# Komatiite-hosted nickel sulphide deposits, Australia

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## EXPLORATION MODEL

### Examples

| | *Type 1* | *Type 2* |
|---|---|---|
| | Silver Swan, Nepean, Scotia, Windarra, Kambalda, Maggie Hays Digger Rocks, Cosmic Boy, Perseverance, Ruth Well* | Black Swan, Honeymoon Well*, Yakabindie, Mount Keith |
| | *Pilbara Craton | *includes type 1 deposits, Gole et al. (1996) |

### Target

(Barnes et al. 1994)

| | | |
|---|---|---|
| | Basal accumulation of massive and matrix nickel sulphide ore. | Central accumulation of disseminated nickel sulphide ore. |
| • Grade | Variable, 1.5–20% Ni, massive ore 2–20% Ni, matrix ore av. 2.5% Ni, minor disseminated ore <1% Ni. | Relatively constant low-grade 0.6–1.5% Ni, may be layered. |
| • Tonnage | 0.05–50 Mt | 5–300 Mt |
| • Metal ratio | Bulk Ni:Cu 7–19 | Bulk Ni:Cu >19 |
| • Metal credits | Cu, Ag, Au, PGM, Co | Cu, As, Co |

### Mining and treatment

***Type 1 deposits***

- Underground and open-pit mining.
- Beneficiation involves 3-stage crushing, followed by conventional (ball and rod milling) and autogenous grinding, sizing using screens and cyclones, cell flotation, drum magnetic separation, thickening, flash/spray drying to produce a dry nickel concentrate to refinery with a concentrate grade of 12% Ni, 1% Cu.
- Sherritt-Gordon hydrometallurgical refining process. Oxidation-hydrolysis using a continuous ammoniacal pressure leach, producing nickel briquettes, copper and ammonium sulphate.
- Flash furnace smelting and simultaneous self-roasting of sulphide ore concentrate, producing nickel matte and Fe silicate slag and precious metal collection.
- BioNIC process piloted by Gencor Ltd at Maggie Hays involves bacterial oxidation of nickel sulphide ore with concentrate grades up to 14% Ni. A ferro-nickel product of variable Fe:Ni can be produced to meet the requirements of stainless steel manufacturers.
- BioNIC process avoids smelting and refining steps and operating and capital costs are one-third of traditional metallurgy.

***Type 2 deposits***

- Open-pit mining.
- Conventional drill, blast, load and haul system.
- Primary gyratory crusher, two-stage grinding and ball milling, flotation feed desliming and conditioning, flotation and concentrate washing and dewatering. Concentrate produced as moist filter cake. Head grade at Mt Keith 20% Ni.
- Refining and smelting as above.
- Activox (Yakabindie) process developed by Dominion during evaluation of the Yakabindie deposit involves fine grinding and low-pressure leach to produce a ferro-nickel oxide product.

Economics of mining depend on suppression of Ni arsenides, Mg silicates, Ni chlorides, and Ni sulphates during metallurgy.

### Regional geological criteria

- Age of extrusion ca. 2.7–3.0 Ga within Archaean greenstone belts in Yilgarn and Pilbara Cratons, Western Australia (Wang et al. 1996, Claoué-Long et al. 1988).
- Regionally extensive komatiite sequences which contain thick olivine cumulate flow units.
- Stratigraphic succession characterised by coeval komatiite/tholeiite and komatiite/felsic-intermediate volcanism.
- Presence of sulphidic flows and/or sulphidic sediments as substrates to komatiite units.

### Local geological criteria

- Komatiite flow unit containing identifiable lava pathways now occupied by olivine-rich cumulates.

***Type 1 deposits***

- Presence of sulphidic substrate to komatiite unit (felsic intermediate volcanics, chemical-exhalative sediments).
- Transgressive embayment features at base of preferred lava pathway—evidence for substrate erosion and/or sulphide trap-site.
- Preferred lava pathway occupied by olivine ortho-mesocumulate flanked by episodically emplaced flow units.
- Podiform, ribbon-like shoots, or second-order channels in broad-shallow embayments.
- Thickness 5–50 m, width 50–300 m, down-plunge extent up to 2 km.
- Chemical evidence of substrate erosion and immediate host-rock contamination.

***Type 2 deposits***

- Large, lenticular zones of thickening with transgressive basal contacts, up to 800 m thick, 1–3 km wide, down-plunge extent >1km, occupied by olivine meso-adcumulate.

### Mineralisation features

- Primary sulphide and oxide minerals: pyrrhotite, pentlandite, pyrite, chalcopyrite, ferrian chromite, magnetite.
- Massive sulphides contain spinel-rich zones, commonly at orebody contacts, pyrite-rich bands, and variable grain sizes and textures influenced by thermal and structural history.
- Primary matrix and disseminated sulphide assemblages (types 1, 2) modified by subsolidus re-equilibration with silicates and by reaction with metamorphic fluids:
  - talc–carbonate-hosted assemblages include pyrite, millerite, vaesite, bravoite, polydymite, arsenic-bearing minerals (e.g. gersdorffite); opaque oxides are magnetite and hematite;
  - serpentinite-hosted assemblages include nickel-rich pentlandite, heazlewoodite, millerite, godlevskite, pyrite, magnetite.
- Supergene alteration profiles:
  - oxide (goethite, carbonate) zone above water table (up to 50–60 m depth);
  - violarite–pyrite zone (80–180 m depth);
  - transition zone to primary ore (80–400 m depth).

## Deposit geochemical criteria

- MgO (anhydrous) in komatiite host rocks; lavas >18 wt% MgO, host olivine cumulates; 30–50 wt% in type 1 deposits, 48–53wt% in type 2 deposits, reflecting variation in olivine content.
- Type 2 deposit geochemistry reflects presence of oMc-oAC ($MgO+FeO/SiO_2$ molecular ratio = 1.95–2.00).
- Chemical variation in host rocks is due to progressive fractional crystallisation of olivine+chromite+clinopyroxene +plagioclase from primitive mantle melts.
- Chemical analyses can be used to identify komatiitic host rocks where metamorphism has reconstituted igneous textures and mineralogy, e.g. Mg#, $M^{2+}/Si$, (Barnes et al. 1988), $MgO–CaO–Al_2O_3$ variation diagram.
- Substrate/crustal assimilation + contamination of komatiites by thermal erosion detected by elevated LREE, Nd, Zr, Y, Ti, Al, Fe (Lesher & Arndt 1995, Barnes et al. 1995, Perring et al. 1996).
- PGE contents elevated in sulphides (500–3000 ppb total PGE in massive sulphides), also weakly anomalous in Se, As (Keays 1982).
- Scavenging of chalcophile elements, including PGE, by sulphide during ascent or after eruption produces Ni depletion in parent lava (Barnes et al. 1995).
- S isotopes match those in substrate sediments (Lesher 1989).
- $Os^{187}/Os^{186}$ ratios in ores show chondritic initial ratios. Os isotopic evidence suggests that S is derived from mantle source, not from sedimentary substrate (Foster et al. 1996).

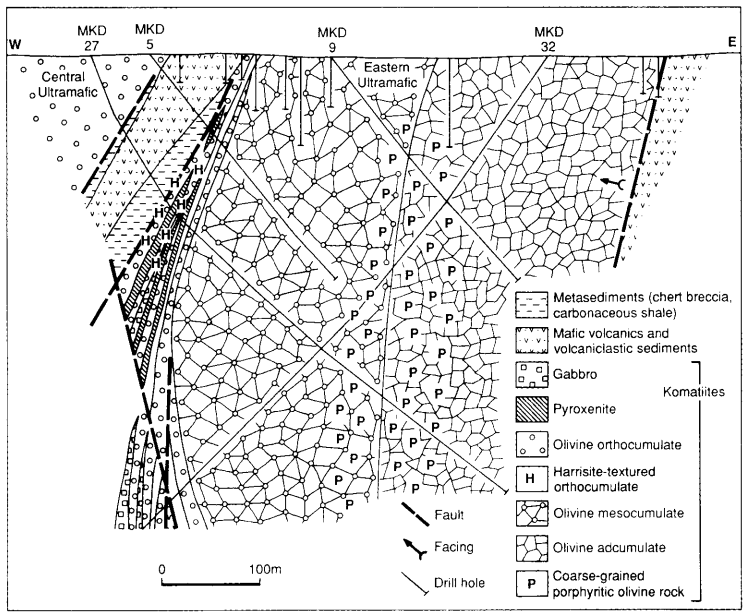


**Figure 1. Interpreted geological cross section through the Mt Keith Ultramafic Complex (Dowling & Hill 1993).**

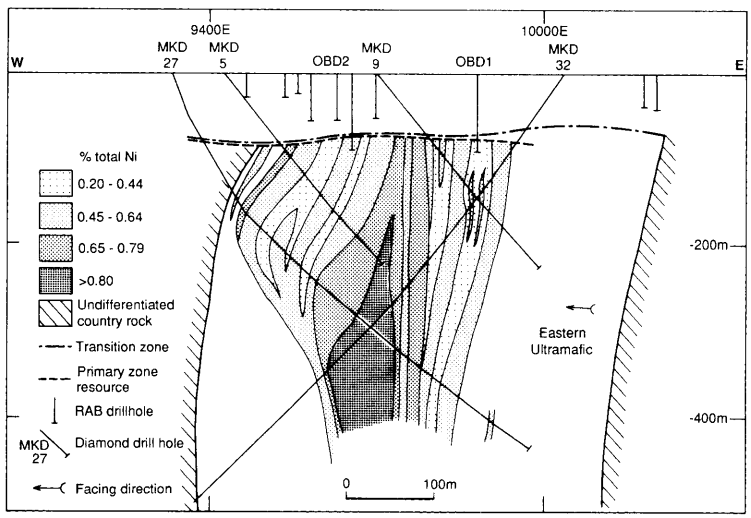


**Figure 2. Interpreted distribution of Ni grade across MKD5 orebody, section 31525N, Type 2 nickel deposit (same section as geological cross section). Data from ACM Ltd, Dowling & Hill (1993).**

## Surficial geochemical criteria

- Most deposits buried beneath laterite, alluvial, colluvial or lacustrine sediments.
- Gossans of massive sulphide, olivine–sulphide cumulate rare, distinguishable by coincident high Ni, Cu, PGE.
- Essential to use regolith mapping to interpret supergene geochemistry sampled by RAB drilling.
- Multi-element scan ICPMS/AAS common analytical methods.
- Ni, Cr, Co, Mn soil/RAB/outcrop geochemical anomalies indicate olivine cumulates.
- Ni, Cu, PGE, Cr coincident soil/RAB/outcrop geochemical anomalies indicate sulphide mineralisation.
- Cu, As, Zn soil/RAB/outcrop geochemical anomalies indicate presence of sulphidic interflow/footwall sediment.
- Mobile metal ion (MMI) technique useful in defining discrete soil geochemistry anomalies over massive NiS orebodies (Mann et al. 1993).

## Geophysical criteria

### *Magnetics*

- Massive sulphide orebodies are magnetic (monoclinic pyrrhotite, magnetite).
- Magnetic susceptibility of komatiite host determined by alteration history:
  - serpentinisation increases susceptibility. Talc-carbonate alteration produces variable to low susceptibilities. Olivine-dominated lithologies generally produce higher susceptibilities.
- Regional aerial magnetic surveys used to locate and define stratigraphic trends involving komatiite sequences:
  - low-level closely spaced aerial magnetic data used to define small-scale prospective volcanic features, such as lava pathways, to resolve structure and detect basal sulphide accumulations.
- Ground magnetic data used for delineating lithological contacts in non-outcropping terrain.

### *Electromagnetics*

- Sulphide ores are poor to good electrical conductors. Deposits are targeted and delineated using surface and down-hole EM techniques. Useful summaries of techniques in McCall et al. 1995, Rekola & Hattula 1995.

## Comments on genesis

***Type 1 deposits***—recent models (Lesher et al. 1984, Lesher 1989, Lesher & Campbell 1993, Barnes et al. 1994, Perring et al. 1995) involve thermal and/or physical erosion of sulphidic substrate at the base of preferred lava pathways. Droplets of immiscible sulphide liquid or a discrete, dense, basal flow of sulphide are carried along by, and scavenge Ni, Cu and PGE from the komatiite lava and are ultimately trapped on the basal contact by a change in flow rheology, change in slope or direction of preferred lava pathway.

***Type 2 deposits***—recognised as extrusive in origin (Hill et al. 1989) and crystallise within large lensoid erosional lava pathways. Consistency of the proportion of sulphide and the Ni grade is a function of segregation of cotectic proportions of sulphide liquid (MSS) and olivine from a lava precisely at sulphur saturation (Duke 1986).

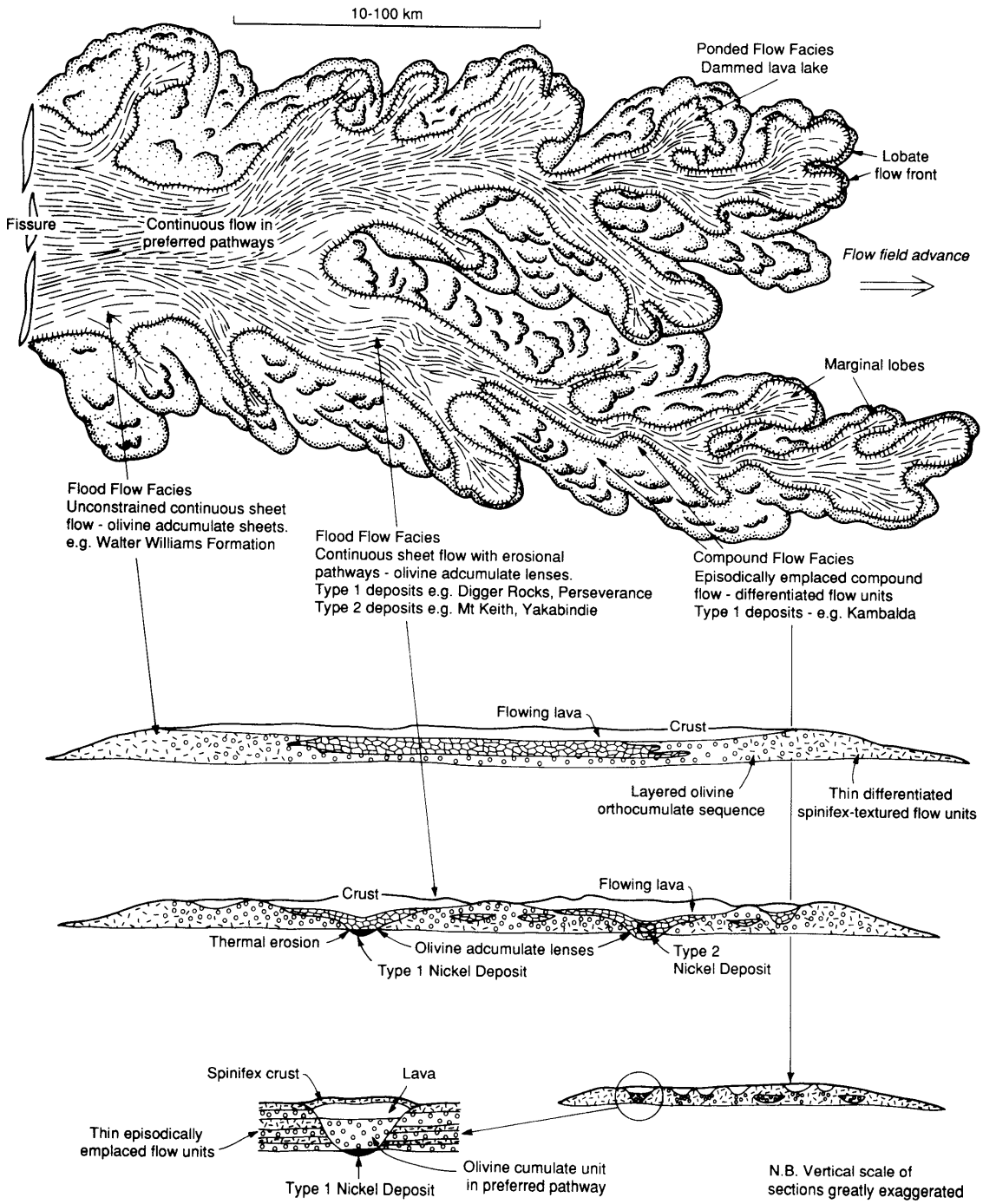


**Figure 3.** ***Upper*** **Schematic lateral section through a regional inflationary komatiite flow field developing via sustained eruption of lava, portraying possible relationships between various volcanic facies, and depicting those eruptive environments (with examples) conducive to the formation of types 1 and 2 Ni deposits (after Hill et al. 1995).** ***Lower*** **Vertical sections through the regional komatiite flow field, illustrating the various volcanic facies depicted in the upper figure, showing lithological associations and the environments of accumulation of types 1 and 2 Ni deposits.**

## Introduction

The nickel exploration boom of the late 1960s and early 1970s led to the discovery of numerous komatiite-hosted Ni-sulphide deposits, associated with variably serpentinised bodies of olivine-rich cumulates. Subsequent research has shown the importance of volcanological processes to understanding the genesis of these deposits. Crucial developments have come through consideration of the fluid dynamics of magmas and magma–crystal mixtures, through observation of the dynamics and geometry of modern-day basaltic lava flows, through application of theory and experimentation on the kinetics of crystal growth from magmas, and, most importantly, from extensive detailed field mapping of komatiitic sequences in the Archaean Yilgarn Block of Western Australia, and elsewhere. From these studies has emerged a new integrated view of the volcanological setting of komatiite-hosted deposits, and a recognition that a complete continuum of deposit types exists.

Nevertheless, komatiite-associated magmatic Ni deposits generally fall into two overall types, based on the nature and abundance of the sulphide ore and the distribution of the sulphide relative to the komatiite host (Lesher 1989, Hill & Gole 1990, Barnes et al. 1994).

In the first type (type 1) the bulk of the ore is either massive Fe–Ni–Cu sulphide or a variable mixture of massive sulphide and an ore characterised by olivine crystals in a continuous matrix of sulphide occupying 30–75% by volume of the rock (called *matrix ore*). Nickel grades of massive sulphide ore range from 2 to 20 wt% and those of the matrix ore generally fall in the range 1–5 wt% (average 2.5 wt%). Ni/Cu ratios of the sulphide fraction are generally >10. The sulphide accumulations are at or near the basal contact of the ultramafic host rock.

The second type of deposit (type 2) is characterised by the dissemination throughout an olivine ortho- to adcumulate host of a consistent proportion of fine-grained sulphide (~2–5 vol%), such that whole-rock nickel grades are generally <1 wt% and consistently average 0.6 wt%.

Both of these styles of mineralisation formed during the eruption and emplacement of komatiite lava, and the processes responsible for their origin form integral components of komatiite volcanology. Successful exploration, therefore, depends on understanding komatiite volcanology and where and how nickeliferous sulphides accumulate to form orebodies during the eruption and flow of komatiite lava.

## Komatiite volcanology

Regionally correlatable komatiite sequences characterise Archaean greenstone belt stratigraphy in the Yilgarn Block of Western Australia. The komatiite lithology shows a wide range of textures arising predominantly from different crystal habits of olivine.

Dendritic or spinifex-textured rocks are characterised by skeletal olivines, which crystallise from lava subjected to high degrees of directional supercooling. In contrast, cumulate-textured rocks arise from the accumulation of more or less equidimensional olivine crystals, which nucleate and grow in dynamic regimes under conditions where temperatures never drop far below the liquidus of the lava.

Cumulate textures are subdivided on the basis of the proportion of cumulus crystals to liquid trapped between the crystals. Olivine adcumulates have little or no intercumulus material, and orthocumulates exhibit high proportions of trapped liquid. Olivine mesocumulates are rocks in which the cumulus crystals have extensive mutual boundary contact, but which contain some primary igneous porosity (Hill et al. 1995).

In Western Australian Archaean greenstone belts, single komatiite flow units display a number of flow profiles. Single and compound flows constitute a range of eruptive complexes, which have been divided by Hill et al. (1995) into a number of mutually gradational facies types.

### *Flood-flow facies*

- Unconstrained continuous sheet flow of lava to produce thick (up to 500 m) sheet-like layered olivine adcumulate bodies and layered ultramafic–gabbro sequences (up to 3500 km$^2$ in area), e.g. Walter Williams Formation in the Norseman–Wiluna Greenstone Belt, Forrestania Greenstone Belt.
- Continuous sheet flow with erosional pathways, giving rise to regionally persistent concordant sheet-like units of olivine orthocumulate (100–200 m thick) with occasional spinifex-textured flow tops, which flank substantially thicker trough-shaped bodies of layered coarse-grained olivine adcumulate up to 1 km thick and 2 km wide, which fill erosional pathways. Komatiite sequences are continuous for over 130 km of strike length, e.g. Agnew–Wiluna Greenstone Belt, Forrestania Greenstone Belt.

### *Compound-flow facies*

- Episodic sheet flows, comprising prolonged preferred lava pathways flanked by marginal compound flow lobes, giving rise to linear trough-shaped features >10 km long, up to 200 m wide and up to 150 m thick, comprising olivine mesocumulates and orthocumulates with minor harrisite layers and thin spinifex-textured flow tops, flanked by sequences of thinner (10–100 m) differentiated spinifex-textured flow units and interflow sediments, e.g. basal Silver Lake Member, Kambalda (described by Cowden & Roberts 1990).

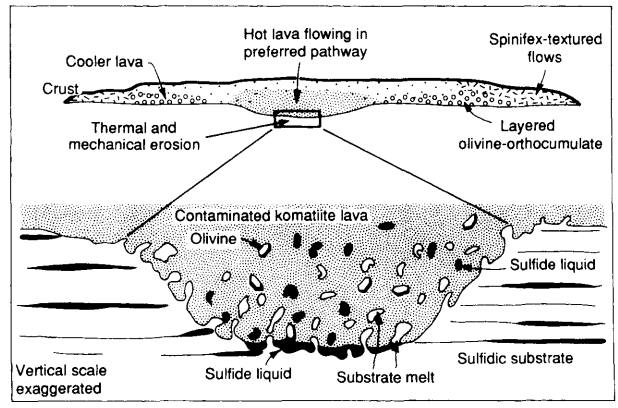


**Figure 4. Schematic cross-section of evolving komatiite flow field, illustrating the process of thermomechanical erosion of sulphidic substrate at the base of a preferred lava pathway and the formation of type 1 Ni deposit.**

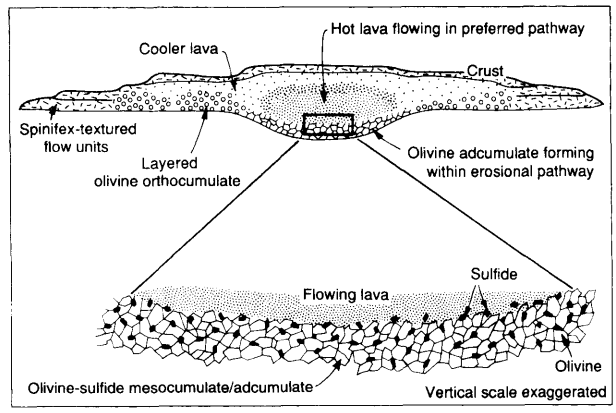


**Figure 5. Schematic cross-section of evolving komatiite flow field, illustrating progressive cotectic accumulation of olivine and sulphide liquid to produce large type 2 Ni deposit within preferred lava pathway.**

- Thin episodically emplaced compound flow lobes, comprising thin differentiated and undifferentiated flow units between 50 cm and 10 m thick and tens to hundreds of metres wide, with no obvious internal pathways.

### *Ponded flow facies*

- Extensive units of fractionated komatiitic rocks, including pyroxenites and gabbros formed by in-situ crystallisation of ponded lava lakes, e.g. Kurrajong (Walter Williams Formation).

Figure 3 shows a highly schematic representation of part of a komatiite flow field (after Hill et al. 1995). It is a generalised model to show how the different volcanic facies could relate to one another as components of a single sustained sheet-flow eruption.

The komatiite field relationships, flow structures, and the distribution of characteristic olivine textures have been interpreted by Hill et al. (1995) and Hill & Perring (1996) as consistent with the mechanisms of flow field emplacement postulated for the long-lived inflationary basaltic sheet flows by Self et al. (1991), Hon et al. (1994) and others.

Relevant features of this model are persistent long-lived lava flows, inflation of flow units under composite visco-elastic and brittle crusts, and the development of preferred pathways or lava tubes, which serve to focus lava flow, provide thermally efficient transport of lava to continuously advancing flow fronts and act as the loci for extensive thermal substrate erosion.

## Volcanogenic setting of nickel deposits

As mentioned above, komatiite-associated Ni deposits commonly consist of a mixture of massive and matrix ore or are almost exclusively disseminated ore. Type 1 deposits comprise accumulations of massive and/or matrix ore at the base of preferred lava pathways in komatiite flow fields. Type 2 deposits comprise accumulations of disseminated sulphide in the central zones of large olivine cumulate bodies, which occupy preferred lava pathways.

It is now generally agreed that the critical difference between the two deposit types lies in how sulphur saturation of the lava was achieved, and whether all the sulphur in the immiscible sulphide liquid which formed the orebodies was initially dissolved in the parent komatiite melt.

Lesher & Campbell (1993) postulated the formation of type 1 deposits by the accumulation of bed-load sulphide liquid which has scavenged Ni, Cu and PGEs from the host lava in suitable trap sites at the base of lava channels. The immiscible sulphide liquid results from the thermal erosion and assimilation of suitable sulphidic substrate during prolonged lava flow (Fig. 4). In

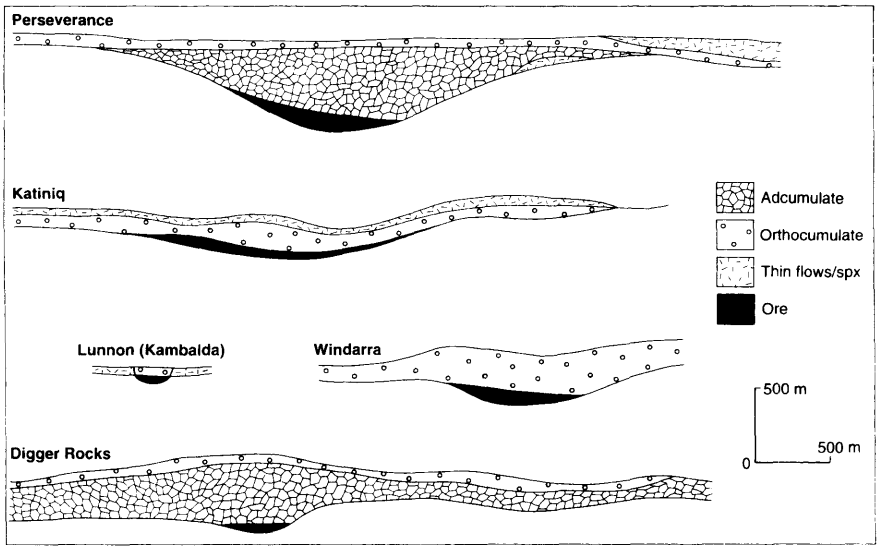


**Figure 6. Selected type 1 deposits drawn to the same scale, illustrating the range in scale of their hosting komatiite stratigraphy (©CSIRO).**

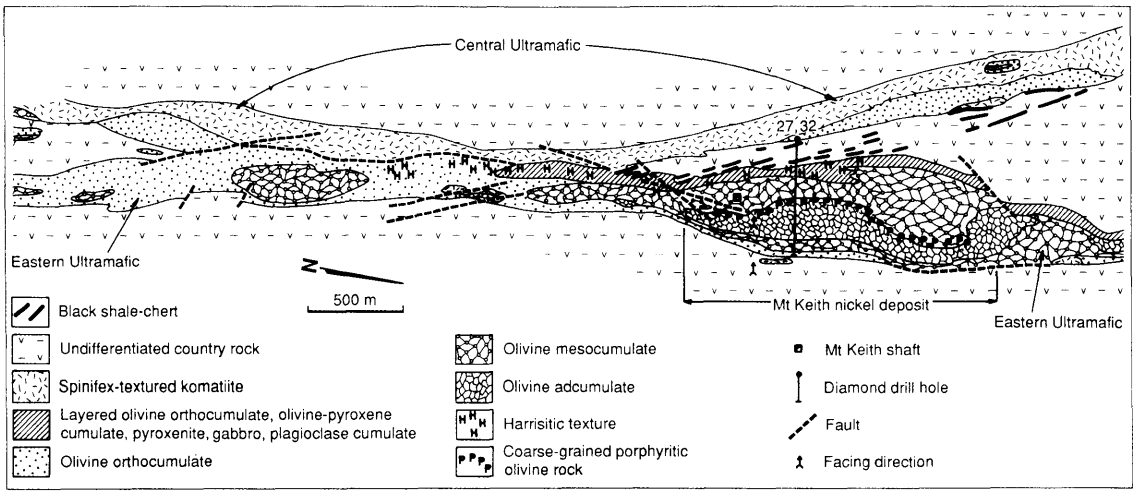


**Figure 7. Geological plan of the Mt Keith ultramafic complex, which is dominated by olivine mesocumulate-adcumulate lithologies occupying a large erosional lava pathway (after Dowling & Hill 1993).**

type 2 deposits, consistency in the proportion of sulphide and Ni grades is interpreted to reflect continuous crystallisation and segregation, within lava tubes, of olivine and sulphide liquid, in cotectic proportions, from flowing lava which is at the point of sulphur saturation triggered by falling temperature, similar to that postulated by Duke (1986; Fig. 5).

Importantly, both types of Ni deposit are hosted by komatiite lithologies which occupy preferred lava pathways or lava tubes. While the principal variable in the classification scheme described above relates to the differing sulphide segregation processes, an additional variable to consider is related to the size and olivine content of the preferred pathway. This varies continuously in komatiite flow fields, as shown schematically in Figure 3. The massive and matrix accumulations of type 1 sulphide are found at the base of the host lava pathways, showing a wide range in size, from relatively small channels or tubes to large regional sheet flows fed by turbulent lava rivers (e.g. Kambalda to Digger Rocks; Fig. 6). In contrast, economic type 2 deposits only occur within large lava pathways which are occupied by olivine mesocumulate–adcumulate lithologies (e.g. Mt. Keith; Fig. 7).

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