MKD5 nickel sulfide deposit, Mount Keith

by

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Abstract

The low grade, high tonnage MKD5 orebody at Mount Keith in central Western Australia is currently the largest nickel producer in Australia. The orebody comprises disseminated Ni–Fe sulfides hosted in a series of cumulate dunite and peridotite units that form part of the Eastern Ultramafic unit, in the northern Agnew–Wiluna greenstone belt. The Archean cumulate sequence is of komatiitic affinity and has been variously interpreted as an intrusive dyke or sill, or, more recently, as the product of a giant komatiite lava river. Nickel sulfide mineralization is interpreted to have formed by cotectic crystallization of olivine cumulus crystals and a sulfide melt phase following sulfur saturation of the komatiitic melt phase. Subsequent hydrothermal serpentinization and talc–carbonate alteration of the ultramafic sequence have resulted in modifications to sulfide phase relations.

Introduction

The giant, low grade, MKD5 nickel sulfide orebody at Mount Keith in the northeastern Eastern Goldfields of Western Australia is currently the largest nickel producer in Australia. Owned and operated by WMC Resources, nickel has been produced since 1994 and currently stands at 377 000 t of Ni metal in concentrate to the end of 2003. Disseminated nickel sulfide mineralization extends over a strike length of 2 km and continues downward to at least 600 m depth (current base of drilling). The bulk of economic mineralization is in the grade range 0.4–1.2% Ni, with typical head grades of current mill feed in the range 0.5–0.8% Ni. The deposit is mined as a single-staged cutback pit using conventional opencut methods. It is a 50 Mtpa operation, of which 11.2 Mtpa is mill feed. The ore is processed by froth flotation, yielding a sulfide concentrate containing 18–27% Ni, depending on ore mineralogy. Minor byproducts include Co, Cu, and platinum group elements (PGE).

Discovery and resources

The name Mount Keith comes from the sheep station on which the deposit is located (later incorporated into Albion Downs Station), which, in turn, was named after a small hill several kilometres to the north of the current opencut. The resident managers of Mount Keith Station in the 1960s were Jim and Eileen Jones. Jim Jones was a keen amateur prospector and, following WMC's discovery of nickel sulfides in Kambalda in 1966, was alert to signs of possible nickel mineralization. In November 1968, he unsuccessfully attempted to use a small water-boring rig to test an outcrop of weathered ultramafic rock in which he'd previously found some gossanous material. Fortuitously, a driller friend arrived at the station at this time with a reverse circulation (RC) drill rig that required repair work. Jim agreed to perform the repairs in exchange for a single RC hole being drilled. The hole was collared 3 m from the site of his abortive water drill attempt, and struck disseminated nickel sulfides at 70 m depth. It is believed that this discovery occurred at the present-day Golgotha prospect in the Central Ultramafic unit and not in the adjacent Eastern Ultramafic, which hosts the MKD5 orebody (Fletcher, M., 1998, pers. comm.)*. Samples of the drill cuttings were passed to geologists from Metals Exploration NL who were working in the Kingston area north of Mount Keith at the time. On returning positive assay results, Metals Exploration, in joint venture with Freeport of Australia, acquired the Mount Keith mineral claims through purchase and pegging, and, in January 1969, commenced a detailed exploration program, targeting both massive sulfides in basal contact positions and broad, low-grade disseminated mineralization. The

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* Drilling in the same area in 1998 confirmed the presence of preserved sulfides at unusually shallow depths relative to the rest of the Mount Keith area (where sulfides are not usually seen at less than 100 m), suggesting the initial recovery was indeed fortuitous.

very poor outcrop and deep weathering profile necessitated reliance on magnetic data to define ultramafic unit boundaries. Initially, 39 000 m of percussion drilling (1296 holes) was carried out. A diamond drilling program followed in July 1969 and, in November of the same year, drillhole MKD5 intersected 176 m at 0.60% Ni, proving the economic potential of the prospect. The first indicated ore reserve for the MKD5 orebody, of 195 Mt at 0.60% Ni, was announced in 1971. A series of joint ventures and changes in ownership followed, together with additional drilling programs, but mining was delayed for over two decades as a consequence of low metal prices and metallurgical problems (principally low Ni recoveries and poor concentrate quality). WMC acquired full ownership of Mount Keith in 1993 and, following commissioning of the metallurgical plant in 1994, began nickel production in October of that year. Current (2003) ore reserves are 308 Mt at 0.56% Ni with an ore resource (inclusive of reserves) of 505 Mt at 0.56% Ni. The projected mine life is in the order of 25–30 years, based on an average annual processing rate of about 11 Mtpa.

Geological setting

The MKD5 orebody is in the Agnew–Wiluna greenstone belt in the Archean Yilgarn Craton of Western Australia (Hill et al., 1990). The belt trends north-northwesterly and is constrained by large- to terrane-scale faults and granitoid bodies (Fig. 1). The belt is most attenuated in the Mount Keith area, with a maximum thickness of 6 km, and changes strike about the Mount Keith position, possibly reflecting an underlying primary structural control. This section of the belt is bound to the west and east by voluminous Archaean granitoids (Barrett et al., 1977). The greenstone sequence in the Mount Keith area includes three ultramafic horizons, locally designated the Eastern, Central, and Western Ultramafic units (Fig. 1; Dowling and Hill, 1990). The ultramafic horizons can be traced 30 km north of Mount Keith to the Honeymoon Well nickel deposit, and 9 km south to the Cliffs–Charterhall nickel deposit. Beyond these limits, definition of the belts is uncertain due to structural complexities. There are well developed spinifex-textured komatiites in the Western and Central Ultramafic units, with sporadic Kambalda-style basal accumulations of massive Ni–Fe sulfide at the base of the Central Ultramafic, notably in the Cliffs–Charterhall deposit area. The Eastern Ultramafic lacks the development of spinifex-textured komatiite anywhere along its strike extent, and contains giant accumulations of extreme olivine-cumulate rocks (dunite and mesocumulate peridotite) with olivine grainsizes up to 2.5 cm. All three ultramafic units dip steeply (and locally subvertically) to the west. Igneous textures and

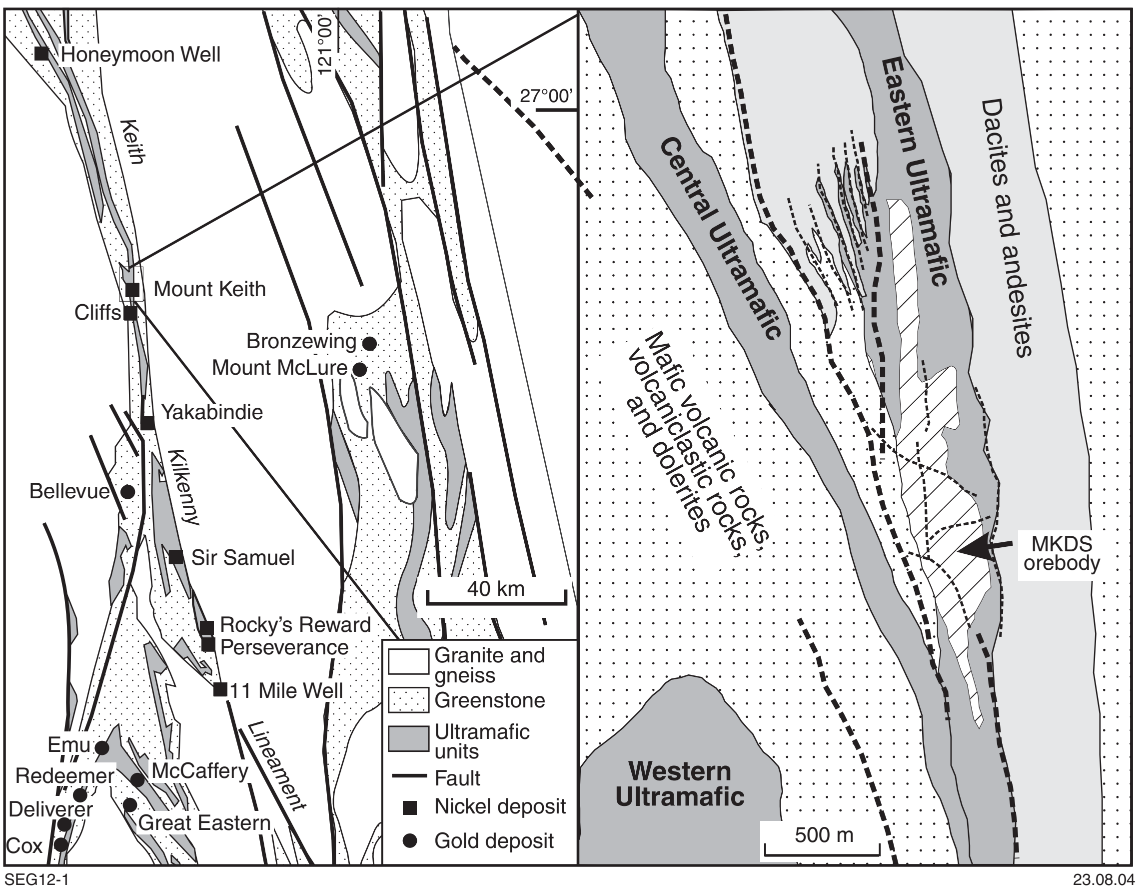

Figure 1. Regional geology of the Agnew–Wiluna belt and the Mount Keith area showing the relationship between the Western Ultramafic, Central Ultramafic, and Eastern Ultramafic units hosting the MKD5 orebody

geochemical trends indicate a west-facing direction for the Eastern and Central Ultramafic units (Naldrett and Turner, 1977; Dowling and Hill, 1990). Local east facings and shallow dips within the Western Ultramafic are attributed to shallowly plunging, tight to isoclinal synclinal folding (Bongers, 1994). The genetic relationship between the three ultramafic horizons has been controversial, but recent work by Rosengren et al. (in press) described preserved upper contacts between the Eastern Ultramafic and hangingwall dacites. These upper contacts preserve features such as incorporation of dacite xenoliths by the Eastern Ultramafic and apophyses of ultramafic rock into the hangingwall dacite, indicating an intrusive origin for the unit. Volcanic textures indicate the Western and Central Ultramafic units are subaqueous extrusive sequences.

In the Mount Keith area, the three ultramafic horizons are enclosed by a sequence of variably deformed and altered intermediate and mafic rocks. The Central and Western Ultramafic units are broadly enclosed by mafic units of basaltic bulk composition that are generally fine grained and deformed (Fig. 1). The footwall to the Eastern Ultramafic consists of monotonous, coherent to in situ, fragmented, dacitic to andesitic, phenocryst-rich lavas (Fig. 1), within which lateral and vertical facies variations have previously been identified by Heptinstall (1991), Palich (1994), and recently reinterpreted by Rosengren (2004). The hangingwall rocks of the Eastern Ultramafic just north of the MKD5 deposit, and near Shed Well and Sarahs Find, consist of dacitic to andesitic rocks, identical to those of the footwall sequence (Rosengren, 2004). The hangingwall to the Eastern Ultramafic at the MKD5 deposit consists of a thin, structurally emplaced, pyritic, chert unit overlain by fine-grained foliated mafic units, which are, in turn, overlain by the Central Ultramafic. The Central Ultramafic is in faulted contact with the Eastern Ultramafic in the southern portion of the MKD5 pit, and at several locations along strike between the MKD5 and Cliffs–Charterhall deposits. The giant MKD5 orebody is a Type IIB nickel deposit, as defined by Lesher (1989), and is hosted in a komatiitic dunite–peridotite body that forms part of a zone of substantial thickening in the Eastern Ultramafic.

State of knowledge of the deposit

Previous work on the general geology and mineralization style of the MKD5 orebody was carried out by Burt and Sheppy (1975), Groves and Keays (1978), Dowling and Hill (1990, 1993), and Hopf and Head (1998), with a more detailed examination of the alteration systematics undertaken by Rödsjö (1999), and Rödsjö and Goodgame (1999). More recently, the igneous geology of the Agnew–Wiluna belt has been the subject of an AMIRA project (P710), led by Dr Steve Beresford of Monash University. Work as part of this project in the Mount Keith area has led to a reinterpretation of the contact relations and emplacement history of the Eastern Ultramafic (Rosengren et al., in press), a facies model for the enclosing dacitic sequence (Rosengren, 2004), and a refinement of the igneous stratigraphy of the Eastern Ultramafic (Rosengren, 2004). The current understanding of the igneous stratigraphy and alteration overprint is a culmination of this work and that of WMC exploration and mining geoscientists since the commencement of mining in the mid-1990s.

Primary lithology

The Mount Keith ultramafic complex hosting the MKD5 orebody can be subdivided into a series of seven primary igneous units (Fig. 2), the boundaries of which are generally parallel to the regional trend of the Eastern Ultramafic. From east to west, the steeply west-dipping units generally become more magnesian and closer-packed olivine cumulates increase in abundance, indicating a westward facing direction for the complex, which is consistent with observations throughout the Eastern Ultramafic (Naldrett and Turner, 1977; Dowling and Hill, 1990).

The lowermost Unit 101, which is in sheared contact with the footwall dacitic sequence, is denoted the Millerite Orthocumulate Domain by local mine geologists, and consists of a former olivine orthocumulate (Ooc on Fig. 3) peridotite that is essentially barren of sulfide mineralization. Unit 102 (Millerite Adcumulate Domain of local mine geologists) lies stratigraphically above, and consists of extreme olivine adcumulate dunite (EOAD on Fig. 3) with subordinate horizons of orthocumulate and pyroxenite, particularly near the base of the unit. Former olivine crystals in the dunite are 0.5–2 cm long, and are typically elongated and aligned in a well-defined igneous fabric. The dunite contains pods and horizons of disseminated magmatic sulfide mineralization, but, for the most part, is sulfide poor. Unit 102 thickens in the northern portion of the complex. Unit 104 (Pentlandite Adcumulate Domain of mine geologists), which overlies Unit 102, consists of olivine adcumulate (Oad on Fig. 3) dunite to mesocumulate (Omc on Fig. 3) peridotite, and is notable for containing a generally uniform distribution of magmatic sulfide mineralization. Former olivine grains tend to be more rounded in this unit, and the presence of lobate intercumulus chromite is conspicuous by the pink–magenta colour of its alteration products; stichtite and woodallite. In the southern and central portions of the complex, Unit 104 is at its widest, with intersections of up to 300 m (true width) containing ore-grade mineralization. These large intersections of economic mineralization have driven the geometry of the openpit mine design. A thin (<10 m) discontinuous zone of unusual olivine rocks is common between the base of Unit 104 and top of Unit 102. Denoted the Porphyritic Olivine Rock Domain (Unit 103; POR on Fig. 3), it locally contains serpentine pseudomorphs after very large olivine crystals (up to 5 cm; Seymon, 1996). Textures are often distinctly amoeboid harrisitic, and a characteristic feature is the presence of brown 'bastite' replacing pyroxene, together with flakes of phlogopite. The bulk chemistry is typically similar to that of an orthocumulate (e.g. Al_2O_3 >0.8% and locally as high as 10%; Table 1). There can be very coarse segregations (up to 10 cm) of sulfides, but these are typically of very low Ni tenor. Pegmatoidal gabbroic segregations containing elevated levels of elements incompatible with ultramafic rocks (e.g. Zr, P, Ti) are

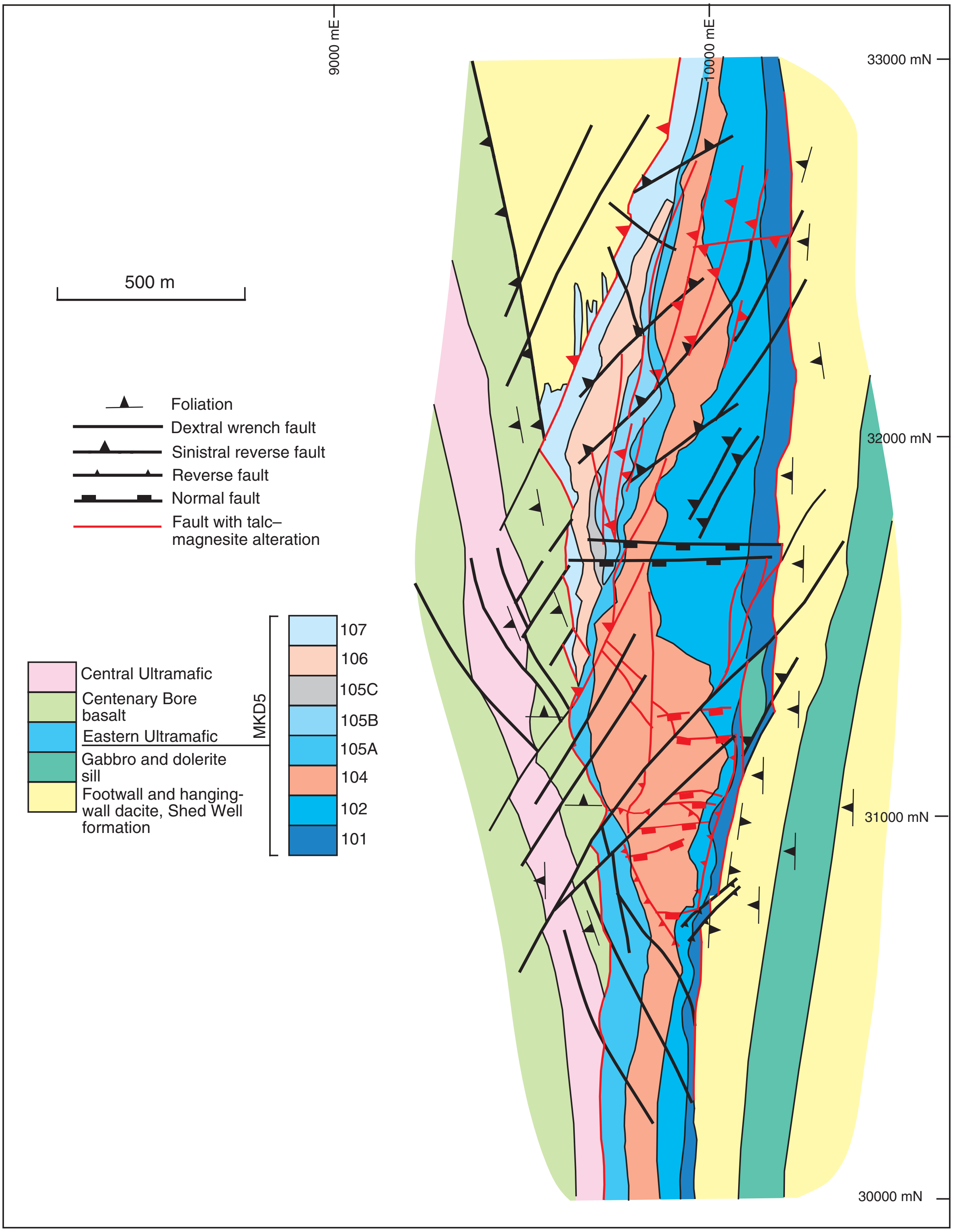

Figure 2. **Schematic plan view showing primary rocks of the Mount Keith ultramafic complex. Plan is constructed at 400RL (ground surface is at 544RL). Explanation of primary stratigraphy is given in the text. Diagram from Rosengren (2004) using structural data from Hayward (2004). Local grid is rotated 4° east from GDA94**

Strongly foliated basaltic hangingwall, abundant leucoxene fibres

Multiple, thin, black shale horizons

46–55.8 m Chert – black shale – pyrite horizon, heavily sheared

Possible 107 orthocumulate — textures obscured by strain and alteration

Zone of heavy shearing

84–90 m Transition from Omc to Oad. Olivine crystal size to 8 mm, abundant interstitial sulfide

111.4 m Olivine crystal size up to 1 cm, sulfide strongly layered, Oad texture becoming more tightly packed

~182 m Oad texture becoming less tightly packed

191–194 m Sheared

194 m Ooc–Omc Crystal size ranges from <1 mm to 8 mm

200 m Ooc with significant phlogopite, bastite, and possible pyroxenes

Patchy interstitial sulfides are present; by 224 m, crystal size is up to 1.5 cm

Well formed Oad by 254 m, stitchite aggregates up to 5 mm at 257 m, abundant sulfides

Strong olivine elongation at 261 m, 275 m, and 303 m; sulfide patchy to absent in these areas

317 m Olivine in bastite groundmass

329 m Thin segregation vein Ooc and sulfide

340 m POR horizon and rapid transition to EOAD of 102 unit with olivine crystal size up to 2.5 cm

370 m POR

408 m EOAD texture layered with finer Oad, layered sulfide also present

450 m POR horizon, shearing, and intense talc–carbonate alteration

482–510 m Zone of interlayered Ooc, harrisite, babbroic and pyroxenitic segregations, and rodingite (possibly felsic xenoliths)

510 m Transition to fine grained 2–4 mm Ooc with numerous segregations and thin hopper olivine horizons (e.g. 542.5 m)

Talc–carbonate alteration begins to obscure textures from about 540 m

101 unit

581 m Felsic xenolith?

?Dolerite intrusion

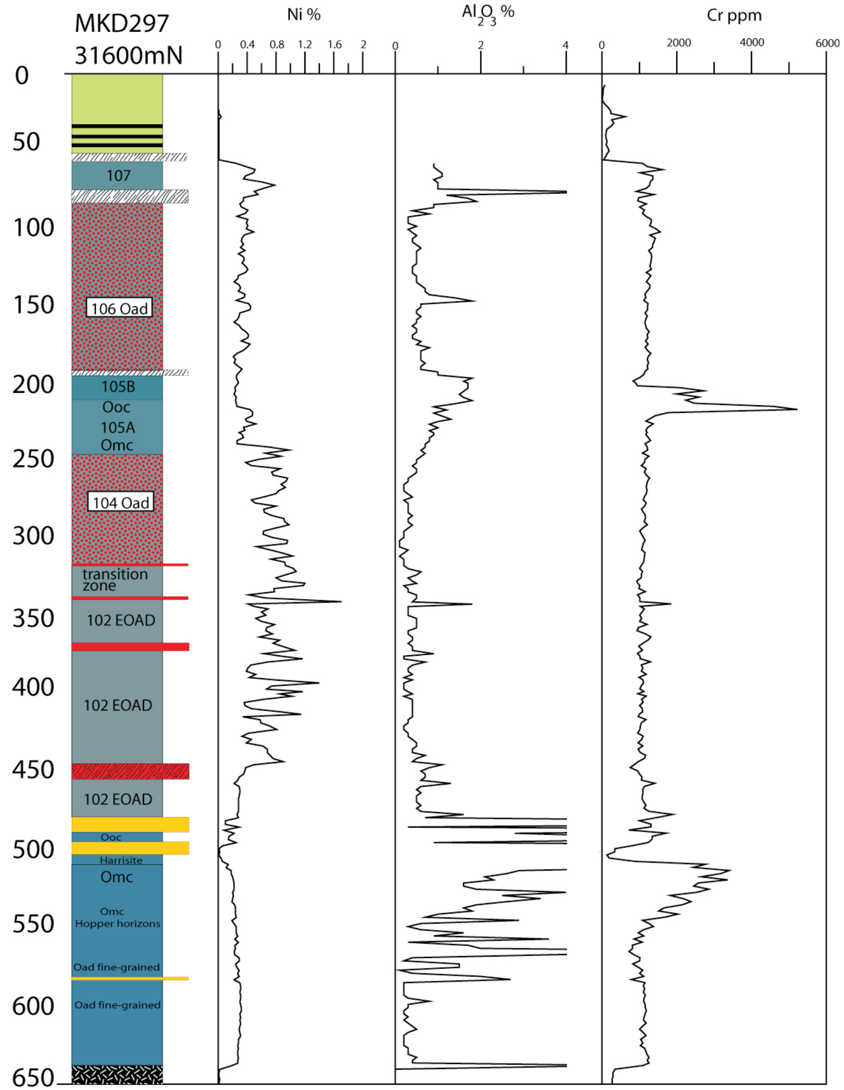

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Figure 3. Downhole geochemical plots for Ni, Al_2O_3, and Cr in diamond drillhole MKD297, with schematic igneous stratigraphy and textural descriptions. Units 101–107 and abbreviations are explained in the text. Drillhole is oriented east–west and located along 31600N on Figure 2

Table 1. Whole rock analyses of MKD5 samples

	1	*2*	*3*	*4*	*5*
			Percentage		
MgO	39.2	40.2	41.2	34.6	38.7
SiO	34.5	34.0	33.3	34.9	36.3
Al Ô	0.3	0.4	0.1	1.1	1.8
Fe^{2} ^{3}	4.6	3.9	4.7	5.3	5.6
CaO	0.33	0.15	0.20	4.4	0.8
Ni	0.65	0.26	0.53	0.38	0.41
S	1.03	0.01	0.3	0.4	0.3
			Parts per million		
Cr	781	835	1 217	1 355	1 853
Co	160	60	127	112	126
Cu	270	5	25	34	23
As	15	35	10	7	9
			Parts per billion		
Ru	14	1	7	na	na
Rh	6	1	4	na	na
Pd	34	1	22	na	na
Os	11	6	7	na	na
Ir	9	4	9	na	na
Pt	13	1	6	na	na

NOTES:
1 Medium grade ore. Lizardite–brucite-altered dunite from central Unit 104 (MKD153 556–558 m)
2 Antigorite–magnesite-altered dunite from upper Unit 102, containing no macroscopic sulfides (MKD153 697–699 m)
3 Sample from ore-grade pod in Unit 102. Antigorite–magnesite-altered dunite (MKD219 512–514 m)
4 Unit 107 serpentine–chlorite-altered orthocumulate peridotite containing trace sulfides (MKD297 64–66 m)
5 Unit 103 serpentine–magnesite–chlorite-altered amoeboid harrisite, containing trace sulfides (MKD297 339.3 – 340.8 m)
na not available

associated with Unit 103, and could represent some type of late-stage melt segregation.

In the northern portion of the ultramafic complex, the Unit 104 adcumulate dunite grades into an essentially barren mesocumulate peridotite unit with an orthocumulate peridotite top, known locally as the Mesocumulate Domain (Unit 105). This unit contains localized pods of pyroxenite, bladed and amoeboid harrisites, and pegmatoidal gabbroic segregations. The upper part of the mesocumulate (sensu stricto) unit is particularly elevated in Cr, with typical levels of 2500 ppm, peaking locally to 6000 ppm (Fig. 3), and is mainly orthocumulate peridotite. Unit 104 in the central and southern portions of the complex is directly overlain by a thin orthocumulate peridotite horizon (Unit 107), which contains some localized pods of ore-grade sulfide mineralization. This unit is in sheared contact with hangingwall rocks, notably the aforementioned pyritic chert unit.

In the northwestern portion of the complex, a body of ad- to mesocumulate dunite (Unit 106) overlies Unit 105 (Fig. 2). Locally denoted the Western Mineralized Domain, it appears to represent a late-stage injection of fresh, uncontaminated magma. Nickel–Fe sulfides are present in the form of relatively coarse intercumulus blebs, characteristically of low Ni tenor. The western margin of this unit consists of orthocumulate peridotites and subordinate harrisites, pyroxenites, and gabbro horizons.

In defining and modelling these units in the ultramafic complex, particular importance is placed on whole-rock major and trace element chemistry, which can be used to define lithological boundaries in areas where hydrothermal alteration has obliterated primary textures, and identify subtle changes in lithology that are not readily noted during conventional core logging. Components such as Al_2O_3 and TiO_2 are useful in this regard, owing to their relative immobility during alteration and relative incompatibility in olivine. Their abundance thus mirrors that of the intercumulus component. Examples of downhole geochemical profiles are given in Figure 3, and representative whole-rock analyses are presented in Table 1.

Alteration overprint

The host dunites and peridotites in the Mount Keith ultramafic complex have been completely serpentinized and locally talc–carbonate altered after deformation and metamorphism to mid-upper greenschist facies (Barrett et al., 1977; Rödsjö; 1999; Rödsjö and Goodgame, 1999). The retrograde serpentinization–carbonation event was initiated by infiltration of H_2O–CO_2-rich fluids, which exploited early contact-parallel and crosscutting (D_2) faults and shears as conduits (Rödsjö, 1999; Widdup, 2000; Hayward, 2004). The geochemical signature of the altering fluids (as indicated by wall-rock chemistry) is consistent with regional Archean gold fluids, i.e. H_2O–CO_2 dominant, As-bearing, and containing low levels of Au, Te, and reduced S (Rödjsö, 1999). Infiltrating fluids reacted with the ultramafic wallrock to produce a talc–magnesite assemblage proximal to the structural conduits, with enveloping antigorite–magnesite haloes. The most distal manifestation of this alteration process is a lizardite–brucite assemblage. The relatively low temperature fluid infiltration (<320°C) has resulted in high levels (up to 20% in run of mine ore) of hydrotalcite group minerals, particularly in areas of low fluid–rock interaction, such as lizardite–brucite alteration zones. Of these, the most common species are iowaite [$Mg_6Fe_2(OH)_{16}Cl_2.4H_2O$], pyroaurite [$Mg_6Fe_2(OH)_{16}CO_3.4H_2O$], and stichtite [$Mg_6Cr_2(OH)_{16}CO_3.4H_2O$], with the last mentioned forming replacements of magmatic chromite grains (Grguric et al., 2001; Grguric, 2004). In addition, the MKD5 orebody is the type locality for woodallite (the chlorine analogue of stichtite; Grguric et al., 2001) and mountkeithite (a mineral related to pyroaurite; Hudson and Bussell, 1981). This sequence of alteration assemblages resembles that described by Eckstrand (1975) in the Dumont serpentinite complex, Quebec, except that no original igneous olivine is preserved in MKD5, and hydrotalcite group minerals are apparently absent in Dumont. Magnesian chlorite appears as an alteration mineral where aluminium levels in the ultramafic rocks are elevated (e.g. in orthocumulate rocks, and adjacent to hanging- and footwall contacts). Late-stage, pegmatoidal, gabbroic bodies within the ultramafic complex are typically rödingitized, particularly when enclosed by ultramafic units that were formerly rich in calcium, such as pyroxenites or orthocumulate peridotites.

Alteration is extremely important from a mineral processing point of view, principally because processing of talc–magnesite-altered ores results in poor quality concentrates. Talc, being a free-floating mineral, reports to final concentrate, which results in unacceptably high MgO levels in this product. In addition, the highest levels of arsenic occur within talc–magnesite zones, and this element is generally upgraded during beneficiation. Lizardite–brucite ores present the least metallurgical problems, with the exception that chlorine levels in final concentrates can be high due to the presence of the aforementioned hydrotalcite group minerals (Grguric, 1999).

Ore mineralogy

Intercumulus sulfide blebs range in size from 40 µm to 1.5 mm (average 0.5 mm) and are usually situated at the triple point junctions of former olivine grains. These blebs consist of aggregates of Ni–Fe sulfide grains surrounded by a corona of magnetite, the outer margins of which are partially replaced by iowaite, chlorian pyroaurite(–tochilinite), or ferroan magnesite in most cases. A coarse network of magnetite ‘crossbars’ is typically present within the blebs (Fig. 4a). Sulfide abundances in ore grade material are usually in the 1–5% range. Such sulfide–gangue textures are representative of the bulk of the nickel mineralization in MKD5. The distribution of ore mineral assemblages is now well defined following an extensive mineral mapping and microanalytical study by the senior author in 2001 (representative microprobe analyses are given in Table 2). A distinctive feature of the deposit is the zonation of sulfide assemblages. This zonation is interpreted to be a consequence of:

- primary variations in sulfur saturation during segregation of sulfides from the primary magma and subsequent cooling (resulting in variations in sulfide to silicate proportions);
- most improtantly, modifications to sulfide–oxide subsolidus phase relations as a result of contrasting oxygen and sulfur fugacity conditions during later hydrothermal alteration.

The main ore zone in MKD5 comprises a pentlandite–pyrrhotite assemblage in Unit 104. Partial to complete hypogene replacement of pyrrhotite by a lamellar intergrowth of pyrite–marcasite–magnetite is extremely common in this unit (Fig. 4a). Owing to a relatively coarse bleb size (locally up to 3 mm), these ores generally yield the highest Ni recoveries during processing. On the margins of the Unit 104, the sulfide assemblage grades to dominant pentlandite with subordinate pyrite, hypogene violarite, or both, with the violarite present as exsolution lamellae in pentlandite grains (Fig. 4b; Grguric, 2002). The adjacent Unit 102 is characterized by a more ‘poddy’ distribution of ore grade material, with ore pods and shoots separated by low grade zones averaging 0.30–0.35% Ni and lacking macroscopically visible blebs. Sulfides are present in the low grade zones as essentially unrecoverable, micron-sized dustings within former olivine grains. This low grade mineralization contains virtually no detectible Cu or PGE, and reflects the alteration of dunite containing no magmatic sulfides*. Sulfide assemblages in the ore pods are sulfur poor relative to Unit 104, and Fe sulfide phases are absent. Assemblages are dominated by high-Ni pentlandite, millerite (Fig. 4c), godlevskite, and hypogene violarite, which have developed as a consequence of elevated fluid fO_2 associated with antigorite–magnesite alteration of the host dunites (Grguric, 2002, 2004). In the northern part of Unit 102, less intense alteration has resulted in contrasting extremely low fluid fO_2, with the consequence that heazlewoodite is stabilized.

The other significant ore domain is Unit 106, the adcumulate–mesocumulate dunite unit in the northwest of the orebody. This unit is characterized by relatively Fe-rich sulfide assemblages with pyrrhotite (partly or completed replaced by lamellar pyrite–marcasite) present in equal or larger proportions to pentlandite. Supergene alteration of the sulfide assemblages are common in this unit due to the presence of late-stage structures that have acted as conduits for supergene fluids.

Within talc–carbonate altered zones, the fO_2 and fS_2 of fluids attending talc–magnesite alteration have resulted in the stabilization of pyrite. Existing pyrrhotite–pentlandite assemblages are usually preserved, with the addition of some hydrothermal pyrite. Magnetite coronas and crossbars on blebs are completely replaced by ferroan magnesite (Fig. 4d). Locally, there is extensive alteration of pyrrhotite and pentlandite along the [0001] plane of pyrrhotite and [111] plane of pentlandite. The result is a distinctive lamellar texture in which relict sulfide lamellae (1–5 µm thick) are interleaved with talc and magnesite. Owing to deformation, these lamellae can be kinked or bent. Although Cu is not elevated in talc zones, modified phase relations have resulted in the formation of minor chalcopyrite associated with Ni and Fe–Ni sulfides (Fig. 4d). Most talc-altered ore contains elevated levels of As (30–6500 ppm) as a consequence of the As content of the alteration fluid. At low levels of whole rock As (<500 ppm), Fe and Fe–Ni sulfide minerals apparently host As in solid solution or as submicroscopic inclusions. At higher As levels, discrete As-bearing opaque minerals such as gersdorffite (NiAsS), nickeline (NiAs), cobaltite (CoAsS), and maucherite ($Ni_{11}As_8$) are common, typically replacing pre-existing pyrrhotite and pentlandite.

Supergene alteration is developed as a subhorizontal zone below the oxide zone and persists to a vertical depth of about 100 m, with some deeper perturbations of the supergene–primary surface along late-stage brittle structures. The supergene zone is defined by the presence of secondary violarite after pentlandite or millerite (Fig. 4e), and an elevated non-sulfide Ni content relative to the protore. There is no significant supergene enrichment of total Ni or Co in this zone. Sulfide minerals associated with secondary violarite include secondary millerite, pyrite, marcasite, and relict pentlandite (Butt and Nickel, 1981). Both the textural characteristics (Figs. 4b and 4e) and mineral chemistry (Table 2) of secondary violarite are markedly different to those of its hypogene

* The Ni grade of this material reflects the fact that natural forsteritic olivines can contain up to 4000 ppm Ni in solid solution. Subsequent serpentinization–carbonation of olivine by fluids containing reduced sulfur results in exsolution of Ni in the form of fine sulfide particles.

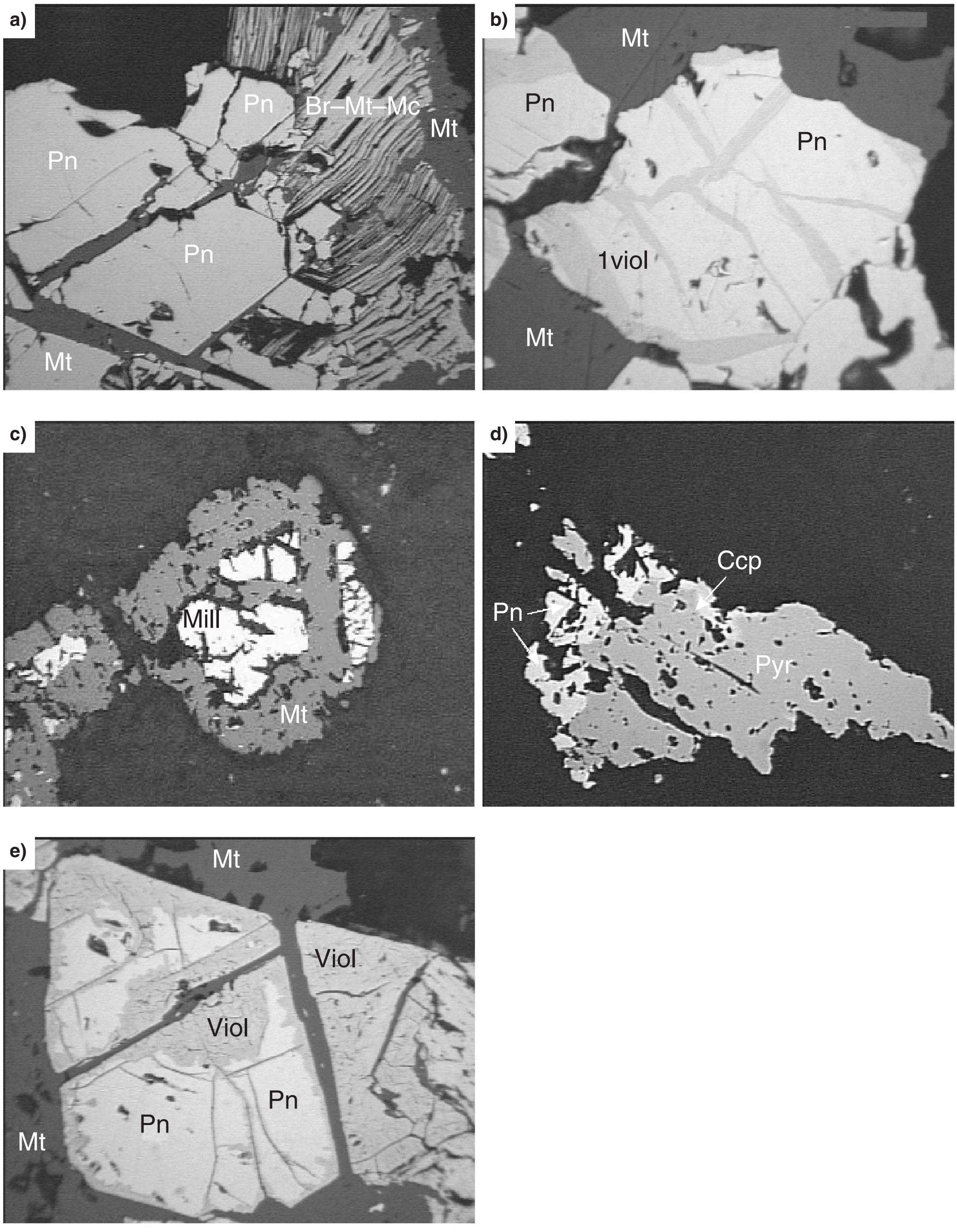

Figure 4. Reflected light micrographs of MKD5 ore textures: a) Detail of a sulfide bleb from Unit 104 showing coarsely crystalline pentlandite (Pn) with magnetite (Mt) rims and crossbars, and associated with a distinctive lamellar intergrowth of bravoitic pyrite, magnetite, and marcasite (Br–Mt–Mc); intergrowth is a hypogene alteration product of pyrrhotite; field of view 600 µm. b) Sulfide bleb from the eastern margin of Unit 104, consisting of pentlandite (Pn) with hypogene violarite (1viol) exsolution lamellae surrounded by a corona of magnetite (Mt); field of view 250 µm; from Grguric (2002). c) Millerite (Mill) bleb from Unit 102 with thick magnetite corona; millerite formed by replacement of pre-existing pentlandite as evident from the relict triangular cleavage; field of view 500 µm. d) Typical sulfide bleb from a talc–magnesite-altered zone in Unit 104 consisting of pyrrhotite (Pyrr), pentlandite (Pn), and minor chalcopyrite (Ccp); note complete absence of magnetite rims or crossbars; field of view 600 µm. e) Sulfide bleb from the supergene zone showing replacement of hypogene pentlandite (Pn) by porous supergene violarite (Viol) along grain boundaries and microfractures; field of view 250 µm; from Grguric (2002)

Table 2. Microprobe analyses of MKD5 ore minerals using wavelength dispersive spectrometers (WDS)

	1	*2*	*3*	*4*	*5*	*6*	*7*
				Percentage			
Co	1.51	0.26	6.23	1.32	0.97	1.13	13.05
Fe	29.85	24.73	17.70	16.77	0.24	8.79	5.00
Ni	35.90	41.86	33.36	39.64	63.02	58.03	14.28
As	0.00	0.09	0.05	0.00	0.11	0.08	47.37
S	32.66	32.84	41.90	38.18	35.25	31.80	19.17
Total	**99.94**	**99.80**	**99.27**	**96.10**	**99.68**	**99.88**	**99.20**

NOTES: 1 Pentlandite from pentlandite–pyrrhotite assemblage, Unit 104 (MKD261 200.0 m)
2 Pentlandite from pentlandite – hypogene violarite assemblage, lowermost Unit 104 (MKD33 220.0 m)
3 Hypogene violarite from pentlandite – hypogene violarite assemblage, Unit 104 (MKD27 498.0 m)
4 Supergene violarite associated with supergene pyrite and relict pentlandite, Unit 104 transition zone (MKD100 140.0 m)
5 Millerite from millerite-only assemblage, Unit 102 (MKD146 270.3 m)
6 Godlevskite from godlevskite–millerite assemblage, Unit 102 (MKD16 252.0 m)
7 Cobaltian gersdorffite from talc–magnesite-altered zone, Unit 104 (MKD34 330.1 m)

equivalent in the MKD5 orebody (Grguric, 2002). Owing to incipient oxidation of sulfide mineral surfaces in the supergene zone, Ni flotation recoveries are significantly lower when treating supergene ores relative to hypogene ores of the same head grade.

Geological and genetic models for the deposit

Large dunite and peridotite bodies of komatiitic affinity containing disseminated NiS mineralization occur in several localities worldwide. Examples additional to MKD5 include the Goliath and Six Mile Well complexes at Yakabindie in Western Australia (Burt and Sheppy, 1975; Naldrett and Turner, 1977; Dowling and Hill, 1990, 1993); Dumont in the Abitibi Province, Canada (Eckstrand, 1975; Duke, 1986); and Hunters Road, Zimbabwe (Prendergast, 2001). These low-grade deposits (Type IIB classification of Lesher, 1989) are significantly different to the more widespread basal massive sulfide deposits, as exemplified by the Kambalda orefield system (Type I classification of Lesher, 1989). The latter are associated with well-developed spinifex-textured komatiites, and are interpreted as products of komatiitic lava flow fields (Gresham and Loftus-Hills, 1981; Lesher et al., 1984; Cowden, 1988).

In contrast to Type I deposits, the emplacement mode of Type II dunite bodies was originally interpreted as either horizontally emplaced sills (e.g. Dumont: Eckstrand, 1975; Duke, 1986) or vertically emplaced dyke complexes (e.g. MKD5: Burt and Sheppy, 1975; Six Mile Well: Naldrett and Turner, 1977). Later work by Barnes et al. (1988), Dowling and Hill (1990), and Hill et al. (1990) reinterpreted the dunite complexes of the Agnew–Wiluna belt as the product of giant lava channels capable of thermomechanically eroding their substrate. The lava channels were interpreted to represent the more proximal facies of Kambalda-style komatiite flow fields. However, the mode of emplacement of Type II deposits in the Agnew–Wiluna belt has been reinvestigated as part of the P710 AMIRA project, and the recognition of preserved upper contacts (Rosengren et al., in press), indicates that an extrusive model for the Eastern Ultramafic in the Mount Keith region is not tenable. A model involving shallow level intrusion into a submarine felsic volcanic sequence is now the preferred interpretation for the emplacement of the Eastern Ultramafic, with the Central Ultramafic possibly representing a comagmatic subaqueous extrusive analogue.

The style and grade of mineralization in Type IIB deposits is worth considering since sulfide mineralized zones in these deposits characteristically have grade distributions centred around 0.6 % Ni and very high Ni/Cu ratios (20–300; Groves and Keays, 1979). The regular distribution of sulfides as intercumulus blebs is interpreted to result from cotectic precipitation or crystallization of olivine cumulus crystals and a sulfide melt phase following sulfur saturation of the komatiitic melt phase (Duke and Naldrett, 1978; Duke, 1986). Although requiring a significant flux of undepleted magma within the ore-forming system, the sulfide formation process itself is relatively static in contrast to the dynamic sulfide entrainment and depositional processes invoked for the formation of massive and matrix sulfide segregations in Type I systems. The centring of the grade distribution at 0.6% Ni is interpreted to reflect the equilibration of the sulfide phase with surrounding cumulus olivine crystals carrying about 4000 ppm Ni and sulfur-saturated komatiitic silicate melt carrying about 2000 ppm Ni (Duke and Naldrett, 1978). The sulfur saturation state of the system depends on parameters such as the aFeO, $a\mathrm{SiO_2}$, $f\mathrm{S_2}$, $f\mathrm{O_2}$, temperature, and pressure of the melt phase (Naldrett, 1989), and variations in these parameters during the formation of the cumulate pile apparently controlled the distribution of sulfide mineralization throughout the MKD5 orebody. Rare occurrences of matrix and massive sulfides, notably in Unit 103, point to deviations from the equilibrium cotectic crystallization process and could reflect highly localized zones of more dynamic (Type I style) sulfide deposition. In contrast to Type I ores, Cu contents of the disseminated mineralization are low (typically 200–300 ppm in ore containing 0.6% Ni), which is consistent with formation via sulfur saturation and sulfide phase precipitation from relatively unfractionated, high-Mg melts (Duke and Naldrett, 1978). Likewise, PGE contents are low (110 ppb combined PGE in ore containing 0.6% Ni; see Table 1).

It is proposed that the starting composition of the intercumulus sulfide blebs was a simple, single phase *mss*. Slow, subsolidus cooling led to exsolution of magnetite in the form of well defined, coarse lamellae (‘crossbars’) and possible solid-state diffusive Ni exchange with host olivine grains. Further cooling below 600 ± 10°C resulted in exsolution of pentlandite from *mss* (see Naldrett et al., 1967). The low-temperature hydrothermal alteration resulted in conversion of some (or, in some cases, all) of the Fe component in the sulfide phases to one or more of the phases magnetite, ferroan magnesite, iowaite, tochilinite–valleriite, ferroan brucite, in the form of distinctive coronas on the blebs. Local fluid compositions and oxidation state dictate the phase that forms. The overall effect of converting a magmatic *mss*-type phase to millerite or heazlewoodite plus one of the abovementioned Fe-bearing gangue phases is a reduction in the particle size of the relict sulfide phase (assuming local scale Ni–Fe mass balance). This grainsize reduction naturally has implications for sulfide liberation during processing, hence, as a general rule, high tenor assemblages in Type IIB orebodies show lower sulfide recoveries relative to lower tenor (pentlandite–pyrrhotite) assemblages.

Regional greenschist facies metamorphism and deformation of the MKD5 deposit were probably not significant in modifying or redistributing nickel sulfide mineralization. During prograde deformation, the unserpentinized dunitic body apparently behaved rigidly, with strain being principally partitioned into surrounding wallrocks. Syn- and post-serpentinization deformation was accommodated by 'block shuffling' of ultramafic lithons along sheared and slickensided surfaces (Widdup, 2000). There is no strong evidence in the MKD5 deposit for hydrothermal remobilization of Ni beyond grain scales; apparent Ni depletion in talc–carbonate zones can be explained by the increase in the specific gravity of the host rock.

Importance of deposit in exploration models

Given current mining technology and metal prices, low-grade, high-tonnage deposits of the Mount Keith style generally need to be near surface and suitable for openpitting to be economic. The number of similar prospects lying within a 50 km radius of Mount Keith (Six Mile, Goliath, Honeymoon Well, Betheno) that, at the time of writing, are still unexploited >20 years after their discovery, is a testament to the narrow economic margins associated with mining and processing these types of deposits. Although all these deposits have large amounts of contained metal, the economics of mining and processing are highly sensitive to open-pit strip ratio, grade distribution, metallurgical parameters of the ore (particularly the proportion of mineralization affected by talc–carbonate and supergene alteration), and proximity to existing processing facilities. The large size and near-surface requirements for these deposits naturally limits exploration targeting options, and in a relatively well defined and heavily explored greenstone terrain, such as the Yilgarn Craton, the chances of a large, near-surface, Mount Keith analogue remaining undiscovered are relatively slim. However, this does not discount the possibility that undiscovered analogues could still remain in ultramafic complexes that are less well explored. Given their inherent low grade (with whole rock Ni contents only 2–3 times greater than those of typical unmineralized dunites), geochemical exploration for Type IIB deposits in highly weathered terrains presents special problems, which have been highlighted by Butt and Sheppy (1975), and Brand and Butt (2001).

From the viewpoint of brownfields exploration, it is perhaps worthwhile emphasizing the potential for some associated massive sulfide mineralization. It has been generally assumed that Type IIB deposits are not associated with massive sulfide segregations (Lesher, 1989), but recent drilling and mining at Mount Keith have shown that massive and matrix sulfide pods, albeit small (tens of tonnes), do occur in these systems.

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