dilution of the signal for e.g. Ti and Cr is equal, i.e. the diluting material is from (say) a granitic source low in both of these components.

Transfer of the technology to other Ni deposit styles will require similar development of the technique and orientation over known mineralized cases.

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