Controls on Ni mineralisation at the Avebury Deposit, Western Tasmania.

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School of Earth, Atmosphere and Environment

Monash University

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STATEMENT OF DECLARATION

This thesis/report contains no material which has been accepted for the award of any other degree or diploma in any university and to the best of the candidate's knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

Ben Mackay-Scollay

November 21st, 2014

For Hannah

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Ben Mackay-Scollay, 21st November 2014.

CONTROLS ON NICKEL MINERALISATION AT THE AVEBURY DEPOSIT, WESTERN TASMANIA

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ABSTRACT

The Avebury Ni deposit in Western Tasmania is considered to be unique in that it was formed by hydrothermal processes and is associated with an ophiolite sequence that was intruded by a granite. Sulphur isotope geochemistry shows that the deposit is unlikely to be magmatic in nature. Trace element geochemistry indicates that the original mineralogy appears to have been heavily overprinted by metasomatic processes driven by the intrusion of a nearby granitic pluton. Petrography indicates that the Ni mineralisation occurred at the same time as the serpentinisation. Implicit 3D modelling based on existing drill data from the original near-mine exploration program suggests that the majority of the mineralisation is at the edges of the mafic-ultramafic host of the deposit, within the heavily metasomatically altered sections at the margins of the ultramafics. Trace element geochemistry indicates that these heavily metasomatically altered sections, referred to in previous work as skarns, consist of both ultramafic and sedimentary lithologies. Scanning electron microprobe work indicates that the nickel in the deposit was not mobilised from the ultramafic rocks as these still have the background nickel contents expected for that lithology. Platinum group element analyses indicate that the Ni was carried in from outside the deposit hydrothermally.

Key words: Nickel, hydrothermal, geochemistry, 3D modelling, sulphur isotopes, platinum group elements

INTRODUCTION

The Avebury Ni deposit is situated in the centre of the Dundas Trough in Western Tasmania, in the Zeehan Mineral Field, a traditional exploration area for Sn W, Zn, Pb and Ag deposits. It consists of three main ore bodies, North Avebury, Central Avebury and Viking. The deposit system contains approximately 28Mt of ore at 0.9% Ni for a total resource of 260,000t. It is hosted within the Middle Cambrian McIvor Hill Complex, which is comprised of both gabbros and cumulate-textured peridotite and dunites that are theorised to be part of an ophiolite sequence. It was discovered in the late 1990s during an exploration campaign targeting Zn; the area had not been considered prospective for Ni mineralisation at the time (Zeehan Zinc, 2002).

The major research question surrounding the Avebury deposit system is the formation of the Ni deposit. There are three competing theories (Keays & Jowitt, 2012). Each competing theory will have differing ratios from platinum group element geochemistry, sulphur isotopes, and whole rock geochemistry. Each theory also has in common the hydrothermal influence of the nearby Devonian Heemskirk Granite. The entire area is within the hydrothermal aureole of this intrusive.

The first theory is that the deposit is a strongly metasomatised pre-existing magmatic sulphide deposit. This would be indicated by moderate to high PGE contents, with positive correlation between the Ni and PGE concentrations. Specifically, Ir should correlate with Ni, as there is no known hydrothermal process that will mobilize Ir (Keays, et al., 1982).

The second theory is that the hydrothermal fluids from the Heemskirk Granite liberated Ni from olivine in the ultramafic rocks and concentrated it in the deposits. This would be characterised by significant depletion of Ni within the host serpentinite rocks of the deposit, as well as low PGE and Cu contents. Dunites with low magmatic sulphide contents in the Heazlewood River Complex, which is co-magmatic with the Avebury ultramafic body, have very low Cu, Pd, Pt and Au contents (Peck, 1990). Mobilization of Ni from the olivines in the ultramafics was the initial theory proposed for the development of the Avebury deposit and the nearby Cuni prospect (Zeehan Zinc, 2002).

The third theory is that the deposit consists of Ni liberated from magmatic sulphides at depth that was leached and transported by the hydrothermal fluids from the Heemskirk Granite. This should be indicated by moderate levels of Cu, Au, Pd and Pt, with deficiencies in Ir and low Ru and Rh. Sulphur isotope data should show that the S in the deposit was from either the Heemskirk granite or the sedimentary, possibly S-bearing rocks, traversed by the fluids from the granite because sulphides in the granite have high $\delta^{34}S$ values, averaging +9.8 per mil (Both, et al., 1969). This third theory will be explored in depth in this work.

Earlier work on the Avebury deposit has focused on the hydrothermal influence of the Heemskirk Granite, and its major, trace and platinum group element geochemistry which suggest that the Ni in the deposit was derived from magmatic sulphides at depth (Keays & Jowitt, 2009). This work endeavours to further reinforce that theory and provide insight into the lithological details of the deposit that control the specific location of the mineralisation within the deposit.

The importance of this research to a new type of Ni exploration model comes with the recent increase in prices for the metal through 2013 and 2014, rising from approximately 6.6 USD/lb to as high as 9.3 USD/lb (Kitko Metals, 2014). Nickel is used in many of the technological devices that support the modern, Western way of life, including the batteries and fuel cells required to power them, as well as in alloys necessary for air travel and transport, and the corrosion protection vital to operating in many harsh environments (Kuck, 2012).

REGIONAL GEOLOGY

Geology

Avebury is located within the Middle Cambrian McIvor Hill complex, which comprises gabbros and cumulate textured dunites and peridotites that are considered to be ophiolitic in origin. This sequence was obducted onto the Neoproterozoic (Ediacaran) Crimson Creek formation, an interbedded, volcaniclastic turbiditic wacke, with intercalated siltstone-mudstone horizons (Crawford & Berry, 1992).

Tectonic History

The Crimson Creek formation was formed during plume-triggered rifting at approximately 600Ma that produced an east-facing volcanic margin with thick a seaward-dipping reflector similar to those off the eastern coast of Greenland. During the Middle Cambrian at approximately 520-515Ma, east-dipping subduction commenced generating a boninitic forearc sequence and initiating the formation of a primitive intra-oceanic arc. These sequences included the eventual host of the Avebury formation, the McIvor Hill Mafic-Ultramafic Complex (MUC) (Keays & Jowitt, 2012). At 510Ma, arc-continent collision saw the emplacement of allochthonous mafic passive-margin sections, which were then overlain by nappe-thrusted Ti-depleted tholeiitic and boninitic lithosphere sections. This additional load on the crust caused the collapse of the passive margin that lead to the formation of the Dundas Trough foreland basin. At approximately 505Ma, the area underwent post-collisional extension that caused the crustal assembly to collapse, and the eruption of the Mt Read Volcanic lavas between 505Ma and 497Ma (Crawford, et al., 2003).

Post-tectonic alteration

The two major driving events of the formation of the Avebury deposit were the overturning of the stratigraphic package containing the McIvor Hill MUC, and the subsequent intrusion of the Devonian Heemskirk Granite into the local stratigraphy.

During the 510Ma tectonic event, the McIvor Hill MUC was overturned in a nappe-thrust interpreted as the F_2 event by McFarlane (2012); this caused the stratigraphy to repeat with the Avebury deposit positioned in the lower limb of the fault. This resulted in the current-day configuration of the McIvor Hill MUC post-dating but sitting underneath the Crimson Creek Formation (McFarlane, 2012). Sitting underneath the Avebury deposit are Silurian sediments of unknown provenance and directly underneath that is the Devonian Heemskirk Granite. A schematic diagram of this can be seen in Figure 1.

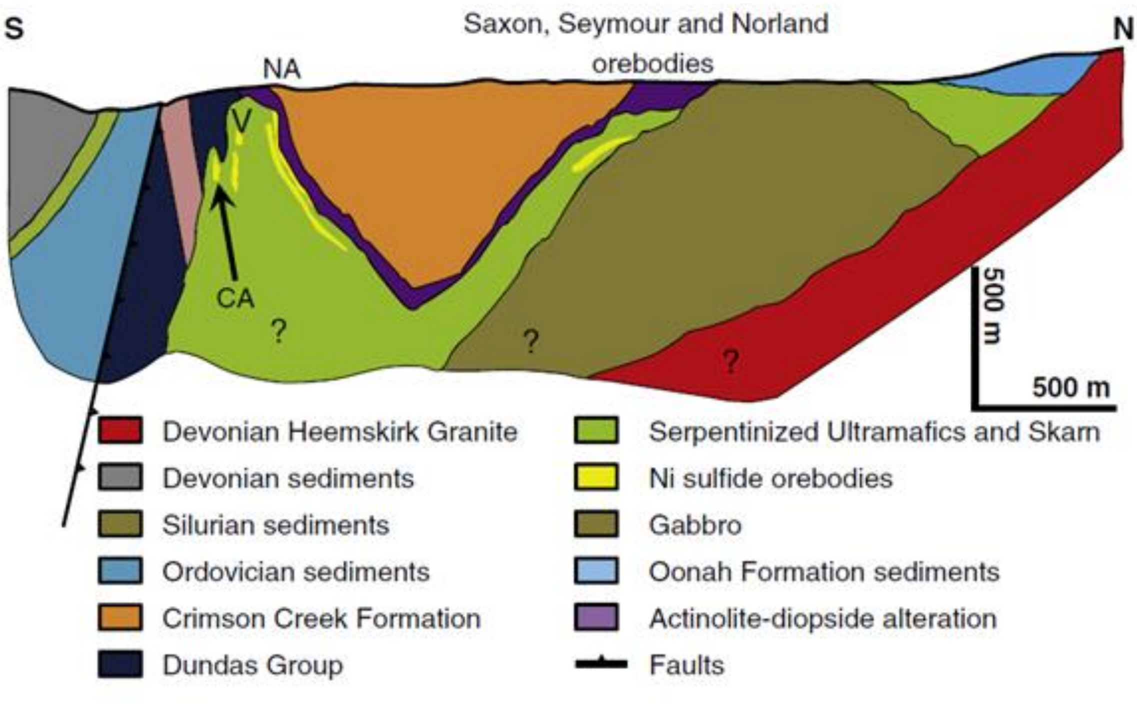

Figure 1. Schematic cross-section of the Avebury area, with the location of the nearby Heemskirk Granite in red. (Modified from Keays & Jowitt (2012)).

The intrusion of the Heemskirk Granite has exerted a great deal of influence on the geology of the area. The entire Avebury deposit is within serpentinised mafic/ultramafic rocks and skarns developed within the hydrothermal contact aureole of the Heemskirk Granite (Keays & Jowitt, 2012). The influence of the granite can be seen in the trace element geochemistry of the samples taken from the Avebury deposit for this study, and will be explored further in the Geochemistry section. The advanced metasomatic alteration of the mafic/ultramafics has resulted in significant serpentinisation and secondary serpentinisation as will be investigated in the Petrography section. The 3D structure of the deposit and the distribution of the mineralised zones in relation to the lithology will be considered in the Implicit Geological Modelling section.

GEOCHEMISTRY

Sulphur isotope geochemistry

Sulphur isotope ratios are used in geochemistry in order to determine the source of the element in sulphides, giving an indication as to the original lithology and amount of alteration within the sulphides. Sulphur ratios are expressed as a part per thousand, or per mil, with the symbol ‰. The two most common isotopes of sulphur in the crust are heavy sulphur ^{34}S and light sulphur ^{32}S, with the isotope exchange between the reduced and oxidised species' expressed as follows:

$$^{32}SO_4^{2-} + H_2{}^{34}S \rightleftarrows {}^{34}SO_4^{2-} + H_2{}^{32}S$$

The theoretical value of the exchange constant is 1.075 at 25°C (Tudge & Thode, 1950). This suggest that when the exchange take place in the crust, it should lead to sulphides being generally depleted in ^{34}S as the heavier isotope preferentially goes into the sulphate phase (Thode, 1970), and the lighter isotope is preferentially reduced by sulphate reducing bacteria, accounting for up to 10% of the difference in 32S/34S ratios (Konhauser, 2007).

The $\delta^{34}S$ levels for magmatic sulphide deposits across the world are generally in the order of -2 to +6 ‰, normalised to the IAEA Vienna CDT (International Atomic Energy Agency, 1993) as shown in Figure 2, adapted from Keays (2014). An exception to this are the Ni ores of the Noril'sk region that have $\delta^{34}S$ values of +5 to +14‰. This is thought to have been the result of the intrusion of the end-Permian mafic sills that make up this ore body interacting with existing Devonian evaporates, with significant contact aureoles in the sediment packages and magmatic anhydrite in the mafic intrusions having even higher $\delta^{34}S$ levels – from +15 to +120‰ (Pang, et al., 2013)

Sulphur isotope geochemistry was completed at the Queens Facility for Isotope Research at Queen's University in Kingston, Ontario, Canada. 20 samples from the Avebury deposit were analysed using their DELTAplusXP Stable Isotope Ratio Mass Spectrometer to determine the ratio between ^{34}S to ^{32}S, the results of which can be seen in Table 1.

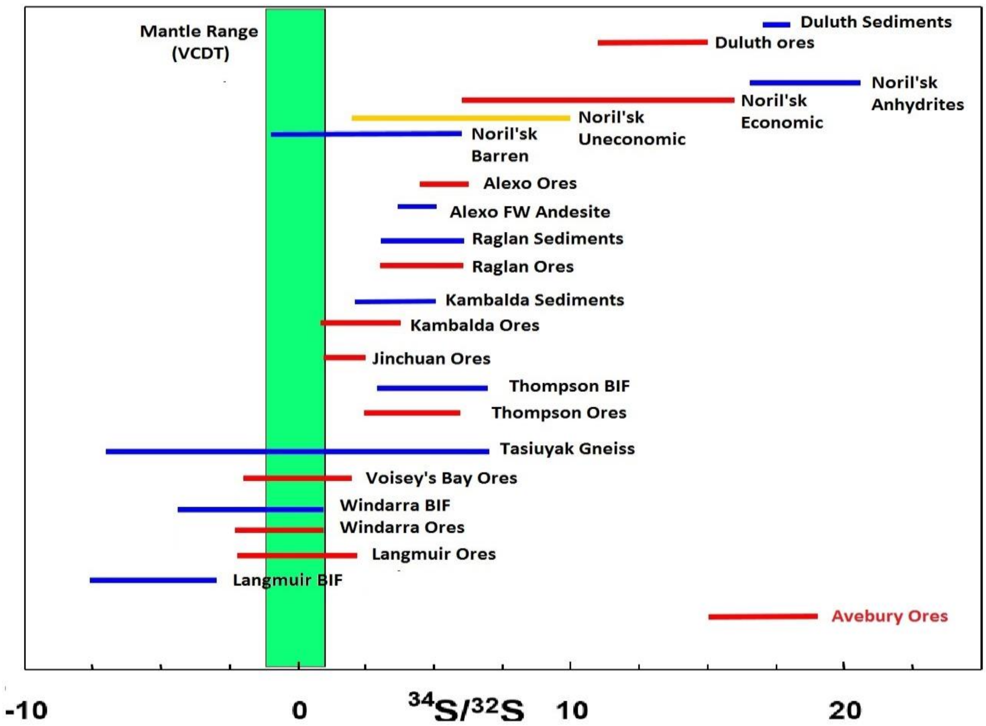

Figure 2. This diagram shows the range of $^{34}S/^{32}S$ ratios seen in magmatic sulphide deposits across the world. Majority of deposits are between -6 and +5‰. Avebury can be seen on bottom right. Adapted from Keays (2014).

Sample	34S ‰	Ni ppm	S ppm
2208_0992	17	4200	4000
2208_0995	19.1	6400	11600
2208_0996	18.8	6400	4600
2208_0997	16.7	7300	4600
2208_0998	17	5100	3800
2208_0999	17.1	11900	9500
2208_1004	16.7	3200	3700
2208_1005	17.2	11200	7500
2208_1009	16.8	2800	2300
2208_1014	16.3	1800	1900
2208_1017	18.3	12900	82700
2208_1018	18.8	12900	14500
2208_1019	18.4	21900	64400
2208_1020	17.4	15700	18000
2208_1021	16.8	34300	60000
2208_1022	16.9	51900	124000
2208_1024	17.8	22400	14600
2208_1027	14.4	3800	7500

Table 1. Sulphur isotope values of Avebury samples analysed in this project. The mean and standard deviation of the $\delta^{34}S$ values is 17.3 ± 1.1‰.

Trace element geochemistry

A suite of 28 samples was taken from existing drill core generated by Allegiance Mining during their 2006-2007 mining campaign. These samples were selected based on attaining representivity across the deposit for the different lithologies present, specifically the McIvor Hill Complex mafic-ultramafics, the Crimson Creek Formation volcanogenic sediments and the heavily metasomatically altered zone between them. These samples were also selected so as to properly represent the range of Ni mineralisation concentrations present, with selections for background levels of Ni at around 2000ppm in the mafic-ultramafic zones and values as high as 5% Ni in the mineralised zones. Samples were also taken from the mafic-ultramafic area where the Ni levels were specifically as low as possible in order to use these samples for microprobe work to determine whether the Ni content in the mineralised zones was linked to Ni depletion from the mafic-ultramafics. Whole-rock trace element geochemistry can be seen in Appendix 1.

Petrography

Ten Avebury samples were selected from drill core to cover the major lithologies present – skarn host, skarn ore, serpentinite host and serpentinite ore, as well as volcanic basaltic lithic breccia and the footwall sediments – and prepared for thin section analysis by Robert Smith at Federation University in Ballarat. The samples were prepared as bonded thin sections in order to facilitate the electron microprobe testing for Ni contents in serpentinites.

These thin sections were then inspected using the Monash University petrographic microscope using with both reflected and refracted light, with the sections observed for primary minerals, alteration minerals and textures, and mineral interactions along boundaries. Figure 3 below shows the relevant interplay between the boundary of pentlandite ($(Fe,Ni)_9S_8$) and magnetite (Fe_3O_4). Thalhammer et al. (1986) looked at the hydrothermal origin of sulphide and arsenide mineralisation and found that this vermicular texture was indicative of simultaneous crystallisation out of an emulsion of Ni- and Fe-rich fluids, as opposed to later deformation and overprinting. Specifically, it was found that none of the processes that created these textures were the result of magmatic activity.

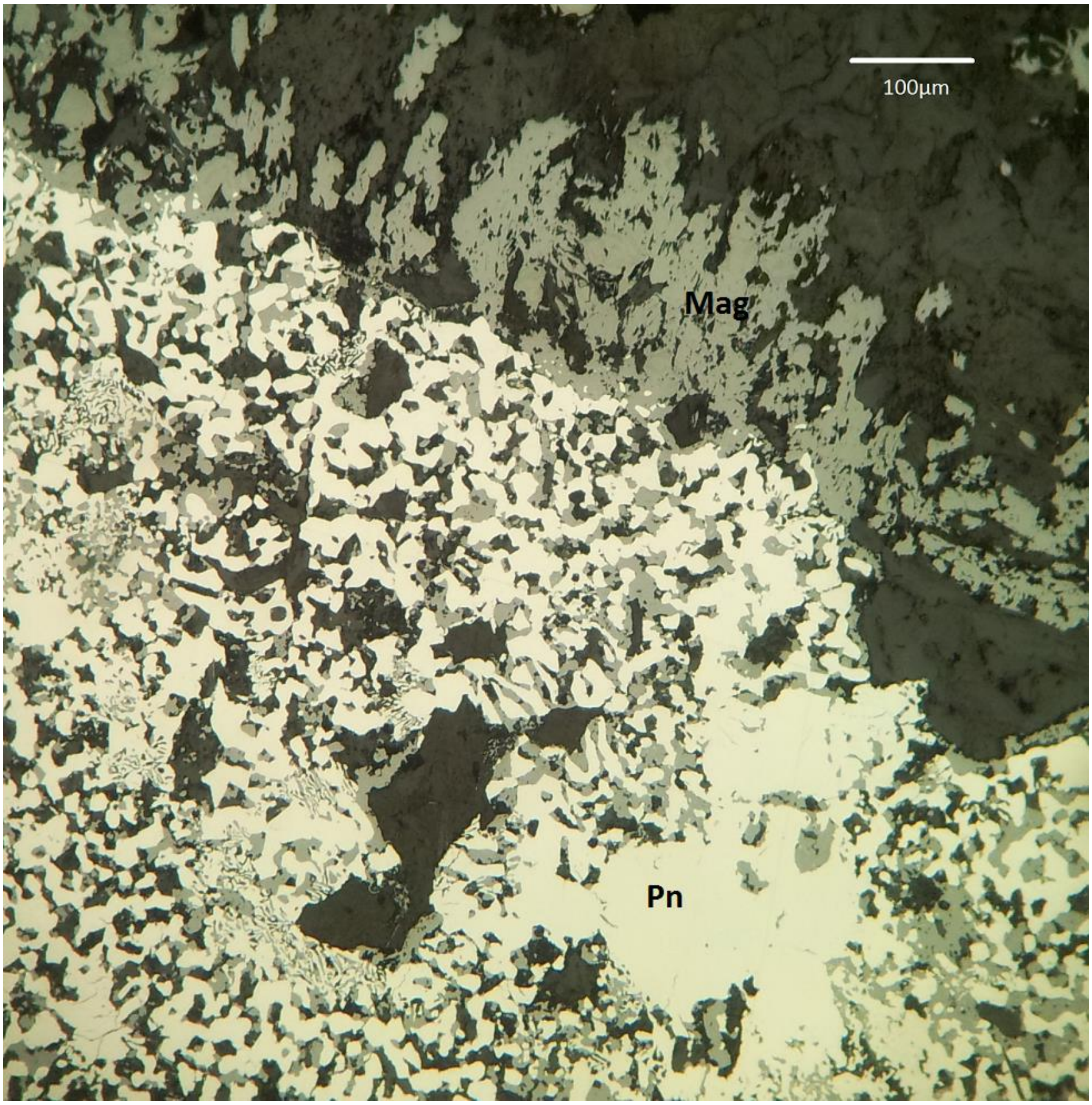

Figure 3. Reflected light image of polished thin section showing intermingled pentlandite and magnetite. This emulsion indicates that they formed near-simultaneously, as the result of hydrothermal activity (Thalhammer, et al., 1986) Mag = magnetite, Pn = pentlandite

IMPLICIT GEOLOGICAL MODELLING

Introduction

A major part of this project was the development of an implicit 3D model of the Avebury deposit, using existing drill data from the historical Allegiance Metals drilling programs, both the initial program and the near-mine exploration completed before the sale to MMG. The program used to complete this model was Leapfrog 3D by ARANZ Geo Limited, specifically the Leapfrog Mining software suite. There are several reasons why this software was chosen over the potential competitors in the field. The first was one of convenience; as the software package that the researcher had the most familiarity with and had unfettered access to without spending additional funds on the acquisition, setup and training of new packages, it was expedient to utilise what was available. From the view of data management, Leapfrog was also seen as providing a fast, efficient method of entering all of the available drillhole data and interpolating it into the required solid volumes for interpretation.

Leapfrog is seen within the industry as allowing for an exponential increase in the speed of the modelling process for volume modelling of many geological scenarios. MMG specifically uses the software as an essential part of their exploration programs, in order to greatly increasing the amount of information that can be consumed by the project geologist in developing their model of a deposit and a model for exploration and exploitation of a deposit (Reed, 2014). Leapfrog also relies on implicit modelling as opposed to explicit. The difference between the two is that implicit modelling uses an interpolant referred to as a Radial Basis Function to interpose structure and lithology onto a data set without the necessity for explicit, time-consuming modelling of every point in the volume cloud. Radial Basis Functions are a real-valued function that in this context converts text-based geological logging into a cloud of distance-based values where each point is interpolated in comparison to the surrounding points (Cowan, et al., 2002). Leapfrog allows the construction of 3D models within a much faster time-frame and without significant manual digitisation, assuming the data are properly formatted. Formatting of the data took a significant amount of time in order to have it correctly entered within Leapfrog for this project.

Modelling

The model built for the Avebury deposit consisted of data drawn from 405 drillholes representing 18 months of surface and underground drilling, with approximately 116,000m of drill core logged. This logging consisted of stratigraphic data, alteration (mineral and mode), and assay data for Ni, Cu, Pb, Zn, Co, S and As. Samples were taken from visibly mineralised sections for metallurgical analysis. The raw data for this are given in Appendix 2. After the data was entered into Leapfrog, a wireframe model was built, as can be seen in Figure 4. From here, overlays were created to look at the boundary between the ultramafics and skarn, seen in Figures 5 and 6.

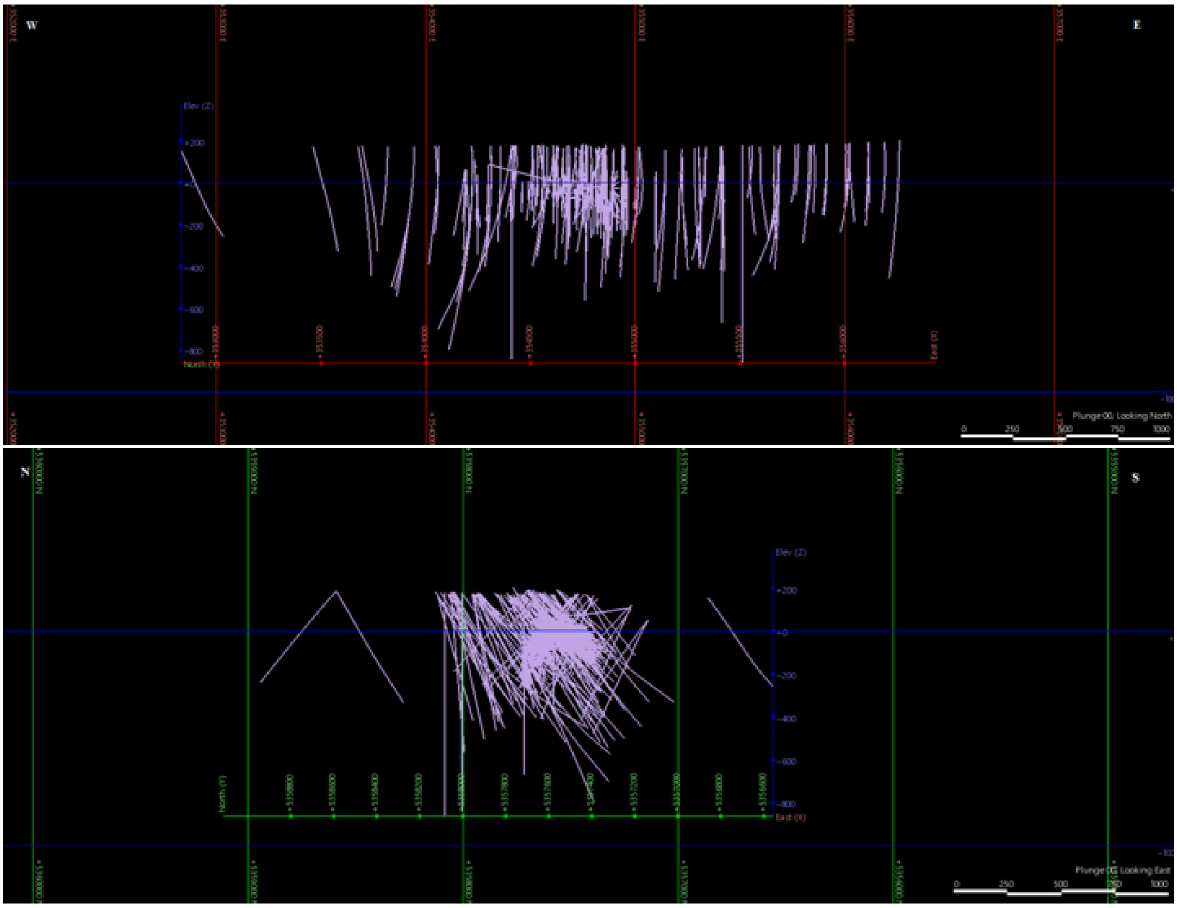

Figure 4. Wireframe model of drilling at Avebury, with views looking North (top) and East (bottom). Individual drillholes in purple.

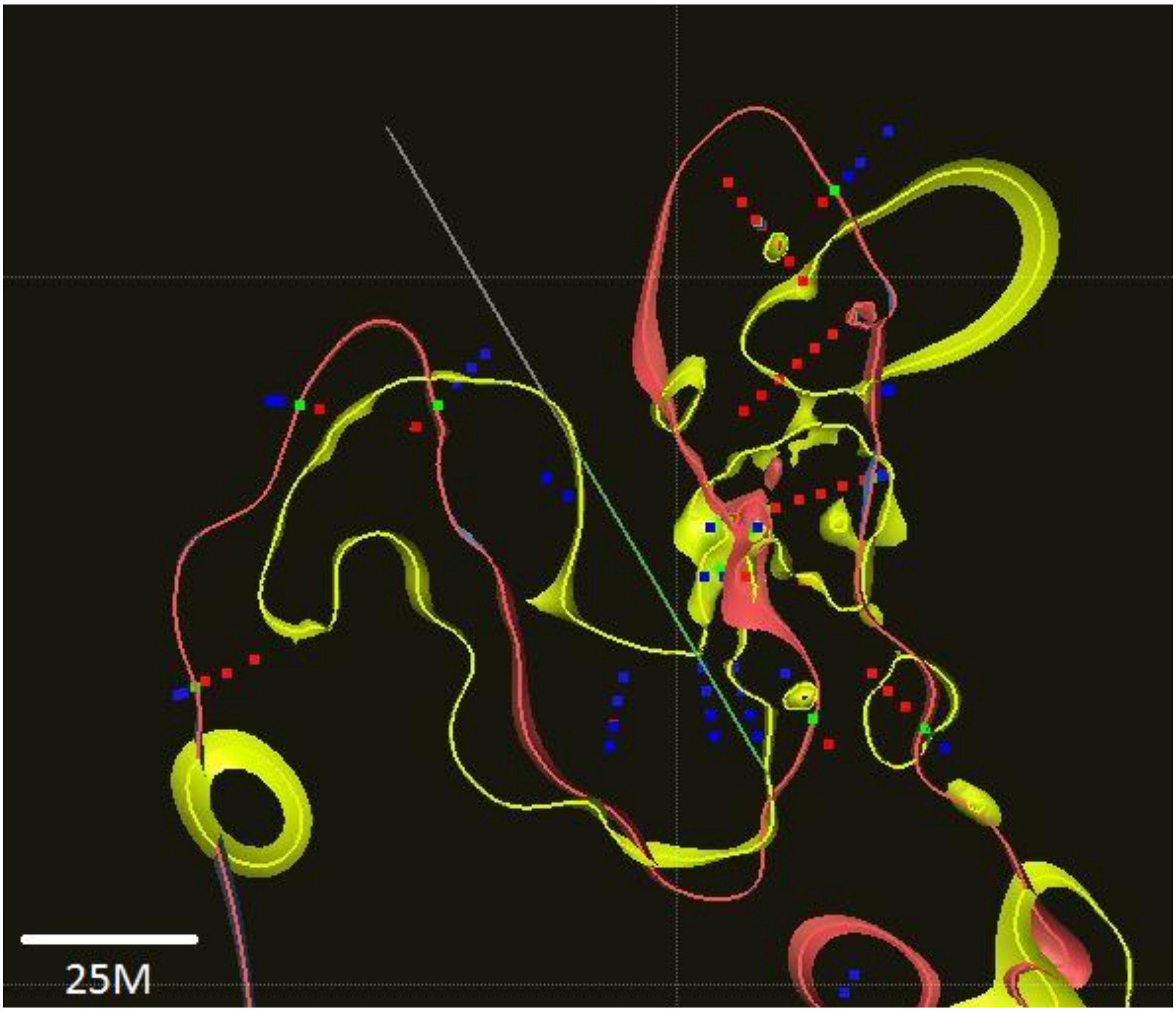

Figure 5. The initial wireframe model with the contact between the MUC and the skarn projected over it. In this image, the Ni grade of >3000ppm is seen in yellow, the interpolated boundary of the MUC is in red, and the small squares are drillhole observations, with blue in the skarn, red in the MUC and green representing the contact. The majority of the Ni mineralisation appears to follow the contact with the majority of it within the skarn. View is facing west.

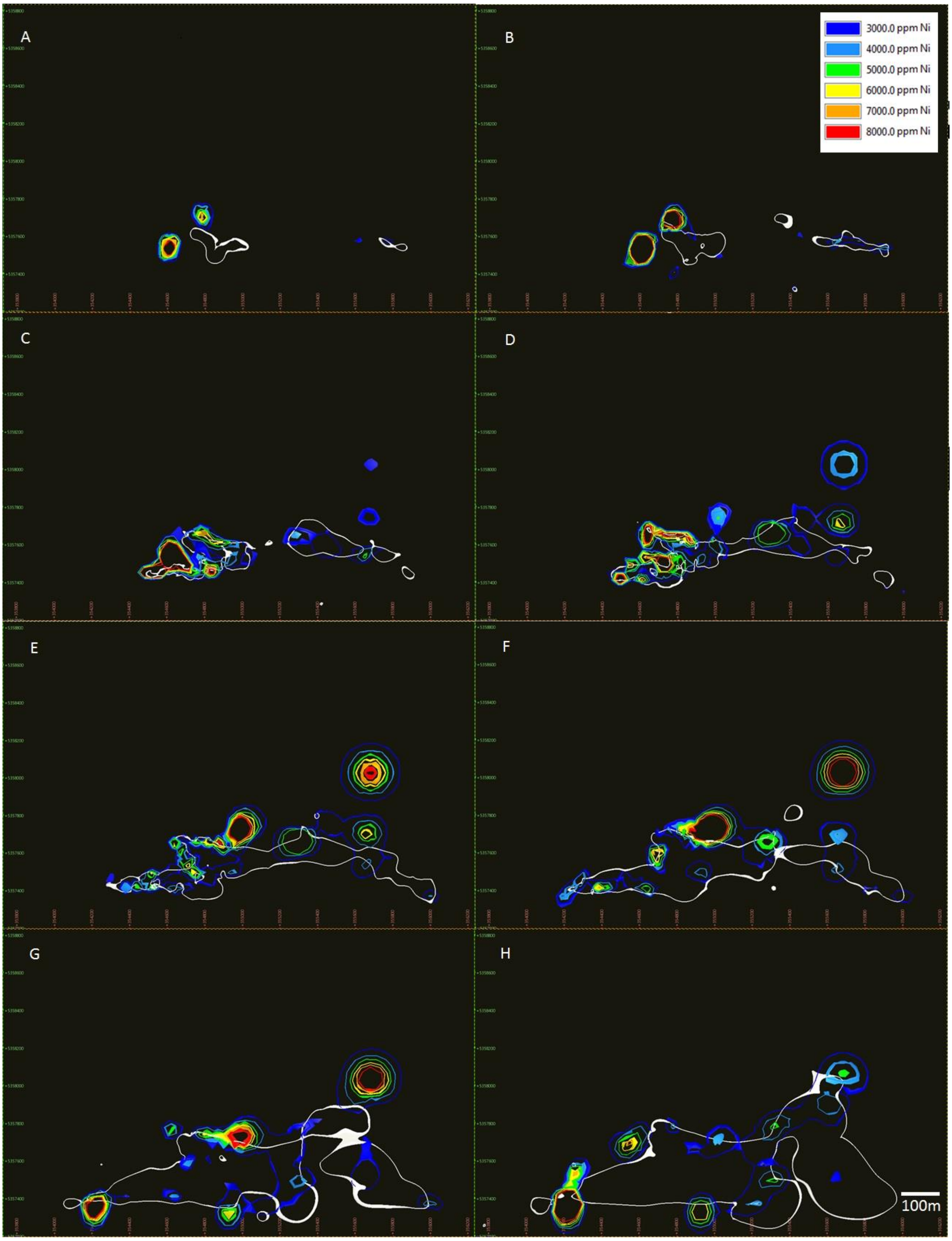

Figure 6. Slices from the wireframe model down through the deposit. In this figure, the formation of pipe-like structures can be seen with Ni grades increasing towards the middle of the pipe. In (D) and (E) an upright tabular Ni mineralisation zone can be seen on the outer edge of the mafic/ultramafic contact. Ni grades in colour as per legend, with

mafic/ultramafic contact in white. Depths: A +100, B +50, C 0, D -50, E -100, F -150, G -200, H -250

The pipe-like structures seen in Figure 6 are interpreted to be flow pathways that have seen pulsatory episodes of hydrothermal fluids pass through, depositing higher and higher grades of Ni in concentric shells. The boundary between the mafic/ultramafic contact and the skarn could have acted as a redox boundary that caused the precipitation of the Ni sulphides, with the volcanigenic siliciclastic Crimson Creek formation acting as a cap on the deposit system, concentrating and spatially restricting the mineralised zones (Keays & Jowitt, 2012).

DISCUSSION

Sulphide Geochemistry

The $\delta^{34}S$ levels of the Avebury samples that are significantly higher than would be expected if the Ni sulphides in the Avebury deposit were strictly magmatic in origin (Table 1, Figure 2). This suggests that the S came from a secondary source, either the Heemskirk granite or the sedimentary rocks traversed by the fluids from the granite.

These sulphur isotope values further reflect the hydrothermal activity of the Heemskirk Granite overprinting the Avebury deposit. From an S isotope study of mineralization associated with the Heemskirk Granite and the Zeehan mineral field, Both et al. (1969) showed that mineralized samples within the granite had an average $\delta^{34}S$ value of +10.5‰ with the highest value at +15.1 ‰. They also reported that $\delta^{34}S$ values dropped off away from the intrusive complex. The Avebury Ni deposit system is proximal to the edge of the Heemskirk Granite intrusion and as such could be expected to have high $\delta^{34}S$ if the S at Avebury came from the Heemskirk Granite. This can be seen in Figure 7.

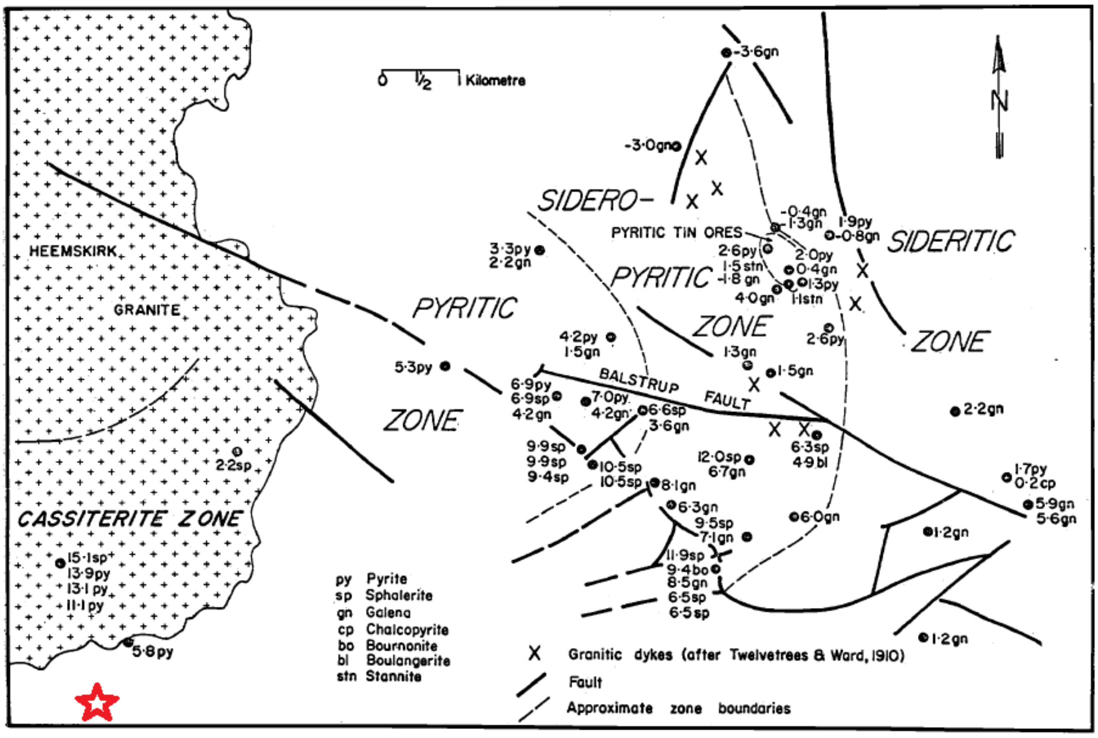

Figure 7. Map showing $\delta^{34}S$ values around Heemskirk Granite. The location of the Avebury deposit is given by the red star. $\delta^{34}S$ drops off with distance from the Heemskirk Granite. (Map is modified from Both et al., 1969)).

The second possible source of the S is that it came from magmatic sulphides somewhere at depth below the Avebury Ni deposit that had formed due to the interaction of a mantle-derived melt with sedimentary rocks that had high $\delta^{34}S$ values. Magmatic Ni sulphide deposits are formed by highly dynamic magmas in which sulphide droplets are able to mix with a large volume of silicate liquid (Naldrett, 1999). Such magmas also thermally erode and assimilate the crustal rocks with which they come in contact; if these crustal rocks are S-bearing, magmatic sulphides are formed (Keays & Lightfoot, 2010). It is suggested that the precursor magmatic sulphides that lie at depth below Avebury had formed due to the assimilation of sedimentary rocks that contained iron sulphides with high $\delta^{34}S$ values. Both et al. (1969) suggest that the high $\delta^{34}S$ values of the Heemskirk granite are also due to the assimilation of crustal rocks that contained S with high $\delta^{34}S$ values, incorporated into the Heemskirk during intrusion.

Whole rock trace element geochemistry was also completed on the samples taken from the Avebury drill core. From this it can be seen that there are two distinct lithologies that make up the heavily metasomatically altered skarn zones. A plot of Yb vs Cr was constructed to determined which of the altered Avebury rocks were derived from ultramafic rocks (which have high Cr/Yb) and which from Crimson Creek volcanogenic sediments (Figure 8). This exercised showed that three of the rocks logged by the mine geologists as skarns produced by the alteration of ultramafic rocks had in fact been derived from the Crimson Creek formation (Figure 8). This exercise demonstrated the usefulness of Cr and Yb, which remain immobile during alteration of rocks, in determining the protoliths of highly altered rocks.

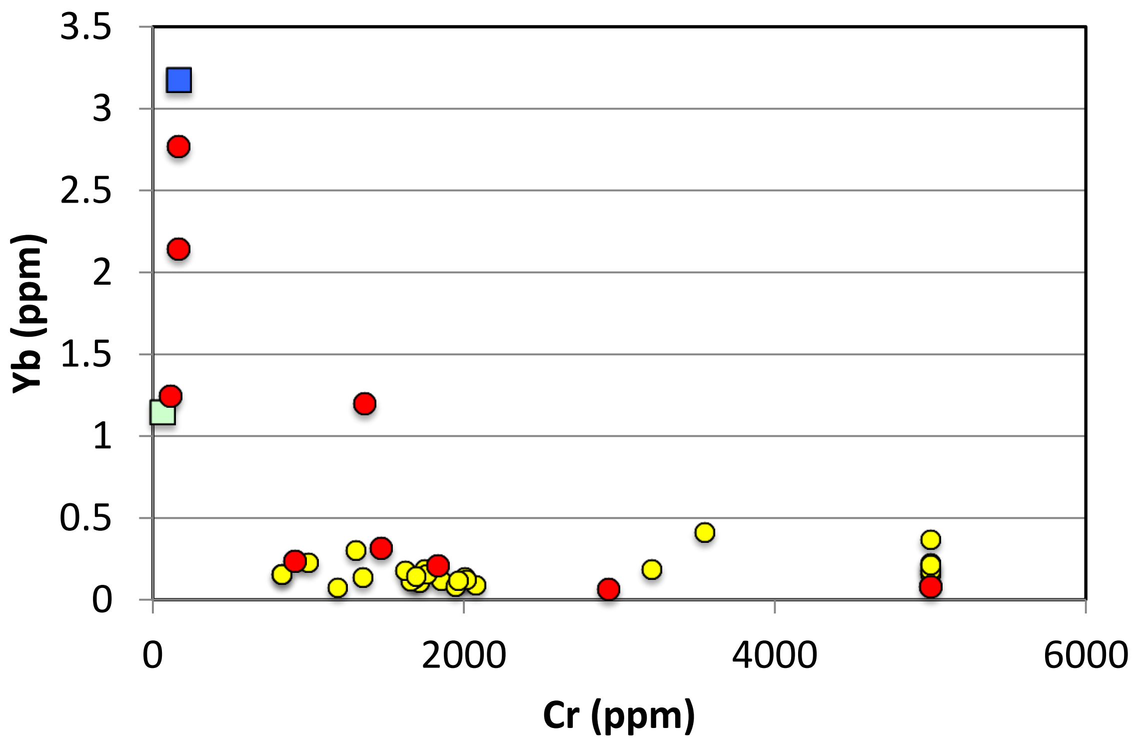

Figure 8: Scattergram of Yb vs Cr for the Avebury samples. Two distinct groups are seen, with high Cr/low Yb results showing the serpentinites and the low Cr/high Yb results

representing the Crimson Creek volcanogenic sediments. The yellow points were originally logged as serpentinites, the green as skarn, the red as skarn serpentinites and the blue as sediments.

The high $\delta^{34}S$ values rule out the possibility that the S in the Avebury ores came from a mantle source. This leaves the possibility that the S came from either the Heemskirk Granite, or from magmatic sulphides at depth that formed due to the interaction of a mantle-derived magma with crustal rocks that contained heavy $\delta^{34}S$ values.

Three Competing Theories

The first scenario considered by Keays et al. (2009) and Keays & Jowitt (2012) is that Avebury is a strongly altered magmatic sulphide deposit. These authors argued that the inverse correlations between Ir and Ni, (as well as between Ru vs Ni and Rh vs Ni) rule out the possibility that Avebury is a metasomatized pre-existing magmatic Ni sulphide deposit (Figure 9). The logic behind this argument is that there is a strong positive correlation between all the PGE and Ni in magmatic Ni-Cu-(PGE) sulphides that are formed from unfractionated sulphide melts. Although the strong negative correlation between Ir and Ni reported by Keays and Jowitt (2012) was not supported by the additional 42 samples analysed in this study, it is very clear from Figure 9 that there is no correlation between Ir and Ni; indeed, the most Ni-rich samples have the lowest Ir contents. The positive correlation between Ir and Cr (Fig. 10) shows that the bulk of the Ir in the Avebury rocks was contributed by the rocks and not by any sulphides in them. The high $\delta^{34}S$ values (from +14.4 to + 19.1‰, with an average of 17.3 ± 1.1‰) of the Avebury sulphides are also strong evidence that the Avebury Ni deposit is not a hydrothermally altered pre-existing magmatic Ni sulphide deposit. The metasomatic fluids would have preferentially carried away any Cu, Au, Pd and Pt in the deposit, while leaving any Ir present, as there is no known method of hydrothermal transport of Ir (Keays et al., 1982). The lack of Ir and the relative enrichment in Cu, Pd (Figure 11), Pt and Au (Figure 12) also provide strong evidence that this deposit was not a magmatic sulphide deposit that was hydrothermally altered *in situ* (Keays & Jowitt, 2012).

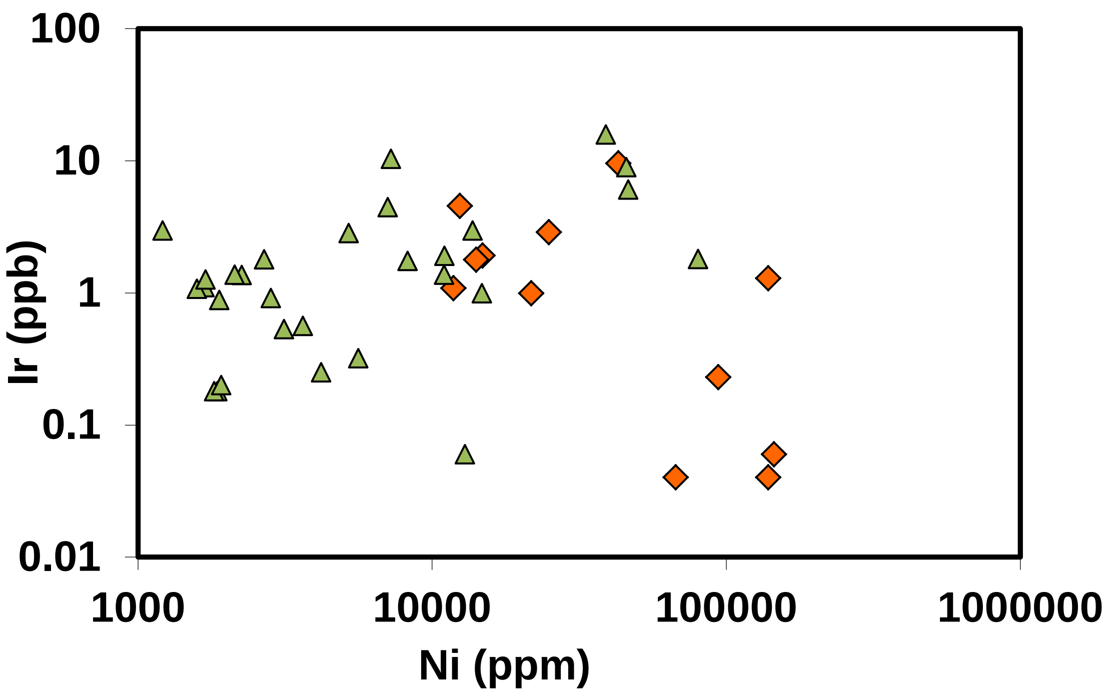

Figure 9. Scattergram of Ir vs Ni in the Avebury rocks. The lack of any correlation between Ni and Ir, indicates that all the Ir in the samples was inherited from the ultramafic rocks and none was contributed by the fluids which brought in the Ni. Data sources: orange diamonds from Keays & Jowitt (2012); green triangles from this study.

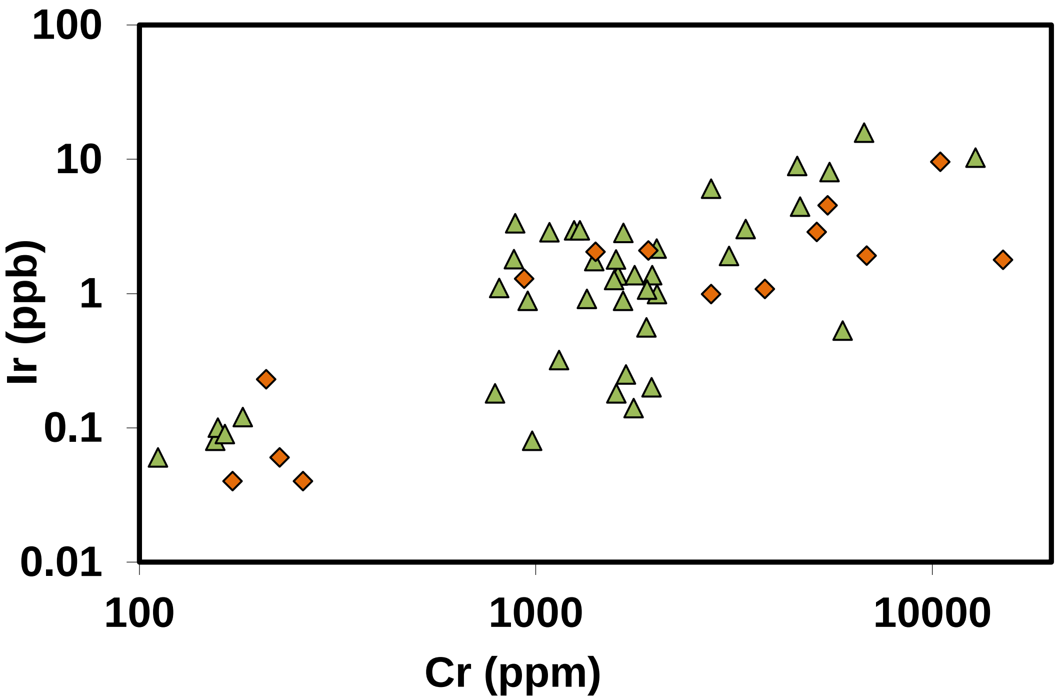

Figure 10. Scattergram of Irv s Cr. The positive correlation between Ir and Cr confirms that the Ir was inherited from the pre-existing ultramafic rocks (El Tokhi, et al., 2014). The samples with the very low Ir and Cr values are Crimson Creek volcanogenic sediments; such rocks generally have very low Ir contents. (Peck, et al., 1992). Symbols are the same as in Figure 9.

The second theory, the mobilisation of Ni from olivine in the mafic-ultramafic rocks of the McIvor Hill complex that hosts the deposit, relies on there being depleted levels of Ni remaining in the serpentinites. The question of Ni depletion of the Avebury ultramafics is addressed by examination of assay for samples from typical drill holes U030 and A250. Results of these comparisons can be seen in Figures 11 through 14.

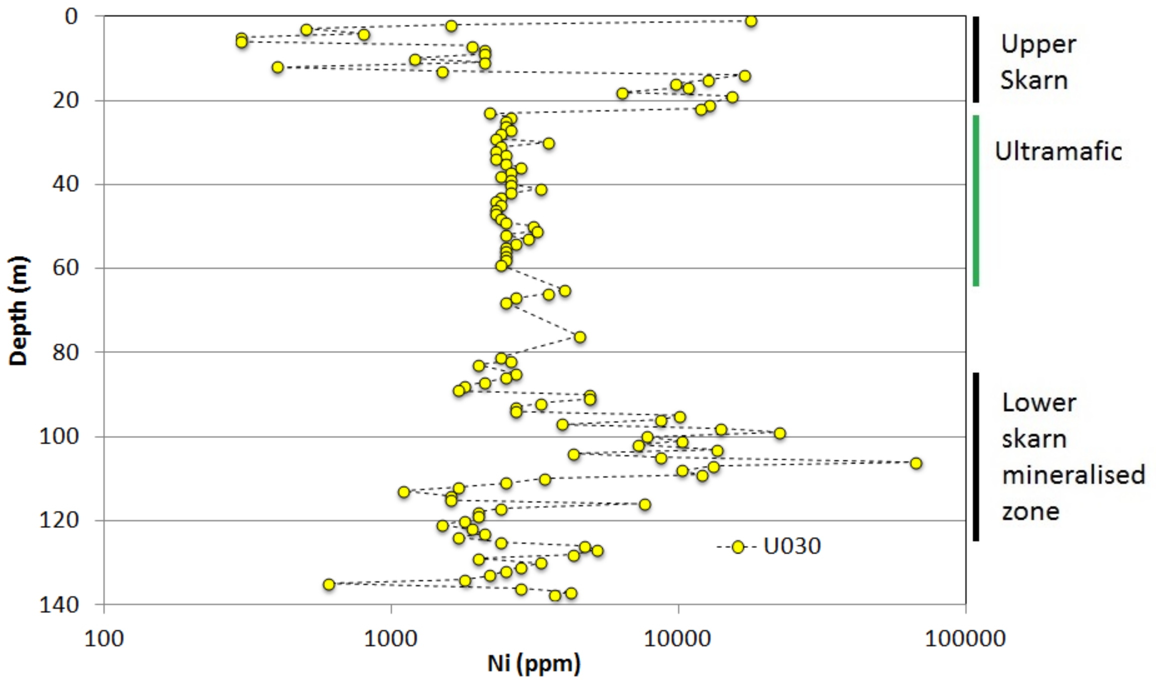

Figure 11. Variation of Ni with depth in underground hole U030. The sampling through the ultramafic zone indicates near-uniform Ni contents with >90% of samples having 2200 to 2600 ppm Ni.

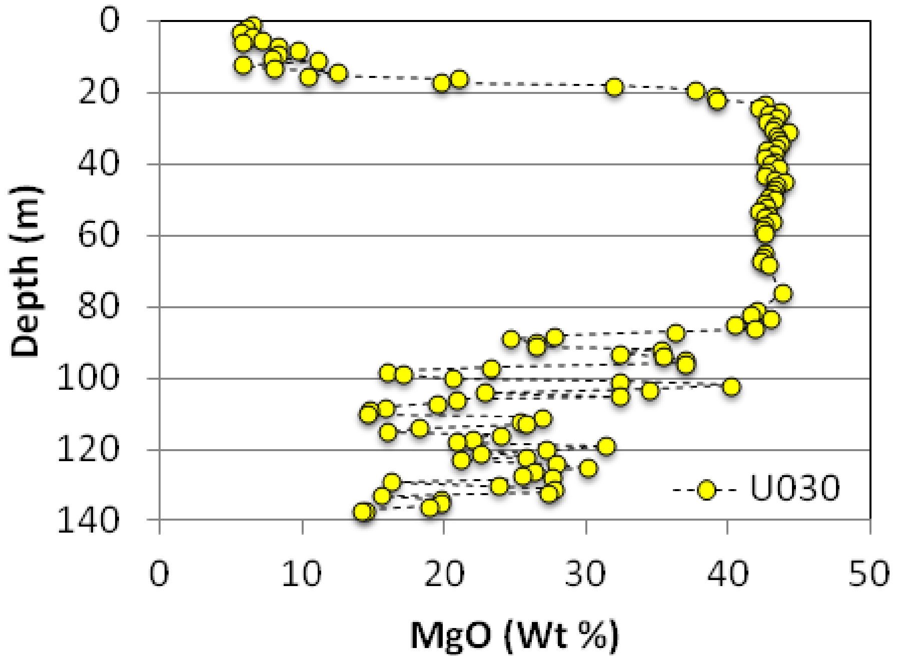

Figure 12. Variation of MgO with depth in drill hole U030. The highly consistent section between 22 and 72 meters ranges from 42.2% to 42.9%, consistent with the McIvor Hill dunites that host the mineralisation (Brown, 1992)

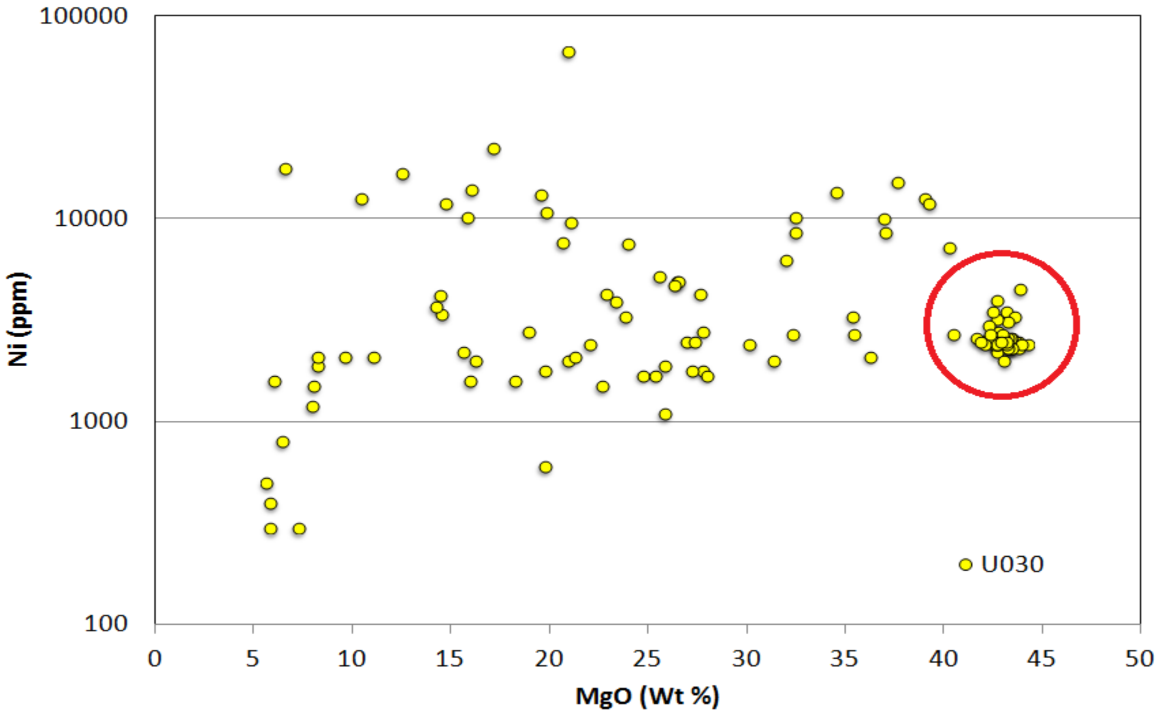

Figure 13. Scattergram showing variation of Ni vs MgO in drill hole U030. The samples circled in red are dunites that contain 1000 to 3000 ppm Ni. Samples with > 4000 ppm Ni are altered serpentinites and skarns that contain sulphide mineralization.

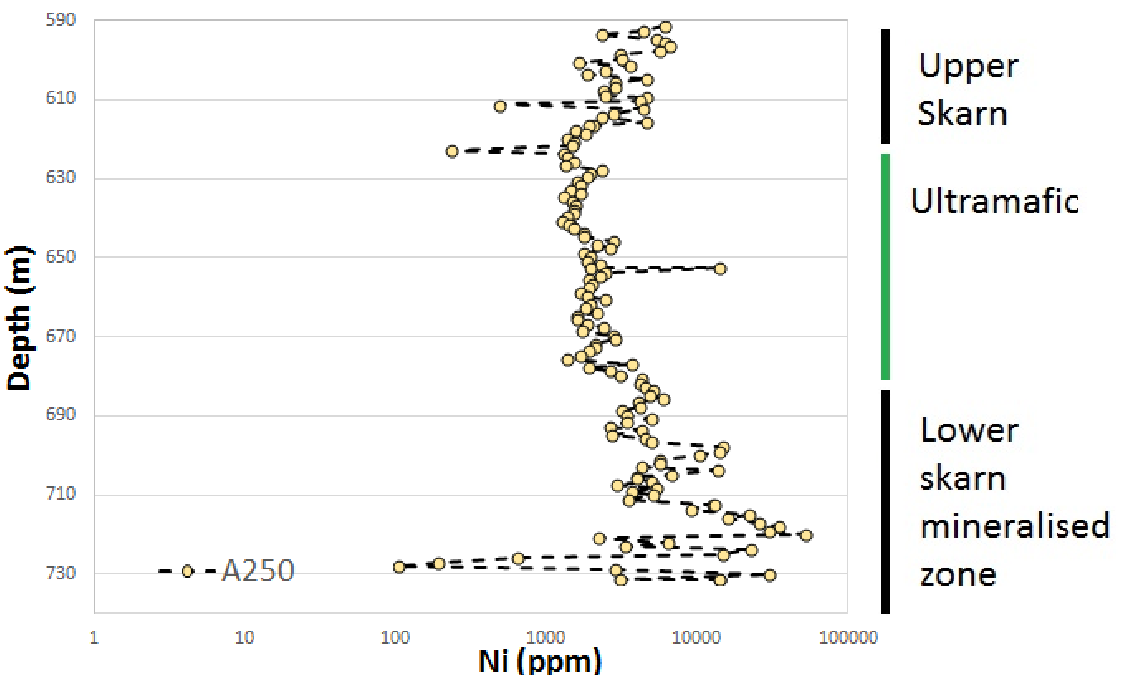

Figure 14. Variation of Ni with depth in surface exploration drill hole A250. This plot indicates the Ni in the majority of the ultramafics remains at expected background levels of Ni, between 1000ppm and 3000 ppm (Hart & Davis, 1978) and shows the different Ni levels across the different lithologies.

Assay data show that the bulk of the serpentinites have 1000 to 3000 ppm Ni, values that are similar to those of the Heazlewood River Complex (Peck, 1990). These values indicate that there is no Ni depletion in the bulk of the serpentinites within the mine environment. In order to test the possibility of Ni depletion further, the Ni contents of serpentine in five samples was determined using an electron microprobe. Full details of the microprobe work are included in Appendix 3. Four samples were used for this work, with a fifth sample probed that proved unsuitable for the purposes of nickel elemental analysis. The average Ni contents of the serpentine minerals in the four samples analysed ranges from 1100 to 3500 ppm (Table 2).

Sample	2208-990	2208-1000	2208-1022	1013
Average Ni ppm:	2880	1800	1100	3510

Table 2. Nickel contents in selected suite of Avebury serpentinite samples.

The results of these analyses indicate that the serpentinites are not depleted in Ni around the sulphides. The sample sites were selected to be close to sulphide blebs and stringers, but at least 8mm away from them in order to remove any uncertainty about the source of the Ni in the serpentinites and to ensure that the probe was not picking up on trace sulphide mineralisation.

Ultramafic rocks such as those in the McIvor Hill Complex can have significant levels of Ni within the olivines, ranging as high as 1000-3000ppm (Hart & Davis, 1978). The high Ni contents of the Avebury olivines do not support the suggestion that the Ni in the ores was sourced from the olivines in the McIvor Hill MUC.

The second theory also has the issue of the preference of Ni liberated during serpentinisation to go into the oxide and silicate phases if there is insufficient S to bind it into the sulphide phase (Donaldson, 1981). The boninitic magmas that formed the co-magmatic Heazlewood River Complex were low in S, with an average of 55ppm (Peck & Keays, 1990) which means that there would have been insufficient S in these magmas to scavenge Ni into the sulphide phase.

The third competing theory is that the Avebury Ni mineralisation has been formed from the leaching of Ni (±Pd-Au) from a previously existing magmatic sulphide at depth, with the sulphides in the path of the hydrothermal fluid vectors from the Heemskirk Granite. The enrichment in such elements as Sn, W and Mo in the Avebury samples taken, and the tendency of these elements to mobilise in late-stage hydrothermal fluids from granitic intrusives (Keays & Jowitt, 2012) combined with the interpreted fluid flow vectors from the 3D modelling provide strong evidence that the mineralization was produced by fluids which had been sourced from the Heemskirk granite. Based on the evidence that all of the

Ir at Avebury was inherited from the ultramafic protolith and that therefore Avebury cannot be a metasomatised magmatic NiS deposit, the strong correlation between Pd and Ni for samples with >2000 ppm Ni provides strong evidence that the Pd and the Ni were derived magmatic sulphides at somewhere at depth below Avebury (Figure 11).The It is possible that the Pd was leached from those sulphides and transported as bisulphide complexes away from the mineralised area (Barnes & Liu, 2012). The Pd could not have been sourced from sulphide-free ultramafic as such rocks have extremely low Pd contents (Keys, 1982; Peck, 1990)

The positive correlation between Au and Ni indicates that the Au in the Avebury rocks was carried by the same hydrothermal fluids as those which transported the Pd and the Ni. The Au would have been leached from the magmatic Cu-Ni-PGE sulphides at depth and then transported by either bisulphide or chloro complexes. (Garofalo & Ridley, 2014; Zhu, 2011).

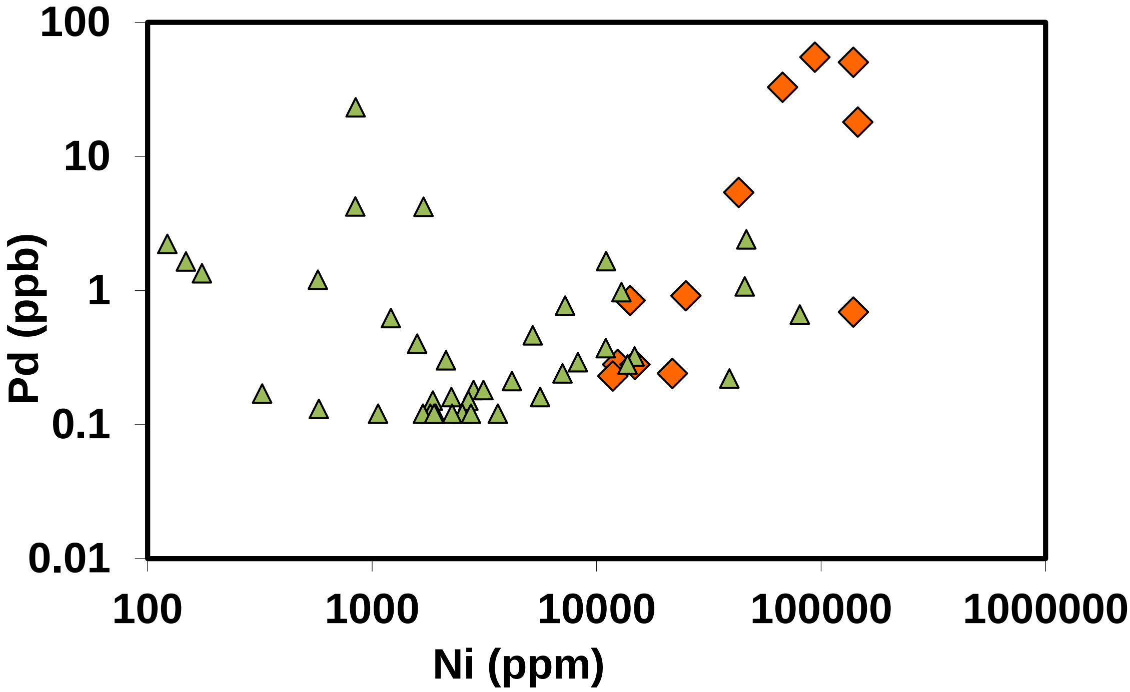

Figure 15. Scattergram of Pd vs Ni for the Avebury samples. Note the good positive correlation between Pd and Ni for samples with >2000 ppm Ni. Symbols as in Figure 9.

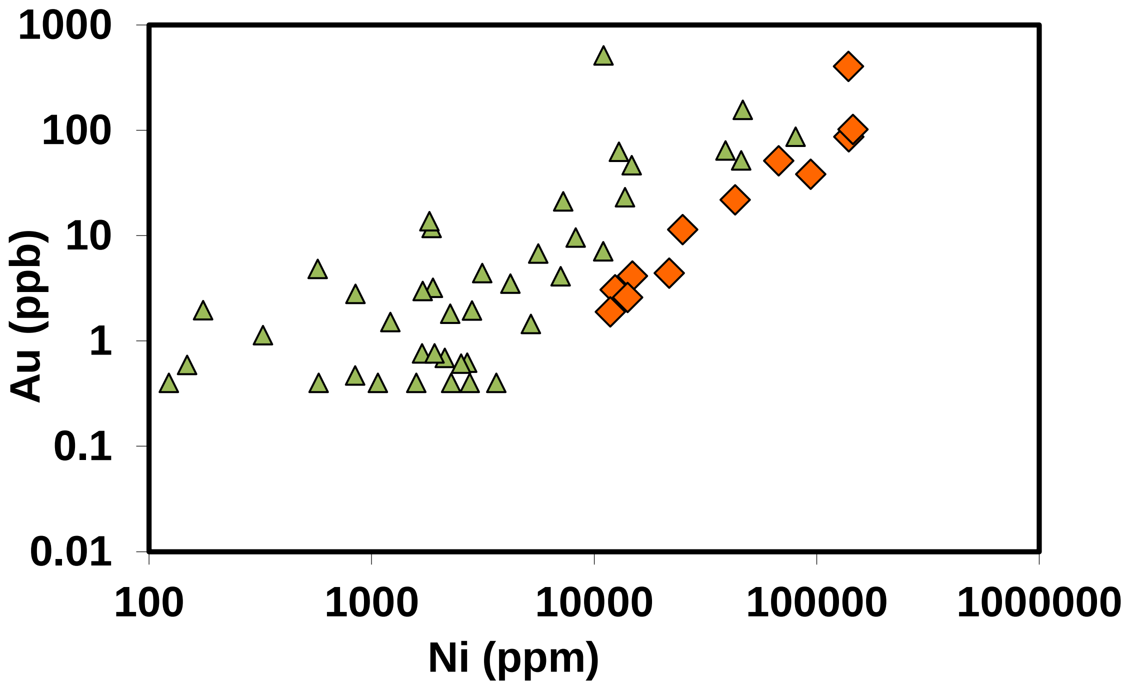

Figure 16. Scattergram of Au vs Ni for the Avebury samples. Note the strong positive correlation between the Ni and the Au contents of the samples with >1000 ppm Ni. Symbols as in Figure 9.

CONCLUSIONS

The Ni ores at Avebury appears to have been formed through hydrothermal action from the nearby Heemskirk Granite scavenging metals from magmatic sulphides at depth. The Heemskirk's influence can be seen in the suite of trace element whole rock geochemistry seen across the deposit and its surrounds, as well as the enrichment in heavy S within the sulphides themselves. This enrichment in heavy S is characteristic of the Heemskirk Granite. The Ni cannot have been mobilised from within the ultramafics during the process of serpentinisation, as these still contain the expected background levels of Ni, from 1000-3000ppm, expected from this type of lithology. The abundance of heavy S also indicates that the Ni cannot have been a magmatic sulphide deposit that has been altered *in situ*. The PGE and Au concentrations within the samples taken from the deposit and from previous work completed also support the hydrothermal model of the formation of the Avebury deposit system.

Microscopy indicates that the alteration at Avebury occurred concurrently with Ni mineralisation, as indicated by the interplay between the pentlandite and magnetite in thin section.

The Ni mineralisation can be traced from the 3D model assembled for the Avebury deposit, and appears to have formed pipe-like structures that may represent weak points in the stratigraphy that the fluids have migrated upwards through. The Ni mineralisation appears to be preferentially hosted within the skarn sections around the fringes of the mafic/ultramafic McIvor Hill Complex dunites.

The model of formation of the Avebury deposit system may be possible to apply to other felsic intrusives in Western Tasmania to form a new exploration model for hydrothermal Ni in the region.

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APPENDIX 1 Whole-rock trace element geochemistry

Please see attached electronic media, file name:

2014_MackayScollay_Appendix1WholeRockGeochem.xlsx

APPENDIX 2 Modelling Data

Please see attached electronic media, file names:

2014_MackayScollay_Appendix2Alteration.csv

2014_MackayScollay_Appendix2AssaysMethods.csv

2014_MackayScollay_Appendix2Collar.csv

2014_MackayScollay_Appendix2Lithology.csv

APPENDIX 3 Electron Microprobe data

Please see attached electronic media, file name:

2014_MackayScollay_Appendix3MicroprobeAnalyses

APPENDIX 4 Leapfrog 3D modelling

Please see attached electronic media, file names:

2014_MackayScollay_Avebury3DLeapfrogModel.lfd

2014_MackayScollay_Avebury3DLeapfrogModel.lfp

APPENDIX 5 AVEBURY DEPOSIT LITERATURE REVIEW

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INTRODUCTION

The Avebury Nickel Deposit, referred to as Avebury herein, is a serpentinite- and skarn-hosted disseminated nickel sulphide deposit located in the central-western coastal region of Tasmania, Australia. Discovered in 1997, the deposit was developed by Allegiance Metals N/L and then purchased by MMG Limited, in 2009 (Allegiance Mining N.L., 2007; MMG Limited, 2013). The resource consists of approximately 260,000t of Ni at 0.9% grade, with associated As content adding complexity to the metallurgical processing of the deposit (Turner, 2004).

A significant question is whether the Avebury Nickel Deposit is a hydrothermally *formed* nickel deposit or a hydrothermally *altered* nickel deposit. This review aims to explore the mineralisation of the deposit and then explore the different models that have been proposed for the formation of the deposit and to examine each of them for their validity.

Geology

The deposit is hosted within the Cambrian McIvor Hill suite, a gabbroic sequence (Keays & Jowitt, 2012) and is substantially altered through the interaction of hydrothermal fluids from the intrusion of the nearby Heemskirk Granite (Lygin, et al., 2010a).

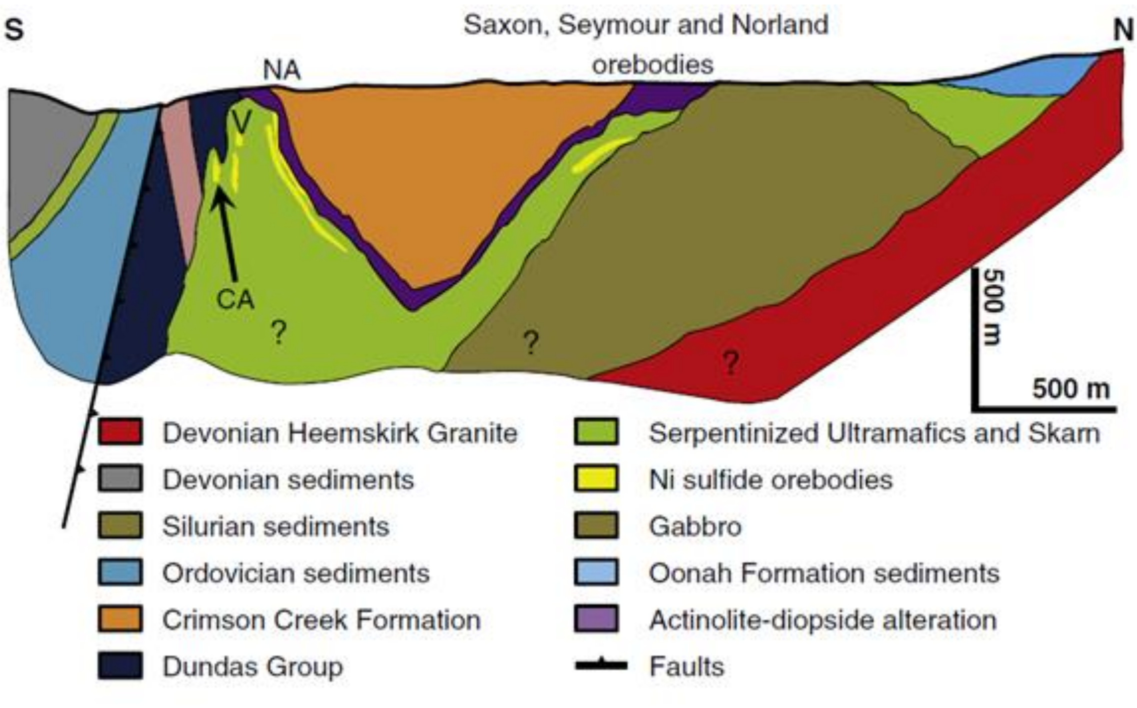

Figure 1. Avebury cross section. CA: Central Avebury, V: Viking, NA: North Avebury. (Modified from Keays and Jowitt (2012)).

McIvor Hill Complex

The McIvor Hill mafic/ultramafic complex consists of a gabbroic zone and an ultramafic zone at this scale, and is overprinted by hydrothermal fluids from the Heemskirk Granite. This is represented on Figure 1 in the "Serpentinised Ultramafics and Skarn". The McIvor Hill complex consists of high Mg boninites and low-Ti tholeiites that have been hydrothermally altered by the Devonian intrusion of the Heemskirk Granite, a biotite-ademellite batholith associated with the Tabberabberan Orogeny (Keays & Jowitt, 2012). This intrusive event resulted in extensive metasomatic alteration of the McIvor, with pervasive phlogopite-biotite and actinolite alteration of the mafic/ultramafic rocks. This alteration extended into the overriding Crimson Creek volcanogenic siliciclastic sediments, resulting in a clinopyroxene-actinolite alteration regime skarn. Extremes of alteration are marked by tourmaline-rich zones (Callaghan & Gibbons, 2008).

Gabbroic Zone

The nearby Melba Flats property is host to outcrops of parallel to subparallel gabbro sills, within interbedded siltstones and greywackes belonging to the Crimson Creek Formation (Keays & Crawford, 2010). These sills are enriched in Ni-Cu-PGE with some historic production having occurred, with the sills thought to pre-date the ultramafic sequence at Avebury (Keays & Crawford, 2010).

Ultramafic Zone

This zone is the host of the majority of the nickel sulphides at Avebury, and consists of an ultramafic dunite body in serpentinite-dominated rocks with associated hydrothermally altered diopside-tremolite-actinolite skarns (Lygin, et al., 2010b). The mineralisation generally consists of thin vein and coarse grain disseminated pentlandite with significant associated magnetite, up to 18% in heavily mineralised sections (Keays & Jowitt, 2009). Spatially, the ore bodies lie within the metasomatic contact aureole of the Heemskirk Granite (Lisitsin, et al., 2013)

Crimson Creek Formation

The Crimson Creek formation consists of an approximately 5km thick succession of interbedded volcaniclastic turbiditic siltstone-mudstone layers that form a cap over the top of the Avebury deposit. There are occasional quartz-rich sandstones and conglomerates throughout the formation, which dates from the Ediacaran period of the Neoproterozoic.

Heemskirk Granite

The Heemskirk Granite is a Late Devonian, locally extensive felsic intrusive, and consists of two main phases: red in the eastern part of the intrusion and white in the west (McClanaghan, 1994). The white granite initially intruded and involved a magmatic vapour phase, which is thought to have played a major role in the mineralisation of the Sn and Pb-Zn-Ag deposits at Zeehan as well as the Avebury Ni. A second phase consisted of the red granite fractionating off the parent magmatic system later and intruding and partially mixing in with the white granite (Heier & Brooks, 1966; Haji-Taheri, 1986). There is extensive mineralisation across the extent of the Heemskirk Granite, nearly all of which is associated with greisens on or past the margins of the intrusion. The exceptions to this are some of the Sn and W mineralisation, specifically the Renison Bell mine near Zeehan (Patterson, et al., 1981). Hydrothermal fluids from the Heemskirk Granite are thought to have overprinted significantly across the geology of the area, with signatures specifically in the mineralised zones at Avebury showing strong correlation to the geochemical makeup of the Heemskirk. This overprint is seen in the characteristic geochemical signatures in the Avebury mineralised rock samples taken, with significant enrichment in W, Bi, U, Pb, Mo, Sn and Sb (Keays & Jowitt, 2012).

Mineralisation

The nickel at the Avebury deposit consists of diffuse, stringer and net-textured pentlandite with associated magnetite. This mineralisation is hosted both within the serpentinites and skarns on their margins. The timing relationship between the magnetite and the pentlandite has yet to be tested through scanning electron microscopy. The host rock in this sample is serpentinite with actinolite-tremolite alteration and limited diopside.

Figure 2. Avebury ore. This picture shows a sample of the Avebury ore, with the magnetite seen in grey and the pentlandite in pale brassy yellow.

Three models have been proposed for the genesis of the Avebury nickel deposit. The first is that the mineralisation is a conventional magmatic Ni-Cu-(PGE) deposit (Keays & Jowitt, 2009), heavily metasomatically altered. The main evidence in support of this model would be moderate to high PGE contents that correlate with Ni contents. Specifically, Ir should have a very strong correlation with Ni as can be seen from the Kambalda magmatic nickel sulphide deposit in Western Australia (Keays, et al., 1982). Iridium is not mobilised by any known hydrothermal fluid, and as such would remain within the system. Keays & Jowitt (2012) showed that there is a strong negative correlation between IR and Ni (as well as REE and Ni and Rh and Ni), hence the Avebury deposit cannot be a magmatic sulphide deposit that was altered *in situ*.

The second model proposed is that Avebury is a hydrothermal Ni deposit where the Ni in the mineralised zones was sourced from the olivine within the serpentinites. This would be indicated through low PGE contents, as the ultramafic dunites that form the system have typically very low PGE contents (<1ppb across the suite). Another indicator would be the Cu and Au content of the dunites and their correlations with the Ni; Cu content specifically should drop steadily as an ultramafic sequence grades from lherzolite to harzburgite then to dunite (LeBlanc, 1991). There is room for further evidence to be gathered in this matter, but it is possible to take proxies from the Heazlewood River Complex (HRC), which is co-magmatic with Avebury (Green & Taheri, 2004). There are strong correlations between Ni and Au from Avebury, as well as very low Cu levels in the HRC that do not correspond with moderate Cu enrichment in Avebury (Keays & Jowitt, 2012). Moderate to strong Pd to Ni correlations in Avebury supports the ruling out of the Ni from the sulphide-free ultramafics (Barnes, et al., 2011).

The final theory for the formation of the Ni at the Avebury deposit - the main theory presented by the current research ongoing at the deposit - is that it is a hydrothermal deposit where sulphides at depth were scavenged for their Ni which was then transported by the same fluids that initially mobilised them (Keays, 2014). Again, this would be indicated by particularly low levels of Ir, as it would not have been transported in the fluids (Keays, et al., 1982). Ru and Rh levels should also be low as these are less mobile in hydrothermal fluids (Genkin, et al., 1976). This is the main focus of the current research being undertaken into the deposit.

PGE Geochemistry

The ratios of platinum group elements to base metals in the samples taken and assayed from previous work can be used as an indicator of the provenance and mobilisation history of the nickel mineralisation at Avebury. Iridium in particular is a useful measure of this as Ir does not mobilise in any known hydrothermal fluid (Keays, et al., 1982). A strong correlation between Ir and Ni in the mineralised zones at Avebury would be a strong indicator that the mineralisation was not deposited hydrothermally. Figure 3 plots the relationship between Ir and Ni in samples taken from the co-magmatic Heazlewood River Complex. This plot shows the relationship between these two variables as having a moderate correlation, indicating that any Ir in the Avebury deposit would have already been present in the ultramafics before alteration.

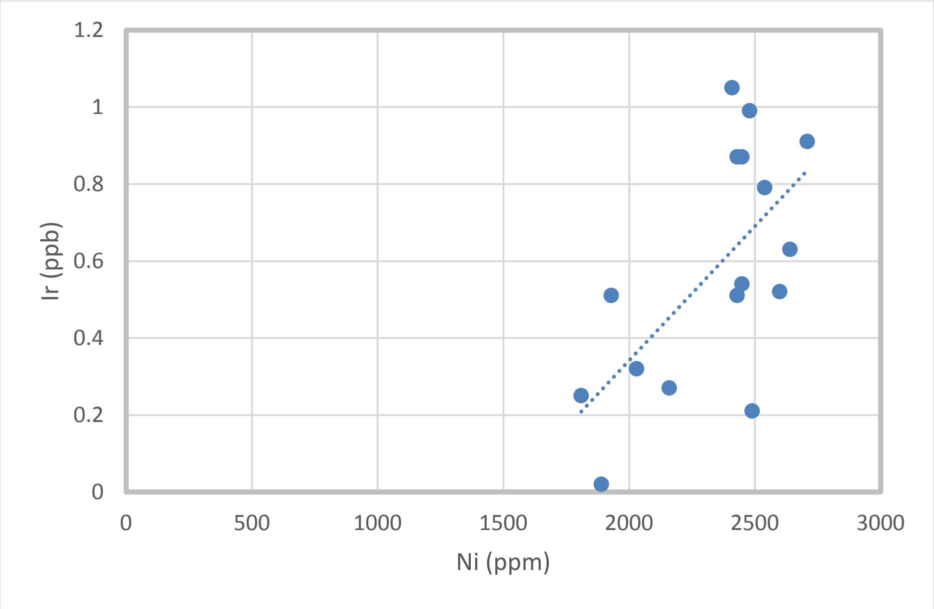

Figure 3. Iridium and nickel content of Heazlewood River Complex samples, showing positive correlation between Ir and Ni (Data from Peck (1990)).

Hydrothermal Alteration

Nickel deposits that are not strictly magmatic are far rarer than their magmatic equivalents (de Almeida, et al., 2007). As such, it is impossible to geologically constrain the environments in which they form, as they can be mobilised out of their original mineralisation zone and transported and deposited through a variety of means (de Almeida, et al., 2007; Pasava, et al., 2013). Other examples of these around the world include the Forteleza de Minas deposit in Brazil, where significant PGE remobilisation has occurred post-magmatically, with in particular the Pt and Pd being drawn out of the main ore body through metasomatic alteration and deposited in drawn out stringer zones distal to the main magmatic deposit (Taufen & Brenner, 1987; de Almeida, et al., 2007). While this is an excellent example of a hydrothermally altered Ni deposit, a significant difference between Avebury and Forteleza de Minas is that Forteleza de Minas is confirmed to be a conventional, magmatic sulphide komatiite-hosted deposit, with the hydrothermal alteration occurring subsequent to the peak of regional metamorphism. The genesis of the mineralisation at Avebury is, in theory, well understood, with PGE assays with a very fine lower limit of detection needed in order to properly constrain the theory further and confirm the model proposed by Keays & Jowitt (2012).

Structural geology and deformation

Prior work has been completed on the Avebury deposit in regards to the structural geology and deformation of the deposit and its host lithologies. Deformation within the nearby Trial Harbour Ultramafic sequence has been linked geometrically to the Avebury ultramafic host (Sloan, 2011). Interpretation and forward modelling has also shown that the McIvor Hill ophiolite complex is also temporally linked to Avebury (Sloan, 2011). The initial deformation event was a west-directed, shallow thrust that superimposed ophiolite sequences onto the already extant basaltic and metasedimentary sequences, distal to the Trial Harbour area, and was part of a regional east-dipping intra-oceanic subduction zone active during the Cambrian Tyennan Orogeny, followed by slab-rollback causing regional extensional deformation during the late Cambrian to early Ordovician (McFarlane, 2012). This was then followed by thin-skinned deformation during the Middle Devonian Tabberabberan Orogeny which formed the tight, upright folds that are the major regional architecture of the Avebury area, as well as the reactivation of the previously normal fault south of Avebury as a reverse fault (McFarlane, 2012). Further minor brittle deformation followed this, still associated with the Tabberabberan Orogeny, and all of the deformation is interpreted to have completed prior to the intrusion of the Heemskirk Granite at 359±1.9Ma (Crawford & Berry, 1992; McFarlane, 2012)

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