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ARTICLE

Internal stratigraphic architecture of the komatiitic dunite-hosted MKD5 disseminated nickel sulfide deposit, Mount Keith Domain, Agnew-Wiluna Greenstone Belt, Western Australia

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Abstract The MKD5 nickel deposit is hosted by the Mount Keith Ultramafic Complex (MKUC), a dunite body of komatiitic affinity located in the Agnew-Wiluna Greenstone Belt, Western Australia. The internal architecture of the MKUC comprises seven distinct internal units that range from extreme adcumulate dunite to relatively fractionated pyroxenitic and gabbroic horizons. The MKUC is divided into three packages of units. The main adcumulate domain (MAD), which is situated in the lower portion of the complex, contains the bulk of disseminated nickel sulfide and is dominated by coarse adcumulate olivine textures. Overlying the MAD is an upper fractionated zone, which is dominated by mesocumulate-to-orthocumulate peridotite with domains containing oikocrystic pyroxenite and gabbroic lenses. An aerially restricted unit comprising texturally and chemically distinct olivine cumulate rocks is known as the western mineralized zone (WMZ). The fractionation trend between the MAD and UPZ indicates a westerly facing for the MKUC, conformable with the bounding stratigraphy. In the MKUC, truncation of some of the uppermost internal stratigraphic units by the hangingwall contact indicates that the unit has undergone structural modification since its emplacement and suggests that a proportion of the upper section has been removed by faulting. Furthermore, vertical and lateral textural transitions within the internal stratigraphy suggest that the MKUC (excluding the WMZ) was emplaced from an essentially continuous magma flow, with the MAD representing the period of highest magma flux and the major constructional period of emplacement. Conversely, the WMZ is interpreted to represent a later pulse of ultramafic magma, emplaced stratigraphically above the main MKUC. Comparison of the MKUC with other komatiitic dunites from both within the Agnew-Wiluna Greenstone Belt and worldwide indicates that despite apparent geometrical differences between lens and sheet komatiitic dunites, a broad facies architecture can be defined. We suggest that the differences in geometry are related to differing degrees of flow localization within dunitic units and are a function of both differences in the thermal characteristics and the degree of litho-facies heterogeneity of the enclosing lithologies.

Keywords Komatiite · Dunite · Archaean · Nickel-sulfide · Mount Keith · Australia

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Introduction

Large dunite bodies of komatiitic affinity occur in several localities worldwide and are largely restricted to Archaean greenstone belts. In addition, thick dunites represent a common feature in the Agnew-Wiluna Greenstone Belt (AWB) of Western Australia and locally host some of the largest komatiite nickel-sulfide (NiS) deposits in the world, such as Mount Keith, Perseverance, and Six Mile Well/

Yakabindie (Burt and Sheppy 1975; Naldrett and Turner 1977; Butt and Nickel 1981; Donaldson et al. 1986; Dowling and Hill 1990, 1993; Hopf and Head 1998; Hill 2001; Grguric and Rosengren 2004).

All the above-mentioned bodies have a minimum thickness of at least 800 m and host significant accumulations of low-grade, disseminated type-2 NiS (Lesher and Keays 2002). Sulfide mineralization occurs as small blebs interstitial to tightly packed olivine adcumulate, which typifies the large dunitic bodies. The low-grade NiS deposits are interpreted to form via cotectic crystallization of cumulate olivine and sulfide from a komatiitic melt (Duke 1986a).

The internal architecture of dunitic bodies is generally difficult to determine due to their large size, lack of exposure, and/or continuous drill coverage and overprinting of original textures by postemplacement alteration. However, at Mount Keith, the large amount of diamond drilling carried out for resource definition and production over the last 10 years, and large pit exposures, has allowed detailed delineation of the internal architecture of the komatiitic dunite. This study documents the complex internal architecture of the Mount Keith Ultramafic Complex (MKUC). Specifically, the aims of this paper are to (1) document the internal architecture of the MKUC, (2) illustrate that type-2 deposits are considerably more complex than just thick adcumulate pods, (3) compare and contrast the architecture of the MKUC with other komatiitic dunites in the AWB and worldwide, and (4) construct a facies model applicable to all komatiitic dunites, which includes geometrical and emplacement differences. This paper forms part 1 of a multidisciplinary study of the internal architecture, volcanology, geochemistry, and genesis of Mount Keith (cf. Fiorentini et al., this volume).

Geological setting

The MKUC forms part of the AWB, which is located in the northern section of the Eastern Goldfields Province, the eastern subdivision of the Archaean Yilgarn Craton, Western Australia. The AWB is the northern extent of the Norseman-Wiluna Greenstone Belt, which has a total strike length of greater that 650 km and is highly endowed in both orthomagmatic nickel and orogenic gold deposits (Hill et al. 1990).

The AWB trends NNW–SSE and is bounded to the east and west by voluminous Archaean granitoids and terrane-scale faults. The Mount Keith region is located within the most attenuated portion of the AWB, approximately 80 km south of Wiluna (Fig. 1). In the Mount Keith area, the greenstone sequence has a maximum thickness of approximately 6 km. The ultramafic portion of the greenstone stratigraphy comprises three komatiite units, locally designated the Mount Keith, Cliffs, and Monument Ultramafic units (Rosengren 2004; Grguric and Rosengren 2004) that can be traced 30 km north to Honeymoon Well and 9 km south to the Cliffs deposit (Fig. 1).

The Monument and Cliffs Ultramafic units are spinifex-bearing komatiite flows with basal cumulate zones as defined by Pyke et al. (1973) and Arndt (1986). The Cliffs Ultramafic unit hosts sporadic accumulations of type-1 basal massive Ni–Fe sulfide (e.g., the Cliffs NiS deposit: cf. Marston 1984). The Mount Keith Ultramafic unit contains no spinifex textures and is dominated by olivine ortho-to-mesocumulate rocks with several thick (>500 m) coarsegrained olivine adcumulate lenses with olivine crystal sizes up to 3.0 cm in size (Dowling and Hill 1990). The Mount Keith Ultramafic unit in the vicinity of the MKD5 nickel deposit is up to 800 m thick and is dominated by coarse olivine adcumulate textures. NiS occur interstitial to former olivine grains with an abundance of 3–5%. The typical sulfide mineralogy comprises pentlandite, pyrrhotite, pyrite and minor millerite, hypogene violarite, godlevskite, and heazlewoodite (Grguric 2003; Grguric and Rosengren 2004).

The three ultramafic units dip steeply (subvertical in places) to the west (Fig. 1), whereas igneous textures and geochemical trends indicate a westerly facing for the Mount Keith and Cliffs Ultramafic units. Local east facings in the Monument Ultramafic unit are attributed to a shallowly plunging, tight-to-isoclinal syncline (Bongers 1994). In the Mount Keith region, the ultramafic horizons are separated by a variably altered and deformed package of mafic and felsic rocks. A monotonous sequence of fine-grained mafic rocks of metabasaltic composition encloses the Monument and Cliffs Ultramafic units. Furthermore, the metabasalts are variably deformed and preserve no obvious igneous features, although deformed pillowed basalts have been observed at the Cliffs deposit, and in other areas of the AWB (Wallace 2003).

The felsic sequence is dacitic in composition and exhibits primary contact relationships with the Mount Keith Ultramafic unit (Rosengren et al. 2005). The dacitic rocks are interpreted as a series of submarine lavas with associated volcaniclastics (Rosengren et al. 2007). The large lateral extent and tabular nature of the felsic units is attributed to their emplacement in a deep marine environment under high hydrostatic pressure, significantly lowering their viscosity (Rosengren et al. 2007). Structural effects have complicated the stratigraphy in the vicinity of the MKD5 nickel deposit, removing portions of the dacitic unit and juxtaposing the MKU and mafic hangingwall. At the southern end of the current MKD5 pit and at several points between MKD5 and the Cliffs deposit, the Mount Keith and Cliffs Ultramafic units are in structural contact.

Komatiitic dunites such as the MKUC comprise greater than 95% modal cumulus olivine and display MgO contents greater than 40 wt.%. During emplacement at/or near the

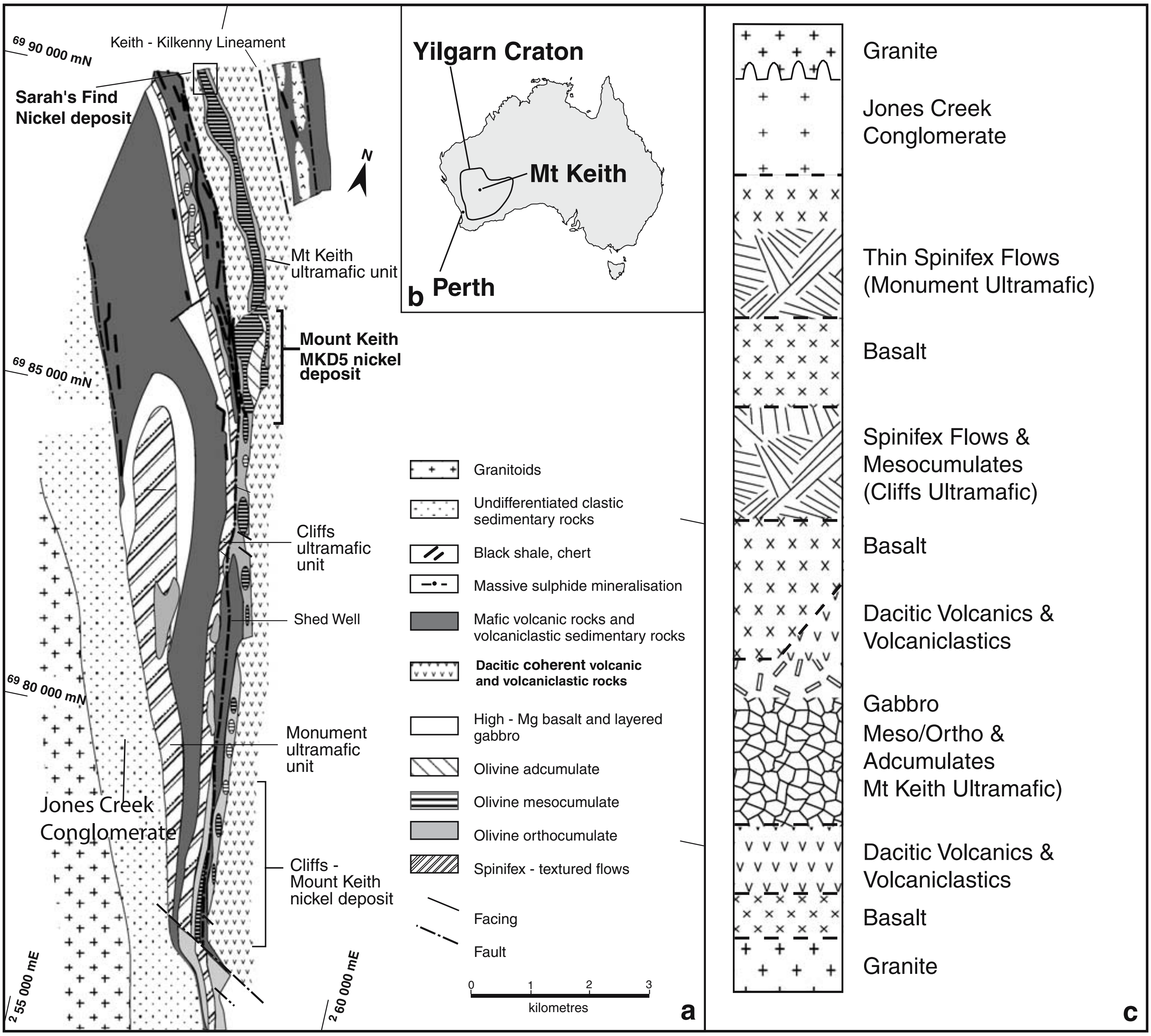


Fig. 1 **a** Local geology of the Mount Keith region displaying the three ultramafic horizons (modified after Dowling and Hill 1990). **b** Location of Mount Keith. **c** Stratigraphic column of the Mount Keith region

surface, komatiitic dunites are particularly susceptible to alteration in particular hydration and carbonation as a result of interaction with hydrothermal fluids. The alteration of dunites by H_2O- and CO_2-rich fluids was described by Eckstrand (1975) and is known as Eckstrand zonation. During hydration, forsteritic olivine is initially converted to a lizardite–brucite assemblage and the minor fayalitic component of the olivine is converted to magnetite, resulting in a characteristic high magnetic susceptibility. With increasing CO_2 content and fluid/rock interaction, the lizardite–brucite assemblage initially coverts to antigorite/magnesite and, finally, to talc/magnesite. Fluid permeates the dunite body along shears and fractures resulting in zoned alteration, with areas closer to shear zones (i.e., where the fluid/rock ratio is highest) displaying the most intense talc-carbonate alteration.

The MKUC has been completely serpentinized and talc-carbonate altered during a retrograde fluid infiltration event, which followed metamorphism to midgreenschist facies (Barrett et al. 1977; Rödsjö and Goodgame 1999). No primary olivine is observed in the MKUC; however, the serpentinization process is not texturally destructive. As a result, the majority of the MKUC displays excellent textural preservation, and olivine can be recognized from its textural features. For simplicity, the prefixes former and meta have been omitted from the rocks described in this paper. Although the component olivine and interstitial liquid have undergone the effects of serpentinization/carbonation and lower greenschist facies metamorphism, they are referred to in terms of their igneous protolith rather than their present altered state.

The internal architecture of the MKUC was first delineated by Burt and Sheppy (1975), who subdivided the MKUC based on the distribution of alteration, textural, and mineralogical features. Dowling and Hill (1990, 1993) and Hill et al. (1995) reassessed the Mount Keith region and refined the internal architecture on the basis of textural and chemical features. Several honors and PhD theses have been completed on various aspects of the MKD5 ore body (e.g., Fardon 1995; Seymon 1996; Brand 1997; Rödsjö 1999; Widdup 2000), along with several internal studies by Western Mining Corporation (WMC) Resources.

Previous stratigraphic models were in some cases only based on one or two sections through the MKD5 orebody. Conversely, the work presented in this paper was conducted synproduction with the MKD5 mine operation and benefited from access to a significantly larger database of drill-core and mine-related information in comparison to most previous studies. Specifically, this study is based on the detailed textural logging of >15,000 m of diamond drill-core. One significant outcome of this study is that the MKD5 displays a significant lateral variation along strike together with the previously documented vertical changes.

Relationship between the MKUC and enclosing stratigraphy

Work undertaken as part of this study (Rosengren et al. 2005) has revealed previously undocumented contact relationships between the MKUC and the stratigraphic dacitic hangingwall. The relationships displayed at the upper contacts are indicative of an intrusive relationship between the MKU and the enclosing dacite. These relationships, coupled with the lack of definitive extrusive features such as spinifex and flow-top breccias (Rosengren 2004), indicate that the MKUC has an intrusive origin. A more detailed description of the contact relationships and intrusive characteristics of the MKUC can be found in Rosengren et al. (2005).

Komatiitic dunite texture types

Komatiitic dunites in the MKUC display a range of olivine cumulus textures. Pyroxene- and plagioclase-bearing cumulate horizons are also present. Each textural variation displays unique packing and grain-size features. Olivine crystals also show a range of morphologies within the MKUC. Table 1 details the variations in texture types seen in the MKUC and their characteristic features, composition, proportion of intercumulus material (ICM) and crystal morphology.

Sulfide mineralogy

Details of the sulfide mineralogy and mineral chemistry of the MKUC have been given in Grguric (2002, 2003). Sulfide blebs range in size from 40 μm to 5 mm (average 0.5 mm) and are usually situated at the triple-point junctions of former cumulus olivine grains. These blebs consist of aggregates of Ni–Fe sulfide grains surrounded by a corona of magnetite, the outer margins of which are in most cases partially replaced by iowaite, chlorian pyroaurite (± tochilinite), or ferroan magnesite. A coarse network of magnetite "crossbars" is typically present within the blebs. Sulfide abundances in ore-grade material are usually in the 1–5% range.

The sulfides were originally deposited as single-phase monosulfide solid solution (MSS) and modifications to sulfide phase relations were subsequently driven by (1) cooling and exsolution, resulting in breakdown of MSS into pentlandite and pyrrhotite, and (2) hydrothermal alteration under varying $fO2$ and $fS2$ conditions, resulting in modifications to sulfide/gangue phase relations. These modifications commonly involve partial or complete conversion of the Fe component of the assemblage to a magnetite or ferroan magnesite corona. The resultant sulfide is thus enriched in Ni leading to the stabilization of nonmagmatic phases such as millerite and heazlewoodite.

Within talc-carbonate-altered zones, the fO_2 and fS_2 of fluids attending talc-magnesite alteration has resulted in the stabilization of pyrite. Existing pyrrhotite–pentlandite assemblages are usually preserved, with the addition of some hydrothermal pyrite. Talc-magnesite alteration is magnetite destructive, and consequently, the magnetic susceptibility of this alteration type is very low. Most talc-altered ore contains elevated levels of arsenic (30–7,000 ppm) as a consequence of the arsenic content of the alteration fluid. At low levels of whole-rock As (<500 ppm), Fe- and Fe–Ni-sulfide minerals appear to host arsenic in solid solution or as submicroscopic inclusions. At higher As levels, discrete arsenic-bearing opaque minerals such as gersdorffite (NiAsS), nickeline (NiAs), cobaltite (CoAsS), and maucherite ($Ni_{11}As_8$) are frequently observed. These minerals commonly form replacements of preexisting pyrrhotite and pentlandite.

Architecture of the MKUC

The MKUC internal architecture model has undergone continual refinement by WMC/BHP Billiton geologists, particularly in relation to defining the ore geometry. More recently, the internal architecture was redefined (Grguric and Rosengren 2004) into numerical codes representing the different units (units 101 to 107) and was based on a combination between texture logging and 3D mapping of a large geochemical database. During the WMC study, a broad

Table 1 Texture types in the MKUC

Texture type	Crystal size	Crystal shape	% ICM	Al_2O_3% approx.	Composition	Degree of supercooling	Growth method
Extreme adcumulate (EOAD)	1 cm to 3 cm	Equant to elongate. Primarily controlled by 120° triple-point junctions	0 to 2	0 to 0.5	Olivine, minor sulfide, chromite and ICM	Very low	Cumulus crystallization
Adcumulate (OAD)	3 mm to 25 mm	Equant to elongate. Primarily controlled by 120° triple-point junctions	0–3%	0 to 0.5	Olivine, sulfide 0–5% minor chromite and ICM	Very low	Cumulus crystallization
Mesocumulate (Omc)	1 mm to 1 cm	Equant to elongate Euhedral to subhedral	3–25%	0.5 to 1%	Olivine, ICM minor sulfide and chromite	Low to moderate	In situ growth and crystal sedimentation
Orthocumulate (Ooc)	1 mm to 1 cm	Equant to elongate Euhedral to subhedral	>25%	>1%	Olivine ICM	Moderate	Crystal sedimentation and in-situ growth
Olivine/Pyroxene cumulate (Upx)	2 mm to 1 cm	Tabular and ragged aggregates	–	>1.5%	Olivine, pyroxene, ICM pyroxenitic glass	–	Cumulus crystallization
Skeletal olivine	5 mm–3 cm	Hollow to partially enclosed “hopper” crystals	–	–	Olivine	High	Temp/nutrient/ H_2O controlled
Harrisitecrescumulate	2 mm–4 cm	Branching/dendritic	25–50%	3–3.5%	Olivine	High/very high	Temp/nutrient/ H_2O controlled
Gabbro	2 mm to 2 cm	Equant to elongate euhedral to subhedral	–	12–18%	Pyroxene and plagioclase ± olivine ± Qtz	–	Equilibrium crystallization

Important features of each texture in the determination of separate units are the crystal size and shape, along with the approximate Al2O3 content

correlation between Al_2O_3 and TiO_2 and textural varieties was established within the MKUC, analogous to that previously identified in the Dumont complex by Duke (1986a).

The lowermost ultramafic unit in the Mount Keith stratigraphy is the “early flows” of Dowling and Hill (1990), a thin komatiite unit originally interpreted to be a series of komatiite flows in the dacitic footwall of the main complex. The MKUC, sensu stricto, comprises a basal olivine orthocumulate layer (unit 101) overlain by a thick, weakly mineralized, extreme olivine adcumulate (unit 102). Unit 102 is overlain by an olivine adcumulate with significant interstitial NiS mineralization designated unit 104. A discontinuous lensoidal olivine pegmatoid unit, known as pegmatoid/porphyritic olivine rock (POR) or unit 103, crosscuts units 102 and 104. Unit 104 grades upwards into an olivine mesocumulate designated unit 105a, which grades into the fractionated pyroxene- and gabbro-bearing unit 105B. The northwestern portion of the MKUC comprises a second olivine cumulate-bearing domain designated the western mineralized zone (WMZ). The WMZ contains units 106 and 107, which are olivine mesoadcumulate and orthocumulate, respectively. Towards the south, structural effects detailed in the following sections have complicated matters, and the uppermost unit is unit 105A. Table 2 summarizes the internal stratigraphic units of the MKUC and their distinctive textural features and mineralogy.

Methodology

This study carried out detailed textural logging of 49 diamond drill-cores throughout the MKUC and utilized geochemical assay data to discriminate subtle textural and petrographic variation among the various lithotypes. Specifically, Al_2O_3 and TiO_2 profiles were utilized to correlate the geochemical and textural architectures of the MKUC. As Al and Ti are incompatible in olivine during crystallization, they concentrate in the residual melt; therefore, cumulate rocks with a greater percentage of residual melt (i.e., orthocumulate) generally have higher Al_2O_3 and TiO_2 levels (Duke and Naldrett 1978; Duke 1986a). Importantly, Al_2O_3 and TiO_2 are relatively immobile during serpentinization and moderate talc-carbonate alteration. The textural variations in the MKUC are thus reflected in the Al_2O_3 and TiO_2 levels.

The broad chemical definitions of the three texture types are adcumulate=<0.5% Al_2O_3, mesocumulate=0.5–1.0% Al_2O_3, and orthocumulate=>1.5% Al_2O_3. Significant fluc-

Table 2 Summary of internal architecture of the MKUC as determined during this study: defining textures from each unit are listed, together with textural and compositional features

Div 1	Numerical code	Defining texture	Textural features	Crystal size	Composition	Typical Al_2O_3 %
WMZ	107	Bimodal orthocumulate	Equant to elongate crystals. Bimodal character increases northwards. Skeletal and harrisitic horizons common	Unimodal=2–4 mm Bimodal small=2–3 mm large=5–10 mm	Olivine ± pyroxene ± stitchtite ± bastite ± sulfide	1–1.5%
	106	Bimodal ad/mesocumulate	Equant to elongate bimodal adcumulate/mesocumuate. Contains numerous thin skeletal olivine horizons and pyroxenitic to gabbroic fractionates	Unimodal=2–8 mm Bimodal Small=2–4 mm large=8–10 mm (rare to 15 mm)	Olivine ± pyroxene, ± sulfide, ± stitchtite ± phlogopite	0.3–0.5%
MAD	105A	Orthocumulate	Poorly formed to subhedral olivines, some interstitial bastite		Olivine ± bastite, ± stitchtite	0.5–1%
	105B	Orthocumulate pyroxenite		1 to 5 mm	Olivine, pyroxene, bastite ± plagioclase ± stitchtite	~2%
	105C	Orthocumulate	Poorly formed to subhedral olivines some interstitial bastite		Olivine ± bastite, ± stitchtite	0.5–1%
	104	Adcumulate	Equant to elongate adcumulate containing 5–6% interstitial sulfide. Rythmic layering defined by changes in crystal size, morphology and sulfide abundance. Crystal shape primarily controlled by 120° triple-point junctions	2 to 25 mm ave=8–10 mm	Olivine ICM sulfide stitchtite	0–0.5%
	103	Porphyritic skeletal	Crosscutting horizon comprised of individual lenses of skeletal, harrsitic and ameboid olivine in a bastite matrix. transgresses 102/104 boundry. Rarely plagioclase may form matrix component	up to 5 cm	Olivine, bastite, zircon, monazite, ilmenite, rutile, baddelyite, plagioclase, phlogopite	2–18%
	102	Extreme adcumulate	Equant to slightly elongate extremely coarse olivine adcumulate. Very low % of ICM. Contains regular zones up to 1 m wide with fine scale cyclic layering of olivine grains and 3–5 mm of ICM. Crystal shape primarilly controlled by 120 triple-point junctions	1 to 3 cm ave=2–2.5 mm	Olivine ICM sulfide stitchtite	0–0.2%
	101	Orthocumulate	Equant euhedral to slightly elongate with rounded terminations. Rythmic layering to thin (2 m) adcumulate horizons is common	1 to 5 mm ave=3–4 mm	Olivine minor stichtite and sulfide	0.5–1%

tuations in Al_2O_3 levels generally reflect the presence of either primary pyroxene- or feldspar-bearing fractionates, or intensely talc-carbonate altered shear zones. Between each of the internal units, the internal stratigraphy of the MKUC displays transitions, which can be sharp (occurring over <1 m) or gradational (over 10–15 m). The gradational nature is well illustrated by the curved Al_2O_3 traces across these boundaries, reflecting the incremental change in the amount of trapped liquid. However, not all profiles show curved traces across boundaries: in particular, the transition between units 105 and 106 is generally represented by a sharp saw-tooth-type boundary. Previously, this distinctive geochemical trace has been interpreted to represent a boundary between successive lava flow units, with the increasing Al_2O_3 levels representative of a flow-top and the sudden drop indicating a fresh pulse of magma.

The detailed textural data have been combined with the geochemical data to produce a detailed representation of the internal architecture of the MKUC projected to the 300 and 400 m Relative Level (RL) (Fig. 2). The original numerical codes have been retained with the addition of some subdivisions. The new architecture work presented here has highlighted the complexities of the internal stratigraphy of the MKUC and the geometries of the faulted contacts between the MKUC and the basalt hangingwall. In the following sections, the textures, mineralogy, and geometry of each lithological unit will be described individually.

Basal apophyses ("early flows")

The "early flows" of Dowling and Hill (1990) were originally interpreted to occur below the main MKD5 ore body and had been identified in three diamond drill holes only (MKD66, MKD89, and UMKD3B). Recent work by Hayward (2004) on pit exposures indicated that the early flows represent a small protrusion from the lower portion of the MKUC sensu stricto into the dacite footwall, which has subsequently been deformed. The lower portion is dominated by fine-to-medium-grained olivine orthocumulate and locally mesocumulate. The orthocumulate is overlain by a unit displaying very coarse skeletal olivine morphologies. Rare spinifex-textured domains occur and are dominated by patchy, random spinifex, with a very small zone (approximately 1 m thick) of apparent plate Spinifex (nomenclature of Pyke et al. 1973).

The early flows are overlain by porphyritic dacite lavas, which separate them from the Mount Keith Ultramafic unit; the same unit is also present beneath the early flows. In light of the new structural constraints, the early flows will be referred to as the basal apophyses from here on.

Unit 101 (basal orthocumulate)

Unit 101 is the lowermost stratigraphic unit of the Mount Keith Ultramafic unit in the MKD5 region, and is present along its lower contact.

Textural features

Unit 101 is texturally an olivine ortho-to-mesocumulate, although exact determination of the textural type is commonly difficult due to alteration and/or structure. Olivine crystal size within the unit ranges from 1 to 5 mm, with an average size of 3–4 mm. Olivine crystal shapes range from equant euhedral to slightly elongate with rounded terminations. Interstitial material is composed of a fine-grained aggregate of serpentinite ± chlorite. Texture varies throughout the unit, with rhythmic layering between the fine orthocumulate and thin (2–4 m) horizons of coarse adcumulate common. The adcumulate layers within unit 101 have crystal sizes ranging 3–10 mm, but textural preservation is typically poor.

Vertical and lateral variations

Unit 101 is difficult to trace without ambiguity along the entire length of the MKUC due to intense talc-carbonate alteration and structural overprints in the lower portions of the ultramafic body. The transition of unit 101 to the overlying unit 102 is generally marked by a zone of intense shearing and texturally destructive talc-carbonate alteration. However, despite the generally poor preservation, the nature of the transition can locally be determined.

The transition is marked by the sudden appearance of fine-grained olivine occurring interstitial to the coarser (2.5–3 cm) and tightly packed olivine, which characterizes unit 102. The transition zone can be 5–15 m wide and has a distinct bimodal texture due to the two olivine grain-size populations. The base of the transition zone is where intense shearing generally occurs. The base of the transition zone is marked by a sharp drop in grain size to an average of approximately 3 mm and an increase in interstitial material to produce an olivine ortho-mesocumulate. The basal contact of unit 101 with the felsic sequence in the footwall is generally affected by shearing and/or intense talc-carbonate alteration, which has obscured or destroyed all original contact features.

Finally, no significant occurrence of magmatic sulfides has been recorded in unit 101; however, secondary heazlewoodite and godlevskite occur as fine blebs (10–100 μm) within former olivine grains. These sulfides are formed as a consequence of the interaction between original silicate Ni in olivine and reduced-sulfur-bearing hydrothermal fluids responsible for serpentinization and talc-carbonate alteration (Grguric 2002).

Unit 102 (extreme olivine adcumulate)

Unit 102 unit overlies the unit 101 basal orthocumulate throughout the MKD5 area. Unit 102 has a maximum thickness of 330 m in the vicinity of 31,600 mN (Mount Keith Mine Grid). Magmatic NiS mineralization is present in unit 102, and is dominated by sulfide assemblages containing pentlandite, millerite, hypogene violarite, godlevskite, and heazlewoodite (Grguric 2002, 2003). In unit 102, the occurrence of a bimodal sulfide grainsize distribution, consisting of intercumulus sulfide blebs (80–700 μm) and fine (1–20 μm) "cloud" sulfide, which occurs as inclusions within former olivine grains, is related to the high level of hypogene alteration, with the bulk of the unit being antigorite–magnesite altered.

The modification to gangue mineral chemistry during hydrothermal alteration resulted in corresponding modifications to the primary magmatic sulfide assemblages (e.g., Eckstrand 1975) and conversion of silicate Ni to fine cloud sulfide. Magmatic (ore grade) mineralization in unit 102 occurs as discrete pods that are laterally extensive along the depth extent of the unit and are associated with elevated Cu (100–900 ppm) and Platinum Group Elements (PGE) (combined 100–700 ppb). Outside of these ore pods, magmatic blebs are absent, and the adcumulate typically contains 0.35–0.4% Ni, reflecting a silicate Ni component alone. Copper and PGE grades are correspondingly very low.

Textural features

Unit 102 is characterized by tightly packed olivine adcumulate with crystal sizes up to 3 cm and an average of approximately 2.5 cm. This texture has been denoted as an extreme olivine adcumulate due to its very coarse grain size and tight crystal packing. The tightly packed nature of this unit (Fig. 3a) prevents the formation of euhedral olivine grains, and crystal shapes are controlled by 120-degree, triple-point junctions. The tight grain packing also constrains proportion of ICM, which is generally very low throughout unit 102.

Within unit 102, there are numerous randomly distributed zones up to 1 m wide, which display fine-scale cyclic layering of coarse adcumulate grains and 3–5 mm of ICM (Fig. 3b). The layered zones are roughly parallel to the strike of the MKD5 unit and the broad internal stratigraphy. Stichtite (after magmatic chromite) occurs throughout unit 102 as lobate to poikilitic grains (up to 1 cm) whose morphology is controlled by the surrounding olivine crystal shapes (Fig. 3c). Where magmatic sulfide grains are present, they tend to be flat and angular due to the close packing of the surrounding olivine crystals.

Vertical and lateral variations

Unit 102 occurs along the entire strike length of the MKUC with a varying thickness and geometry (Fig. 2). The unit attains the maximum thickness of ca. 330 m between 31,500 and 31,600 mN (Mount Keith Mine Grid). Conversely, unit 102 thins significantly to the south of 31,400 mN, where it attains a minimum thickness of approximately 40 m (Fig. 2). Despite the variations in thickness, unit 102 generally exhibits extreme adcumulate texture development in all areas, even within the thinner southern portions of the unit.

As described above, unit 102 displays a gradational transition into the underlying unit 101; the nature of this transition is similar along the length of the MKD5 ore body and varies in thickness between 5 and 15 m. The transition between unit 102 and the overlying unit 104 is marked by a decrease in grain-size and packing density and the appearance of continuous interstitial sulfide in unit 104 (dominated by pentlandite–pyrrhotite assemblages). The contact between unit 103 and unit 104 is a sharp transition occurring over 1–2 m: The change from extreme olivine adcumulate to adcumulate is the most visually striking feature.

Fig. 2 Internal architecture of the MKUC projected to 300 m RL. ▶ **a** Illustration of a 2D plan view of the MKUC. Due to steep dip, this view is essentially a cross section through the entire complex. **b** Schematic log of MKD276 illustrating internal subdivisions and Ni content through the MKUC. Note the elevated Ni values within unit 104. **c** Schematic log of MKD297 illustrating internal subdivisions and correlations with changing Al_2O_3 values. Note significant thinning of unit 104 relative to MKD276. **d** Composite section of two holes MKG45 and MKG56. Note the presence of dacitic hangingwall and footwall and correlation of Al_2O_3 peaks with pyroxene-rich horizons. **e** Schematic log of MKG 59 illustrating architecture of the northern portion of the MKUC. The highly irregular nature of the Al_2O_3 profile reflects the increasing proportion of pyroxene and harrisite-rich horizons in this region. The *heavy line* gives an indication of the basic shape of the geochemical profile

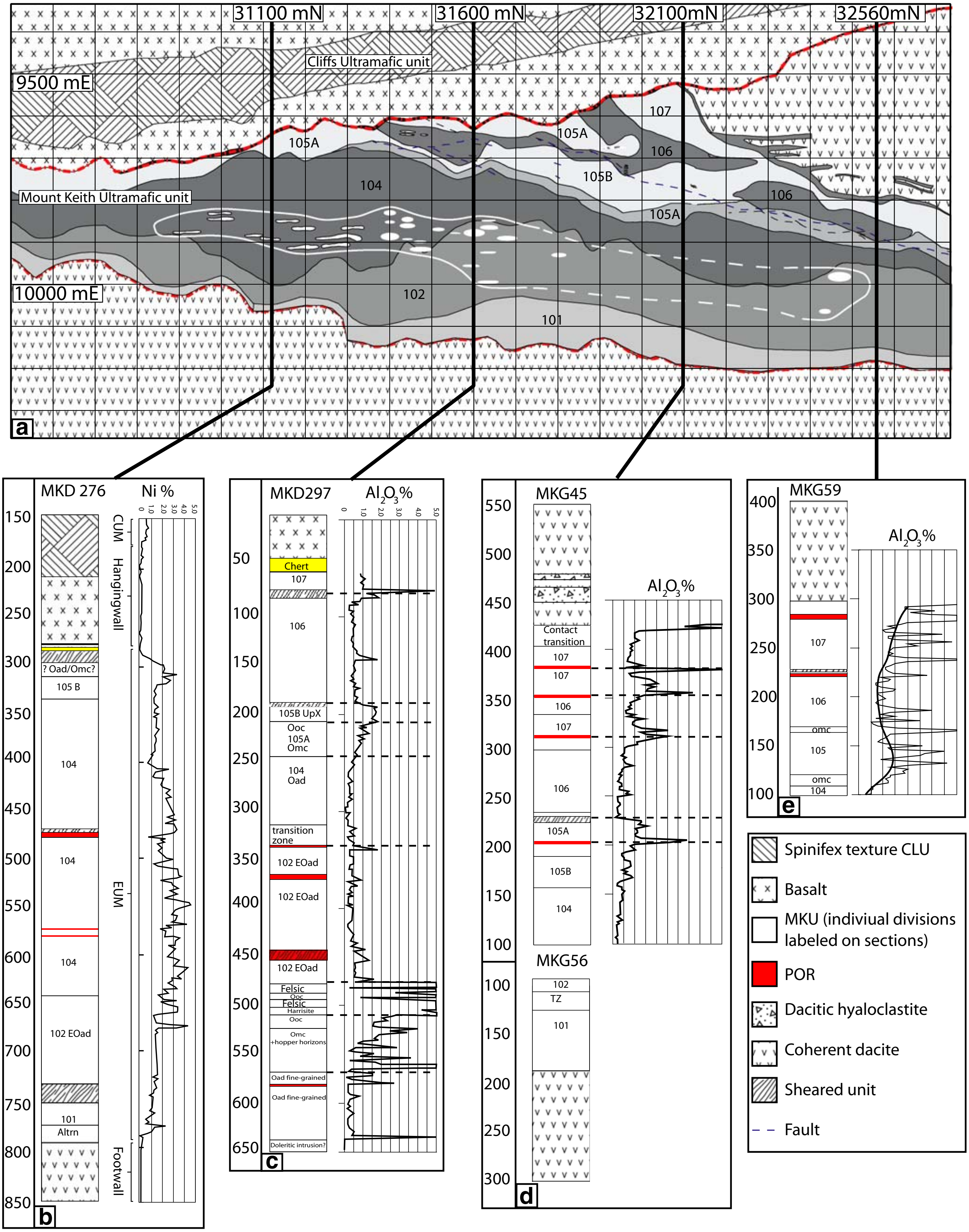
In the northern portion of MKD5 (31,500 to 31,700 mN), numerous veins or dykelets of POR (described in following section) occur at the boundary between units 102 and 104. Earlier work considered this unit as a marker horizon defining the boundary between units 102 and 104 in all areas. However, detailed work undertaken during this study shows that the POR transgresses the contact (Fig. 2). Finally, the abundance of sulfides is highly variable throughout unit 102, with high-grade (0.6–0.8% Ni) pods occurring in the upper portion of the thicker northern section.

Unit 104 (main ore adcumulate)

Unit 104 is roughly located in the center of the MKUC and hosts the bulk of the mineralization in the MKD5 deposit. The current open pit mine design is thus optimized on the geometry of this unit.

Textural features

Unit 104 is characterized by medium-to-coarsely crystalline olivine adcumulate, which contains 5–6% sulfide as small blebs interstitial to olivine crystals (Fig. 3c,e). Olivine crystal sizes range 0.2–2.5 cm and are dominated by an average grain-size of 0.8–1 cm, with lesser 0.2–0.4 cm crystals filling smaller spaces among larger crystals. Typically, olivine crystals within unit 104 are equant with ragged terminations, as crystal shapes are controlled primarily by 120-degree, triple-point junctions among adjacent crystals. Euhedral crystals are generally rare. The major textural variation is a pronounced change in crystal morphology from equant crystals to preferential elongation along one axis. The elongate crystals have aspect ratios of approximately 1.5–2 and have ragged terminations similar to the equant grains. The long axes of olivine crystals


31100 mN
31600 mN
32100mN
32560mN
Cliffs Ultramafic unit
9500 mE
Mount Keith Ultramafic unit
10000 mE
105A
104
105B
106
107
102
101
a
MKD 276
Ni %
CUM
Hangingwall
EUM
Footwall
? Oad/Omc?
105 B
102 EOad
101
Altrn
b
MKD297
Al2O3%
Chert
107
106
105B UpX
Ooc
105A
Omc
104
Oad
transition zone
102 EOad
Felsic
Ooc
Harrisite
Omc +hopper horizons
Oad fine-grained
Doleritic intrusion?
c
MKG45
Contact transition
MKG56
102
TZ
101
d
MKG59
omc
105
e
Spinifex texture CLU
Basalt
MKU (indiviual divisions labeled on sections)
POR
Dacitic hyaloclastite
Coherent dacite
Sheared unit
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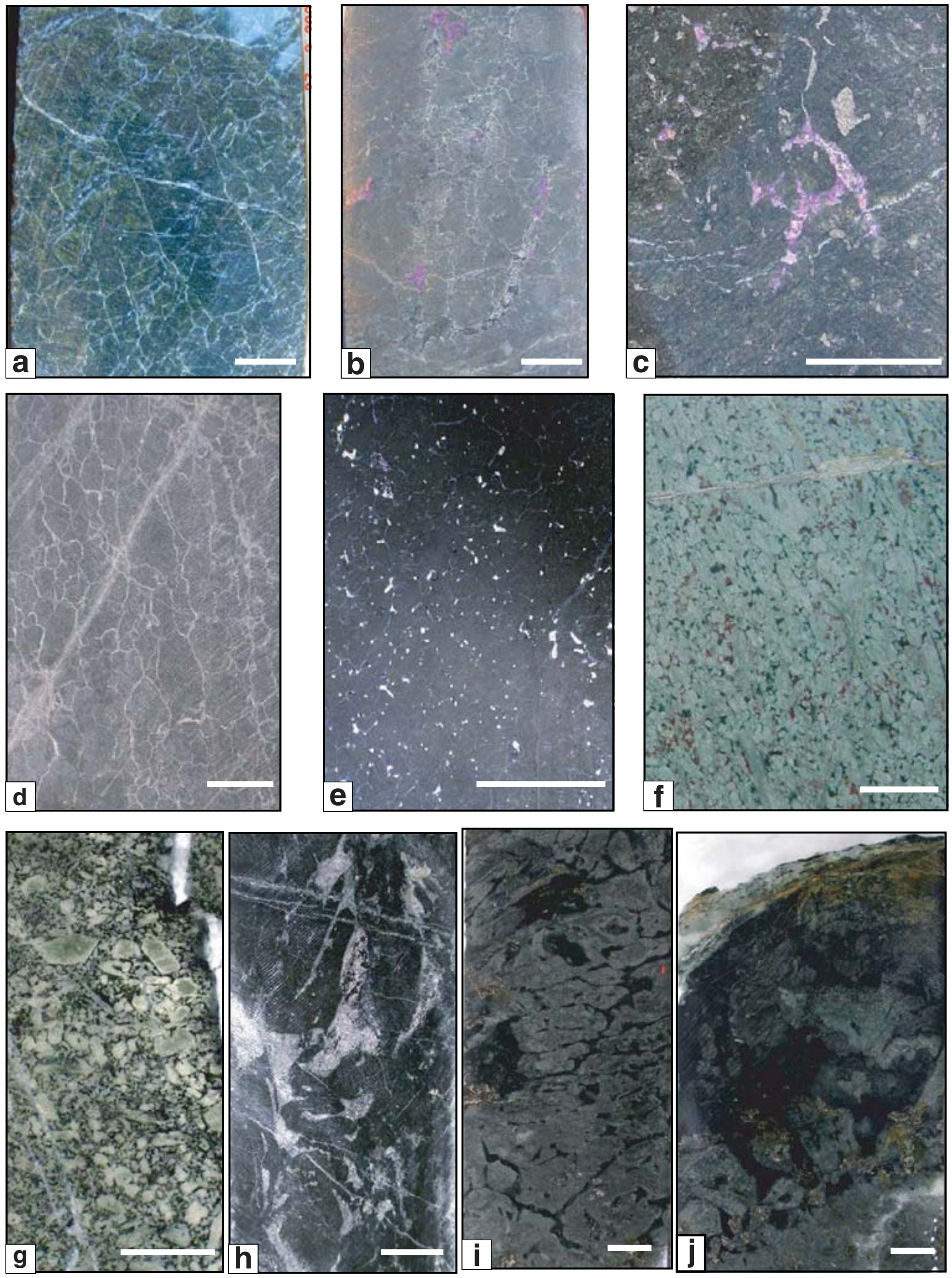


Fig. 3 Texture types in the Mount Keith Ultramafic unit. All *scale bars*=1 cm. **a** Extreme olivine adcumulate in unit 102. Note tight packing and large olivine crystals. **b** Unit 102 olivine adcumulate with layers of ICM. **c** Poikilitic stichtite (after chromite) in 102. **d** Tightly packed, elongate olivine adcumulate in unit 104. Note elongation of olivine and absence of sulfide. **e** Typical ore material from unit 104, olivine-sulfide meso- to adcumulate. Note smaller, more equant olivine crystals compared to previous photo. **f** Mesocumulate from unit 105A. **g** Orthocumulate from unit 105B. **h** Skeletal olivine in unit 107. **i** and **j** POR from unit 103. Note the large crystal size and skeletal-to-hopper form

display a strong alignment, and in the majority of cases the long axis is oriented roughly perpendicular to the gross layering of the MKUC. However, in rare places, an alignment parallel to the gross layering is also observed. Similar features were noted at Six Mile Well by Hill et al. (1990).

The change in crystal shape occurs over intervals as short as a few tens of millimeters and shows a strong correlation with change in abundance/absence of interstitial sulfides (Fig. 3d,e). A similar relationship is noted between crystal size and sulfide abundance. Typically, in sulfide-poor layers, olivine crystals are larger (up to 2.0 cm) than in areas with abundant sulfide mineralization (crystal size 8–10 mm). Sulfides are crudely layered throughout unit 104, generally on a scale of tens of centimeters; in this pattern, sulfide-poor layers show a consistently coarser olivine grain size. Sulfides occur interstitial to olivine grains and range in size from 0.5–4 mm. Sulfide blebs, which generally display lobate morphologies, may be equant or elongate depending on the morphology of the enclosing grains.

The sulfide mineralogy of unit 104 can be classified into two key types: (1) selvage zone assemblages and (2) core zone assemblages. Selvage zone assemblages occur in relatively thin (ca. 10–40-m-wide) zones adjacent to the contacts with units 102 and 105. They are characterized by whole-rock S/Ni ratios <1 and sulfide assemblages dominated by pentlandite, hypogene cobaltian violarite, and minor pyrite. The sulfide textures and mineral chemistry of these zones was described in detail by Grguric (2002). Core zone assemblages make up the bulk of the mineralization within unit 104 and are dominated by sulfide blebs consisting of coarsely intergrown pentlandite and pyrrhotite and whole-rock S/Ni >1. Partial to complete hypogene replacement of pyrrhotite by a lamellar intergrowth of pyrite–marcasite–magnetite is extremely common in this unit.

Secondary minerals that replaced chromite (e.g., stichtite, woodallite: cf. Barnes 1998, 2000) are also present throughout unit 104, occurring interstitial to olivine as both euhedral grain shapes and as lobate/poikilitic aggregates up to several centimeters in size (cf. Fig. 3c). The bulk of unit 104 is altered to an intimately intergrown lizardite–brucite–hydrotalcite group assemblage, which is characteristically black in color due to the presence of finely distributed magnetite. The hydrotalcite group minerals are dominated by compositions along the iowaite–pyroaurite join (Grguric 2003) and generally occur as stockworks of cross-fiber veins (5–10 mm wide) throughout unit 104.

Vertical and lateral variations

Unit 104 is present throughout the strike length of the MKD5 deposit: the geometry of the unit is dominated by two ovoid-shaped zones of thickening. The larger of the thickened zones attains a maximum thickness of >300 m at 31,100 mN. Unit 104 thins to <100 m by 30,800 mN and to <50 m in the vicinity of 32,000 mN. The second ovoid thickens to approximately 150 m at 32,000 mN and thins to approximately 40 m by 32,500 mN. Within unit 104, the textural layering defined by olivine crystal shapes and sulfide abundance occurs on a scale of centimeters to meters; however, the dominant textural form is equant olivine ranging 8–10 mm in size with 4–6% intestinal sulfide and stitchtite.

The upper boundary of unit 104 is marked by a sharp transition from olivine adcumulate to the mesocumulate unit 105B. Approaching this boundary, the grain size within unit 104 drops from 5–8 mm to 1–2 mm and the texture develops a distinct bimodal character. The boundary is defined by a relatively abrupt increase in the amount of ICM and is reflected by the steady increase in the levels of Al_2O_3 and TiO_2 (Fig. 2). Thin (ca. 50 cm) horizons of very coarse skeletal olivine locally occur near the boundary. Interstitial sulfide mineralization associated with unit 104 stops abruptly over the transition to unit 105B.

Unit 105 (upper fractionate zone)

Unit 105 comprises three subdivisions, which are divided on the basis of texture, composition, and chemistry and denoted as units 105A, B, and C. Units 105A and B are the most widespread throughout the MKUC, whereas unit 105C is sporadically developed.

Textural features

Unit 105 displays a continuous transition from tightly packed olivine mesocumulate (Fig. 3f) through to loosely packed olivine orthocumulates (Fig. 3g) with significant amounts of oikocrystic pyroxene and back to olivine mesocumulate. The internal subdivision of this unit is based partially on this textural variation. The gradational transition from mesotoorthocumulate and olivine pyroxene cumulate is reflected in the smooth curving increase in the levels of Al_2O_3 from the lower unit 105A to unit 105B (Fig. 2c).

The mesocumulate unit 105A is the lowermost unit and is in direct contact with the underlying unit 104. Olivine crystals are dominantly equant with poorly formed to rounded terminations; crystal size ranges from 1–5 mm. Interstitial material is dominated by fine-grained serpentinite, although thin (ca. 2 mm) bastite-rich areas are common. Unit 105B comprises loosely packed olivine orthocumulates of varying crystal size and shape. Olivine crystals range from 2–10 mm in size and display ragged morphologies. Unit 105B also contains pyroxene-rich horizons, which comprise significant amounts of oikocrystic pyroxene enclosing olivine crystals. Within the unit 105B horizons, there are gabbroic segregation domains, which comprise pyroxene and oikocrystic plagioclase.

Unit 105 locally contains significant amounts of intercumulus stichtite (after chromite), with Cr concentrations of up to 6,000 ppm. The abundance of stichtite and high Cr levels is typical of unit 105. Unit 105C is not widely developed or preserved in the MKUC. It contains both olivine ortho- and mesocumulate textured rocks with anhedral olivine crystals ranging in size from 1 to 10 mm. Zones of oikocrystic pyroxene enclosing olivine are present in unit 105C. The origin of unit 105C is uncertain and is discussed in the following sections.

Vertical and lateral variations

Unit 105 is transitional across its entire vertical thickness, from olivine mesocumulate in unit 105A to fractionated olivine pyroxene cumulate and gabbroic segregations in unit 105B. The thickness of unit 105 ranges between 40 and 130 m and is thickest at 32,100 mN. The unit is underlain by unit 104 in all areas of the MKD5 deposit. However, the upper margin of unit 105 varies along the strike length of the deposit (Fig. 2). In the southern portion (30,100 to 31,350 mN) of MKD5, unit 105 forms the uppermost unit of the MKU, where it is in sheared contact with the mafic hangingwall sequence. North of 31,350 mN, unit 105 is overlain by unit 106, an adcumulate-textured unit.

The boundary with unit 104 is gradational from adcumulate (104) to mesocumulate (105A) and is defined by an increase in ICM and a decrease in grain-size from 8–10 mm down to 3–5 mm. A continuing increase in ICM marks the transition into the more evolved core of the unit (105B). Unit 105C appears to have a gradational contact with unit 105B and into unit 106. However, a significant shear zone has nucleated on this contact, which typically obscures and/or removes unit 105C, juxtaposing units 105B and 106 (Fig. 2).

Unit 106 (WMZ adcumulate)

Unit 106 is located at the center of the WMZ and is dominated by adcumulate textured dunite. Interstitial NiS mineralization occurs within the WMZ adcumulate; however, sulfide mineralization in the WMZ has significantly lower tenor (i.e., S/Ni ratios >3) than mineralized zones in units 102 and 104. In unit 106, sulfide assemblages are dominated by pyrrhotite and pentlandite, with partial to complete hypogene replacement of pyrrhotite by a lamellar intergrowth of pyrite–marcasite–magnetite. Sulfide grain size is relatively coarse and locally reaches 5 mm.

Textural features

Unit 106 displays a large number of textural variations throughout the MKUC (Fig. 4). Textures generally include unimodal olivine adcumulate, bimodal adcumulates, mesocumulates, crescumulate/harrisite, and gabbroic domains. Unimodal adcumulates generally comprise equant olivine crystals. In less tightly packed domains, well-formed crystal terminations are visible, although the majority of crystals are rounded with poorly formed terminations. In more tightly packed examples, most crystal shapes are controlled by 120-degree, triple-point junctions. Crystal size within equant adcumulates ranges between 4 and 10 mm, with an average of 8 mm.

Bimodal textured adcumulates occur regularly in unit 106 and generally comprise tightly packed olivine crystals of two distinct size fractions: a smaller 2–4-mm fraction and larger fraction of 8–10 mm (rare examples up to 15 mm). The larger olivine crystals are evenly distributed throughout a matrix of the finer fraction. The larger crystals can be elongated slightly along one axis and generally have well-formed terminations. The long axis of the large grains is generally aligned; the fabric orientation is roughly parallel to the large-scale layering of the MKD5. The smaller olivine grains are equant with poorly formed terminations. Bimodal textured adcumulate are less tightly packed than their equant equivalents, albeit only slightly.

Unit 106 locally grades to olivine mesocumulate, particularly at the borders of harrisitic horizons. The mesocumulate layers are relatively thin (4–5 m) and occur in both the equant and bimodal adcumulate. Due to the relatively minor increase in ICM, the mesocumulates are texturally similar to the adcumulates surrounding them. Crescumulate-textured units occur as thin (ca. 20–30-cm-thick) horizons near the boundaries of unit 106. Olivine crystals are up to 3 cm in size and have skeletal or hopper morphology (Fig. 3h). Sulfide and stichtite (after chromite) occur interstitial to olivine crystals. Stichtite occurs as both 1–2-mm equant grains and as lobate aggregates up to 3 cm in diameter. Similarly, sulfides occur as lobate blebs up to 5 mm in diameter; bleb shapes are controlled by the enclosing olivine grains. Sulfide abundance is variable throughout unit 106 and is generally layered on a scale of tens of centimeters.

Vertical and lateral variations

Unit 106, which occurs from 31,360 to 32,640 mN (Mount Keith Mine Grid), displays significant variation in texture and upper contact geometry along its lateral extent. Unit 106 is generally overlain by unit 107, except between 31,300 and 31,400 mN on the 400-m RL projections and between 31,850 and 31,920 mN on the 300-m RL In these areas, unit 106 is in direct fault contact with the hangingwall mafic/pyritic shale sequence. To the north, unit 106 shares a transitional boundary with unit 107, defined by an increase in the proportion of ICM as the adcumulate becomes the meso-orthocumulate of unit 107.

The transition between units 106 and 107 is sharp, occurring over 4–6 m. Vertical variations within unit 106 are dominated by sharp transitions from adcumulate to crescumulate/harrisite with thin mesocumulate haloes. Lateral variation within unit 106 consists of a gradational change in the dominant textural type over its entire strike length. Figure 4 illustrates the gradational change between the different adcumulate texture types within unit 106.

The southerly portions of unit 106 (31,760 to 31,600 mN) are dominated by tightly packed equant adcumulates with a constant crystal size. Laterally to the north, the adcumulate texture develops an increasingly pronounced bimodal texture where many of the larger olivine crystals gradually become elongated and aligned (Fig. 4). To the north, the adcumulates also contain crescumulate horizons and gabbroic domains. In the vicinity of approximately 32,500 mN, unit 106 is a loosely packed mesocumulate with numerous skeletal crystals and is texturally indistinguishable from the overlying unit 107. North of approximately 32,600 mN, the merged units 106/107 (WMZ) appear to lens out of the stratigraphy. As a result, in this area, unit 105 is the uppermost unit of the MKUC.

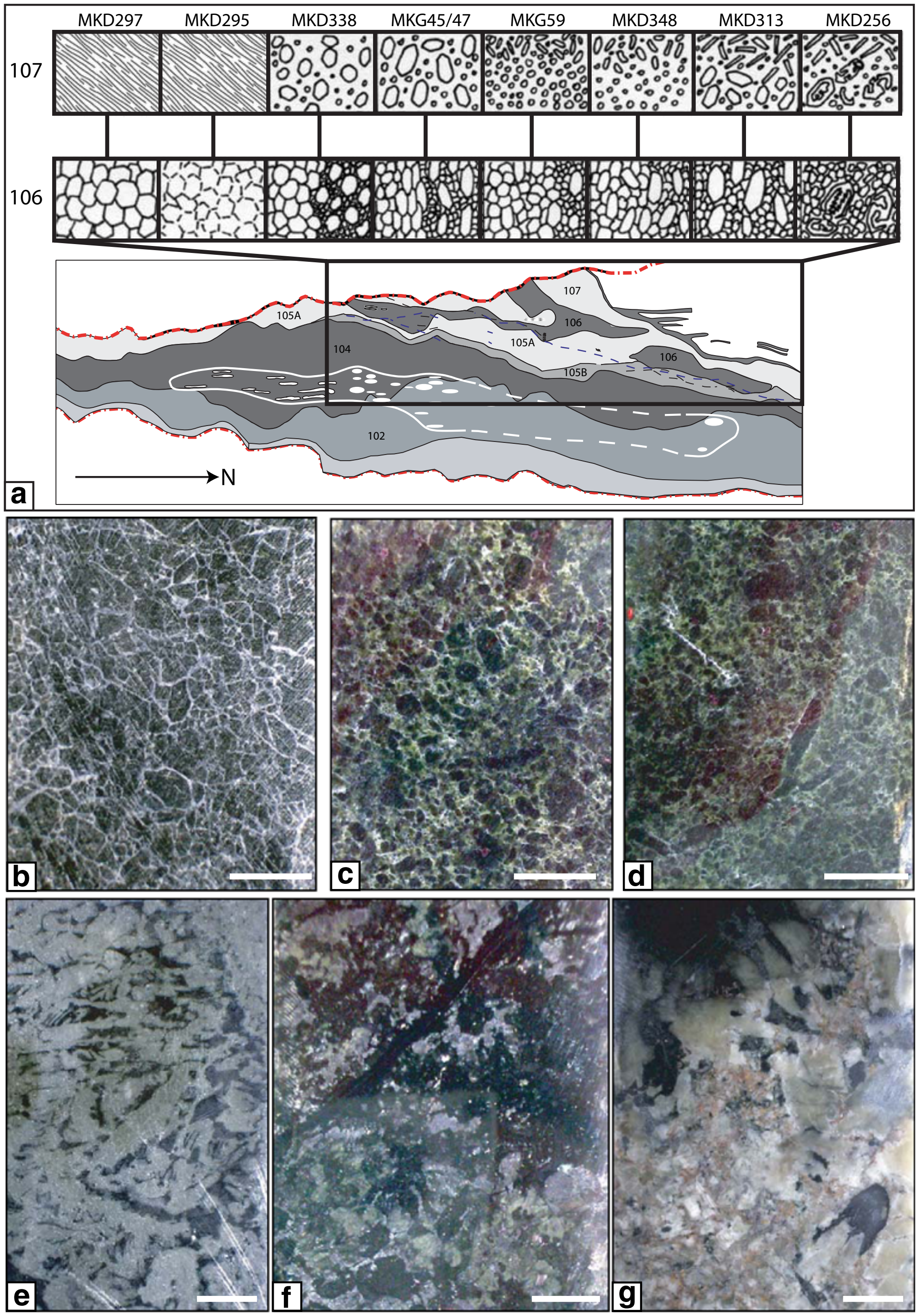


Fig. 4 **a** Textural variations along the lateral extent of units 106 and 107 illustrating the increasing proportions of the elongate and eventually skeletal olivine towards the north end of the MKUC. All different textures are schematically illustrated in filmstrips of unit 106 and 107. **b** Equant adcumulate. **c** Bimodal meso-to-adcumulate. **d** Elongate mesotoadcumulate. **e** Skeletal olivine. **f** Pyroxenite. **g** Gabbroic segregation in unit 107

The 3D geometry of unit 106 is also highly variable. At 400 m RL, unit 106 appears as a continuous single unit. However, at 300 m RL, unit 106 appears to have bifurcated around a pyroxenitic orthocumulate unit, similar in character to unit 105B. The lack of drilling information together with the occurrence of significant shearing and foliation along the contacts between units hamper an accurate determination of the true 3D geometry of the uppermost portion of the MKUC in this area. A second break in continuity is present between 32,200 and 32,300 mN, where unit 106 overlaps in a 2D view, separated by an ortho-mesocumulate unit similar in character to unit 105.

Unit 107 (orthocumulate/pyroxenite)

Unit 107 is the uppermost cumulate stratigraphic subdivision of the MKUC and is restricted to the WMZ.

Textural features

Unit 107 displays a range of compositions and related textures. Compositional variance is marked by the presence of pyroxenite and gabbro in the more fractionated areas. The majority of unit 107 comprises olivine meso-orthocumulate, with orthocumulate as the major texture type and lesser mesocumulates; crescumulate and harrisitic horizons are common. As observed in other units (e.g., unit 106), both unimodal and bimodal crystal size distributions are present, with bimodal being the most common textural form.

Olivine crystal size within bimodal orthocumulates is 2–3 mm for the finer-size fraction, whereas the larger-size fraction has a consistent size of 5–10 mm. The finer olivine crystals are equant with poorly developed terminations. Large olivine crystals occur as both poorly formed equant and well-formed elongated crystals. In close proximity to the hangingwall contact, fine-grained bimodal orthocumulates occur with elongated rice-shaped grains up to 7 mm long in a groundmass of fine (2–3 mm) rounded olivine. Unimodal orthocumulate crystal size ranges between 2 and 4 mm: individual crystals are equant with poorly developed terminations.

Pyroxenitic upper margins are also recorded in the MKUC (in drill-holes MKD313, MKD256, and MKD260) and vary in thickness from 2 to 20 m. The pyroxenitic units locally display well-developed oikocrystic textures. Crystal size within pyroxenites ranges from 2 to 8 mm, with the finer crystals closer towards the hangingwall contacts. Pyroxene crystals occur as both equant and feathery elongated grains. Crystals generally display ragged morphologies and display strong interlocking textures.

Gabbroic units occur both as the uppermost portions of the MKUC and as discrete plagioclase-bearing domains, which are inferred to be late-stage magmatic segregations within units 105, 106, and 107. The primary mineralogy of the gabbros is dominated by pyroxene and plagioclase. Due to encapsulation in ultramafic rocks, gabbroic segregations are commonly rodingitized and locally converted to massive, grossular-rich assemblages without preservation of igneous textures. Crystal size ranges from 2 to 15 mm for both pyroxene and plagioclase, with both phases displaying a roughly equal grain size in any individual area. Pyroxene crystals are well-formed, generally clumped as large (2–4 cm) glomerocrystic aggregates. Plagioclase grains are present as both well-formed euhedral crystals.

Vertical and lateral variations

Moving northwards within the MKUC, unit 107 is first observed at 31,400 mN and is present along the upper margin of the MKUC. Similarly to unit 106, unit 107 displays significant variation in texture, upper-contact relationships, and 3D geometry along its lateral extent. Unit 107 is in contact with the hangingwall stratigraphy to the MKUC along its entire length; however, from 31,400 to 32,080 mN, it is in sheared contact with the highly deformed, structurally emplaced basaltic hangingwall. Conversely, from 32,080 mN, unit 107 is in contact with the stratigraphic hangingwall, a dacitic lava flow complex (Rosengren et al. 2007). The contact relationships between unit 107 and the dacite are interpreted as primary and demonstrate the intrusive relationship of the MKUC and the surrounding stratigraphy (Rosengren et al. 2005).

The texture and composition of unit 107 vary along the strike extent of the unit. In the more southerly portions of unit 107, textures comprise both bimodal and equant orthocumulate units, neither of which shows significant elongation of olivine grains. Progressing north (drillholes MKG45, 47, 59, and MKD348), bimodal orthocumulate with elongated olivine (in the large crystal fraction) becomes prevalent. Approaching the upper contact, fine-grained orthocumulate with equant and elongated, rice-shaped grains is the dominant texture type.

Upper pyroxenitic/gabbroic margins are not developed at this point. In the northernmost extents of the MKUC where the body begins to thin, unit 107 is characterized by bimodal olivine orthocumulate to mesocumulate with well-developed upper pyroxenitic horizons. Well-developed harrisite and crescumulate horizons are present in this region and increase in proportion northwards, where large (1–1.5 cm) skeletal olivine crystals are common and display a number of morphologies (Fig. 4e). The gradation between the fine-grained orthocumulates/pyroxenites, which occur at the upper contact, and the underlying unit 107 is generally overprinted by shearing and/or alteration. As a result, the nature of this transition is unclear.

Unit 103 (POR)

The POR occurs in multiple horizons throughout the MKUC and was first documented by Burt and Sheppy (1975) as a pegmatoid peridotite. Previous studies have described this unit as a stratigraphic marker horizon contained within unit 104 and interpreted to have formed:

(a) during stagnant periods in the flow of a lava (Fardon 1995; Seymon 1996)
(b) by interaction with sea water infiltrating the lava channel during periods of magmatic quiescence (Hronsky et al. 1994)
(c) as an accumulation of contaminants and felsic ocelli, which have risen upwards through the unit 101 and 102 melt pile (Rödsjö 1999)

The architectural work conducted during this study indicates that the POR (now designated unit 103) cross-cuts units 104 and 102 and does not define a stratigraphic layer within the MKUC.

Textural and mineralogical features

Unit 103 is dominated by very coarse olivine (Fig. 3i,j) grains set in a fine-grained groundmass dominantly comprised of brown bastite (after pyroxene). Olivine grain-size ranges from 0.5–4 cm, but true grain dimensions are generally disguised by the width of drill core. Olivine crystals show a wide range of morphologies but are dominated by skeletal/hopper morphologies. Other shapes include branching “herring bone”-shaped olivine, rounded olivine, and branching harrisitic. The unit also contains variable amounts of primary phlogopite mica, which occurs as 1–2-mm flakes within the bastite groundmass. Phlogopite contents can reach levels of 2–5%, suggesting a relatively high H_2O content. The high H_2O content in a silicate melt would allow rapid diffusion, contributing to the coarse crystal sizes and branching morphologies, which are typical of this unit.

Plagioclase (altered to fine-grained sericite) is present in discrete domains and occurs as an interstitial phase to olivine. Accessory phases within the groundmass include ilmenite, rutile, zircon, baddeleyite, and monazite (Goodgame 1997). Unit 103 is highly enriched in incompatible elements such as titanium, zirconium, and rare earth elements. Zirconium levels of up to 700 ppm are common in unit 103 (Goodgame 1997; Fiorentini 2005). Both the high volatile content (reflected in the presence of primary volatile-bearing minerals) and the levels of incompatible elements indicate that unit 103 represents a late-stage, ultramafic pegmatoid within the core of the MKUC.

Vertical and lateral variation

In the MKUC, unit 103 occurs as a semicontinuous horizon between 30,850 and 32,600 mN, which cross-cuts the unit 102/104 boundary. Given the variable size of each occurrence, unit 103 most likely comprises numerous lenses, which may be complexly interconnected, forming an anastomozing network. No systematic variation in texture or lithology is recorded along the strike extent of this unit.

Summary of internal architecture

The MKUC can be divided into three architectural domains, each containing a number of previously defined units: the main adcumulate domain (MAD), the upper fractionated zone (UFZ), and the WMZ. A schematic stratigraphic column for the MKUC is illustrated in Fig. 5. The MAD contains the unit 101 basal orthocumulate, the unit 102 extreme olivine adcumulate, the unit 104 adcumulate, and the unit 103 pegmatoid swarm. The lowermost unit of the MAD is unit 101, which has a gradational boundary into the overlying, very coarse-grained, and sporadically mineralized unit 102. Unit 102 is overlain by unit 104, a coarse-grained adcumulate with well-developed interstitial pentlandite/pyrrhotite-rich sulfide mineralization. Unit 103, previously interpreted as a possible marker horizon, crosscuts both units 102 and 104. The MAD domain comprises a significant amount of the MKUC and contains the majority of NiS mineralization, hosted primarily in the thickened portions of unit 104. NiS mineralization is also present within unit 102. The UFZ contains the three subunits of unit 105 and has a gradational contact with the underlying MAD.

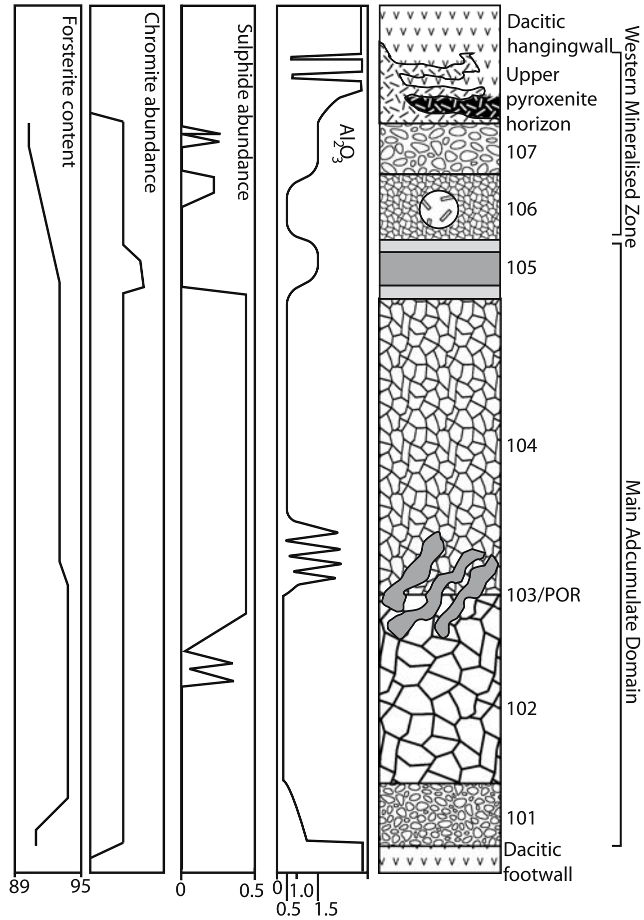


Fig. 5 Schematic stratigraphic column for the entire MKUC indicating the internal stratigraphic units, and schematic traces for Al_2O_3, sulfide abundance, chromite abundance, and forsterite content

The WMZ forms the upper sequence of the MKUC in the NW part of the complex and comprises units 106 and 107. Unit 106 displays a gradational contact with the underlying 105 subunits, although it is not as sharply defined as other transitions in the MKUC. The unit 105–

106 boundary is generally the focus of shearing and talc-carbonate alteration. Unit 106 appears to bifurcate between the 300- and 400-m RL levels, resulting in a complex geometry between successive levels of the WMZ. The exact nature of the bifurcation is unclear; resolution of the geometry is limited by drill spacing in the area. Unit 107 conformably overlies unit 106 and is the uppermost stratigraphic division of the WMZ and MKUC. Unit 107 displays a wide variation in texture along its strike extent, with skeletal textures and upper pyroxenitic domains common in the northern parts of the MKUC.

Texture formation

The internal units of the MKUC show a diverse textural zonation from tightly packed, very coarse olivine adcumulates to crescumulate/skeletal olivine and granophyric textured gabbros and pyroxenites. The differing crystal morphologies are generally utilized to discriminate between the individual units within the MKUC; however, they also provide indications on the cooling history and flow dynamics of the magmatic system.

Cumulate textures

The production of adcumulate rocks can be ascribed to primary texture development, referring to the method of accumulation of initial crystals (i.e., sedimentation vs in-situ growth) and secondary texture development (e.g., overgrowth: cf. Hunter 1996). Secondary texture development refers to the magmatic processes, which operate on the initial crystal mush, modifying the textural relations between grains to reduce pore volume. Specific studies on crystallization within komatiitic dunite complexes are rare: studies have focused on accumulation of crystal clusters in komatiite lava flows (Campbell 1978; Jerram 1996; Jerram et al. 2003) rather than the coarse adcumulate growth in dunite bodies.

The production of an essentially single-phase adcumulate requires a significant reduction in the pore volume of the rock, which may occur through crystal growth, textural equilibration, compaction, and recrystallization/annealing (Hunter 1996 and references therein). Crystal growth requires the continued enlargement of the initial phase (olivine in komatiitic dunites) without the crystallization of an abundant poikilitic cementing phase (Hunter 1996). "The volume fraction of synataxial overgrowth vs interstitial (poikilitic) cementation is a critical function of the temperature of the mush in relation to the temperature of saturation of any poikilitic cementing phase" (Hunter 1996). This statement is insightful for komatiitic systems because of the large temperature interval between the olivine-chromite solidus and the next precipitating phase, thus permitting significant growth of olivine prior to the crystallization of the next interstitial phase.

Compaction of the crystal pile reduces pore volume by expulsion of remaining interstitial magma via mechanical compaction. Further reductions in pore volume can be achieved via viscous deformation of the grains by diffusive creep, Ostwald ripening, thermal annealing, recrystallization, or dislocation creep (Hunter 1996). All of the above processes contribute to the textural equilibration of the cumulate (Hunter 1987). Textural equilibration results in rocks where there is a constant grain boundary contact angle between like phases; in addition, because large grains have a lower grain boundary curvature, textural equilibration will also result in an increase in average grain size (Hunter 1987). In the case of olivine, the contact angle is 1,200 as illustrated in Fig. 3a (unit 102 coarse adcumulate).

Skeletal and harrisitic textures

There are numerous occurrences of other branching and skeletal olivine morphologies. The conditions necessary for the development of skeletal textures within komatiitic rocks have been ascribed to a number of influences such as supercooling of the melt, nutrient-controlled competitive growth, and compositional gradients in isothermal growth conditions (Donaldson 1977). The influence of supercooling on olivine crystal morphology was investigated by Donaldson (1976), who defined several differing crystal morphologies at increasing degrees of supercooling. At high degrees of supercooling, growth of existing crystals is favored over nucleation of new crystals resulting in large grains with hollow and branching morphologies.

Faure et al. (2003) performed detailed microscopic studies of quenched olivine textures and determined that many of the previously defined subdivisions (e.g., Donaldson 1976) were the result of differently orientated slices thorough the same type of crystal geometry. Donaldson (1977) also suggested that a sudden decrease in the crystal content of the melt could trigger branching growth under isothermal conditions. Branching and skeletal olivine crystals display fractal geometries (i.e., they display geometries that are scale-independent); the physical processes, which govern the growth of branching harrisites and crescumulates, have been investigated by Fowler et al. (1989) and modeled using a variant of the diffusion-limited aggregation model (DLA). The DLA-based simulations produced fractal geometries very similar to those observed in komatiites and layered intrusions, suggesting that this physical process is an important part of the formation of crescumulate/harrisitic and skeletal olivine morphologies (cf. Shore and Fowler 1999; Faure et al. 2003; Faure et al. 2006).

The conditions required for the growth of skeletal and particularly branching and crescumulate olivine crystals are met in stagnated pockets or layers of magma within a komatiite unit, where the magma can experience high degrees of supercooling. Stagnated areas will also have low crystal contents, and possibly compositional gradients, suitable to the models proposed by Donaldson (1977).

Texture formation in the MKUC

The MKUC displays a full gradation of cumulus textures from orthocumulate to extremely well-developed olivine adcumulate with almost no porosity and a high degree of textural equilibrium. Olivine orthocumulates and mesocumulates are interpreted to form when the magma cools relatively quickly, trapping early-formed crystals in a matrix of komatiite glass.

The orthocumulates typically comprise euhedral olivine crystals. In the MKUC dunites, there are numerous textural features, which provide insights into the formation of the cumulate textures. Bimodal olivine populations in the upper portions of the MKUC (units 106 and 107 in particular) suggest that these units carried at least some intratelluric olivine crystals when they intruded. The intratelluric phenocrysts represent the larger crystal population with a finer crystal groundmass, although it is not clear whether the finer crystal population formed via in-situ crystallization or crystallization/sedimentation from the melt.

Hill et al. (1990) review the problems associated with the accumulation of pure olivine adcumulate via crystal sedimentation and postcumulus processes. The authors conclude that adcumulate formation requires a combination of two factors: (1) very low degrees of supercooling and (2) efficient removal of depleted melt (reject solute). Low degrees of supercooling suppress the formation of nuclei and favor the growth of existing crystals, whereas efficient removal of depleted melt is necessary to keep growing crystals supplied with nutrients. Hill et al. (1990) propose that these conditions are met in vigorously flowing komatiite magma over a bed of growing crystals; furthermore, the authors argue that the adcumulate textures occurring at Mount Keith, Perseverance, Six Mile, and elsewhere in the AWB formed by in-situ solidification at the cooling front.

However, as pointed out by Hunter (1996), in a strongly adcumulate rock, the role of the primary texture development phase will be heavily obscured by secondary texture development. The presence (or absence) of intratelluric phenocrysts in the coarser adcumulate units of the MKUC (i.e., units 102 and 104) is difficult to establish due to the well-developed secondary (igneous) textures (particularly unit 102). This problem is compounded by the fact that any compositional difference that may have existed between crystal core and overgrowth would most likely have been destroyed by the combination of solid state diffusion/equilibration at high temperatures, followed by serpentinization or talc-carbonate alteration. However, there are several textural variations within the unit 104 that suggest that more than one type of crystallization process was in operation.

Variations in crystallization regimes during the emplacement of this unit could account for the textural and sulfide layering within unit 104. In unit 104, the are four basic texture types (Fig. 6): (1) equant + sulfide, (2) equant − sulfide, (3) elongated perpendicular to gross layering, and (4) elongated parallel to gross layering. Equant + sulfide is the most abundant texture type within unit 104 and represents the dominant mode of crystallization within the unit. The proportions of olivine to sulfide and the centering of grade distribution around 0.6% Ni is interpreted to represent the cotectic crystallization of olivine and sulfide from the magma (Duke and Naldrett 1978; Duke 1986b; Hill et al. 1990; Grguric 2003).

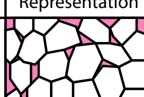
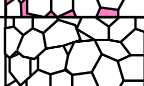
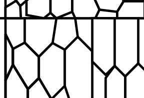
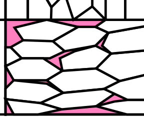
Texture type	Graphic Representation	Occurrence	Sulphide Abundance	Olivine Crystalsize	Comments
Equant + sulfide (1)		Abundant throughout 104	Well-developed interstitial sulfide up to 5%	8-10 mm	Well-mineralised, finest grainsize of 104. Lowest degree of textural equilibrium compared to other 104 texture types
Equant - sulfide (2)		Common non-mineralised layers in 104	Very fine to no sulfides	10-15 mm	Poorly to non-mineralised, similar texture to 1 but with coarser grain size and higher degree of textural equilibrium
Perpendicular layering (3)		Thin (2-6 m) layers in 104	Very fine to no sulfides	10-20 mm	Very poorly to non mineralised. Strong alignment of long olivine axis perpendicular to gross layering of MKUC
Parallel layering (4)		Rare layers up to 15m thick in 104. more commonly found in 106	Well-developed interstitial sulfides 3-5%	10-20 mm	Layering defined by long axis of olivine, parallel to gross layering of MKUC. Sulphide well-developed. Moderate textural equilibrium

Fig. 6 Internal texture variations within the olivine adcumulate in unit 104, illustrating changes in olivine morphology and crystal size as a function of sulfide abundance. Note the association between equant olivine and interstitial sulfide mineralization

As with most adcumulate units in the MKUC, the mechanism by which primary crystals accumulated is obscure. However, the equant nature of the crystals and their smaller size relative to the rest of unit 104 suggests that, irrespective of whether the crystals grew in-situ or were sedimented from the melt, the presence of a crystallizing sulfide phase retarded their growth ("crystal growth poisoning"). The fact that sulfide-poor or sulfide-free horizons (i.e., texture type 2, Fig. 6) within unit 104 typically have a larger crystal size supports this observation. Texture types 3 and 4 (Fig. 6) show a well-developed, shape-preferred orientation perpendicular and parallel to the gross layering of the MKUC, respectively.

The perpendicular shape-preferred orientation of texture type 3 suggests that olivine grains were growing in-situ into a melt reservoir via nutrient-controlled or competitive growth processes (Hunter 1996), in which there was very little to no precipitation of sulfide, thus allowing coarse crystal growth. Conversely, texture type 4 displays development of interstitial sulfide phase and a shape-preferred orientation parallel to the MKUC layering, which indicates different formation processes. Areas of shape-preferred orientation parallel to the gross layering are rare in the MAD, but relatively common in the WMZ.

The textures within the MAD indicate that textural development was a combination of in-situ crystallization and crystal settling, both of which were affected by secondary processes to varying degrees. The presence of a cotectically crystallizing sulfide phase had a strong effect on olivine crystallization, reducing the size and packing density of olivine where sulfide was present. The extremely olivine-rich nature of the cumulates in the MAD indicates that the magma from which they were formed was continually being replenished over the course of emplacement. However, the decreasing forsterite content from unit 102 upwards suggests that the magma became slightly more evolved and cooler over time.

The upper portions of the MKUC are dominated by meso-orthocumulate rocks with pyroxenitic to gabbroic fractionates. The presence of these textural and compositional variations has been interpreted as a decrease in magma flow rate culminating in eventual stagnation, which permitted in-situ fractionation and the formation of the upper horizons (Dowling and Hill 1990). In specific domains of the MKUC, areas of crescumulate/harrisitic growth and skeletal olivine indicate that local supercooling, compositional gradients, and crystal-free melt existed, triggering the growth of skeletal and fractal olivine morphologies.

Such domains indicate areas of stagnant flow, most likely pockets of trapped melt within the crystallizing cumulate pile. The very large size of some skeletal crystals in these areas (up to 3 cm) suggests that the large size of these crystals could be partly in response to the influence/accumulation of volatile phases in the stagnated domains, which aided diffusion and enhanced crystal growth.

Discussion

The MKUC is a giant dunite body of komatiitic affinity, which hosts huge reserves of nickel as disseminated NiS. Several other komatiitic dunites occur in the Agnew-Wiluna Greensone Belt (e.g., Six Mile Well, Perseverance, and Walter Williams Formation) and globally (e.g., Dumont Sill, Shangani, Epoch, and Hunters Road). All the above mentioned dunitic bodies display common features. In addition, even if each dunitic body has a unique geometry, two distinct categories are generally recognized: lens-shaped or sheet-like, depending on their broad geometrical character. Lens-shaped dunites include the MKUC, Perseverance, and Six Mile, whereas Dumont, Shangani, and Walter Williams Formation have a sheet-like morphology (Fig. 7).

Dunite lenses

The MKUC, the Perseverance Ultramafic Complex, and Six Mile Well are characterized by lens/pod accumulations of olivine adcumulate, which are enclosed in olivine meso-orthocumulate sequences (Fig. 7). The lenses represent zones of significant thickening of the host ultramafic unit and generally host significant accumulations of NiS. The internal architecture of the lens-shaped dunites also varies significantly among bodies.

The MKUC has seven identifiable internal textural units, as described in this paper. Each unit has distinct textural and chemical features, with some of the thicker units displaying internal igneous textural and cryptic layering on a scale of tens of centimeters to meters. In comparison to the MKUC, the Perseverance Ultramafic Complex does not exhibit such a varied internal architecture, instead displaying a simpler stratigraphy, which is dominated by the large adcumulate lens. The MgO values within the thicker adcumulate portions of the MKUC (units 102 and 104) vary between 35 and 45 wt.% (Hill et al. 1990; Fiorentini et al. this volume); lower MgO values roughly coincide with elevated Ni, reflecting the reduced volume of olivine in the olivine/sulfide cumulates. The same phenomenon occurs in the adcumulate lens of the PUC (Brand et al. 1994) and is the basis of the internal subdivision illustrated in Fig. 7.

Forsterite contents of the MKUC (Fig. 8) range from Fo90 to Fo93.5 (Dowling and Hill 1990; Barnes 1994) and show a decrease upwards through the complex from unit 102 (Fo93.5) to unit 104 (Fo90 to Fo93.5) and the upper series (Fo91.5 and Fo93). In contrast, the PUC ranges from

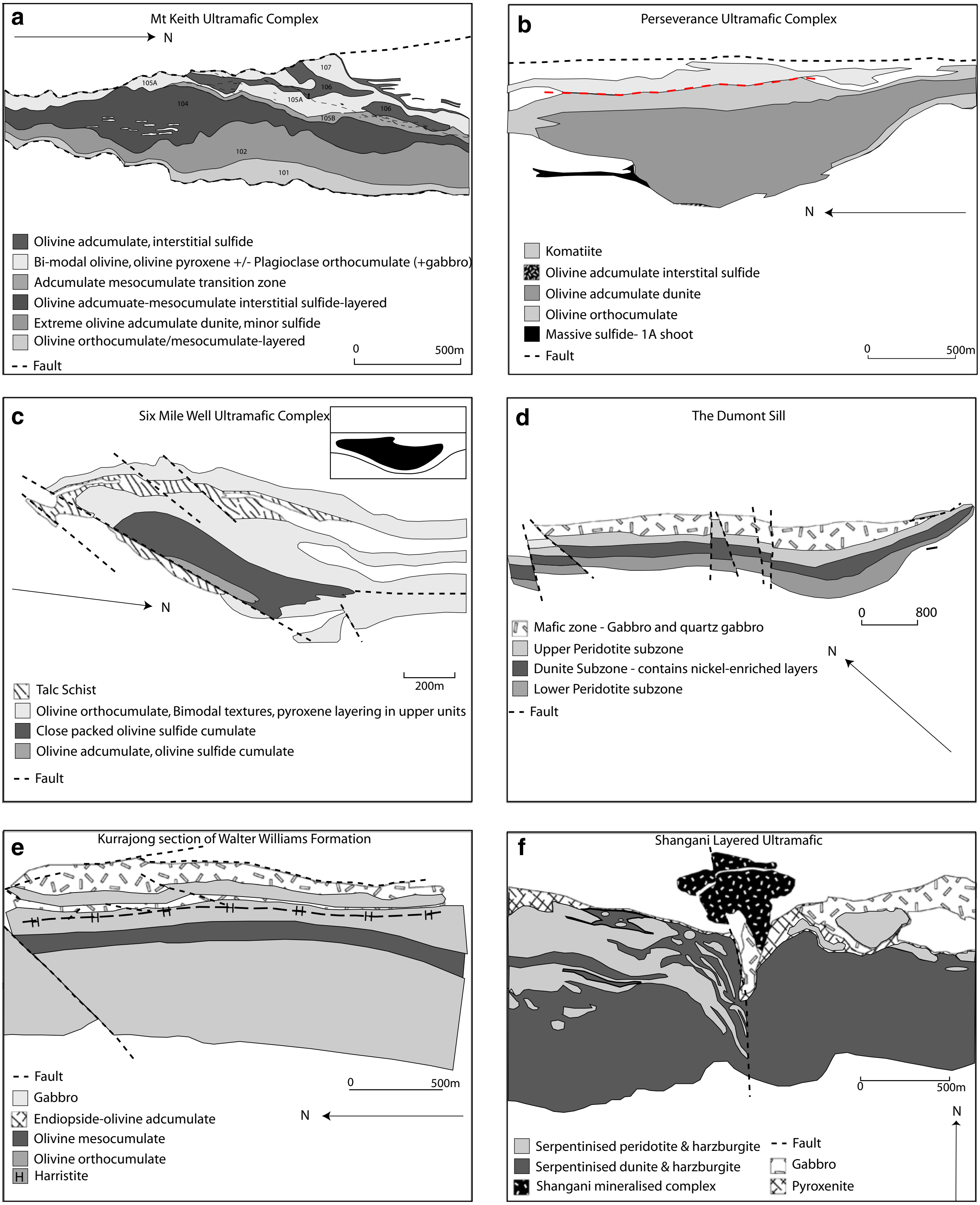


Fig. 7 Comparison of the internal stratigraphic architecture of six komatiitic dunites from the AWB and worldwide: **a**–**c** display lens geometries, whereas **d**–**f** are sheet-like. Note the sheet dunites have significantly thicker evolved upper margins than lens dunites. However, despite the differing proportions of individual lithologies within each dunite, both lens and sheet dunites share a similar architectural order

Fo93 to Fo94.5 and displays a steady upwards increase in forsterite content (Barnes et al. 1988; Hill et al. 1990).

The Six Mile dunite body was initially subdivided into four zones (A, B, C, and D) by Naldrett and Turner (1977). The subdivision was later expanded by Hill et al. (1990), who renamed the zones 1 through 4 and subdivided zone 3 into 3a and 3b. Zones 1 and 2 consist of cyclic layers of olivine orthocumulate/mesocumulate (zone 1) and olivine ortho-adcumulate with olivine sulfide cumulates (zone 2). In zone 2, the forsterite content of olivine ranges from Fo89 to Fo91.2 (Naldrett and Turner 1977; Hill et al. 1990). Similar to the upper portions of the MKUC (particularly units 105B and 107), in zone 1 of the Six Mile dunite body, evolved olivine orthocumulates contain pyroxene oikocrysts and display a bimodal orthocumulate texture. The upper portion of zone 3 (3a) comprises olivine adcumulate with minor interstitial sulfide, whereas the lower portion (3b) is essentially sulfide-free (Hill et al. 1990).

In the Six Mile dunite body, relict olivine is common and ranges in composition from $Fo_{93.7}$ to $Fo_{94.7}$ (Hill et al. 1990), significantly higher than in the MKUC (Fig. 8). The presence of a poorly mineralized olivine adcumulate underlying the main ore horizon is similar to the relationship between units 104 and 102 in the MKUC. The lowermost zone intersected by drilling is zone 4, which is dominated by medium-to-coarse-grained olivine adcumulate ($Fo_{92.6}$ to $Fo_{93.8}$) but is characterized by crystal size and textural and phase layering with abrupt changes between sulfide, grain size, and textural layers common (Hill et al. 1990). Lower layered ortho-meso- and adcumulates are present in all three lenticular dunites to varying degrees.

Unit 101 of the MKUC varies in thickness and texture along strike but generally exhibits a rhythmic layering between ad-meso- and orthocumulate (dominant) with rare harrisitic horizons. The Perseverance Ultramafic Complex also has a moderately developed lower orthocumulate along its southern flanking margin. Both the MKUC and Six Mile are chromite-saturated throughout with variable amounts of both lobate/poikilitic and cumulus stichtite (after chromite). However, the Perseverance Ultramafic Complex contains no chromite throughout the entire dunite core (Barnes et al. 1988). The lack of chromite within the Perseverance Ultramafic Complex may reflect emplacement as a hotter, more primitive dynamic magma. In all three lens dunites examined in this study, the igneous layering is roughly concordant with the strike of the ultramafic units and surrounding stratigraphy.

Dunite sheets

The Dumont Sill (Canada), the Walter Williams Formation at Kurrajong (Western Australia), and the Shangani Sill (Zimbabwe) display a sheet-like geometry in that they lack zones of significant thickening and contain internal units, which have a relatively constant thickness relative to each

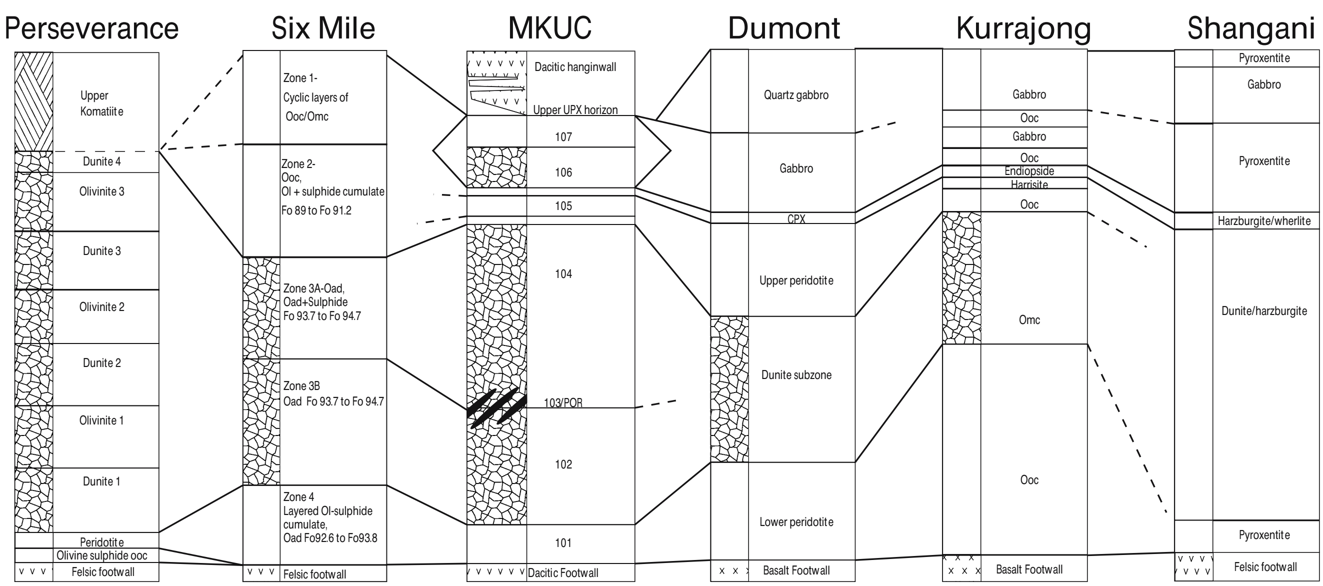


Fig. 8 Facies correlation among selected lens and sheet dunites. The lower ultramafic section is similar in all six dunites studied, the main variation being the thickness of the adcumulate core, which is generally thinner in sheet dunites than lens dunites. The upper and lower sections are generally separated by a pyroxene-rich horizon. The upper evolved section commonly fractionates to thick gabbroic units in sheet dunites, whereas lens geometries typically show thinner, sporadic gabbros around the upper margin. Cyclic repeats are possible in both geometries: sheet dunites can display a return to adcumulate, whereas lens dunites typically cycle between olivine orthocumulates and gabbroic sequences

other (Fig. 7). The internal architecture of the sheet-like bodies varies significantly from that of lenticular dunites: the most obvious difference is the occurrence and thickness of pyroxenitic and gabbroic horizons on the upper margins of the sheet-like bodies.

The Dumont, Kurrajong, and Shangani bodies contain thick accumulations of evolved material at their upper margins (Fig. 9). The lithology, thickness, and sequencing of the upper fractionates varies among the three bodies, but a common broad sequence is present. All three bodies contain a lower ultramafic unit, typically comprising a central olivine mesoadcumulate core enclosed by an upper and lower olivine orthocumulate/peridotite (e.g., Dumont, Kurrajong).

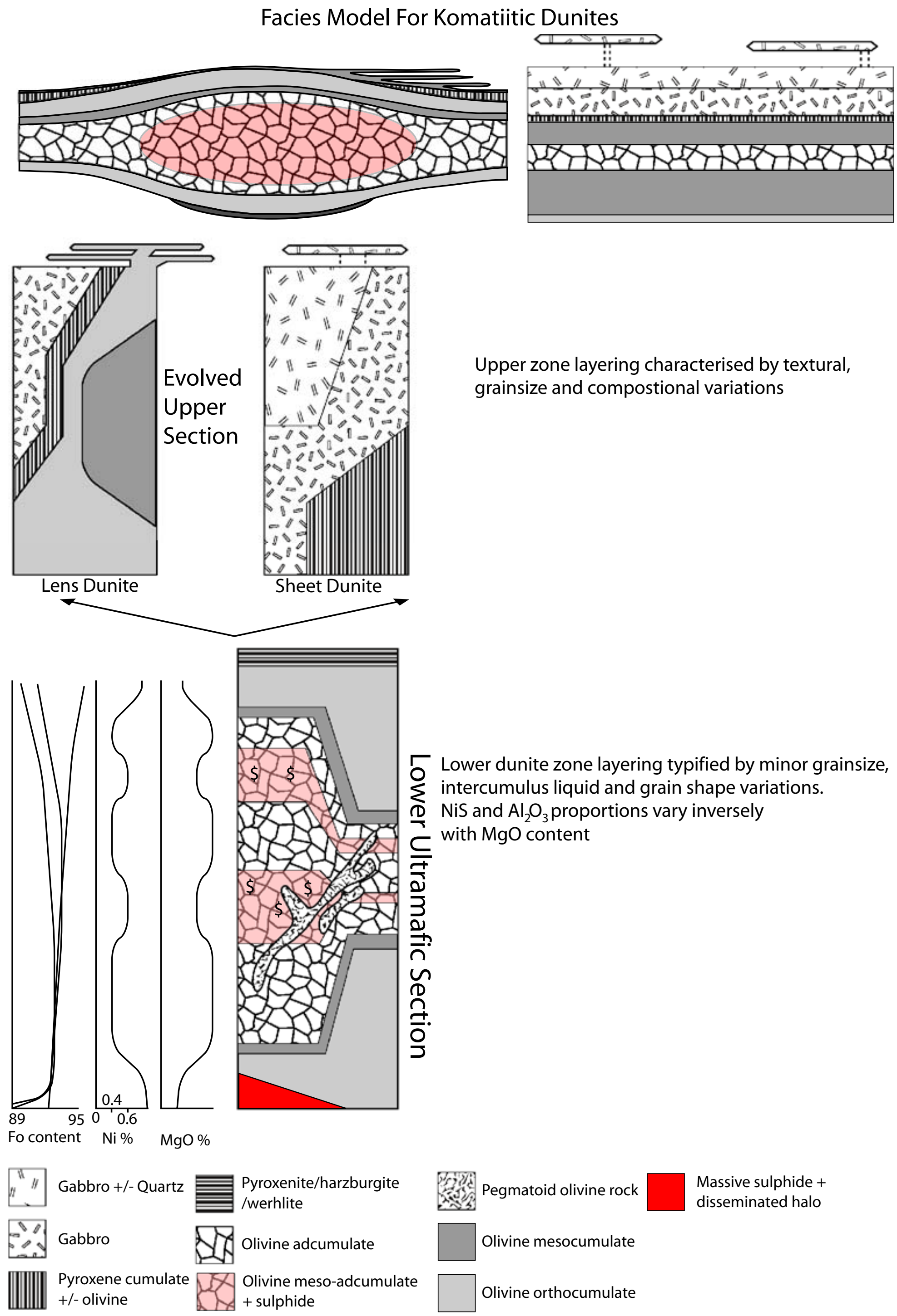


Fig. 9 Facies model for komatiitic dunites. The facies model is divided into two parts: a lower ultramafic section and an upper evolved section. The main differences between lens and sheet dunites are outlined

The boundary between the upper peridotite layer and the evolved sequences is marked by a relatively thin pyroxene-rich layer, which varies between the 10-m-thick clinopyroxene layer at Dumont (Duke 1986b) and the 1–2-m-thick orthopyroxene layer at Kurrajong (Hill et al. 1990). The exact composition of the boundary layer is different in each case: wehrlite/harzburgite at Shangani, orthopyroxene ± olivine at Kurrajong, and clinopyroxene cumulate at Dumont. The evolved sequences at the three locations are comparable: both Dumont and Kurrajong exhibit a gradation from gabbro to quartz-gabbro (although Kurrajong exhibits two cyclic repeats) with a doleritic margin preserved at Kurrajong. A similar doleritic margin is present in places within the MKUC. Conversely, Shangani exhibits a well-developed pyroxenite horizon overlying the wehrlite/harzburgite layer, which grades into a gabbroic upper unit.

Although not directly comparable, due to the difference in geometry and amount of fractionated material present, some parallels can be drawn between the stratigraphic architecture of the sheet and lenticular dunites, particularly the well-preserved upper portions of the MKUC. Figure 8 illustrates the internal stratigraphy of the MKUC and interpreted correlation of internal subdivisions between lenticular and sheet dunites. The lower units of the MKUC (units 101, 102, and 104) form the MAD of the body and are directly comparable with the dunite core of Perseverance and Six Mile (zones 3 and 4). The adcumulate and mesocumulate cores within the ultramafic zone of sheet-like dunites represent a similar facies but are generally less well-developed, with the exception of areas of the Walter Williams Formation, where adcumulate layers can reach up to 400 m in thickness (Hill et al. 1990). The upper, more evolved portion of the MKUC (units 105–107) is complicated by the presence of a second, substantial adcumulate horizon (unit 106), although this appears to be a separate magma pulse from the majority of the MKUC. No directly comparable analogs occur in the Perseverance dunite.

Facies model for komatiitic dunites

Previously, komatiitic dunites have been described in detail as separate entities, focusing on the individual occurrences. Hill et al. (1990) produced a facies model for komatiitic dunites, which separated the lens and sheet dunites, citing the difference in substrate (mafic vs felsic), volcanic environment (cataclysmic sheet flow vs channelized lava river), and flow-rate as the main differences between the two facies. However, comparison between the detailed internal architecture of the MKUC defined in this paper and a number of other komatiite dunite bodies with both sheet and lens geometries suggest that, despite a number of differences, a common architecture can be defined and a broad facies model for komatiitic dunites constructed (Fig. 9). The facies model is divided into two parts: a lower ultramafic section and an upper evolved section. The lower ultramafic section comprises a lower olivine orthocumulate, which grades through a mesocumulate into an adcumulate core. The thickness of the adcumulate core is variable but is typically thicker in lens dunites than sheets, although the adcumulate layer in parts of the Walter Williams Formation (e.g., Goongarrie and Comet Vale; Hill et al. 1990) reaches thicknesses of up to 400 m. The dunite core may comprise multiple adcumulate units defined by differences in texture and sulfide content (e.g., units 102 and 104 in the MKUC; Perseverance) or may be essentially continuous except for sulfide layering (e.g., Dumont).

Layering within the adcumulate core is typified by minor variations in olivine crystal size and abundance of interstitial liquid and sulfide. Cyclic variations in MgO content are generally observed and vary inversely to those of NiS and Al_2O_3, reflecting the changing proportion of sulfide, liquid, and olivine. The olivine ortho- and mesocumulates surrounding the adcumulate vary in thickness and are generally thicker in the sheet flow facies. The thickness of the ortho-mesocumulate sheath appears inversely proportional to the thickness of the dunite core; hence, lens dunites (and sheet dunites with thick adcumulate layers) have relatively thin ortho-mesocumulate layers.

NiS mineralization is a common feature of the lower ultramafic section in both lens and sheet dunites. Mount Keith, Perseverance, and Six Mile host economic accumulations of NiS, whereas Dumont (economically marginal) and Shangani contain weakly disseminated mineralization. The only other known dunite with a recognized unit 103 pegmatoid-type horizon is located at Palm Well in the AWB north of Mount Keith (Fiorentini 2005). The upper margin of the lower ultramafic section is marked by a transition to a pyroxene-rich cumulate, which varies in composition between harzburgite/wehrlite to pyroxene cumulates with minor olivine.

The evolved upper portions of both lens and sheet dunites display significant differences in the relative proportions of lithologies; however, both types exhibit upward fractionation trends through to gabbro. Despite not being ubiquitous (e.g., Dumont), the upper section of sheet dunites may comprise a pyroxenite of varying thickness. The dominant lithology of the sheet, upper, evolved section is gabbro, which varies in composition between clino/orthopyroxene + plagioclase ± quartz. Textures range from subophitic to granophyric. The upper sections of sheet dunites may display cyclic repeats. Kurrajong displays two fractionation cycles; the lower gabbroic section is truncated by an olivine orthocumulate, which repeats the fractionation trend to gabbro. The upper margin of the evolved segment may be marked by a pyroxenitic or doleritic selvage (e.g., Shangani, Kurrajong). The gabbroic upper section may spawn independent detached bodies, which intrude the overlying stratigraphy such as at Dumont (Duke 1986a, b), Kurrajong (Hill et al. 1990), and Shangani (Viljoen et al. 1976; Prendergast 2003).

The evolved upper section of lens dunites comprises a varied sequence of olivine-rich rocks that range in texture from orthocumulate to mesocumulate. However, the MKUC exhibits development of a second, albeit smaller, adcumulate core (unit 106 adcumulate), which is interpreted not to be an integral part of the MKU emplacement process. Cyclic textural and compositional repeats within the fractionated upper unit occur in zones 1 and 2 at Six Mile Well (Naldrett and Turner 1977) and in units 105 A and B at Mount Keith. The more evolved sections contain pyroxene, which is typically oikocrystic (e.g., zone 1 at Six Mile Well), whereas the MKUC displays pyroxene-rich layers in both units 105 and 107. These layers appear similar in character and distribution to the pyroxene-rich horizons, which occur between the lower ultramafic section and evolved upper zones in sheet dunites. Discontinuous gabbroic segregations may occur throughout the more fractioned sections.

The lithologies at the upper margins vary between olivine orthocumulate, pyroxenite, and gabbroic-to-doleritic units. The geometry of the dunite lens may control the distribution of the more evolved segments. Specifically, orthocumulate/pyroxenite forms the uppermost unit in the channelized portion, whereas gabbroic units form in the more marginal portions. Apophyses of ultramafic material within the overlying sequence are recorded at Mount Keith.

All the lens dunites examined in this study are emplaced within felsic host sequences. Generally, the lens shape of these types of dunites is attributed to thermal erosion of the felsic substrate, which has a relatively low melting point. The geometry of sheet dunites has been attributed to their association with more refractory hosts such as basalt (e.g., Kurrajong and Dumont). However, Shangani is emplaced within a felsic sequence and displays sheet morphology with a thick evolved upper section. Rosengren et al. (2007) indicated that, in felsic-hosted systems, the litho-facies of the felsic host has an influence on the localization of flow within the intruding sill.

The differing geometries and lithological proportions of lens and sheet dunites may be related to differing flow regimes within large komatiitic sills. In this model, lens dunites result from continued, focused flow-through, whereas sheet dunites represent stagnated emplacement of large bodies of magma with minor recharge events responsible for upper cyclic units. The empirical association between a sheet dunite complex and its basalt substrate may be related not only to the higher melting point of the basalt host, but also to its more homogenous nature, which results in little focusing of flow during emplacement.

Conclusions

The internal architecture of the MKUC is complex, with seven readily distinguishable internal stratigraphic subdivisions recognized in this study. The internal units vary from extreme olivine adcumulates to loosely packed orthocumulates and evolved sequences, such as pyroxenite and gabbro, in the upper margins. This progression indicates a west-facing for the complex, concordant with the enclosing stratigraphy. Individual units show fine-scale textural and cryptic layering; NiS mineralization occurs in economic concentrations in large areas of the MKUC. The geometry of the internal units and evidence of localized truncation against the hangingwall sequence indicate that a portion of the MKUC has been removed during deformation.

Comparison between the MKUC and other dunite bodies of both lenticular and sheet geometry has revealed significant empirical similarities, irrespective of their differing geometries. The similarities have been used to construct a broad facies model for komatiitic dunites, which encompasses the differing geometries and lithological proportions of lens and sheet dunites, concentrating on the internal architecture sequences that are surprisingly similar across all dunites examined in this study. The essential features of the dunite facies model defined here are:

1. Komatiitic dunites comprise two separate subdivisions, a lower ultramafic section, and an upper evolved section.
2. The lower ultramafic section comprises an olivine adcumulate core with an ortho-mesocumulate sheath.
3. The upper evolved section comprises olivine orthocumulate, pyroxenite, gabbros and/or dolerites, and quartz-gabbros.
4. The boundary between the upper and lower sections is marked by a pyroxene-rich cumulate.
5. Associated gabbroic-to-ultramafic apophyses are common.
6. Dunite geometry is controlled both by magma flux and host lithology properties, the latter having a degree of influence on the former.

This study has shown that detailed examination of komatiitic dunites reveals a complex internal stratigraphy and that these bodies do not simply comprise a monotonous sequence of olivine cumulates.

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