Disseminated and Massive Nickel Sulphide deposits, Honeymoon Well Complex, Western Australia

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Abstract: Both disseminated and massive Ni sulphide mineralisation is hosted in a variety of komatiitic rocks within the Honeymoon Well ultramafic complex, located in the northern part of the 2700 Myr old Agnew-Wiluna greenstone belt, Western Australia. The ultramafic complex, extending over a 10 x 2 km area, is a structurally thickened part of the Mt Keith Ultramafic Sequence. This sequence hosts the nickel deposits at Perseverance, Yakabindie and MT Keith. The Honeymoon Well sulphide resource is 155.5 MT at 0.71% Ni (includes 2.5 MT at 3.36% Ni) in one massive and three disseminated sulphide deposits. Despite greenschist facies metamorphism and several episodes of deformation igneous textures are widely preserved in the ultramafic rocks.

The host rocks of the disseminated deposits are totally serpentinised olivine accumulate, mesocumulate and minor orthocumulate. Sulphide assemblages are dominated by pentlandite and heazlewoodite and occur in modified magmatic-textured lobate to blebby aggregates interstitial to former olivine grains. The massive sulphide deposit consists of massive sulphide, massive sulphide breccia and matrix sulphide hosted in a sequence of spinifex-textured thin komatiite flows. These sulphides have significantly lower Ni/S ratio than the disseminated sulphides reflecting an Fe-rich sulphide assemblage of pyrrhotite - pentlandite - pyrite - chalcopyrite. All the Ni sulphide deposits are thought to have been originally part of a single mineralised horizon with lateral variations in physical volcanology leading to the formation of komatiite sequences ranging from those dominated by olivine mesocumulate - adcumulate to those dominated by spinifex-textured thin flows. Subsequent stratigraphic stacking within a D1 thrust duplex and D2 folding and strike slip shearing has significantly displaced two of the deposits from their original stratigraphic position. Late As-bearing carbonate fluids have affected parts of the sulphide deposits.

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Introduction

The Honeymoon Well nickel deposits, located approximately 45 km south of Wiluna (26°40'S,120°25'E), are the most northerly of numerous known nickel sulphide deposits within the 2700 Myr old Agnew - Wiluna greenstone belt (Fig. 1; Marston,1984; Hill et al., 1995; Gole et al., 1998). Both disseminated and massive nickel sulphide deposits are present within the deformed and metamorphosed Honeymoon Well ultramafic complex. Despite alteration to lower greenschist facies serpentine-rich and minor talc-carbonate assemblages igneous rock types can be generally recognised through a combination of preserved relict igneous textures, metamorphic mineralogy and geochemistry. Recognition of igneous protoliths and reconstruction of the igneous stratigraphy show that the disseminated and massive sulphide deposits are hosted by distinctly different komatiitic rocks that in turn reflect formation in markedly different volcanic settings.

Bedrock in the Honeymoon Well area is covered by 50 to 120 m of overburden and most geological data have been derived from 830 diamond drill holes and a similar number of percussion holes as well as detailed aeromagnetic data. Much of these data have been obtained since the early 1990’s and thus were unavailable for earlier studies of the Honeymoon Well deposits (Donaldson and Bromley, 1981; Gole and Hill, 1988). Drill hole core and rock chips have been logged for igneous and metamorphic textures, rock and vein mineralogy, and assayed for a range of sulphide- and lithology-related elements. Igneous rock names are used where appropriate in this report despite complete metamorphic reconstitution of the igneous silicate mineralogy and partial to complete reconstitution of igneous oxides and sulphides.

The current sulphide resource is 155 MT at 0.71% Ni (0.4% Ni cut off, <300 m depth) in one massive and matrix sulphide deposit and three disseminated sulphide deposits. This includes a massive sulphide resource of 2.5 MT at 3.36% Ni. Nickel grades in all the disseminated deposits are slightly to significantly higher than at Mt Keith (460 MT at 0.58% Ni; George, 1996) and at Yakabindie (520 MT at 0.47% Ni; North Limited, 2000) which are hosted by similar komatiite sequences.

Regional geological setting

At Honeymoon Well the greenstone belt is 6-7 km wide and composed of a regional west-younging sequence of a lower basalt/gabbro unit, including a laterally persistent basaltic komatiite flow, felsic to intermediate volcanic and volcaniclastic rocks, a heterogeneous komatiite sequence and a western felsic/basalt sequence (Liu et al., 1995). Local eastyounging is due to minor folds associated with fault zones. The ultramafic sequence, which within the Honeymoon Well complex is 1.5 to 3.0 km wide, consists of a diverse suite of metamorphosed komatiite lithologies including spinifex-textured rocks, olivine orthocumulate, mesocumulate and adcumulate (oOC, oMC, oAC). Minor augite and augite-plagioclase cumulates define fractionated cyclic units within the presumed upper parts of the ultramafic sequence. All the ultramafic lithologies are interpreted to have formed in a volcanic setting (see Hill et al., 1990, 1995).

In the area around Wiluna and within the Honeymoon Well ultramafic complex the komatiite stratigraphy has been duplicated by faulting. Duplication is interpreted to have taken place during D1 thrust faulting. Folding and deformation during D 2 resulted in the formation of talc-carbonate-rich NNW trending strike slip faults and shear zones that further duplicated parts of the sequence. The stratigraphic stacking accounts, in part, for the anomalous thickness of the ultramafic rocks atHoneymoon Well compared to the remainder of the belt. Much of the ultramafic sequence, particularly at Honeymoon Well and probably to the immediate south, appears to be allochthonous. Strike-slip faulting has removed a 5 km long section of the ultramafic sequence immediately north of the Honeymoon Well ultramafic complex. Some of the D2 faults and shears are probably reactivated D1 thrust surfaces. The main metamorphic alteration in the area is associated with D2 strike slip fault development (Eisenlohr, 1992). This structural and metamorphic evolution is similar to that proposed for the southern part of the Norseman-Wiluna greenstone belt (Swager, 1997). Metabasalt assemblages at Honeymoon Well indicate lower-most greenschist facies metamorphic grade (Donaldson and Bromley, 1981). Komatiites are altered to serpentine-dominant and local talc-carbonate assemblages.

Honeymoon Well Geology

Regolith

The ultramafic sequence occurs below a 50-120 m cover of cemented sands and grits (5-25 m), transported clays and minor basal gravels (0-40 m) and a residual regolith (30-60 m). The residual regolith varies markedly over the ultramafic rocks compared to adjacent lithologies. Over the ultramafic rocks the regolith profile is highly variable and has been variably stripped since its formation (Mitchell, 1997). Where complete it consists of an upper brown, strongly leached, highly porous and partially silicified, goethite-rich upper saprolite, a green-grey clay-rich lower saprolite, and then saprock overlying the bedrock. Within the saprolite over oAC and oMC are hard, highly porous, laterally discontinuous silica-minor goethite layers that range up to 30 m in thickness.

Bedrock Lithologies

Ultramafic Rocks

Where igneous textures are preserved oAC display polygonal-textured olivine pseudomorphs and triple-point junctions with adjacent pseudomorphs and have negligible igneous porosity (see Donaldson and Bromley, 1981). Olivine grain sizes range up to 2.5 cm but are mostly 4-10 mm. Stichtite after chromite forms lobate, porous aggregates at some triple-point junctions. Within oMC olivine pseudomorphs are mostly 3-8 mm across while stichtite content (0.5- 5%) and aggregate size is highly variable. Olivine orthocumulates have a wide variation in igneous porosity and texture. Low porosity orthocumulates generally have coarser, more evengrained olivine pseudomorphs, whereas high porosity rocks show a wide range in olivine grain size, sometimes within the same rock, and with grain shapes ranging from euhedral to hopper to harrisitic. These latter rocks are mostly associated with spinifex-textured rock sequences. At a few localities, delicate igneous textures are very well preserved within 20-40 m thick sequences of thin spinifex-textured flows. Mostly, however, deformation and metamorphic recrystallisation has destroyed spinifex textures, with former thin flows now represented by interlayered tremolite-chlorite and serpentine-tremolitechlorite schists or talc-carbonate altered equivalents.

Some spinifex-textured rocks and associated oOC show evidence of partial melting and high-temperature recrystallisation. In such rocks textures and mineral compositions differ markedly from those in typical komatiites (Gole et al., 1990). Spinifex olivine plates are bent and interstitial spaces are composed of polygonal aggregates of partially altered clinopyroxene, orthopyroxene, minor olivine, plagioclase and spinel. Two pyroxene thermometry yields temperatures of 1055 to 1140ºC, just below the low pressure komatiite solidus (Thy, 1995). These features reflect metamorphism, partial melting and subsequent slow cooling within a 40-60 m thick sequence of spinifex-textured flows that are located between two thick stratigraphic sequences of olivine-rich cumulates. Thermal modelling shows that post-magmatic conductive cooling of these two cumulate piles, if they were formed within a period of about ten years, would re-heat the intervening flows to the observed metamorphic temperatures (Gole et al., 1990). These very distinctive rocks, which require a very restrictive set of circumstances to form, are part of an horizon, termed the Recrystallised Marker Horizon (RMH; Fig. 1), that is critical in the stratigraphic reconstruction of the Honeymoon Well ultramafic complex.

No traceable stratigraphic layering has been recognised within the main mass of oAC but has been recognised in various states of preservation within the marginal ultramafic sequences (Fig. 1). Strain within the ultramafic rocks has been markedly heterogeneous with widespread preservation of igneous textures in massive-textured rocks with foliated and shear fabrics restricted to relatively discrete zones. However most rocks have a well developed network of anastomosing veins, many of which appear to be minor faults. It is thus likely that the bulk strain of rock units, even those with well preserved igneous textures, will be high.

Many of the talc-carbonate rocks are foliated reflecting penecontemporaneous alteration and deformation within fault/shear zones permeable to CO2-bearing fluids. Lizardite + graphite schists reflect alteration and deformation within H2O-rich fluid regimes.

Rock Compositions

Typical compositions of the main ultramafic rock types are given in Table 1. Variations in composition between oOC, oMC and oAC largely reflect differences in igneous porosity (ie. olivine packing density). The MgO/(MgO+FeO) ratio of oMC and oAC varies widely from ~0.7 to 0.95, but the extent to which this reflects differences in original olivine composition or effects of metasomatism during serpentinisation is difficult to determine on current data. The low CaO value in the oMC is due to loss during serpentinisation as is common in such rocks (Donaldson, 1983).

The compositions of rocks containing fine-grained random olivine spinifex and flow-top breccia sampled from all the Honeymoon Well deposits are generally similar, with anhydrous MgO contents of 27-29% (Table 1).

Spinifex-textured rocks and spatially associated, high porosity oOC at Honeymoon Well commonly have very significant S values due to metasomatic addition.

Other Lithologies

Rocks in contact with, and in places included within the ultramafic complex consist of a wide range of volcanic rocks that include tholeiitic basalt and related gabbro, andesite, dacite and minor rhyolite as well as intermediate and minor felsic volcaniclastic rocks (Harrison, 1995; Russell, 1995). Minor pyritic black shale and chert are also present. Within the intermediate to felsic rock sequence immediately east of Harrier are discontinuous, thin layers of Ni sulphide-bearing peridotitic komatiite. The stratigraphic significance of these is unknown. The basalts and gabbros are composed of actinolite, albite, chlorite, quartz, and leucoxene (Donaldson and Bromley, 1981). Some gabbros contain metamorphic magnetite formed by alteration of igneous ilmenite and are highly magnetic. The andesitic and dacitic rocks contain feldspar, quartz, chlorite, mica, actinolite and carbonate in widely varying proportions. Metasomatised rocks contain abundant carbonate, mica and minor arsenopyrite and tourmaline.

Lithological Distribution

Coarse-grained oAC forms the core and makes up the bulk of the komatiite complex, with oMC, oOC, spinifex-textured rocks and minor, medium-grained oAC occurring around the margins and as narrow horizons within the complex (Fig. 1). Dips of lithological units and structures are highly variable ranging from 30º to vertical.

Most contacts between major rock units, both within and bounding the ultramafic complex, are faults. There are two very broad types: a) discrete faults defined by 5 - 20 cm wide mylonite zones with well preserved igneous-textured rocks on either side and with little associated carbonate alteration. These are interpreted to be relicts of D1 thrust faults: b) foliated and brecciated zones, highly variable in width and definition, that appear to be contemporaneous with metamorphic alteration. Some of these zones, particularly those along the margins of the ultramafic complex, are associated with intense carbonate alteration. Some appear to be strike slip faults and some may be reactivated D1 thrust faults. Within ultramafic rocks these faults may change along strike or down dip from relatively well-defined shear zones into a wide, poorly-defined anastomosing network of veins and small shears.

The Harrier and Corella sulphide deposits are interpreted to be hosted by equivalent stratigraphic sequences. This correlation is based on several features. In terms of host lithology, mineralisation style and sulphide compositions (Table 2) the deposits are very similar. Secondary they are linked by patchy zones of bedrock disseminated Ni sulphides. Further, to the west and stratigraphically overlying these deposits, is the distinctive RMH, a discontinuous horizon not only containing recrystallised spinifex-textured flows but also intermediate to mafic volcanic rocks and minor sedimentary units (Fig. 1).

The two main ultramafic horizons in the south of the prospect are thought to be stratigraphic equivalent units that have been duplicated by a strongly foliated, talc-carbonate altered D2 strike slip fault located along the east side of the Harrier deposit and extending northwards along the eastern contact of the komatiite complex (Fig. 1).

The host sequences of the Hannibals - Harakka and Wedgetail deposits and other weakly mineralised spinifex-textured sequences occur as thin, fault-bounded units along the western ultramafic contact (Fig. 1). These are interpreted to be D1 thrust slices. Based on the presence of Ni sulphide mineralisation, the similarity in sulphide composition between the Hannibals and Harrier-Corella deposits (Table 2) and particularly the presence within the Hannibals deposit of recrystallised spinifex rocks (see below), it is thought that these fault slices were derived from lateral equivalents to the Harrier-Corella mineralised horizon.

Augite and augite-plagioclase cumulates, tremolitechlorite rocks (after spinifex-textured rocks) and high porosity, fine-grained olivine orthocumulates located along the western contact of the south east ultramafic sequence appear to define the stratigraphic top of the main Honeymoon Well ultramafic unit. Similar ultramafic and mafic rocks together with felsic rocks that form a structurally disrupted block within the northern part of the ultramafic complex are also probably remnants of this upper stratigraphic contact. This top unit is, however, not preserved elsewhere within the ultramafic complex.

The thickness of the oAC in the central and northern part of the prospect is thought to be a result of repetition by D1 thrust faults of an originally extensive and thick oAC body. The abrupt northern termination of the ultramafic complex, where the width changes from 3 km to 0 m over 1.5 km of strike, occurs at the intersection of these thrust faults with a D2 strike slip fault that defines much of the eastern ultramafic contact (Fig. 1). No ultramafic rocks are present along strike for at least 5 km to the north of the Honeymoon Well complex.

Ultramafic Rock Mineralogy

Olivine adcumulate and oMC do not retain igneous minerals except for minor to trace amounts of partly altered chromite that may be present within stichtite aggregates (see also Donaldson and Bromley, 1981). The dominant metamorphic assemblages are lizardite - pyroaurite - stichtite - magnetite + brucite + chromite and lizardite - brucite - pyroaurite - stichtite (i.e. magnetiteabsent). This latter assemblage, which occurs in zones 20 m wide up to areas 0.5 x 1.5 km in extent, is highly unusual in serpentinised olivine-rich cumulates. Pyroaurite includes other sjogrenite group minerals, particularly iowaite (Donaldson and Bromley, 1981). Antigorite - carbonate - magnetite + stichtite and particularly talc - carbonate + magnetite assemblages, although they may dominate in large volumes of rock, are mostly associated with faults and shear zones particularly where these occur along ultramafic/country rock contacts. Olivine orthocumulate and most spinifex-textured rocks consist of variable proportions of serpentine (mostly antigorite), tremolite, chlorite, carbonate, magnetite and relict igneous chromite. Chromite generally occurs as equant grains, rimmed and veined by magnetite although partly skeletal chromites are present within osOC at Wedgetail and Corella. In places oOC contain minor igneous kaersuitite and rarely clinopyroxene.

Recrystallised spinifex-textured rocks and associated oOC generally retain coarse-grained pyroxenes and, except in some rocks from drill hole 74HWD003 (Gole et al., 1990), only rarely retain other minerals from their high temperature metamorphic assemblage, these minerals being altered during regional metamorphism. Augite and augite-plagioclase cumulates may retain igneous clinopyroxene but mostly consist of tremolitechlorite and actinolite-albite-epidote-chlorite-leucoxene assemblages respectively.

In the ultramafic rocks the presence of pseudomorphic lizardite, antigorite and talc-carbonate assemblages indicates that these formed directly from the igneous mineralogy (Wicks and Whittaker, 1977). Carbonate-rich fluids appear to have been spatially related to relatively discrete permeable zones. Non-pseudomorphic (i.e. igneous texture destroying) antigorite-carbonate is commonly superimposed on pseudomorphic lizardite assemblages and occurs in selvedges to carbonatebearing veins, shears and faults. Talc-carbonate rocks are mostly non-pseudomorphic suggesting that many of these assemblages also developed in already altered rocks. This assemblage is, however, commonly spatially associated with faults and shears, movement of which would cause recrystallisation and thus also result in formation of non-pseudomorphic textures. T h e s e relationships and the spatial distribution of assemblages suggest that, over time, carbonate fluids expanded away from initially relatively restricted CO2 fluid pathways. In restricted areas, for example at Wedgetail and the central parts of Harrier, late arsenic - carbonate + gold-bearing fluids have further altered the rocks.

The lizardite-dominant rocks in particular have a high vein density. At Honeymoon Well vein densities, measured as veins (>1mm wide) per metre, are on average 10 - 12 whereas at Mt Keith and Yakabindie casual observations suggest values of 1 - 4. Vein minerals consist of pyroaurite, iowaite, brucite, carbonate, magnetite, serpentine, trace amounts of gypsum and, within or near the sulphide deposits, minor Fe, Cu and Zn sulphides. The vein assemblages are markedly Mg - Fe-rich and Si-poor relative to their host rocks and suggest that, in places, extensive metasomatism has accompanied serpentinisation. Pyroaurite - iowaite - brucite-rich and carbonate-rich veins tend to be mutually exclusive and occur in separate zones although individual veins are commonly laminated with different assemblages. In antigorite and particularly talc - carbonate rocks the vein mineralogy is less complex being dominated by carbonate and magnetite.

Sulphide Textures

Disseminated Sulphides

In olivine sulphide mesocumulate (osMC) and olivine sulphide adcumulate (osAC) sulphide aggregates were moulded between closely-packed olivine pseudomorphs and hence have a general lobate shape (see Donaldson and Bromley, 1981, for detailed descriptions). Sulphide aggregates in olivine sulphide orthocumulate (osOC) tend to be more blebby and may be relatively coarse-grained (up to 5 mm) due to the greater space between former olivine grains. Metamorphic reconstitution of the rocks has, in many cases, greatly modified the shape and the mineralogy of these aggregates. In rocks that have been strongly recrystallised, and particularly where nonpseudomorphic antigorite - carbonate or talc - carbonate has replaced a large proportion of lizardite, all evidence of former igneous sulphide aggregates has been destroyed and sulphides have been redistributed into irregular, scattered and smaller aggregates. In rocks with relatively low Ni/S ratios sulphide aggregates are commonly veined and partly surrounded by magnetite, whereas in rocks with higher Ni/S ratios magnetite is a minor component or is entirely absent. In these latter rocks heazlewoodite - pentlandite and heazlewoodite-only assemblages occur and sulphide aggregates are commonly not located along former olivine grain boundaries, have ragged to irregular outlines and do not retain igneous lobate shapes. In these rocks igneous textures are rarely preserved due to extensive recrystallisation of serpentine. Sulphide aggregates are also commonly intergrown with antigorite and carbonate. Even in lizarditedominated lithologies (i.e. most osMC and osAC) antigorite needles and carbonate occur along former olivine grain boundaries and in interstitial areas and hence are commonly intergrown with sulphides. In places, antigorite needles and, particularly in osOC, chlorite and talc are strongly intergrown with sulphides such that the sulphides fill angular, wedge-shaped areas between silicate grains.

Massive sulphides

In both massive sulphide and massive sulphide breccia, which are present in the Wedgetail deposit, interlocking anhedral to blocky grains of pyrrhotite, pentlandite, pyrite and minor to trace gersdorffite generally form a massive fabric, and there is only minor development of weakly foliated massive sulphide. Minor chalcopyrite forms small i n t e rg r a n u l a r, irregular shaped grains. Gersdorffite is related to arsenic - gold - carbonate alteration that probably significantly postdates the main regional metamorphism (Hagemann et al., 1995) suggesting that the massive sulphide ores acquired their microtextures very late in the structural/metamorphic evolution of the area.

Supergene Alteration

Supergene alteration of primary sulphide assemblages, similar to that seen in other Ni deposits in the Yilgarn Craton (e.g. Butt and Nickel, 1981) occurs in the upper, very weathered parts of the deposits (Mitchell, 1997) and in patches deep within the deposits. Violarite, pyrite and magnetite are the common alteration products in rocks with a Ni/S ratio below about 1.3. In rocks with Ni/S ratio >1.3 millerite may occur as alteration along grain boundaries and fractures in pentlandite and heazlewoodite or be finely intergrown with violarite.

Deposit Geology

Nickel sulphides occur in two deposit types: disseminated sulphides (trace to 5 modal percent) in olivine-rich cumulates (osMC, osAC, and osOC in the Harrier, Corella, Hannibals, and Harakka deposits) and sulphide-rich rocks (massive sulphide, sulphide breccia and osOC in the Wedgetail deposit) hosted by spinifextextured flows. The Harakka deposit is relatively small and will not be described.

The main deposits are described below in order of their stratigraphic preservation with the Harrier deposit being the best preserved and the Hannibals and Wedgetail deposits occurring in allochthonous fault blocks.

Harrier Disseminated Sulphide Deposit

The Harrier deposit occurs in the south of the Honeymoon Well prospect along the eastern contact of the main oAC-bearing ultramafic unit (Fig. 2). The deposit contains 43.0 MT at 0.64% Ni (0.4% Ni cut off, <300 m depth). The nickel sulphides at Harrier are hosted by osMC with minor osOC. The deposit, which is overlain by between 55 - 120 m of overburden, extends along strike for at least 1700 m and varies in width from 30 to 140 m.

To the east, the ultramafic sequence is in fault contact with metamorphosed andesitic to dacitic lavas and volcaniclastic rocks, and thin, discontinuous olivine spinifextextured komatiite units, in places containing disseminated and massive nickel sulphides. In plan view this faulted contact is sub-parallel to the stratigraphy (Fig. 1) although in cross section it cuts the stratigraphy at highly variable angles (Figs. 3 and 4).

The lower part of the ultramafic stratigraphy has been removed by the eastern boundary fault. The stratigraphy to the west of the fault, however, appears to be relatively intact, and indeed the Harrier deposit appears to be the least structurally disrupted of the Honeymoon We l l deposits. The nickel sulphide-bearing sequence grades up-sequence into barren oMC and then, in places, into oAC. North of 11000N the olivine cumulate pile bifurcates around the RMH (Fig. 2), here composed of spinifex-textured flows, andesitic and minor basaltic volcanic rocks and minor pyritic and cherty sedimentary rocks. This unit is up to 100 m thick and dips 60-75o to the east (Fig. 4), although younging directions derived from the flows are westerly indicating that the sequence is overturned.

Between 10500N and 11000N, where the oAC is relatively thick and is in direct contact with the mineralised sequence, the RMH is absent (Fig. 3). The RMH re-appears south of 10500N as a 50 m thick unit of oOC, minor recrystallised spinifex-textured rocks and bladed metamorphic olivine - pyroxene rocks, the latter similar to those in areas of amphibolite metamorphic facies in the south of the Agnew - Wiluna belt. These relationships suggest that the RMH has been thermally eroded within a 500 m wide channel-like feature by komatiite lava prior to the formation of the oAC. North of 11000N the oAC on the western side of the RMH thickens into the oAC body that forms the core of the Honeymoon Well ultramafic complex (Fig. 1) The nickel-sulphide mineralisation, north of 10700N, is constrained to one osMC unit with minor layers of osOC in the north.

This unit extends to the south where other sulphide-bearing units are also present. These units are separate igneous layers with different bulk compositions. The western-most unit is composed of osAC and is lens-shaped in plan view. It is located in the area where the RMH is absent (Fig. 2), at or near the base of a possible oAC-filled channel. Other mineralised units in this area appear to be igneous layers rather than structural duplicates of the extensive osMC horizon. The true width of the sulphide-bearing horizons is highly variable ranging from 10 m to 140 m. Just to the west of the southern-most part of the RMH, and effectively on the southern margin of the oAC-filled channel way, is a 20 - >100 m thick body composed of osOC (Fig. 2). The sulphides consist of pyrrhotite and minor pyrite and occur intergrown with magnetite in modified magmatic-textured lobate aggregates intergranular to former olivine. These rocks are strongly depleted in nickel such that despite sulphur contents of up to 1.7%, Ni contents are mostly below 1700 ppm (Table 2).

The mineralogy of the Ni sulphide host lithologies is dominated by lizardite-rich assemblages. A significant proportion of the host sequence has, however, been altered by carbonate-bearing fluids resulting in a zoned pattern with lizardite assemblages giving way to antigorite-carbonate assemblages which, in places, envelope talc-carbonate rocks. Most talc-carbonate rocks are strongly recrystallised, massive rocks or are foliated, although rare pseudomorphed igneous textures are present in low strain zones.

Nickel Mineralisation

The depth to the oxide/supergene sulphide boundary ranges from 70 to 100 m being deepest in the north. The width of the supergene zone is variable being almost non-existent on some sections but up to 65 m thick on 11600N. The transition zone is generally 20 - 30 m thick and again is thicker in the north. In the primary zone the sulphide content of the mineralised ultramafic rocks typically varies between 1 to 5 modal percent, being highest in osOC which may contain >3% Ni. In lizardite-rich osMC sulphides typically form lobate aggregates between former olivine grains whereas in osOC sulphides in the intercumulus space are blebby. In antigorite-carbonate and particularly talc-carbonate rocks strong recrystallisation of gangue minerals has destroyed much of the magmatic texture of sulphide aggregates, and sulphides are commonly intergrown with antigorite blades, talc aggregates or relatively coarse-grained carbonate grains. Arsenic - bearing minerals are patchily associated with these latter rocks.

Within the primary sulphide zone pentlandite + trace chalcopyrite, pentlandite - heazlewoodite and minor heazlewoodite-only are the dominant sulphide assemblages in lizardite and most antigorite-rich rocks. In lizardite-rich assemblages chalcopyrite mostly occurs in veins with pyroaurite, brucite, magnetite and pyrite, and is only rarely present in relict magmatic sulphide aggregates. In talc and some antigorite-rich rocks the sulphides consist of pentlandite, millerite, trace chalcopyrite, pyrrhotite and patchy gersdorffite, niccolite and maucherite.

As in the other disseminated sulphide deposits the mineralisation can be divided into two types based on Ni/S ratio and Cu contents (Table 2): 1.High-Cu mineralisation, containing 40 - 2000 ppm Cu, having relatively low Ni/S ratios (range 0.5 - 1.3) and with the sulphide mineralogy dominated by pentlandite with trace tochilinite, chalcopyrite and in places pyrrhotite. Alteration to violarite and minor pyrite is relatively abundant even deep within the deposit. This mineralisation type is generally similar to that in the Mt Keith and Yakabindie disseminated Ni sulphide deposits further south in the Agnew - Wiluna belt (Burt and Sheppy, 1975; Hill et al., 1990). 2.Low-Cu mineralisation containing 0 - 40 ppm Cu, having high Ni/S ratios (range 1.2 - 3.0) and with the sulphides being pentlandite and heazlewoodite with minor alteration to millerite.

In rocks with high Ni/S ratio magnetite is absent from the mineral assemblage. Most samples of this type contain no detectable Cu (detection limit of 5 ppm) despite Ni grades of up to 2% and elevated Co and PGE. This ore type forms about 40% of the Harrier resource. These mineralised types form large coherent blocks within the deposit (Fig. 5). There are slight differences in the gangue mineralogy between these two ore types. The high-Cu ore is commonly hosted in dark green lizardite- rich assemblages and some antigorite - carbonate assemblages with veins containing a relatively high proportion of carbonate. The low-Cu ore is mostly hosted by dark to very light green lizardite-rich rocks containing a low proportion of antigorite-assemblages and the vein mineralogy is dominated by brucite and pyroaurite/iowaite. Based on Cu, the contact between ore types is sharp (over 2 - 6 m) whereas other geochemical differences (S, Fe) are gradational (over 5 - 50 m). These geochemical gradients are reflected in a zoned pattern in primary sulphide + magnetite assemblages of Ni-poor pentlandite - chalcopyrite + pyrrhotite-magnetite (Ni/S ratio <0.8), pentlandite + chalcopyrite + magnetite, (0.8 - 1.3), Ni-rich pentlandite - heazlewoodite + trace magnetite (1.3 - 2.0) and heazlewoodite + rare magnetite (2.0 - ~3.0).

Corella Disseminated Sulphide Deposit

The Corella deposit is located along the north east contact of the Honeymoon Well ultramafic complex. The deposit contains 53.5 MT at 0.62% Ni (0.4% Ni cutoff, <300 m depth) and extends for 1400 m with widths of 20 to 100 m (Fig. 6). The Corella sequence is composed of a wide variety of lithologies including oAC, osAC, oMC, osMC, high porosity osOC and oOC and minor spinifextextured flows. These flows have been recrystallised under high temperature metamorphic conditions (Gole et al., 1990) and together with minor andesitic and basaltic volcanic rocks form the RMH. Spinifex-textured flows within this horizon show both westerly and easterly younging directions. The latter are thought to be due to local folds associated with shear zones.

The ultramafic sequence is strongly deformed and sheared with many lithological units, including mineralised lithologies, occurring as fault-bounded boudins on various scales. Lithologies interdigitate as a result of both original stratigraphic relationships and structural dislocation. Because of the shearing the density and thickness of veins are significantly higher at Corella than at the other deposits.

Between the shears and faults within the ultramafic rocks, igneous textures are generally well preserved. The metamorphic mineralogy of the osOC and oOC consists dominantly of pseudomorphic antigorite - carbonate with minor chromite, tremolite, chlorite and rarely kaersuititic amphibole. The originally more olivine-rich rocks are mostly altered to lizardite - brucite - stichtite-bearing assemblages. In places these assemblages are altered to non-pseudomorphic antigorite - carbonate and talc - carbonate assemblages. Talc - carbonate alteration occurs mostly along the eastern ultramafic fault contact and is generally outside the limits of the Ni sulphide resource.

The ultramafic sequence is sub-vertical over the N-S extent of the deposit although in the south, the deeper parts of the sequence dip to the west (Figs. 7 and 9). To the east the ultramafic rocks are in fault contact with basalts and minor gabbros in the northern part, and with andesitic rocks to the south (Fig. 1 and 6). In plan this fault is sub-parallel to the mineralised sequence. In cross section however the fault has variable attitudes. In the north it dips to the west and truncates the mineralised sequence at depth (Fig. 8), and in the south it dips to the east away from the mineralisation (Fig. 7). Due to this fault the lowermost part of the ultramafic stratigraphy is missing. Within the preserved part of the ultramafic sequence the interpreted stratigraphy is, from east to west, barren oAC, the mineralised sequence of osAC, then osMC with overlying osOC and oOC.

This sequence was originally capped by spinifex-textured flows and mafic to intermediate volcanic rocks that form the RMH. Up-sequence and to the west of the RMH is minor oMC, then medium-grained oAC grading into the very coarse-grained oAC that forms the central core of the Honeymoon Well ultramafic complex. T h i s stratigraphy is very similar to that at the Harrier deposit. The patchy distribution of the RMH along the eastern side of the Honeymoon Well complex (Figs. 1 and 6) is a function of probable extensive thermal erosion by komatiite magma from which the overlying oAC unit formed and also later structural dislocation.

Nickel Mineralisation

The mineralised sequence varies along strike being dominated by osOC and osMC in the north to osAC and minor osOC in the south (Figs. 6, 8 and 9). To the north the sequence thins and grades into barren oAC whereas to the south the mineralised sequence is truncated by a NW trending fault. The depth to the oxide/supergene boundary is 55 to 75 m, and is the shallowest of the deposits because the transported clay layer is absent over most of the deposit. The thickness of the supergene zone is mostly 10 m or less.

In the central and northern parts of the deposit, transition zone sulphide assemblages occur in patches and zones throughout the deposit, even at the deepest levels. In the south the transition zone occurs only as a narrow horizontal layer below the supergene zone and at depth the sulphides are almost exclusively primary sulphides.

The thicker mineralised parts of the deposit in the area of 16100-16200N and 16700-17000N appear to result from stratigraphic repetition by faulting, presumably related to early thrusting. Although the thicker parts of the mineralisation appear to form coherent blocks, in detail a combination of original stratigraphy and deformation has resulted in numerous small, discontinuous lenses of mineralisation occurring in otherwise barren rocks. This is particularly the case on the sections south of about 16400N. Nickel grades vary from 0.35 to >2.5% being highest in the osOC. As at Harrier both high-Cu and low-Cu mineralisation types are present although the proportion of the low-Cu type is relatively low.

Hannibals Disseminated Sulphide Deposit

The Hannibals deposit is located along the western contact of the Honeymoon Well ultramafic complex within a fault-bounded, west-younging sequence of oMC and minor oAC, oOC and spinifex-textured rocks that can be traced for about 2.4 km along strike (Fig. 1). This same sequence hosts the Harakka deposit. The deposit contains 36.1 MT at 0.70% Ni (0.4% Ni cut off, <300 m depth). It is divided into western and eastern overlapping fault blocks (Fig. 10), which are stratigraphic equivalents repeated along a central fault zone (probably a reactivated D1 thrust fault). The eastern boundary of the eastern fault block and much of the western block are against the central oAC along a major, discrete, planar fault with mylonite fabrics preserved in places. This fault transgresses the mineralised sequence at a low angle to the stratigraphy and is interpreted as a relatively well preserved D1 thrust fault.

To the west the mineralised sequence is in fault contact with a sequence of tholeiitic basalt flows, some of which have doleritic to gabbroic centres, and minor interflow carbonaceous and pyritic shale. The ultramafic rocks along this contact are mostly schists derived from spinifex-textured flows. In places spinifex textures are preserved and indicate both easterly and westerly younging directions. Flows further from the contact are consistently west-younging and the easterly directions are due to folding along the faulted contact.

In the eastern block the stratigraphy of the sulphide-bearing sequence is relatively intact and igneous layering is sub-vertical (Fig. 11). A high Ni-grade core within the mineralisation plunges in a general SE direction. Thin oOC and spinifex-textured rock units occur lateral to the high grade core suggesting that the sulphide shoot fills a possible 30-80 m deep, 150 m wide channel. In the western fault block the lithological distribution appears to be more complicated due to possible layerparallel faulting. The block extends southward for several hundred metres as a narrow (20-60 m wide) sequence between the central fault and metabasalts to the west. A high Ni-grade core appears to be sub-horizontal within the mineralised sequence which thins dramatically to the north and south. The mineralised sequence bottoms at depth against the folded, western metabasalt/ultramafic fault contact and is truncated on the east by a fault contact with oAC (Fig. 11) . Recrystallised spinifex-textured rocks and associated fine-grained oOC occur in fault slices (Fig. 10) that are interpreted to be derived from the RMH.

Nickel Mineralisation

Mineralisation consists of disseminated sulphides containing trace to ~3 modal percent sulphide with Ni grades ranging from 0.35 % to 2.4%. The sulphide-bearing units are variously preserved igneous horizons with gradational to sharp contacts with barren or weakly mineralised oMC. Many of the sharp mineralisation, contacts are on minor faults. Down dip and along strike from the central portions of the mineralisation the sulphide layers thin and generally become lower grade and interdigitate with barren rocks. The depth to the oxide/supergene boundary ranges from 60 to 104 m and the supergene zone averages 15 m thick.

Most sulphides typically occur as scattered aggregates enclosed by oxide, carbonate and silicate gangue minerals. Sulphide aggregates typically have modified lobate shapes which reflects the predominance of mesocumulate-textured host rocks and general lack of strong recrystallisation. Chalcopyrite mostly occurs in veins with pyroaurite, brucite, magnetite and pyrite and is only rarely present in relict magmatic sulphide aggregates.

The mineralisation can be divided into low and high Cu types with the low-Cu ore type forming about 60% of the volume of the deposit. The eastern and western fault blocks have different mixes of these two mineralisation types with the eastern block having a higher proportion of the low-Cu type, hence having a lower overall Cu content and significantly higher Ni/S ratio together with higher lizardite, pyroaurite/brucite and lower carbonate contents compared to the western block.

Wedgetail Massive Sulphide Deposit

The Wedgetail deposit is located along the north western margin of the oAC complex. The deposit has a strike length of 1700 m and varies in width from 10 to 80 m (Fig. 12). The deposit contains an estimated 22.9 MT at 1.08% Ni (0.5% Ni cut off, <300 m depth). Of this 2.5 MT at 3.36% Ni represents a high grade zone which includes massive sulphide and massive sulphide breccia mineralisation.

The Wedgetail deposit comprises disseminated and massive sulphides hosted by a north-striking, westyounging, moderate to steep easterly dipping sequence of oOC and spinifex-textured rocks. In the south the mineralised sequence is in fault contact with the central oAC (Fig. 13). At depth and to the north the sequence is separated from the oAC by a fault wedge of felsic volcanic rocks up to 80m thick (Fig. 14). To the west the mineralised sequence is in fault contact with variably deformed felsic to mafic metavolcanic and metasedimentary rocks that typically have a strong subvertical cleavage. North of the inflection in the oAC contact around section 18800N, the mineralised sequence pinches out at depth where the faults that mark the eastern and western contacts join. On some sections a thin layer of breccia massive sulphide extends down dip along the combined fault plane (Fig. 14). South of 18800N the sequence is open below the depth of drilling (300-500 m vertical depth).

Spinifex-textured rocks within the mineralised sequence usually occur as small patches and zones generally close to the western contact. Complete flow profiles are mostly not preserved, although rarely there is sufficient textural preservation in A-zones to allow a younging direction to be determined. However at depth in the southern part of the deposit a 30 m thick sequence of very well preserved spinifex-textured flows is present that indicate a younging direction to the west, i.e. the sequence is overturned (Fig. 13). Mineralised rocks occur above and below the flows which grade laterally into osOC, probably reflecting a change from crystallisation within a channel way (osOC) to a temporary overbank environment (rapidly cooled thin flows). Similar lateral changes occur within disseminated mineralisation at the Perseverance nickel deposit (Barnes et al., 1988). It must be born in mind, however, that Wedgetail occurs in a fault block, and as such is only a slice of the original stratigraphic sequence. Olivine orthocumulates and osOC mostly contain nonpseudomorphic antigorite assemblages with only minor preservation of lizardite assemblages. Talc-carbonate assemblages are generally confined to contacts although much of the southernmost part of the mineralised sequence is altered to assemblages containing talc, carbonate, and chlorite.

Nickel Mineralisation:

Nickel grades within the mineralised sequence generally increase from east to west, with massive sulphide present in places along or close to the western faulted contact. Sulphide breccia, which comprises 30-90% sulphide and contains 1-20 cm sized, angular clasts of ultramafic and foliated country rock, also occurs along this contact. The massive sulphide/sulphide breccia varies in thickness from a few centimetres to several metres (maximum 12 m). No massive sulphide is recognised as being in its original stratigraphic position, all being thought to have been remobilised along faults and shears. The base of the oxide zone ranges from 70 to 90 m with the underlying supergene zone extending to 117 to 204 m depth. The transition zone ranges from 178 to 265 m depth with some deeper patches along fractures and faults.

Primary zone sulphides consist of pyrrhotite, pentlandite, pyrite, minor chalcopyrite and trace gersdorffite. Massive sulphide consists of interlocking polygonal shaped, relative coarse grains (up to 1.5 mm) of pyrrhotite and pentlandite, with pyrite in some samples. Chalcopyrite forms small intergranular, irregular shaped grains. A preferred alignment of grains or compositional layering is only rarely observed in the massive sulphide. In osOC the sulphides are strongly intergrown with metamorphic gangue minerals and form irregular aggregates that mostly do not show typical magmatic shapes.

Very minor low-Cu ore, comprised of pentlandite and heazlewoodite, is restricted to low grade zones along the eastern contact of the mineralised sequence. Nickel/sulphur ratios within Wedgetail mineralisation are significantly lower than those of the other Honeymoon Well deposits, reflecting the Fe-S-rich nature of the sulphide assemblages (Table 2). Massive sulphide exhibits Ni/S ratios of 0.17-0.4, whereas ratios for osOC range from 0.2-0.9, with only very minor areas of higher values.

Other Sulphide Occurrences

Minor to trace sulphides occur as layers and patches 1-20 m thick in places within the main mass of oAC. Some of these disseminated sulphides form lobate aggregates between former olivine grains and appear to be modified igneous sulphides. Others, however, occur as ragged grains within olivine pseudomorphs and, although they may be associated with elevated whole rock Ni values (mostly 0.3-0.45%, rarely higher), do not have elevated Cu, Pt or Pd. Such sulphides appear to be of metasomatic origin, forming during serpentinisation from Ni and Co released from altered olivine and from S introduced with the metamorphic fluids. In places rocks containing such sulphides have Ni grades above that of barren rocks suggesting some loss of Mg and other major element components during serpentinisation to allow residual enrichment of barren Ni values to these slightly elevated values. Within and around the margins of the Ni sulphide deposits are veins containing trace to 90% sulphide. Vein thickness ranges from 0.5 mm to rarely >1 m. The veins mostly occur in lizardite-rich rocks and apart from sulphide contain pyroaurite, brucite, magnetite, lizardite, chrysotile and rarely antigorite and carbonate. The vein mineralogy suggests that they are part of the greenschist facies regional metamorphic and metasomatic alteration of the ultramafic rocks.

In lizardite-dominant mineralisation a high proportion of chalcopyrite occurs within such veins. Around the margins of deposits the primary zone vein sulphides are pyrrhotite, pyrite, tochilinite, chalcopyrite, trace pentlandite and sphalerite. The distribution of the sulphide-bearing veins around Ni sulphide deposits appears to be highly erratic.

Model for evolution of Honeymoon Well Complex

An interpreted stratigraphic reconstruction of the Honeymoon Well ultramafic complex is shown in Fig.15. The lowermost komatiite unit contains all the known Honeymoon Well Ni sulphide deposits. This correlation is made on the basis of; (a) physical linking of similar stratigraphic packages between Corella and Harrier; (b) the western sulphide deposits are all hosted in fault blocks with some contacts being mylonites; (c) the presence of significant Ni sulphide mineralisation and the similarity in mineralisation style and composition between the western and eastern disseminated deposits; and (d) the presence of recrystallised spinifex-textured thin flows along the length of the RMH as well as within Hannibals. These latter two points are particularly powerful arguments for the correlation.

It would be expected that magmatic sulphides from temporally different igneous sequences or even perhaps from widely separated localities within the same sequence would have undergone different magmatic histories and thus have dissimilar compositions (eg. Naldrett and Barnes, 1986; Barnes et al., 1997). The very similar compositions, particularly the similar Ni/Pd, Pt/(Pt + Pd) and Pd/Ir ratios (Table 2), of the disseminated deposits thus strongly argues for these sharing the same magmatic history. The recrystallised spinifex-textured rocks require such restricted and unusual circumstances to form (Gole et al., 1990) that these are unlikely to be duplicated within two different sequences in the same general locality. Honeymoon Well is the only known locality for these rocks in the world.

Lateral variations in stratigraphic profiles along this unit reflect crystallisation in different volcanic facies (see Hill et al., 1995, 1996). These range from crystallisation within 5-8 km wide, long-lived turbulent flow channels sustained by very high lava supply rates that form thick, layered olivine-cumulate dominated sequences to periodically emplaced, thin, rapidly cooled lava flows that results in sequences of spinifex-textured flows.

Although Wedgetail is within a fault slice and thus not the complete stratigraphic sequence, and also that the massive sulphide is interpreted to be physically remobilised along a fault, the presence of spinifex- textured flows and of matrix and massive sulphide suggests that in volcanic setting it is generally similar to that of a Kambalda style deposit (Type 1 of Barnes et al., 1994) and is likely to have formed near the flow front of an advancing komatiite flow field or marginal to any regional-scale lava channel way (Hill et al., 1996). Reconstruction of the stratigraphy of the disseminated deposits shows significant differences between the deposits with spinifex-textured flows occurring within the Hannibals mineralised sequence, and relatively thick, laterally persistent oOC and osOC units occurring within the Corella sequence, whereas at Harrier olivine-rich cumulates dominate the mineralised sequence.

These differences may reflect more marginal (at Hannibals) to more central positions (at Corella) relative to a major flow channel. The variable but relatively high modal abundance of sulphide within the Honeymoon Well disseminated deposits suggests that much or all of the magmatic sulphide was physically introduced into the deposits within turbulently flowing silicate lava rather than being the result of insitu olivine-sulphide cotectic crystallisation as proposed at the slightly lower Ni grade deposits at Mt Keith and Yakabindie (Hill et al., 1996). The similarity of the sulphide compositions between Honeymoon Well disseminated deposits suggests that the magma from which the deposits were formed came from a very large homogeneous source.

The mineralised unit is capped by spinifex-textured rocks which are in turn overlain by basalt and andesitic volcanic and minor sedimentary rocks. The base of the unit is not preserved but originally the unit was probably, in places, >250 m in thickness.

The upper komatiite unit formed within a few tens of years after the lower unit (Gole et al., 1990). Its character varies along strike and in the Honeymoon Well area contains a coarse-grained oAC body, originally 500 - 1000 m thick by >6 km long in apparent cross section, formed in a massive komatiite lava channel (Hill et al., 1990, 1995). To the south the oAC body thins into an oOC-dominated sequence whereas to the north proximal lateral equivalents are not preserved. The unit is capped by spinifex-textured flow rocks and in places fractionated sequences of pyroxenite and gabbro. Thermal erosion occurred along the basal contact of this very broad lava flow channel, removing in places the underlying intermediate and mafic lavas and volcanoclastic rocks and part of the top section of the mineralised komatiite sequence. During igneous cooling remnants of this top section were partially melted and metamorphosed to high temperatures (Gole et al., 1990). Some of the scattered disseminated Ni sulphides with Ni grades of 0.35-0.6% Ni within the central oAC body appear to have formed by local magmatic S-saturation and cotectic crystallisation of olivine and sulphide. The pyrrhotite-rich sulphides present in osOC and osMC east of and up-sequence of the RMH at Harrier occur in relatively high modal proportions and must have been physically introduced to their present position as highly fractionated sulphide liquid within strongly chalcophile-element depleted silicate lava.

The ultramafic stratigraphy outlined above is generally similar to that proposed by Barnes et al. (1988) for the Perseverance Ni deposit in the southern part of the Agnew-Wiluna belt. Early deformation of the Honeymoon Well sequence occurred within a D1 thrust duplex with an apparent sense of movement of north block to the south. The geometry of this duplex was probably greatly influenced by the size and competency of the unmetamorphosed oAC body. The oAC unit itself was stacked and thin thrust slices of the lower mineralised ultramafic horizon were emplaced along the top (now western) margin of the duplex.

Folding of the greenstone belt sequence and strike-slip faulting during D2 was accompanied by lower greenschist facies metamorphism. Strike-slip faulting resulted in further duplication of the stratigraphy in the southern part of the Honeymoon Well prospect, again with an apparent sense of movement of north block to the south, as well as removing the northern proximal equivalents of the Honeymoon Well ultramafic horizons.

At Wedgetail the bulk composition of massive sulphide dominantly reflects magmatic processes, and apart from relatively minor redistribution of Cu and the addition of As to parts of the deposit there appears to have been relatively little adjustment of the sulphide bulk composition during metamorphism. The Ni-rich bulk sulphide compositions of the disseminated sulphide deposits are, however, a function of interaction with metamorphic fluids. The sulphide deposits are located adjacent to major faults that have acted as pathways for migration of larg e volumes of fluid. Highly reduced fluids that may form during progressive alteration of ultramafic rocks (Frost, 1985) have caused complete leaching of Cu and partial loss of Fe, S and Zn from parts of the sulphide deposits and of Fe from large volumes of barren ultramafic rocks. In the latter, magnetite is absent from lizardite-brucite-iowaite dominated alteration assemblages resulting in low magnetic susceptibility for such serpentinites present, for example, south east of Wedgetail and east of Hannibals-Harakka (see Fig. 5, Bourne, 1996). In the disseminated sulphide deposits the metasomatism has formed a zoned pattern in Cu content, whole rock Ni/S ratio and primary sulphide assemblages.

The sulphide zones are defined by pentlandite-minor pyrrhotite-chalcopyrite, pentlandite-only, pentlandite-heazlewoodite and heazlewoodite-only assemblages. Zones containing pyrrhotite and chalcopyrite represent the least altered sulphide assemblages whereas heazlewoodite-only assemblages occur in the most strongly leached rocks.

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