REGOLITH GEOLOGY OF THE MT KEITH, MKD5 NICKEL SULPHIDE DEPOSIT, WESTERN AUSTRALIA

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ABSTRACT

The Mt Keith MKD5 nickel sulphide deposit is located 80 km south of Wiluna and 90 km north of Leinster The deposit is situated within the Norseman-Wiluna Greenstone Belt of the Yilgarn Craton and represents the word's largest known dunite-hosted Arch(an nickel sulphide deposit The current resource of MKD5 is 460 Mt at 0 6% Ni

The mineralogical and geochemical composition of the primary komatiitic rocks at MKD5, their weathered equivalents and overlying exotic material have been studied in two cross-sections The first section runs sub parallel to the regional strike of the komatiites and the pit walls have allowed extensive regolith profile mapping The second section, perpendicular to the regional strike of the komatiites, has provided extensive geochemical and mineralogical information through drill hole sampling

The base of weathering extends below 120 m over the mineralised sequences but is much shallower over barren lithologies The regolith has been broadly divided into three main units, (1) in situ and residual, (2) mixed zone and (3) exotic cover The in situ regolith is composed predominantly of degraded serpentine, neo-formed hydrated Mg-silicates, carbonates, silica and minor Fe oxides. The top of the in situ regolith is marked by a sharp decrease in Mg content, referred to as the Mg-discontinuity This is overlain by the collapsed ferruginous saprolite (residual regolith) in which some element abundances (eg Cu, Cr, PGEs) are significantly increased, due to residual concentration processes

The unconformity between weathered Archean and overlying exotic cover is clearly visible in pit exposures but, in detail, there is a mixed zone, up to 15 m thick, with chemical and mineralogical characteristics of both the underlying and overlying regolith The exotic cover, above this mixing zone, is up to 30 m thick and characterised by elevated concentrations of olivine-incompatible elements and authigenic minerals of multiple provenance

Key words: Regolith, ultramafic rock, nickel sulphides, weathering, Mg-discontinuity

INTRODUCTION AND EXPLORATION HISTORY

The MKD5* deposit (Figure 1) is situated within the Agnew-Wiluna Greenstone Belt and, at 550m above sea level, is located on the higher levels of the interior plateau Nickel mineralisation was first discovered at Mt Keith in November 1968 by Mr J Jones, who intersected Ni and Fe sulphides in the fresher part of an outcropping ultramafic unit, some 1200 m S of the deposit (Burt and Sheppy, 1975) This discovery led Metals Exploration Ltd (managers), Freeport and Australian Consolidated Minerals Ltd to form a joint venture in late 1968 and acquire tenements in the region

In early 1969, magnetic and induced-polarisation geophysical surveys were undertaken in the Mt Keith region, along with extensive shallow rotary drilling to gain geological and geochemical data. Targets generated from this preliminary exploration were diamond drilled systematically and, in November 1969, Ni sulphides were intersected by drill-hole MKD5 Development of the MKD5 deposit commenced in May 1993 by the current owners, WMC Resources Ltd, with the first nickel sulphide ore crushed in September 1994. The current resource at MKD5 stands at 460 Mt at 0 6% Ni (1996 WMC Annual Report to Shareholders)

The depth of weathering in the Mt Keith region varies according to lithology, alteration, mineralogy, presence of sulphides and the degree and intensity of shearing The orebody is concealed beneath a thick cover of exotic sediments This paper describes the geomorphology of the Mt Keith region and the major regolith zones developed over the MKD5 olivine cumulate and is based on mapping, drill-hole information, petrographic studies and SEM and XRD analysis of samples of material collected for studies by Butt and Nickel (1981) and Brand (1997).

GEOLOGY AND MINERALISATION

The stratigraphy in the Mt Keith region is composed of ultramafic sequences (olivine cumulates and thin spinifex textured flows), basalts, volcanic and volcano-clastic rocks and sedimentary rocks The ultramafic sequence at Mt Keith is lenticular It faces W, dips 80-85°, and has undergone low- to mid-greenschist metamorphism The major komatiitic rock types include sulphide-bearing olivine mesocumulate, olivine orthocumulate, talc-carbonate altered orthocumulates and a porphyry olivine rock The non-sulphide mineralogy consists of hydrated Mg silicates (lizardite, antigorite, chrysotile, talc), Mg oxy-carboxyl hydroxides (brucite, stichtite, pyroaurite, iowaite), spinels (chromite, magnetite), carbonates (magnesite, dolomite), tremolite-actinolite and chlorite The disseminated sulphide mineralogy is dominated by pentlandite, with minor millerite, violarite and pyrrhotite. Trace amounts of pyrite, chalcopyrite, heazlewoodite, gersdorffite, polydymite, tochilinite, sphalerite and ex-solved Co sulphides are also present

REGOLITH LANDFORMS.

The Mt Keith region is characterised by low topographic relief (15-25 m) and shallow gradients (<1:150). The greenstone strike-ridges are dissected by alluvial systems, and a breakaway that crosses the greenstone belt 15 km S of the MKD5 deposit, marks a drainage divide (Figure 2). To the west, the divide is marked by the Barr-Smith plateau, developed over the western Mt Keith Granodiorite intrusion The Barr-Smith plateau is a major topographic feature in the region that represents a largely depositional regime, with yellow sands dominant on the back slopes. A major erosional surface is developed on the western side of the range exposing silcretes and kaolinitic saprolites in the breakaways and alluvial systems (Churchward, 1977; Butt, 1985) In contrast, the granitoids east of the Agnew-Wiluna greenstone belt form a flat, subdued topography The greenstone landscape is dominated by depositional regimes around and to the south of the MKD5 deposit, and erosional regimes to the north Lateritic profiles, developed over the greenstone lithologies, are mostly complete or partly truncated and may be overlain by exotic transported material Lateritic residuum, saprolite and mottled saprolite dominate the greenstone terrains, where exposed

The deepest cover (50 m and greater) is present in alluvial channels, shallowing over the channel flanks The MKD5 deposit lies on the southern flank of a broad alluvial channel, beneath red sandy colluvium This channel transects the greenstone belt perpendicular to its strike, and drains N and W from the Barr-Smith Range, to connect with a major regional-scale drainage-system that flows E to Lake Maitland Such channels can contain groundwater calcretes that, under certain conditions, host economic uranium deposits (e g , Yeelirrie, 40 km W of the MKD5 deposit; Cameron, 1984) A red-brown siliceous hardpan is extensively developed in the transported material Coarsely laminated and developed from a depth of 2 to 10 m, this material is referred to as the "Wiluna Hardpan" (Bettenay and Churchward, 1974) A more detailed description of the landforms, regolith and soils in the Mt Keith region is given by Churchward (1977) with regolith geology of the region compiled by Craig and Churchward (1995) and Kojan et al (1996)

REGOLITH PROFILE

REGOLITH OVER THE MKD5 DEPOSIT

At MKD5, the depth of weathering is greatest (down to 120m) over mineralised olivine mesocumulate rocks, shallowing to 70-80 m over barren adcumulates Along shears, including those along the margins of the Mt Keith Ultramafic Complex (MKUC), weathering has penetrated much deeper, in places, to 600 m.

REGOLITH UNITS

The in situ regolith at the MKD5 deposit, developed over the olivine-sulphide mesocumulate and olivine mesocumulate rocks, comprises, from the base of weathering, saprock (117-55 m depth), lower saprolite (67-47 m depth), upper saprolite (59-39 m depth) and collapsed Fe-saprolite (44-29 m depth). The mottled zone (35-9 m depth) is a zone of mixing and has mineralogical and geochemical characteristics of both the underlying collapsed ferruginous-saprolite and overlying exotic sediments. The latter include lateritic gravels (17-5 m depth) and arenaceous and argillaceous sediments (9-2 m depth) These contain alluvial and colluvial units of varying provenance, composition and age Deposition took place at several stages during the evolution of the regolith, with some sediments probably being deposited during the main phase of deep chemical weathering Consequently, in places, the lateritic profile transgresses the residual-transported unconformity The regolith stratigraphy developed over MKD5 is shown in Figure 3

In comparison, the sediment cover over the talc carbonate altered olivine orthocumulate is much thinner. Saprolite extends to some 10m below the surface, grading upwards into a thin horizon of weakly developed mottles, overlain by a thin hardpan layer of lateritic gravels and arenaceous and argillaceous sediments The unconformity between the residuum and the sediments is easily identified at this eastern margin of the MKUC and over the adjacent felsic and mafic wall rocks, but is indistinct over the sulphide-bearing olivine mesocumulate and adcumulate.

Other than the complex nature of the unconformity that marks the boundary between the transported overburden and the residual, weathered serpentinite, the most noticeable features of the profile are the sharp chemical, mineralogical and colour changes between the saprolite and overlying collapsed ferruginous saprolite This boundary marks the disappearance of serpentine and carbonates and the accumulation of silica and Fe oxides, and has been termed the Mg-discontinuity (Brand, 1997) A schematic regolith profile developed at Mt Keith is shown in Figure 4.

STRUCTURE IN THE REGOLITH

Primary Archaean structures have influenced the development of the regolith overlying the MKD5 deposit, acting as conduits for ground-water flow and locus for profile slumping. These Archaean structures can be traced through in situ regolith and into overlying transported overburden, due to local reactivating These reactivated structures are exemplified by manganese coated slickensides developed in the upper saprolite The nature and dimensions of dome structures formed along the contact between upper saprolite and the overlying collapsed ferruginous saprolite over the olivine adcumulate are controlled by the reactivation primary structure These domes have massive silica accumulations at their base resulting, in part, from the break down of hydrated-Mg silicates

REGOLITH HORIZONS OF OLIVINE (-SULPHIDE) MESOCUMULATES

Saprock

The boundary between bedrock and saprock is marked by a colour change from dark green to pale grey-green The saprock can exceed 30 m in thickness, and contains core-stones of unweathered protolith. Its mineralogy is dominated by primary serpentine, with minor magnesite, dolomite, magnetite, chromite, silica and talc Soluble Mg-hydroxides (e g , brucite) and Mg hydroxy-carbonates (e g., pyroaurite and iowaite) disappear close to the weathering front This results in microvoids in the cores of serpentine grains, surrounded by zoned serpentine segments The removal of soluble components at the weathering front has increased porosity and decreased bulk density of the saprock (from 2 56 to 2 30 g/cm3) Primary sulphides, dominantly pentlandite, are altered to supergene forms such as violarite and pyrite (Butt and Nickel, 1981)

Saprolite

The transition between saprock and saprolite is gradational and some core-stones of saprock are preserved in the lower saprolite. Over the mineralised portion of the MKUC, the transition is normally marked by loss of secondary sulphides Mineralogically, the saprolite is composed of serpentine, magnesite-dolomite, silica, Fe oxides (magnetite-maghemite-hematite-goethite), minor talc, chromite, smectite and, in the upper saprolite, rare kaolinite

Close to the top of the upper saprolite, silica has impregnated the grain partings in serpentine, encapsulating Fe oxides, whereas the serpentine itself has been dissolved, leaving voids that, nevertheless, maintain the relict primary fabric. The abundance of Fe oxides (goethite) increases throughout the profile as Fe is released from the weathered serpentine minerals

Unlike saprolite developed over serpentinised olivine orthocumulate rocks, smectites are rare in the regolith developed over the MKUC. Where smectites occur, they are typically associated with zones of increased Al (e g., shaft section; Butt and Nickel, 1981), within fractured zones and associated with weathered low-Mg ultramafic rocks.

Collapsed ferruginous saprolite (residual plasmic zone)

The base of the ferruginous saprolite, developed over the serpentinised olivine cumulate, marks the position of the Mg-discontinuity and a zone of textural collapse (non-isovolumetric weathering) forming a major chemical and mineralogical boundary within the residual profile This collapsed ferruginous saprolite contains sub-horizontal layers of silica and segregations of Fe oxide that can be traced laterally for over 100 m. Internal to the zone, blocks of intensely silicified saprolite after dunite are preserved, with secondary silica decreasing in abundance higher in the profile. Mineralogically, the zone is composed of Fe oxides (maghemite-hematite-goethite), silica, smectites, trace amounts of chromite and talc, and rare, authigenic, anatase in the upper part of the zone. Texturally, the zone resembles a sediment with laminated sub-horizontal layering. At the top of the zone, kaolinite increases in abundance, marking the gradational boundary between the residual profile and the overlying exotic sediments.

Mottled zone (transported and mixed zone)
A mottled zone blankets the whole MKUC and adjacent footwall and hangingwall rocks. This is a clay-rich horizon, dominated by competent, irregular, red-brown mega-mottles, up to 800 mm in length, set in a bleached to tan-brown kaolinitic matrix. Smaller-scale mottles, patchy silicification and multi-coloured (green, blue and yellow) clays are also present. Over the MKUC, the lower portion of the mottled zone intersects the mixed horizon, whereas in the footwall and hangingwall rocks, mottles are developed in the saprolite. The provenance of this mixed material is enigmatic, since it has morphological, geochemical and mineralogical features consistent with both the transported (anatase, gibbsite, zircon and rutile) and residual (chromite, serpentine) components of the regolith. The mega-mottled clay developed at the MKD5 deposit is similar to materials that infill and characterise palaeochannels in the Yilgarn Craton (Anand et al., 1993).

Lateritic gravels (transported)
Lateritic gravels are thickest over the serpentinised MKUC, thinning out over the talc-carbonated orthocumulates and adjacent country rocks. The gravels consist of matrix- and clast-supported Fe-rich pisoliths and nodules, which are unconsolidated or cemented. Both individual and compound nodules are present. Towards the margins of the MKUC, the nodules are polymictic and include clasts derived from granitic, volcanic, basaltic and ultramafic country rocks and fragments of vein quartz. The lower part of the gravel horizon is dominated by goethite and the upper part by hematite. The matrix consists of kaolinite, smectites and quartz, with minor authigenic anatase and gibbsite.

Arenaceous and argillaceous sediments (transported)
Poorly sorted, polymictic alluvial and colluvial sediments, up to 10 m thick (mean 6 m) overlie the MKUC and adjacent country rocks. These sediments are sharply unconformable on the footwal felsic volcanic rocks. Quartz is dominant throughout the sediments, with decreased abundance towards the base, where kaolinite and hematite are more abundant. Traces of feldspar, calcite, talc and mica occur throughout, especially towards the top, and are derived from clasts of partly weathered country rocks. Sub-horizontal to horizontal laminations have developed throughout this horizon, commonly marked by thin coatings of precipitated Mn oxides. These result from a poorly-understood surficial process referred to as "hardpanisation", which includes partial-cementation of sediments by hyalite (opaline silica).

DISCUSSION AND CONCLUSION

Development of the regolith at Mt Keith

In reconstructing the weathering history of the regolith at Mt Keith, factors that may affect chemical and physical processes such as climate, structure and lithotype must be considered. The following discussion attempts to place the development of a weathered ultramafic at Mt Keith into a sequence of events.

- Initially, weathering associated with seasonally humid conditions promoted the removal of soluble products from serpentinised komatiites (e.g., oxy-carboxyl hydroxides) resulting in the development of the saprock from the underlying protolith. Close to the weathering front, relict forsteritic olivine became hydrated to serpentine, carbonates dissolved and sulphides oxidised. Limited local erosion of the surface removed surficial unconsolidated sediments.
- Continued weathering and leaching formed saprolite that generally resulted in decreased bulk rock density increased porosity, deepening of the weathering front and partial collapse of the upper profile, together with residual accumulation of resistate phases (e.g., chromites).
- Loss of serpentine and sharp decrease in Mg marks Mg-discontinuity, above which silica, smectites and Fe oxides dominate. Above the Mg-discontinuity, resistate phases accumulated and the concentration of less soluble elements or soluble elements associated with insoluble phases (e.g., Ni associated with Fe oxides), increases.
- The Fe oxide-dominated upper profile dehydrated and hardened to form an Fe-rich duricrust, resulting

in textural loss in the upper regolith Dehydration involves conversion of goethite to hematite, resulting in elements such as Ni and Cr being expelled and either reprecipitated in the lower profile or leached from the system The Fe-rich duricrust overlying the collapsed Fe-saprolite at Mt Keith marks the position of an unconformity

- Continued weathering resulted in collapse and compaction of the profile and caused slumping and reactivation of primary structures At the MKD5 deposit, collapse resulted in a basinal depression, on the lenticular komatiitic sequence, that has been infilled by locally derived material during periodic flooding. As more material was deposited, the overlying pressure exceeded the tensile strength of the ferruginous saprolite, resulting in further collapse, textural loss and mixing by illuviation and biotic processes These processes increased the concentration of exotic elements (e g , Al, Zr, Ti) across the unconformity to form the mixed zone Collapse was probably assisted by periodic water saturation.
- Following the onset of aridity, circulating groundwaters along structures caused further leaching of silica from the ferruginous saprolite Mottling, resulting from redistribution of Fe above the water table, generally occurred within the exotic material. This mottled zone grades into the overlying lateritic gravels, which, in turn, are overlain by younger transported sediments, suggesting that the lateritic gravels were formed in situ or washed in from the adjacent landscape These partly cemented gravels are composed of pisoliths, probably derived from the underlying mottled zone, and lithic fragments derived from the adjacent landscape and coated by Fe oxides
- The timing of the precipitation of Mn oxides within the ultramafic profiles remains unclear The Mn oxides at the Mg-discontinuity at the MKD5 deposit could not be dated by K-Ar methods (Vasconcelos, verbal communications, November 1996) However, textural evidence suggests that at least some of the Mn oxides precipitated prior to collapse and slumping of the profile (Mn-rich slickensides along joint planes) Similarly the timing of near surface hardpanisation is unknown Regional silicification occurred during the mid-Miocene throughout inland Australia (Mabbutt, 1980) in the transition to a more arid climate. At the MKD5 deposit, the silicification of the upper 10 m of the regolith is possibly contemporaneous with silicification within the Mg-saprolite (as suggested by Butt and Nickel, 1981)

Thus, the development of deep regoliths at the MKD5 deposit has formed through a sequence of events involving the dynamic interaction of geological and climatic factors Whether these events were periodic or a continuum still remains conjecture Also uncertain is the timing of the weathering events; with improved dating technology, the age of weathering within the Yilgarn Craton will be better understood Similarly, the important factors controlling weathering remains a much debated subject However, from the above discussion, the position of the regional water table, controlled by topography, climate, and tectonic activity, is fundamental

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List of Figures

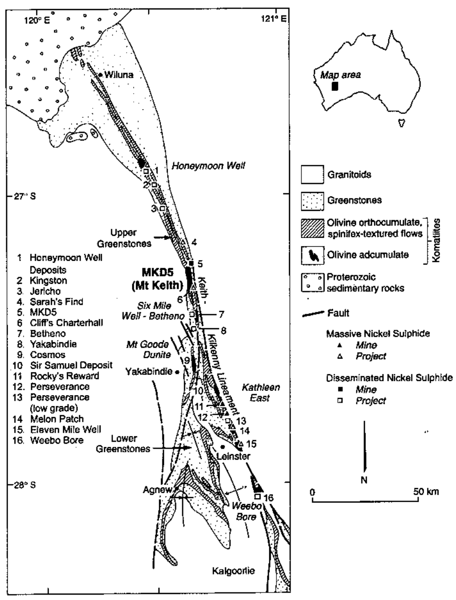
Figure 1: Geology of the Agnew-Wiluna Greenstone Belt between Weebo Bore and Wiluna showing the distribution of komatiite rocks and the location of nickel sulphide deposits (map modified from Hill et al , 1995)

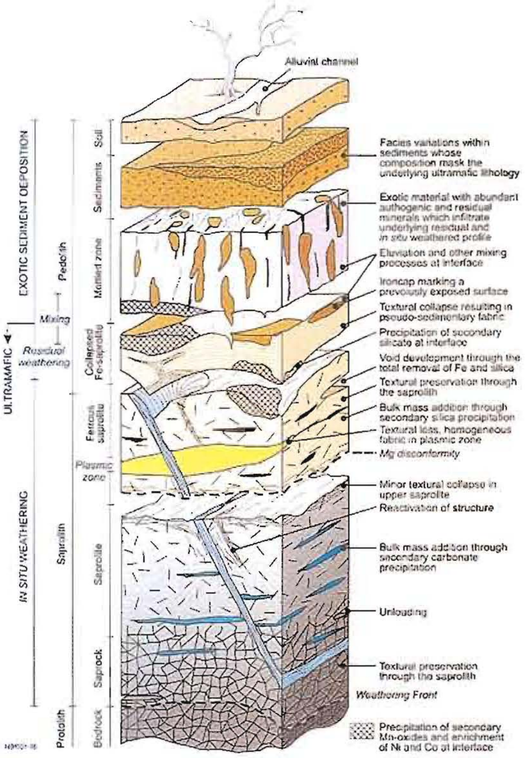
Figure 2: Regolith landform map of the Mt Keith district compiled for this study (interpretation based on Landsat TM imagery generated by the WMC Image Processing Laboratory using data set TM110-79 TM image bands included Ratios 5/7 (red); 4/7 (green); 4/2 (blue), histogram normalised, edge enhanced All data have been atmospherically corrected; original pixel size 30 m)

Figure 3: Regolith stratigraphy of the MKD5 deposit east pit wall (Stage A) on section 10030 mE

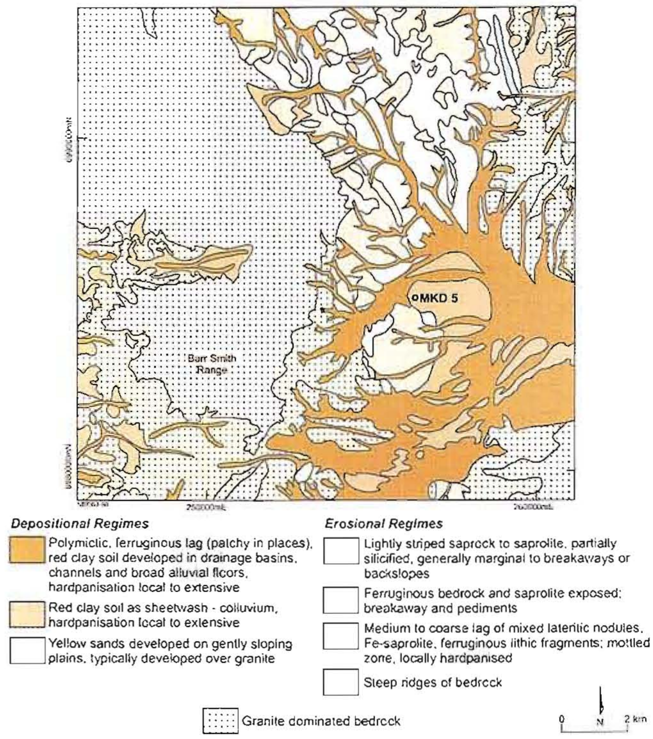
Figure 4: Model of the regolith profile developed over the high MgO komatiitic rocks at the MKD5 deposit

- The Ni sulphide orebody referred to in the published literature and on government maps as Mt Keith is referred to by the current owner (WMC Resources Ltd) as MKD5 (the number assigned to the diamond drill-hole which first intersected Ni sulphides at the mine location) in order to distinguish it from other prospects in the same area, also known as Mt Keith Thus the contemporary name, MKD5, is used throughout this paper

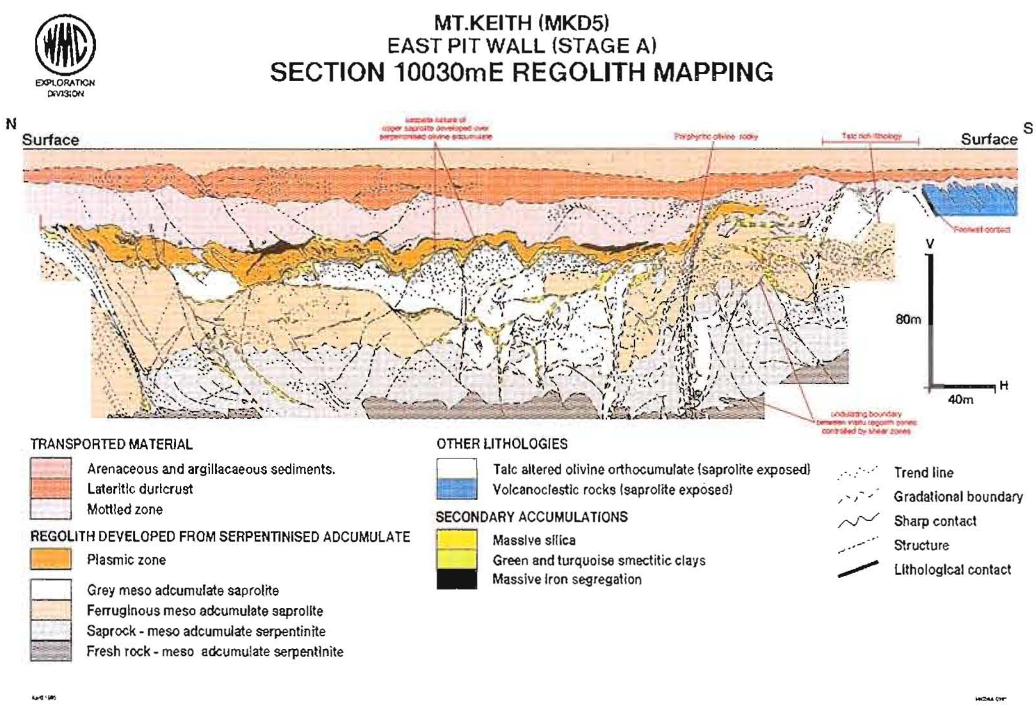




Alluvial channel
EXOTIC SEDIMENT DEPOSITION
ULTRAMAFIC
IN SITU WEATHERING
Pedolith
Mixing
Residual weathering
Saprolith
Protolith
Soil
Sediments
Mottled zone
Collapsed Fe-saprolite
Ferrous saprolite
Plasmic zone
Saprolite
Saprock
Bedrock
Facies variations within sediments whose composition mask the underlying ultramafic lithology
Exotic material with abundant authogenic and residual minerals which infiltrate underlying residual and in situ weathered profile
Eluviation and other mixing processes at interface
Ironcap marking a previously exposed surface
Textural collapse resulting in pseudo-sedimentary fabric
Precipitation of secondary silicate at interface
Void development through the total removal of Fe and silica
Textural preservation through the saprolith
Bulk mass addition through secondary silica precipitation
Textural loss, homogeneous fabric in plasmic zone
Mg disconformity
Minor textural collapse in upper saprolite
Reactivation of structure
Bulk mass addition through secondary carbonate precipitation
Unloading
Textural preservation through the saprolith
Weathering Front
Precipitation of secondary Mn-oxides and enrichment of Ni and Co at interface



MKD 5
Barr Smith Range
Depositional Regimes
Polymictic, ferruginous lag (patchy in places), red clay soil developed in drainage basins, channels and broad alluvial floors, hardpanisation local to extensive
Red clay soil as sheetwash - colluvium, hardpanisation local to extensive
Yellow sands developed on gently sloping plains, typically developed over granite
Erosional Regimes
Lightly striped saprock to saprolite, partially silicified, generally marginal to breakaways or backslopes
Ferruginous bedrock and saprolite exposed; breakaway and pediments
Medium to coarse lag of mixed lateritic nodules, Fe-saprolite, ferruginous lithic fragments; mottled zone, locally hardpanised
Steep ridges of bedrock
Granite dominated bedrock
0
N
2 km



EXPLORATION DIVISION
MT.KEITH (MKD5)
EAST PIT WALL (STAGE A)
SECTION 10030mE REGOLITH MAPPING
N
Surface
S
Surface
V
80m
H
40m
TRANSPORTED MATERIAL
Arenaceous and argillacaeous sediments.
Lateritic duricrust
Mottled zone
REGOLITH DEVELOPED FROM SERPENTINISED ADCUMULATE
Plasmic zone
Grey meso adcumulate saprolite
Ferruginous meso adcumulate saprolite
Saprock - meso adcumulate serpentinite
Fresh rock - meso adcumulate serpentinite
OTHER LITHOLOGIES
Talc altered olivine orthocumulate (saprolite exposed)
Volcanoclastic rocks (saprolite exposed)
SECONDARY ACCUMULATIONS
Massive silica
Green and turquoise smectitic clays
Massive iron segregation
Trend line
Gradational boundary
Sharp contact
Structure
Lithological contact