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EXCURSION GUIDE

ERUPTIVE ENVIRONMENT AND GEOCHEMISTRY OF ARCHAEAN ULTRAMAFIC, MAFIC AND FELSIC VOLCANIC ROCKS OF THE EASTERN YILGARN CRATON

P.A. Morris, S.J. Barnes, and R.E.T. Hill

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EXCURSION C2 - ERUPTIVE ENVIRONMENT AND GEOCHEMISTRY OF ARCHAEAN ULTRAMAFIC, MAFIC AND FELSIC VOLCANIC ROCKS OF THE EASTERN YILGARN CRATON

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Introduction

Archaean ultramafic, mafic and felsic volcanic rocks are exposed in a 700 km long NW trending belt between Norseman and Wiluna in the Eastern Yilgarn Craton of Western Australia (Fig. 1). This excursion has been designed to illustrate the variety of volcanic associations present in this belt, by examining well exposed volcanic successions. Several recognised stratigraphies for greenstone successions, especially in the southern part of the belt between Norseman and Menzies, have been erected through studies of the gold and nickel mineralisation of the Norseman - Wiluna Belt, and through systematic regional mapping by the Geological Survey of Western Australia. Where possible, the volcanology and geochemistry of greenstones are discussed in terms of this stratigraphic framework.

The excursion is divided into two broad parts: the first three and a half days (mainly led by P.A. Morris) deal largely with the volcanology of mafic and felsic parts of the greenstone sequence. The latter four and a half days (led by R.E.T. Hill) concentrate on komatiite volcanism in the northern part of the belt.

The 650 000 km^2 Archaean Yilgarn Craton is divided into two parts, high-grade granite-greenstone to the west, and low-grade granite-greenstone to the east

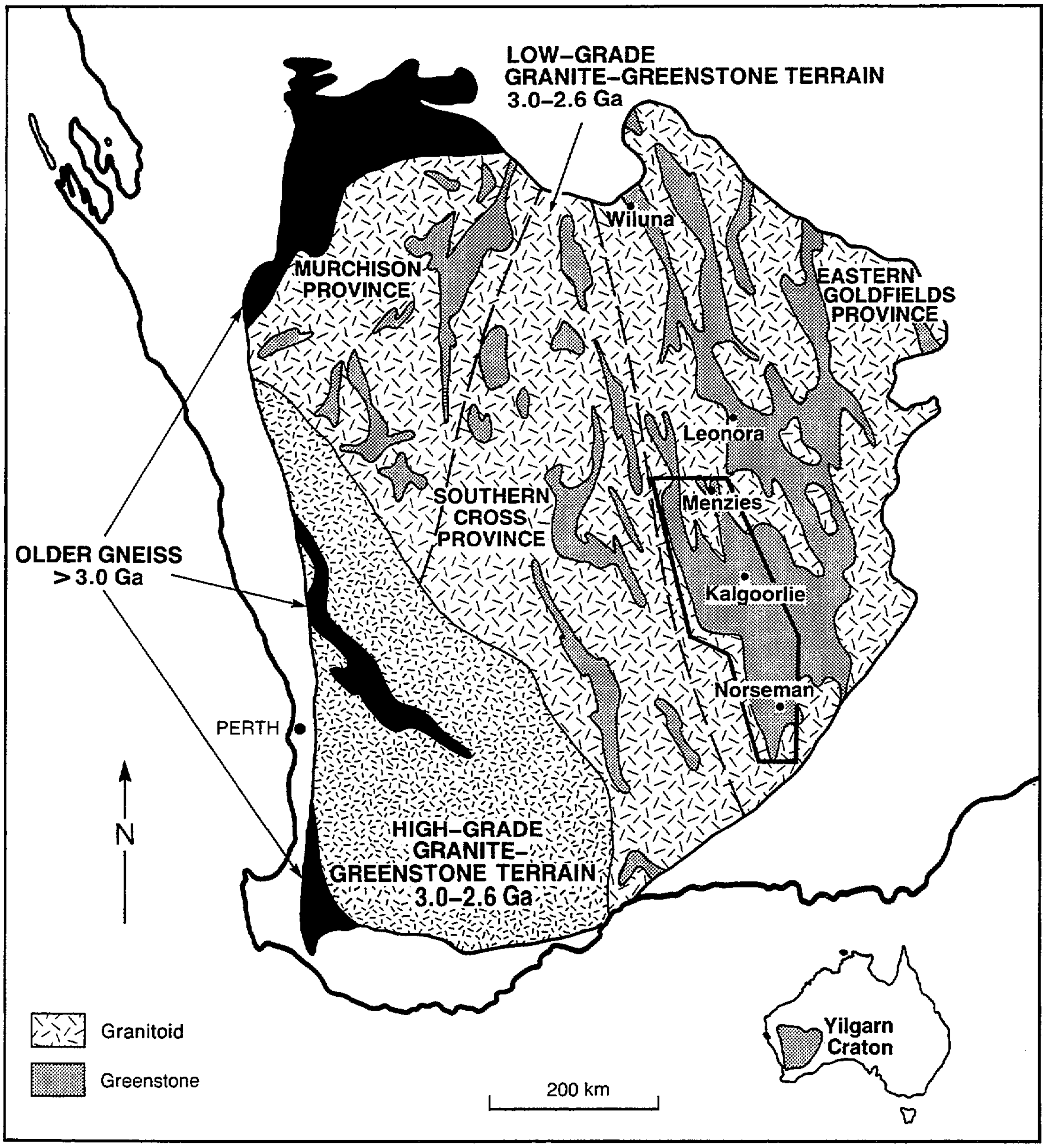

Figure 1. Geological map of the Yilgarn Craton (after Myers, 1988; province boundaries from Gee & others, 1981). The boxed area shows the extent of the Kalgoorlie and Norseman Terranes (Swager & others, 1990) shown in Figure 3.

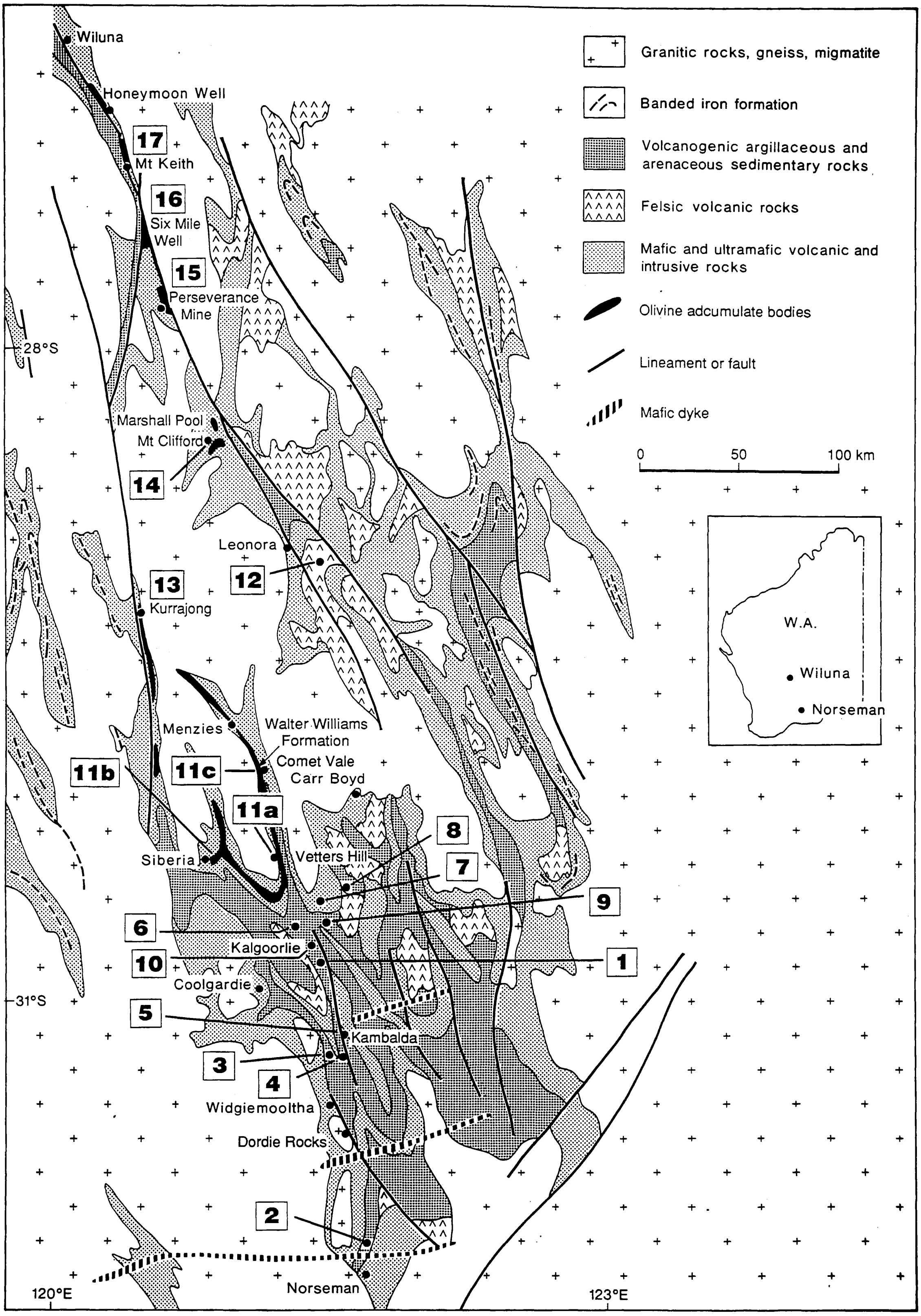

Figure 2. Geological map of the Norseman-Wiluna Greenstone Belt, showing location of the numbered excursion stops described in this guidebook.

(Gee & others, 1981), the latter containing the Eastern Goldfields Province (Fig. 1).

Granitoids and supracrustal greenstones extend approximately 200 km north and south of Kalgoorlie. Within this belt, eleven tectonostratigraphic terranes are recognised by Swager & others (1990) and Swager and Ahmat (1992) based on stratigraphy and structural style (Fig. 3). Due to their rich gold and nickel mineralisation, the Kalgoorlie and Norseman Terranes are the best understood, and the former has been subdivided into six tectonostratigraphic domains.

The stratigraphy of the Kalgoorlie Terrane (Table 1) comprises a lower basalt unit, komatiite unit (with a locally developed basaltic upper part), upper basalt unit, a felsic volcanic and sedimentary unit, and a polymictic conglomerate unit. The Norseman Terrane (Table 2) has a mafic to felsic volcanic succession at its base overlain by banded-iron formation (BIF) and clastic sedimentary sequence, then a thick sequence of basaltic rocks with a minor ultramafic component. The Mt Kirk Formation has now been assigned to the Kalgoorlie Terrane by Swager & others (1990).

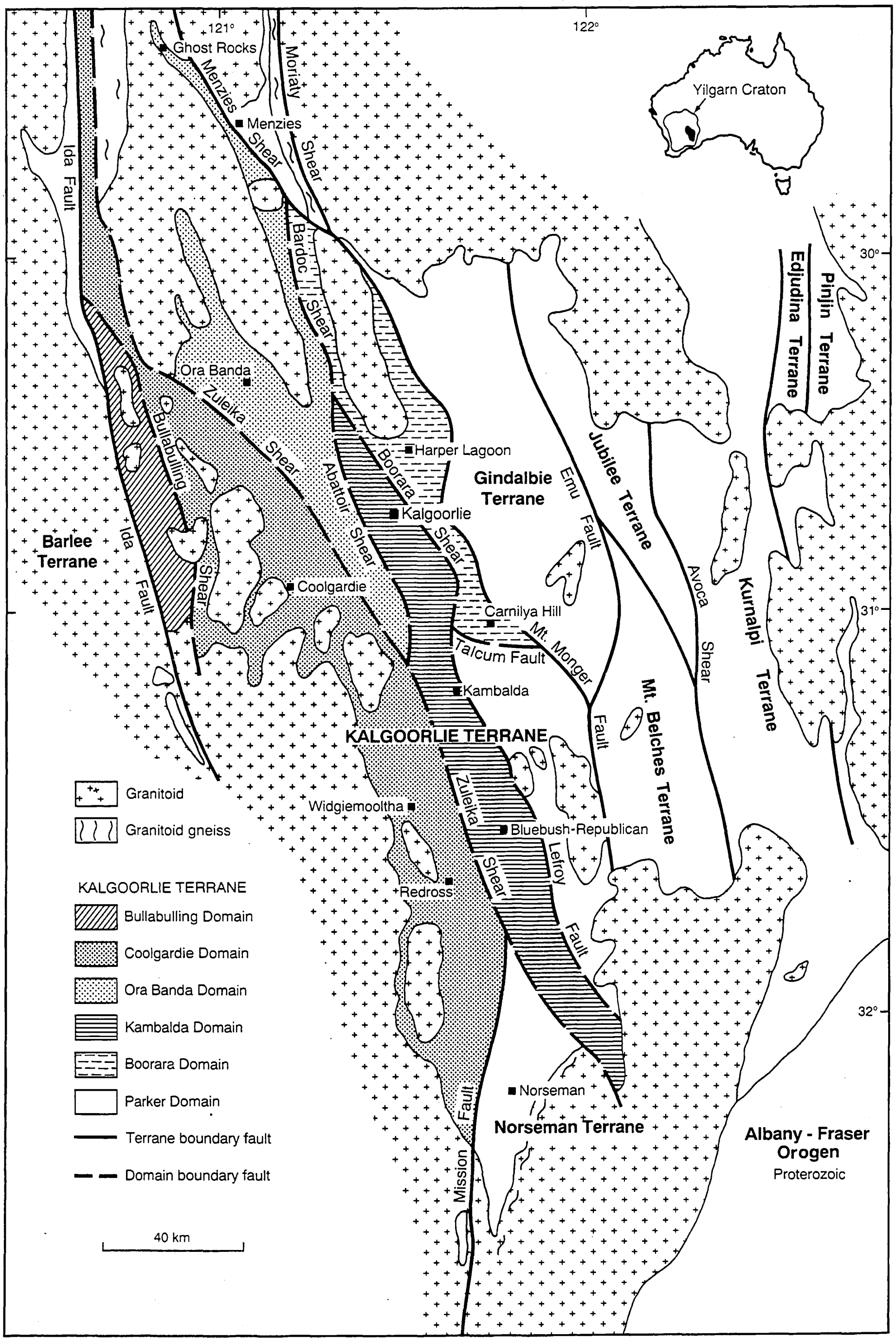

Figure 3. Domains of the Kalgoorlie Terrane, and postulated terranes east of the Kalgoorlie Terrane (after Swager and Ahmat, 1992).

Table 1. Stratigraphic Correlations Within The Kalgoorlie Terrane (from Swager & others, 1990)

Stratigraphic Succession	Ora Banda Domain	Kambalda Domain	Coolgardie Domain	Boorara Domain
Polymictic conglomerate unit	Kurrawang Formation	Merougil Conglomerate	Absent	Absent
Felsic volcanic and sedimentary unit	BLACK FLAG GROUP Pipeline Andesite (Orinda Sill) (Ora Banda Sill)	BLACK FLAG GROUP White Flag Formation Spargoville Formation Junction Dolerite Condenser Dolerite Golden Mile Dolerite Triumph Gabbro	BLACK FLAG GROUP White Flag Formation Powder Sill Spargoville Formation	Felsic unit, volcanic and sedimentary rocks.
				Big Blow Chert
Upper basalt unit	GRANTS PATCH GROUP Victorious Basalt Bent Tree Basalt (Mt Pleasant Sill) (Mt Ellis Sill)	KALGOORLIE GROUP Paringa Basalt Defiance Dolerite Williamstown Dolerite Victory Dolerite	COOLGARDIE GROUP Absent or thin and discontinuous	Absent or thin and discontinuous
		Kapai Slate		
Komatiite unit	LINGER AND DIE GROUP Big Dick Basalt Siberia Komatiite Walter Williams Formation	KALGOORLIE GROUP Devon Consols Basalt Tripod Hill Komatiite Kambalda Komatiite	COOLGARDIE GROUP Hampton Formation	Highway Ultramafics
Lower basalt unit	POLE GROUP Missouri Basalt Wongi Basalt	KALGOORLIE GROUP Lunnon Basalt	COOLGARDIE GROUP (Golden Bar Sill) Burbanks Formation (Three Mile Sill)	Scotia Basalt
Reference	Witt (1987, 1990)	Roberts (1988), Woodall (1965)	Hunter (1993)	Christie (1975), Witt (1990)

Table 2. Stratigraphy of the Norseman Terrane (after Doepel, 1973).

Formation	Member	Thickness (m)
Mount Kirk(1)	Mount Thirsty Beds	
	Abbotshall Beds	
Woolyeenyer	Desirable Pillow Lavas	6000+
	Crown Basalt	180
	Nulsen Slate	2
	Royal Amphibolite	110 - 200
	Bluebird Gabbro	60 -110
	Gee Cee Slate	2
	Mararoa Pillow Lava	1280
	Venture Slate	1 - 3
	Kingswood Basalt	420
Noganyer	Holstein Jaspilite	
	Iron King	
	Hopetoun Jaspilite	
	Lady Mary	
	Lady Miller Jaspilite	
	Marell Schist	
	Attlee Jaspilite	
	Raggedy Member	
	Bon Accord Jaspilite	
	Sawpit Member	
Penneshaw		

(1) Now assigned to the Kalgoorlie Terrane by Swager & others (1990).

In the northeastern part of the Eastern Goldfields Province, no comprehensive stratigraphy has been recognised due to complex interdigitation and structural complexity. Two associations are recognised (Hallber, 1985, 1986) base on felsic volcanic and sedimentary rock assemblages.

Deformation and Metamorphism

The greenstone sequences are characterised by a well-developed NNW structural trend outlined by faults, folds, and elongate granitoids (Gee, 1979; Swager & others, 1990). Four phases of deformation are recognised (Swager & others, 1990), comprising early recumbent folding (D_1), upright folding with NNW-SSE fold axes (D_2), transcurrent faulting and associated folding (D_3), and regional shortening (D_4). This deformation has resulted in regional scale thrust stacking of greenstones (Swager and Griffin, 1990) and tectonic thickening of the greenstone pile.

Detailed metamorphic studies have been carried out by McQueen (1981), Bickle and Archibald (1984) and Wong (1986). Typical mafic rock assemblages are actinolite - chlorite - albite - epidote - quartz - zoisite, whereas in ultramafic rocks, the mineralogy is serpentine - tremolite - talc - chlorite - opaques, with talc - carbonate at higher X_{CO_2}. Felsic rocks are characterised by quartz - albite/oligoclase - chlorite (amphibole) - biotite - muscovite. Regional metamorphism is characterised by low to intermediate pressures (< 4.5 kb), which peaked during D_2 - D_3 deformation, contemporaneous with syn-D_3 granitoid emplacement (Binns & others, 1976; Swager & others, 1990). Two styles of regional metamorphism are recognised (Binns & others, 1976). In the parts of greenstones away from granitoids, static style metamorphism prevails, with lower grades (prehnite-pumpellyite to upper greenschist) and some preservation of original textures. Closer to granitoids, a dynamic style of metamorphism occurs, with higher grades (greenschist to amphibolite), and correspondingly poorer textural preservation.

Stratigraphy And Volcanology Of Mafic And Ultramafic Volcanic Rocks

The Kalgoorlie Terrane

Due to the poor and discontinuous exposure, and weathering, much use is made of diamond drill core for information on the volcanology of greenstones, and to obtain samples for chemical analysis (Morris & others, 1991; Morris, 1993).

Lower Basalt Unit

The lower basalt unit of the Kambalda Domain (Lunnon Basalt) consists of an unknown thickness of massive and pillowed tholeiitic basalt flows. Of fifty nine flow units identified in drill core, 76% are less than 5 m thick (Morris, 1993) Through most of the sequence, the rarity of interflow sedimentary rocks implies rapid eruption. A higher proportion of sedimentary rocks at the very top of the Lunnon Basalt coincides with pillow breccia, hyaloclastite and bleached basalt fragments, consistent with the waning of basaltic volcanism.

In the Ora Banda Domain, the lower basalt unit consists of two parts. The lower part (Wongi Basalt) comprises little pillow lava and abundant pyroxene spinifex- and variolitic textured basalts (i.e. high-Mg composition). The overlying Missouri Basalt is commonly pillowed, texturally more monotonous, and notably more felsic, with locally developed vesicles, and plagioclase phenocrysts.

Similar flow characteristics to the lower basalt unit at Kambalda are observed in the lower basalt unit at Widgiemooltha-Redross (Coolgardie Domain). At Coolgardie, the lower part of the lower basalt unit comprises pyroxene spinifex textured and variolitic basalt, overlain by a coarsely plagioclase-phyric basalt.

Komatiite Unit

In the Kalgoorlie area of the Kambalda Domain, the komatiite unit (Hannans Lake Serpentinite) is 300 - 900 m thick, largely composed of serpentinised ultramafic rocks. Keats (1987) described 1 - 10 m thick laterally extensive flow units at Serpentine Bay (Hannan Lake - SEE EXCURSION STOP 1), which had well developed basal cumulate zones and spinifex textured tops. In the Kambalda area, the komatiite unit shows wide variations in thickness, lensing out in some areas, and reaching up to 1000 m in others. The lower member (Silver Lake Peridotite), consists of thick (25 - 100 m), high MgO komatiite flows with locally developed thin (2 - 10 m), spinifex-textured tops, and abundant sulphidic sedimentary rocks (Gresham and Loftus-Hills, 1981). The upper member (Tripod Hill Komatiite) is a sequence of thinner (1 - 10 m) less MgO-rich komatiite flows with well developed spinifex texture, and locally developed varioles and sedimentary rock intervals. Detailed volcanological work has been carried out by Thomson (1989a, b).

The lower part of the komatiite unit in the Ora Banda Domain, the Walter Williams Formation, is 600 - 900 m thick (Hill *& others*, 1990). This unit comprises a basal orthocumulate succeeded by mesocumulate, adcumulate, olivine harrisite, and a thin orthocumulate (SEE EXCURSION STOP 11). The overlying Siberia Komatiite (exceeding 2.5 km thick at Ora Banda) comprises olivine and pyroxene spinifex textured flow units, with localised gabbro. Within the Siberia Komatiite, sedimentary rocks and breccia are only locally present, and it is assumed that lava was episodically emplaced onto a flat surface.

At Widgiemooltha (Coolgardie Domain), the komatiite unit shows similar lithologic characteristics to the komatiite unit in the Kambalda area. At Coolgardie itself, Hunter (1993) recorded a 600 m thick sequence of komatiite flows, with variably developed cumulate and spinifex textured units.

The komatiite unit in the Boorara Domain comprises cumulate and spinifex textured flow units, which are strongly carbonated. At Harper Lagoon (SEE EXCURSION STOP 8) a well exposed ultramafic-mafic sequence includes cumulate and spinifex textured ultramafic extrusive rocks, pyroxenite, and variolitic and vesicular basalt.

The upper part of the komatiite unit in the Kambalda area (Devon Consols Basalt) consists of pillow lava, clastic sedimentary rocks and dolerite. The unit shows variable thickness up to 200 m. The upper part of the komatiite unit in the Ora Banda Domain is a 500 m thick sequence of variolitic, pillowed basalt (Big Dick Basalt).

Upper Basalt Unit

In the Kambalda Domain near Kalgoorlie, the upper basalt unit (Paringa Basalt) is best exposed at Mt Hunt (SEE EXCURSION STOP 1), where about 200 m of basalt is overlain by 2 - 20 m of chert, 150 - 250 m of coarser grained basalt, thin chert, and 250 m of pillowed and variolitic basalt. At Kambalda, the Paringa Basalt exceeds 1000 m in thickness, comprising basalt, and less common dolerite and sedimentary rocks. The unit includes the Defiance Dolerite, the locus of significant gold mineralisation (Roberts and Elias, 1990).

The lower part of the upper basalt unit in the Ora Banda Domain (Bent Tree Basalt), up to 3000 m thick, comprises both massive and pillowed aphyric basalt. Dolerite and gabbro make up 50% of this unit in some areas. A locally developed slate unit separates the Bent Tree Basalt from the overlying Victorious Basalt, a 2000 m thick massive to pillowed unit with conspicuous well-developed plagioclase megacrysts and coarser grained doleritic horizons (Witt, 1990).

The upper basalt unit in the Ora Banda Domain shows markedly different volcanological characteristics to the Kambalda Domain, in particular the higher proportion of massive flows and smaller amount of mass-flow breccia.

Norseman Terrane

Archaean rocks of the Norseman Terrane strike NNE and dip approximately 055 W (Doepel, 1973; McGoldrick, 1993). They are surrounded and intruded by granitoids, and cross-cut by east-northeast trending Proterozoic dikes (Hallberg, 1987). Compared to the Kalgoorlie Terrane, the Norseman Terrane has fewer ultramafic rocks, more abundant BIFs, and appears to have an older mixed mafic volcanic and clastic sedimentary unit. The style and degree of deformation and metamorphism are similar to the Kalgoorlie Terrane.

The Woolyeenyer Formation consists of massive and pillowed basaltic lava flows (SEE EXCURSION STOP 2). Flow units range from 1-8m thick and are usually thinner than those recorded from the Kalgoorlie Terrane. Throughout the succession, interpillow material is uncommon and the lava is usually non-vesicular. These characteristics are similar to those of the lower basalt unit at Kambalda and indicate the eruption of uniform, low-viscosity magma with a low volatile content.

Stratigraphy And Volcanology Of Felsic Volcanic Rocks

Kalgoorlie Terrane

Of the two greenstone units overlying the mafic and ultramafic sequence in the Kalgoorlie Terrane (Table 1) only the Black Flag Group contains felsic volcanic rocks. Most published stratigraphies of the Black Flag Group record a lower felsic to intermediate volcanic and associated volcaniclastic succession, overlain by dominantly volcaniclastic rocks with only a minor volcanic component (e.g. Travis & others, 1970; Hunter, 1993).

The lower part of the Black Flag Group is exposed in the Gidji Lake area, northwest of Kalgoorlie-Boulder (SEE EXCURSION STOP 7). Facies represented include cohesive, locally brecciated rhyolite lava, oligomictic and polymictic breccia and conglomerate, and interbedded volcaniclastic sandstone and siltstone. Cohesive and jig-saw brecciated rhyolite, the latter with only a few foreign clasts, is interpreted as the core and margin respectively of a subaqueous lava lobe (cf Yamagishi, 1991; De Rosen Spence & others, 1980; Cas, 1992), the breccia resulting from *in situ* quenching of lava in contact with water, and limited reworking. Oligomictic breccia is interpreted as a mass flow or high-concentration turbidity current deposit derived from the erosion of the lava lobe. The overlying sedimentary rocks show characteristics of turbidity current deposition (size grading and cross-bedding). Chaotically-bedded blocks of redeposited sedimentary rocks are interpreted as slumped blocks of partially consolidated reworked ash. Slumping was probably initiated by volcanic activity, such as the eruption of rhyolite lava.

Diamond drill holes from the Lakewood area (SEE EXCURSION STOP 6), approximately 15 km southeast of Kalgoorlie-Boulder, intersect part of the lower Black Flag Group, comprising roughly equal proportions of volcaniclastic, epiclastic, and volcanic rocks. Volcaniclastic rocks comprise open and closed framework oligomictic and less common polymictic breccias, pebbly sandstone, massive, poorly-bedded sandstone, interbedded sandstone and shale, and thinly bedded carbonaceous and pyritic shale.

Coherent dacite lava is flow-banded, but in parts, flow banding is less well developed, and the core is weakly brecciated. It is interpreted as a subaqueous lava lobe. Brecciated lava, with fragments showing jig-saw fit texture (cf Cas, 1992) are marginal to, and gradational with coherent dacite lava. Disorganised, clast-supported oligomictic breccia is found within coherent dacite lava, or adjacent to jigsaw fit breccia. The clasts are all dacitic, and lithologically similar to both coherent dacite lava. Weakly polymictic breccias with variable amounts of matrix are both normal and reverse graded. This facies grades into interbedded volcaniclastic and epiclastic sandstone and siltstone.

Jig-saw fit breccia is consistent with in-situ brecciation with no clast rotation, attributed to quenching of lava in contact with water (i.e. quench brecciation; Cas and Wright, 1987; Yamagishi, 1991; Cas, 1992). Chaotic, disorganised breccia is interpreted as spalled off quench breccia fragments that have accumulated as a mass flow deposit on the lobe margin. More distal parts of this sequence show sedimentary structures consistent with mass flow and turbidity current deposition. Outcrops of other lava lobe/breccia/redeposited sediment associations include Morgan's Island (SEE EXCURSION STOP 4) near Kambalda.

The upper part of the Black Flag group comprises andesite and dacite, as agglomerates, tuff breccias and tuffs and less common columnar-jointed lava flows at White Flag Lake, northwest of Kalgoorlie.

Felsic Volcanic Rocks Of The Kanowna Area

Felsic volcanic rocks in the Kanowna area, approximately 20 km northeast of Kalgoorlie, show complex structural and stratigraphic relationships with mafic and ultramafic volcanic rocks (Taylor, 1984; GSWA mapping).

Coarse grained felsic fragmental rocks crop out over 5km^2 at Perkolilli, 21 km northeast of Kalgoorlie-Boulder. Taylor (1984) estimated a stratigraphic thickness of about 1500 m (SEE EXCURSION STOP

9). Two facies are present, the most common (about 95% of the outcrop) being a poorly sorted clast-rich breccia, and the other a better sorted, locally bedded breccia unit.

Williams (1971) described the breccias in terms of a volcanic centre, whereas Taylor (1984) believed the succession had been redeposited, based largely on the absence of glass shards, favouring subaerial erosion of ignimbrite or rhyolite domes and flows by steep gradient streams, depositing the resultant debris in an adjacent graben. The glassy nature of blocks and matrix, localised evidence for welding, and the primary (glassy) nature of a cross-bedded unit argue for hot emplacement. This deposit resembles small volume pyroclastic flows (nueés ardentes or block and ash flows) such as those described by Wright & others (1980), Smith and Roobol (1982), and Roobol & others (1987).

Felsic Volcanism In The Northeastern Goldfields

Regional mapping over an area of 20 000 km^2 has been carried out in the northeastern Goldfields area by Hallberg (1985, 1986), who recognise two greenstone associations, differing largely in terms of felsic volcanic and sedimentary rock assemblages. The lower Association 1 is characterised by dacite and rhyolite volcanism and associated sedimentation, whereas the overlying Association 2 is andesite dominated. A sequence of rhyolite-dominated volcanic rocks to the west of the area post-dated Association 2 rocks. These rhyolitic centres to the west of the belt are well exposed in the Melita area as a series of subaerial volcanics, overlain, interdigitated with and underlain by mafic volcanic rocks. Rhyolite is the dominant lithology. The two volcanic centres in the Melita have been termed the Melita and Jeedamya Volcanic Centres respectively by Witt (1993). The Melita Volcanic Centre comprises rhyolitic ash, lapilli tuff, pyroclastic breccia, and minor dacite flows (SEE EXCURSION STOP 12). Lithologies are dominated by vitric fragments, with subordinate crystals and few lithic fragments. Witt (1993) attributed these poorly sorted and massive deposits to pyroclastic flows resulting from a Plinian eruption. Associated well bedded fine grained ash deposits (some with accretionary lapilli) represented airfall deposits, some of which had been reworked. Witt (1993) calculated 900 km^3 of eruption products from the Melita Volcanic Centre.

The Jeedamya Volcanic Centre to the south is less well exposed (Witt, 1993), consisting of rhyolitic to rhyodacitic pyroclastic rocks, related epiclastic rocks, minor felsic porphyry, basalt, and dolerite.

Geochronology

Published U-Pb SHRIMP and conventional (i.e. mass spectrometric) ages for greenstones of the Kalgoorlie and Norseman Terranes are summarised in Table 3. The value of geochronological data is constrained by the small amount of data, limited stratigraphic control in sampling, and the difficulty in comparing ages derived by different techniques. The age of the komatiite unit of the Kalgoorlie Terrane is constrained by a date of 2702 ± 4 Ma on a sedimentary unit (interpreted as an airfall tuff) above the lowest komatiite flow, and the Kapai Slate (2692 ± 4 Ma), at the top of the komatiite unit. Three sets of zircon ages are presented from the Victory Dolerite (base of the Devon Consols Basalt). The relatively imprecise age of 2693 ± 50 Ma agrees with that of the Kapai Slate (top of the Devon Consols Basalt), but zircons from the same sample give younger more precise ages of 2669 ± 11 Ma, which Claoué-Long & others (1988) interpret as reflecting a later event. Ages of 3100 - 3400 are interpreted as zircons from basement to the greenstones, and widely quoted as evidence for a silica crust beneath the volcanic pile. The 2669 age is almost the same as the post-D_2 to syn-D_3 Kambalda Granodiorite (2662 ± 4 Ma: Hill and Compston, 1987), which offers some control on the end of tectonism.

The 2676 ± 4 Ma age for a 'felsic volcanic' at Kalgoorlie (Claoué-Long, personal communication, 1990) is notably younger than the presumed stratigraphically equivalent unit at Ora Banda, the Pipeline Andesite (2704 ± 8 Ma). An age of 2698 ± 4 Ma for tuff from Kanowna, 20 km northeast of Kalgoorlie is similar to the Ora Banda age, whereas the age of 2687 ± 3 Ma for the Mt Kirk Formation at the south of the Kalgoorlie Terrane, is similar to the Black Flag Group at Kalgoorlie. Although the remaining data from the northeastern Goldfields and the Kurnalpi Terrane are sparse, they fall into two broad age groupings: near 2720 Ma (Mt Geramtong, Bennetts Dam) and a younger group similar in age to the Kanowna and Pipeline Andesite ages (Pig Well, Teutonic Bore).

Campbell and Hill (1988) have recorded an approximate 2900 Ma (revised to 2938 ± 10 Ma by Hill & others, in prep.) age for the felsic volcanic component in the Penneshaw Formation (Norseman Terrane), and have dated a chert in the Noganyer Formation at 2706 ± 5 Ma. Hill & others (1992) have dated a tholeiitic dyke cross cutting the Woolyeenyer Formation at 2714 ± 5 Ma, and Hill (pers. comm., 1990) has suggested that the Woolyeenyer Formation is the same age as the lower basalt unit (Lunnon Basalt) at Kambalda.

LITHOLOGY	AGE (GA)	INTERP	DATA SOURCE	TECHNIQUE
Kalgoorlie Terrane - Mafic And Ultramafic Rocks				
Sediment above lowest komatiite flow, Kambalda Komatiite	2702 ± 4	M	Claoué-Long and Compston (1987)	S
Kapai Slate	2692 ± 4	M	Claoué-Long & others (1988)	S
Kalgoorlie Terrane - Felsic Volcanic Rocks				
Intrusive felsic porphyry, Suprise Mine, Coolgardie	2686 ± 5	M	Pidgeon (1986), Pidgeon and Wilde (1989, 1990)	C
Felsic tuff, 10 km SE of Kanowna	c 2700 (discordant)	M	ibid	C
Pipeline Andesite, Black Flag Group	2704 ± 8	M	ibid	C
Quartz-albite dyke, Victory Gold Mine, Kambalda	2680 + 21, -12	M	Clark & others (1988)	S
Felsic volcanic unit, Mt Kirk Formation	2687 ± 3	M	Hill & others (1991)	S
Felsic volcanic, Kalgoorlie	2676 ± 4	M	Claoué-Long, pers. comm., 1990	S
Norseman Greenstones				
Felsic unit, Penneshaw Formation	2938 ± 10	M	Hill & others (in prep.)	S
"Hydrothermal" zircons, cherty horizon, Noganyer Formation.	2706 ± 5	M	Campbell and Hill (1988)	S
Basalt sill, feeder to Woolyeenyer Formation	2714 ± 5	M	Hill & others (in prep.)	S
Other Greenstones				
Felsic volcanic, Bennett's Dam, Bulong	2715 ± 14 (xenocrysts: 2841 ± 26)	M	Compston & others (1986)	S
Felsic volcanic, Mt Germatong gold mine, 10km ENE of Leonora.	2735 ± 10	M	Pidgeon (1986), Pidgeon and Wilde (1989, 1990)	C
Felsic volcanic, Pig Well, 18km NE of Leonora	2696 ± 3	M	ibid	C

Table 3. U-Pb zircon geochronology of greenstones, Eastern Yilgarn Craton. Interp (interpretation) - M is magmatic. Technique : S - SHRIMP, C - conventional (mass spectrometric).

Geochemistry Of Volcanic Rocks In The Kalgoorlie and Norseman Terranes

A regional geochemical study (Morris & others, 1991; Morris, 1993) has been completed with the objective of improving understanding of vertical and lateral variations in chemistry of volcanic rocks in the Norseman - Menzies area.

Basalt Chemistry in the Kalgoorlie Terrane

Morris (1993) has identified two broad groupings of basalts in the Kalgoorlie Terrane. Their characteristics are summarised in Table 4. The first (termed Group 1 here) largely consists of samples from the lower basalt unit, whereas the second (Group 2) comprises most members of the upper basalt unit. Some samples (e.g. from the upper part of the komatiite unit, and the lower basalt unit in part of the Coolgardie Domain) are compositionally intermediate between the two groups. There are, notable exceptions to assigning basalts to one of the two groups based purely on stratigraphic position. In the Ora Banda Domain, the lower part of the lower basalt unit (Wongi Basalt) belongs to Group 2, whereas the overlying Missouri Basalt belongs to Group 1, as do the two upper basalt units (Victorious and Bent Tree Basalts). In the Kambalda Domain, samples from the upper basalt unit from Bluebush-Republican belong to both groups.

Ti/Zr, REE chemistry, and Nd isotope chemistry suggest strong similarities between MORB and Group 1 basalts, indicating a mantle source that was homogeneous, depleted in incompatible and LREE, with $\varepsilon_{Nd} > 0$, and depleted in garnet due to a previous melting event. Chemical variation within this group reflects fractional crystallisation, and various degrees of partial melting, with minimal crustal contamination.

Groups 1 and 2 display significant differences in incompatible elements and ε_{Nd}, which imply that the two groups are genetically unrelated. Group 2 is lithologically more diverse (basaltic komatiites and tholeiites), has $(La/Yb)_{CN} \geq 1$, with both $\varepsilon_{Nd} > 0$ and < 0, yet similar Ti/Zr, which suggests the group has a common petrogenetic thread regardless of stratigraphic position or domain affiliation. Although some chemical variation within this group can be explained by low-pressure fractional crystallisation, this cannot explain basaltic komatiites with high MgO, Cr and Ni, but with $(La/Yb)_{CN} \gg 1$ and high Zr, which are likely to have undergone crustal contamination.

Komatiite Chemistry in the Kalgoorlie Terrane

Komatiites from Kambalda and Kalgoorlie (Kambalda Domain), and Widgiemooltha-Redross (Coolgardie Domain) overlap extensively in chemical composition. Comparing komatiites from the Kambalda and Coolgardie Domain, Ti/Zr ratios are constant and close to chondritic. Al/Ti ratios for komatiites from these domains are very slightly Al enriched (by less than 10%) relative to the chondritic value. Komatiites from the Siberia Komatiite Formation in the Ora Banda Domain show slightly lower (by about 10%) Al/Ti ratios compared with the Kambalda and Coolgardie Domains, but identical Ti/Zr ratios. These variations may reflect either derivation of the Ora Banda Domain ultramafic rocks from an Al-depleted source (through garnet

Table 4. Geochemical characteristics of Group 1 and Group 2 basalts from the Kalgoorlie Terrain (Morris, 1993).

	GROUP 1	GROUP 2
Ti/Zr*	106	76
Zr/Y*	2.4	>3
Al_2O_3/TiO_2	20	$\geq$ 20
$(La/Yb)_{CN}$	~1	$\geq$ 1
La_{CN}	10	$\geq$ 10
Σ_{Nd} (T = 2.7 Ga)	> 0	> 0; < 0
Lithology	tholeiites	tholeiites and basaltic komatiites

*unfractionated. Value is slope of line of best fit.

removal?), or contamination by an aluminous component such as continental crust in the Kambalda and Coolgardie Domains. However, the difference in Al/Ti ratio between the domains is small, and may not be statistically significant given the number of samples available. A larger data set is necessary to test for significant regional differences.

Basalt Chemistry in the Norseman Terrane.

All extrusive rocks analysed from the Woolyeenyer Formation are tholeiitic basalts, and are well correlated in terms of Ti/Zr with a line of best fit sloping at 81compared to 106 for the Lunnon Basalt.

Most REE patterns are similar to those of Group 1 rocks, with LREE/HREE enrichments about 8 - 15x chondrite. Samples with high Ti, Zr and Y also have relatively low MgO, and Cr and Ni decreases with increasing Zr, indicating the major control on tholeiite composition is fractional crystallisation.

Geochemistry Of Felsic Volcanic Rocks

Regional studies of the geochemistry of felsic volcanic rocks have been undertaken in the northeastern Goldfields by Hallberg (1985, 1986), Giles and Hallberg (1982), and in the Kambalda - Kalgoorlie - Melita area by Morris (in prep.).

Morris (in prep.) has shown that both the Black Flag Group and the two volcanic centres in the Melita area are weakly bimodal, Hallberg's (1985) Association 2 volcanic centres comprise basalt - andesite - dacite - rhyolite (e.g. Welcome Well, Bore Well).

The behaviour of compatible and incompatible elements with increasing silica indicates that fractional crystallization exerts a major control on the chemistry of the Black Flag Group, whereas variable degrees of partial melting and fractional crystallization control the chemistry of felsic volcanic rocks at Melita.

Black Flag Group felsic rocks have steep REE patterns ($(La/Yb)_{CN} \sim 100$), whereas felsic volcanic rocks from the Melita area have similar LREE contents but flatter patterns ($(La/Yb)_{CN} \sim 3$), with negative Eu anomalies (Eu/Eu* = 0.5). Relative to the Black Flag Group, felsic volcanic rocks from the Melita area and Kanowna have higher SiO_2, Y, HREE, Nb, and lower Sr, Al_2O_3. The Black Flag Group chemistry is similar to high Al trondjhemite - tonalite - dacite (TTD) described by. Drummond and Defant (1990) and Defant & others (1991), whereas the Melita and Kanowna felsic rocks resemble low Al-TTD.

Tectonic Setting Of the Kalgoorlie Terrain

U-Pb ages >3000 Ma old for zircons in sedimentary and igneous rocks in the Kalgoorlie Terrane (Compston *& others*, 1986) indicates that the mafic and ultramafic volcanic rocks have probably been erupted through sialic crust. The high proportion of mafic and ultramafic volcanic rocks in the Kalgoorlie Terrane relative to adjacent terranes has led several authors to suggest the Kalgoorlie Terrane formed in a rift flanked by platform sequences (Williams, 1974; Groves and Batt, 1984). A rift is consistent with the rapid outpouring of magma, the abundance of pillow lava, the fine-grained nature of intercalated sedimentary rocks, and the pronounced (NW-SE) polarity of the Kalgoorlie Terrane.

A Tectonic Model For The Kalgoorlie Terrane.

Morris (1993) has suggested fan-shaped opening of an intra-continental rift to explain the distribution of mafic and ultramafic volcanic rocks in the Kalgoorlie Terrane. The volcanic products in the rift are consistent with deep water eruption: i.e. pillow lava, fine-grained sedimentary rocks, with some of the latter representing ash fall-out from the volcanic arc. Initially, the rift opens at a greater rate to the north, and komatiite magma rises to the surface. Some of the komatiite is contaminated by and fractionated within the continental crust prior to eruption (i.e. Wongi Basalt of the Ora Banda Domain;), whereas further south, the komatiite acts as a heat source to melt the asthenospheric mantle producing tholeiitic basalt that is variably fractionated in crustal magma chambers prior to eruption (i.e. lower basalt of the Kambalda and most of the Coolgardie Domains). Accelerated rifting in the north of the rift results in crustal thinning and eruption of uncontaminated and variably fractionated komatiite. The lava flows from north to south, broadly parallel to the rift. The rift then closes faster in the south than the north, and komatiite provides a heat source for basalt production in the Ora Banda Domain, but is erupted in a variably contaminated and fractionated state to the south in the Kambalda Domain.

Further compression of the rift results in closure of magma conduits, and komatiite now melts the lower crust, which has been converted to amphibolite under different P, T, and X_{fluid} conditions to produce felsic volcanic rocks of the Black Flag Group and Melita felsic volcanics.

EXCURSION C2 - STOP DESCRIPTIONS

STOP 1. The Kambalda Domain Stratigraphy At Hannan Lake and Mt Hunt

The Hannan Lake and Mt Hunt traverse is located about 15 km southeast of Kalgoorlie and contains exposure of most members of the Kambalda Domain stratigraphy, apart from the lower basalt unit. The geology of the area is shown in Figure 4.

Due to its geological importance, participants are requested not to hammer the rocks at this excursion stop.

Komatiite Sequence At Serpentine Bay

Komatiite flows of the Hannan Lake Serpentinite (the komatiite unit of Swager & others, 1990) are exposed on the shore of Hannan Lake. Despite the talc carbonate alteration, textures are sufficiently well preserved to identify flow units, which are between 1 and 10 m thick, and young to the east. They comprise cumulate B-zones overlain by spinifex textured A-zones. The mineralogy of the cumulate zone is talc - carbonate - serpentine - magnetite, after olivine, whereas spinifex textured zones comprise coarse sheaves of talc - carbonate - albite - chlorite - magnetite, after platy olivine. To the east, drill holes in the lake and scattered island outcrops reveal basalt and sedimentary rocks of the upper part of the komatiite unit (Devon Consols Basalt), the Kapai Slate, and the upper basalt unit (Paringa Basalt).

Mount Hunt

The traverse from the base to the top of Mount Hunt illustrates the structural complexity of the greenstone stratigraphy, exemplified by several repetitions of the prominent Kapai Slate. Description of this section is taken from Hallberg (1972) and Swager & others. (1990).

Pillowed and variolitic Devon Consols Basalt (i.e. upper basaltic part of the komatiite unit) crops out in the creek at the start of the traverse. The pillows are zoned, with a more felsic core and chlorite + feldspar rich rim. Varioles composed of albite, amphibole and chlorite form a transitional zone between core and rim.

Overlying the Devon Consols Basalt is a prominent outcrop of cherty Kapai Slate, which is locally pyritic

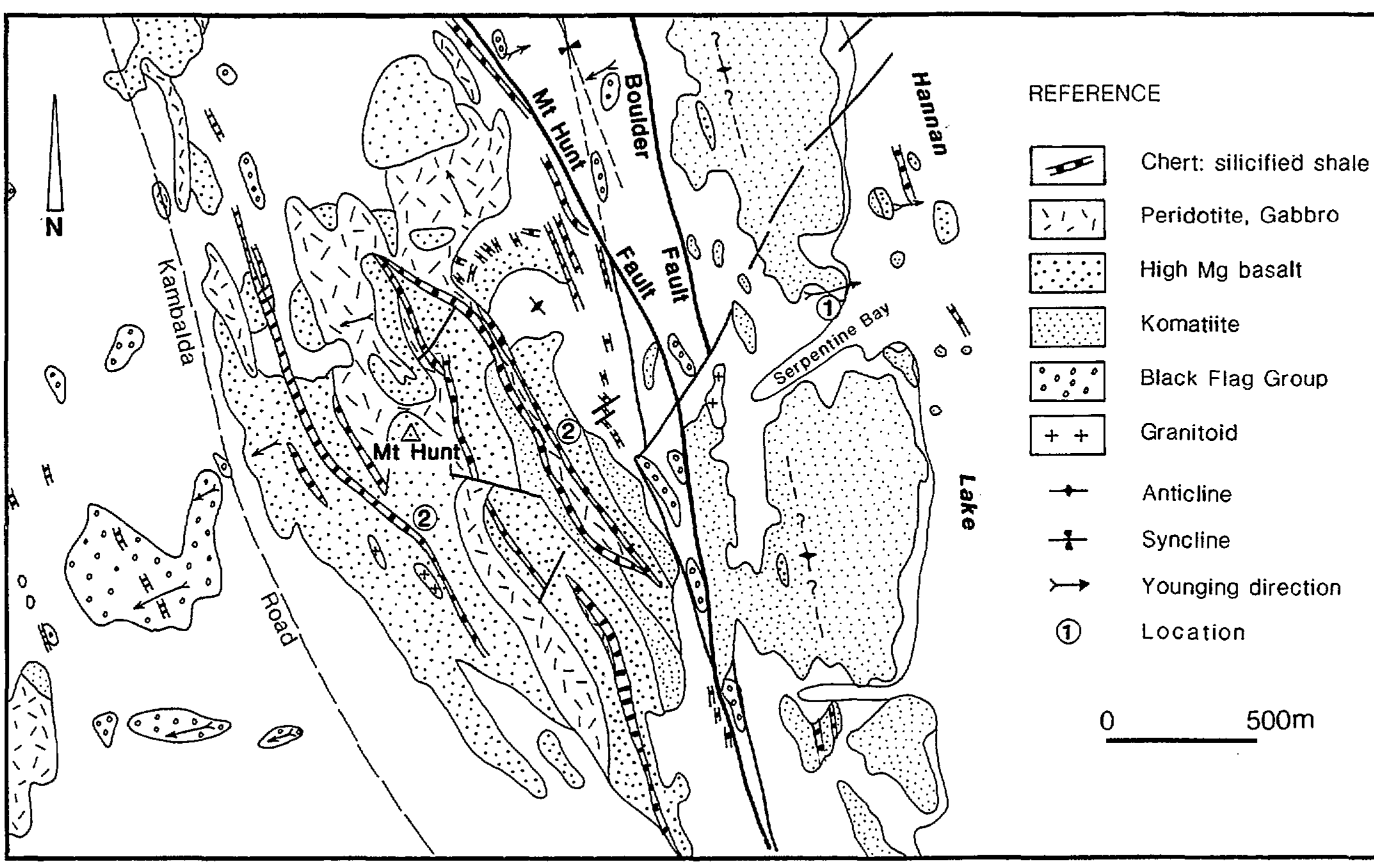

Figure 4. Detailed outcrop map of the Hannan Lake - Mount Hunt area (after Griffin & others, 1983; Swager & others, 1990).

and carbonaceous. Adjacent to the Kapai Slate are rubbly outcrops of the Williamstown Dolerite, now talc - tremolite - serpentine - magnetite - apatite, after peridotite. The unit is heterogeneous along strike, including gabbro and norite (Williams and Hallberg, 1973).

Further to the west, a fold repeats Kapai Slate, then Devon Consols Basalt, then Kapai Slate again. The remainder of the traverse to the top of Mount Hunt crosses the upper basalt unit (Paringa Basalt), characterised by acicular amphibole in a fine grained matrix of amphibole, biotite, chlorite, albite, clinozoisite, and quartz. This 'pyroxene spinifex texture' is characteristic of high-Mg (> 10 wt% MgO)composition .

Black Flag Group On The Kalgoorlie - Kambalda Road

To the west of Mt Hunt on the Kalgoorlie - Kambalda Road are reworked volcaniclastic rocks of the Black Flag Group, the regional extensive felsic volcanic and volcaniclastic unit overlying the mafic - ultramafic succession. At this locality, the Black Flag Group are characterised by graded and current bedding, scour structures, rip-up clasts, and locally developed conglomerate. Clasts in the latter are dominantly felsic volcanic lithologies, but mafic varieties are also present. The underlying Paringa Basalt forms weathered, locally pillowed exposures on the eastern side of the road.

STOP 2. Desirable Pillow Lavas, Woolyeenyer Formation (Norseman Terrane)

On the western shore of Lake Cowan (Fig. 5, Fig. 6) is a well exposed, 6 km long lakeside sequence of mainly tholeiitic basalt from the upper part of the Woolyeenyer Formation (Hall and Bekker, 1965; Doepel, 1973). While outcrop rapidly degenerates into rubble inland, areas of continuous exposure on the lakeshore and islands give a three-dimensional view of the stratigraphy. This stop is to examine this lakeside exposure north of the causeway across Lake Cowan.

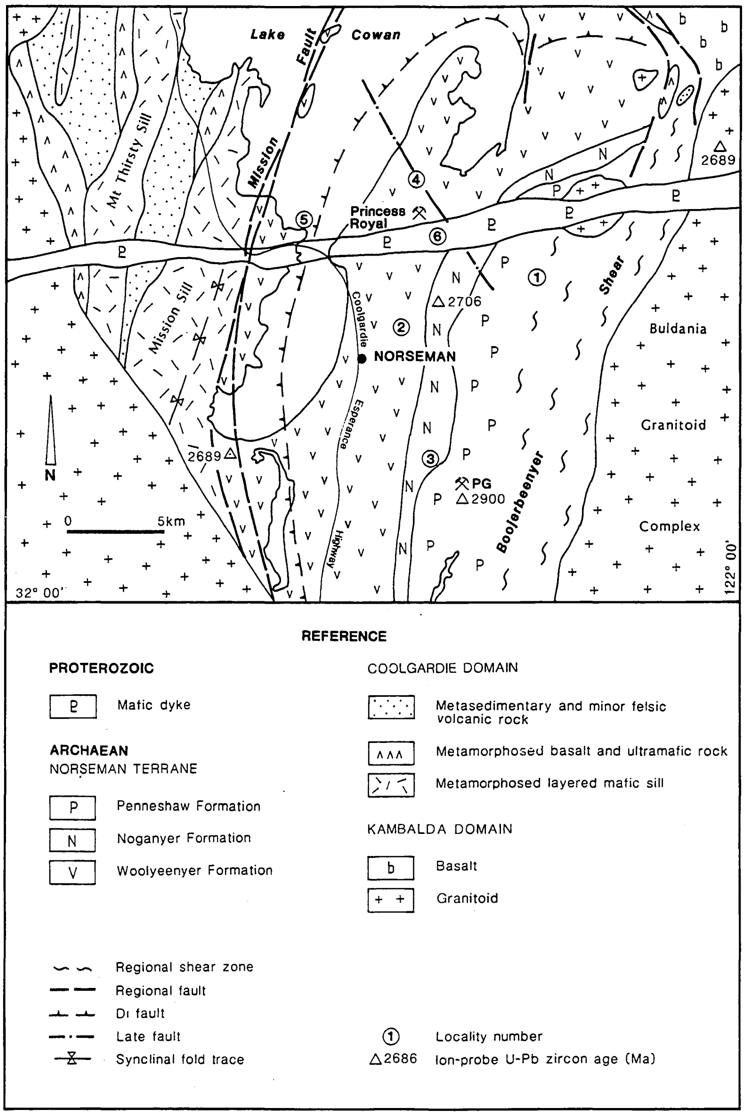

Figure 5. Regional geology of the Norseman area, after Swager & others (1990)

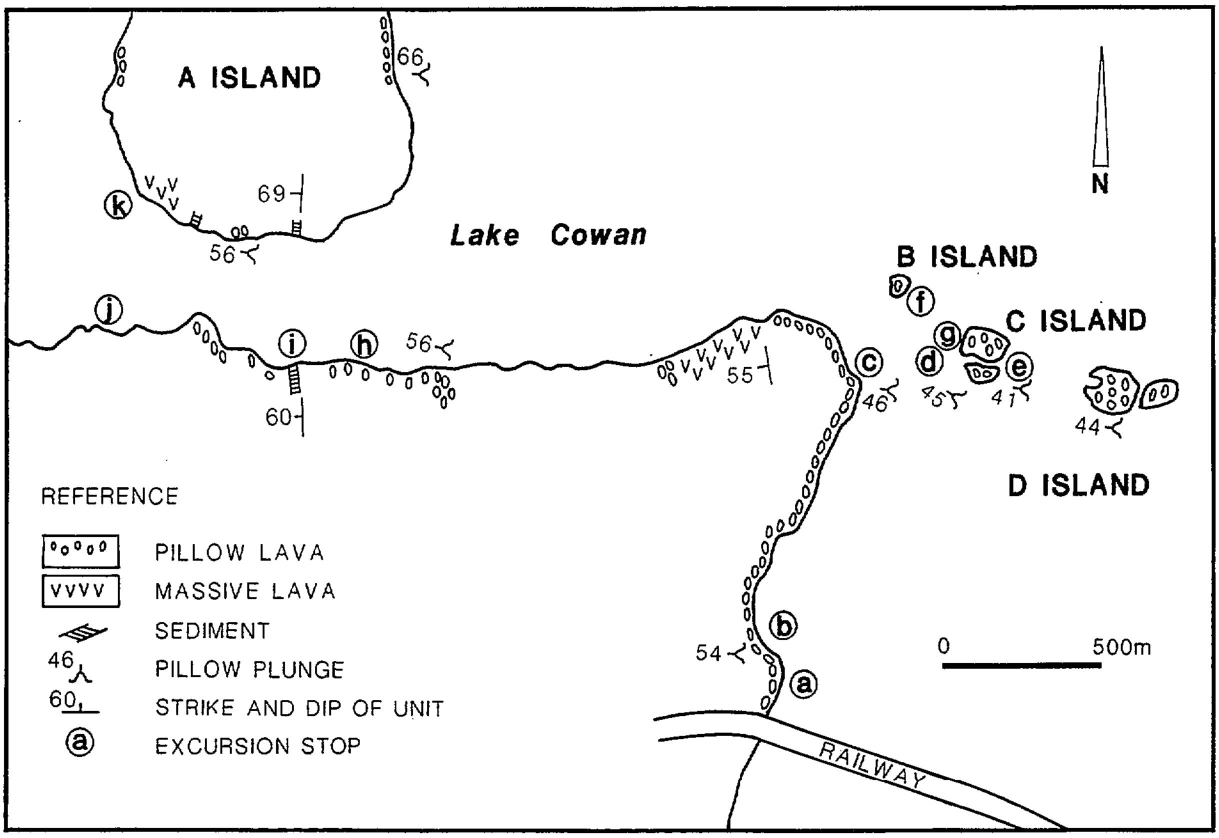

Figure 6. Detailed geology of the upper Woolyeenyer Formation on the western shore of Lake Cowan. From Swager & others (1990).

At the excursion stop, the basalts dip west at about 45°, and, according to pillow morphology, young in this direction. A variety of features are developed in this sequence (Fig. 6). At the beginning of the traverse (sites a and b) are well developed variolitic pillow basalt, and more massive doleritic units which could be high-level intrusions or interiors of thick flows. Three-dimensional views of lava lobes and pillow tubes are exposed at site c. Pillow tubes also crop out at site e, and pillow lava at site f has well developed varioles overprinted by pipe vesicles. Pillow breccia occurs at site g.

Moving west, these relatively undeformed pillows become progressively elongated parallel to the regional shear (subparallel to strike), and pillow lava is notably more recrystallised (site h). Uncommon interflow sedimentary rocks are felsic and fine grained, with scattered garnet porphyroblasts (site i and along strike on island A). A flow unit with well developed variolitic texture outcrops at site j. North across the lake on the island (site k), an outcrop comprises aligned amphibole needles. The texture is metamorphic, and not pyroxene spinifex texture, although it is likely that the unit is a concordant high-Mg flow, now totally recrystallised.

STOP 3. Fragmental Rocks of the Black Flag Group

Felsic rocks of the Black Flag Group form low, featureless outcrops to the west of Kambalda and south towards Widgiemooltha.

At one of these localities, approximately 1 km east of the Coolgardie - Widgiemooltha road (Fig. 7), grey, plagioclase-phyric felsic volcanic rocks with numerous inclusions of pink feldspar porphyry form bouldery outcrops.

In thin section, the rock is quite strongly recrystallised and heterogeneous. Aggregates of granoblastic feldspar, quartz and biotite up to 7 mm diameter are set in a groundmass of quartz, feldspar, biotite, and subordinate chlorite and muscovite. Less common single crystals of subhedral plagioclase (up to 5 mm) are cloudy and variably sericitised, and some are replaced by feldspar and biotite. Subordinate quartz grains (< 2 mm) are weakly embayed.

Although texturally different to the Morgans Island rhyolite (see Stop 4), this unit is mineralogically and chemically similar. This, and other compositionally similar, coarsely porphyritic units are interpreted as high-level, subvolcanic equivalents of lava lobes.

Stop 4. The Black Flag Group At Morgans Island: Subaqueous Lava Lobe And Associated Breccia

Cohesive felsic lava, breccia, and volcaniclastic sandstone and siltstone of the Black Flag Group crop out on the western side of Lake Lefroy at Morgans Island (Griffin, 1990; Brauns, 1991: see Fig. 7). The succession is unconformably overlain to the west by fluviatile sandstones and polymictic conglomerates of the Merougil Beds (Griffin, 1988). Sedimentary structures in the upper part of the sequence, and the relationship to the Merougil Beds indicates the sequence youngs to the west.

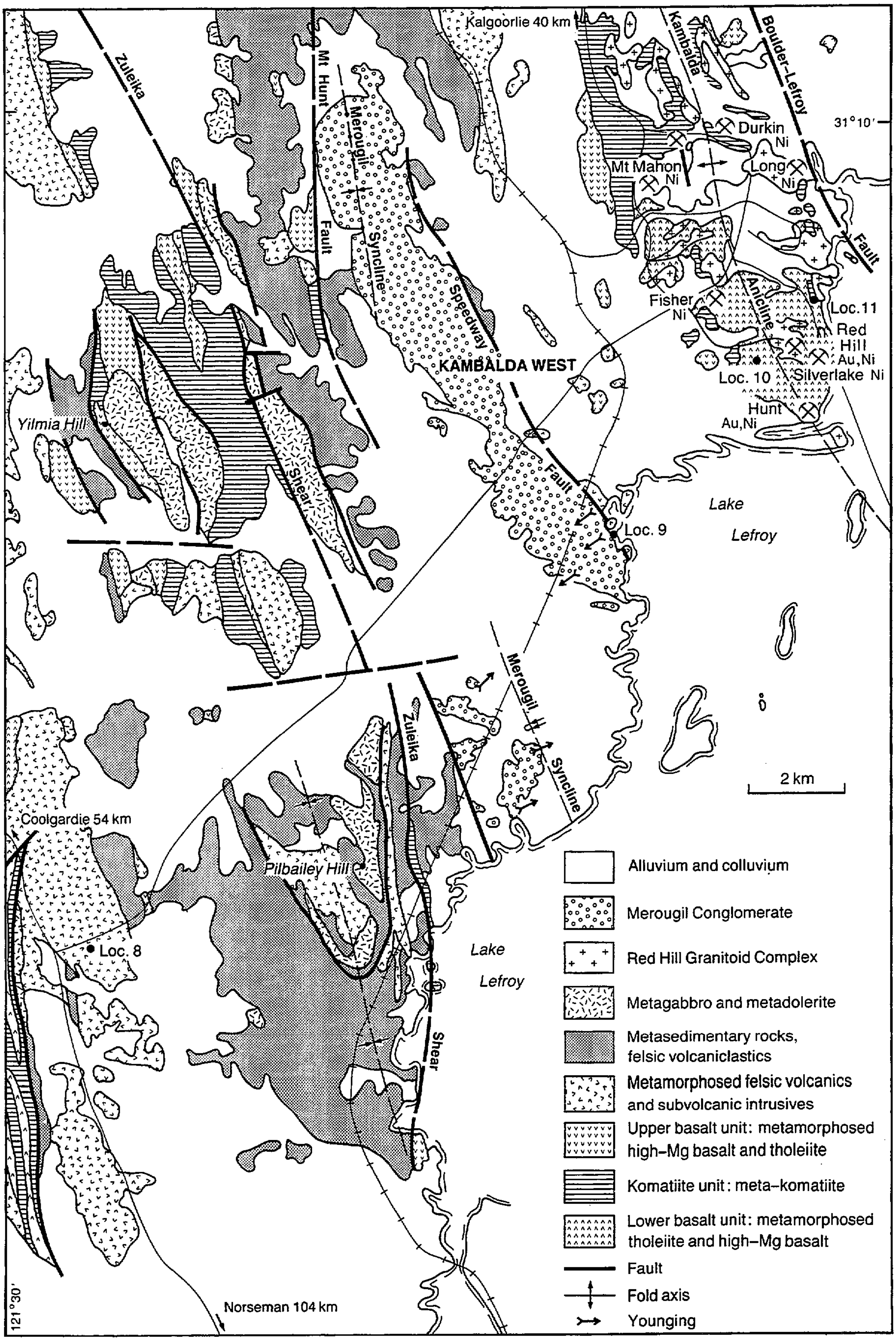

Figure 7. Geology of the area southwest of Kambalda, showing the location of excursion stops 3 and 4. After Griffin and Hickman (1988) and Swager & others, (1990).

At the bottom of the succession (i.e. to the east), rhyolite lava forms an elongate N - S outcrop in Lake Lefroy. It is a minimum 200 m thick, and lacks any internal subdivision. The rock is homogenous and buff coloured, with scattered phenocrysts of feldspar and subordinate quartz in an originally glassy groundmass.

In thin section, plagioclase phenocrysts (optically oligoclase; up to 2.5 mm) are euhedral, weakly resorbed, and sericitised. Quartz phenocrysts up to 4.5 mm are weakly embayed and rounded, and show some undulose extinction. These phenocrysts, and scattered disseminated aggregates of biotite flakes (some ghosts after ?amphibole), are set in a groundmass of weakly granoblastic quartz and feldspar, and wispy muscovite.

On the mainland to the southwest of the peninsula, is oligomictic breccia, with subangular dacite clasts lithologically identical to cohesive lava. The breccia is clast supported, with individual clasts up to 40 cm diameter. At one locality, the dacite is more cohesive. Lithologically similar breccias show local development of jig-saw fit texture.

Interpretation Of The Morgans Island Succession

The following interpretation draws from work of Brauns (1991) and published accounts of De Rosen Spence & others (1980), Yamagishi (1991), and Cas (1992).

The strong lithologic similarity of lava and oligomictic breccias at Morgans Island indicates a genetic relationship. The sequence is interpreted as a subaqueous lava lobe surrounded by an in-situ breccia, which resulted from the quenching of lava in contact with water. Movement of the lava following extrusion and brecciation would result in spalling off of angular lava fragments and deposition of these as massive, largely oligomictic, clast supported breccias. Finer grained components of these breccias could represent quench fragmentation of the lobe. The sequence is interbedded with volcaniclastic sandstones, again dominated by felsic volcanic debris, although containing some mafic lithologies. These were deposited during periods of quiescence between lava lobe extrusion, and as they comprise compositionally similar material to lava lobes, they probably represent distal, turbidity current deposits from lobe erosion.

STOP 5. Channel And Flank Facies Of Komatiite Flows (KNO Coreyard, Kambalda)

The Kambalda Komatiite formation consists of up to 1200 m stratigraphic thickness of komatiite flows, divided into the Silver Lake (lower) and Tripod Hill (upper) members (Cowden and Archibald, in prep.) (Figure 8). The Silver Lake Member comprises thick olivine-rich flows with thin intercalated sulphidic sediments, and contains the nickel mineralisation. This is overlain by the Tripod Hill Member, up to 1000 m thick, consisting of thinner (1 to 20 m) less magnesian flows without intercalated sediments. There is an overall decrease in MgO content of the komatiitic rocks upward through the Kambalda Komatiite, from values up to 45% in cumulate rocks near the base to 16% in rocks typical of the upper part of the Tripod Hill Member. Chemically, the rocks are typical alumina-undepleted komatiites with depleted incompatible trace elements.

Mineral assemblages at Kambalda are strongly dependent upon metamorphic fluid phase compositions, and talc-carbonate alteration is widespread. Hydrated olivine orthocumulates consist of antigorite, chlorite, magnetite, tremolite and chromite with or without sulphides. Carbonated equivalents show variable degrees of replacement of antigorite by talc and magnesite. Originally spinifex textured rocks are converted to tremolite - chlorite - antigorite or tremolite - chlorite - dolomite - magnesite - magnetite assemblages. Textural preservation is variable, the best preserved examples being in non-carbonated spinifex rocks.

The Silver Lake Member consists of one or more 25 m to 100 m thick high-Mg komatiite flows with thick lower cumulate B-zones and thin upper spinifex A-zones. Lateral variations in internal structure and differentiation of flows, and distribution of interflow sediments and Ni-sulphide bodies, define two time-equivalent volcanic facies. These were originally defined empirically as "Ore Environment" and "Non-Ore Environment" (Gresham and Loftus Hills, 1981) depending on the presence or absence of thick basal Fe-Ni sulphide accumulations, and have since been referred to in genetic terms as "channel" and "sheet flow" facies (Fig. 9, after Cowden and Roberts, 1990).

The channel facies is characterized by thick units of up to 100 m of olivine orthocumulates with minor olivine harrisite layers, thin intervening spinifex zones and an absence of interflow sediments (Fig. 9). The thickest flow unit is at the bottom, and typically hosts the major thickness of Fe-Ni sulphides. Up to three subsequent flow units occur above it. Channel Facies units occupy linear belts at least 10 km long but no more than 500 m wide (Cowden and Roberts, 1990). In some cases "Hanging Wall" ore zones occur stratigraphically vertically above the major "Contact Ore" zones and consist of massive sulphide bodies directly overlying spinifex zones of the underlying flow.

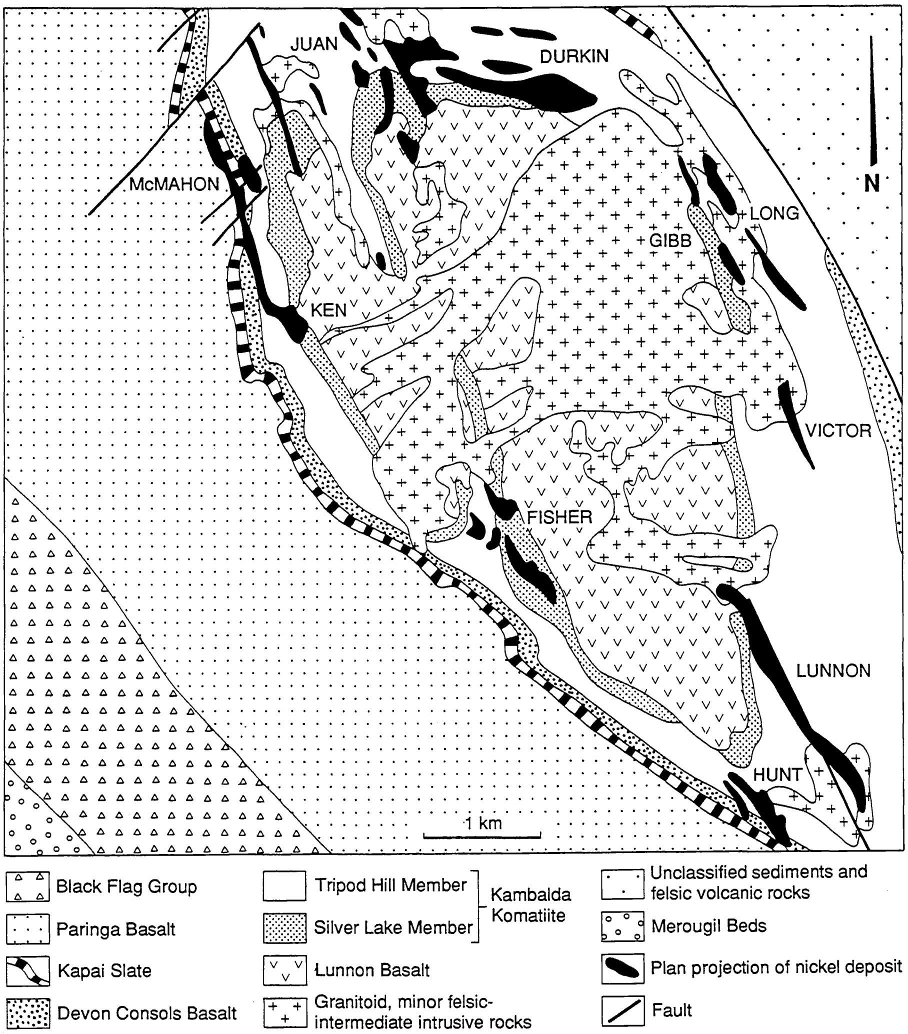

Figure 8. Geological map of the Kambalda Dome, after Cowden and Roberts (1990).

The basal "Contact Ore" zone at the base of the thick lower flow is usually in direct contact with the footwall Lunnon Basalt. Interflow sediments, which occur along the basalt - komatiite contact in the flanking sheet flow environment, are absent below contact massive ore in all cases except for the Foster and Mount Edwards orebodies (Cowden, 1988). There is some controversy as to whether the Contact Ore and its host komatiite flow occupy primary topographic troughs or channels within the basalt substrate. There is no question that many of the Kambalda ore bodies occupy physical troughs in the footwall surface, but the controversy centres on the extent to which these are artifacts of subsequent low-angle faulting. It is clear that thermal erosion of thin footwall sediment layers has occurred in some if not all cases.

Sheet Facies komatiites occur gradational with and flanking the Channel Facies units. They are thinner (10-20 m) and poorer in cumulus olivine than the laterally equivalent Channel Facies flows, and are well differentiated into A and B zones. Thinner flows correlate laterally over hundreds of metres, and in some cases (e.g. Durkin - Cowden, 1988) can be correlated with flow units of the Channel Facies. Thin interflow sediment units are common, but pinch out in the transitional zones between Sheet Flow and Channel environments (Fig. 9). Frost and Groves (1989) document the occurrence in several deposits of thin units comprising spherical felsic ocelli in a fine grained mafic matrix, overlying the spinifex zones of flanking flows in the transition zone between Channel and Sheet Flow facies (Fig 9).

The volcanic stratigraphy of central Channel Facies with flanking Sheet Flow facies is now generally accepted as the result of flow of komatiite lava down primary central feeder channels, with episodic overflow to form thin "overbank" sheet flows (Cowden, 1988; Lesher & others, 1984). Precisely the same geometry and process is seen in modern basaltic lava flows on Hawaii. The open nature of the central channels is recorded by the high proportion of cumulus olivine to spinifex zones. Lava was continuously flushed through the channel, spilling periodically over the side, and leaving behind an olivine-rich residue formed by

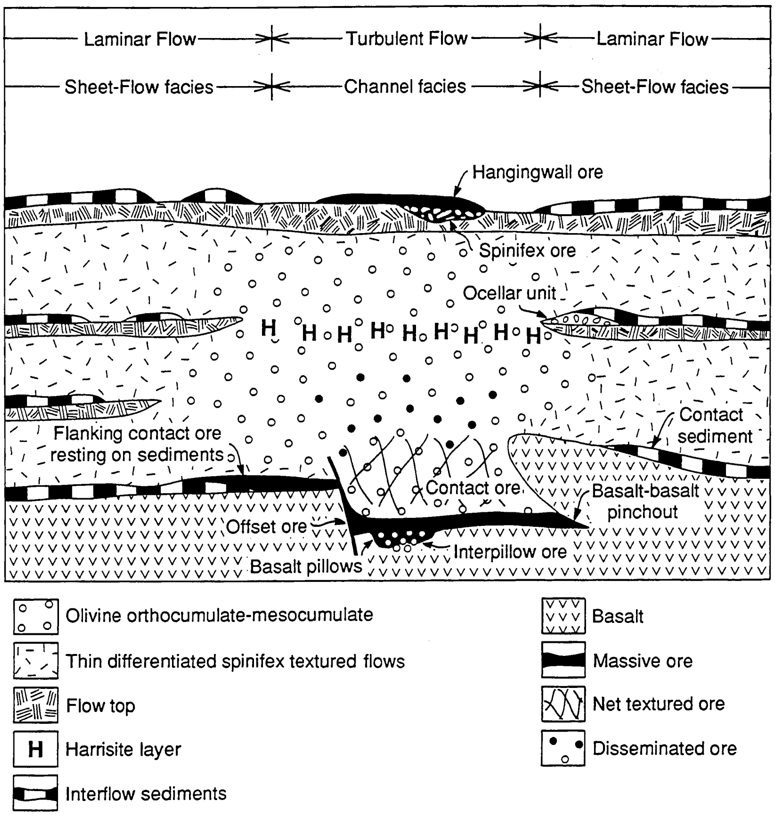

Figure 9. Diagrammatic cross-section showing relationship between channel and sheet flow facies and sulphide mineralisation in the Silver Lake Member of the Kambalda Komatiite Formation, modified from Cowden and Roberts (1990).

crystallization at the temporary channel floor. Periodic stagnation within the channel is recorded by the development of distinctive harrisite zones, which probably grew upward from the channel floor from temporarily stagnant lava beneath a quenched flow top. Flow down the channel occurred beneath a floating quenched skin, which was periodically absorbed into the flowing lava and remelted as observed in modern day basalt flows. During periods of particularly rapid extrusion, komatiite lava overflowed levee banks on either side of the main channel to form thin sheet flows, which differentiated in situ to form typical thin layered flows with well developed spinifex zones.

The ocellar units described by Frost and Groves (1989) in the transition zone between channel facies and flanking sheet flows are interpreted to have formed as a result of partial melting and assimilation of interflow sediment at the base of the main channel. Contaminated siliceous melt rose as a "scum" on the flowing komatiite lava, and accumulated at the banks of the channel. The ocellar rocks provide firm evidence for the operation of thermal erosion, at least on a small scale, beneath komatiite flows at Kambalda.

STOP 6. Felsic Lava Lobes And Associated Breccias In Drill Core From The Lakewood Area (Western Mining Corporation Coreyard, Kalgoorlie)

Thirteen diamond drill holes from an early phase of exploration in the Kalgoorlie area are held by Western Mining Corporation. All have been drilled south of Kalgoorlie in the Lakewood area, sufficiently far enough away from the mineralized Golden Mile that the effects of carbonation and deformation are only weakly developed. Despite this, the core retains a bedding parallel foliation, and has been metamorphosed to greenschist facies.

Three of these thirteen holes contain several hundred metre long intersections of the Black Flag Group, the felsic volcanic unit overlying the main ultramafic and mafic sequence of volcanic rocks. Of these three holes, one (SE3) contains about 1300 m of Black Flag Group devoid of any intrusive rocks that are found in the other two holes.

Representative lithologies of the Black Flag Group are displayed:

(1) Background sediments. (TRAYS 4113' to 4178').

These are thinly laminated to thinly bedded carbonaceous shales, some with sandstone interbeds. The shale is locally sulphidic, and has suffered some soft sediment deformation. Evaporite mineralogy has been recorded by Golding and Walter (1979), and interpreted by them as evidence for shallow water deposition.

(2) Polymictic mass flow breccias and turbidite sequences (TRAYS 1748' to 1792'). Polymictic breccias and sandstones are limited in terms of their mineralogy (quartz and feldspar), and clast type (dacite - rhyolite), consistent with derivation by wastage of lava lobes and reworking of tuffaceous deposits. Carbonaceous fragments are interpreted as rip ups of the substrate, and the matrix has a high carbonaceous content..

(3) Cohesive and brecciated lava (TRAYS 578' to 685', and 853 to 1280). The upper 600 m of Black Flag Group in SE3 comprises cohesive, flow banded, locally brecciated dacite and rhyolite. Breccias comprise jig-saw fit and chaotic, disorganised deposits. Logging of this core (Morris, 1993) has shown a few sharp contacts between cohesive parts of the lava lobes, but the normal situation is cohesive lava gradually becoming glassy and brecciated, giving way to jig-saw fit breccia, chaotic breccia, and more polymictic deposits. The sequence is interpreted in terms of a subaqueously erupted lava lobe with in situ quench breccia. Gravity fall of this breccia (possibly promoted by lobe movement causing breccia to spall) resulted in chaotic largely oligomictic breccia deposited near the lobe margin, whereas polymictic deposits result from mass flow.

STOP 7. Felsic lava lobe and associated sedimentary rocks of the Spargoville Formation, Black Flag Group At Gidji Lake.

Felsic volcanic rocks exposed 15 km northwest of Kalgoorlie form part of the Spargoville Formation, the lower unit of the Black Flag Group (Hunter, 1993).

On the eastern side of the Kalgoorlie - Leonora railway line is a rubbly outcrop of pale green - yellow conchoidally fractured rhyolite, with locally developed globular features, possibly spherules. The rock contains a few quartz and feldspar phenocrysts up to 1 mm long. About 60 m to the north, a rhyolite-dominated breccia has a few angular mafic clasts. In thin section, this rock contains subangular locally cuspate felsic volcanic rock fragments up to 5 mm, comprising feldspar laths with minor quartz and rare amphibole pseudomorphs. Locally, fragments show jig-saw fit texture. Between the clasts is cryptocrystalline quartz and thin blades of feldspar with scattered opaque oxide and abundant secondary carbonate and sericite. The rock shows characteristics of a weakly reworked, autobrecciated rhyolite or dacite.

To the southeast, lithologically similar rhyolite crops out in a break-away. It is succeeded to the north by a poorly sorted open and closed framework breccia dominated by volcanic fragments. Immediately north, matrix-supported pebbly sandstone is succeeded by medium grained sandstone and shale interbeds. Low angle cross bedding indicates the sequence youngs northwards, with the rhyolite at the base. Further north, chaotically arranged blocks of thinly bedded felsic volcaniclastic sandstone form a clast supported breccia with little matrix. Individual blocks show graded bedding, cross bedding and slump structures. Petrographically, the sandstones comprise 1 - 4 mm thick lamellae, which are individually size graded. The coarser lamellae consist of clasts of angular quartz, perthitic feldspar, plagioclase, subordinate muscovite, and rare subangular to rounded granoblastic and cryptocrystalline quartz + feldspar rock fragments. All phases are < 1 mm diameter, and there is abundant secondary calcite and minor opaque material. The angularity of clasts and dominance of crystals indicates reworking of a crystal rich tuff.

Several explanations have been offered for this unit, including dewatering of a loosely consolidated sedimentary sequence, collapse of a volcanic cinder cone, and slumping of variably consolidated sediments (partial liquefaction) initiated by earthquake shock (Swager & others, 1990).

This felsic succession is interpreted in terms of subaqueous extrusion of dacite or rhyolite lava, with associated autobrecciation, overlain by mass flow and turbidity current deposits composed of degraded lava and reworked coeval pyroclastic deposits. The chaotically bedded breccia unit represents thixotropic failure of partially consolidated, wet, reworked crystal-rich ash, initiated by eruption.

STOP 8. Komatiite and basalt at Harper Lagoon.

The Harper Lagoon sequence preserves a wide range of mafic and ultramafic rock types. The komatiite consists of cumulate and spinifex textured (flow) lithologies, whose top is marked by a differentiated dolerite-gabbro. Pillow lavas are atypical for the eastern Goldfields in that they are conspicuously amygdaloidal, indicating either shallow water eruption, or highly volatile magma.

This stop examines a well exposed succession of komatiites and variolitic pillow basalt and breccia 28 km northeast of Kalgoorlie-Boulder (Fig. 10). These rocks lie in a southeast-plunging regional anticline. Ahmat, (personal communication, 1991) has tentatively correlated them with the komatiite unit in the Kambalda and Ora Banda Domains of the Kalgoorlie Terrane.

The stratigraphic sequence (Ahmat, 1993) is as follows: komatiite (> 30 m), basaltic pillow breccia (40 m), komatiite (30 - 80 m), dolerite - gabbro (25 - 30 m), komatiite and high-Mg basalt (5 m), basaltic pillow breccia (10 - 20 m), variolitic pillow basalt (100 m), and amygdaloidal pillow basalt (40 m).

The komatiite units show well developed cumulus and some spinifex texture. The overlying dolerite-gabbro was taken to be intrusive by Williams (1970) and

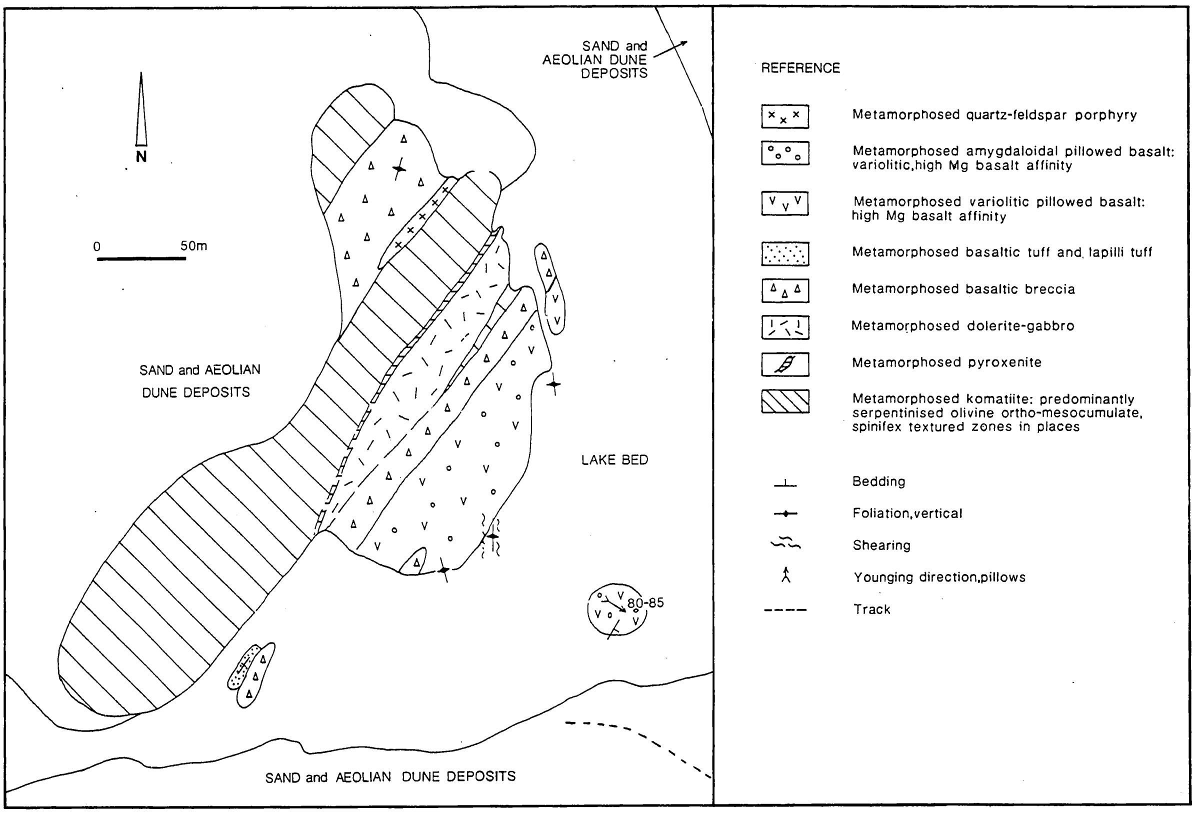

Figure 10. Geological sketch map of the Harper Lagoon area. From Swager & others (1990).

Groves and Gee (1980), but Ahmat (personal communication to P A Morris, 1991) believes it may represent a differentiated part of the komatiite flow.

Basaltic breccias comprise angular clasts up to 15 cm in diameter. They are lithologically similar to amygdaloidal basalt. Variolitic pillow basalt on the prominent headland crops out as pillow tubes and lobes. Varioles are usually concentrated in pillow cores, as coalesced masses. These rocks are weakly amygdaloidal. In thin section, amphibole is the dominant phase, with subordinate chlorite, albite, epidote, carbonate, pumpellyite and brown mica. The texture was originally vitrophyric.

On the small island opposite the headland are good outcrops of pillow basalt, which are amygdaloidal and weakly variolitic. Amygdales form concentric bands parallel to pillow rims, whereas varioles are more common in pillow cores. In some pillows, varioles are overprinted by amygdales. In thin section, pillow basalt contains fine grained tremolite (after pyroxene), and subordinate chlorite, accompanied by epidote, plagioclase and titanite. Varioles are relict clinopyroxene, albite, with minor tremolite and carbonate. The albite occurs as tiny spherules about 0.25 mm. The clinopyroxene is of a similar form to that in the host.

Pillow breccia

Fragments are up to 3.5 cm diameter, angular and show weak perlitic structure, with occasional vesicles up to 0.2 mm on fragment margins. The mineralogy is dominated by interlocking feathery to blocky and weakly pleochroic (green-colourless) amphibole, with rare chlorite patches plus feldspar. Grain size decreases towards the fragment edge. Minor secondary calcite. In between the fragments, are crowded glassy cuspate fragments (bubble interstices), hyaloclastite (?pillow spalls) and rare sediment.

Variolitic basalt.

The host basalt comprises pale green mats of actinolitic amphibole, with patches chlorite and rare pseudomorphs after olivine. Varioles are more felsic than the host, consisting of feathery euhedral amphibole in a groundmass of granoblastic feldspar and bladed amphibole. Varioles are occasionally cut by vesicles, which are now infilled by calcite.

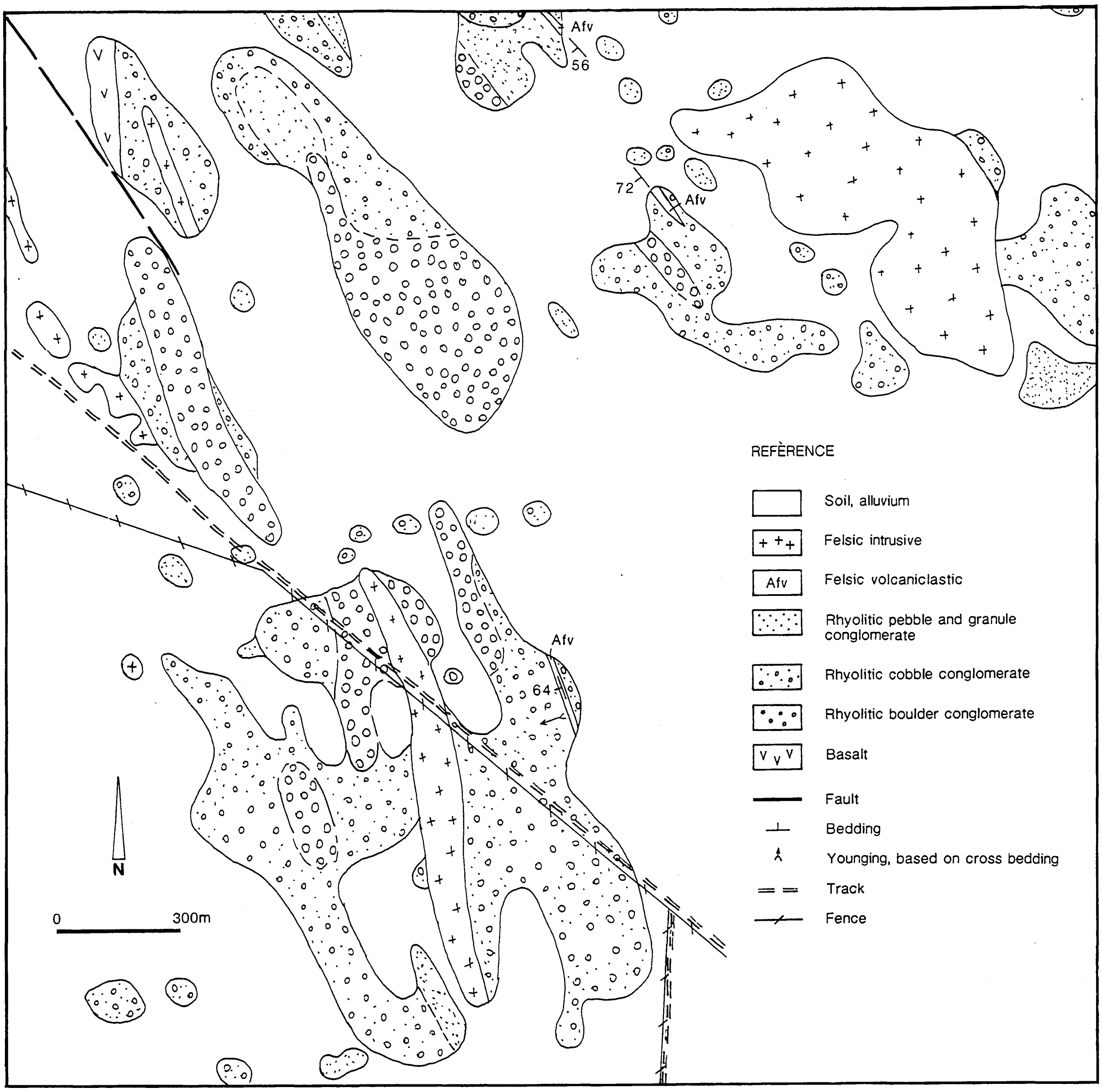

Figure 11. Geological sketch map of part of the Perkolilli felsic fragmental complex. After Taylor (1984) and Swager & others (1990).

STOP 9. Felsic Fragmental Rocks At Perkolilli, Kanowna Area.

Poorly sorted felsic volcanic breccias crop out at Perkolilli, 21 km northeast of Kalgoorlie-Boulder (Fig. 11). The breccias largely consist of rhyolite and dacite clasts, and show both open and closed framework. A cross bedded unit consists of crystal fragments in a devitrified glassy groundmass. Williams (1970) interpreted the unit as a felsic volcanic centre, whereas Taylor (1984) maintained the sequence was a mass flow deposit from a tectonically active volcanic terrane.

Morris (in prep.) has noted that the glassy nature of these rocks, the limited clast content and the presence of welding, the small volume are consistent with deposition as a hot, small volume pyroclastic flow, such as block and ash flows described by Wright & others (1981) and Smith and Roobol (1982).

STOP 10. Visit To KCGM's Big Pit (Talk By Paul Sauter, KCGM)

STOP 11. Komatiites of The Walter Williams Formation

The komatiitic rocks which extend from Siberia through Broad Arrow, Menzies to Kurrajong are broadly correlatable with those of the Kalgoorlie-Kambalda area. There is, however one striking difference: the presence of a laterally extensive unit of coarse-grained olivine adcumulate at the base of the komatiite pile. The adcumulate body forms part of the Walter Williams Formation (WWF). The WWF can be traced continuously from southwest of Siberia to the Kurrajong anticline in the Mt Ida greenstone belt (Fig. 12).

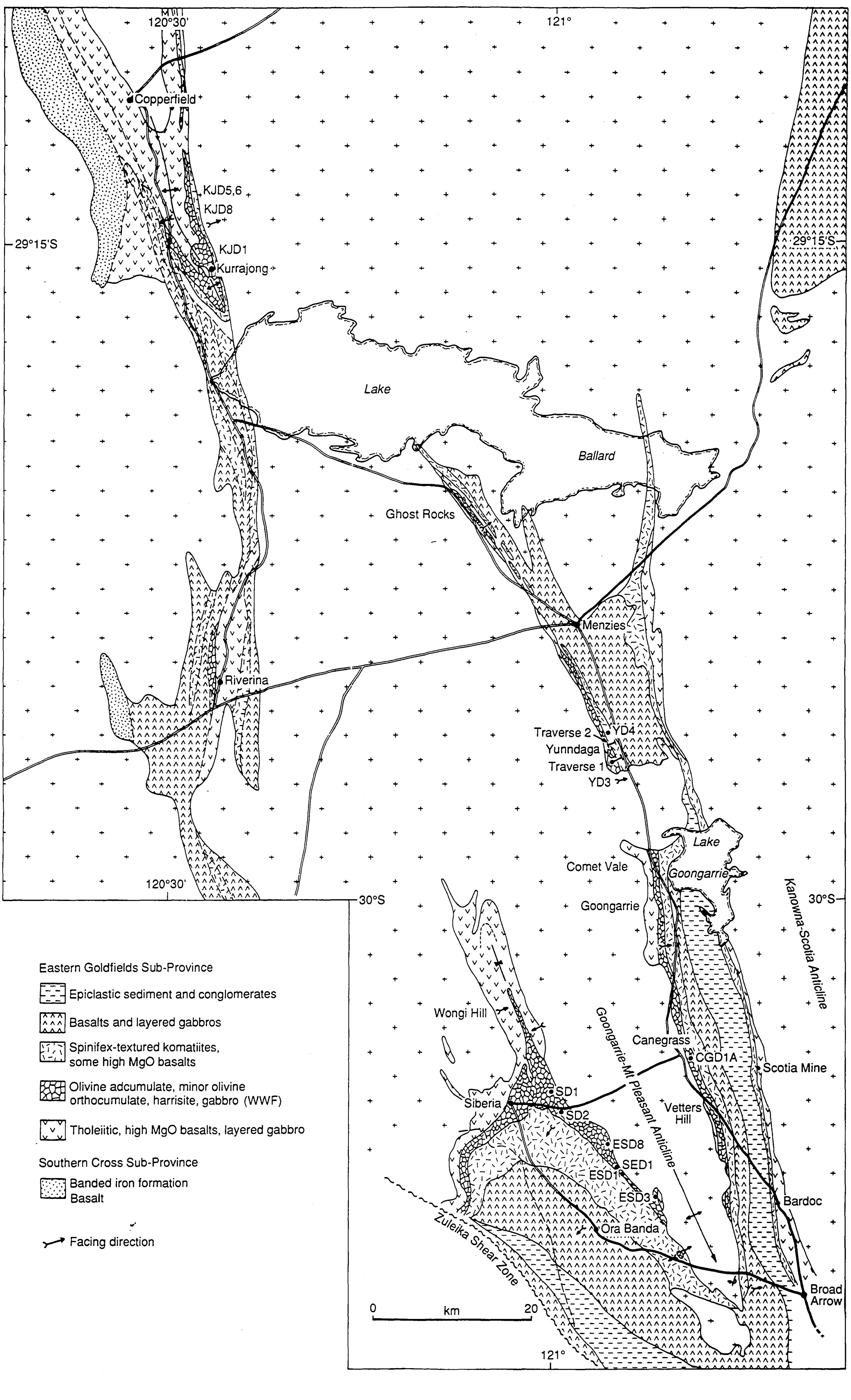

Figure 12. Geological map of the Walter Williams Formation.

Stratigraphic columns through the WWF (Fig. 13) show the gross layering and lateral lithological variations. South of Ghost Rocks the lower ultramafic zone of the WWF is dominated by a thick olivine adcumulate layer, which grades laterally to olivine mesocumulates and orthocumulates to the north between Ghost Rocks and Lake Ballard and at Kurrajong. North from Yunndaga, the upper zone of the WWF is a layered gabbro which thickens northwards from approximately 30-40 m at Yunndaga to 100 m at Ghost Rocks and 180 m at Kurrajong.

In the Siberia-Yunndaga section the lowest sub-unit of the WWF is a variably serpentinised, fine to medium grained olivine orthocumulate containing oikocrysts of pyroxene and rare kaersutitic amphibole. The olivine grain size increases and intercumulus porosity decreases upwards, so that the rock type gradually changes to a mesocumulate and then to an adcumulate composed of mostly fresh, pleochroic brown 1-2 cm polygonal-textured olivine with minor chromite. Immediately above the adcumulate is a 2-5m layer of coarse-grained olivine harrisite. Above the harrisite is a 20-40 m thick subunit of fine-grained olivine orthocumulate containing several 30 cm thick layers of clinopyroxene-olivine cumulate. In places this is overlain by apparently lensoidal gabbro bodies up to 50 m thick or by a 2-3 m thick sedimentary rock layer. Where the gabbro and sedimentary rock are absent it is difficult to define the top of the WWF as the upper orthocumulate is similar to that forming the B zones of the overlying flows.

Stop 11a. The Walter Williams Formation at Vetters Hill. The field stop at Vetters Hill displays olivine adcumulates of the central part of the stratigraphy, exposed as a siliceous laterite that caps the hill. The facing is easterly. From the road to just past the fence are serpentinites with fine-grained orthocumulate and uncommon spinifex textures. Rubble covers the lower part of the hill although a few low outcrops of orthocumulate occur. About 3/4 of the way up the hill are olivine harrisites in thin rubbly outcrop. Above these and extending to the back slope is adcumulate-textured siliceous laterite. Laterite with orthocumulate textures occurs just above the contact with strongly foliated metabasalt. There is a marked contrast in the preservation of igneous textures between the ultramafic and mafic rocks over this contact. From the top of the hill the dump at the Sand King open pit mine, near the western extent of the Walter Williams Unit, is visible.

Stop 11b. The Walter Williams Formation in the Western Mining laterite pit at Siberia. Western Mining excavated a number of small pits within weathered olivine adcumulate of the Walter Williams Formation. This pit was mined for silica (with a bonus of up to 2% Ni) for the WMC nickel smelter. This field stop provides outstanding exposure of completely silicified dunite ("silica cap") produced during the lateritic weathering of the serpentinised olivine adcumulate, displaying remarkable pseudomorphic textural preservation in a rock now containing 99% SiO2. This style of weathering is characteristic of extremely olivine

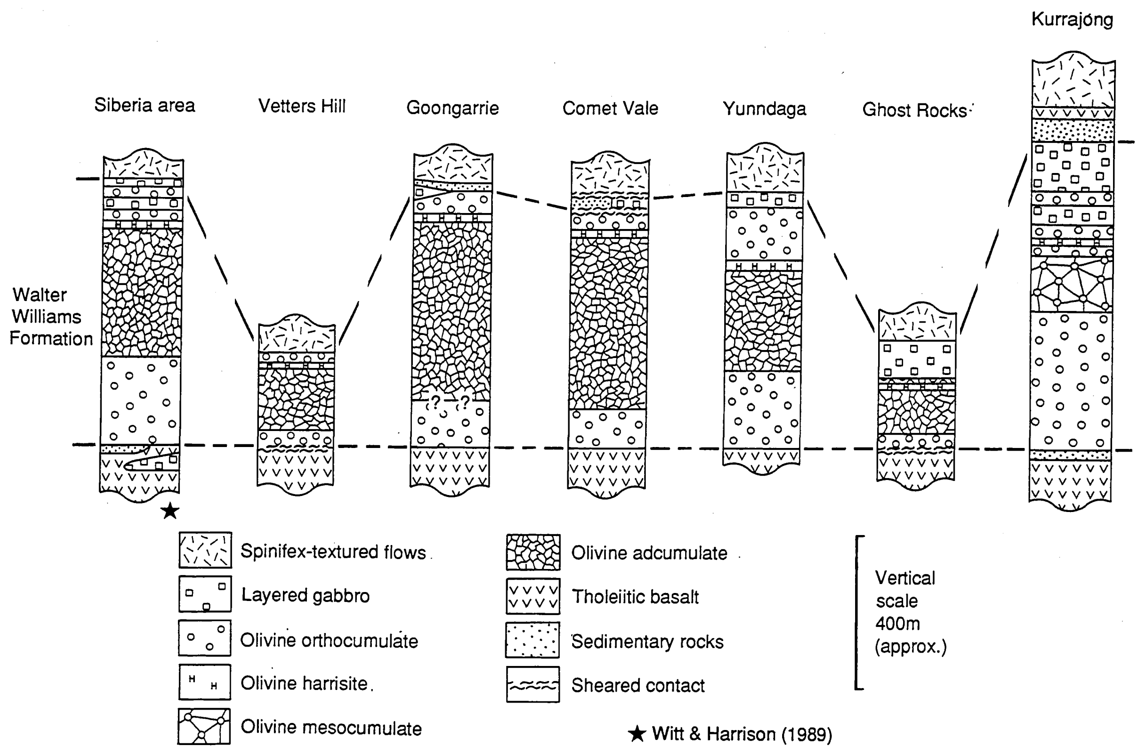

Figure 13. Stratigraphic profiles through the Walter Williams Formation. See Figure 12 for locations.

rich rocks in the Yilgarn Block. Pseudomorphs of serpentinised dunite with fine bladed antigorite along grain boundaries are present on the northern side of the pit.

Stop 11c. The Walter Williams Formation at Comet Vale (shore of Lake Goongarry).

The upper sections of the Walter Williams Unit will be seen (Fig. 14). At the beginning of the traverse, on the old WMC grid base line, and on the flat area immediately to the east, the adcumulate is covered by ferruginous laterite cap and only in a few places are adcumulate textures preserved. Down the eastern slope of the hill, lower down the laterite profile, adcumulate textures are well displayed in siliceous laterite. The olivine harrisite and its abrupt contact with the adcumulate can be seen just before the steep drop on the eastern side of the hill. The harrisites have been etched by weathering and their three-dimensional shapes are well shown. Down the slope fine- grained orthocumulate with several 30cm thick pyroxenite layers outcrop. On the flat ground further east only patchy low outcrop of orthocumulate is present. The rocks here are highly sheared and numerous pegmatites are present. Two major shear zones intersect in this area. Across the shear zones to the northeast are unstrained spinifex-textured flows that form part of the Siberia Komatiitic Volcanics. These are part of a rotated block striking southeast and bounded to the south by a shear zone and to the north by intrusive granite

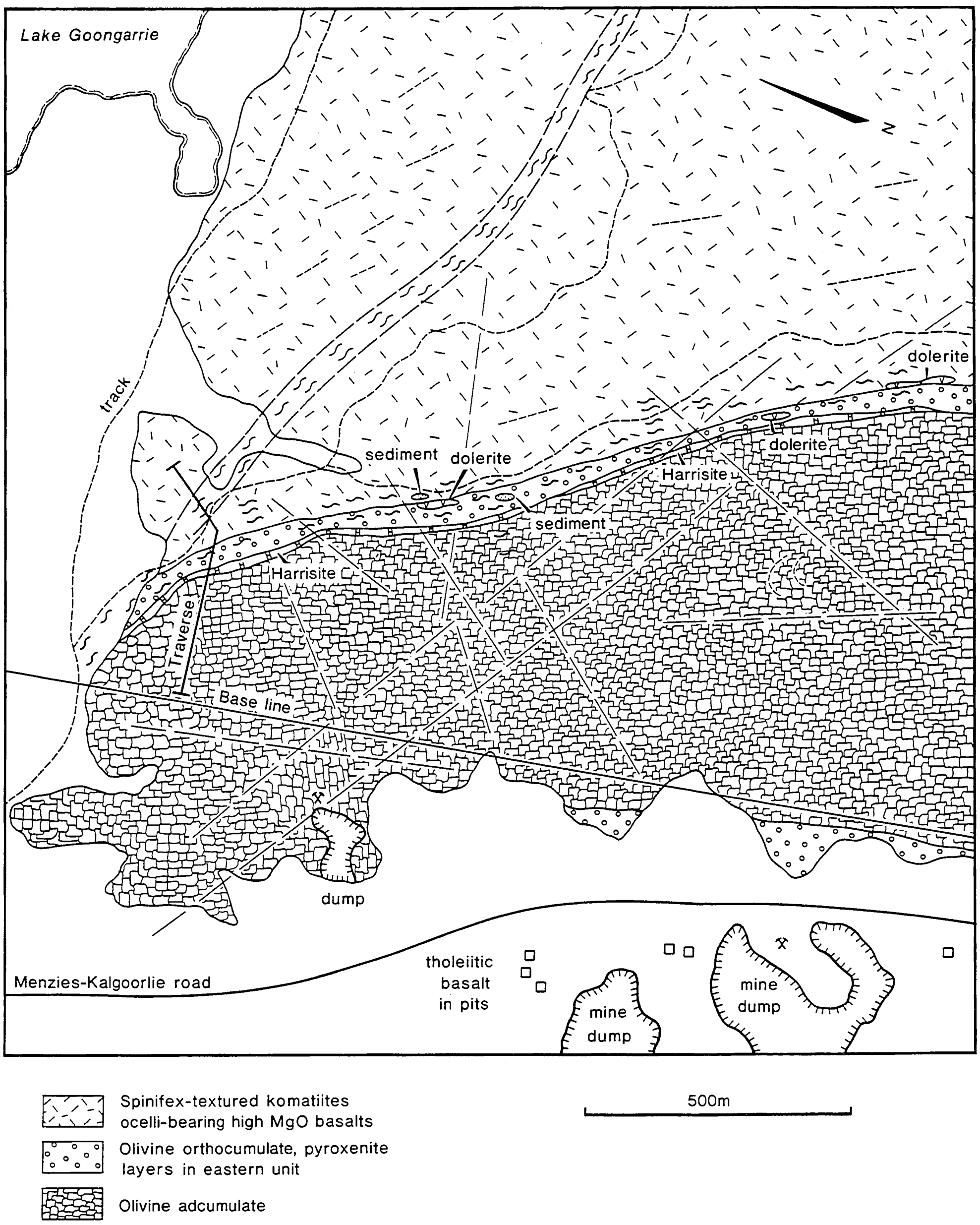

Figure 14. Geological map of the Walter Williams Formation at Comet Vale.

STOP 12. Felsic volcanic rocks of the Melita Volcanic Centre.

Hallberg (1985) and Witt (1993) have described two centres of felsic volcanism in the Melita area, southeast of Leonora. Witt (1993) termed these centres the Jeedamya Volcanic Centre, and the Melita Volcanic Centre. Of the two, the Jeedamya centre is less well exposed, consisting of dacite and rhyolite pyroclastic rocks and related epiclastic rocks, felsic porphyry, and minor mafic extrusive and intrusive rocks.

This stop examines part of the Melita Volcanic Centre. Witt (1993) has recorded rhyolitic ash, lapilli tuff, breccia, and minor dacite flows. He noted the dominance of vitric fragments over crystal and lithic components. Deposits consisted of both primary volcanic deposits and reworked lithologies.

Felsic tuffs and breccias outcrop south of Cobbie Well in and near a railway cutting, 4 km east of Melita homestead. Best exposures are in low hills east of the railway line (over the fence). The lithologies are fine grained blue-grey tuffaceous rocks to the north of the outcrop, and weakly eutaxitic breccias to the south.

In thin section, the tuff is fresh and non-foliated. Single crystals of quartz (75% of clast population), alkali feldspar (15%), and albitic plagioclase (10%) occur in a cryptocrystalline groundmass of quartz and subordinate chlorite. The quartz grains (up to 1 mm) are locally bipyramidal, but more commonly anhedral and embayed. Alkali feldspar grains (1.5 mm) are cloudy, euhedral, and usually broken, with weak oscillatory zoning. Plagioclase grains (1 mm) are subhedral and broken. less common rock fragments comprise feldspar laths with interstitial chlorite, or chlorite clots, up to 2 mm diameter. Within the groundmass, some amorphous areas have minute spherules developed.

The breccias comprise angular and cuspate felsic volcanic rock fragments up to 4 cm are largely matrix supported, and best seen on weathered surfaces. Some fragments show flow banding, and flattening of fragments indicates a weakly developed eutaxitic texture. More basic amygdaloidal ?flow rocks crop out near the fence.

In thin section, the felsic breccia is recrystallised, although outlines of cryptocrystalline elongate rock fragments up to 1.5 cm are preserved, some with embayed quartz microphenocrysts. Other fragments show weakly developed banding, and the matrix is cryptocrystalline quartz with minute spherules.

Across the fence and to the south bedded tuffaceous rocks are exposed (dip about 040 to the northeast) in the railway cutting. These comprise crystal rich lithologies typical of the Melita Volcanic Centre, and more aphanitic, glassy varieties.

If time permits, travel 2.5 km west from the Kookynie - Malcolm road towards Melita homestead, and stop to examine felsic breccia and agglomerate on the south side of the road. One unit in particular comprises rounded to subrounded felsic volcanic clasts up to 50 cm diameter, locally showing clast support. Clasts included flow banded and eutaxitic felsic volcanics, vesicular ?dacites, fine grained blue-grey tuffs (cf hills adjacent to railway). In thin section, the matrix to this deposit contains a variety of felsic volcanic rock fragments, which are angular and up to 3 mm long. The matrix is cryptocrystalline quartz with minute spherules, infilled with radiating albite. Many fragments are cuspate and elongate. One comprises needles of feldspar in a murky black (?glassy) groundmass, whereas another contains strongly embayed microphenocrysts of quartz in a cryptocrystalline groundmass. Less common are fragments with microphenocryst quartz in a chloritic matrix. The fragment type, form, and the matrix to the fragments suggests some type of hot deposition.

STOP 13. The layered lava-lake facies of the Walter Williams Formation at Kurrajong

The exposures at Kurrajong (Fig. 15) cover well-exposed layered ultramafic and gabbroic cumulates of the northern lava-lake facies of the Walter Williams Formation. The lower ultramafic zone consists of tightly packed, layered olivine mesocumulate. This unit includes up to four 0.5-3 m thick layers of Mg-augite-olivine adcumulate defining the tops of beheaded cyclic units. In the upper section of the zone there are thin layers of olivine-augite and olivine-chromite-augite orthocumulates containing a distinctive very coarse-grained olivine harrisite layer near the top.

The gabbro zone consists of two cyclic units, the lower one of which is beheaded. Each cycle consists of a lower olivine orthocumulate, overlain by a 1-2 m thick diopside adcumulate with olivine in the lower part and plagioclase oikocrysts in the upper part, then a layer of diopside-plagioclase cumulate with quartz present over much of the section in granophyric intergrowths. Patches of coarse-grained, branching harrisitic clinopyroxene occur in the central and upper parts of the gabbros. The upper cycle is capped by an upward fining, ophitic-textured dolerite which grades into a pyroxene-phyric basaltic flow-top breccia, containing 8-10% MgO. This is too low in MgO to represent the liquid which crystallised the ultramafic cumulates, and must represent the late ponding of fractionated liquid within the lake. Earlier formed flow tops were continually remelted.

Localities marked by numbered pegs correspond to layers in the stratigraphic columns in Fig. 15. *Traverse 1* covers the upper portion of the ultramafic zone and the lower of the two olivine orthocumulate - gabbro cyclic units. At location 1 rubble of lateritic silica cap is developed over olivine mesocumulates. The traverse proceeds eastward over subdued outcrop of two thin augite-olivine cumulate layers (location 2), then over rubble and outcrop of olivine orthocumulate and a small outcrop of olivine mesocumulate, to location 3 where there is one of several chromite-rich zones.

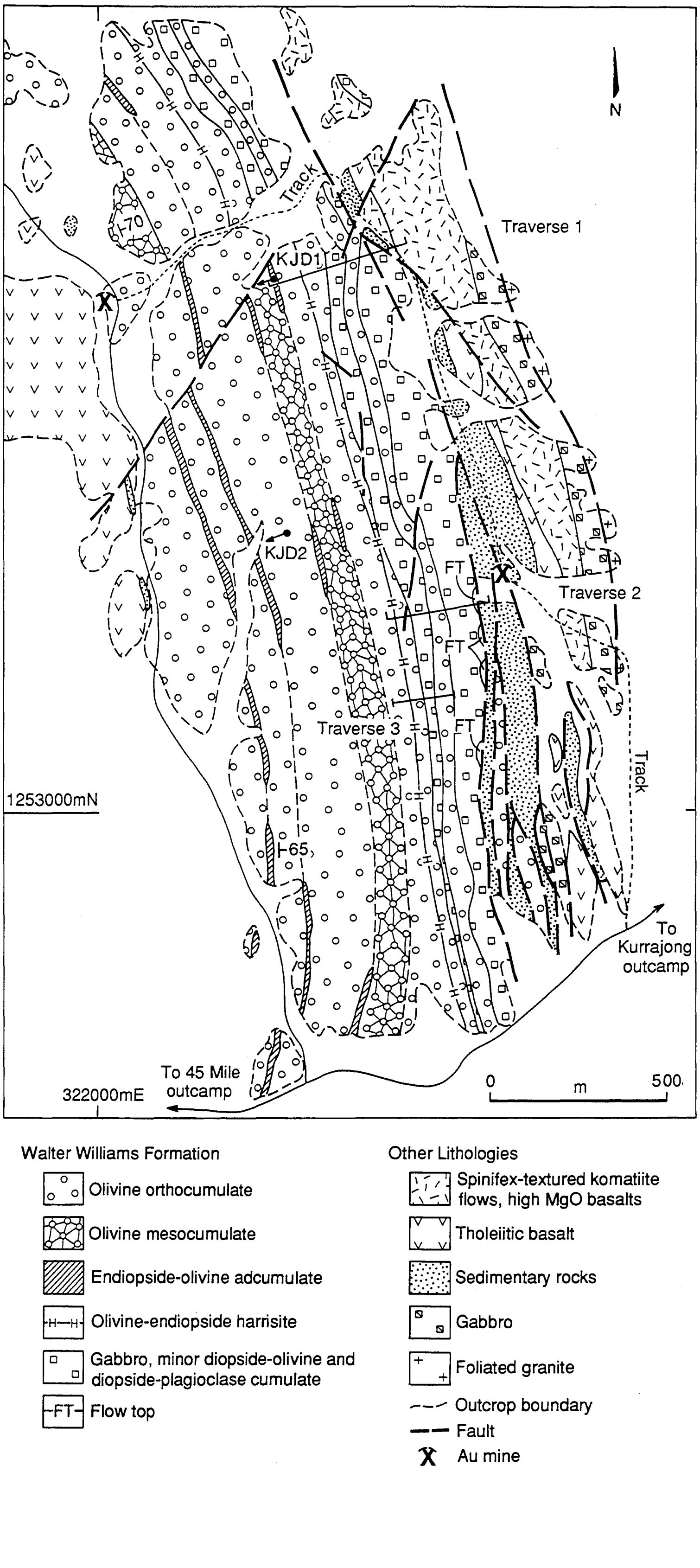

Figure 15. Geological map of the Kurrajong layered lava lake sequence, showing location of traverses shown in Fig. 16.

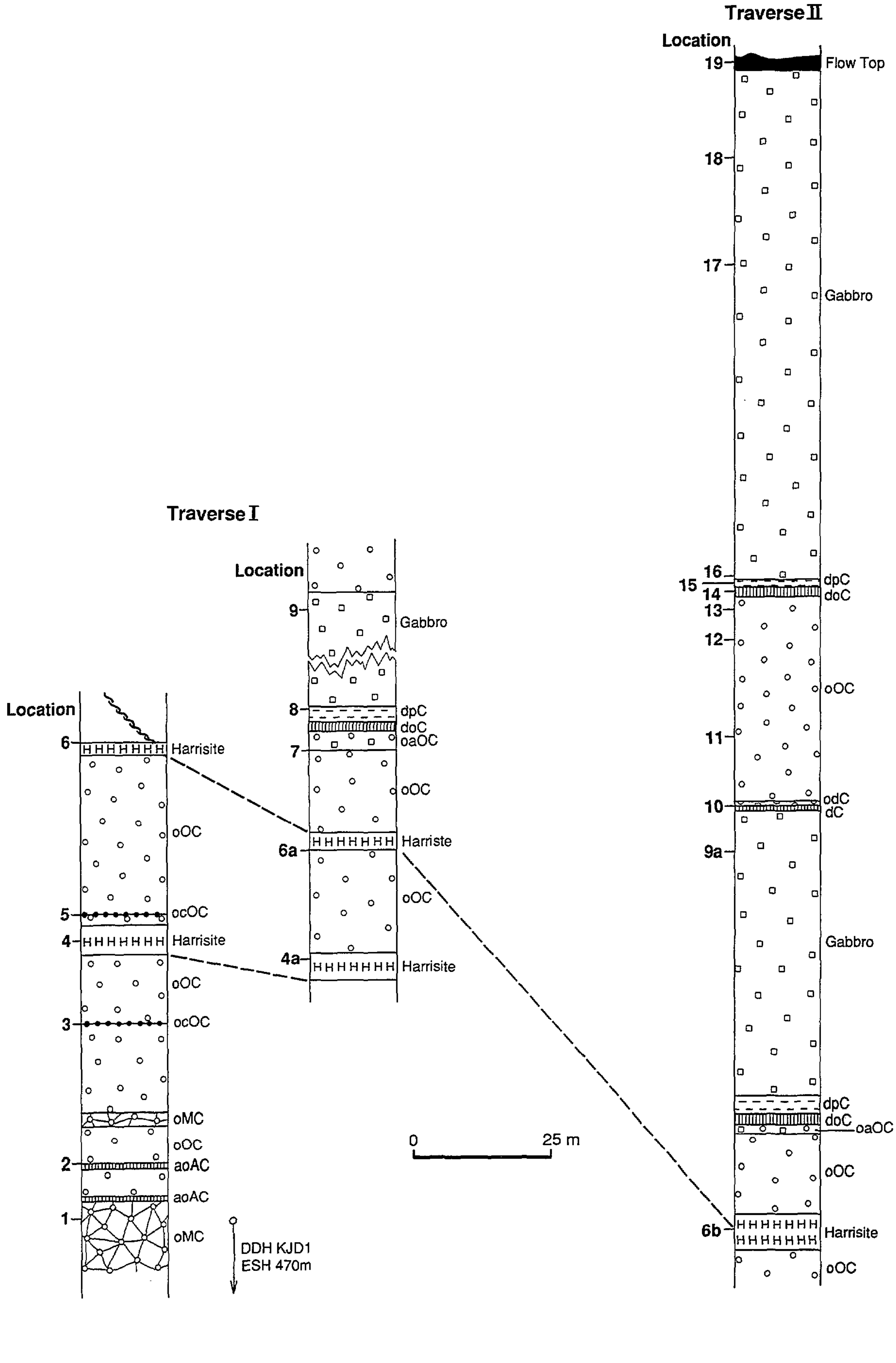

Figure 16. Lithological profiles illustrating surface traverses through the Kurrajong sequence, in area shown in Fig. 15.

Location 4 is the lower of two distinct coarse-grained harrisite layers. Here the outcrop is mostly rubbly and better examples of this unit occur about 100 m to the south. Just above this harrisite at location 5 is another distinctive chromite-rich zone. The olivine orthocumulates continue over the top of the hill to location 6, the upper of two harrisite units which is here in fault contact with gabbroic rocks of the lower gabbro cyclic unit. Traverse 1 then moves south about 100 m to location 4a, which is once again the lower olivine harrisite unit and proceeds eastwards over the lower of the two olivine orthocumulate - gabbro cyclic units.

Location 6 is an olivine harrisite which marks the top of the ultramafic zone. From this location the traverse passes over olivine orthocumulate at the base of the cyclic unit, to locations 7 and 8 which together span a few metres over which there is a sequence olivine orthocumulate, olivine diopside cumulate, diopside olivine cumulate, diopside-plagioclase cumulate (gabbro). (The pyroxene rich units do not outcrop well). Location 9 is over the ridge, on gabbro outcrop. This concludes traverse 1.

Traverse 2 (1 km south of traverse 1, Fig. 15) begins at the upper harrisite unit marking the top of the ultramafic zone, location 6c (Fig. 16), and proceeds over the lower gabbro unit equivalent to the last stop of traverse 1. At location 10 there are two layers of diopside cumulate and olivine-diopside cumulate, the latter grading into olivine orthocumulate up-slope. These layers form a marginal zone at the base of the upper cyclic unit, and represent hybrid magma formed during the new magma pulse. Locations 11, 12 and 13 are within olivine orthocumulate displaying unusual pillow-like weathering. At the top of the ridge, locations 14 to 16 span 3 metres of stratigraphy including diopside olivine cumulates, diopside plagioclase cumulate and gabbro. The traverse proceeds over gabbro displaying a variety of textural variants including feathery plagioclase, harrisitic pyroxene and granophyric clots. The grainsize decreases gradually, and the traverse ends with the flow top breccia at location 19.

The WWF is the crystallisation product of a massive sheet flow with different lobes experiencing different crystallisation conditions. In the Ghost Rocks - Siberia area, crystallisation conditions within the flow favoured the growth of olivine adcumulate and were relatively constant with ponding and *in situ* fractionation restricted to the waning stages of eruption. At Kurrajong, ponding, *in situ* differentiation and influxes of new magma occurred throughout the history of the flow.

Komatiites of the Agnew-Wiluna segment of the Norseman-Wiluna Greenstone Belt

Stop 14. The Mt. Clifford - Marshall Pool area

The Mt Clifford and Marshall Pool Ultramafic Complexes are located 50 km north of Leonora, within a southern extension of the Agnew-Wiluna greenstone belt (Fig. 17). In both areas there is a large, poorly-exposed, olivine adcumulate body which conformably overlies a sequence of pillowed tholeiitic basalts and is in turn overlain by a thick sequence of spinifex-textured flows. The Mt Clifford and Marshall Pool ultramafic sequences appear to be stratigraphically equivalent, and probably once formed a single extensive sheet (Donaldson & others, 1986).

At Mt Clifford, the ultramafic rocks occur in an asymmetric fault-bounded syncline plunging 45 degrees to the NE (Fig. 18). At the base of the ultramafic sequence is a 1 km thick olivine adcumulate body exposed as silica cap. At the top of the upper olivine adcumulate subunit there is a transition, over about 30 m, to an inhomogeneous olivine orthocumulate containing poikilitic pyroxene and patches of coarse-grained (up to 10 cm) olivine harrisite. Overlying this zone is a well-exposed layered gabbroic body which forms the fractionated top of the underlying olivine cumulate body. The gabbro is in turn overlain by a 150 m thick layered unit containing olivine orthocumulate and bladed olivine textures. This unit incorporates the Marriott's nickel prospect (Travis, 1975), an unusual occurrence of Fe-Ni sulphides as 1 cm diameter spherical blebs (now replaced by limonite) within olivine orthocumulates. The sequence is capped by a 1 km thick pile of thin spinifex-textured flows, which were among the first examples of ultramafic lavas to be recognised in Australia (Barnes & others, 1974;

At Marshall Pool (Fig. 18), the ultramafic rocks define a shallow north-plunging syncline, the core of which comprises a well-exposed thick sequence of komatiites and high-MgO basalts. Thinner komatiite flows (2-5 m) exhibit a wide variety of well-preserved and spectacular spinifex textures, whereas thicker flows are predominantly olivine orthocumulates. The flow sequence is underlain by a non-outcropping adcumulate body, about 500 m thick. The adcumulate body, which has a basal marginal zone containing oikocrystic kaersutite, is compositionally layered (Donaldson & *others*, 1986) and directly overlies tholeiitic basalts on the eastern limb of the syncline, but is separated from them by a sequence of spinifex-textured komatiites on the western limb. The field stop will be on an area of well-preserved spinifex-textured flows containing some remarkable examples of very coarse grained olivine spinifex textures (see Hill & others, 1990, pages 3-11).

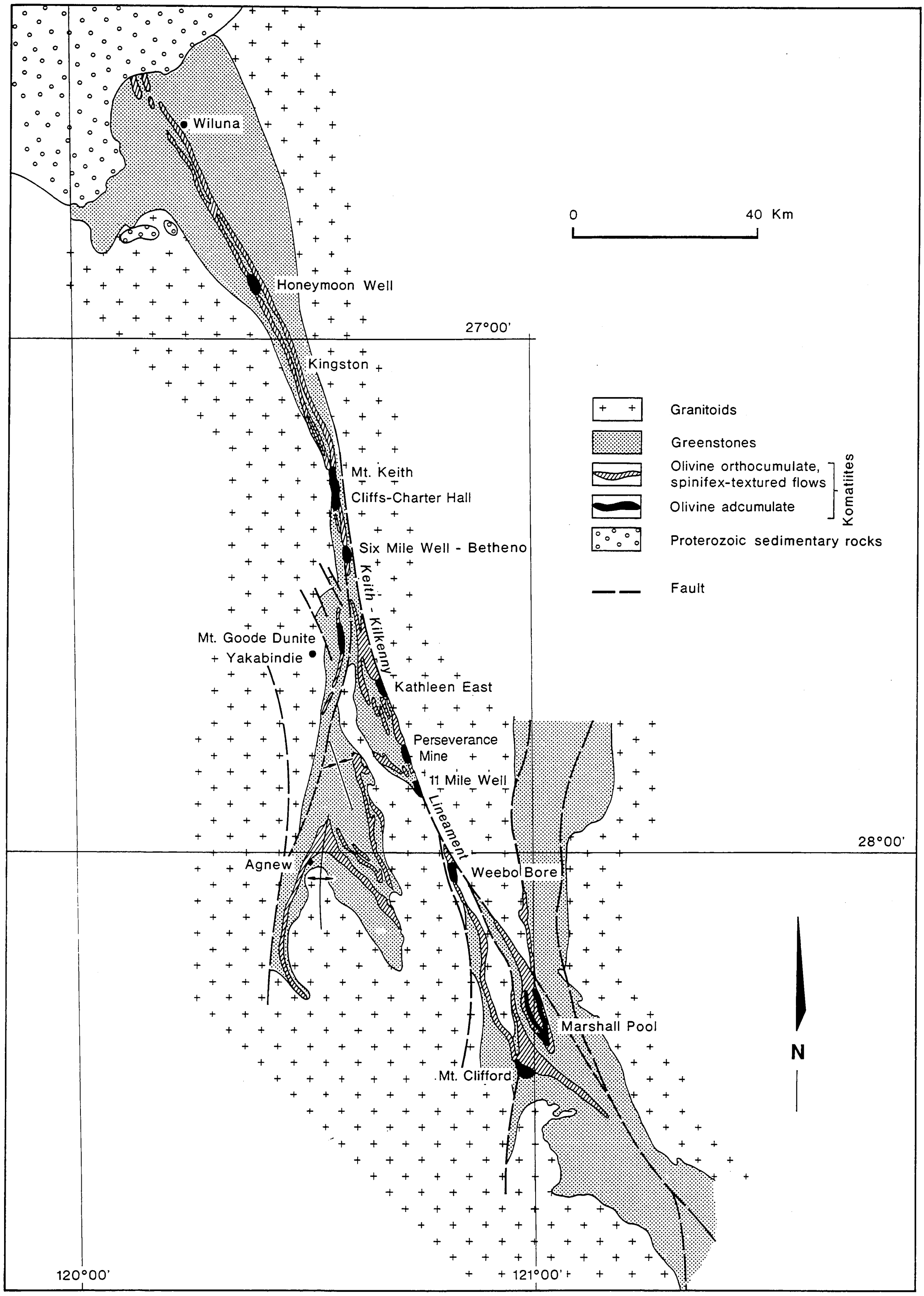

Figure 17. Regional geology of the Agnew-Wiluna greenstone belt from Mt. Clifford to Wiluna, showing distribution of komatiites and komatiitic dunite bodies.

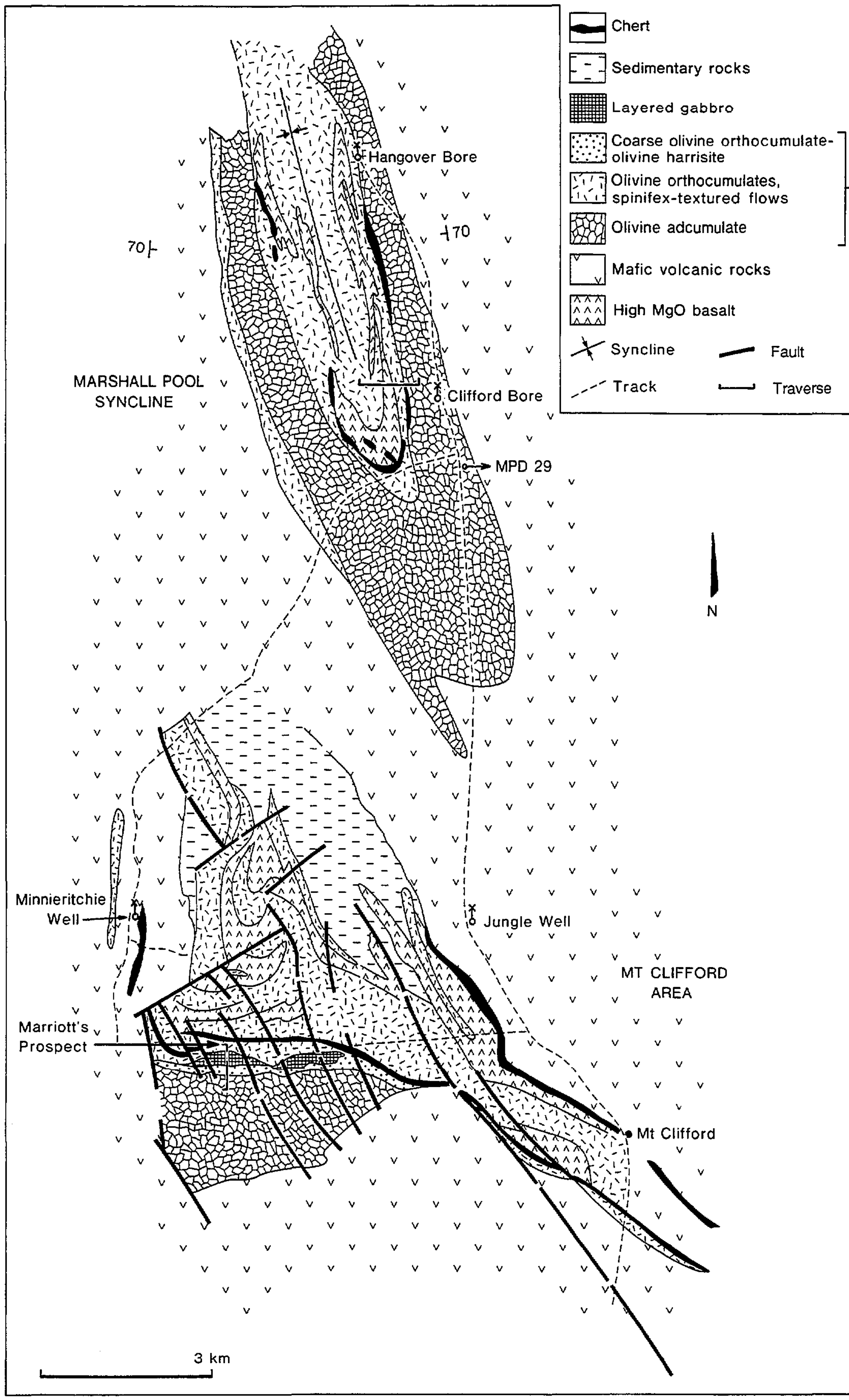

Figure 18. Geology of the Mt. Clifford - Marshall Pool area.

Stop 15. Komatiites of the Perseverance Nickel Mine area

The Perseverance and neighbouring Rocky's Reward deposit are situated near the south-eastern extremity of the Agnew-Wiluna greenstone belt (Fig. 17), which contains in excess of 100 km strike length of continuous komatiite stratigraphy. Throughout the belt komatiites are intercalated with felsic volcanic rocks.

The Perseverance ultramafic complex is a 700 m thick stratiform body of metamorphosed ultramafic rocks of komatiitic affinity consisting of spinifex-textured flows, layered olivine orthocumulate and mesocumulate and a central body of coarse- grained olivine adcumulate (Fig. 18). The complex stratigraphically overlies and significantly postdates a sequence of komatiite flows that host the Perseverance (Agnew) and Rocky's Reward Ni sulphide deposits.

The rocks of the mine area have been subjected to peak metamorphic conditions of about 550°C and 3 kb (Gole & others, 1987) and the komatiites have been reconstituted to olivine- tremolite-chlorite-cummingtonite assemblages, with olivine- antigorite in the more magnesian rocks. Retrogression of olivine to serpentine is common.

The most prominent feature of the geology is the olivine adcumulate body, which measures about 2 km north to south, 700 m east to west and plunges at 70-80° to the south (Fig. 18). The adcumulate, which forms a large zone of thickening within the Perseverance ultramafic sequence, mainly consists of brown pleochroic polygonal-textured olivine grains with sizes up to 2 cm. Toward the north and south extremities, and on the eastern margin, the body contains layers of olivine mesocumulate and orthocumulate. These increase in proportion away from the adcumulate core. The adcumulate is flanked to the north by a laterally extensive sequence of olivine mesocumulates and orthocumulates with very subordinate differentiated flows. To the south the sequence contains numerous thin flows composed of metamorphic olivine, tremolite, chlorite and cummingtonite in widely varying proportions with spinifex textures preserved locally.

The Perseverance complex is overlain by a mixed sequence of highly deformed komatiites, high-Mg basalts and felsic volcanics, truncated by the Perseverance Fault. The entire sequence is steeply overturned, faces east, and dips at 70-80° to the west.

A series of deformed east-facing komatiite flows is stratigraphically below the adcumulate and hosts the Ni sulphide ore of the Perseverance mine (Barnes & others, 1988b). These flows extend northward from the base of the adcumulate body and host the Rocky's Reward Ni sulphide deposit located about 3 km north of the Perseverance mine. This mineralized flow sequence is separated from the Perseverance ultramafic sequence by a progressively thicker stratigraphic section of felsic

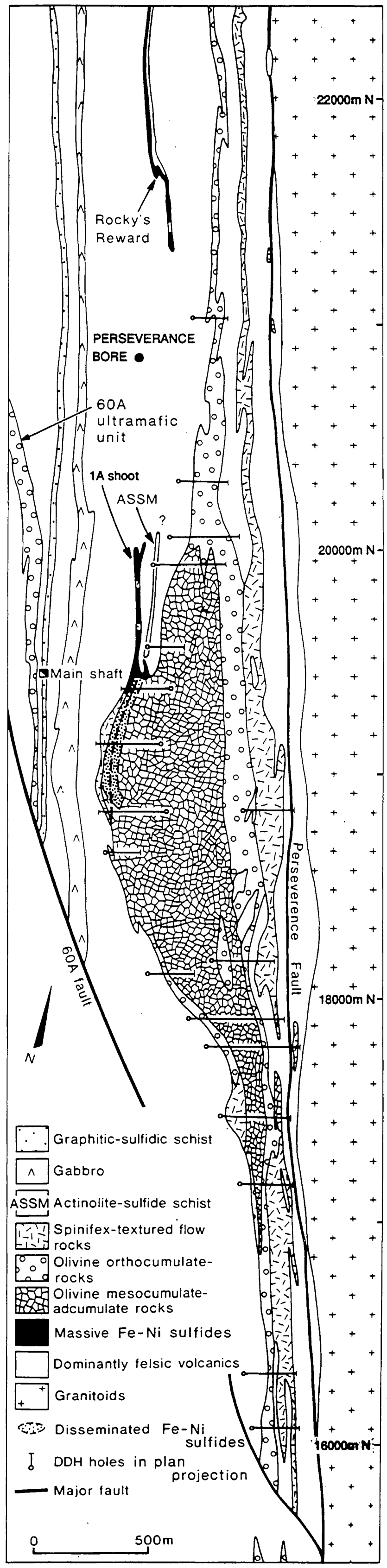

Figure 19. Geology of the Perseverance Ultramafic Complex.

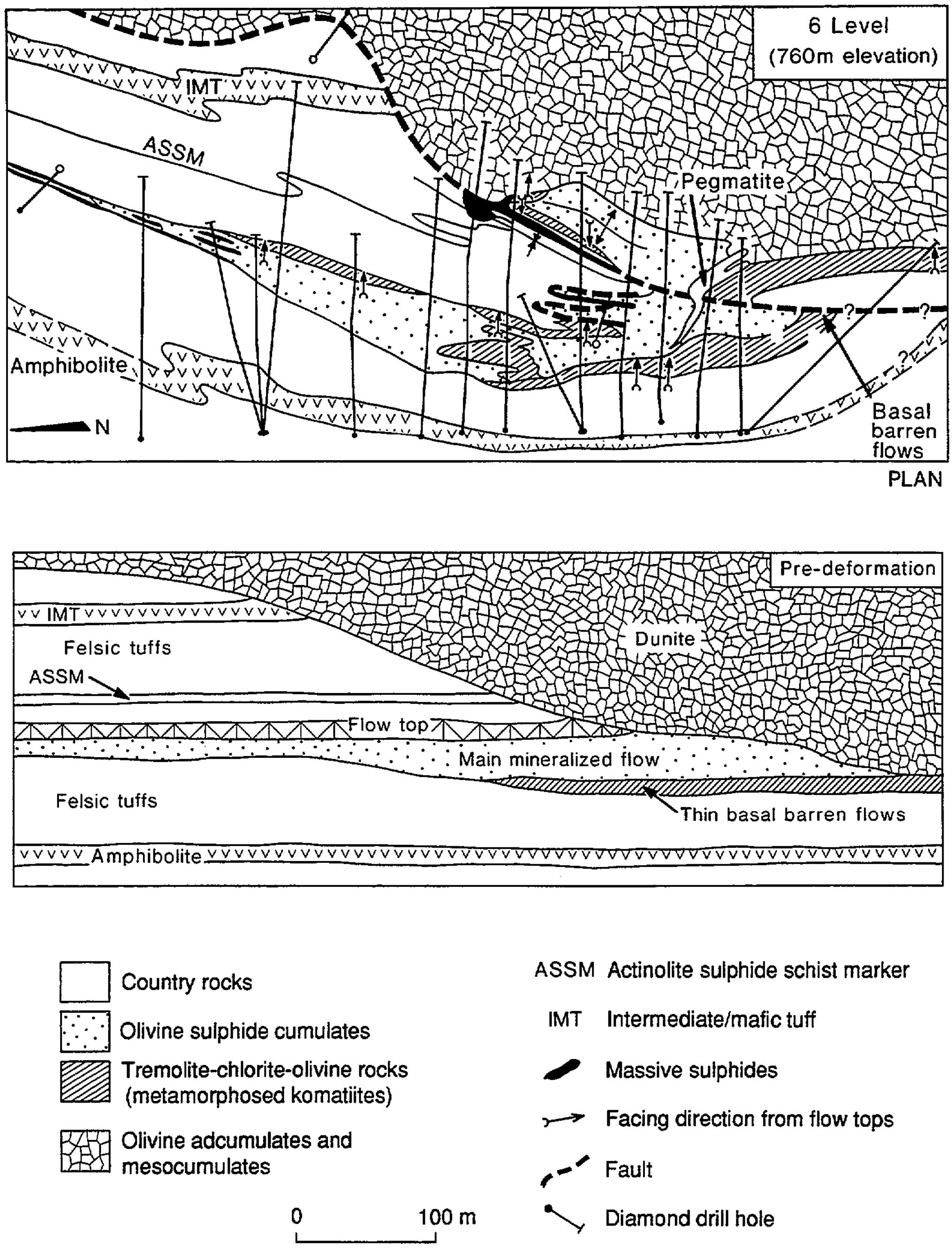

Figure 20. Simplified geology of no. 6 level of the Perseverance nickel mine (top), with pre-deformation stratigraphic reconstruction (bottom)

country rocks which attains a maximum present thickness of about 250 m. These country rocks consist of quartz-biotite-felspar metasediments and dacitic to rhyolitic metavolcanics containing distinctive marker units. To the south, this stratigraphy and the mineralized flow sequence are progressively truncated by the base of the adcumulate body (Fig. 20). To the south of the Perseverance mine the mineralized flow sequence is apparently absent, but geological relationships in this area are poorly defined because of lack of data.

The Perseverance open pit is developed within the main mass of matrix ore (olivine sulphide cumulate) of the mineralised flow, directly overlain by the cloud sulphide zone in the lower part of the main dunite lens, and itself overlain by coarse grained barren dunite. Drill core from the mine area illustrates profiles through the mineralised flow, material from the central dunite lens, and spinifex-textured flows laterally correlative with the dunite lens. Typical metamorphic mineral assemblages and textures will be seen. Drill core from the Rocky's Reward deposit will illustrate profiles through the mineralised flow unit, spectacular bladed metamorphic olivine in re-textured matrix ore, and tremolite-chlorite rocks interpreted as metamorphosed komatiite flow tops.

Stop 16. The Six Mile Ultramafic Complex (Yakabindie)

The Six Mile Well ultramafic complex (Fig. 21) is one of several mineralized olivine adcumulate lenses delineated in the Yakabindie region during nickel exploration in the late 1960s and early 1970s and contains a significant tonnage of low-grade disseminated nickel sulphide mineralisation.. It is one of five similar adcumulate pods over a strike length of 5 km, at the same stratigraphic level, exposed as small hills capped by dense brown jasperoidal and scoriaceous laterite which pseudomorphs primary igneous olivine cumulate textures. The pods are enclosed in marginal zones of olivine orthocumulate and exhibit gradational lateral contact with thinner orthocumulate and spinifex-textured horizons which originally linked them (Fig. 21). These pods are now interpreted as cross sections through a sinuous and/or braided komatiite lava channel.

The Six Mile Well ultramafic complex (900m long and 400m thick) has been extensively drilled and it illustrates many of the features of the adcumulate lenses of the Agnew-Wiluna greenstone belt. The complex is concordant with the west-facing stratigraphy and has a steep southeasterly plunge. To the north the adcumulate lens has gradational contacts with olivine orthocumulates. The eastern and southern margins form a NNE-trending fault that dips steeply to the southeast with more moderate dip at depth. The western margin is sheared and dips steeply westward.

The main mass of the complex consists of layered olivine adcumulates and orthocumulates containing disseminated nickel sulphides. These gradually give way upward to an orthocumulate-dominated sequence which displays cyclical variation from medium-grained olivine mesocumulate-adcumulate to olivine orthocumulate on a scale of several metres. Cryptic chemical variation is evident within these cyclic units. Some of the orthocumulates contain serpentinised pyroxene oikocrysts, whereas others contain remnants of primary intercumulus aluminous amphibole and apatite.

The field stop traverses the southern end of the complex. The traverse passes westward over well-folded chert at the SE fault contact with the complex, and proceeds across a zone of no outcrop over the olivine adcumulate to the well exposed layered olivine orthocumulates of the upper part of the section. This unit is exposed as a serpentinite with good relict igneous texture. In the immediate hanging wall area there are subdued outcrops of sheared orthocumulate (now talc schist) enclosing the hanging-wall chert.

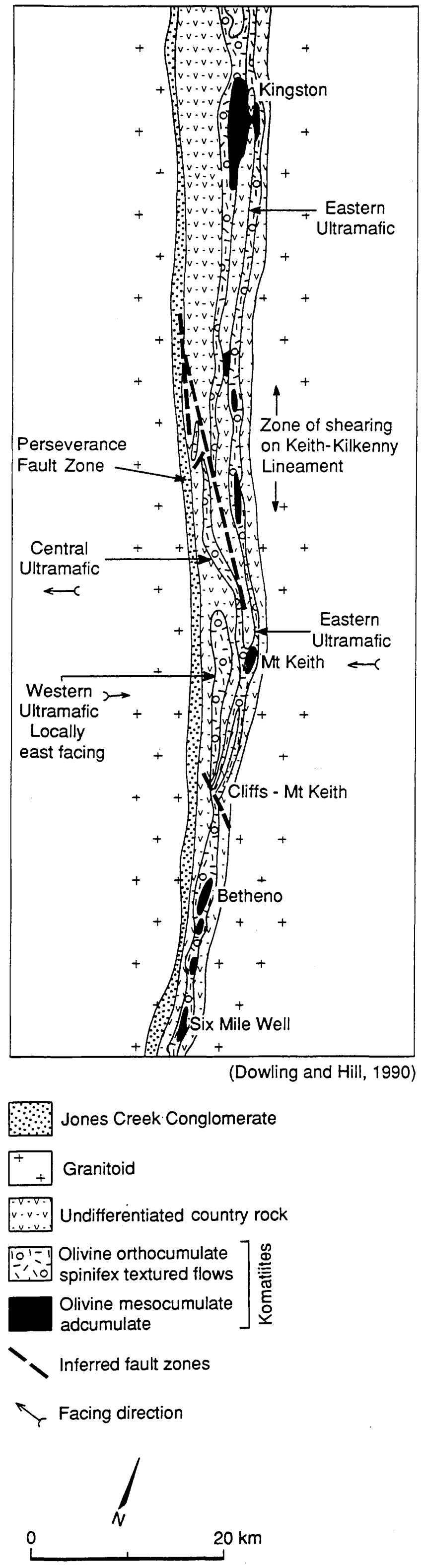

Figure 21. Geological map of the Agnew-Wiluna belt between Six Mile and Kingston, showing distribution of dunitic pods within the komatiite stratigraphy.

Stop 17. The Mt. Keith Region

The Mt. Keith region occupies the most attenuated part of the Agnew-Wiluna greenstone belt (Fig. 17). The region is structurally complex with a pronounced NNW-trending linearity and vertical to steep dips to the west. Within the 60 kilometres of strike between Six Mile Well and Kingston there are at least four significant accumulations of nickel sulphide. Deposits at Betheno, Mt. Keith and Kingston contain vast reserves of low grade disseminated nickel sulphide hosted by olivine adcumulate-orthocumulate lithologies. Small deposits of massive sulphide and olivine-sulfide cumulate associated with thin komatiite flows, such as the Cliffs-Mt. Keith deposit, also occur within this area.

Three separate major komatiite units, the Eastern, Central and Western Ultramafic Units and several minor units have been mapped between Six Mile Well and Kingston (Fig. 21, Fig. 22). The major units vary in thickness and continuity along strike, and young and dip steeply to the west. Easterly younging directions have been determined in the Western Ultramafic to the west of Mt. Keith indicating the presence of a regional synclinal axis up the centre of the belt. In places the major units are juxtaposed as a result of faulting or thermal erosion.

All of the ultramafic rocks have been metamorphosed in the presence of H_2O- and CO_2-bearing fluids to mid-upper greenschist facies. Igneous olivine, pyroxene, amphibole and chromite are preserved in places. Typical assemblages consist of tremolite, actinolite, chlorite, antigorite, lizardite, brucite, pyroaurite, talc, magnesite, dolomite, stichtite, and magnetite. In the ultramafic rocks primary igneous textures are well pseudomorphed and vary from adcumulate through mesocumulate, orthocumulate and harrisite, to spinifex types.

The Eastern Ultramafic Unit (Fig. 22) is dominated by olivine orthocumulates, but is characterized by lenticular bodies of olivine adcumulate-mesocumulate in gradational contact with laterally equivalent sequences of olivine orthocumulate and spinifex-textured flows. Low-grade disseminated nickel-sulfide mineralisation occurs in several of the layered olivine adcumulate-mesocumulate bodies. The Mt. Keith Ultramafic complex (MKUC) hosts the MKD-5-Mt. Keith deposit (270 mt of 0.6 wt% Ni) which is the most significant of these deposits.

Lithologies which constitute the MKUC are illustrated on diamond drill hole section MKD 27,32 (Fig. 23). There is a basal zone of olivine orthocumulate overlain by a thick zone of unmineralised coarse-grained olivine adcumulate and a thick zone of layered, mineralized orthocumulate (the MKD-5 orebody), both of which contain units of a coarse grained porphyritic olivine rock. This sequence grades laterally and vertically into an upper zone of predominantly olivine orthocumulate (partly mineralized), but which is characterized by fractionated sequences which contain branching olivine harrisite, layered, olivine-pyroxene cumulates, gabbros and plagioclase cumulates. Primary kaersutitic amphibole oikocrysts occur sporadically in the olivine orthocumulates of this upper zone.

The disseminated sulphide mineralisation within the MKD-5 deposit forms in layers of variable thickness from centimetres to tens of metres. Pentlandite is the dominant sulphide with subordinate pyrrhotite, millerite, and heazlewoodite, and minor chalcopyrite, violarite and gersdorffite. The present nickel-rich sulphide assemblage results from both primary magmatic and subsequent metamorphic processes.

The Central Ultramafic Unit is separated from the Eastern unit by an interval of mafic and felsic volcanic rocks with impersistent thin komatiite flows. The Central Ultramafic Unit is predominantly composed of sequences of thin differentiated olivine- and pyroxene-bearing spinifex-textured flows which become more evolved towards the west, and subordinate units of olivine orthocumulate. It contains zones of thickening occupied by layered olivine adcumulates and mesocumulates with disseminated sulphide mineralisation. Discontinuous layered olivine-pyroxene-plagioclase cumulates occur at the top of the unit. Thin interflow sediment horizons (pyritic, tuffaceous shales, chlorite schists and black shales) are present throughout.

The Cliffs-Mt. Keith massive nickel sulphide deposit is associated with the earliest flow of the Central Ultramafic Unit and is confined to embayments and flexures in the faulted contact zone (Fig. 22). The massive sulphide is best developed in zones characterized by the absence of a basal black shale. It is stratified with a basal massive zone which is overlain by matrix and their disseminated layers.

The Western Ultramafic Unit is interpreted to be the youngest of the major komatiite units. It is composed of a sequence of thin differentiated olivine- and pyroxene-bearing spinifex-textured flows, and thicker zones of olivine orthocumulate. In the central part of the unit are small bodies of gabbro associated with pyroxene-rich flows. Numerous thin interflow sediments are present throughout the Unit.

In contrast to the Eastern and Central Ultramafic Units, which are dominated by very olivine-rich cumulates, the Western Ultramafic with its preponderance of spinifex-textured rocks is indicative lower eruption rates, thin sheet flow and episodic emplacement. These flows are well exposed to the west of the present Leinster-Wiluna road, in a series of small outcrops within which well developed olivine and pyroxene spinifex textures, cumulate textures, flow tops and B1 zones can be seen. No samples are to be taken from these outcrops, which are listed as a geological monument.

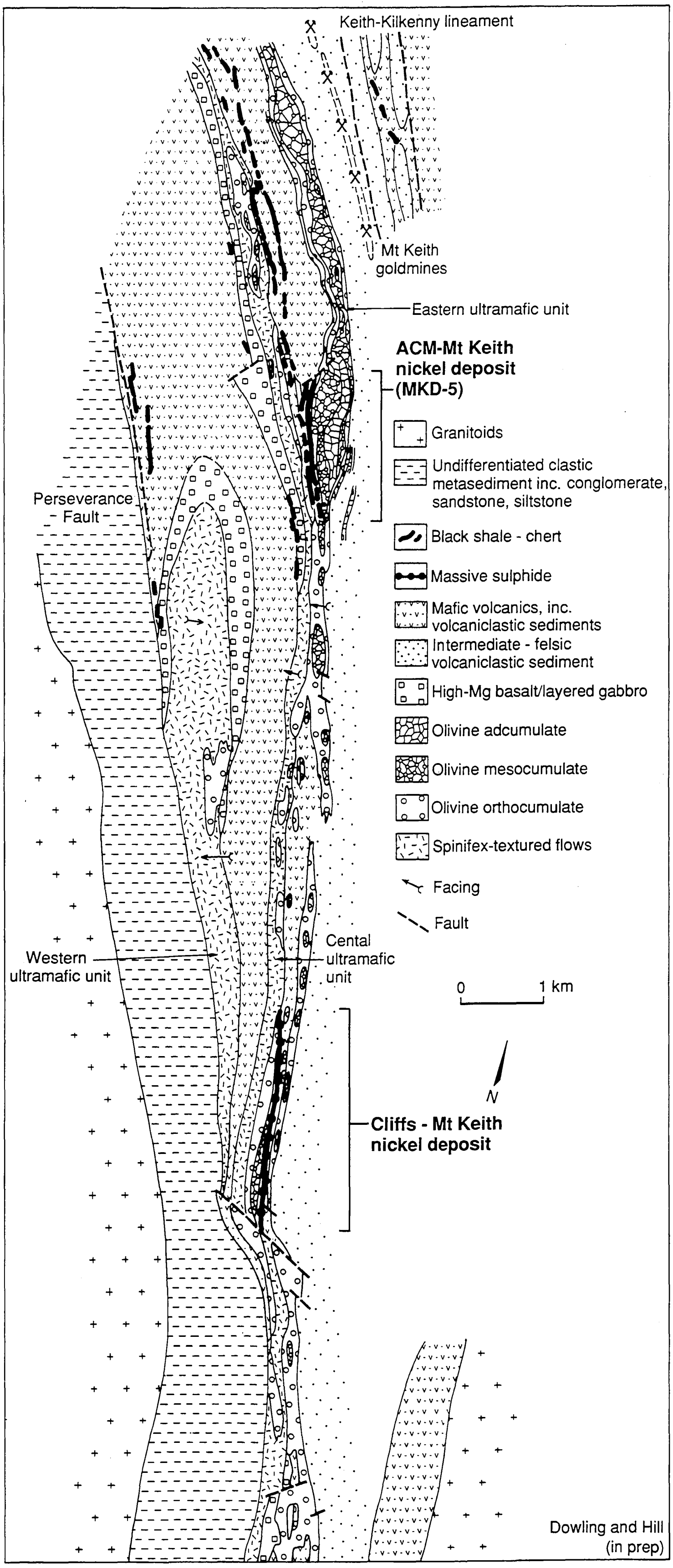

Figure 22. Geological map of the Mt. Keith area.

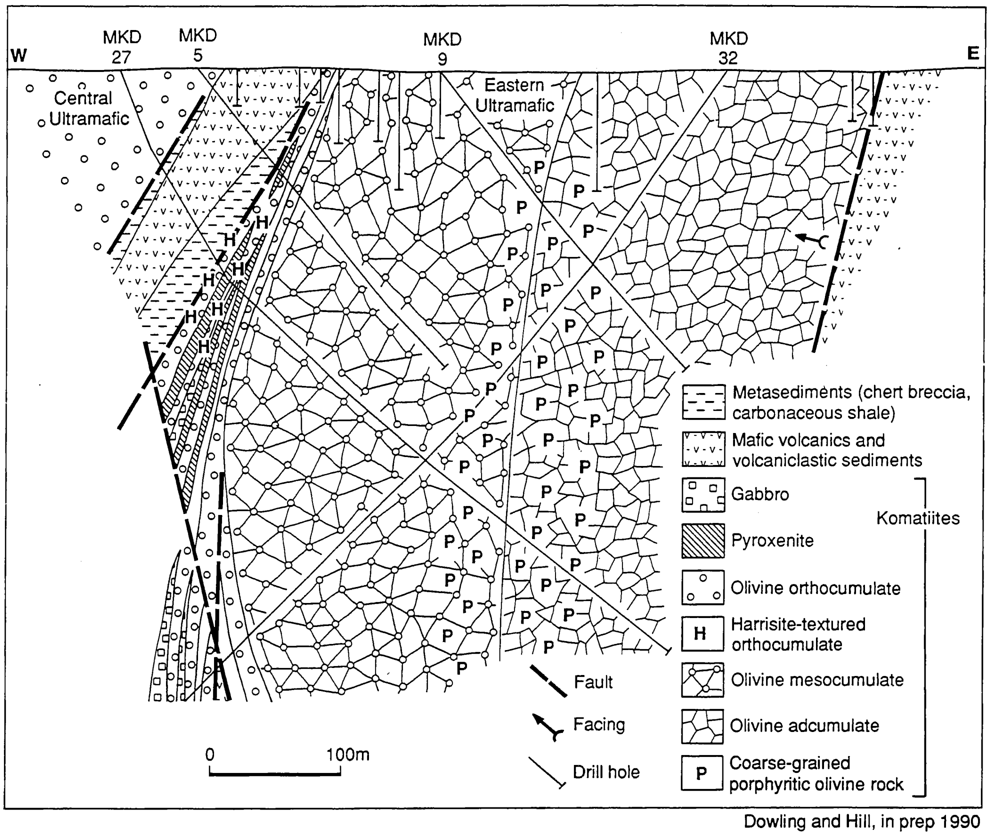

Figure 23. Interpretive geological cross section through the Mt. Keith nickel deposit.

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