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KOMATIITES OF THE NORSEMAN–WILUNA GREENSTONE BELT, WESTERN AUSTRALIA — A FIELD GUIDE

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Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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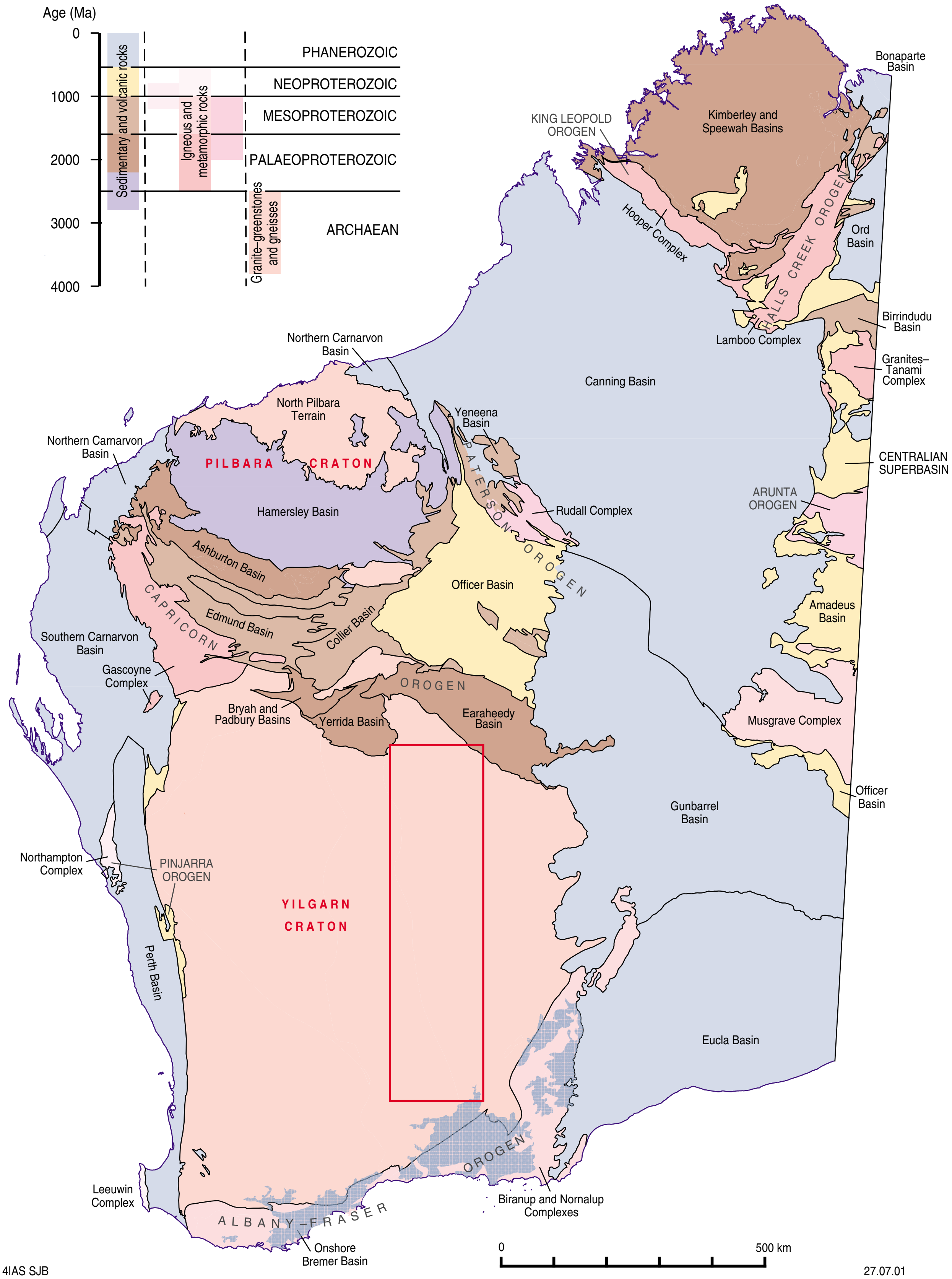

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Komatiites of the Norseman–Wiluna Greenstone Belt, Western Australia — a field guide

by

R. E. T. Hill[1], S. J. Barnes[1], and S. E. Dowling[1]

Introduction

This is an excursion guide to selected komatiite localities in the Norseman–Wiluna Greenstone Belt of Western Australia, between Kalgoorlie and Mount Keith (Fig. 1). The main purpose of the excursion is to illustrate the volcanology-based, facies approach to understanding komatiites that has been developed by CSIRO over the last 20 years. This period has seen a major progression in the understanding of komatiites, from the earliest stages when thick olivine-cumulate bodies were regarded as intrusive dykes to a modern interpretation where all the elements of the komatiite stratigraphy are recognized as extrusive components of large komatiite flow fields.

The understanding of such flow fields has been revolutionized in the last decade by studies of modern Hawaiian basaltic flow fields, and of large basaltic sheet flows in flood basalt provinces. These studies have recognized the significance of features such as lobe-by-lobe emplacement, preferred lava pathways, inflation and endogenous growth, and thermal erosion at the base of established lava pathways. The current thrust of komatiite research is the application of this understanding to mapping and interpreting komatiite flow fields, and using the results to aid exploration for their contained nickel deposits.

The crucial first step is recognition of the textural variability of komatiites, and their spatial significance. Much of the research carried out at CSIRO over the last 20 years has been based on mapping, on the surface and in drillcore, of the spatial distribution of komatiite lithologies on both detailed local and broad regional scales. The focus of this excursion is the presentation of these results.

Textural variability in komatiites

Komatiites show a wide range of spectacular textures, often within the same lava flow, arising predominantly from the many different habits displayed by olivine. There are two basic types of texture: dendritic or 'spinifex' textures, in which olivine takes on a variety of skeletal forms, and cumulate textures arising from accumulations of approximately equidimensional olivine crystals. Both types of texture are widely developed within the Norseman–Wiluna Greenstone Belt although, contrary to common perception, spinifex textures are relatively rare and restricted compared with cumulus textures.

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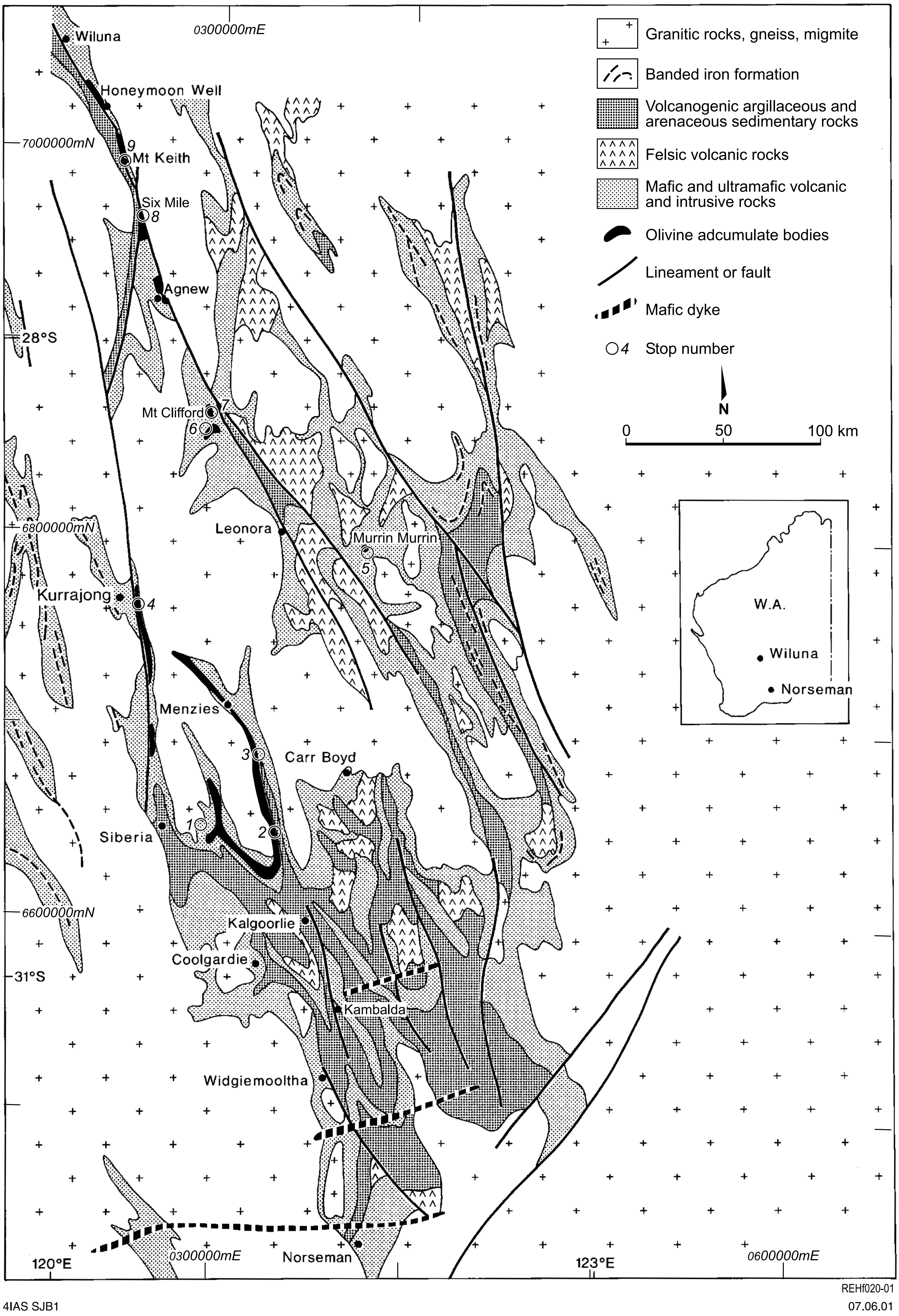

Figure 1. Simplified geology of the Norseman–Wiluna Greenstone Belt, showing excursion localities

Spinifex textures

The Munro Township locality in the Abitibi greenstone belt in Ontario (Arndt et al., 1977) provides the type example of textural variation within komatiite flows. From the base to top, a typical flow consists of a thin, fine-grained, fractured and brecciated flow top, a middle zone of dendritic or 'spinifex-textured' olivine crystals, and a lower zone of olivine cumulates characterized by loosely packed polyhedral crystals (Fig. 2).

In detail, the spinifex zone is characterized by an upper portion of fine-grained, randomly oriented olivine plates (the A2 zone). The top of the A2 zone grades upward into the chilled flow top, and consists of fine, randomly oriented, feathery olivine dendrites. These increase in grain size downward into an open random spinifex texture, consisting of coarser, randomly oriented olivine plates within a groundmass of finer, feathery olivine and clinopyroxene (Fig. 2A). The A2 zone grades with increasing grain size and alignment into the lower plate-spinifex (A3) zone. This consists of large olivine plates (30 cm – 1 m across), roughly perpendicular to the flow surface.

Cumulate textures

In the thicker flow units, a range of textures exists within the cumulate or 'B' zone, from orthocumulate through mesocumulate to adcumulate. These textures have great genetic significance, particularly in the areas covered by this excursion guide.

Cumulate textures are subdivided on the basis of the proportion of cumulus crystals to the crystallization products of magma trapped between the cumulus crystals.

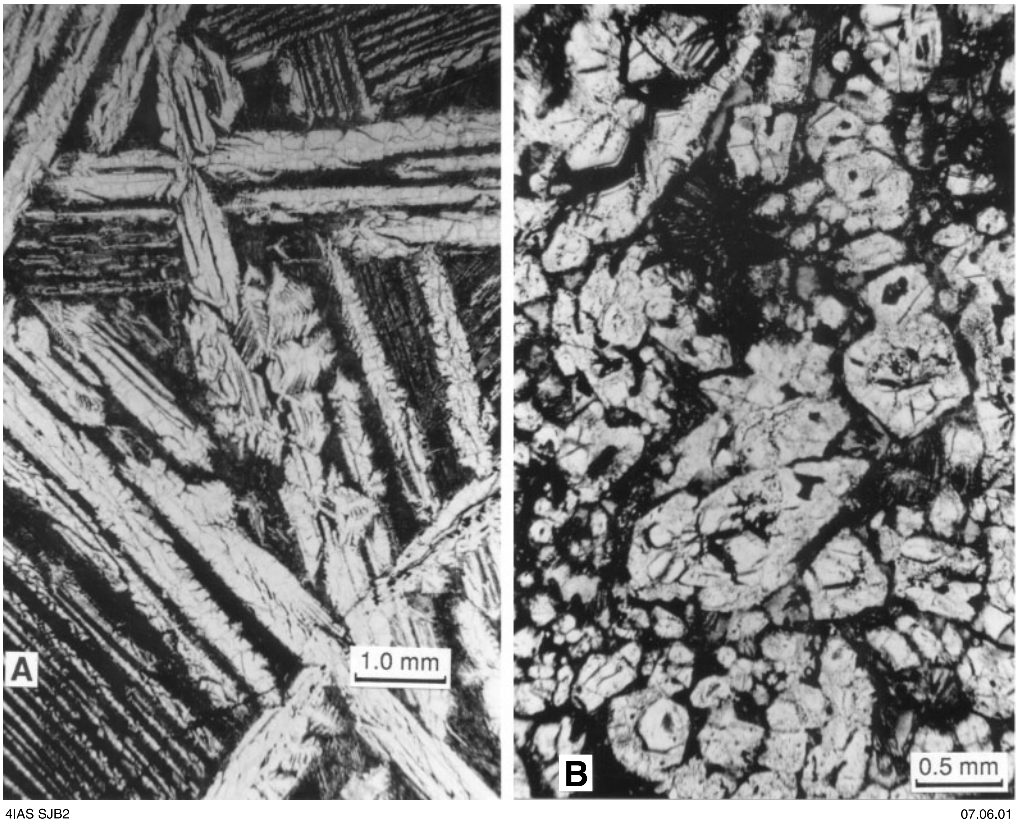

Figure 2. Textures in thin komatiite flows: A) olivine spinifex texture, showing plates of olivine with skeletal morphologies; B) olivine orthocumulate showing euhedral olivines, some with hollow cores. Samples from the Western Ultramafic Unit, Mount Keith

Orthocumulates are rocks that exhibit a high proportion of crystallized trapped intercumulus liquid, with subhedral to euhedral cumulus crystals. Adcumulates are rocks that have little or no intercumulus material and are characterized by anhedral crystals exhibiting a very high degree of mutual boundary contact and triple-point junctions. Mesocumulates are rocks in which the cumulus crystals exhibit extensive mutual boundary contact, but retain some recognizable primary igneous porosity and some original crystal faces and terminations. Olivine orthocumulate, mesocumulate, and adcumulate textures are illustrated in Figure 3.

A rare but important rock type is olivine harrisite (Fig. 3D). This is a special case of a transition from orthocumulate towards spinifex texture, and is characterized by coarse, branching dendritic olivine crystals, similar to the type example of harrisite in the Rhum layered intrusion (Donaldson, 1974). Harrisites commonly form persistent but thin layers at the top of thick adcumulate layers in thick komatiite sheet flows.

Origin and significance of komatiite textures

Textures of komatiites indicate the conditions under which they crystallized: rapid cooling and high degrees of supercooling produce fine random spinifex, moderate cooling rates form coarse spinifex textures, and slow cooling rates and low degrees of supercooling result in polyhedral cumulus-textured olivines. Adcumulates form in dynamic regimes where temperatures at the site of crystallization never dropped very far below the liquidus. Spinifex textures indicate supercooled crystallization beneath free cooling surfaces, driven by relatively rapid upward heat loss, and adcumulates indicate crystallization in large, long-lived, very hot lava pathways or sheet flows.

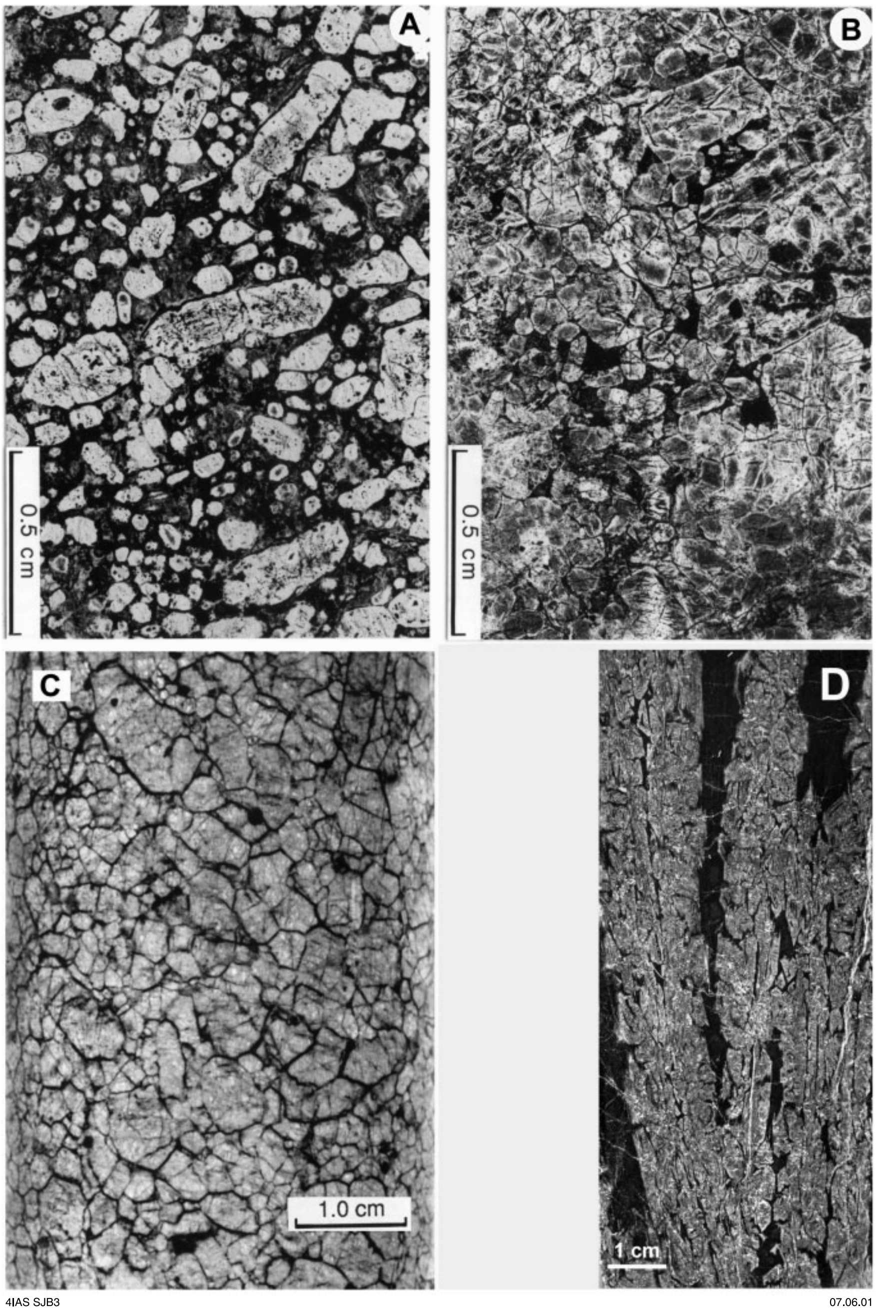

Figure 3. Olivine cumulate textures in komatiitic cumulate bodies: A) olivine orthocumulate (serpentinized), showing euhedral idiomorphic olivine crystals in open framework or point contact. Interstitial material is altered glass and finely crystalline groundmass (thin section, transmitted light); B) olivine mesocumulate (serpentinized). Some interstitial material (altered, black). Most grains are in face contact, but some olivine crystal faces are visible (thin section, transmitted light); C) olivine adcumulate, showing 100% olivine grains in face contact, with common 120° triple junctions between grains (incident light on curved surface of drillcore); D) olivine harrisite, with coarse branching olivine crystal(s), from Kambalda (incident light on polished drillcore)

Excursion localities

Excursion localities are marked on Figure 1.

The Walter Williams Formation

The supracrustal rocks that extend from Siberia to Menzies (Figs 1 and 4), and farther north through to Kurrajong, are broadly correlative with rocks of the Kalgoorlie–Kambalda region. There is one striking feature of the komatiitic rocks — a laterally extensive unit of coarse-grained olivine adcumulate. This is the most extensive body of olivine adcumulate known in the Yilgarn Craton. It forms part of the Walter Williams Formation, which can be traced continuously from southwest of Siberia to the shores of Lake Ballard northwest of Menzies, and to the Kurrajong Anticline in the Mount Ida greenstone belt (Fig. 4).

The Walter Williams Formation is a layered body, traceable over an area of about 35 × 130 km, consisting of a lower zone of olivine cumulates and an upper zone of gabbroic rocks (Gole and Hill, 1990; Hill et al., 1995). The proportion of olivine cumulates to gabbro varies along strike as does the igneous porosity within the lower olivine-cumulate zone.

The formation is interpreted as part of a very large komatiite flow field. The southern part formed as a vast sheet lobe, resulting in the development of an extensive thick pile of olivine cumulates. In the north the flow underwent ponding, in situ fractionation, and repeated influxes of new batches of lava (Gole and Hill, 1989, 1990).

Stratigraphic profiles through the Walter Williams Formation (Fig. 5) show the gross layering and lateral lithological variations. South of Ghost Rocks, the lower ultramafic zone of the Walter Williams Formation 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 Walter Williams Formation is a layered gabbro, which thickens from approximately 30–40 m at Yunndaga to 100 m at Ghost Rocks and 180 m at Kurrajong.

Estimates of the true thickness of the unit are greatly hampered by the lack of dip information, and the relative thicknesses shown in Figure 5 are conjectural. At Vetters Hill the estimated thickness is about 200 m, just south of Menzies it is only 50 m, and at Ghost Rocks it is again 100–200 m. The unit certainly appears to thin from an area about 10 km south of Menzies northward to Lake Ballard, although this may in part be due to deformation, as some of the rocks in this area are highly strained. For convenience in the following discussion, the Walter Williams Formation is considered in two segments: the southern segment extending from Siberia around the Mount Pleasant anticline to Menzies, and the northern segment in the Kurrajong Anticline.

Siberia to Menzies area

The stratigraphy in the area has been described by Witt (1987; Fig. 6). Several of the stratigraphic units, including the komatiites, can be confidently traced from the Siberia area to north of Menzies (Fig. 4). The stratigraphy consists of a lower series of basalts, a thick pile of komatiites, a series of layered gabbroic bodies and basalts, and finally a sedimentary sequence. These rocks have been deformed by open regional-scale folds: the Goongarrie – Mount Pleasant Anticline in the west, and the Kanowna–Scotia Anticline in the east, separated from one another by the Bardoc Tectonic Zone (Fig. 4; Swager, 1997; Swager et al., 1990).

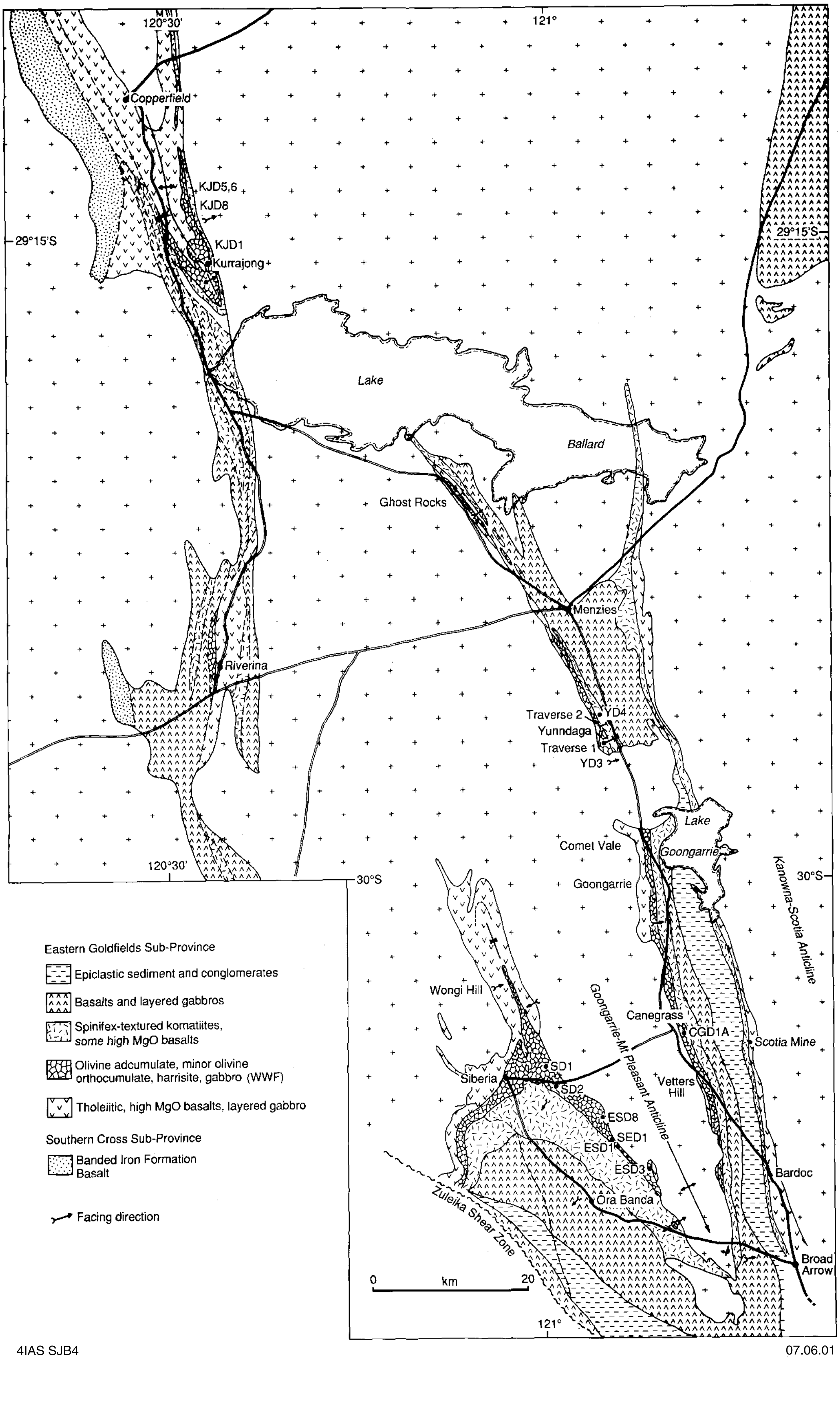

Figure 4. Geological map of the Walter Williams Formation, showing the distribution of the olivine adcumulate unit. Data from CSIRO mapping, incorporating data from GSWA mapping by Swager (1997), Swager et al. (1990), and mapping by J. Hallberg, N. Harrison, and N. Herriman

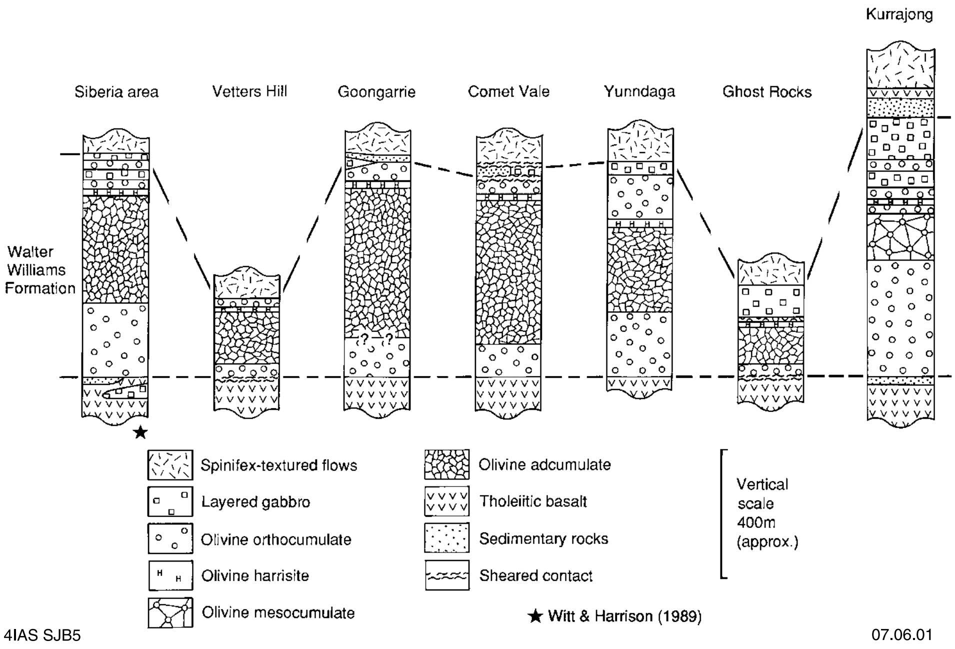

Figure 5. Stratigraphic profiles through the Walter Williams Formation. See Figure 4 for locations

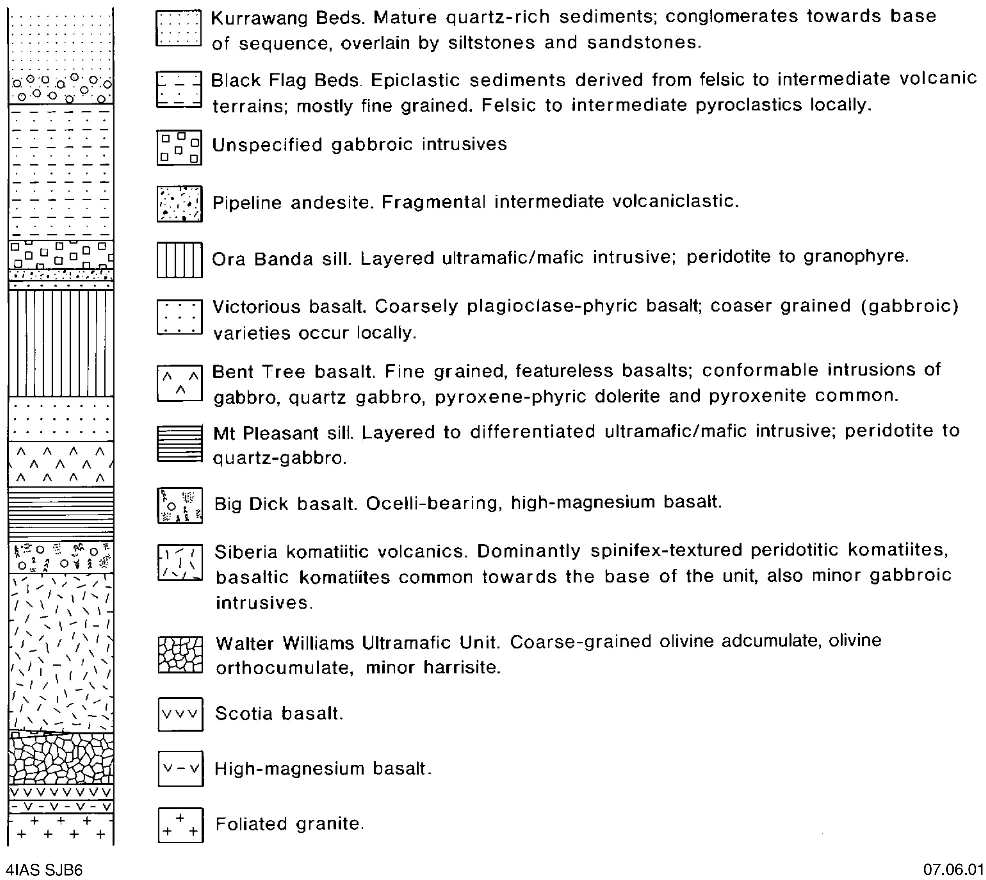

Figure 6. Stratigraphy of the supracrustal sequence in the Ora Banda area (after Witt, 1987)

Regional stratigraphy

The lowermost stratigraphic unit in the area, exposed in the Goongarrie – Mount Pleasant Anticline west and north of Siberia, consists of high-Mg basalt. This unit is overlain by tholeiitic basalts and layered gabbros, which are particularly well exposed in the Wongi Hill area where facing directions from the gabbros indicate the presence of a gently southerly plunging syncline. The footwall sequence is also present in the Goongarrie – Comet Vale area. Elsewhere around the Goongarrie – Mount Pleasant Anticline, the footwall sequence is either stoped out by granite or present as only a thin sliver of tholeiitic basalt on the margin of the greenstone belt. The footwall tholeiitic basalts exposed in the Missouri openpit, north of Siberia, are pillowed. These well-preserved pillows contain no vesicles, implying formation at water depths greater than about 500 m.

The komatiites can be divided into two very different units: the Walter Williams Formation, composed largely of olivine cumulates, and the overlying Siberia Komatiitic Volcanics composed of thin spinifex-textured flow lobes up to 5 m thick. Both olivine and clinopyroxene (‘string-beef’) spinifex textures are present, reflecting a wide range in liquid compositions. There are numerous thin interflow sediments throughout the flow sequence. In the lower parts of the pile, there are some apparently discontinuous 3–5 m-thick dolerite bodies similar to those in the upper orthocumulate part of the Walter Williams Formation. Differentiation in the flows provides evidence of facing direction throughout the area, and shows that the structure is a southeasterly plunging anticline–syncline pair with a steeply dipping eastern limb and a shallowly dipping central limb. Dips are very shallow around the synclinal closure at Siberia.

The sequence of diverse igneous rocks overlying the komatiites has been considered as one unit for simplicity in Figure 5. In addition to the igneous rocks, thin sediments are present between the major stratigraphic units. Some major units within this sequence have been traced from Ora Banda to just south of Lake Goongarrie (Fig. 4). Facing directions derived from the layered gabbros within this sequence confirm those obtained from the underlying komatiite flows. Sedimentary rocks comprise the youngest group of supracrustal rocks in the area and are present southwest of Ora Banda in the southern-central part of the Broad Arrow – Menzies belt, but do not extend north to the Menzies area. These rocks typically outcrop poorly and are invariably highly deformed.

Internal stratigraphy and petrography of the Walter Williams Formation

Around the Mount Pleasant Anticline, the lowest subzone of the Walter Williams Formation is a fine- to medium-grained olivine orthocumulate containing oikocrysts of pyroxene and rare kaersutitic amphibole. It is similar to some of the marginal rocks from the Marshall Pool and Mount Clifford dunites (Donaldson et al., 1986). The subzone is serpentinized to varying degrees, although igneous textures are commonly well preserved (Fig. 7).

Very few drillholes intersect the lower contact. From the base up, the olivine grain size increases and intercumulus porosity decreases through the orthocumulate units, so that the rock type gradually changes to a mesocumulate (Fig. 7A) and then to an adcumulate (Fig. 7B). The adcumulate typically has a grain size of 1–2 cm, although just south of Menzies it is finer grained (2–3 mm). Such a small grain size is rare in olivine adcumulates of the Norseman–Wiluna Greenstone Belt. Samples obtained from the few drillholes that intersect the adcumulate show the olivine to be mostly fresh (Fig. 7B), with a brown pleochroism typical of metamorphosed relic igneous olivine. Typically, the grain margins are colourless due to recrystallization induced by strain. However, in some of the adcumulates from northeast of Ora Banda, the brown colour extends to grain boundaries, and these are some of the best preserved olivine

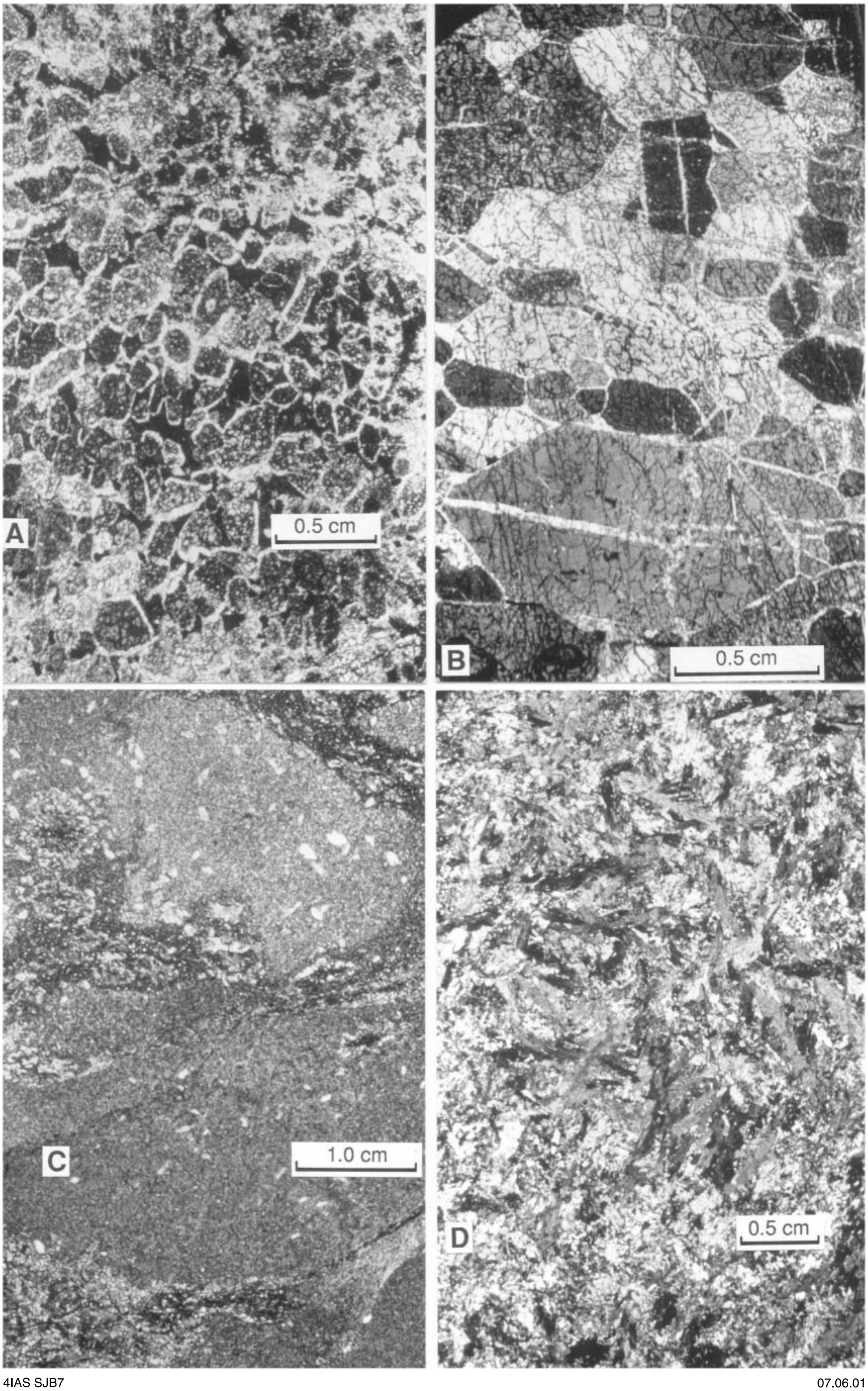

Figure 7. Lithologies from the Walter Williams Formation: A) olivine mesocumulate, with fresh olivine showing marginal replacement by antigorite; B) unserpentinized olivine adcumulate; C) quenched high-Mg basaltic flow-top breccia; D) gabbro. All photomicrographs with crossed polars

adcumulates to be seen in the Yilgarn Craton. Antigorite is the most common serpentine mineral, forming platy intergrowths along olivine grain boundaries. This texture is well preserved in the silica cap in the laterite pit at Siberia (see **Locality 1** below).

Immediately above the adcumulate is a very characteristic coarse-grained olivine harrisite, well exposed at Comet Vale (see **Locality 1** below). The transition from the adcumulate to the harrisite occurs over a few metres and is very abrupt. Wherever the top of the adcumulate is exposed, the harrisite unit, which is only 2–5 m wide, is present. The persistence of this unit is remarkable. Above the harrisite is a 20–40 m-thick unit of fine-grained olivine orthocumulate. Within this unit, a few metres above the base, are several 30 cm-thick pyroxenite layers. These layers are best seen at Comet Vale where they are well exposed (see locality description below). At other locations they are preserved as subdued outcrop or as rubble.

The top of the Walter Williams Formation is marked at Goongarrie and Bardoc (Fig. 4) by a 2–3 m-thick layer of fine-grained sedimentary rock, and at Yunndaga and farther north by fine- to medium-grained gabbroic rocks. At Goongarrie bodies of gabbro are present within the orthocumulate unit. Just south of Menzies and the Ghost Rocks area, the gabbro is characteristically layered. Yunndaga is the only locality where unaltered samples are available through almost the entire thickness of the Walter Williams Formation, from percussion drillholes along three traverses across the body. Whole-rock analyses of handpicked chips from one of these traverses, which also intersects the overlying spinifex-flow sequence, are plotted in Figure 8. The most MgO-rich section is the upper part of the adcumulate, a feature shared by the Mount Clifford and Perseverance olivine adcumulate bodies. The TiO_2 value is a measure of the porosity of these rocks and clearly defines the orthocumulate and adcumulate subzones of the Walter Williams Formation. The Cr_2O_3 value is highest, up to 3.4% (anhydrous), close to the lower orthocumulate–adcumulate contact, due to the presence of abundant cumulus chromite. The NiO value in olivine increases upward through the body,

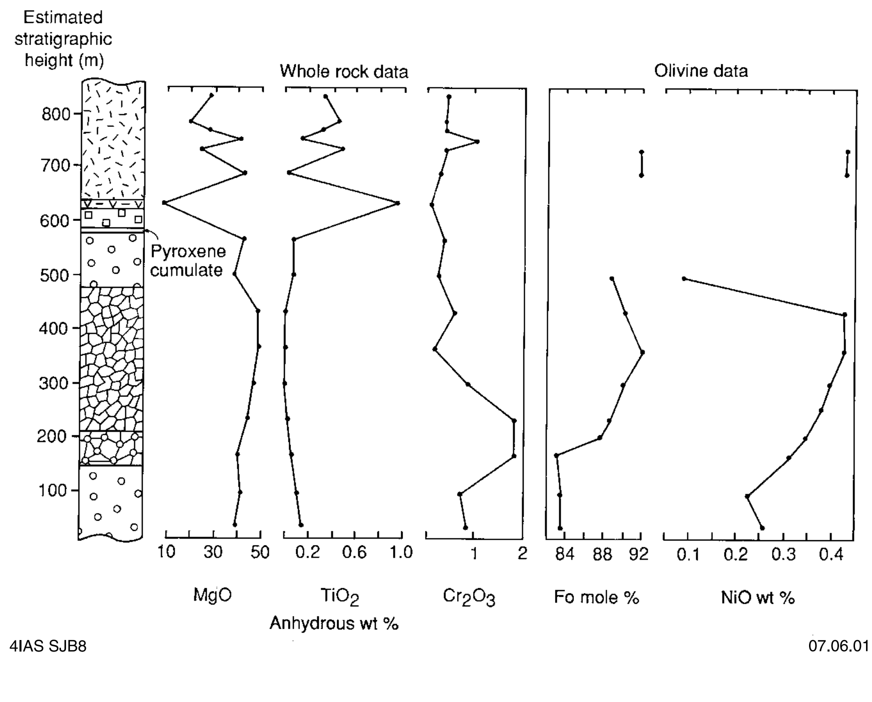

Figure 8. Lithological and geochemical profiles through the Walter Williams Formation and the lower part of the Siberia Komatiitic Volcanics, Yunndaga. See Figures 5 and 6 for legend

reaching a maximum in the most MgO-rich adcumulate. There is no evidence for nickel depletion in olivine, as seen elsewhere in the belt, indicating that the parent lava to the Walter Williams Formation adcumulate was undersaturated with respect to sulfur. No sulfide accumulations are known from the Walter Williams Formation around the Goongarrie – Mount Pleasant Anticline.

Locality 1: Lower part of the Walter Williams Formation, Siberia area

From Ora Banda townsite, take the Davyhurst road from crossroads at Ora Banda pub, about 20 minutes drive to Siberia townsite crossroads (AMG 0303030E 6652270N). For the basal contact locality, follow the Davyhurst sign, about 1 km to road junction (AMG 0302670E 6653490N), then turn right and go about 150 m to start of traverse. For Siberia SM7 laterite pit locality, take east-northeasterly trending road from Siberia townsite crossroads, go about 4 km to T-junction (AMG 0306775E 6653185N) and turn right, to track junction (AMG 0307415E 6652790N). Follow track on west side of road, which leads to spoil dump at southeast end of pit (AMG 0307260E 6652720N).

Locality 1.1: Basal contact

The footwall tholeiitic basalt and the lower orthocumulate unit of the Walter Williams Formation are exposed (1 on Fig. 9). The orthocumulate outcrops as weathered serpentinite (AMG 0302844E 6653630N). Outcrop and chips from drillholes into the laterite indicate that the orthocumulate extends several hundred metres east of the contact, suggesting a very shallow dip. A series of percussion drillholes (between AMG 0302908E 6653776N and AMG 0302908E 6653776N) sampled the basal unit, and shows the upward progression into more olivine-rich cumulates. Rocks adjacent to the contact are intruded by pegmatites. The Missouri, Sand King, and Camperdown gold mines are a few kilometres north along this contact. The area has been worked as a dryblowing patch.

Locality 1.2: Western Mining Corporation SM7 nickel laterite pit

Exposures in this pit (2 on Fig. 9) provide a spectacular illustration of the unique style of weathering of very olivine rich rocks in the Tertiary laterite profile. Adcumulates become converted to a ‘silica cap’ containing more than 90% chalcedonic silica, but perfectly preserving the original adcumulate texture and commonly the textures associated with serpentinization of olivines. Pseudomorphs of adcumulate with fine-bladed antigorite along grain boundaries are present on the northern side of the openpit. This is the best locality for collecting samples of silica cap. The openpit was mined for silica flux (with a bonus of up to 2% Ni) for the WMC nickel smelter. The nickel laterite mining operations elsewhere in the Yilgarn Craton (as at the nearby Cawse deposit) mine the nickeliferous clays from the profile overlying the silica cap layer — these have been eroded in this locality.

Locality 2: Vetters Hill

Vetters Hill is immediately beside the main Kalgoorlie to Menzies highway (Fig. 4). Stop on highway (at AGM 0329360E 6651850N), cross railway line on west side of road and climb hill.

A complete section through the Walter Williams Formation is seen in the siliceous laterite that caps the hill. The ultramafic unit is unusually thin at this locality, having an apparent thickness of about 150 m compared to 600–900 m elsewhere in its southern outcrop area. The facing is easterly and we shall walk down stratigraphy (at least initially). 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 there are a few low outcrops of orthocumulate. About three-quarters of

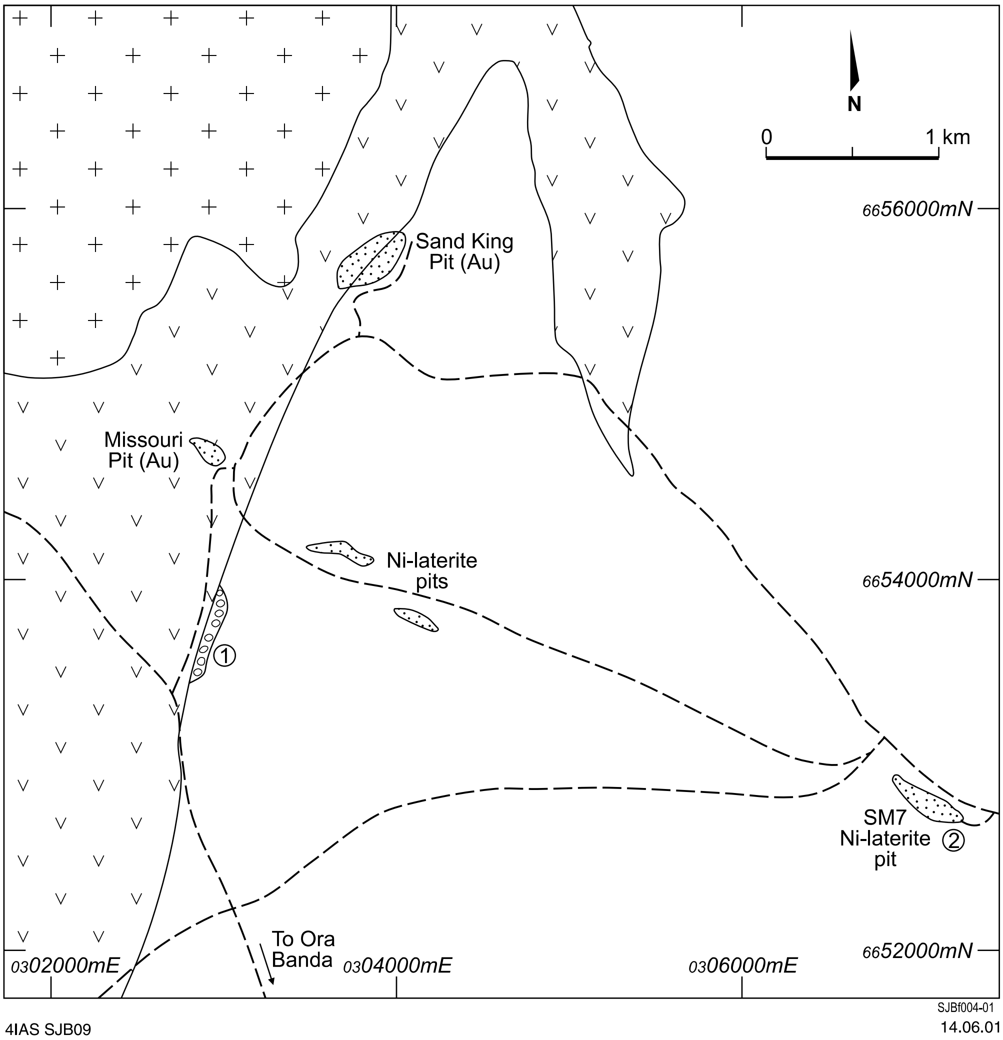

Figure 9. Geological map of the Siberia area, showing Locality 1 and the basal contact of the Walter Williams Formation (v pattern = tholeiitic basalt; + pattern = granite; o pattern = olivine orthocumulate)

the way up the hill (AMG 0329260E 6651700N) there are olivine harrisites in thin rubbly outcrop. Above these and extending to the back slope is adcumulate-textured siliceous laterite. Laterite with orthocumulate textures is present just above the contact with strongly foliated metabasalt (AMG 0329120E 6651770N). There is a marked contrast in the preservation of igneous textures for the ultramafic and mafic rocks over this contact. From the top of the hill, the dump at the Sand King openpit mine, near the western extent of the Walter Williams Formation, is visible. Well-developed dark-brown silica cap over olivine adcumulates is developed around the northern end of the hill (AMG 0329170E 6651310N).

Locality 3: Comet Vale

From the Kalgoorlie–Menzies highway, take the track to the east until the junction with highway (at AMG 0319000E 6685940N). Follow the track to the intersection with baseline track (AMG 0319573E 6685573N). Follow baseline track to crest of hill (AMG 0319573E 6685573N), and the start of the traverse.

At this locality, the upper sections of the Walter Williams Formation and the overlying spinifex-textured flow sequence (Siberia Komatiitic Volcanics) are seen. At the beginning

Figure 10. Geological map of the Comet Vale area, showing Locality 3. See Figure 5 for legend

of the traverse (Fig. 10) on the old WMC grid baseline, and on the flat area immediately to the east, the adcumulate is covered by ferruginous laterite cap and adcumulate textures are preserved only in a few places. 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 (AMG 0319813E 6685498N). The harrisites have been etched by weathering and their three-dimensional shapes are well shown (Fig. 11).

Note: Participants are requested not to use hammers or remove sample material from this outcrop.

Down the slope, fine-grained orthocumulate with several 30 cm-thick pyroxenite layers outcrop (AMG 0319827E 6685530N). On the flat ground farther 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 southeasterly, bounded to the south by a shear zone and to the north by intrusive granite.

Locality 4: Kurrajong area — the northern segment

Access from Leonora – Mount Ida road from Leonora town centre, to T-junction (AMG 0311220E 6812740N). Turn left at sign to Mount Ida, heading south-southeast, passing Copperfield mine (AMG 0252685E 6779087N). Good samples of Cat Rock are available on the mine dump. At T-junction (AMG 0259100E 6749980N), turn left (east) and proceed 500 m to Riverina outcamp (marked on 1:100 000 sheet; gate at AMG 0259527E 6749808N; Riverina outcamp can also be reached via main road from Menzies). Go through the outcamp, pick up track heading north (from AMG 0259569E 6750012N), not northeast-heading track, which also goes off from this point. Track heads north then runs northeast, then east across anticline axis. Turn left at indistinct track junction (AMG 0262900E 6755504N; bus passage is not possible past here). Track follows creek at first, in and out of creek then out on flat (indistinct), and reaches T-junction (AMG 0262344E 6757824N; mine symbol on map refers to small openpit on left). Turn right (to AMG 0262774E 6757900N), close to KJD1 (AMG 0262770E 6757856N) for start of Traverse 1 (Fig. 12).

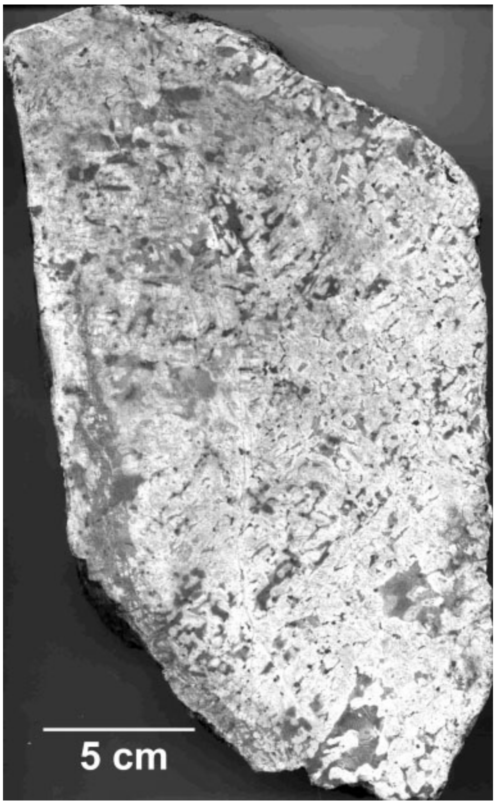

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Figure 11. Olivine harrisite from the Walter Williams Formation at Comet Vale (incident light on polished slab)

The best exposure of the Walter Williams Formation in the north is in the fault-bounded Kurrajong Anticline, in the Mount Ida greenstone belt about 35 km northwest of Ghost Rocks (Figures 1, 4, and 12).

The stratigraphy of the Kurrajong Anticline comprises, from bottom to top: pillowed tholeiitic basalt, a thin black shale, the Walter Williams Formation, a sedimentary horizon, a thin basalt, spinifex-textured komatiite flows, and an upper gabbroic unit. The sedimentary rocks overlying the Walter Williams Formation consist of medium- to fine-grained arkosic to sandy units with minor chert. The sequence is most complete and best exposed in the KJD1 area (Fig. 12).

The area within the anticline north of the old CRA campsite (Fig. 12) is completely buried by loose pisolitic laterite, whereas south of the camp the laterite has mostly been stripped except over the more olivine-rich ultramafic lithologies where siliceous capping is still present. The siliceous capping preserves the igneous textures of the underlying rocks. The area was explored by CRA for nickel in the late 1960s and early 1970s and nickel sulfides were discovered in the northern part of the east limb of the anticline around KJD5 and KJD6 (Fig. 4). CRA drilled a total of 12 diamond drillholes within the anticline. One of these, KJD1 (Fig. 12), was drilled in an area where the gabbro member, as well as the upper part of the ultramafic succession, is very well exposed. Data from this drillhole and from two nearby surface traverses are plotted in Figure 13.

The stratigraphy is similar to that between Ghost Rocks and Siberia (Fig. 4), although the thickness of the spinifex flow unit, equivalent to the Siberia Komatiitic

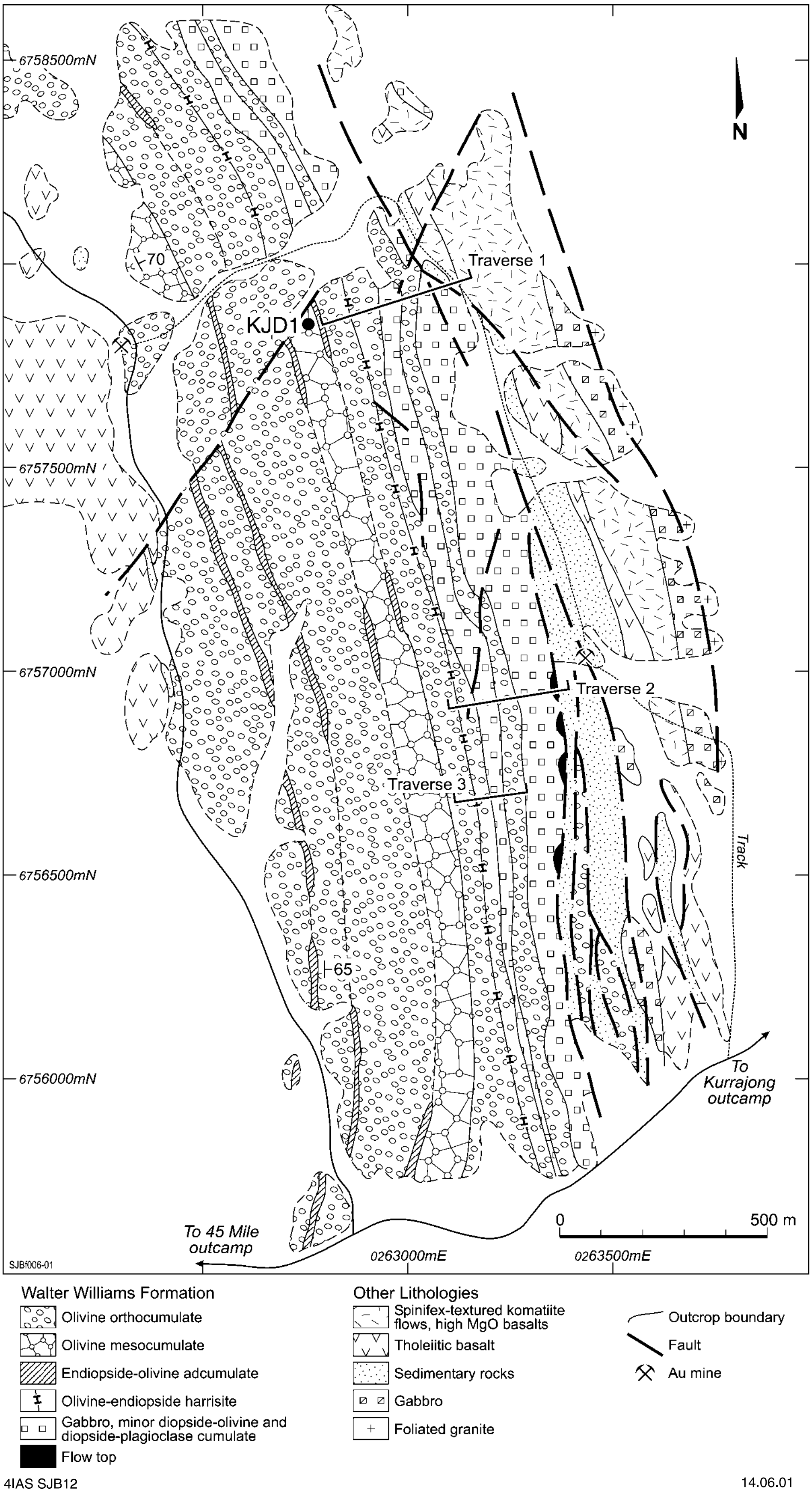

Figure 12. Geological map of the KJD1 area within the Kurrajong Anticline, showing Locality 4

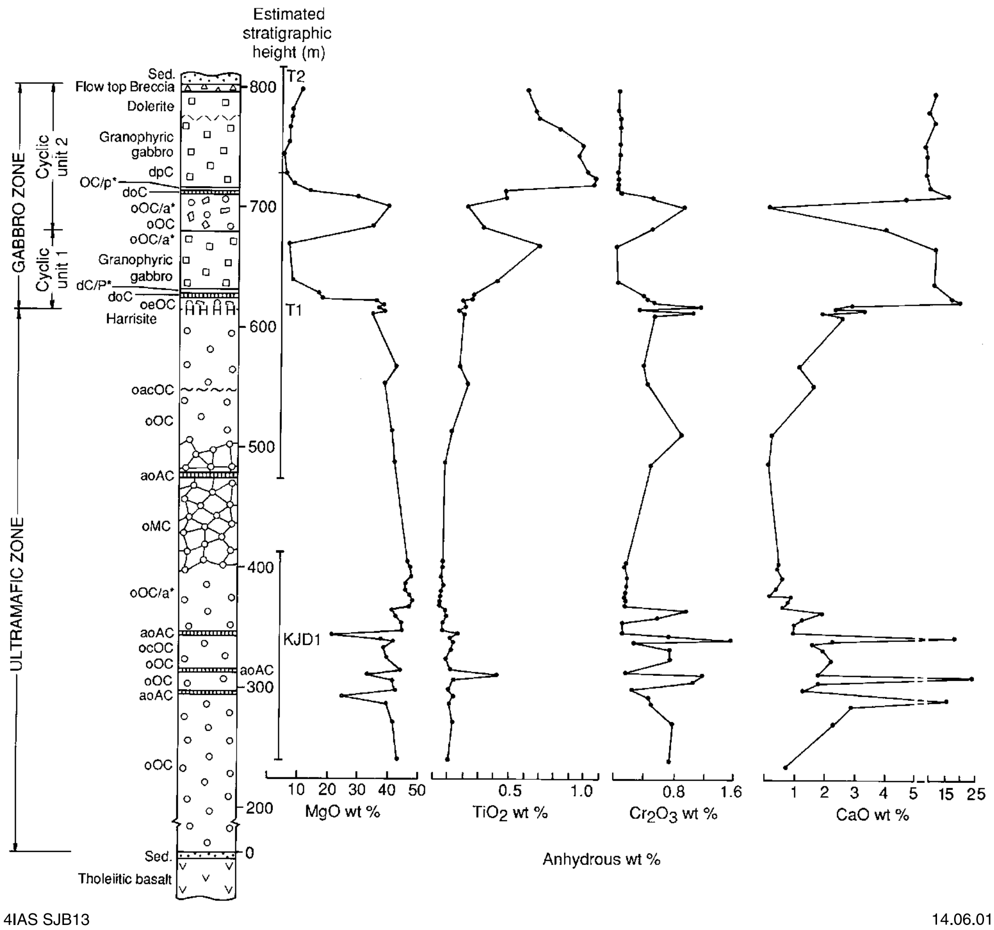

Figure 13. Composite profile showing variations in lithology and whole-rock geochemistry along Traverse 1 – KJD1, and the upper part of Traverse 2, KJD1 area, Kurrajong. See Figure 12 for location. Abbreviations: aoAC = augite olivine adcumulate; dC/p* = diopside cumulate with plagioclase oikocrysts; doC = diopside olivine cumulate; dpC = diopside plagioclase cumulate; oacOC = olivine augite chromite orthocumulate; oeOC = olivine enstatite orthocumulate; oMC= olivine mesocumulate; oOC = olivine orthocumulate; oOC/a* = olivine orthocumulate with augite oikocrysts; ocOC = olivine chromite orthocumulate; OC/p* = orthocumulate with plagioclase oikocrysts; Sed = sediment

Volcanics, is much reduced within the Kurrajong Anticline. The Walter Williams Formation is about 800 m thick in the KJD1 area on the eastern limb of the fold, but thins along the western limb. Although part of the change in apparent thickness may be due to a change in dip and attenuation, the preservation of delicate igneous textures in rocks along the western limb suggests that the reduction in thickness is partly an original feature. The ultramafic zone of the Walter Williams Formation consists mostly of olivine orthocumulate with olivine mesocumulate in the central part. In the central part there are at least four thin Mg-augite–olivine adcumulate layers, which are 0.5 – 3 m thick and consist of Mg-augite (or an altered assemblage) and altered olivine in a polygonal aggregate. This section contrasts with the adcumulate-dominated ultramafic zone to the south.

Traverse 1

In the upper section of the ultramafic zone in the KJD 1 area (Fig. 12) a 5 mm-thick chromite layer (AMG 0262887E 6757852N) is developed within an olivine–Mg-augite–chromite orthocumulate with about 30 modal percent chromite. Chromite shows a characteristic ‘chicken wire’ texture around original olivines (Fig. 14).

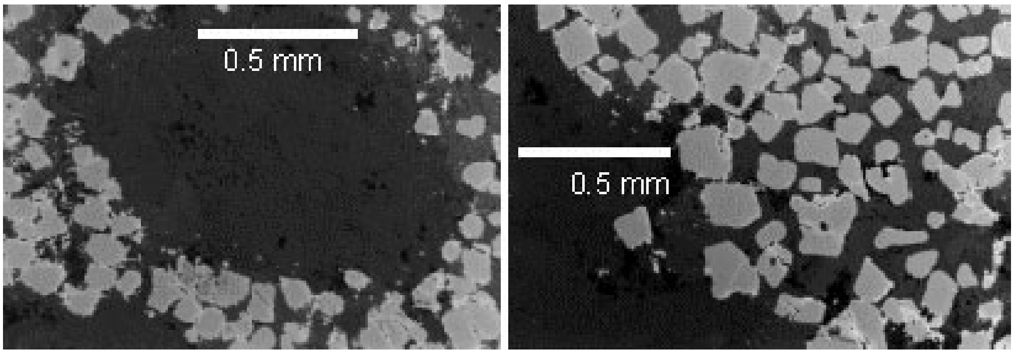

Figure 14. Photomicrograph of chromite-rich layer, with 'chicken-wire' texture, from Traverse 1, KJD1 area

Traverse 1 proceeds from KJD1 to the chromite layer then turns south along the ridge to the harrisite outcrop (AMG 0262908E 6757746N). This is a very coarse grained olivine harrisite with pyroxene oikocrysts, similar to that seen at Comet Vale. This unit is very laterally persistent and can be traced for at least several kilometres along strike. The traverse then proceeds east up the section to a layer of olivine–clinopyroxene cumulate with plagioclase oikocrysts (AMG 0262966E 6757736N). This section is an excellent illustration of the way new cumulus phases appear in the section first as oikocrysts then as idiomorphic grains.

Traverse 2

For Traverse 2, pick up same track again just north of KJD1 and continue east. Track turns at right angles and heads south-southeast parallel to strike, just above top of Walter Williams Formation, to abandoned mine site (AMG 0263427E 6757095N).

Traverse 2 begins at the flow-top breccia of the Kurrajong section of the Walter Williams Formation, which is exposed patchily (around AMG 0263357E 6757078N). 'String-beef' pyroxene-spinifex rocks can be found as float, but have not yet been located in outcrop. Traverse then continues to the west down the section through gabbros, layered olivine–pyroxene cumulates, and olivine orthocumulates.

Traverse 3

From end of Traverse 2 (at around AMG 0262600E 6756900N), head about 200–300 m south to follow Traverse 3 back up the section.

This provides a more detailed exposure of the layering at the top of the ultramafic member as it traverses a hill top where there is minimal scree cover. Here there are two harrisite units, the top one being the persistently outcropping horizon (Fig. 15). Whether the other units are as persistent and covered by scree elsewhere is unknown.

The gabbro zone overlying the ultramafic member at this locality consists of two well-defined cycles (Fig. 13). The lower cycle is cut off by an olivine orthocumulate layer at the base of the upper cycle, whereas the upper cycle is capped by an upward-fining, ophitic dolerite that grades upward through a thin and impersistent unit of pyroxene spinifex-textured komatiite into a pyroxene-phyric basaltic flow-top breccia (Fig. 7C). This sequence provides critical evidence that the Walter Williams Formation is extrusive in origin. Apart from the uppermost section of the upper cycle, the two cycles are very similar, with a lower olivine orthocumulate, then a diopside layer, 1–

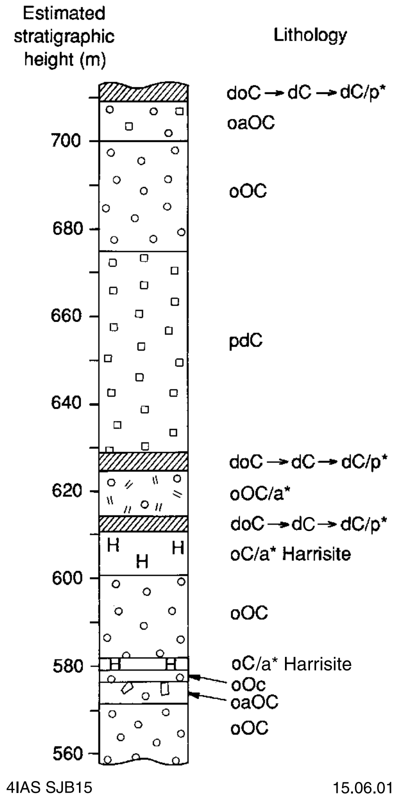

Figure 15. Lithological profile, Traverse 3, KJD1 area. Abbreviations: dC = diopside cumulate; dC/p* = diopside cumulate with plagioclase oikocrysts; doC = diopside olivine cumulate; oaOC = olivine augite orthocumulate; oC/a* = olivine cumulate with augite oikocrysts; oOC = olivine orthocumulate; oOC/a* = olivine orthocumulate with augite oikocrysts; pdC = plagioclase diopside cumulate

2 m thick, of polygonal diopside containing altered olivine in the lower part and plagioclase oikocrysts in the upper part with an intervening layer of pure diopside. The upper and lower contacts are sharp. Above the diopside layer are diopside–plagioclase cumulates with varying mineral proportions. Above this are non-cumulate gabbros (Fig. 7D). Quartz is present throughout much of the thickness of the gabbro units in what may have been granophyric intergrowths. In the upper gabbro, quartz disappears up sequence just below the dolerite. Within both gabbro units, but more particularly in the upper gabbro, there are patches of branching, coarse-grained harrisitic clinopyroxene in a matrix of interlocking plagioclase laths and areas of recrystallized quartz and feldspar.

Geochemical profile, KJD1 area

The geochemical profile through the Walter Williams Formation (Fig. 13) clearly shows the lithological layering just described. In the ultramafic zone, the relatively high contents of TiO_2 and CaO (as well as Al_2O_3), reflect the higher igneous porosity of these rocks compared with those in the ultramafic zone at Yunndaga. The section within KJD1 contains cyclic layering in the central part of the ultramafic zone. Upward increases in CaO and decreases in MgO reflect changes in the model proportions of olivine and pyroxene below each of the three Mg-augite–olivine cumulate layers intersected. Above the third layer, similar geochemical variations are present, but here the cycles stopped before a clinopyroxene layer could form. The rocks formed in each successive cycle in this sequence contain more MgO and less CaO, reflecting an increase in the packing density of olivine. It may also reflect, in part, a change to more forsterite-rich olivine compositions.

In the gabbro zone, the two fractionation cycles are clearly defined by the geochemical profile (Fig. 13). Through most of the upper diopside–plagioclase cumulate and granophyric gabbro unit, MgO increases and TiO_2 decreases upward (as does FeO and P_2O_5), suggesting that the rocks in the upper section crystallized downward from the flow-top breccia. This is also indicated by the upward fining of grain sizes. The lower gabbro unit contains less TiO_2 and P_2O_5 than the upper gabbro, but these components increase upward suggesting that the lower gabbro was cut off before they could accumulate to the levels seen in the upper gabbro. Clinopyroxenes in the Walter Williams Formation are chromium-rich Mg-augites and diopsides. They contain up to 1.4 wt% Cr_2O_3 and 3.55 wt% Al_2O_3 and have low concentrations of TiO_2. Those from the peridotites are commonly less calcium-rich than those from clinopyroxenite layers. However, pyroxene is only sporadically preserved throughout the formation, so it is not possible to determine whether there are any systematic changes in composition with locality or stratigraphic height.

Interpretation of the Walter Williams Formation

The Walter Williams Formation is the crystallization product of a massive sheet flow with different lobes experiencing different crystallization conditions. In the Ghost Rocks – Siberia area, crystallization conditions within the flow favoured the growth of olivine adcumulate and were relatively constant, with ponding of lava 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. The massive flow that formed the Walter Williams Formation contrasts markedly with the thin flows that make up the overlying Siberia Komatiitic Volcanics. This latter sequence resulted from episodic emplacement of lava lobes that cooled sufficiently to allow the development (and preservation) of flow tops and spinifex zones before the next emplacement. Within the Walter Williams Formation, sheet lobe crusts were continually destroyed by lava convection and the continued influx of new lava until the present top was formed very late in the history of the flow.

Locality 5: The Murrin Murrin komatiite complex in the Kilkenny Syncline

From the Leonora–Laverton road turnoff at the sign to Minara Station (AMG 0376637E 6805271N). Go to T-junction (AMG 0382481E 6799706N), turn right at sign to Malcolm–Leonora. Turn left on access track (AMG 0380180E 6795780N). At the end of the bus-passable track (AMG 0380686E 6795247N), close to waypoint 1, is the basal contact of Murrin Murrin ultramafic complex.

The Murrin Murrin area (Fig. 1) is the site of the largest nickel-laterite mining project in Australia. The distribution of these laterites, their preserved profiles, and the nature and extent of nickel enrichment are the result of a complex interplay between supergene processes, regolith profile erosion, and variation in ultramafic protoliths (igneous and metamorphic).

A detailed mapping study carried out by CSIRO in the mid-1990s found that the Murrin Murrin ultramafic cumulates are komatiitic in origin, and their large lateral extent is the result of widespread areas of shallow dip associated with fold-interference structures. The Kilkenny Syncline (Fig. 16), in the southern part of the lease area, shows steep dips and excellent exposure, and is one of the best areas in the Yilgarn Craton to examine the field relationships between thick adcumulate bodies, spinifex-textured flows, and gabbroic cumulates formed from differentiated komatiite lava.

Regional geology

The Murrin Murrin area is in the central part of the Norseman–Wiluna Greenstone Belt, between Laverton and Leonora (Fig. 1). The overall setting is within a sequence

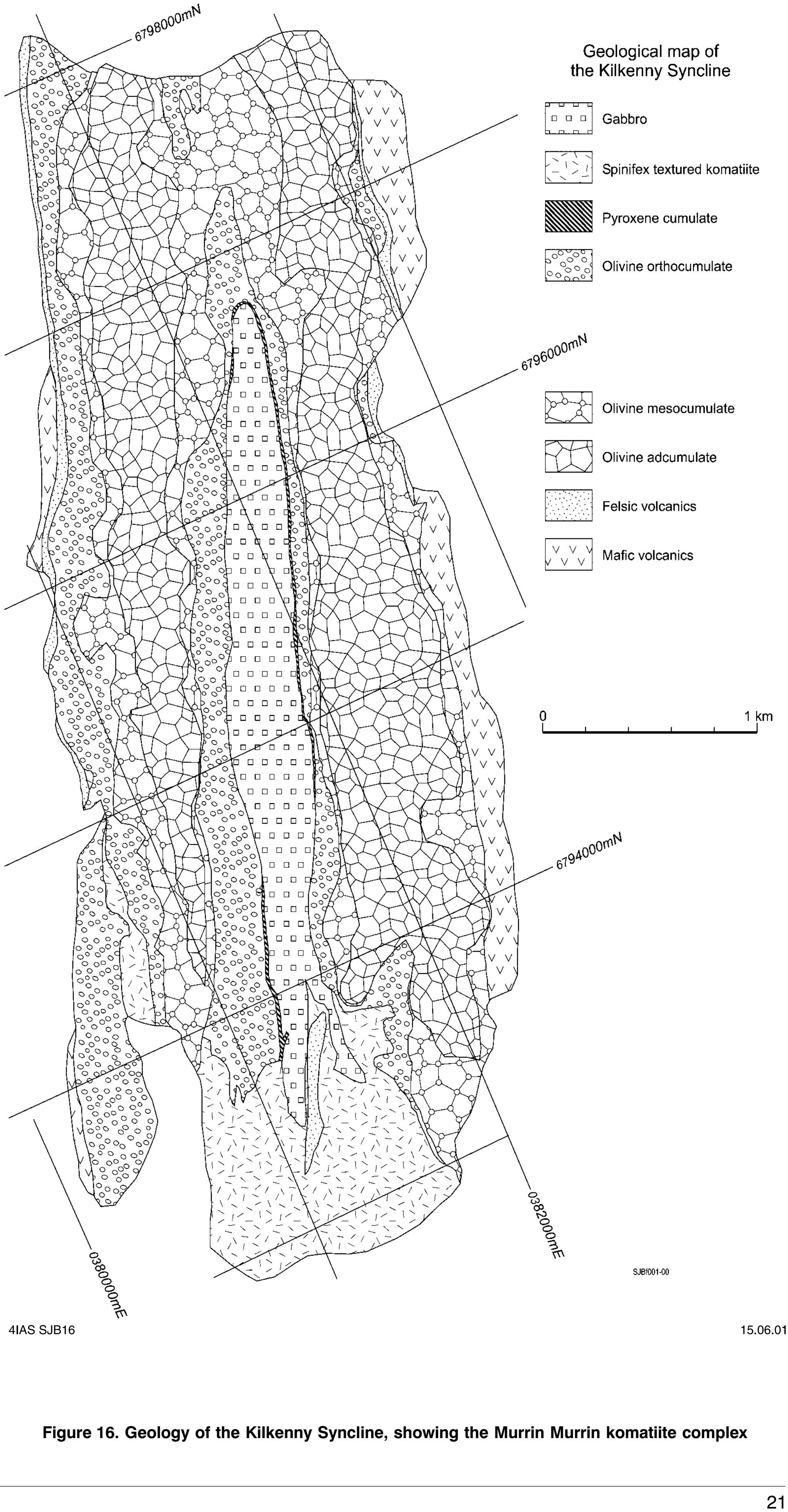

Figure 16. Geology of the Kilkenny Syncline, showing the Murrin Murrin komatiite complex

of dominantly intermediate, felsic, and mafic volcanic rocks with intercalated epiclastic sediments, deformed by at least two phases of folding. The dominant structure in the Murrin Murrin area is a series of isoclinal or near-isoclinal north-northeasterly trending synclines and anticlines.

The regional stratigraphy comprises ‘Association 2’ of Hallberg (1985), and can be interpreted as an intercalation of basaltic and high-Mg basaltic flows with epiclastic felsic volcanic rocks derived from a number of emergent felsic volcanic centres. The rocks of the Murrin Murrin Ultramafic–Mafic Complex (MMUMC) are derived from high-Mg basaltic lavas, and overlie a thick sequence of tholeiitic pillow basalts, with a thin, discontinuous layer of felsic tuff at the contact.

The rocks of the MMUMC in the Murrin Murrin area are folded into the near-isoclinal south-southwest-plunging Kilkenny Syncline (Figs 16 and 17). The internal stratigraphy is made up of a thin basal chill zone, overlain by an ultramafic cumulate section, several hundred metres thick, with olivine orthocumulates at the top and bottom and mesocumulates to adcumulates in the centre. This is overlain by gabbroic differentiates, either in direct contact or separated by one or more thin layers of pyroxene cumulate (Fig. 18). The core of the syncline in the northern part of the excursion area is occupied by gabbroic rocks, grading laterally to the south into multiple small flow lobes of spinifex and ocellar-textured high-Mg komatiitic basalts.

The critical features of the MMUMC to be visited are the basal chill zone, layered olivine orthocumulates, the contact zone between ultramafic and gabbroic layers, the lateral gradation within the ultramafic zone into spectacular pyroxene spinifex-textured komatiitic basalt flow lobes, and the lateral gradation between gabbro and high-Mg basalt lobes. The area provides one of the best examples known where a thick pile of olivine cumulates can be traced laterally in outcrop into demonstrably extrusive spinifex-textured rocks.

The excursion examines critical parts of the stratigraphy in the area of best exposure, in the southwestern part of the map area. A detailed outcrop map based on CSIRO mapping by M. Hunter, J. Liimatainen, R. Hill, and S. Barnes is shown in Figure 17, with the following localities identified.

The access track from the main dirt road traverses well-developed pillow basalts in the footwall of the MMUMC.

Locality 5.1: Basal chill zone

Locality 5.1 (AMG 0380772E 6795244N) shows exposures of olivine-spinifex rocks forming the basal chill zone of the MMUMC. The northernmost of the two outcrops (AMG 0380781E 6795442N) exposes this zone almost directly in contact with a thin unit of bedded felsic tuffs, dipping at approximately 70° to the east. The basal chill zone shows spectacularly developed olivine-chevron spinifex textures (Fig. 18E), in a rock of high-Mg basalt composition with around 12 wt% MgO (Fig. 19).

The basal chill zone is no more than 5 m thick, and is overlain by a layer of olivine orthocumulate, which in places contains thin discontinuous harrisite layers. The thickness of this layer is unknown in the absence of detailed knowledge of dips, but the combination of rare dip indications on the footwall felsic tuffs and the overall outcrop pattern implies that dips are 70° or more, and the true thickness approximates the outcrop width of around 300 m. This orthocumulate layer is overlain by a central core of olivine mesocumulate and adcumulate, which is approximately 500 m thick, forming the substrate to the economically significant nickeliferous laterites that cap the hills in the area.

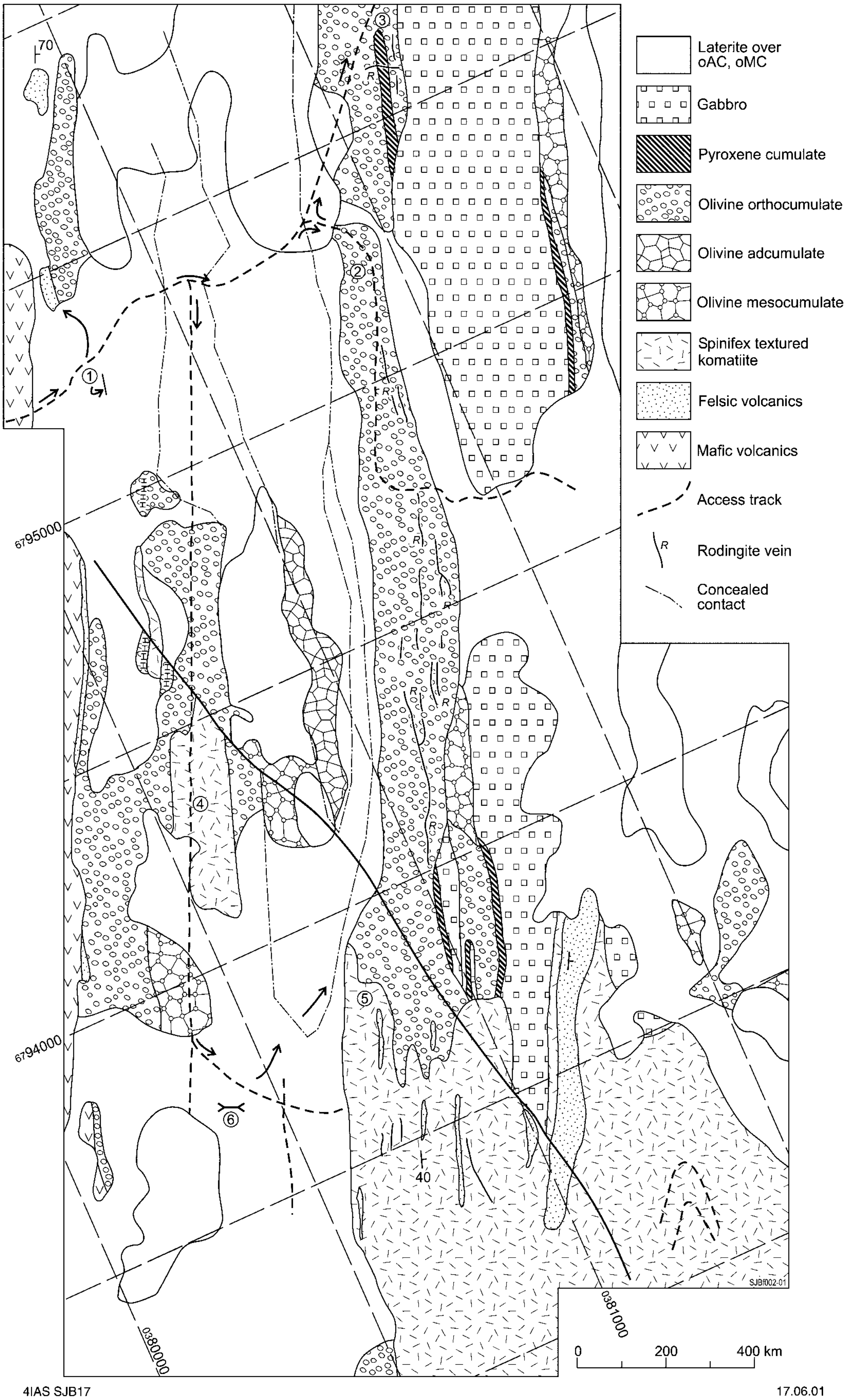

Figure 17. Detailed outcrop map of the southwestern part of the Kilkenny Syncline area, showing the access track and Localities 5.1 to 5.6 (numbers in circles). Abbreviations: oAC = olivine adcumulate; oMC= olivine mesocumulate

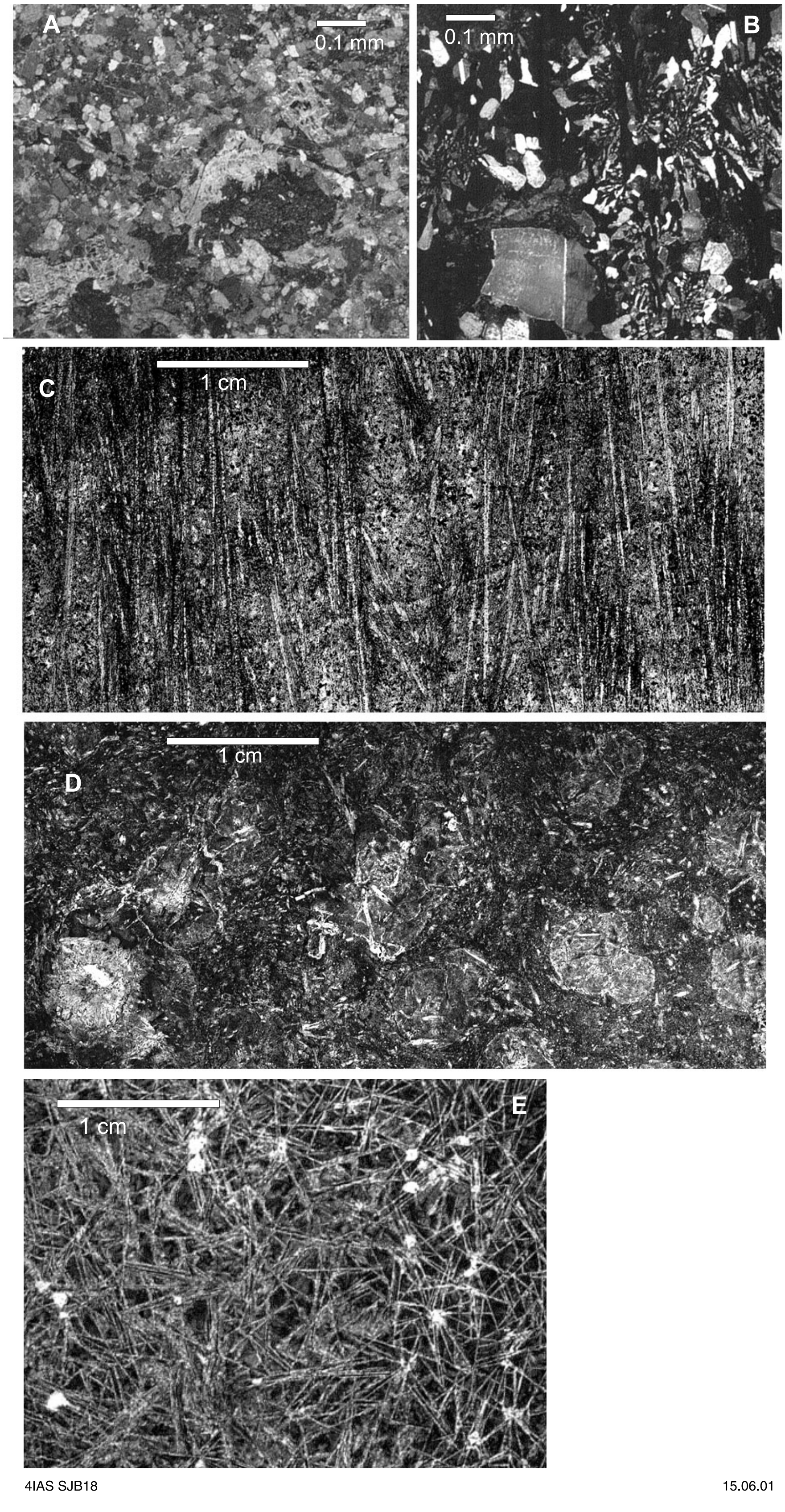

Figure 18. Photomicrographs of Murrin Murrin ultramafic rocks: A) websterite, containing clinopyroxene orthopyroxene mesocumulate from Locality 5.3 (crossed polars); B) rodingite from Locality 5.3, showing relict granophyric texture, presumably inherited from the original felsic intrusive; C) coarse pyroxene 'string-beef' spinifex, Locality 5.4; D) spheroidal ocellar texture in basalt, Locality 5.6; E) chevron olivine spinifex in basal chill zone, Locality 5.1

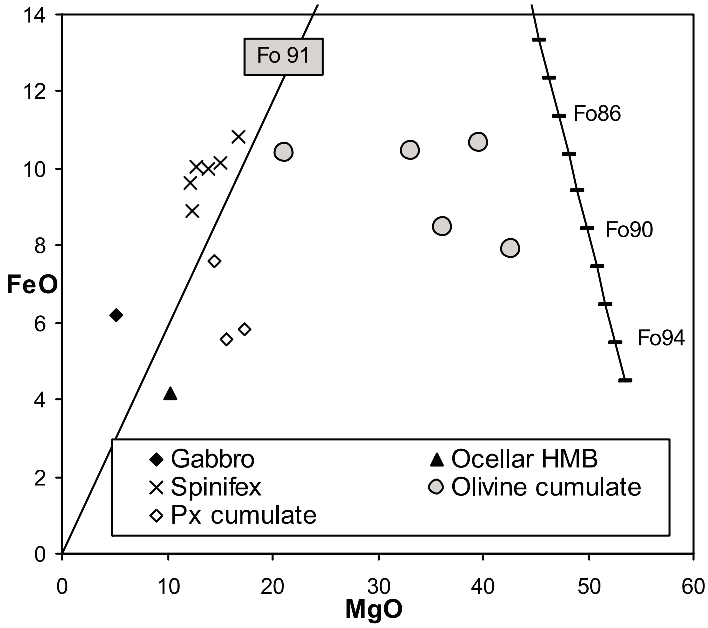

Figure 19. Plot of FeO vs MgO (recalculated anhydrous wt%) for samples from the Murrin Murrin Ultramafic–Mafic Complex. The sloping solid line on right shows pure olivine compositions; the line labelled 'Fo_{91}' shows compositions of liquids in equilibrium with Fo_{91} olivines

Locality 5.2: Layered olivine orthocumulates

Locality 5.2 (AMG 0381447E 6795217N) is reached from Locality 5.1 by driving (four-wheel drive access only) across dissected laterite terrain.

The Tertiary weathering profile can be well seen in places. The central adcumulate band is commonly weathered to highly siliceous hardpan or 'silica cap' covered by lateritic clays. This central olivine-rich band is stratigraphically overlain by a continuous 200 m-thick layer of very well layered coarse-grained olivine orthocumulates, characterized by a strong layer-parallel preferred orientation of olivines and an abundance of hollow 'hopper' grains, very well exposed at Locality 5.2. Layers are defined by flat alignment of olivine crystals with no preferred lineation.

Locality 5.3: Contact between ultramafic and gabbroic cumulates

The contact zone between the ultramafic and gabbroic cumulates is exposed here (AMG 0381665E 6795652N). Over about a 30 m strike width there is an interlayering of olivine orthocumulate, pyroxene-rich gabbro, and a porphyritic olivine websterite, consisting of 80-90% cumulus clinopyroxene grains with larger orthopyroxene and rare olivine phenocrysts (Fig. 18A). The precise thickness of these pyroxenite layers is difficult to determine because of the rubbly nature of the outcrop. However, it is clear that the transition from olivine to pyroxene plus plagioclase was rapid, and there was a very small crystallization interval of only pyroxene. This is consistent with the known phase equilibria of evolved komatiite liquids, and explains the common relationship in many komatiitic cumulate sequences where olivine-rich cumulates pass very rapidly into gabbros.

A common rock type at this locality is a highly unusual calcium-rich metasomatic rock, rodingite. This rock has a strongly bladed texture, and is superficially reminiscent of olivine-spinifex texture. In thin section it is evident that the rock consists mainly of diopside, prehnite, and an abundance of other calc-silicate minerals. It also contains graphic eutectic-like textures (Fig. 18B) that suggest a felsic granophyre protolith. The rodingite units are in places semiconformable and clearly crosscutting in other places, and are interpreted as a network of calcium-metasomatized felsic dykes.

Locality 5.4: Spinifex-textured komatiitic basalt flow lobe

From Locality 5.3 go back to the main north–south gridline (AMG 0381060E 6795380N) and proceed south to Locality 5.4 (AMG 0380586E 6794337N).

Outcrops running across the main baseline track expose spectacular 'string beef' pyroxene-spinifex textures in a well-differentiated flow lobe. From top to bottom, the lobe consists of about 50 cm of quenched vesicular flow-top autobreccia grading down in a random pyroxene-spinifex A2 zone, which itself grades down into an A3 zone, up to 7 m thick, consisting of spectacular downward-flaring sheaves of pyroxene needles, individually a metre or more long (Fig. 18C). This is underlain by a cumulate B zone, consisting of highly altered, fine-grained olivine orthocumulate. Spinifex rocks contain 11 to 13% MgO (anhydrous). The lobe is overlain by a thin unit of bedded felsic tuff containing accretionary lapilli, indicative of a subaerial origin.

This lobe is one of a series of similar lobes occupying a stratigraphic thickness of up to 50 m, which is overlain, underlain, and flanked at either end by medium- to coarse-grained olivine orthocumulates and mesocumulates. This clearly extrusive unit is completely surrounded by the main mass of the MMUMC cumulate pile.

Proceeding to the south from this location, outcrops along the baseline track are of conventional olivine mesocumulate with 1–3 mm green 'knots' visible on the surface. These knots are composed of clusters of small cumulus chromite grains mantled by secondary chlorite.

Locality 5.5: Test costean in lateritic clays

From Locality 5.4 drive down baseline and veer off to left around north side of small Anaconda Nickel costean (AMG 0380422E 6793707N).

This is a test costean in lateritic clays after olivine mesocumulates. Relic textures of the igneous protoliths can be seen in the pit spoil.

Locality 5.6: Lateral gradation between gabbro and high-Mg basalt lobes

From end of costean at Locality 5.5, travel across flat outwash plain north-northeasterly, stop on east side of small creek (at about AMG 0380750E 6793900N).

The traverse is approximately 250 m to south and back, over lateral transition between layered olivine orthocumulates and flanking high-Mg basalt flow-lobes with spinifex textures (e.g. AMG 0380694E 6793643N) and well-developed ocellar textures in places (e.g. AMG 0380694E 6793643N; Fig. 18D). This sequence of flow lobes broadens out to the south and forms the core of the syncline; thin interbeds of felsic tuff up to 1 m thick are also exposed.

Summary and interpretation

The Kilkenny Syncline exposures illustrate two important relationships:

- The crystallization history is characteristic of high-Mg mafic liquids derived by fractionation of komatiites. Parent magmas to the complex were komatiitic basalts, having between 12 and 16% MgO, and crystallizing olivines with compositions between Fo_{87} and Fo_{91} (Fig. 19). Liquidus relations were such that clinopyroxene and orthopyroxene replaced olivine on the liquidus very close to the point where plagioclase also began to crystallize. This accounts for the rapid transition from olivine cumulates to gabbros with thin, discontinuous intervening pyroxenite layers.

- The lateral stratigraphic variation is interpreted as the product of a ponded differentiated lava lake flanked by episodically emplaced thin flow lobes. The Kilkenny Syncline exposures provide some of the clearest field evidence yet seen for the extrusive origin of a thick komatiitic cumulate sequence.

Komatiites in the Agnew–Wiluna Greenstone Belt

Regional geology

The Agnew–Wiluna Greenstone Belt (Figs 1 and 20) is an attenuated belt, characterized by major wrench faults traceable over hundreds of kilometres, at least two phases of complex folding, and commonly steep dips. Conditions of peak metamorphism increase southward from prehnite–pumpellyite grades in the Wiluna area to lower amphibolite in the Perseverance area, and decrease again to lower greenschist in the region of Mount Clifford.

Faulting in the belt has produced elongate tectonic slices within which lithological correlation is relatively easy given sufficient outcrop, exploration drilling, and aeromagnetic data. There is a general lack of exposure, and in places extensive fault imbrication and steep plunges combine to render stratigraphic reconstruction difficult. Komatiite rocks are almost continuous over at least 200 km of strike.

Stratigraphy

Several studies of aspects of the regional stratigraphy of the belt have been undertaken (Dowling et al., 1989; Durney, 1972; Marston and Travis, 1976; Naldrett and Turner, 1977; Platt et al., 1978; Thom and Barnes, 1977). Naldrett and Turner (1977) proposed a subdivision into Lower and Upper Greenstone sequences, separated by an unconformity, for lithologies between Agnew and Mount Keith. Stratigraphic correlations north from Yakabindie have been refined and modified after surface mapping and detailed petrographic and geochemical studies of diamond drillcore by Dowling and Hill (1990).

The komatiites to be visited on this excursion are confined to the Upper Greenstone sequence (Fig. 21). This consists of a basalt unit, including minor high-Mg variants, overlain by a thin chert, a thick sequence of felsic to mafic volcaniclastic and minor pelitic sedimentary rocks, and black shales, and a zone up to 2.5 km thick that includes the extensive komatiitic volcanic rocks interspersed predominantly with layered gabbroic units, high-Mg and tholeiitic basalts, and subordinate felsic volcanic rocks. Fine- to medium-grained clastic sedimentary rocks and the graben-fill Jones Creek Conglomerate constitute the youngest exposed sequences.

Mount Clifford – Marshall Pool area

From Leonora go north about 85 km on the Goldfields Highway towards Leinster and turn left at prominent track (at AMG 0314260E 6872360N). Proceed to gate on north–south fenceline (AMG 0311910E 6871510N), turn left (south) down fenceline (to AMG 0312010E 6867260N), turn right and follow prominent east–west track west along fenceline (track veers away from fenceline several times at gates through north–south fences) to gate (at AMG 0304780E 6867250N). Go through gate, turn left down north–south fence, passing Hangover Bore (AMG 0304910E 6866610N; Fig. 22). Continue

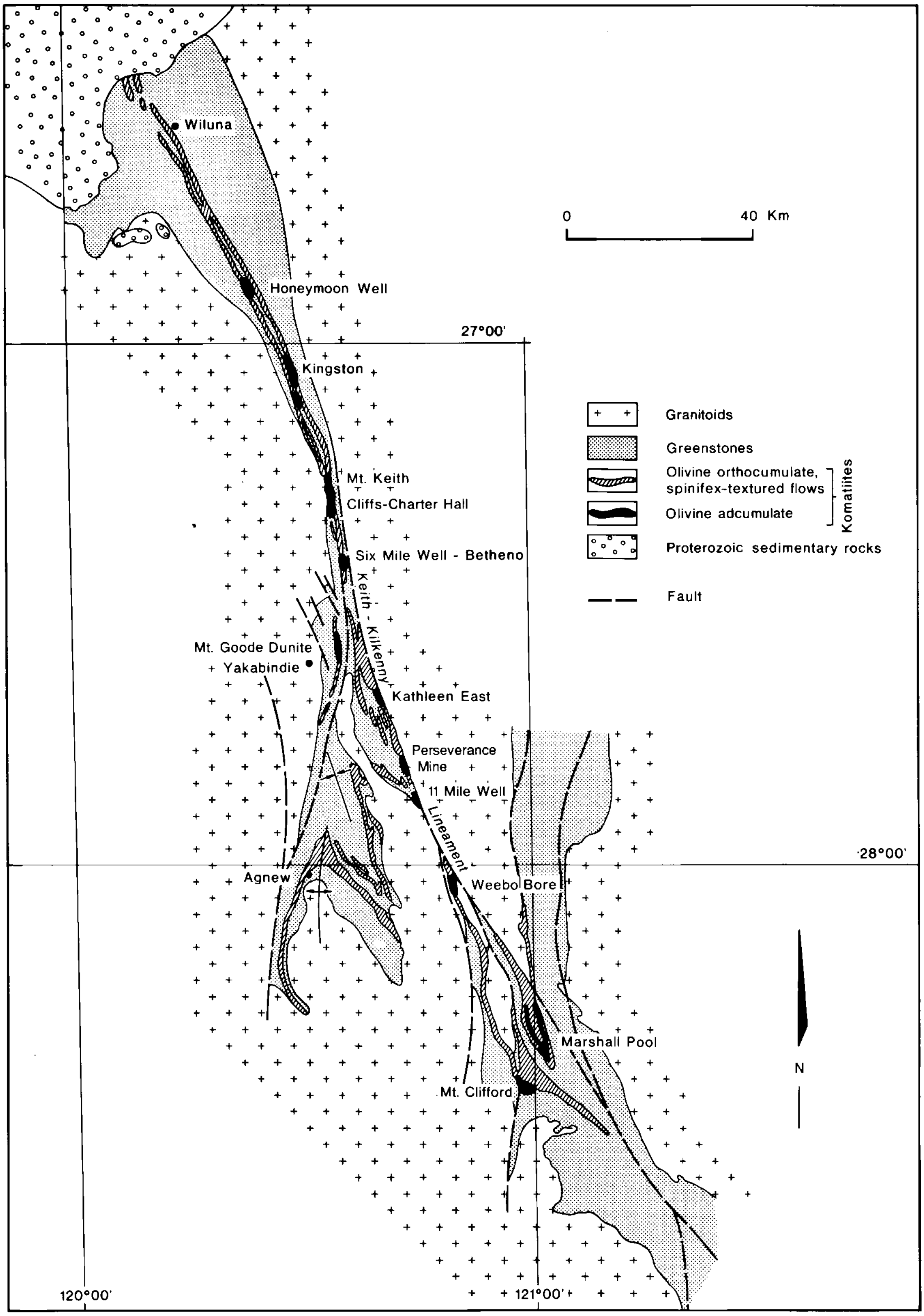

Figure 20. Regional geology of the Agnew–Wiluna Greenstone Belt from Mount Clifford to Wiluna, showing the distribution of komatiites and komatiitic dunite bodies

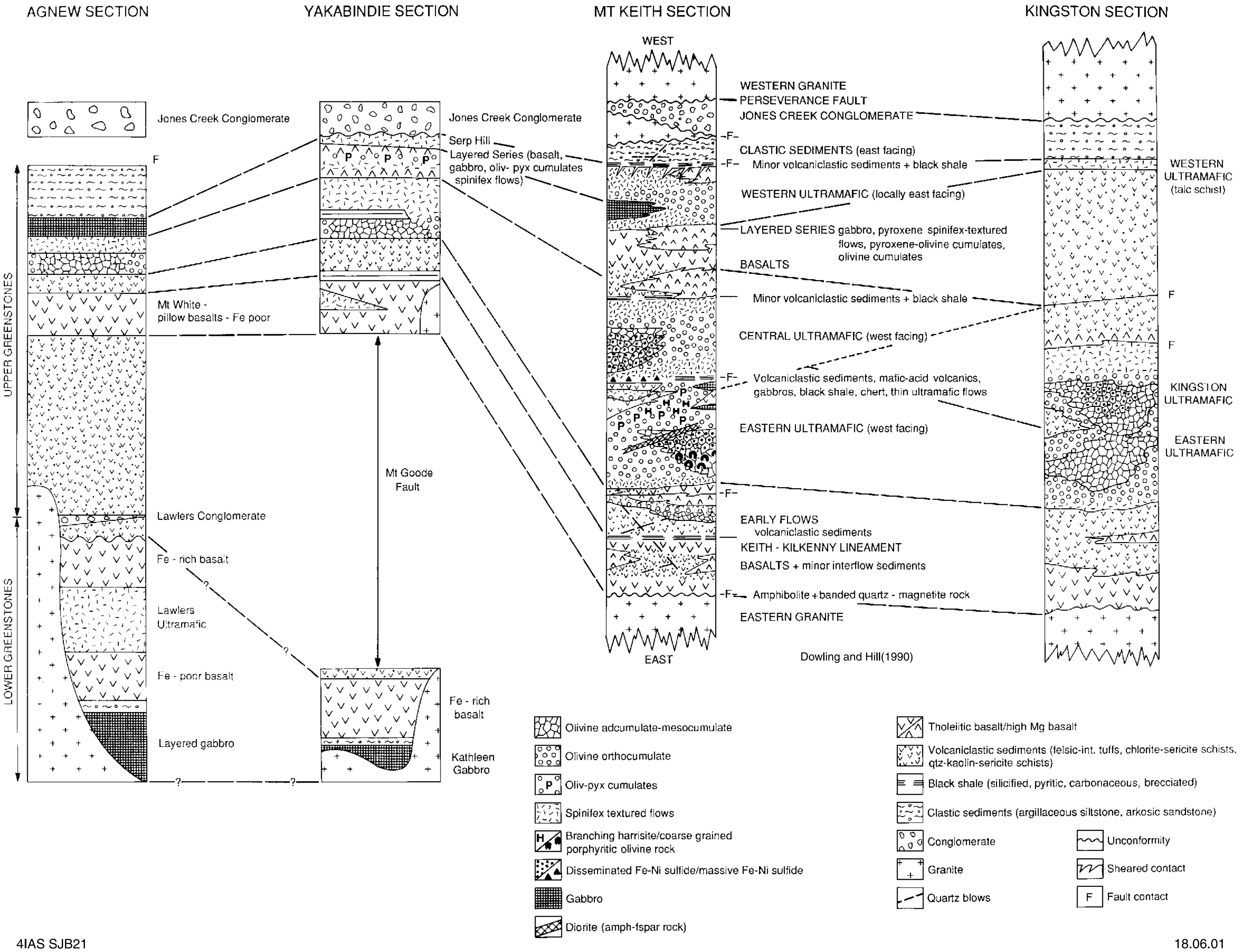

Figure 21. Schematic geological sections across the Agnew–Wiluna Greenstone Belt (Mount Keith column after Dowling and Hill, 1990; others after Naldrett and Turner, 1977)

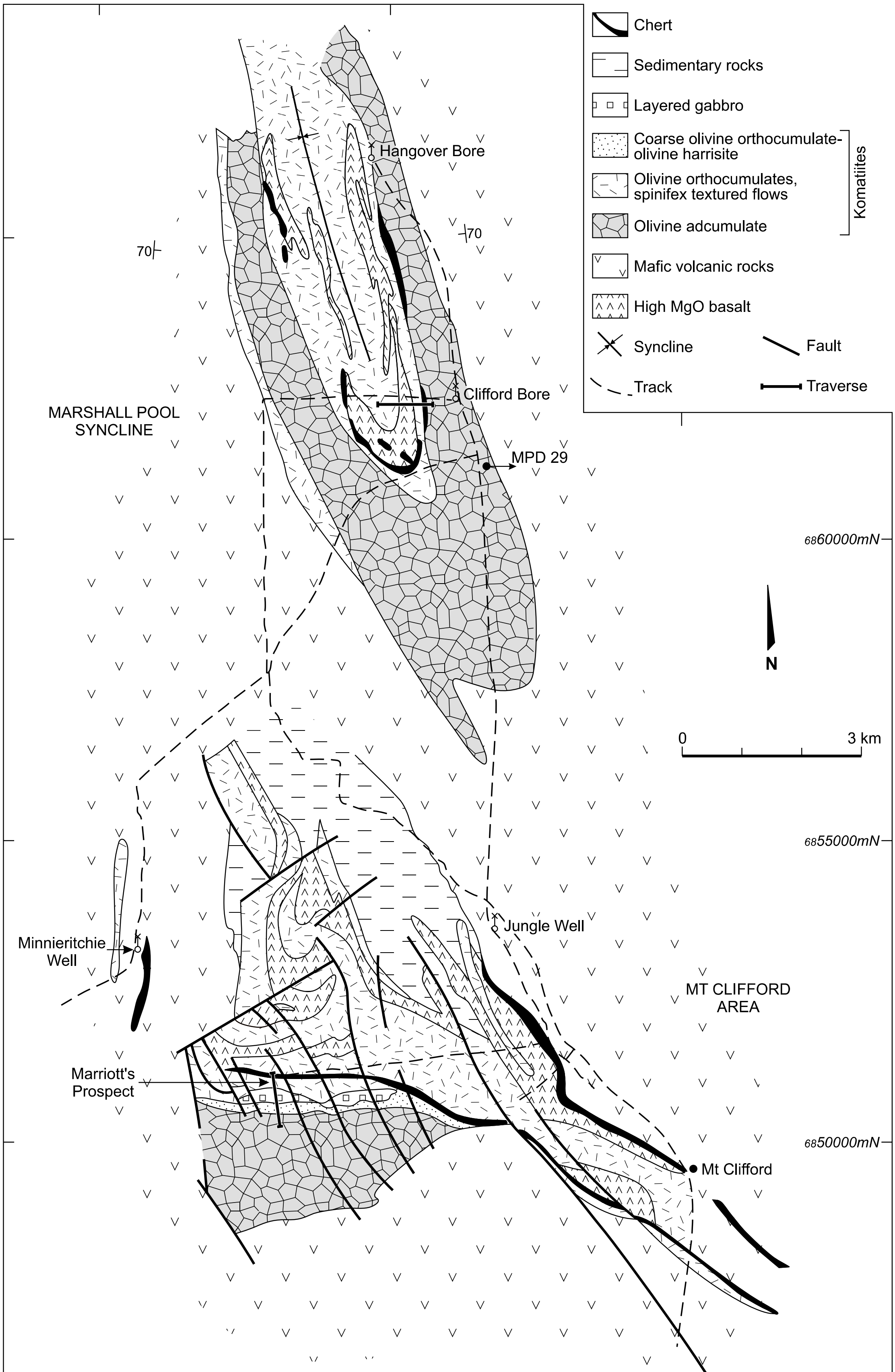

Figure 22. Regional geology of the Mount Clifford – Marshall Pool area (after Donaldson, 1982)

south-southeasterly along same track to Clifford Bore (AMG 6862400N). The Marshall Pool traverse is along this east–west fenceline. Continue south for the Marriott's – Mount Clifford traverse (see below).

The Mount Clifford – Marshall Pool ultramafic complexes are 50 km north of Leonora, within the southern extension of the Agnew–Wiluna Greenstone Belt. Definitive correlation with the stratigraphy farther north is not possible due to the structural complexity, but the nature of the komatiites is consistent with correlation with the Upper Greenstone Sequence of the Agnew–Wiluna Greenstone Belt farther north.

The Mount Clifford – Marshall Pool block is characterized by gently folded sequences of mafic, ultramafic, and felsic volcanic rocks, and epiclastic rocks. Peak metamorphic grades range from lower amphibolite to lower greenschist facies from the northern end of the block to its southern extremity. An interpretive geological map of the area (Fig. 22) has been compiled from mapping by Thom and Barnes (1977), exploration data generated by Western Mining Corporation, and detailed descriptions of ultramafic rocks from Geological Survey of Western Australia Bulletins and other publications (Barnes et al., 1973; Donaldson, 1982; Donaldson, 1983; Donaldson et al., 1986; Travis, 1975). We are indebted to these authors, especially M. Donaldson, for much of the following petrographic and geochemical data.

The ultramafic lithologies at Mount Clifford and Marshall Pool commonly exhibit similar sequences, and although they have suffered extensive low-grade pervasive alteration, they have retained spectacular primary igneous textures. The ultramafic succession, exposed in a pair of open synclines, includes a large, poorly outcropping olivine-adcumulate body overlain by a thick sequence of spinifex-textured flows and olivine orthocumulates. The olivine-adcumulate body conformably overlies a thick sequence of pillowed tholeiitic basalts, although they are separated by a thin chloritic sedimentary unit. The Mount Clifford and Marshall Pool cumulate bodies are tentatively correlated on the basis of aeromagnetic data and percussion drilling (Donaldson et al., 1986).

Locality 6: Mount Clifford area

The supracrustal lithologies define an asymmetrical fault-bounded syncline plunging 45° to the northeast (Fig. 22). At the base of the ultramafic stratigraphy, a 1 km-thick olivine-adcumulate body outcrops sporadically as jasperoidal silica cap exhibiting pseudomorphed igneous textures. Overlying the adcumulate is a sequence of coarse-grained olivine orthocumulates with sporadic development of harrisitic textures, overlain in turn by a layered gabbroic body with a fine-grained and locally pyroxene spinifex-textured flow top. This layered unit is in turn overlain by a komatiite sequence comprising a laterally restricted 150 m-thick olivine orthocumulate unit (the Marriott's nickel prospect) and an arcuate 1 km-thick pile of thin spinifex-textured flows. Directly above the Marriott's olivine-orthocumulate unit are two sedimentary horizons (Fig. 23).

The Mount Clifford olivine-cumulate body dips to the north at about 30° (Fig. 23) and consists of several units, of which only the basal one is well defined. A 1 m-thick layer at the base, composed of chlorite and amphibole, is interpreted as an altered chilled margin in contact with the chloritic metasediment (Donaldson et al., 1986). Above this layer, igneous textures are clearly discernible and define a gradual change with increasing olivine, from rocks with oikocrystic pyroxene to olivine adcumulate over the next 50 m. This marginal zone is similar to the olivine-orthocumulate units at the base of the Walter Williams Formation between Ghost Rocks and Siberia. Above this level, abundant relict colourless olivine is preserved. Fine-grained disseminated subhedral chromite crystals are a common accessory mineral. At a height of 343 m above the base there is a thin Mg-augite pyroxenite layer, which marks the top of the

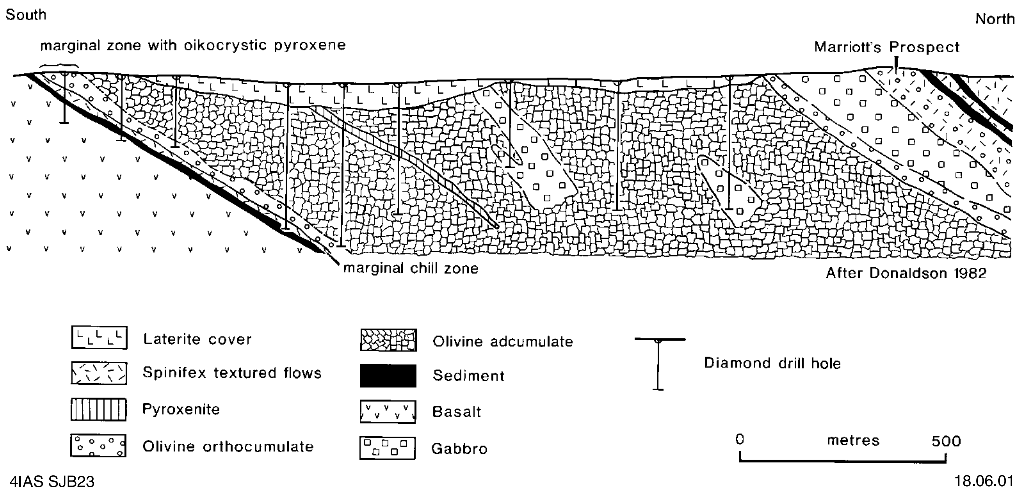

Figure 23. Geological cross section through the Mount Clifford complex and the Marriott's prospect, Locality 6 (after Donaldson, 1982)

basal olivine-adcumulate unit. Above this layer the olivine adcumulate continues to the upper-orthocumulate marginal zone in contact with the layered gabbro. There is a gradual increase in the forsterite content of olivine upward, from the base to the top of the adcumulate body (Fig. 24) — a feature common to many of the adcumulates of the Norseman–Wiluna Greenstone Belt. This variation is irregular on a smaller scale, crudely reflecting the presence of cryptic layering (Donaldson, 1983). In the lower basal dunite unit there is a definite in situ fractionation trend from $Fo_{90.5}$ to $Fo_{86.5}$ over the upper 100 m. A gradual increase in forsterite content upward through the adcumulate crystal pile is also exhibited by the olivines at Perseverance (Barnes et al., 1988), Six Mile Well, and Yunndaga, and is probably common to most of the adcumulate bodies. In the lower basal dunite, chromite is a prominent accessory phase (up to 2 wt%) as ubiquitous disseminated subhedra. Above the pyroxenite layer, where olivine compositions are higher than Fo_{92}, chromite is very rare and grains exhibit an irregular anhedral shape, interstitial to olivine. The change in modal proportion of chromite is reflected in whole-rock Cr_2O_3, which is relatively constant at about 1 wt% in the lower basal dunite and drops rapidly across the pyroxenite layer to a constant 0.2 wt% in the upper adcumulate pile (Donaldson et al.,1986). This phenomenon of cumulus chromite being rare, anhedral, and intergranular in adcumulates with olivine compositions greater than Fo_{92}, and in higher proportions in the form of anhedral to subhedral grains in adcumulates with olivines less than Fo_{92}, is a common feature of these ultramafic bodies (Barnes, 1998). The adcumulates are only sporadically exposed as silica cap in the upper few metres, and the traverse begins here.

Traverse from the Mount Clifford dunite to Marriott's nickel prospect

See Figure 22. From Clifford Bore, continue down north–south track to Jungle Well (AMG 0306800E 6853500N). Follow track to south-southwest to junction (AMG 0307683E 6851635N), turn sharp right and proceed west-southwest along old gridline track to dead-end at fenceline (AMG 0302980E 6851060N) and park. Walk south down fence then slightly east to start of traverse (at AMG 0303100E 6850500N). Traverse proceeds roughly north-northwest.

The contact zone between the adcumulate body and the base of the well-layered pyroxenites and gabbro is reasonably well exposed over the first 100 m of the traverse.

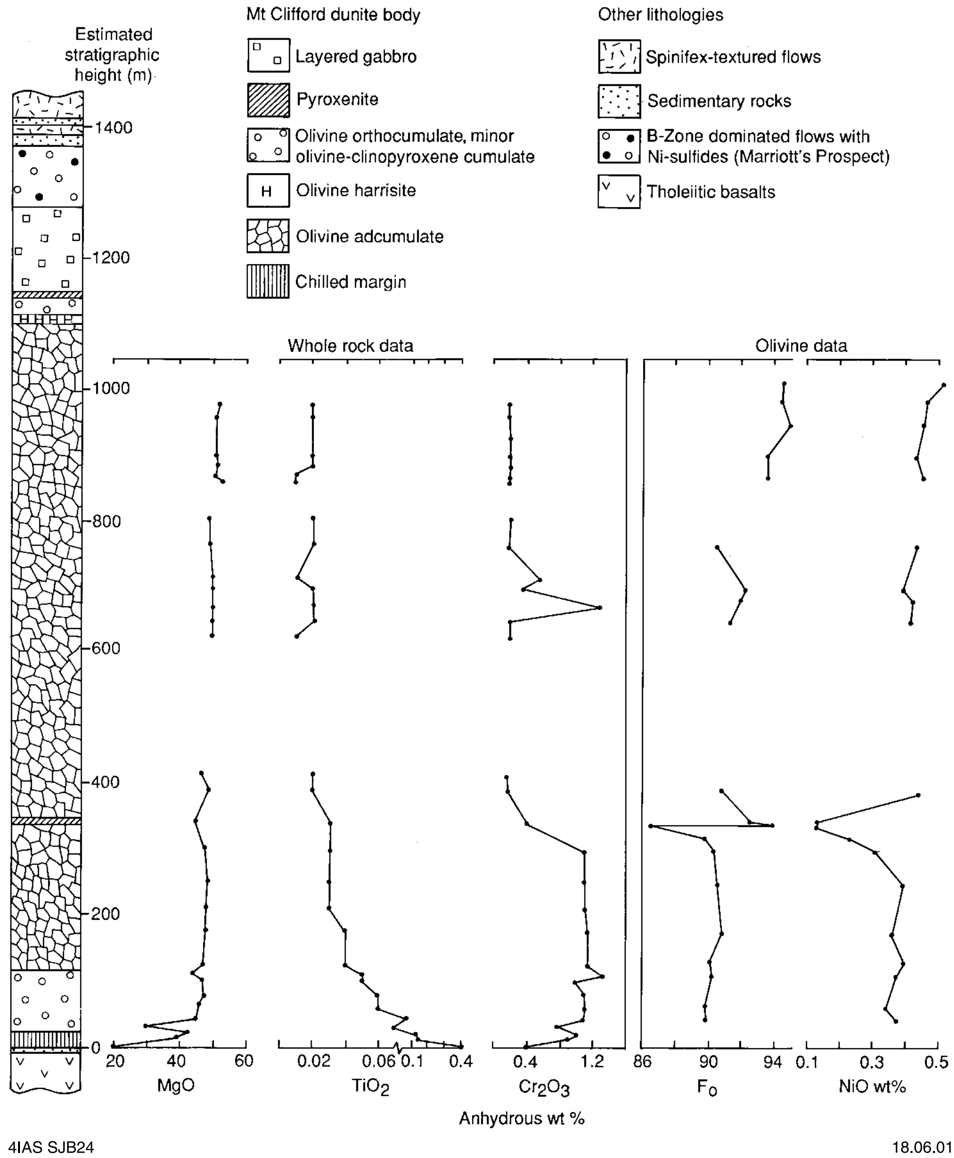

Figure 24. Lithological and geochemical profile through the Mount Clifford complex, roughly along the line of the traverse (after Donaldson, 1983)

Rubbly outcrop in this zone exposes a change over about 30 m from coarse-grained olivine adcumulate to an inhomogeneous olivine orthocumulate with pockets closely approaching olivine harrisite (AMG 0303097E 6850543N).

The orthocumulate–harrisite zone is overlain by a variety of bimodal porphyritic pyroxenite (AMG 0303060E 6850606N), coarse clinopyroxenite (AMG 0303068E 6850696N), and pyroxene-rich gabbros (AMG 0303062E 6850842N). Continuing northwesterly, bearing towards the fence, the traverse continues through rubbly outcrop of layered gabbros. Fine-grained upper-chill zone of gabbro, with minor amounts of 'string beef' clinopyroxene spinifex, is exposed on the fenceline (AMG 0302977E 6850944N). The presence of spinifex textures, conformable nature of the ultramafic–gabbro contact, and overall similarity to other localities visited on this excursion lead to the conclusion that the gabbro is an extrusive differentiated component formed within the same flow complex as the adcumulate body, probably by lava which backed up within a blocked flow pathway and fractionated in situ.

Moving to the east and continuing up section, the traverse continues through the Marriott's nickel prospect (AMG 0302977E 6850957N). Spinifex-textured flows with thin B zones and 1 cm spherical sulfide globules are well exposed and sample material is abundant. The Marriott's prospect has an inhomogeneous, laterally restricted olivine orthocumulate directly overlying the chilled flow top on the gabbro, and is interpreted as a composite flow sequence (Donaldson et al., 1986). The rocks exhibit well-preserved pseudomorphs after closely packed polyhedral olivines in a fine-grained feathery matrix, and several thin zones with coarse-grained herringbone or branching plate-olivine pseudomorphs. Nickel sulfides are concentrated in three narrow zones in the unusual form of scattered spherical blebs up to 1 cm in diameter within olivine orthocumulates (Travis, 1975). Fresh samples contain unusual sulfur-deficient mineralogy, including trevorite (Ni-magnetite), heazlewoodite, and native metal (Hudson and Travis, 1981). At surface these blebs have been replaced by limonite.

Locality 7: Marshall Pool area

The mafic and ultramafic rocks of the Marshall Pool area define the shallow north-plunging Hangover Bore syncline, 15 km north-northeast of the Marriott's prospect (Fig. 22). The core of the syncline is well exposed with a thick sequence of komatiites with extremely well preserved relict igneous textures and high-magnesium basalts. The thinner komatiite flows (2–5 m) exhibit a variety of spinifex textures, whereas the thicker flows are predominantly olivine orthocumulates. Discontinuous albite-rich cherty sediment horizons are interbedded with flows. Unlike the Mount Clifford area, there is no gabbro between the upper spinifex flows and the underlying olivine adcumulate body at Marshall Pool. The adcumulate does not outcrop — its extent has been outlined by many exploration percussion drillholes throughout the area and two diamond drillholes that were completed by WMC to intersect the eastern basal contact. In recent times the laterite developed over the dunite has been explored extensively by Anaconda Nickel as a potential lateritic nickel resource.

At its base on the eastern side the olivine adcumulate is in contact with a thin sheared chloritic sedimentary rock. The adcumulate is estimated to be about 500 m thick, its upper limit being fixed by the presence of a thin cherty sedimentary horizon. Above the eastern basal contact there is a marginal zone similar to that at Mount Clifford, but with better preserved igneous textures. On the western side a basal zone of spinifex-textured rocks can be identified in surface laterite cap and in percussion drill chips. The spatial and contact relationships between this horizon and the olivine adcumulate are not yet known. The marginal zone on the eastern limb is 50 m thick. The lower 20 m comprises a thin amphibole–chlorite chill zone grading to a horizon with former amphibole or pyroxene phenocrysts, which itself grades into an olivine orthocumulate with oikocrystic paragisitic and edenitic amphibole. These amphiboles were interpreted by Donaldson (1983) as primary igneous minerals. Twenty metres above the contact, oikocrysts of chromium-rich Mg-augite enclose serpentinized olivines, and a gradual increase in modal olivine with height results in olivine adcumulate at 50 m.

The Marshall Pool structure is estimated to be at least 15 km long and, although it has not been firmly established, the Mount Clifford sequence may be stratigraphically equivalent. The basal contact zone of each of the olivine-adcumulate bodies and the immediate contact relationships are uncertain, but it is interpreted that the original substratum to the komatiite sequence was basalt. These features point to the olivine-adcumulate body as being originally in the form of an extensive sheet with similarities, including associated lithologies, to the larger Walter Williams Formation to the south, although no time equivalence is inferred. Such a sheet-like form is in contrast to the laterally restricted olivine-adcumulate bodies confined to the ultramafic sequences between Agnew and Honeymoon Well, which have a felsic volcanic substrate.

Marshall Pool traverse

The traverse is at the top of the plateau forming the core of the syncline, along the east–west fenceline west of Clifford Bore (Fig. 22). It can be accessed by either of two ways starting from the gate on the road in from Bannockburn (AMG 0302858E 6857802N). Either proceed through the gate to the T-junction just beyond, and proceed northeastward along the established track to the Clifford Bore fenceline, (AMG 6862400N), west along fenceline to start of outcrop of spinifex rocks, (about AMG 0305700E). If gate is locked, proceed north along fenceline from gate to east–west fenceline (AMG 0302797E 6862288N), turn east to west end of traverse (AMG 0304780E 6862400N). Can then continue along fenceline to track just west of Clifford Bore, then turn down track back towards gate to pick up access into Mount Clifford – Marriott's traverse.

The traverse is through rubbly subcrop of differentiated spinifex-textured flow lobes with very well preserved olivine-plate spinifex. This is an excellent locality for samples of spinifex-textured rocks. The book-like morphology of parallel olivine plates in A3 zones of the flow lobes is particularly well represented here.

Yakabindie to Mount Keith section

The Yakabindie to Mount Keith section of the Agnew–Wiluna Greenstone Belt (Fig. 20) exemplifies a distinctive komatiitic flow facies. Lenticular bodies of olivine adcumulate are flanked and linked by thinner sheets of orthocumulate and spinifex-textured rocks. Upper Greenstone komatiites are well exposed in the Yakabindie area and in parts of the Mount Keith region (Fig. 20).

Younging directions have been obtained in these areas from diamond drillcore and ultramafic outcrop. In the Yakabindie region, lowermost basaltic rocks outcrop southwest of Kathleen East (Fig. 20), in the core of an anticline with a shallow northerly plunge. The basaltic rocks are overlain by felsic volcanic tuffs and epiclastic sedimentary rocks and in turn by komatiitic volcanic rocks and basalt. The upper part of the stratigraphy, consisting of layered basalts, gabbros, and pyroxenites, is exposed in the 'Serp Hill' syncline (Fig. 25) just south of Six Mile Well. The Yakabindie stratigraphy can be confidently correlated from Six Mile Well through Mount Keith to Kingston (Fig. 21; Dowling et al, 1989). The region is structurally complex, with a pronounced north-northwesterly strike and vertical to steep dips. At least three extrusive ultramafic units can be traced for over 60 km of strike length from Six Mile Well – Serp Hill to Kingston. Correlation of the komatiites southward from the Six Mile Well – Yakabindie area to the Perseverance ultramafic complex is less well established in detail, but it is clear that there is continuous komatiite stratigraphy between Kathleen East and Eleven Mile Well south of Perseverance. It is difficult to extend stratigraphic correlations southward to the areas of Weebo, Marshall Pool, and Mount Clifford, and their correlation with the Upper Greenstones of the Agnew–Wiluna Greenstone Belt stratigraphic pile is conjectural.

The komatiite-bearing interval of the Upper Greenstone Sequence is continuous for at least 100 km of strike length. The komatiites form from one to five layers of variable thickness, usually underlain by felsic to intermediate volcaniclastic sedimentary rocks, cherts or black shales. The komatiites consist mainly of spinifex-textured flows and thick olivine-orthocumulate units, and contain zones of thickening (5 × 1 km) that are elliptical in plan and occupied by concordant bodies of layered olivine adcumulates and mesocumulates. Examples of such bodies in the Agnew–Wiluna Greenstone Belt are Perseverance, Kathleen East, Goliath, David, Six Mile Well, Betheno, Mount Keith, Kingston, and Honeymoon Well (Figs 20 and 25).

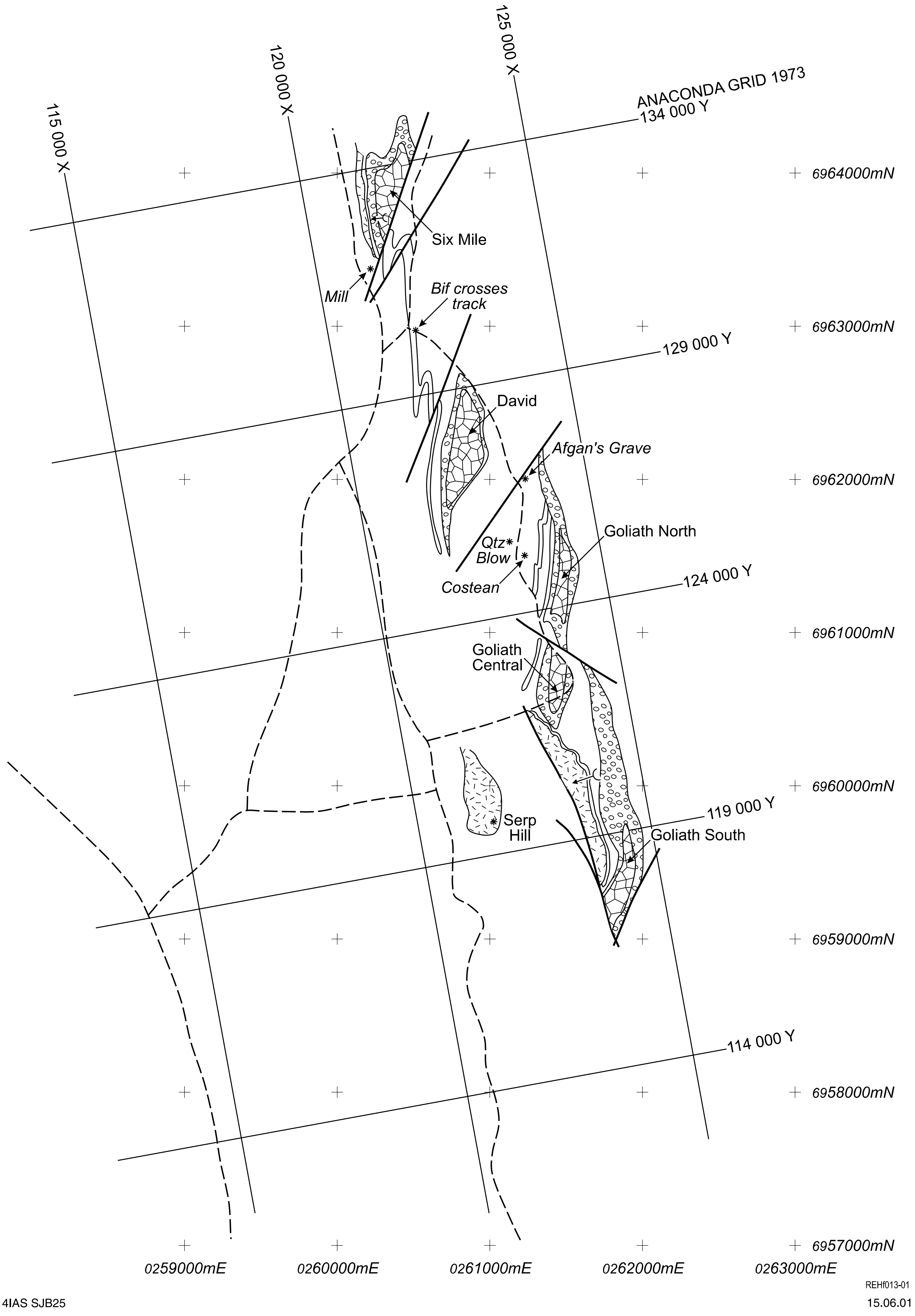

Figure 25. Geological map of the Yakabindie area, including Six Mile Well (modified from Naldrett and Turner, 1977)

These adcumulate bodies have been interpreted as dykes (Burt and Sheppy, 1975; Marston et al., 1981), as subvolcanic sill-like feeder chambers for the overlying spinifex-textured komatiites (Naldrett and Turner, 1977), and extrusive cumulate bodies (Donaldson et al., 1986; Hill et al., 1995). Hill et al. (1995) established after detailed field studies that these adcumulate bodies exhibit gradational contacts with laterally equivalent spinifex-textured flows and olivine orthocumulates, and in many cases are also directly overlain by spinifex-textured flows. This consistent relationship indicates that the dunite bodies form an integral part of the volcanic stratigraphy. Some of the bodies exhibit mineralogical, textural, and compositional layering on the scale of centimetres to metres, as at Six Mile Well (Hill, 1982; Naldrett and Turner, 1977), Honeymoon Well (Donaldson and Bromley, 1981; Gole et al., 1996; Gole and Hill, 1990), and Mount Keith (Dowling et al., 1989; Dowling and Hill, 1993). Others, such as those at Mount Clifford and Marshall Pool (Donaldson, 1982) exhibit marginal chill-zone facies. Olivine adcumulate–orthocumulate lithologies may host huge reserves of low-grade (0.5 – 1.5 wt% Ni) disseminated nickel sulfide (e.g. Mount Keith, Honeymoon Well, Betheno, and Six Mile Well). They are classified as Class 2 Deposits (Hill et al., 1989), and were formerly known as Intrusive Dunite Associated deposits (Marston et al., 1981). Rarer higher grade (2–8 wt%) nickel reserves, such as those at Perseverance, Rocky's Reward, and Cliffs – Mount Keith, are present as zones of massive sulfide and olivine–sulfide cumulate associated with thin komatiite flows. These deposits are now known as Class 1 Deposits (Hill and Gole, 1990), and were formerly classified as Volcanic Peridotite Associated deposits (Marston et al., 1981).

Our favoured current interpretation is that these lenticular olivine-adcumulate bodies occupy flow pathways formed by progressive emplacement and inflation of large lava flow fields during prolonged, voluminous eruptions. In some or all cases the flow pathways were deepened by thermal erosion of the substrate, as a result of prolonged flow of komatiite lava within large lava pathways (Barnes et al., 1988; Hill and Perring, 1996). The adcumulates formed by progressive accretion of olivine crystals onto the floor of the flow, under conditions of minimal supercooling whereby growth of existing crystals was favoured over nucleation of new ones. This in situ crystallization origin is favoured over an origin by gravitational accumulation of transported crystals followed by squeezing out of trapped interstitial liquid. A critical piece of evidence is the widespread nature of skeletal or poikilitic chromite grains, which must have formed by rapid growth at the crystal–lava interface (Barnes, 1998; Barnes and Hill, 1995).

Locality 8: The Six Mile Well ultramafic complex

The area is accessed via the bitumen highway from Leinster to Wiluna. Turn right off the bitumen about 12 km north of Yakabindie Homestead (turnoff at AMG 0256585E 6957417N). Proceed roughly east to crossroads on old Agnew–Wiluna road (AMG 0258815E 6959243N), go straight ahead to Y-junction (AMG 0259343E 6959755N) and bear left, continue on to prominent windmill on Jones Creek (AMG 0260216E 6963381N). Mill is located close to quartzite unit on south end of map area in Figure 26.

The Six Mile Well ultramafic body (Fig. 26) is one of several mineralized olivine-adcumulate pods delineated in the Yakabindie area by Anaconda Australia during an intensive nickel exploration programme in the late 1960s and early 1970s. CSIRO undertook research in the region during 1982–83 and the following description is based on this work. More recently, extensive drilling and evaluation have been undertaken on the Six Mile deposit by Dominion Mining and North Limited. The deposit is now in the hands of WMC Ltd. The published global measured in situ resource as at June 1998 for Six Mile, Goliath North, and Serp Hill is estimated at 137.6 Mt at 0.52% Ni (Register of Australian Mining, 2000–01). Five of the olivine-adcumulate pods include

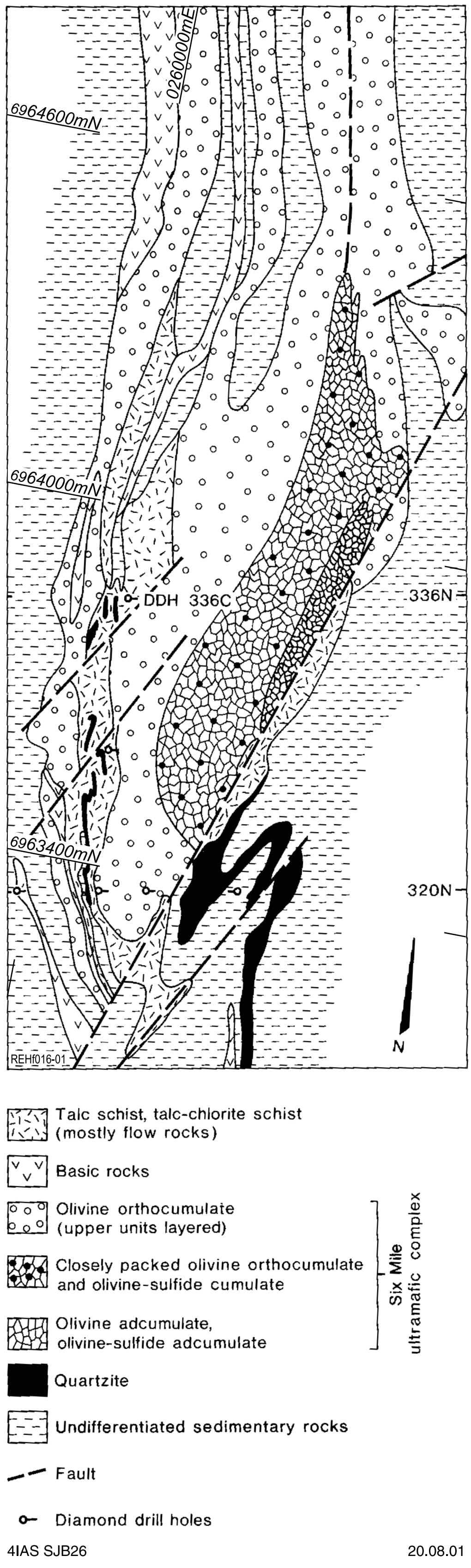

Figure 26. Interpretive geological map of the Six Mile Well olivine adcumulate lens (Hill, 1982; modified from Naldrett and Turner, 1977)

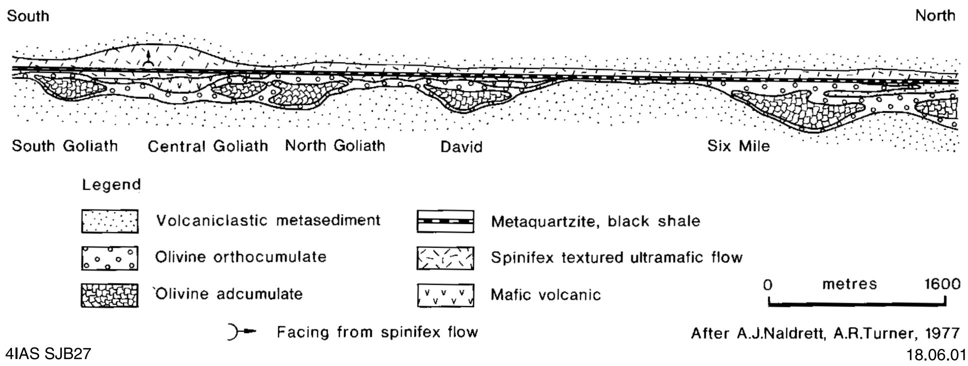

Figure 27. Reconstruction of the Six Mile Well, David, and Goliath adcumulate lenses before folding and faulting (after Naldrett and Turner, 1977)

Six Mile, David, Goliath North, Goliath Central, and Goliath South, which are in close association in the highly dismembered northern part of the area (Fig. 25). The pods are at the same stratigraphic level and exposed as small hills capped by dense brown ferruginous jasperoidal and scoriaceous laterite cap, which pseudomorphs the primary igneous olivine-adcumulate texture. The bodies are enclosed in marginal zones of olivine orthocumulate and exhibit gradational lateral contact with thinner orthocumulate and spinifex-textured horizons. Reconstruction of the stratigraphic relationships prior to folding and faulting (Fig. 27) illustrates that the five lenses were originally linked laterally by these persistent thinner lithologies. Naldrett and Turner (1977) concluded that the adcumulate bodies were linked intrusive bodies, representing subvolcanic feeder channels filled by the intrusion of crystal-charged magma comprising 90% olivine grains and 10% silicate liquid, surrounded by a lubricating sheath richer in liquid now preserved as olivine orthocumulates. The Six Mile Well Complex (Hill, 1982) is 900 m long and 400 m thick, and is concordant with its north–south striking and west-facing stratigraphy (Fig. 27). Its sheared western margin dips steeply westward and its eastern margin is a north-northeasterly striking, southeasterly dipping fault (Fig. 28). To the north the dunite body grades into olivine orthocumulates. Naldrett and Turner (1977) described igneous layering or cyclicity in the peridotite envelope on the western margin of the complex. This cyclicity was reflected in regular variations in MgO, CaO, Ni, and Al_2O_3, indicative of a west-facing direction in keeping with that of the surrounding stratigraphy. The surface expression of the body varies from rubbly friable ferruginous silica cap over the olivine adcumulate to fresh outcrops of serpentinized olivine orthocumulate on the western margin. The complex has been metamorphosed at lower amphibolite facies and then retrogressed to assemblages of serpentine (lizardite, antigorite), brucite, magnetite, pyroaurite, magnesite, dolomite, talc, chlorite, and tremolite. Igneous textures have been preserved. At the southern end of the complex, the fault at the eastern footwall contact is steep near the surface and shallows appreciably at depth (Fig. 28). The primary igneous contact was not intersected in this area despite deep drilling, and the true nature of the footwall contact is unknown.

Igneous textures grade from olivine adcumulate to olivine orthocumulate westward and upward across the igneous stratigraphy. There is a consistent correlatable primary igneous lamination. On section 320N four major igneous zones (Fig. 28) with characteristic predominant igneous features (Fig. 29) can be delineated. Boundaries between the various zones are somewhat diffuse, although within each layer, sharp contacts are common between contrasting igneous lithologies and finer scale textural and grain-size layers. Correlation of the macrolayers from drillhole to drillhole within the single drill section is possible. Intense alteration and local severe tectonic disruption

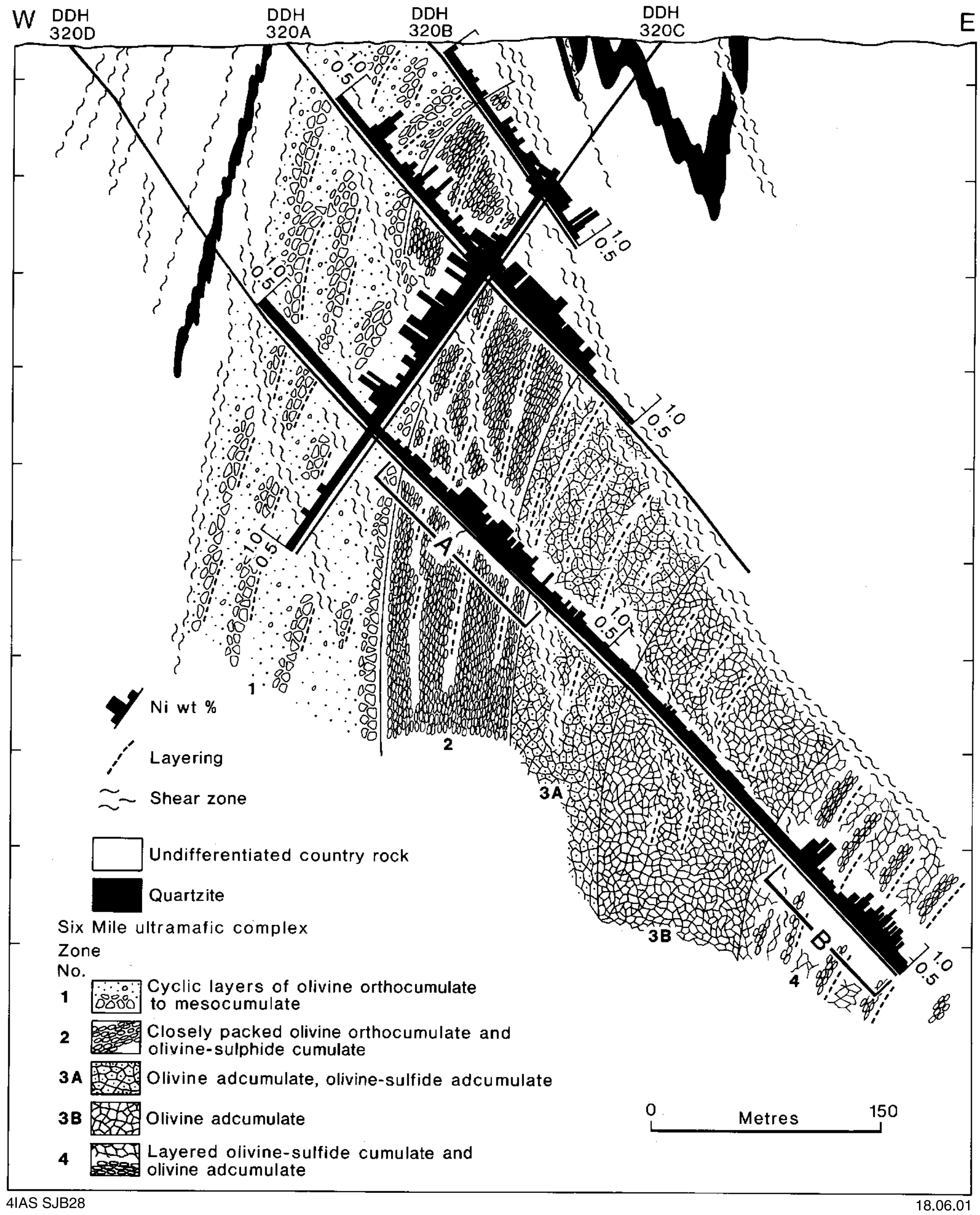

Figure 28. Geological cross section through the Six Mile Well ultramafic complex along gridline 320N (after Hill, 1982)

inhibit correlation between drill sections; however, there is sufficient evidence to indicate that the complex has a steep southeasterly plunge.

Zone 1: The western marginal orthocumulate zone shows cyclicity from medium-grained olivine mesocumulate–adcumulate to olivine orthocumulate on a scale of several metres. Some of the more evolved orthocumulates contain serpentinized pyroxene oikocrysts, whereas others contain relics of primary unaltered intercumulus aluminous amphibole and apatite. In the orthocumulates, olivine is commonly bimodal in size with grain-sized frequency peaks at 300 µm and 3 mm. The present mineralogy of the rocks of this unit includes antigorite pseudomorphs after olivine, rarer lizardite, chlorite, talc, ferroan magnesite, dolomite, very rare brucite, and ubiquitous minor fine-grained subhedral zoned spinel. The bulk of the rocks in this zone are barren of sulfide.

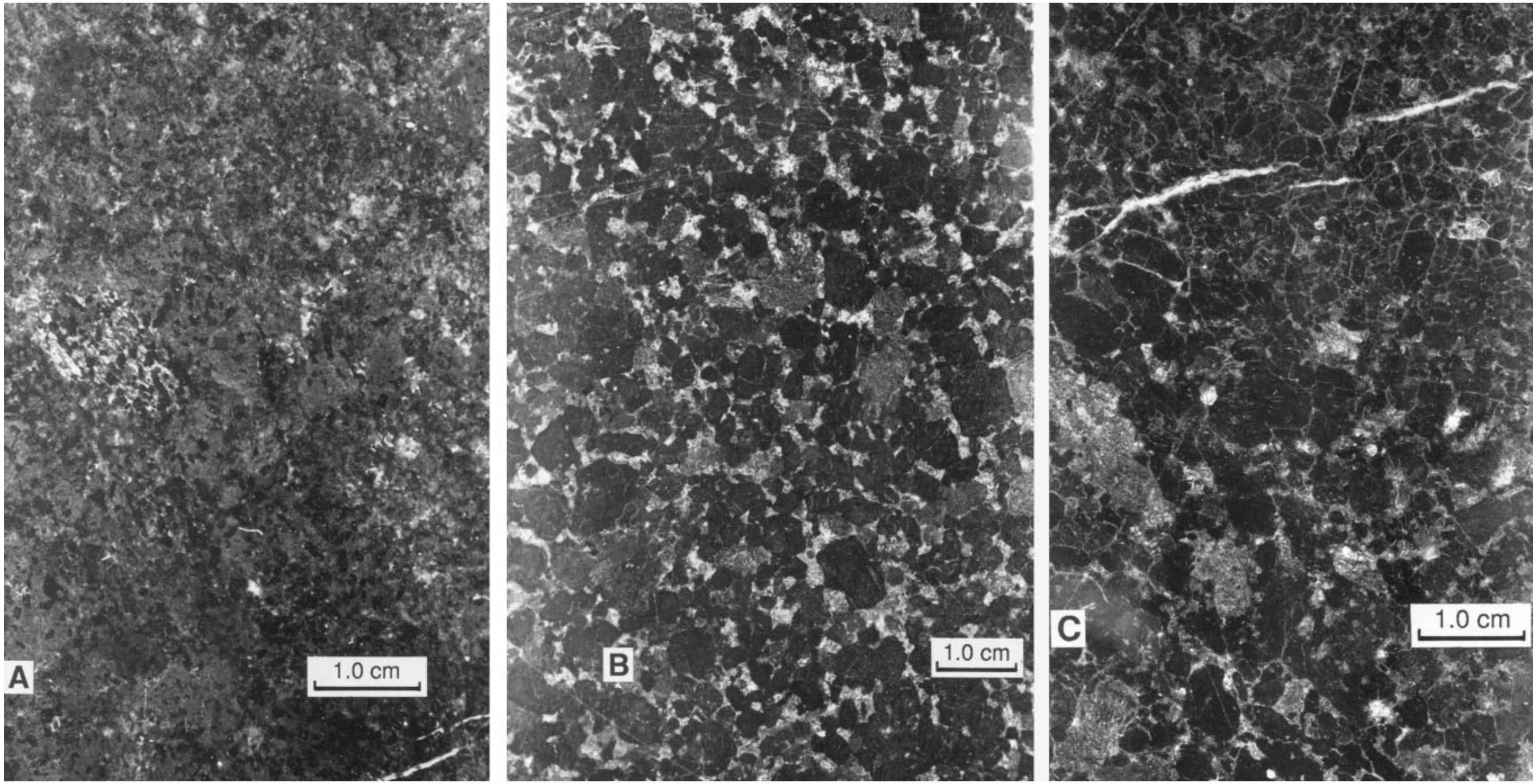

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Figure 29. Characteristic rock types from the Six Mile Well ultramafic complex: A) medium-grained olivine orthocumulate with clinopyroxene oikocrysts (left centre); B) olivine–sulfide orthocumulate; sulfide blebs (white) are associated with patches of interstitial liquid (grey) between serpentinized cumulus olivines (black); C) sharp contact between layers of olivine mesocumulate (serpentinized, top) and coarser olivine–sulfide orthocumulate (lower half). All photographs of incident light on polished drillcore

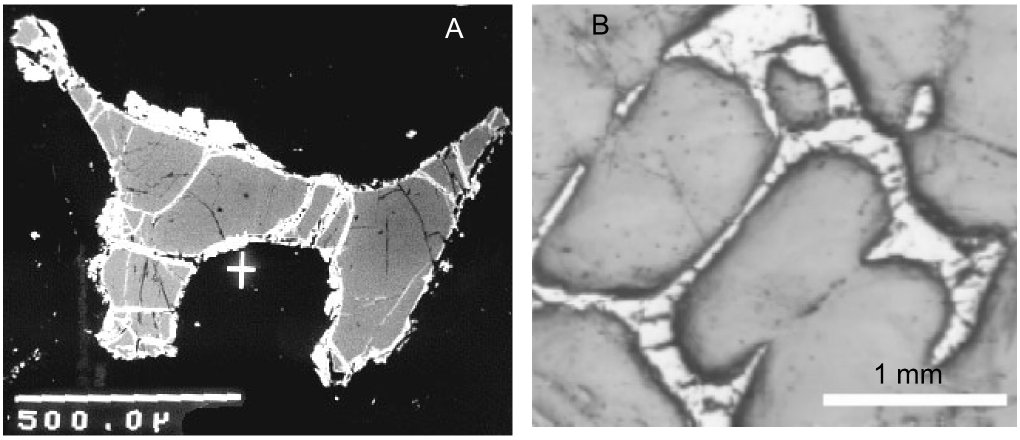

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Figure 30. Poikilitic and interstitial chromite grains from the olivine adcumulate lens at Six Mile Well (left: backscattered electron micrograph; right, reflected light photomicrograph)

Zone 2: is 100 m thick, and characterized by abrupt textural and grain-size layering and is dominated by closely packed olivine orthocumulate and olivine-sulfide orthocumulate. Cumulus sulfide is commonly confined to finer grained layers, which contain higher proportions of intercumulus liquid. Some layers are coarse grained and exhibit adcumulate textures. Contacts between mineralized and unmineralized lithologies are typically sharp (Fig. 29C). Serpentine pseudomorphs after olivine vary from antigorite–carbonate assemblages to lizardite–brucite. Primary intercumulus silicates have been altered to chlorite, talc, and carbonate. Minor cumulus subhedral spinel is ubiquitous.

Zone 3: is an essentially sulfide free coarse-grained (about 1 cm) mosaic-textured olivine adcumulate. A large proportion of this zone contains relict olivine, and in places the rock is essentially unaltered. Olivine compositions range from $Fo_{93.7}$ to $Fo_{94.7}$ and are relatively uniform throughout the zone. Chromite is very rare in these adcumulates, but in contrast to the other units it is characteristically anhedral and in some cases poikilitic (Fig. 30).

Zone 4: is the lowermost unit intersected by drilling. It is the second significant sulfide-bearing zone on section 320N. Medium- to coarse-grained olivine adcumulate is the dominant lithology; however, the zone is characterized by the presence of grain-size, textural, and phase layering. Abrupt changes from fine- to medium-grained olivine–sulfide mesocumulate to coarse-grained barren olivine adcumulate are common. Rare relict olivine is present in the upper levels of the unit and its composition is within the range $Fo_{92.6}$ to $Fo_{93.8}$.

The gradual change from olivine adcumulate to orthocumulates with higher initial igneous porosities, and fractionation towards more evolved compositions upward across the complex, from Zone 3 to the western margin, is suggested by plots of MgO–FeO–SiO_2 for representative samples from each zone (Fig. 31). Significant cyclic variations in compositions from Zone 1 were described by Naldrett and Turner (1977). This feature and the wide range in compositions illustrated by rocks from Zone 2 are in direct contrast to the tight groupings displayed by the rocks from Zones 3 and 4. The olivine adcumulates from Zone 4 are consistently more iron-rich than those from Zone 3.

The Six Mile Well complex exhibits textural, mineralogical, and compositional layering on scales ranging from centimetres to tens of metres. The layering parallels

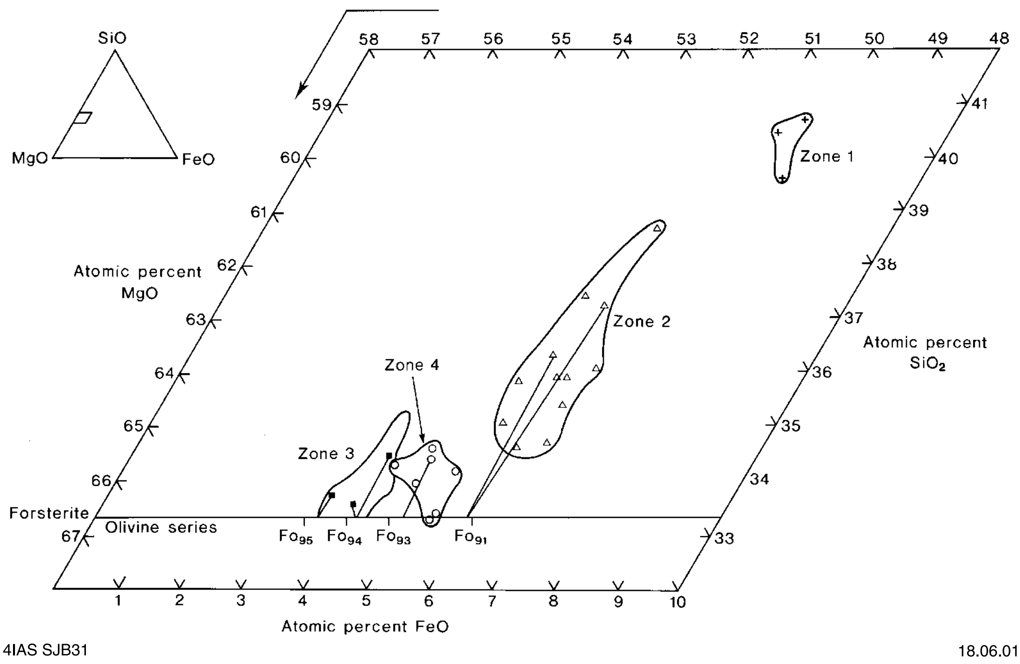

Figure 31. MgO–FeO–SiO_2 plot (atomic proportions) of bulk rock compositions from the Six Mile Well ultramafic complex, showing change to progressively more iron-rich compositions upward through the complex

an igneous lamination and is concordant with the dip and strike of the enclosing stratigraphy. The complex is characterized by thick zones of olivine adcumulate, and cyclic layering whose mineralogical and chemical features indicate a west-facing direction in accordance with the surrounding spinifex-textured volcanic rocks. There is a gradual change to more fractionated rocks towards the top of the complex. These features are not consistent with an origin via the intrusion of a crystal-charged mush. A magma of 90% crystals and 10% silicate liquid would not have the physical properties of a crystal mush and could not be intruded as such. The layering within the Six Mile Well body could not be produced during such a process.

The accumulation of thick zones of olivine adcumulate and orthocumulate characterized by mineralogical, textural, and compositional layering is indicative of in situ crystallization in a relatively dynamic magmatic environment, involving continued replenishment of komatiite magma and periodic variation in factors such as magma composition, cooling rate, and the degree of supercooling. The Six Mile Well complex is confined to a stratigraphic horizon of ultramafic lithologies, including spinifex-textured flows and olivine orthocumulates. A gradual change along strike from olivine adcumulates to orthocumulates northward has been documented by extensive diamond drilling. It is proposed that the spinifex-textured rocks, olivine orthocumulates, and the Six Mile Well lithologies are consanguineous and extrusive, and that their textural and compositional differences reflect different volcanological environments.

The Mount Keith region

The Mount Keith mine site is accessed by the bitumen highway between Leinster and Wiluna.

The Mount Keith deposit is the largest low-grade sulfide nickel deposit in the world, and the largest known ‘Type 2’ komatiite-hosted deposit. It is currently being mined by WMC Ltd at their Mount Keith operation. At June 2001 the Mount Keith deposit had a total nickel resource of 477 Mt at 0.4% Ni, comprising a measured resource of 255 Mt at 0.4% Ni, an inferred resource of 130 Mt at 0.4% Ni and an indicated resource of 92 Mt at 0.4% Ni (data from WMC web site). Mineralization is associated with a large olivine-adcumulate body, which in many ways is typical of those found in this part of the belt.

This summary of the Mount Keith region contains the results of a detailed investigation carried out by S. E. Dowling and R. E. T. Hill in collaboration with Australian Consolidated Minerals (Dowling and Hill, 1990, 1992; Dowling et al., 1989; Hill et al., 1995). The Mount Keith region occupies the most attenuated part of the Agnew–Wiluna Greenstone Belt (Fig. 21). The region is structurally complex with a pronounced north-northwesterly trending linearity and vertical to steep dips to the west. The stratigraphic succession at Mount Keith has been placed within the Upper Greenstone Sequence by Naldrett and Turner (1977) and can be correlated with the Yakabindie Sequence to the south (Dowling and Hill, 1992). The regional geology has previously been described by Bunting and Williams (1979), Elias and Bunting (1978), and Burt and Sheppy (1975). The ultramafic rocks are within an Archaean layered succession of tholeiitic basalts, layered gabbros, high-Mg basalts, felsic to intermediate volcaniclastic and clastic sedimentary rocks, and acid volcanic rocks, with minor carbonaceous shales and cherts. The boundaries of the greenstone belt are defined by the Eastern and Western Granites. An east-facing sequence of arkosic arenites and boulder conglomerates, the Jones Creek Conglomerate, lies unconformably on the margins of the Western Granite, and defines the Perseverance Fault. The eastern margin of the belt consists of a sequence of felsic volcaniclastic sedimentary rocks, basalts, and folded, banded quartz–magnetite rocks that has been extensively invaded by granite. The Keith–Kilkenny Lineament is expressed as a wide zone of shearing along the eastern margin. Outcrop is poor and there are extensive deposits of alluvium and colluvium in the north and east of the region, resulting from a complex history of subaerial weathering dating from the Mesozoic. Details of weathering and geochemistry of the weathering profile developed over the ultramafic rocks in the Mount Keith nickel deposit are described by Butt and Nickel (1981) and Burt and Sheppy (1975).

The regional metamorphic grade decreases from lowermost amphibolite facies near Six Mile Well to middle greenschist facies near Honeymoon Well. In the Mount Keith region, the ultramafic rocks have been metamorphosed in the presence of fluids bearing H_2O and CO_2 to middle–upper greenschist facies. Igneous olivine, pyroxene, amphibole, and chromite are occasionally preserved. Typical assemblages consist of tremolite, actinolite, chlorite, antigorite, lizardite, brucite, pyroaurite, talc, magnesite, dolomite, stichtite, and magnetite. The ultramafic rocks are characterized by static igneous textures with a locally developed weak foliation in contrast to the dynamic metamorphic textures exhibited by the country rocks. In the ultramafic rocks, primary igneous textures are usually well pseudomorphed and vary from adcumulate through mesocumulate, orthocumulate, and harrisite to spinifex types. In zones of shearing and fluid access, extreme talc–carbonate–chlorite alteration has resulted in a massive or schistose fabric.

The 60 km of strike from Betheno to Kingston contains at least five significant nickel-sulfide deposits (Fig. 32). Deposits at Betheno, Six Mile, Mount Keith (including Sarah's Find massive sulfide), and Kingston are composed of huge resources of low-grade (0.5 – 1.5 wt% Ni) disseminated nickel sulfide hosted by olivine adcumulate–orthocumulate lithologies. The Cliffs – Mount Keith deposit consists of zones of massive sulfide and olivine–sulfide cumulate associated with an olivine-rich komatiite flow. A summary of the exploration history of the Mount Keith region is given in Marston (1984).

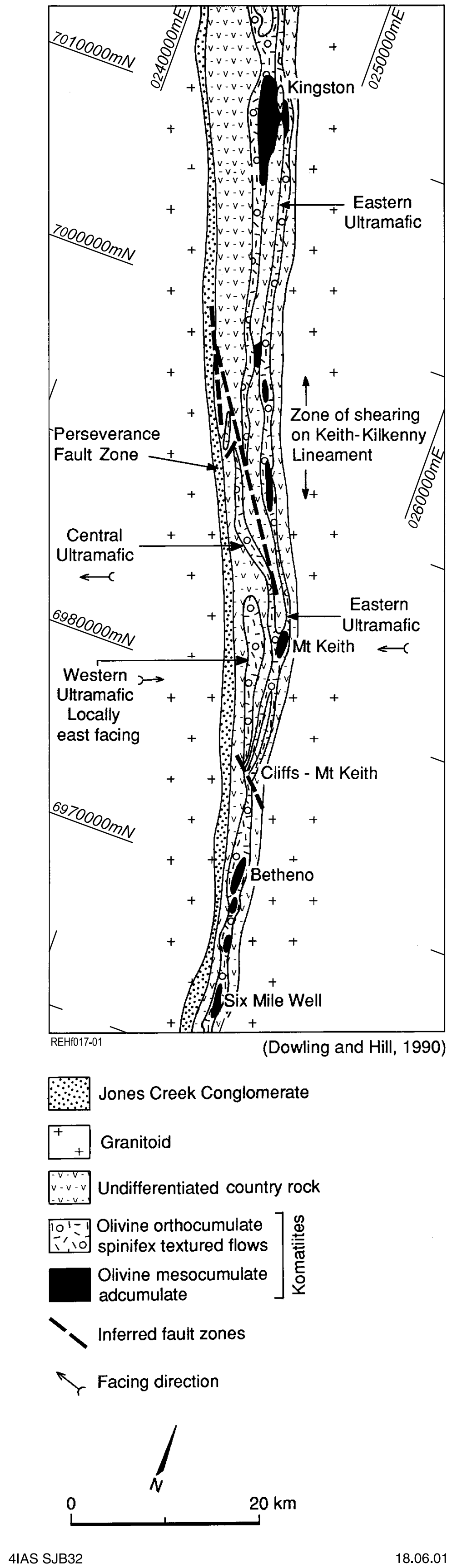

Figure 32. Geology of the area between Six Mile Well and Kingston, showing the major stratigraphic units (after Dowling and Hill, 1990)

Three major separate komatiite units, the Eastern, Central, and Western Ultramafic Units, have been mapped between Kingston and Betheno. They exhibit considerable variation in thickness and continuity along strike. The Eastern and Central Units face and dip steeply towards the west everywhere, and are juxtaposed in places as a result of strike-slip faulting or thermal erosion. A south-plunging synclinal closure to the west of the Mount Keith deposit generates opposing facings in the Western Ultramafic Unit, which is regarded as the youngest of the three units (Fig. 33). The komatiite sequence is interpreted to young towards the west. The main Mount Keith orebody is hosted by the Eastern Ultramafic Unit, and the Type 1 Cliffs – Mount Keith orebody is hosted by the Central Ultramafic Unit.

A stratigraphic column (Fig. 21) suggesting relative age relationships of the lithologies has been based on several factors, including petrographic and geochemical properties of the major ultramafic units, facing directions from spinifex-textured flow lobes, and the non-repetitive nature of blocks of mafic–felsic volcanic and sedimentary country rock. The existence of complex regional faulting and folding is recognized and the potential for some equivalence of the various komatiite units is understood; however, the present geological database supports the interpretation presented in the stratigraphic column.

The Early Flows

East of the Eastern Ultramafic Unit is a thin ultramafic unit, the Early Flows. This unit has been intersected in three diamond drillholes east of the Mount Keith deposit. The continuity of the Early Flows and their stratigraphic and structural relationships with the Eastern Ultramafic Unit are unknown at present. The unit is 55 m thick in diamond drillhole MKD-66 and is west facing. A basal olivine orthocumulate (mesocumulate in places) is overlain by a layered zone composed of harrisitic olivine orthocumulates and pyroxene–olivine cumulates, and an upper zone of thin differentiated spinifex-textured flows and pyroxene-rich cumulates that pass upward into a layered gabbroic sequence. The basal olivine orthocumulate consists of varying proportions of cumulus olivine, oikocrystic pyroxene and kaersutite, and interstitial liquid. Olivines in the ultramafic rocks north of Betheno are completely serpentinized, so it has been necessary to use indirect methods based on whole-rock chemistry to estimate original igneous-olivine compositions. Olivine compositions in the early flows are less magnesian ($Fo_{89.3}$) than those in other ultramafic units in the area, which typically become more magnesian up stratigraphy. The early flows are apparently more differentiated or contaminated (or both). In contrast to all other ultramafic units that have near-chondritic Al_2O_3/TiO_2 ratios, the Early Flows unit has an Al_2O_3/TiO_2 ratio of 24.5, which is suggestive of crustal contamination of the magma on the way to the surface.

Locality 9.1: The Eastern Ultramafic Unit and the Mount Keith orebody

Within the Mount Keith region, the Eastern Ultramafic Unit is dominated by olivine orthocumulates, but characterized by lenticular bodies of olivine adcumulate–mesocumulate that have gradational contacts with laterally equivalent sequences of olivine orthocumulate and spinifex-textured flows. Low-grade disseminated nickel-sulfide mineralization in layered olivine adcumulates–mesocumulates occupy several of these zones of thickening. The Mount Keith Ultramafic Complex (MKUC) is the largest such zone in the Eastern Ultramafic Unit, and hosts the Mount Keith disseminated nickel-sulfide deposit, with proven reserves estimated at 464 Mt of ore at 0.54 wt% Ni.

The MKUC consists of a basal zone of olivine orthocumulate overlain by a thick zone of unmineralized coarse-grained olivine adcumulate and a thick zone of layered, mineralized olivine mesocumulate which is the orebody (Figs 34, 35, and 36). Both units contain bodies of an unusual coarse-grained orthocumulate called ‘porphyritic

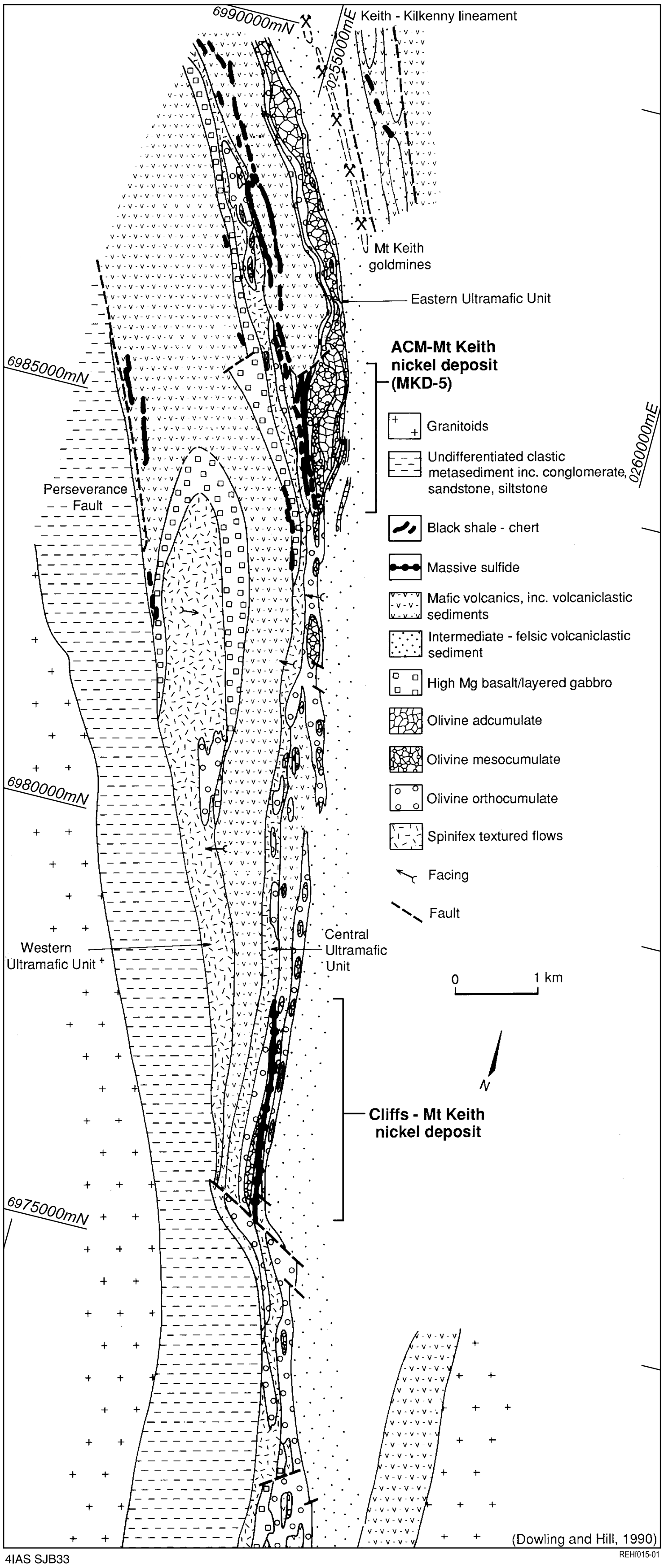

Figure 33. Detailed geological map of the Mount Keith area, from outcrop and drillholes (after Dowling and Hill, 1990)

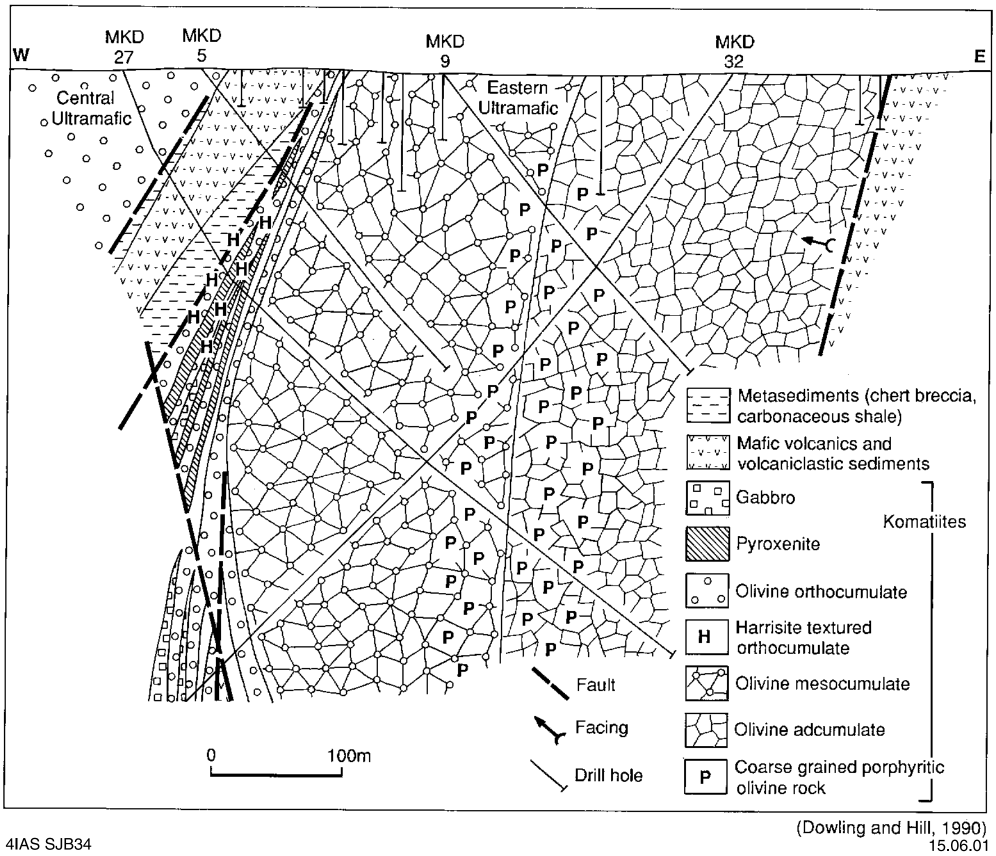

Figure 34. Interpreted geological cross section through the Mount Keith orebody (after Dowling and Hill, 1990)

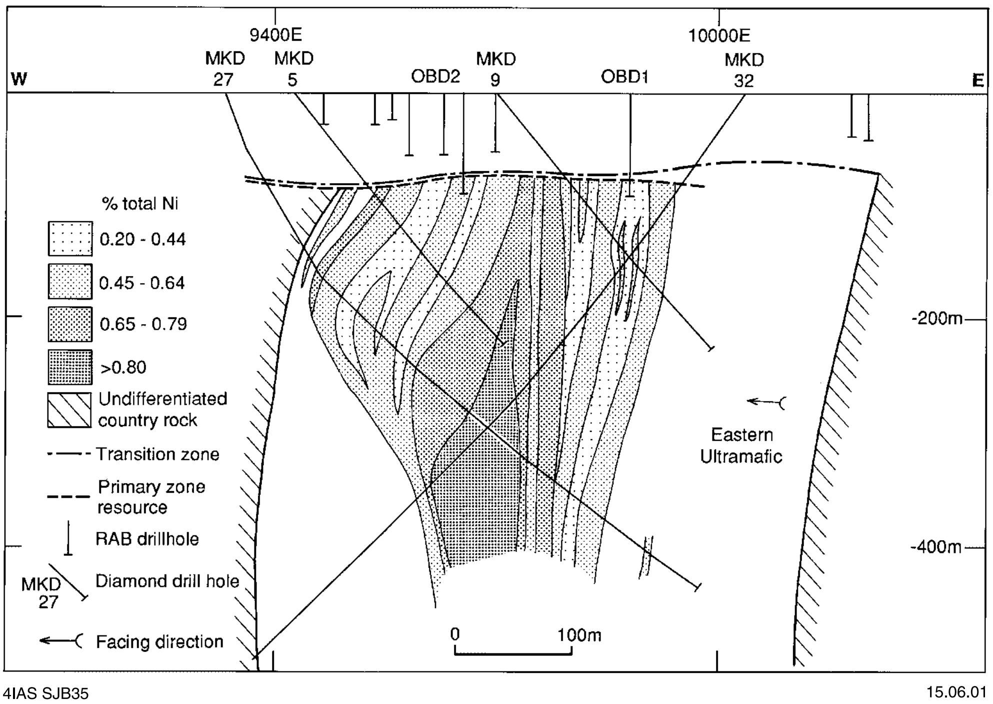

Figure 35. Distribution of nickel grade across the Mount Keith orebody (same section as Fig. 34; data from Australian Consolidated Minerals Ltd)

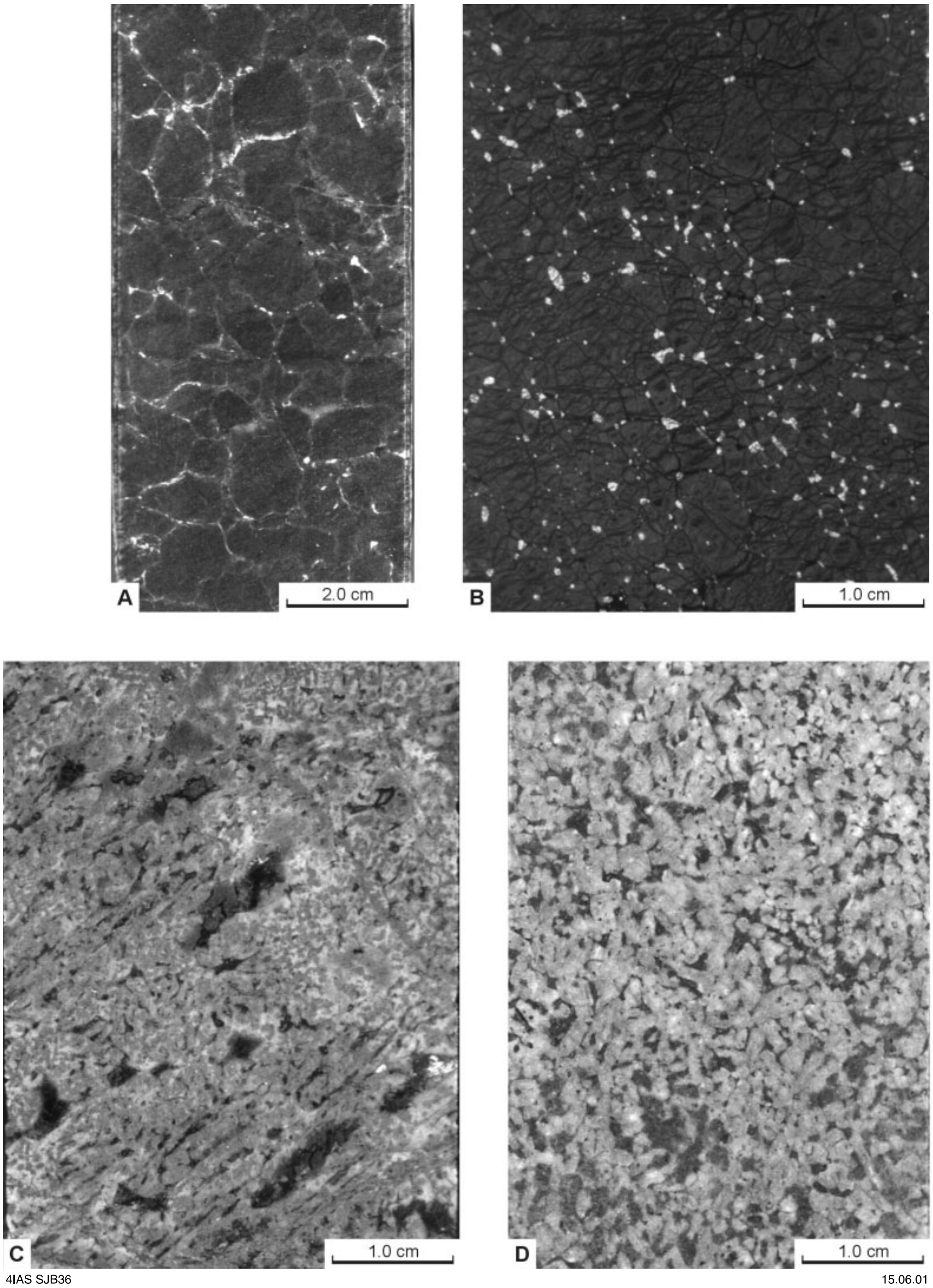

Figure 36. Representative lithologies from the Mount Keith Ultramafic Complex: A) olivine–chromite adcumulate with stichtite after interstitial chromite (grey); B) olivine–sulfide adcumulate with sulfide blebs (white) interstitial to serpentinized olivine; C) olivine harrisite; D) olivine orthocumulate from upper layered sequence rocks. In (B) and (C), olivine is light grey in dark fine-grained altered groundmass. All photographs of incident light on polished drillcore

olivine rock' (Fig. 37). This rock type comprises large branching and partially resorbed dendritic olivines, which can be interpreted as a harrisite crystallized from patches and narrow semi-stratiform layers of liquid that migrated into low-pressure zones and cracks during the partial collapse of olivine orthocumulate during cooling. This sequence grades laterally and vertically into an upper zone of predominantly olivine orthocumulate, characterized by the presence of branching olivine harrisite, layered olivine–pyroxene cumulates, pyroxene cumulates, gabbros, and plagioclase cumulates. This assemblage of lithologies is suggestive of ponding and in situ fractionation of evolved komatiitic liquid. Primary kaersutitic amphibole is present as oikocrysts in the olivine orthocumulate in this upper zone, and zones of olivine–sulfide orthocumulate are intermittently developed. Coarse-grained mesocratic hornblende–plagioclase rocks and metasomatically altered (rodingitized) gabbro dolerite dykelets transgress the ultramafic stratigraphy.

A geochemical profile through the orebody is shown in Figure 38. An interesting feature of this profile is the distribution of Cr, which is largely controlled by the abundance of cumulus chromite. Chromite is pervasive through the complex, and is extensively replaced and pseudomorphed by late hydrothermal stichtite. In the lower stratigraphic zones, which are relatively low in Cr, chromite shows interstitial and poikilitic morphologies. In the more fractionated rocks in the upper zones D and E , chromite abundance increases and the morphology changes to subhedral and euhedral (Barnes, 1998). This changeover in Cr abundance and morphology corresponds roughly

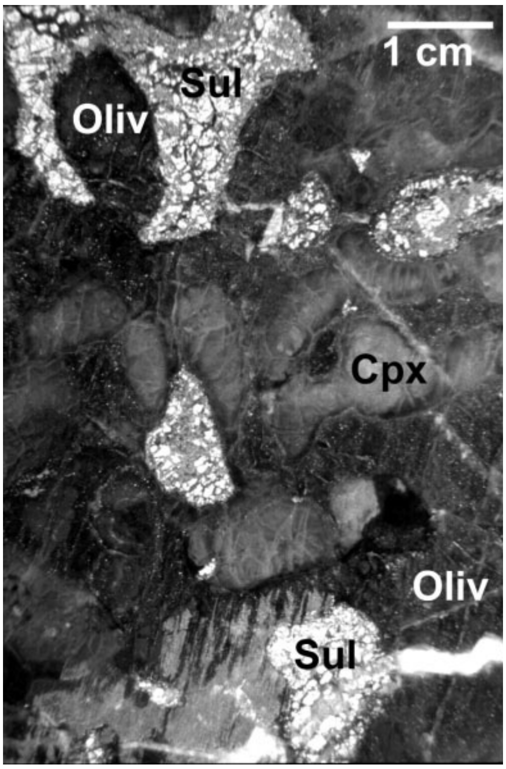

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Figure 37. Porphyritic olivine rock, Mount Keith Ultramafic Complex (after Dowling and Hill, 1990; Oliv = olivine, Sul = sulfide, Cpx = clinopyroxene)

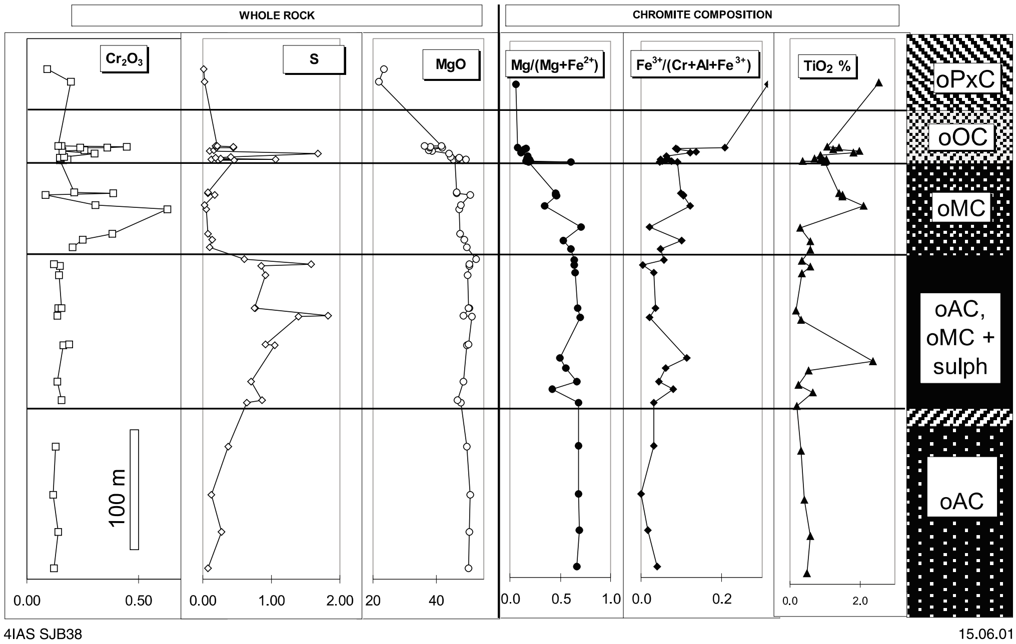

Figure 38. Vertical geochemical profile and trends in chromite composition through the centre of the Mount Keith Ultramafic Complex and Mount Keith orebody. Abbreviations: oAC = olivine adcumulate; oMC= olivine mesocumulate; oOC = olivine orthocumulate; oPxC = olivine pyroxene cumulate; Sulph = sulfide

with the drop-off in sulfide abundance at the top of the ore zone. Chromite compositions become more enriched in ferric iron compared to Cr and Al, and enriched in TiO_2, in the more orthocumulate rocks upsection, reflecting extensive reaction between cumulus chromites and trapped intercumulus magma (Barnes, 1998). The marked decrease in Mg content in chromites in the upper part of the section is a metamorphic effect related to extensive fluid influx in the antigorite–carbonate rocks on the western margin of the complex.

Alteration: Anastomosing zones of talc-carbonate alteration are prevalent in the central portion of the mesocumulate, and the margins of the MKUC exhibit extreme hydrothermal alteration. There is a large variation in the nature and distribution of silicate, oxide, and sulfide phases, and this is a result of their depth in the weathering profile, proximity to the margins of the ultramafic complex, to fractures, faults, and intrusives, and the igneous lithology and bulk-rock composition. After extrusion, as temperatures decreased with the cooling of the ultramafic pile, fluids bearing CO_2, S, Cl, and F migrated inwards from the margin and along faults and fractures towards the core. Serpentinization fronts followed by carbonation fronts moved progressively inwards from the margins as described by Eckstrand (1975). In the silica-rich, less-magnesian marginal rocks, the olivine–pyroxene–amphibole cumulates were partly replaced by pseudomorphic antigorite–carbonate assemblages. The serpentinization of the more magnesian olivine mesocumulates–adcumulates involved the topotactic replacement of olivine by lizardite, with intergrown brucite and fine-grained disseminated magnetite, and the formation of fine-grained bladed and mosaic antigorite in intercumulus areas. The first metamorphic peak in the MKUC was related to the burial of the ultramafic sequence, with increased pressure and temperature and increased CO_2 levels in fluids. This resulted in the recrystallization of lizardite to interlocking bladed antigorite in variable proportions. Fine-grained aggregates of carbonate were almost always associated with the antigorite. A second metamorphic peak in the MKUC may have been related to higher heat flow and structural disruption to the stratigraphy generated by the emplacement of the granites. This event was marked by the development of crosscutting veinlets of antigorite–brucite, which can be seen replacing carbonate. This low-CO_2 event has also been recognized to the south at Six Mile Well (Hill, 1982).

Mineralization: The mineralization within the MKD-5 nickel-sulfide deposit is disseminated and characteristically layered. It is commonly confined to the olivine mesocumulate, although minor thin mineralized layers are present in the olivine adcumulate. The distribution of nickel grade within the MKUC on a vertical section through drillholes MKD 27 and 32 is portrayed in Figure 35.

The olivine-sulfide cumulates are believed to have formed by the cotectic accumulation of olivine and sulfide liquid of monosulfide-solid-solution composition from sulfur-saturated komatiite liquid. The original sulfide would have been similar in composition and mineralogy to most magmatic massive ores, solidifying and exsolving the assemblages of varying proportions of pyrrhotite, pentlandite, pyrite, and chalcopyrite. The disseminated low modal distribution of the sulfide, and its association with a preponderance of olivine have been responsible for significant chemical and mineralogical reconstitution. Sub-solidus re-equilibration of olivine and subordinate sulfide during initial cooling has involved nickel enrichment of the sulfide. Subsequent redistribution of nickel from olivine to sulfide has accompanied the process of serpentinization during metamorphism. Within the MKD-5 deposit, sulfide assemblages are characterized by a Ni/S ratio of 1.02 and a high Ni/Cu ratio of 52 (Keays and Davidson, 1976).

The present sulfide mineralogy of the deposit is the result of primary magmatic, secondary hydrothermal, and weathering processes. Pentlandite is the dominant sulfide, with subordinate pyrrhotite, millerite, and heazlewoodite, minor chalcopyrite, violarite, and gersdorffite. Supergene violarite, pyrite, and marcasite commonly replace pentlandite and pyrrhotite in the upper zone of oxidation and throughout the deposit in zones that have permitted high fluid access during weathering. The sulfides are present as medium- to coarse-grained lobate patches interstitial to olivine pseudomorphs; very fine grained dust (5–15 m) disseminated throughout olivine pseudomorphs; fine-grained (50 m) aggregates concentrated in intracrystal partings, intercrystal margins, and cross-cutting veinlets; and fine-grained disseminated crystals intergrown with carbonate, commonly in marginal talc–carbonate altered rocks. In most of the mineralized rocks, intergranular lobate patches are rimmed, veined, and replaced by magnetite; some are intergrown with carbonate and antigorite laths.

Interpretation of the MKUC: The nature and distribution of lithologies, igneous textures, and whole-rock major- and trace-element patterns are indicative of the MKUC having formed by olivine accumulation within a major flow pathway during a period of voluminous continuous eruption. Textural variation in the olivine adcumulate–mesocumulate reflects variations in the extent of supercooling at the crystal–liquid interface as a result of fluctuations in flow rate. Variations in chromite and sulfide abundance and olivine compositions have arisen from changes in the composition of the flowing lava, which are products of the fractionation of the parent komatiite magmas either en route to the surface from the mantle or as it flowed over the surface. The formation of lobate chromite in olivine adcumulates–mesocumulates is thought to be the result of simultaneous crystallization of chromite and olivine at high temperatures.

Harrisitic orthocumulates are believed to have formed by directional cooling through the top of the lava flow. Their presence in the middle of a thick pile of adcumulates is taken to mean that the height of the flowing lava column above the crystal pile was not large, such that occasional drops in flow rate resulted in sudden increases in the effective cooling rate at the lava – crystal pile interface. It is likely that the thickness of the lava was at least an order of magnitude less than the final thickness of the crystal pile.

The pyroxene cumulates and gabbroic rocks at the top of the complex imply in situ crystallization and fractionation of evolved komatiite lava. Our favoured hypothesis is that local damming of the flow due to clogging of the lava pathway downstream produced small lava lakes. These underwent in situ fractionation resulting in differentiated sequences of cyclically layered olivine, pyroxene, and plagioclase cumulates.

The Eastern Ultramafic Unit is overlain by sequences of brecciated pyritic chert and carbonaceous shale, agglomerate, mafic volcanic rocks, volcaniclastic sedimentary rocks, and minor thin komatiite flows. These intercalated lithologies are the product of contemporaneous ultramafic–mafic–felsic volcanism from submerged and emergent centres, interspersed with quiescent periods. Komatiite extrusion represented a short-lived but widespread event, and the composition and morphology of the substrate would have determined the form of the komatiite flow.

The Central Ultramafic Unit

The Central Ultramafic Unit faces and dips steeply towards the west. The unit is typical of the komatiite stratigraphy of this part of the belt: sheets of orthocumulate-dominated spinifex-textured flow lobes flank thicker units of olivine adcumulate and mesocumulate with disseminated nickel-sulfide mineralization. The flanking sequences are predominantly composed of thin, differentiated olivine- and pyroxene-bearing spinifex-textured flows that become more evolved towards the west, subordinate units of olivine orthocumulate, and marginal discontinuous layered olivine–pyroxene–plagioclase cumulates. Numerous thin interflow sedimentary horizons (pyritic, tuffaceous shales, chlorite schists, and black shales) are present throughout the unit. A massive iron–nickel sulfide deposit (the Cliffs – Mount Keith deposit of 2.5 Mt at 2.7 wt% Ni) is associated with the earliest flow unit (an olivine orthocumulate) and appears confined to embayments and flexures in the faulted contact zone (Fig. 33).

The massive sulfide is best developed in zones characterized by the absence of a basal black shale, with a basal massive-sulfide layer overlain by matrix and then disseminated sulfide layers. Three types of thin komatiite flows can be distinguished in diamond drillcore from the Central Ultramafic Unit: texturally undifferentiated massive olivine-orthocumulate flows; texturally differentiated olivine-bearing spinifex-textured flows exhibiting classic Munro Township-style textural differentiation (Arndt et al., 1977); and texturally differentiated pyroxene-bearing spinifex-textured flows exhibiting textures described by Barnes et al. (1983).

The nature and distribution of lithologies, igneous textures, and the whole-rock major- and trace-element patterns are indicative of the Central Ultramafic Unit having formed in a dynamic volcanogenic environment. Early thin flows were confined by the growth of levee banks or pre-existing topographic structures (or both). More sustained eruption rates and turbulent flow led to the deepening of the flow channel and the crystallization of the olivine–sulfide cumulates, with the volume percent of sulfides decreasing upward in the channel to eventually form layered olivine–sulfide mesocumulates–adcumulates. Flanking deposits of olivine orthocumulates and spinifex-textured flow rocks representing floodplain sequences and sheet flow formed during periodic overflow of the central channel. Sequences of thin differentiated spinifex-textured flow rocks, which became more evolved towards the west, formed during episodic flow and fractionation (in lava tubes or tongues) during the waning stages of this event.

The Layered Series

The Layered Series lies east of the Western Ultramafic Unit and comprises a sequence of pyroxene spinifex-textured flows, layered gabbroic rocks, and olivine orthocumulates. Outcrop is not sufficient to determine conclusive facing directions or to establish a genetic link via fractionation for these rocks.

Outcrops of similar associations of rocks have been mapped at Betheno between the Western and Central Ultramafic Units. Further south in the Yakabindie area, Naldrett and Turner (1977) mapped a sequence of olivine- and pyroxene-bearing spinifex-textured komatiite, pyroxenite, pyroxene gabbro, and Mg-basalt associated with elliptical pods of olivine orthocumulate in the Serp Hill Syncline.

Locality 9.2: The Western Ultramafic Unit

From the main Leinster to Wiluna highway, the outcrop (AMG 0255290E 6983280N) is immediately adjacent to the Mount Keith mine dumps. The outcrop is on WMC's Mount Keith mine lease and can only be visited by arrangement with the company.

Note: This locality is a Geological Monument and hammering and sampling are not permitted.

The Western Ultramafic Unit (WUU) is composed of a sequence of shallowly dipping, thin, differentiated olivine- and pyroxene-bearing spinifex-textured flows and thicker zones of olivine orthocumulate. Gabbros are associated with pyroxene-bearing spinifex-textured flow rocks within the olivine-bearing spinifex-textured flow rocks in the centre of this unit. A high-Mg basalt sequence lies to the west of the WUU. Numerous thin horizons of interflow sediments have been identified throughout the unit. Outcrop mapping and limited diamond drilling west of the Mount Keith orebody indicate that the WUU flows here young to the east. Dips vary from 50° to subhorizontal, giving rise to a broadening of the outcrop area. In this region there is good outcrop of olivine- and pyroxene-bearing spinifex-textured flow rocks. Fresh rock is usually present less than 5 m below the ironstone-gravel overburden and is exposed in creek channels and shallow scrapes. Geochemical profiles constructed from samples collected from traverses across outcrop near diamond drillholes confirm the easterly facing established by mapping and diamond drilling.

Figure 39 summarizes the lithogeochemistry for a sequence of olivine-bearing spinifex-textured flow rocks.

Near the Cliffs deposit (Fig. 33) WUU flows dip vertically and young to the west, implying the existence of a synclinal structure between this locality and the site of the Mount Keith Homestead. A compositional continuum exists between the olivine orthocumulate and olivine- and pyroxene-bearing spinifex-textured flow rocks. This trend is the olivine control line. As in the olivine-bearing spinifex-textured flows of the Central Ultramafic Unit, elements compatible with olivine, MgO, and Ni are positively correlated and reach their maximum values in the B zone, whereas elements incompatible with olivine, such as CaO, TiO_2, Al_2O_3, FeO, and Cu, all vary antipathetically with respect to MgO (Fig. 39). These elements reach high values in the flow top, A3 zone, and B1 zone. These relationships reflect the relative proportions of olivine and variably fractionated liquid in different zones within a flow, and also the mobility during alteration of elements such as Ca and Cu. Within the lattice-textured and 'stringy-beef' zones of a pyroxene-spinifex textured flow, MgO, FeO, Ni, and Cr vary sympathetically and decrease upward. These trends reflect the greater amount of ferromagnesian minerals compared to liquid in the 'stringy-beef' zone. In contrast, CaO, Al_2O_3, and Cu all vary antipathetically with respect to MgO, reaching maximum values in the lattice zone.

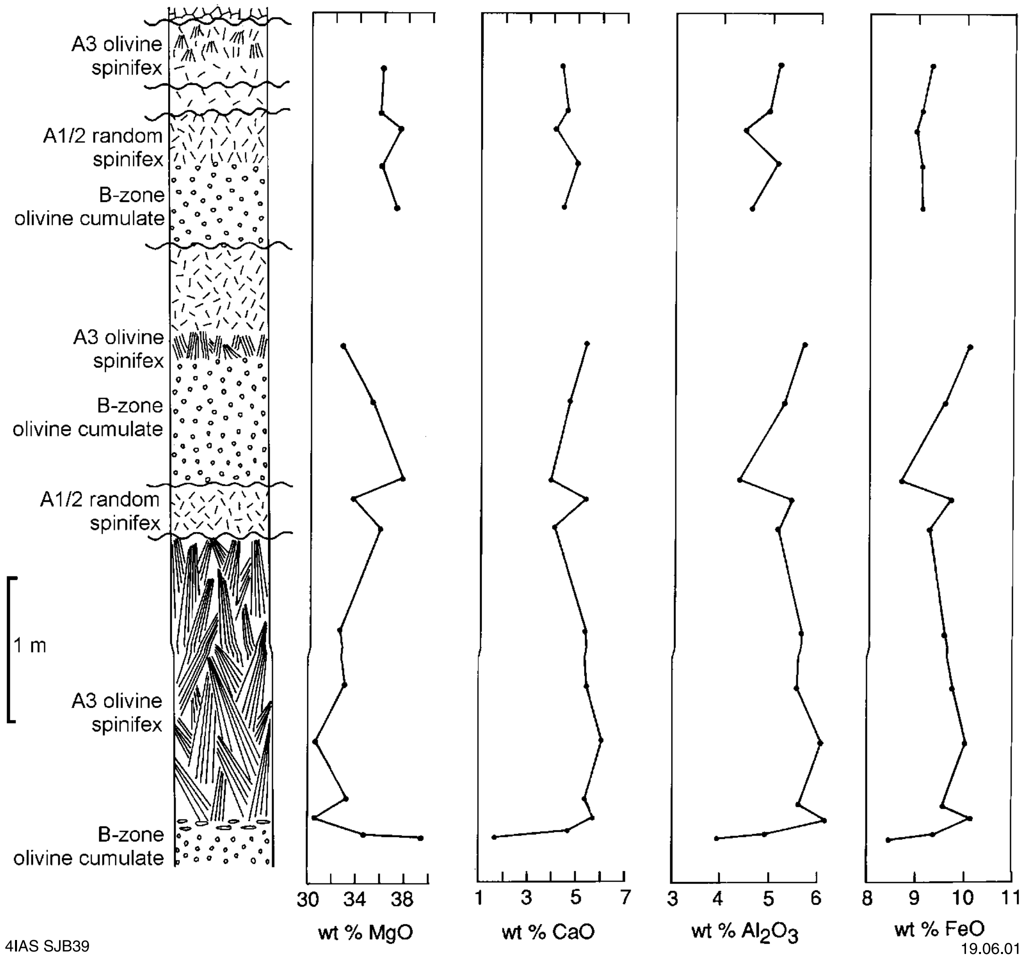

Figure 39. Geochemical profile through spinifex-textured komatiite flows (outcropping at 255270E, 6983284N) of the Western Ultramafic Unit, southwest of the MKD5 orebody (after Dowling and Hill, 1990)

The Western Ultramafic Unit is believed to represent thin sheet lobes in floodplain sequences formed during episodic flow during the waning stages of flow field emplacement. Liquids from which the olivines in the Western Ultramafic Unit crystallized were the most magnesian of all ultramafic units. The trend to more-forsteritic olivines towards the west may indicate that the flow rocks making up the Western Ultramafic Unit are closer to the vent or that they have been formed from a more-primitive, less-contaminated magma.

The Western Ultramafic Unit outcrops contain some of the best outcrops of pyroxene and olivine komatiite flows in the northern Agnew–Wiluna Greenstone Belt. The morphologies of olivine and pyroxene crystals in the A zones of the flows can be seen very clearly.

Volcanic architecture of komatiite sequences

This field excursion serves to illustrate that in Western Australian Archaean greenstone belts, komatiite flow fields and component flow units display a wide diversity of rock types, as defined by the proportion and habit of olivine crystals. This section of this excursion guidebook is sourced from Hill (in press). Diagnostic lithological profiles and along-strike changes in profile character exhibited by komatiite sequences provide the basis for distinctive volcanic architectures or facies variants (Hill et al., 1995) described below.

Flood flow facies

Flood flow facies contain extensive regional sheet-like, layered olivine-adcumulate bodies and layered ultramafic–gabbro sequences up to 3500 km^2 in areal extent (e.g. Walter Williams Formation in the Norseman–Wiluna Greenstone Belt; Forrestania Greenstone Belt, Western Australia; Hill et al., 1995; Perring et al., 1995; Fig. 4).

Large sinuous trough-shaped bodies of predominantly layered olivine adcumulate up to 1 km thick and 2 km wide, often grade upward into fractionated sequences including pyroxenites and gabbros. They are flanked by regionally persistent sequences up to 200 m thick, comprising many thinner flow units of predominantly layered olivine orthocumulate with rare spinifex-textured crusts. This volcanic architecture is exemplified by komatiite sequences in the Agnew–Wiluna Greenstone Belt, (Fig. 20), which extend for over 130 km (Dowling and Hill, 1990, 1993) and by komatiite sequences in the Forrestania Greenstone Belt (Perring et al., 1995).

Compound flow facies

Compound flow facies are linear trough-shaped features more than 10 km long, up to 200 m wide and up to 150 m thick, comprising olivine orthocumulates and mesocumulates, with spinifex-textured flow tops. They are flanked by a distinct but complex sequence of thinner (50 cm – 100 m) areally restricted flow lobes, including layered spinifex-textured and unlayered varieties. The basal Silver Lake Member at Kambalda exhibits this style of volcanic architecture (described by Cowden and Roberts, 1990; Fig. 40).

Ponded flow facies

Ponded flow facies are extensive layered and fractionated komatiite units that include pyroxene cumulates and pyroxene–plagioclase cumulates (e.g. in the Kurrajong area, Walter Williams Formation; Gole et al., 1990; Hill et al., 1995; Fig. 12), and upper ponded zones of flood flow facies sheet flows, such as Mount Keith (Dowling and Hill, 1993).

Komatiite volcanology

Detailed field mapping in Western Australia (Hill et al., 1990, 1995) revealed that komatiites occupy vast lava flow fields, possibly larger than those observed in more recent basaltic provinces. This is confirmed by age dating (Nelson, 1997), which showed that in Western Australia, komatiites from Kambalda to Perseverance and beyond, over a strike length of 400 km, are the same age within the precision of the U–Pb zircon sensitive high-resolution ion microprobe (SHRIMP) method.

Since the greater proportion of komatiite lithologies consists of various types of olivine cumulates, most of which are interpreted to have accumulated from flowing or stationary lava at low to moderate cooling rates, any eruptive model for the emplacement of the vast komatiite flow fields that incorporate all or some of the facies variants described above, should involve thermally efficient lava-transport processes, such as tube-fed lava delivery, a preponderance of laminar flow, and emplacement under an effective insulating crust.

The basalt connection

Pioneering work by Hon et al. (1994) and Self et al. (1996, 1997) has provided a comprehensive understanding of the process of emplacement of regionally extensive pahoehoe flow fields on shallow slopes, in Hawaii and in continental flood-basalt terrains. The following schematic illustrations and discussions of the main features of the inflationary processes are of particular relevance to komatiite volcanology and are sourced from Hill (in press).

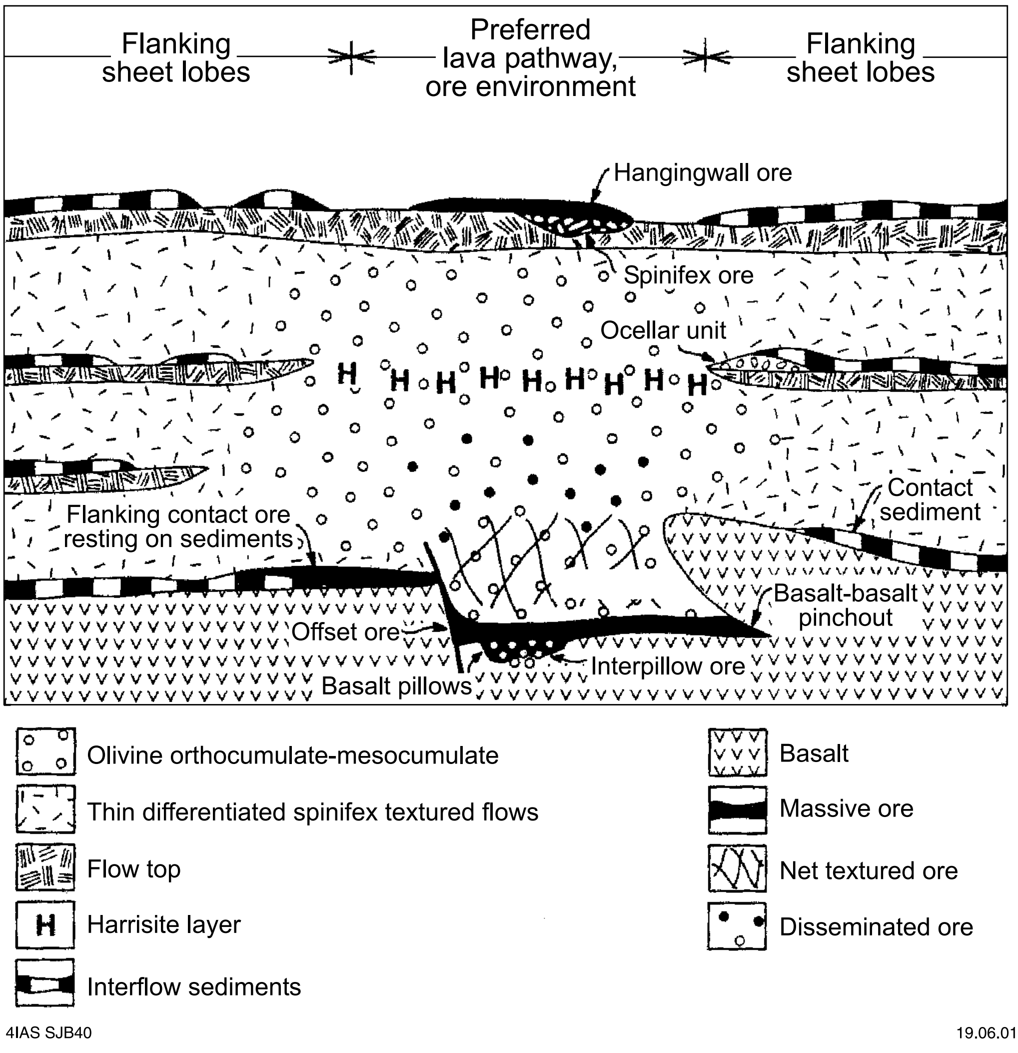

Figure 40. Diagrammatic cross section of compound flow facies komatiites, showing the relationship between the lava pathway and flanking sheet lobes, and the nature and distribution of sulfide mineralization in the Silver Lake Member of the Kambalda Komatiite Formation (after Cowden and Roberts, 1990)

Figure 41 illustrates the advance and inflation of lava flowing on sufficient slope to focus flow from left to right, with limited radial spreading. A sheet flow lobe forms when hot lava is erupted from a suitable source, and it propagates with low aspect ratio beneath a rapidly forming thin plastic and later brittle aphanitic crust. As the crust thickens it develops sufficient strength to slow lobe advance and retain incoming lava. The lava lobe continues to cool through its upper surface, and eventually accretes cool viscous lava to the overlying brittle crust. The progressively thickening composite viscoelastic and brittle crust is moved upward by the force of expansion of the lava core induced by lava injection into the lobe. This is the process of inflation and the lava lobe thickens by the process of endogenous growth. As the viscous crustal accretions are progressively moved upward, they cool and eventually assume brittle behaviour. The viscoelastic component of the crust is induced by directional cooling through the upper surface and it reflects the rheological behaviour of lava within the melting range (Hon et al., 1994). This upper layer plays an increasingly significant role in the ability of the composite crust to eventually hold back the lava lobe advance and retain incoming lava thereby causing inflation. Initially the viscoelastic crust is thin, allowing for rapid inflation and as the composite crust and its viscoelastic component thicken, inflation slows and eventually compensates only for continued crustal growth (Hon et al., 1994). A thin basal brittle layer also forms when the hot flowing lava first contacts the cool substrate; however, it is inhibited from thickening rapidly by the hot continuously flowing overlying lava.

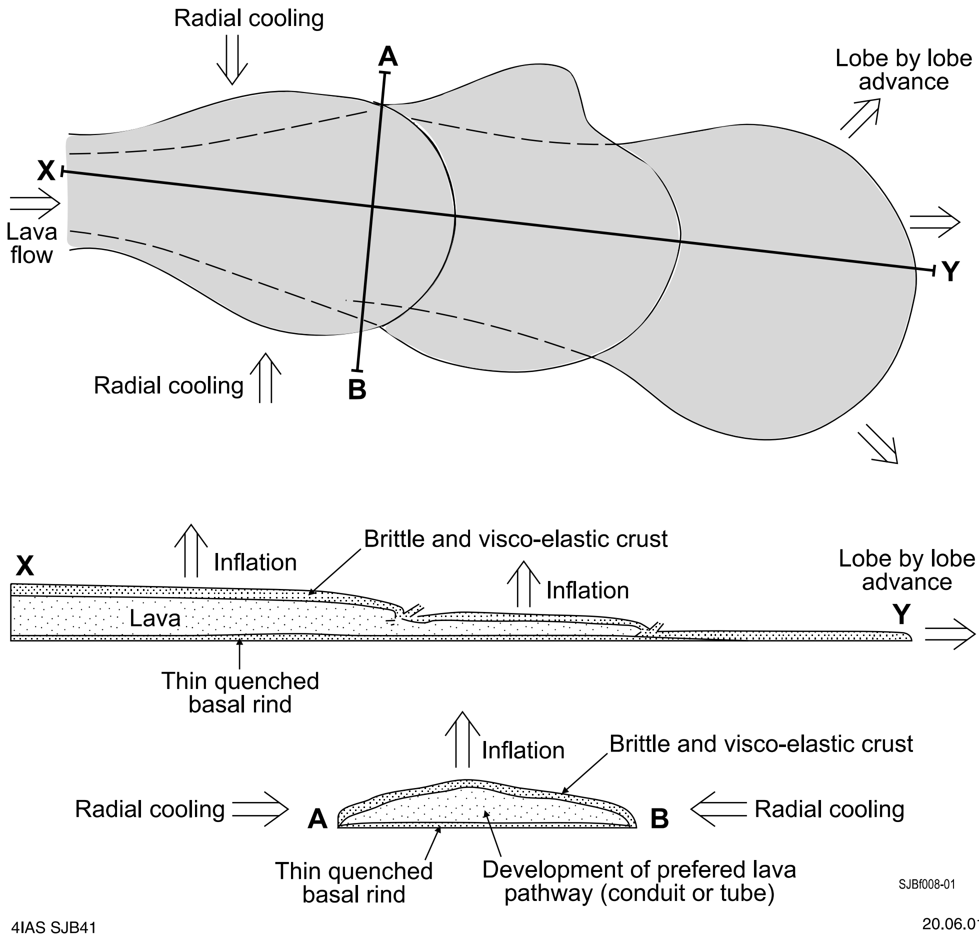

Figure 41. Schematic representation on plan and cross section of lobe-by-lobe advance and lobe inflation, of a basalt flow field (after Hill, in press)

Eventually, the hydrostatic pressure induced by the growing lava core may exceed the withholding strength of the composite crust at the flow front, and a new lava lobe breaks out. The process of flow advance, inflation, and endogenous growth is thus repeated. Longitudinal and cross sections illustrating the inflationary processes are also depicted in Figure 42. The thickening upper crust acts as an effective insulating layer, allowing considerable lava flow-through at very low cooling rates (e.g. about 0.1 %/km, Thordarson and Self, 1998). The rate of flow advance varies from almost continuous to slow and episodic, depending on such factors as lava flux, lava viscosity, palaeoslope, and surface topography.

On shallow slopes, basalt sheet lobes reach 100s to 1000s of metres in areal extent and exhibit considerable radial dimension; however, each lobe may be the product of several coalesced smaller breakouts. As the flow continues to advance downslope, as a series of interconnected lobes, the earlier inflated lobes begin to suffer radial cooling and progressive inward solidification. This forces lava flux to concentrate in the centre of the flow, forming preferred lava pathways that eventually become lava tubes (Fig. 42). Tube formation via this process provides for continuous efficient transport of lava to the advancing flow front with minimal temperature loss. Observations of active lava tubes in Hawaii by Kauahikaua et al. (1998) have revealed that the continuous passage of lava over months to years results in substantial thermomechanical erosion of basalt at the base of the tubes.

Continued uplift and fracture of the accreted tube roof and its monoclinal edge permits extensive episodic breakouts of lava from the conduit, which form lobes that inflate and advance as separate flows.

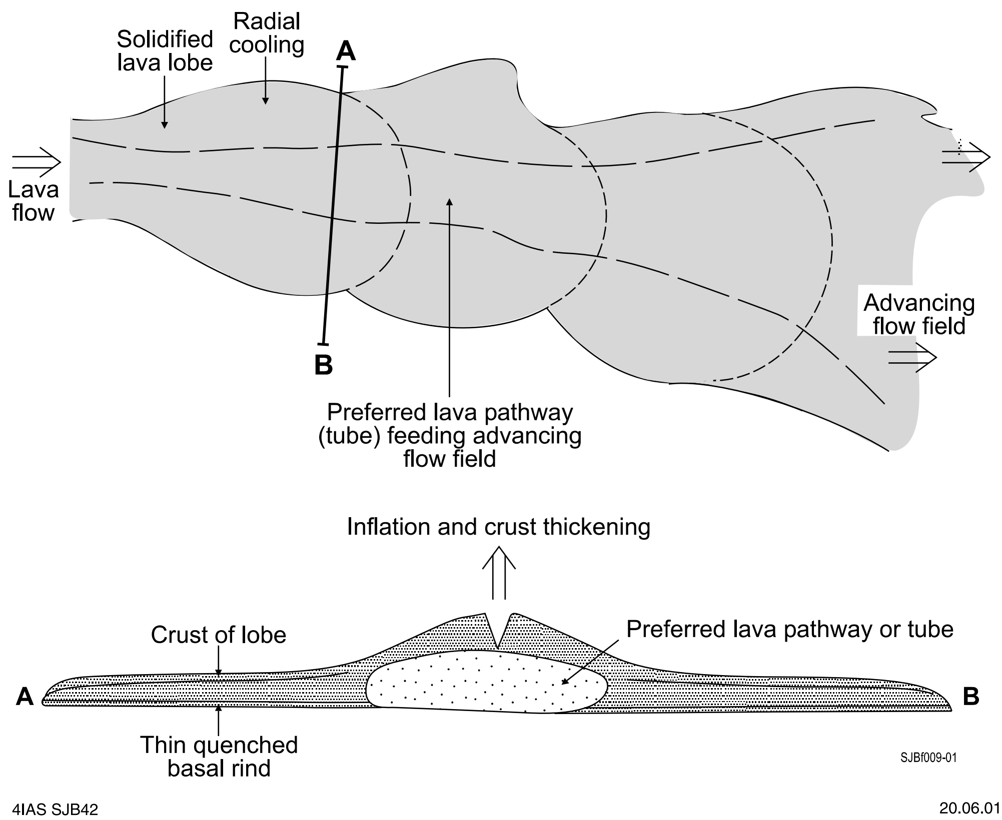

Figure 42. Schematic plan and cross section of a basalt flow field, showing lobe-by-lobe advance and development of a preferred lava pathway or tube via radial cooling, (after Hill, in press)

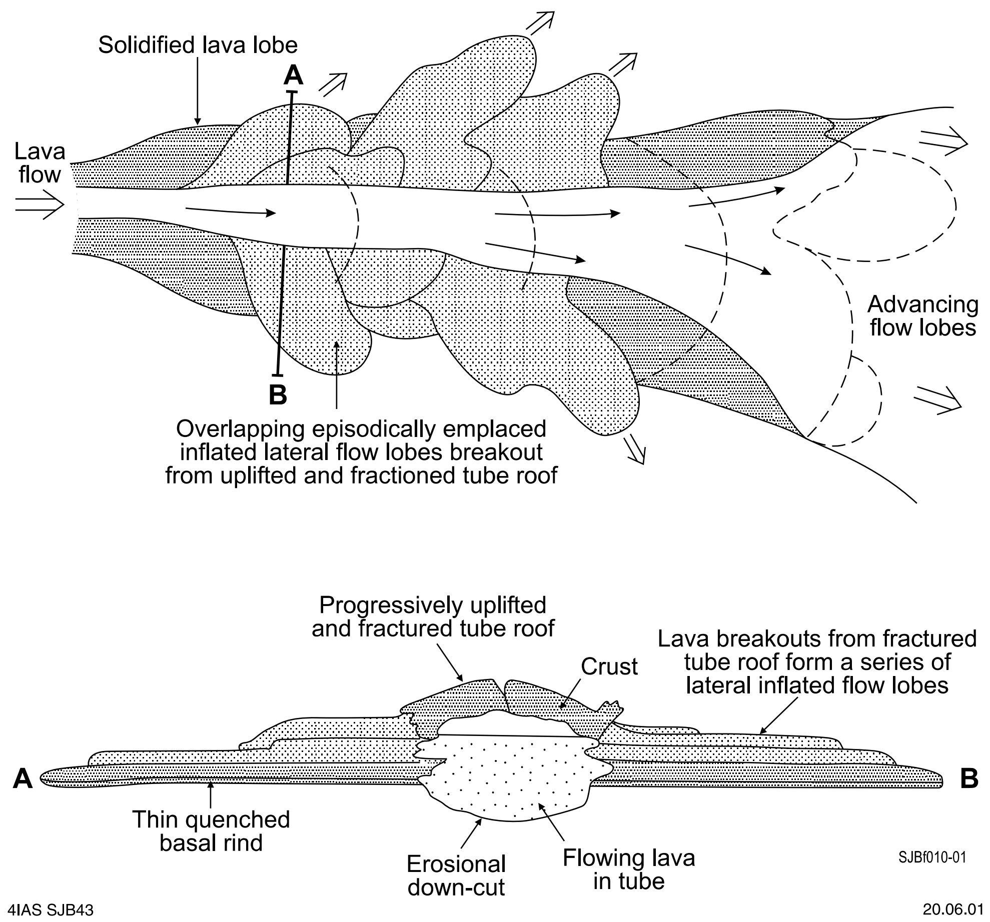

Figure 43. Schematic plan and cross section of a basalt flow field, showing uplift and fracture of a tube roof allowing breakout of flanking inflated sheet flow lobes, and substrate erosion in a long-lived lava tube (after Hill, in press)

The volcanic architecture resulting from this emplacement process is that of a parent lava conduit or conduits flanked by a broad complex stratigraphic sequence of episodically emplaced, inflated, lateral lobes and subsidiary flows, fed by their own distributary tubes (Fig. 43).

Hon et al. (1994) speculated that inflation, endogenous growth, and insulated lava pathways also played a major role in the emplacement of large submarine flow fields, which commonly exhibit similar volcanic architecture.

Inflationary komatiite flow fields

The critical and relevant factors of this model for vast basaltic flow-field emplacement are: persistent long-lived lava flow and its predominance over lava-supply rate as the controlling factor influencing aerial dimensions of flow fields; the inflation of sheet flow lobes under composite viscoelastic crusts; endogenous growth; and the development of preferred lava pathways or tubes. These preferred lava pathways or tubes serve to focus lava flow, and provide thermally efficient rapid delivery of lava to continuously slowly advancing flow fronts, and act as loci for extensive thermal erosion.

Despite differences in density, viscosity, chemical composition and temperature between basaltic and komatiitic lavas, the inflationary lava emplacement process provides an elegant explanation for the emplacement of vast komatiite flow fields. The pattern of thermal regimes required for the development of recurring lithological field relationships, facies variations, and internal structures of flow units, identified in komatiite sequences through detailed mapping (Hill et al., 1990, 1995; Dowling and Hill, 1990, 1993; Perring et al., 1995; Gole et al., 1990 and others) and described earlier, are consistent with those required by the volcanic architecture of their basaltic analogues. Likewise, inflation, endogenous growth, and tube delivery are processes supporting the nature, aerial extent, thickness, and lithological profiles documented for komatiite flows and component flow lobes in the Archaean greenstone belts of Western Australia.

Hill et al. (1995), Hill and Perring (1996), and Hill (1999, in press) applied the dynamic inflationary model to explain the development of each of the komatiite facies identified to date and described earlier, and showed how the different facies could relate to one another as components of a single sustained eruption that produced a vast komatiite flow field (Fig. 44).

Flood flow facies

Flood flow facies is formed by long-lived unconstrained continuous and rapid sheet flow proximal to the eruptive vent, involving constant switching of embryonic lava pathways, under a continually forming, fracturing, and re-forming insulating crust. It is interpreted as the environment where thermal conditions are suitable for the accumulation of vast sheets of olivine adcumulate after initial nucleation and crystal growth on the floor, or basal quenched rind of the flow. Episodic changes in lava flux, and direction of preferred flow result in complex internal layering within the adcumulate sheets. These bodies are flanked by time-equivalent olivine orthocumulate-dominated

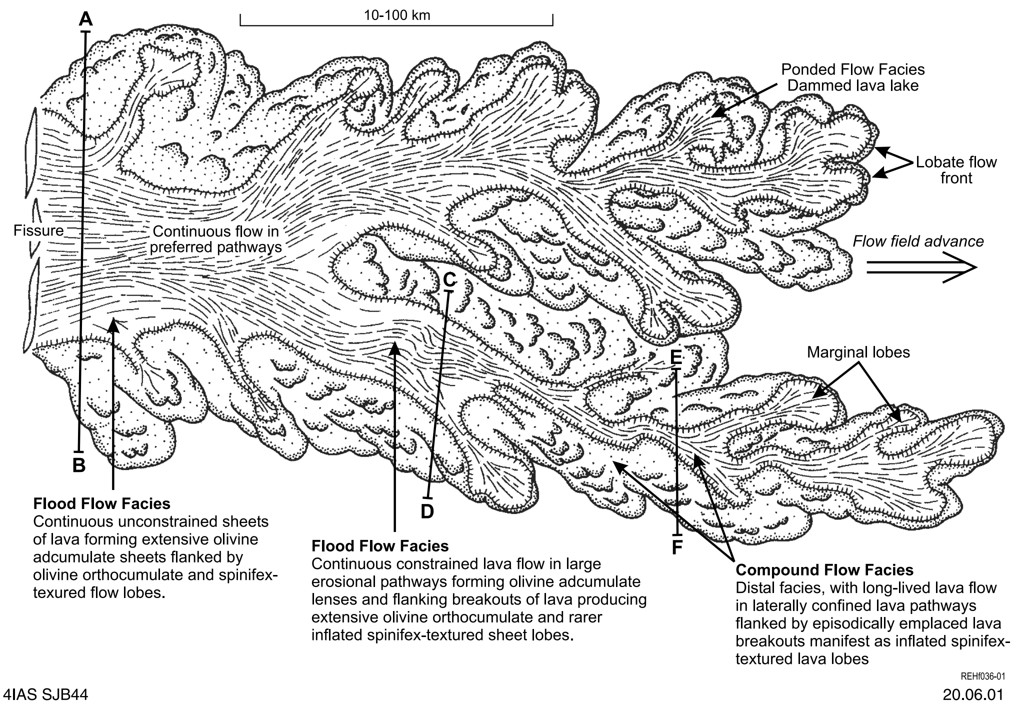

Figure 44. Schematic depiction of a vast inflationary komatiite flow field, showing how various facies may relate to one another during one long-lived continuous eruption

flow units and distal spinifex-textured flow lobes, which form and grow as inflated marginal lobes, and crystallize as a result of thermal edge-effects and slowed radial propagation (Figs 44 and 45). The adcumulate sheets are capped by a thick crust and an underlying variably fractionated orthocumulate–gabbro sequence, which formed from ponded lava when eruption ceased.

The progressive evolution of broad preferred lava pathways and ultimately lava tubes, in the liquid cores of aerially extensive interconnected sheet lobes as the flow field propagates down slope, is accompanied by the initial sedimentation, crystallization, and accumulation of layered olivine orthocumulate-dominated flow units. The preferred lava pathways become the loci of additional flux of hot lava, under the influence of radial cooling, and flow under a progressively thickening and uplifted composite aphanitic and spinifex-textured flow crust. The high lava flux and turbulent flow, and inherent instability of the uplifted crust, result in almost continuous lateral lava breakouts, producing large extensively coalesced compound flows, forming a complex flanking stratigraphy composed of layered olivine-orthocumulate-rich flow units (Figs 44 and 46). The almost continuous sequential emplacement of lateral sheet flows, and therefore lack of significant inflation, is evidenced by only occasional development of composite spinifex-textured and aphanitic flow crusts in terrain exhibiting this volcanic architecture.

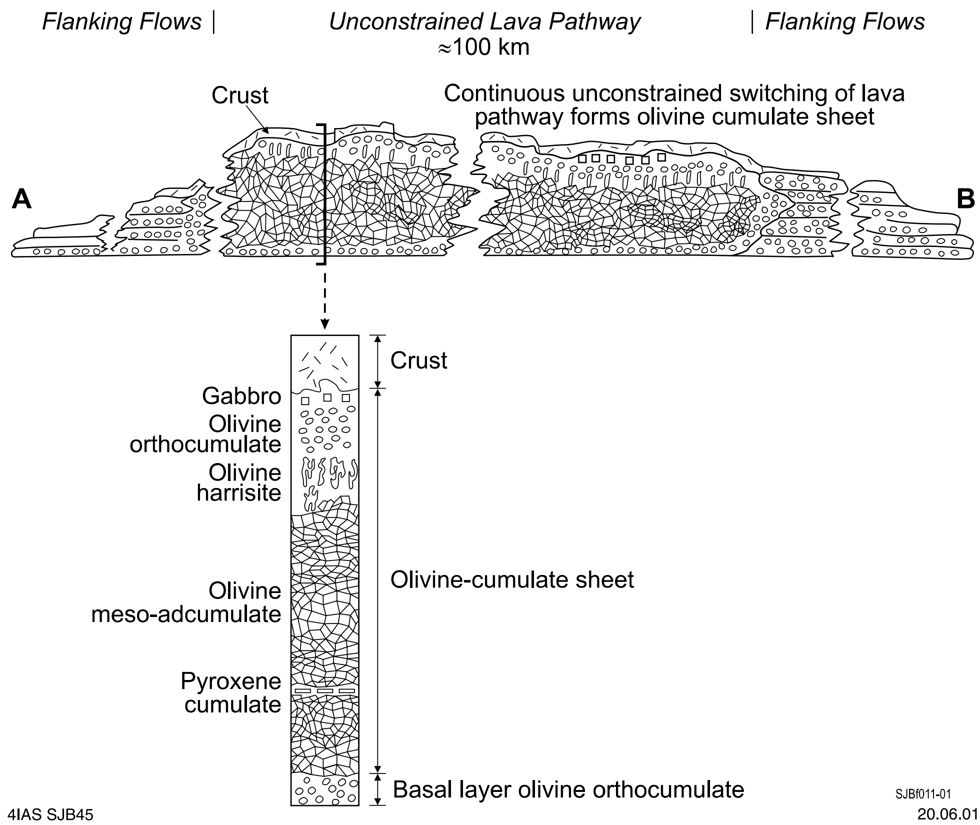

Figure 45. Schematic cross section A–B (from Fig. 44) of flood flow facies I, showing olivine adcumulate sheets flanked by sheets of olivine orthocumulates and spinifex-textured flows, and a typical lithological profile through an olivine adcumulate sheet (after Hill, in press)

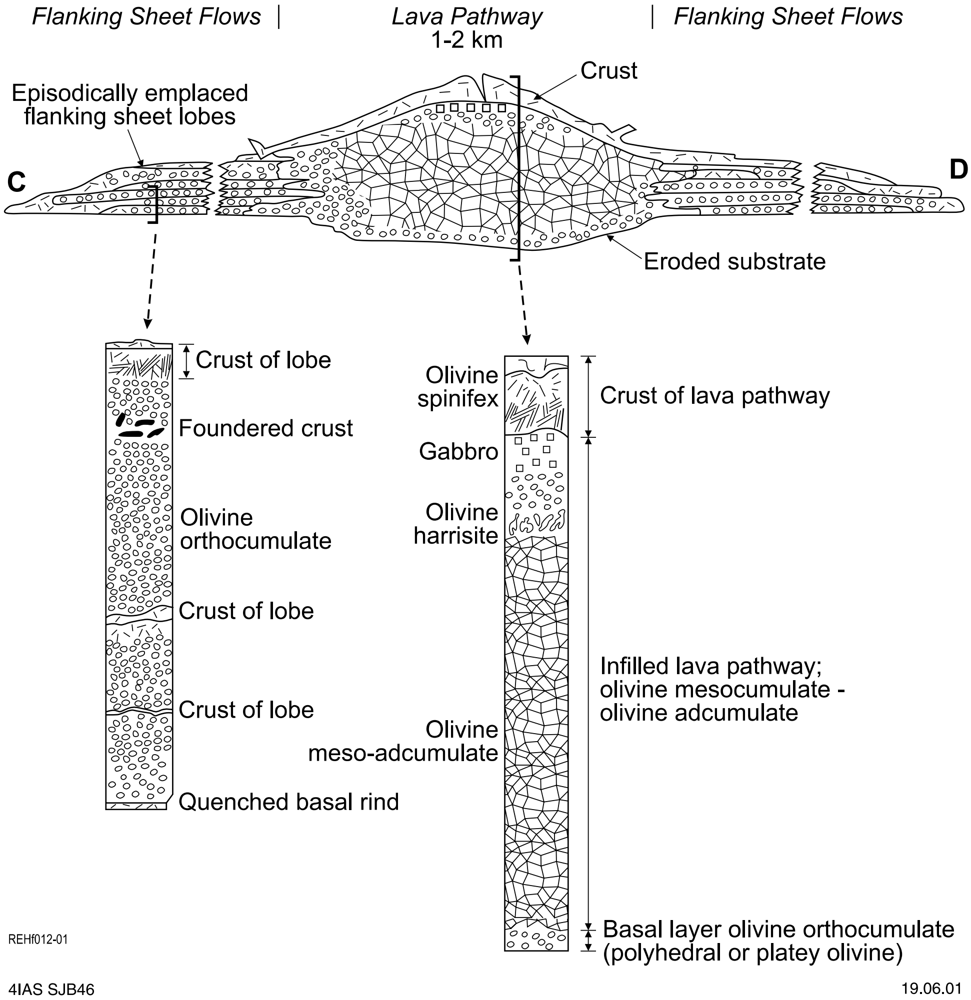

Figure 46. Schematic cross section C–D (from Fig. 44) of lithological associations in flood flow facies II, showing trough-shaped bodies of olivine adcumulate and flanking olivine orthocumulate-rich sheet lobes; also showing representative lithological profiles (after Hill, in press)

The continuous passage of hot lava initiates extensive thermal erosion of the substrate, resulting in the formation of deep, broad thermal erosion troughs at the base of the lava pathways. Heterogeneous nucleation and growth of olivine, on the walls and floor of the erosional pathways as the lava continues to flow at temperatures near the lava liquidus, eventually gives rise to layered olivine-adcumulate bodies resembling long sinuous ribbons with lenticular cross section. These large infilled lava pathways are also characterized by the crystallization and fractionation of upper olivine-orthocumulate gabbro sequences from ponded lava after the eruption ceases.

Compound flow facies

The thermally insulated major lava conduits provide efficient delivery of hot komatiite lava to the distal frontal lobes of the advancing flow fields (Fig. 44). Figure 47 schematically illustrates application of the inflationary model to the episodic propagation of the distal environment (Fig. 44), and in particular reveals how the classic Munro Township spinifex-textured flow unit can form from an initial low aspect-ratio sheet lobe, through the process of inflation and endogenous growth, rather than via

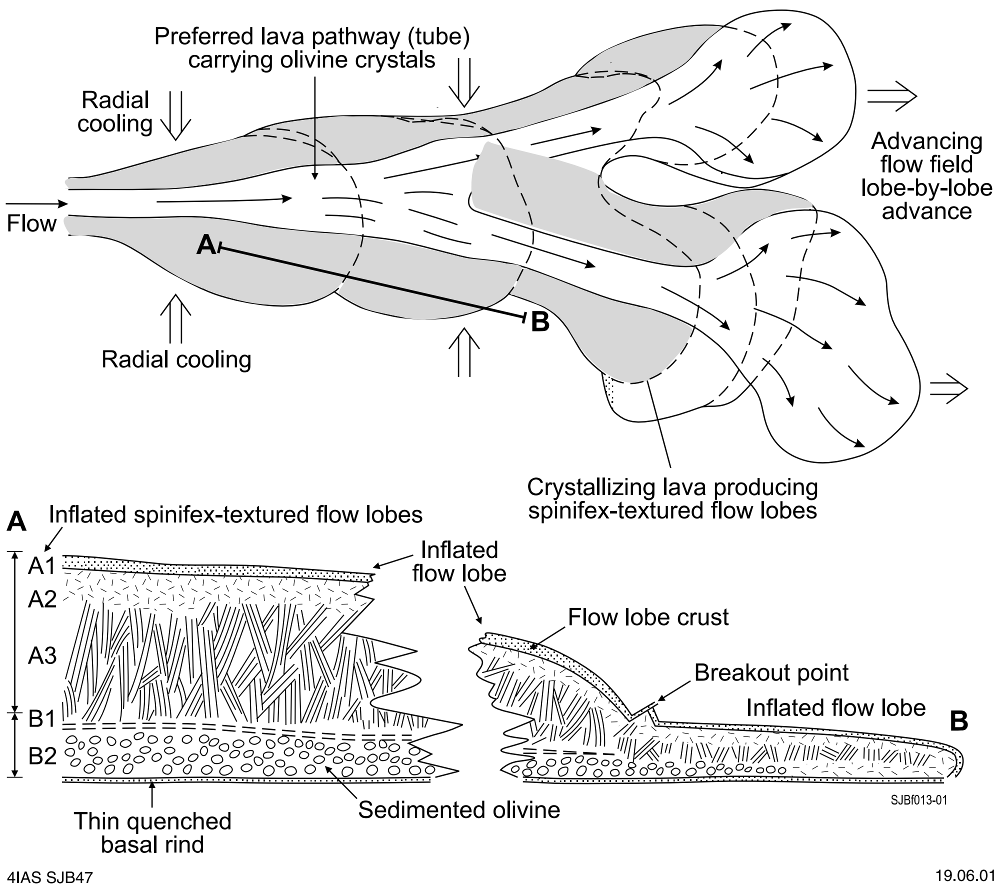

Figure 47. Schematic cross section A–B (from Fig. 44) of compound flow facies, representing lobe-by-lobe advance of komatiite flow field (distal environment), and showing the development of a lava pathway and inflation of successive interconnected lobes to produce a classic spinifex-textured profile (after Hill, in press)

the crystallization of ponded lava proposed earlier by Arndt (1986) and Huppert et al. (1984).

It is proposed that a thin brittle crust develops at the upper surface of a thin komatiite sheet lobe soon after breakout and flow. In the same manner as basalt sheet lobes, this is followed soon after by the formation of an underlying sub-liquidus viscoelastic layer whose thickness reflects the thermal gradient from liquidus to solidus of the lava. The composite crust eventually holds back lobe advance, retains incoming lava, and the lobe begins to inflate. Continuous cooling through the lobe roof triggers endogenous growth and the progressive formation of the classic spinifex-textured flow unit profile. Initially, the brittle aphanitic crust is underplated by A2 random spinifex via homogeneous nucleation and random growth of olivine plates. As inflation, endogenous growth, and thickening of the viscoelastic layer continue, the A2 spinifex zone moves upward into the zone of brittle behaviour, and conditions preferentially favour the continued growth of olivine plates oriented perpendicular to the lobe crust (A3 zone). It is proposed that the aligned A3 olivine plates crystallize near the base of the viscoelastic layer (i.e. near the liquidus isotherm) and lengthen as the crystals are progressively uplifted away from their crystallization plane (i.e. via the process of inflation and endogenous growth; Figs 48 and 49).

Orientation of the long sheaves of A3 olivine parallel to the highest direction of heat loss through the lobe crust is commensurate with the C axis being the direction of highest heat conductivity in olivine plates (Shore and Fowler, 1999). Although A3

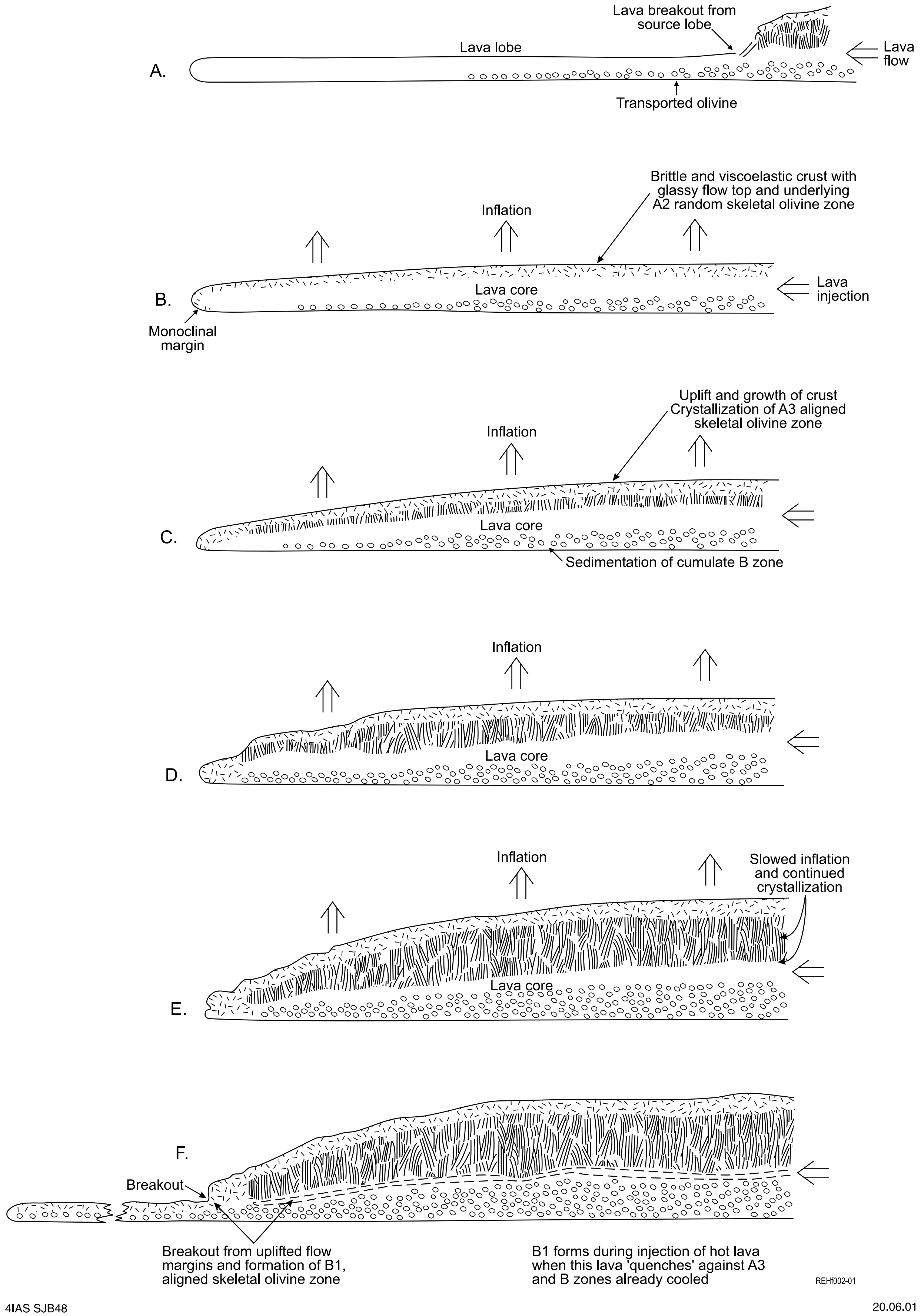

Figure 48. Schematic diagram showing the model for the proposed progressive formation of a classic spinifex-textured flow unit in the process of lobe emplacement inflation and breakout (after Hill, in press)

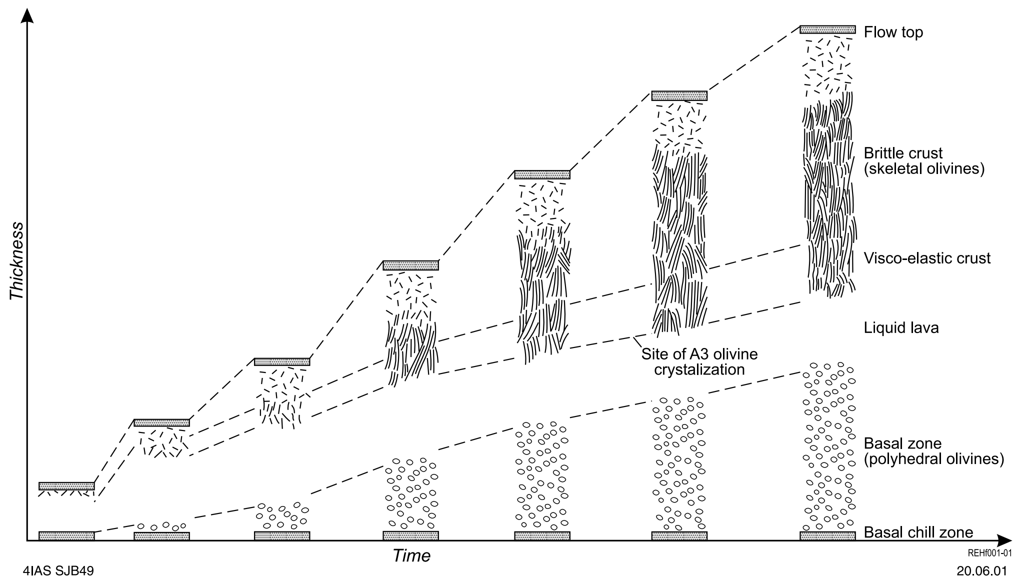

Figure 49. Schematic representation of inflation and endogenous growth, showing the progressive formation and thickening of a vertical profile through an inflating komatiite lava lobe (after Hill, in press)

olivines would continue to crystallize and grow into the lava core of the flow after inflation ceased, the length of the A3 zone is probably a crude measure of the extent of inflation of the komatiite lobe.

It has been commonly agreed that komatiite lavas were erupted free of xenocrystic olivines; however, the presence of graded bedding in olivine orthocumulate flow lobes, and bimodal polyhedral–platey olivine orthocumulates in sheeted flow units and in the lower zone of spinifex-textured flow units, presents evidence for sedimentation of transported olivine crystals rather than in-place crystallization from parental lava.

Arndt (1986) proposed that the olivine-cumulate B zone of spinifex-textured flows forms by direct crystallization of olivines within the lower zone of ponded flows where rates of heat loss through the substrate are low. The inflationary-flow model allows for the B zone being formed via the progressive gravitational accumulation of olivine from lava being injected into the static flow lobe during inflation. Spinifex-textured flow units only 15 cm thick have been observed to exhibit well-developed orthocumulate textured B zones, in addition to A2 and A3 spinifex zones and it is difficult to believe a gradient in cooling rates across such thin flows would be sufficient to allow development of this textural layering.

The narrow B1 zone of stubby olivine plates, aligned in lobe cross-section and random in planar section in the inflationary model, is formed when a breakout occurs at the lobe front and new lava that enters the lobe quenches against the relatively cool overlying A3 and underlying B2 zones. The presence of a B1 zone is therefore proposed as evidence of lava breakout prior to lobe solidification (Fig. 48; i.e. episodic propagation).

Preferred pathways eventually develop within the interconnected distal sheet flows, and intermittent uplift and fracture of the pathway crust provides the loci for episodic breakout of marginal lobes, which inflate, cool, and crystallize proximal to their source to produce relatively thin, often poorly developed, spinifex-textured flow units (Fig. 50).

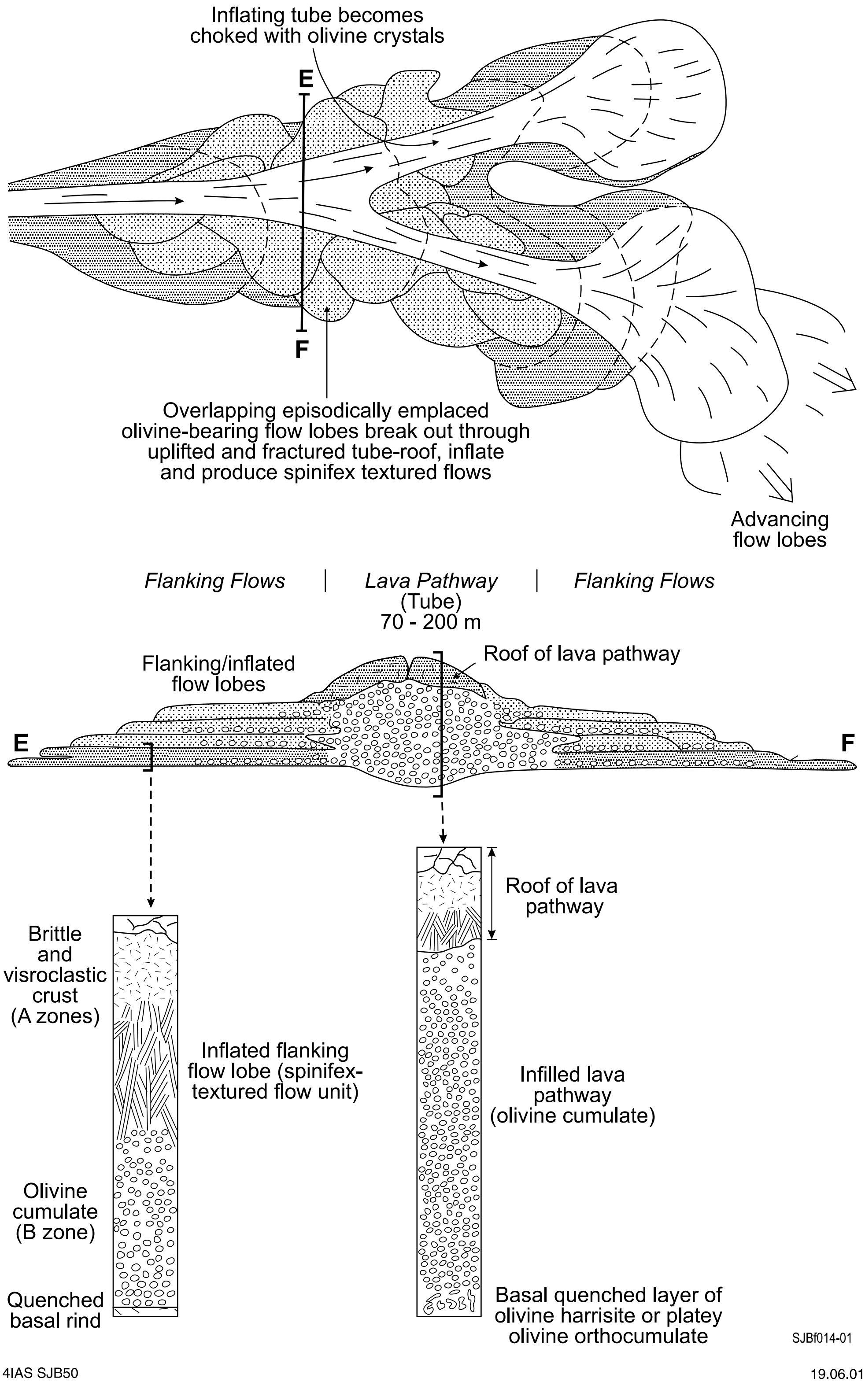

Figure 50. Schematic plan and cross section E–F (from Fig. 44) showing lithological associations for compound flow facies, and depicting lobe-by-lobe advance and development of a mature lava pathway and flanking breakouts in an advancing komatiite flow field. Also shown are lithological profiles of infilled lava pathways and flanking spinifex-textured lobes (after Hill, in press)

A high proportion of cumulus or sedimented olivine in the pathways is due to accretion of olivine from flowing lava and, possibly, the stagnation of olivine-choked lava as the conduits become blocked and flow ceases. Thin spinifex and harrisitic zones crystallize in the conduits under newly formed crust during periods of lava stagnation, or significant drop in lava flux (Fig. 50).

Persistent flow of hot lava through the preferred pathways in the distal environment is believed to thermomechanically erode and assimilate substrate rocks in a similar manner to the lavas in those conduits delivering much higher lava flux. High heats of fusion of olivine and the large crystallization interval for komatiite lavas combine to underpin their ability to produce significant substrate erosion (Huppert et al., 1984), although the amount of erosion depends largely on the nature of the substrate (Williams et al., 1998).

Consequences of the inflationary model

There are important geological and geochemical consequences of the inflationary emplacement model. Episodically emplaced lava breakouts flanking lava conduits record the nature and composition of lava that flowed through the conduit over a long period of flow field emplacement. These flanking flow units commonly, therefore, have no genetic links to lithologies now occupying the pathway.

The preferred lava pathways contain greater thickness of olivine cumulates, with commonly higher packing densities than the flanking lobes and contain fewer spinifex-textured horizons or flow crusts. Therefore rocks occupying the lava pathways consistently exhibit higher individual and average whole-rock MgO and Ni contents, and lower concentrations of incompatible elements such as Al, Ti, Zr and light rare-earth elements (i.e. lava pathways can be distinguished from their associated flanking flows using compatible/incompatible element ratios, e.g. Mg/Al, Ni/Al).

Supracrustal contamination of lava that has eroded and assimilated substrate lithologies during its sustained passage through erosional lava pathways, produces identifiable signatures in major-, minor-, and trace-element concentrations in the flanking lobes, which are breakouts from the inflated lava pathways. These contamination signatures are not necessarily identifiable in lithologies that now occupy the lava pathway. Diagnostic signatures are enrichment in light rare-earth elements and incompatible element ratios such as Zr/Ti. Contamination of komatiite lava flowing through long-lived conduits, by the thermomechanical erosion and assimilation of felsic tuff and banded iron-formation in the Forrestania Greenstone Belt, Western Australia, has been sufficient to change major- and trace-element chemistry of the fractionated lava to the point where orthopyroxene has accumulated at the floors of lava pathways (Perring et al., 1996).

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