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Excursion Guidebook

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Excursion 1

Greenstone Terranes and the Eastern Goldfields Seismic Traverse

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This excursion examines aspects of the regional stratigraphy and structure of late Archaean greenstones in the southern part of the Eastern Goldfields Province.

Swager & others (1990) divided the greenstones in the southern Eastern Goldfields into several tectono-stratigraphic terranes bounded by major shear zones. Some terranes can be divided into domains separated by shear zones across which some elements of the regional stratigraphy and/or structure cannot be traced (Fig. 1).

The best-defined of these terranes, the Kalgoorlie Terrane, is characterised by a distinctive volcano-sedimentary sequence (approximately 2700 Ma; Claoue-Long & others, 1988) containing lower basalt, komatiite, variably developed upper basalt and a poorly exposed felsic (acid to intermediate) volcanic and volcaniclastic rock unit, locally overlain by coarse clastic basins. Komatiite forms a regional marker that has been studied in detail by Hill & others (1987).

To the west, the Ida Fault forms the boundary between the Kalgoorlie and Barlee Terranes (Fig. 1). The latter consists of numerous elongate greenstone belts surrounded by granite and granite gneiss. Its regional stratigraphy comprises basal quartzite (including local quartz pebble conglomerate and large-scale cross-bedding) overlain by basalt with interleaved komatiite and banded iron formation (BIF). Near the top, basalt is interleaved with metasedimentary rocks and felsic volcanic complexes. One large felsic complex unconformably overlying this sequence has a U-Pb zircon age of circa 2735 Ma (Pidgeon & Wilde, 1990), suggesting the Barlee Terrane greenstones are some 20 Ma older than those in the Kalgoorlie Terrane.

Several fault- or shear-bounded greenstone domains or terranes can be distinguished to the east of the Kalgoorlie Terrane (Fig. 1). Little or no reliable geochronology is available for these greenstones.

The Gindalbie Terrane consists of a lower unit of felsic volcanic rocks (rhyolite-dacite, plus some basalt-andesite) overlain by a strongly deformed ultramafic-mafic sequence (Ahmat, in prep. a). The contact between the felsic and mafic sequences is interpreted as an early regional layer-parallel fault, but it is not known whether it is an extensional or contractional fault. The felsic rocks may predate the Kalgoorlie Terrane. The internally folded and repeated ultramafic rocks are interpreted as komatiites with characteristics in common with those in the Kalgoorlie Terrane (Ahmat, in prep. a), and may be coeval.

The boundary of the Gindalbie Terrane with the Jubilee domain to the east is the Emu Fault which is largely hidden under a polymictic conglomerate (Penny Dam Conglomerate). Southwards along strike, this conglomerate appears transitional to an extensive greywacke sequence with interbedded BIF (Mount Belches beds). Conglomerates in the southern Goldfields occupy synformal or fault-bounded basinal structures overlying or adjacent to major boundary faults. The conglomerates, the youngest rocks, are foliated, metamorphosed and locally altered and mineralized. They are interpreted to have formed after early thrusting and regional doming, because they overlie D1 thrust faults lo-

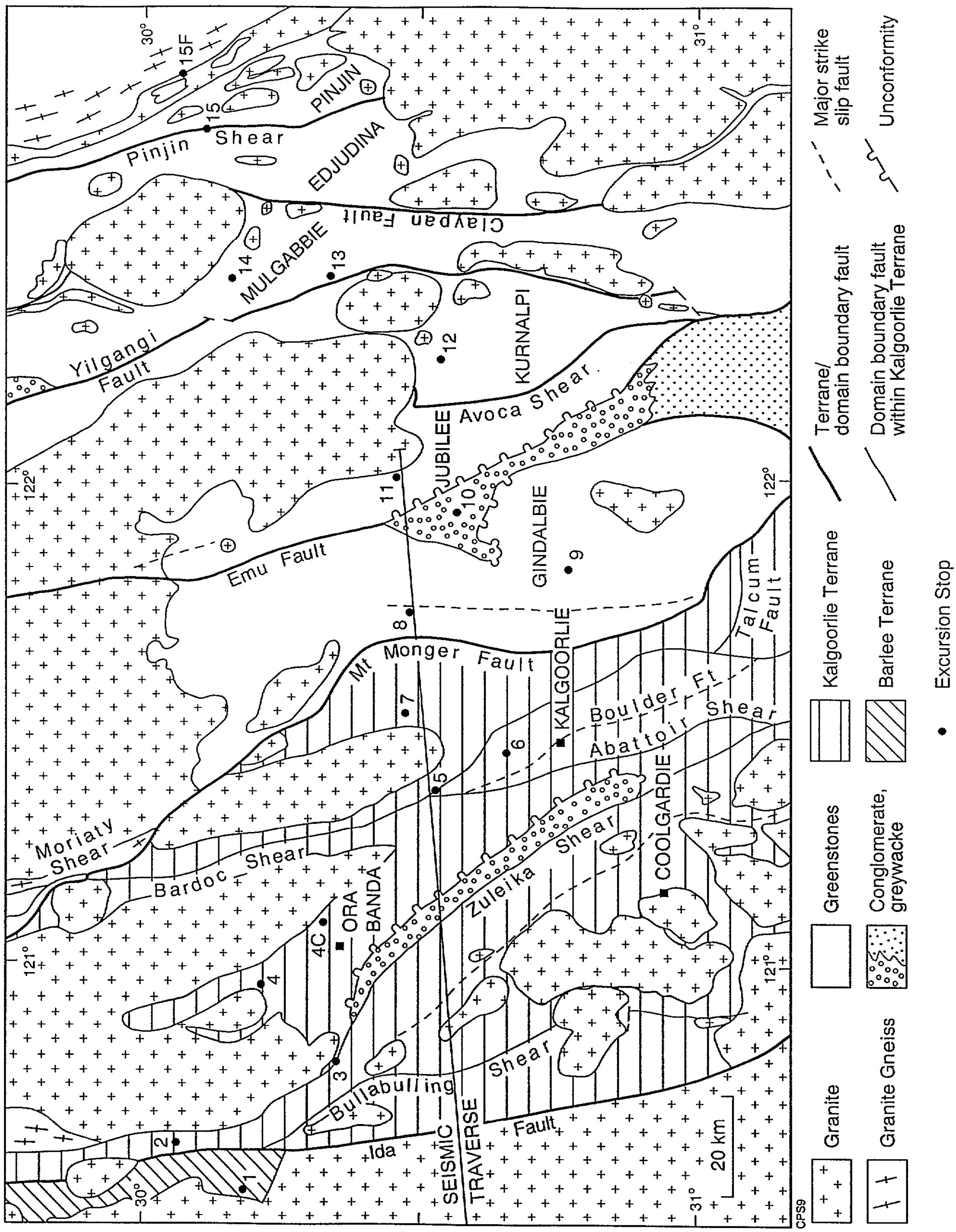

Fig. 1. Regional overview of the granite-greenstones of the central southern Eastern Goldfields Province. Major shear zones and faults separate various terranes and domains; the Kalgoorlie and Barlee terranes are highlighted. Approximate positions of the AGSO 1991 seismic traverse and excursion localities are shown.

cally. They may have been deposited during regional extension (inferred from seismic reflection studies: see below) and/or subsequent regional shortening.

The Jubilee domain is characterised by a homoclinal, west-younging sequence of interleaved basalt, komatiite and felsic volcanic rocks. At least four regionally discontinuous komatiite layers occur at different levels; they may be structural repeats of the same flow unit, or, alternatively, reflect more than one phase of komatiite volcanism.

The boundary of the Jubilee domain with the Kurnalpi domain to the east is the poorly exposed Avoca Shear, which may appear as a major, shallow west-dipping shear in seismic reflection data (Goleby & others, 1993).

Further east, two domains, provisionally called Kurnalpi and Mulgabbie, are separated by a regional discontinuity called the Yilgangi Fault. To the north, the Yilgangi Fault is buried under a polymictic conglomerate in a synformal setting similar to that of the Penny Dam Conglomerate. The Yilgangi Fault is the southern continuation of the Kilkenny Fault (or Keith–Kilkenny lineament of Williams & others, 1976), and may be an important terrane boundary. In the area shown in Fig. 1, the Kurnalpi and Mulgabbie domains contain similar rock types in similar tectono-stratigraphic packages, although the Mulgabbie domain contains substantial volumes of intermediate rocks. On a regional scale, both domains contain repeated mafic-to-felsic volcanic sequences, explained by Williams (1976) in terms of volcanic cycles, and show substantial truncations of structures and stratigraphy against the Yilgangi Fault.

The Edjudina domain is characterised by prominent, continuous BIFs with metasedimentary rocks intruded by large volumes of dolerite-gabbro, and by laterally highly variable mafic, intermediate and felsic volcanic rocks, including several distinct felsic complexes.

The easternmost domain, Pinjin (Fig. 1), contains medium to high grade amphibolite with interleaved intermediate and felsic schist, BIF and some tremolite schist after peridotite. It is in contact with migmatitic banded granite gneiss to the east. The Pinjin Shear separates the low-medium grade Edjudina domain from the medium-high grade schists of the Pinjin domain. Schists within the Pinjin Shear contain down-dip mineral lineations with west-side-down movement indicators, suggesting relatively late stage (syn- to post-peak metamorphism?) uplift.

The deformation history in the Kalgoorlie Terrane (Archibald & others, 1981; Swager & others, 1990) includes D1 thrusting and recumbent folding, and D2 upright folding and reverse faulting due to east-northeast–west-southwest shortening. More localized D3 north-northwest trending sinistral shears and D4 north-northeast trending dextral faults can be resolved within a progressive D2 shortening regime. Structural studies elsewhere in the Goldfields have recognized D1 and D2 as regional events, and have also drawn attention to an early, extensional deformation phase (DE), largely restricted to high strain granite gneiss-greenstone contacts with north-south stretching lineations (Hammond & Nisbet, 1992; Williams & Currie, 1993; Williams & Whitaker, 1993). These contacts are exposed in regional high grade domes, akin to metamorphic core complexes. Witt (1992) argued that, in the Melita area, the DE event post-dates D1 thrusting.

Three stages of granitoid intrusion (pre- to syn-D2, syn-D2 and late tectonic) can be recognized on structural criteria (Witt & Swager, 1989). Campbell & Hill (1988) and Hill & others (1992) dated the three main intrusive events at about 2.68, 2.66 and 2.62-2.60 Ga. Banded granite gneiss has been interpreted as possible sialic basement (Archibald & Bettenay, 1977; Griffin, 1990), but no U-Pb zircon age determinations have been published.

The Australian Geological Survey Organisation 1991 Eastern Goldfields seismic transect crosses the Barlee, Kalgoorlie, Gindalbie and Jubilee terranes and domains (Figs. 1, 2). Initial results (Drummond & others, 1993; Goleby & others, 1993; Williams & others, in prep.) give for the first time a detailed impression of crustal scale structures. Most major structures interpreted from regional mapping can be seen in the seismic reflection data, and can be traced to deeper crustal levels. Here the main features are briefly summarized.

The basal contact of the greenstones lies at depths between 4 and 7 km, and is underlain by presumably gneissic basement characterised by strong subhorizontal reflectors. This basal contact is interpreted as a major décollement because of stratigraphic truncations on limbs of regional domes or anticlines in the Kalgoorlie Terrane (Fig. 2). Such truncations, without substantial stratigraphic thinning or lateral variations, suggest major extension rather than shortening or thrusting indicated by the D2 structures mapped at the surface. The domes are underlain by duplexes of inferred felsic rocks, and contain flat cigar- or surfboard-shaped granite plutons in their hinges. This, as yet poorly understood,

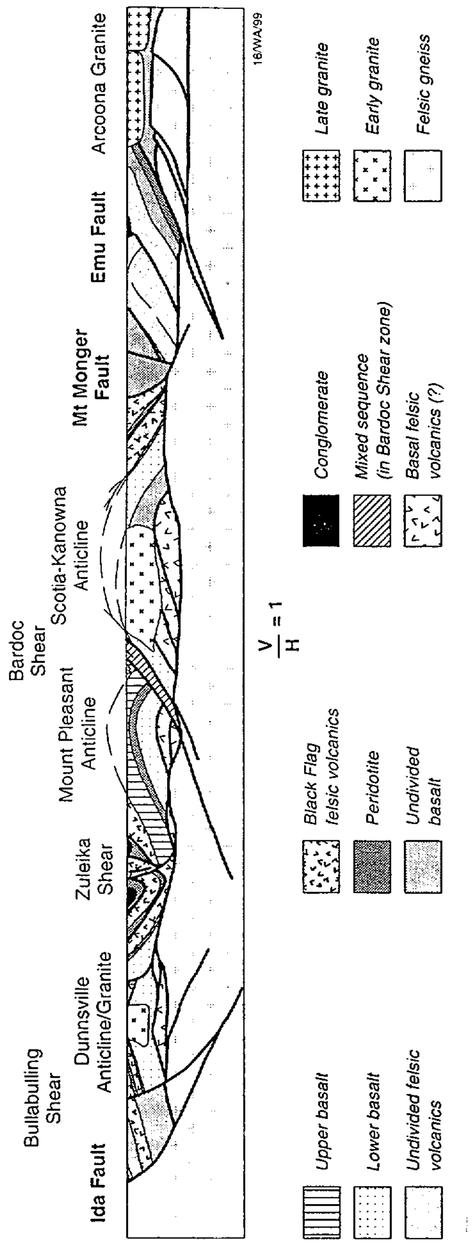

Fig. 2. Geological interpretation of the AGSO Eastern Goldfields seismic line. From Goleby & others (1993).

extensional event probably postdates early north-to-south D1 thrusting, and predates D2 shortening (thrusting and open folding).

The Ida Fault, the terrane boundary between the Barlee and Kalgoorlie terranes, is imaged as a gently east-dipping crustal scale fault that can be traced to a depth of nearly 30 km. Beneath this fault trace, the crust-mantle boundary (Moho) drops gently eastwards from 33 to 38 km depth. The Bardoc Shear ('tectonic zone') appears as a gently west-dipping fault, possibly offsetting the basal décollement in a normal sense (Figs. 2, 4). The eastern limb of the Mount Pleasant anticline is truncated by the Bardoc Shear. The final geometry shown in Fig. 2 may result from a complex history including major regional extension after D1 thrusting, but before east-west stacking during D2 regional shortening.

The eastern end of the seismic traverse appears to show a basement high, expressed at the surface by a distinct granite belt. High grade gneiss does not appear along the traverse, but does crop out some 60 km along strike to the north where it is associated with strongly foliated granite and high grade amphibolite. This suite of rocks may represent exposure of deeper crustal levels.

Excursion localities

Locality 1: Callion—mafic rocks and banded iron formation (BIF)

This locality, three kilometres west of the Callion mine, is situated within an east-dipping sequence comprising several units of BIF and shale with intercalated basaltic and doleritic rocks of tholeiitic composition. This sequence is interpreted to lie in the Barlee Terrane, west of a major regional structure, the Ida Fault. The fault is probably represented in this area by a zone of shearing which separates the Barlee Terrane from the Kalgoorlie Terrane (Fig. 3). The Kalgoorlie Terrane sequence in this region is characterised by abundant mafic and ultramafic rocks with subordinate felsic volcanic and sedimentary rocks. Interpretation of aeromagnetic data suggests that any surface expression of the fault should lie beneath the basalt scree and laterite cover east of the Callion mine.

The sequence exposed here is typical of BIF sequences immediately west of the Ida Fault. It consists of prominent ridge-forming BIF units containing beds which may be up to 3 m thick but are usually much thinner. Quartz-magnetite/hematite banding is on a scale of 1 cm down to much less than 1 mm. Tight intrafolial folds are abundant and larger outcrop-scale folds can be seen in places.

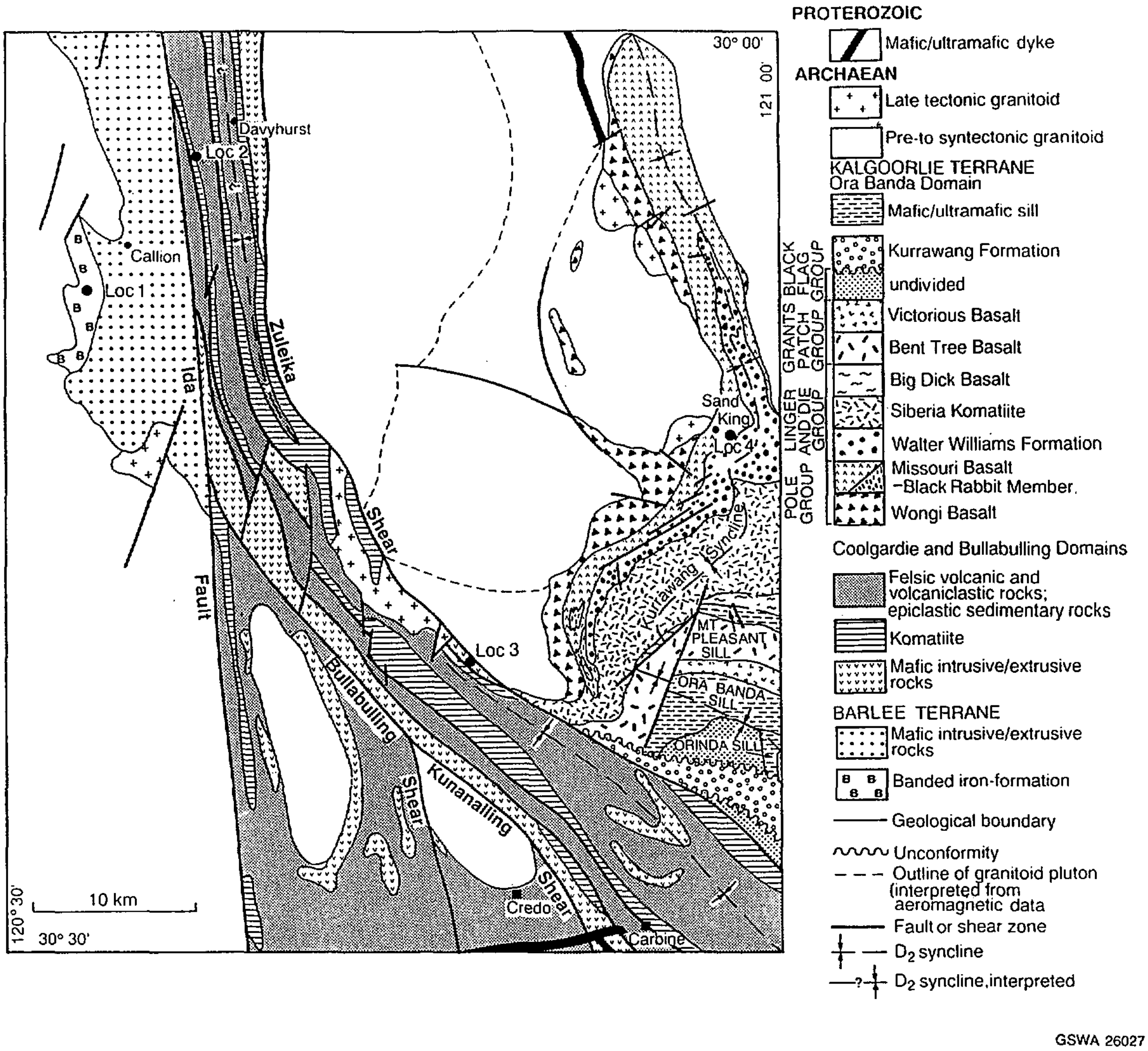

Fig. 3. Interpreted solid geology of the Davyhurst–Siberia district showing localities 1-4. From Wyche & Witt (1991).

There is a shallow south-plunging bedding-foliation intersection lineation.

The major BIF ridges are separated by thicker units of basalt and dolerite which are largely concealed beneath laterite and scree. It is not known whether each of the major BIF ridges represents a separate unit or whether there has been large-scale structural repetition of one or more units. The easternmost sedimentary unit in the sequence consists of grey shale.

It is often difficult to relate sequences in one greenstone belt in the Barlee Terrane to those in adjacent belts. The greenstones at Callion differ from those in the nearest belt to the west, the Yerilgee greenstone belt, about 45 km away, in that they do not appear to include ultramafic rocks whereas the BIFs in the Yerilgee sequence are intercalated with tremolite-chlorite schists. The Callion BIFs also appear to have a higher iron content than those in the Yerilgee belt which typically have a much higher proportion of cherty material. Recent mapping in the eastern part of the Barlee Terrane suggests that there is more regional variation in the stratigraphy than in the Kalgoorlie Terrane.

Locality 2: Eileen open pit—altered and deformed ultramafic sequence

At this locality, recent mining has exposed a unit of foliated tremolite-chlorite rock typical of sheared ultramafic rocks throughout the region. This unit is part of a poorly exposed, complexly deformed Kalgoorlie Terrane sequence which lies between two major shear zones, the Ida Fault to the west and the Zuleika Shear to the east (Fig. 3).

The Davyhurst district has a recorded production of about 10 tonnes of gold, dating from the turn of the century.

Locality 3: Chadwin—Zuleika Shear

The Zuleika Shear is a major structure which can be traced for over 300 km. It is marked by a zone, in places more than 1 km wide, of attenuation and deformation. Although the sequences to the east and west of the shear are broadly similar, it has not been possible to match individual units across it and it is probable that it was a long-lived structure whose history included a late stage component of transpression (Fig. 3).

At Chadwin, the Zuleika Shear is represented by a suite of strongly deformed and moderately metamorphosed rocks derived from sedimentary, felsic volcaniclastic, mafic and ultramafic rocks. A unit of leucogabbro occupies much of the open area south of Chadwin Well. Between this unit and the workings at the well is a sequence of biotite- and hornblende-bearing felsic to intermediate schists. It is difficult to ascertain precursor rock types but relict bedding in some outcrops indicates a significant sedimentary/volcaniclastic component. The shear zone, like many others in the Eastern Goldfields, is poorly exposed but is probably centred on the line of workings and costeans around the wellsite. A range of metamorphic rocks are to be seen in dumps and in drill chips. They include fine-grained slate with randomly oriented hornblende porphyroblasts, intermediate schist and amphibolite. Northeast from the well is a mainly mafic metamorphic sequence which has been extensively intruded by granite and pegmatite. Dark amphibolite is the main rock type but the low hills immediately north of the well contain tremolite-rich rocks with occasional patches of relict olivine spinifex texture. There are also lenses of felsic porphyroclastic schist which may represent former felsic volcanic-volcaniclastic rocks within the mafic sequence.

The association of amphibolite with ultramafic and felsic porphyroclastic rock is like that in the Ora Banda sequence at Black Rabbit, 9 km east of here (Wyche & Witt, 1991), and may represent part of the Ora Banda Domain which has been dragged around to the west during dextral movement on the Zuleika Shear.

Locality 4: Siberia—Ora Banda East area—komatiite

Several short stops will examine the stratigraphy of the Walter Williams Formation (WWF) and Siberia Komatiite (SK) which together form the prominent regional ultramafic volcanic marker unit in this part of the Kalgoorlie Terrane (Fig. 3). The WWF is a thick pile of adcumulate dunite with orthocumulate margins. Hill & others (1987) proposed a volcanic origin for these rocks suggesting the WWF developed as the crystallization product of a massive sheet flow. This contrasts with the Siberia Komatiite (Witt, 1990) which consists of numerous komatiite flows characterised by olivine spinifex textures, interleaved with layers of high-Mg basalt and thin interflow sediment.

Stop A. Missouri mine

Olivine orthocumulate at the base of the WWF overlies fine-grained feldspar-phyric tholeiitic Missouri Basalt (Wyche & Witt, 1991). This basal orthocumulate is typically altered, and contains serpentine carbonate pseudomorphs after olivine (up to 3 mm) in a matrix of fine-grained tremolite, chlorite, serpentine, magnetite talc.

Stop B. Ni-Co silica pits

Silicified olivine adcumulate of the WWF. Coarse-grained (up to 2 cm) adcumulate texture is well preserved in ferruginous silica cap-rock, developed widely over the WWF. The silicified adcumulate was mined to provide a silica flux for the Kalgoorlie Nickel Smelter.

Stop C. Ora Banda Pipeline Section

The transition between the WWF and SK consists of an unusual association of high-Mg pyroxenite, gabbro and leucogabbro (Witt & Harrison, 1989; Witt, 1990). This association, with variable thickness and complexity, is of regional extent (Hill & others, 1987).

The lower part of the gabbroic association consists of interlayered gabbro (90%) and pyroxenite (10%). The ophitic to subophitic gabbro shows internal layering with variable grainsize (1-4 mm), and contains small pyroxene phenocrysts (1-3 mm). The metamorphic assemblage is actinolite + plagioclase + minor ilmenite and titanite. Witt & Harrison (1989) report a whole-rock analysis of similar gabbro from within Siberia Komatiite to be comparable in composition to high-Mg basalt. Coarse-grained pyroxenite layers (4-8 mm) are predominantly tremolite after clinopyroxene.

Unusual leucogabbro with a distinctive "spotty" texture occurs towards the centre of the gabbroic association. The mafic minerals–plagioclase ratio is variable, giving rise to an irregular layering on the scale of a few centimetres. The leucogabbro is a medium-grained, ophitic to subophitic rock consisting predominantly of plagioclase and actinolite after clinopyroxene. The "spotty" texture is caused by prominent amphibole (pseudomorphs after pyroxene) oikocrysts, each up to 1 cm across, which form up to 10% of the rock. Centres of oikocrysts are inclusion-free, but plagioclase is subophitically included in the oikocryst margins. Less easily recognized in the field are oikocrysts of titanite, similar in size to the amphibole oikocrysts. The titanite encloses unaltered, rounded, cumulus grains (0.5-1 mm) of diopside-rich pyroxene. Relict diopside is also common within metamorphic actinolite.

The lowermost flows of the Siberia Komatiite overlie the gabbroic association, and these include both olivine and pyroxene spinifex-textured rocks. High-Mg basalt flows invariably occur in close association with the gabbroic rocks (Witt & Harrison, 1989).

Locality 5: Panglo open pit—metasediments, gabbro in Bardoc tectonic zone

The Panglo trial pit has exposed a subvertical sequence of finely bedded and well-foliated slate and quartzo-feldspathic siltstone intruded by dolerite-gabbro. This sequence lies within the Bardoc tectonic zone which is characterised by strong deformation and regional disruption of the stratigraphy (Witt, 1987; Hancock & others, 1990). It separates two less deformed domains within the Kalgoorlie Terrane. West-younging basalt and komatiite crop out along and east of the highway some 500 m to the east. The metasedimentary rocks contain bedding-parallel faults with substantial disruption, and are cut by steep east and west-dipping reverse faults. Primary gold mineralisation associated with carbonate, pyrite and arsenopyrite alteration occurs along sheared dolerite-metasediment contacts. The Bardoc tectonic zone is imaged in the seismic data as a distinct package of shallow west-dipping reflectors that only steepen close to the surface (Fig. 4).

Locality 6: Gidji—felsic volcanic rocks

Felsic volcanic rocks exposed about 13 km north-northwest of Kalgoorlie lie within the lower part of the Black Flag Group, an extensive felsic volcanic and volcaniclastic sequence overlying the mafic-ultramafic volcanics in the Kalgoorlie Terrane.

On the eastern side of the Kalgoorlie–Leonora railway line there is a rubbly outcrop of pale green-yellow conchoidally fractured rhyolite (Table 1, analysis 110690) with locally developed globular features, possibly spherules. The rock contains a few quartz and feldspar phenocrysts up to 1 mm. About 60 m to the north, a rhyolite-dominated breccia has a few angular mafic clasts. In thin section, this rock contains subangular, locally cuspate felsic volcanic rock fragments up to 5 mm, containing feldspar laths with minor quartz and rare amphibole pseudomorphs. Locally, fragments show a jigsaw texture. Between the clasts is cryptocrystalline quartz and thin laths of feldspar with scattered opaque oxide and abundant secondary carbonate and sericite. The rock shows characteristics of an autobrecciated rhyolite or dacite.

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

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

The preferred interpretation of this succession involves subaqueous extrusion of dacite or rhyolite lava with associated autobrecciation, followed by deposition of mass flow and turbidity current sediments composed of degraded lava and reworked coeval pyroclastics. The 'teepee' structured units represent thixotropic failure of partially consolidated, wet, reworked crystal-rich ash, initiated by seismic activity.

Locality 7: Gordon—interleaving of mafic, ultramafic and felsic volcanic rocks

The Gordon area (Figs. 1, 5) is unusual in the Kalgoorlie Terrane in that there is evidence for coeval mafic, ultramafic and felsic volcanic activity. In a 2.5 km wide, north-south trending zone west of the Gordon mine, felsic rocks are interleaved with komatiite, tholeiitic basalt, dolerite, carbonated mafic and ultramafic rocks, and chert. The zone occurs within a 10 x 5 km area dominated by felsic rocks which has been described as a major

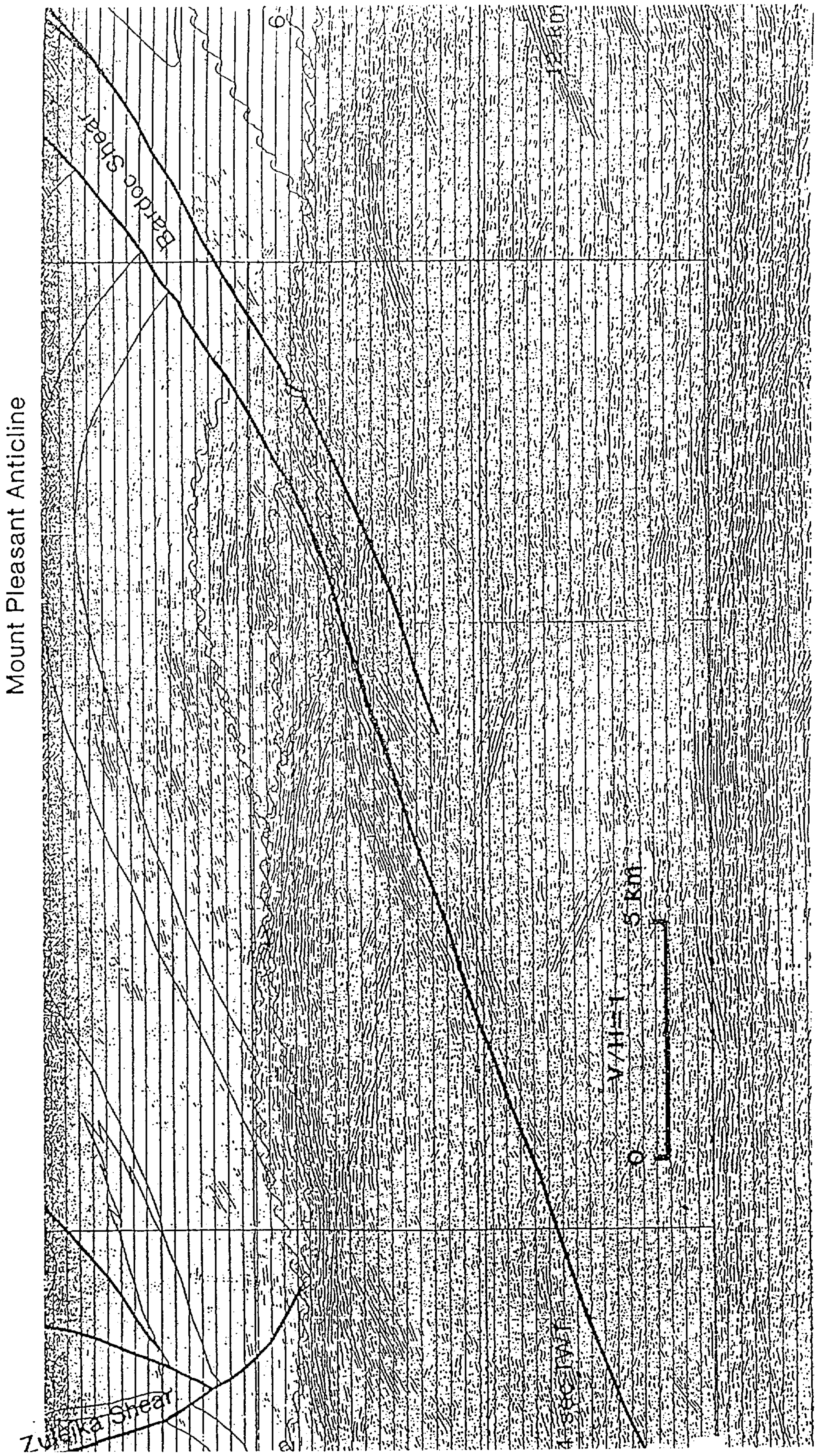

Fig. 4. Seismic reflection profile with geological interpretation showing the Bardoc Shear and Mt Pleasant Anticline. From Goleby & others (1993).

Number	110690	016	009	114195	114193	111903	110883
SiO2	69.2	65.74	63.92	72.5	64.4	65.21	48.4
TiO2	0.39	0.18	0.28	0.37	0.6	0.36	1.07
Al2O3	14.5	17.19	16.63	15.6	16.2	15.29	15.6
Fe2O3	0.99	1.00	1.74	1.01	1.69	1.85	3.70
FeO	0.51	0.45	0.66	1.43	3.24	1.30	7.83
MnO	<0.05	0.03	0.05	<0.05	0.07	0.06	0.21
MgO	0.56	0.50	0.73	1.42	2.9	2.63	7.41
CaO	1.44	1.95	2.67	0.14	0.7	4.23	11.4
Na2O	0.18	7.76	7.54	0.31	7.83	5.88	1.35
K2O	10.2	3.70	3.60	4.08	0.05	3.04	0.06
P2O5	0.11	0.07	0.13	0.13	0.31	0.14	0.08
LOI	2.93	1.38	1.38	3.06	2.66	1.68	4.11
Total	101.01	99.95	99.33	100.05	100.65	101.67	101.22
Trace Elements (ppm)							
Ba	607	1010	839	611	136	1570	52
Cr	17	<5	5	16	45	133	301
Cu	<4	13	8	4	<4	25	134
F		950	1250				
Ga	15	21	23	18	20	18	16
Hf	2.38						
Nb	0.36	13.8	27.2	<7	<7	<7	<7
Ni	4	6	7	17	39	44	148
Pb	25	14	21	<4	21	22	<4
Rb	242	82	99	101	<2	85	<2
Sc	1.79	2.7	3.3	7	8	8	31
Ta	<0.05		<5	<5	<5	<5	<5
Th	9.21	9	14	5	9	8	<2
U	2	4	2	<2	<2	2	<2
V	27	16	29	38	86	65	285
Y	4.18	6.6	10.1	9	12	10	22
Zn	6	38	57	36	108	57	96
Zr	139	84	148	139	211	180	88
Rare Earth Elements (ppm)							
La	30.93			15	37	20	<5
Ce	62.58	65.1	87.1	33	83	47	<6
Pr	7.27						
Nd	25.42	36.3	43.7				
Sm	4.21	5.89	8.39				
Eu	1.13						
Gd	3.15						
Tb	0.31						
Dy	1.08	1.42					
Ho	0.18						
Er	0.44	0.71	0.88				
Tm	0.06						
Yb	0.37	0.48	0.75				
Lu	<0.05						

110690 -- Rhyolite, Gidji Lake. 016 -- Coarse grained part of Gilgarna Rock syenite (Johnson, 1991). 009 -- Medium grained part of Gilgarna Rock syenite (Johnson, 1991). 114195 -- Rhyolite, Gordon. 114193 -- Amygdaloidal dacite, Gordon. 111903 -- Dacite pyroclastic flow, Mulgabbie. 110883 -- Basalt, Gordon.

TABLE. 1. Major, trace and rare earth element data.

acid volcanic centre by Williams (1970). The felsic complex straddles the boundary between the Scotia Basalt (lower basalt) and Highway Ultramafics (komatiite) and occurs on the eastern limb of the regional D2 Scotia–Kanowna Anticline. Good east-younging indicators include pillow structures in basalt and spinifex textures in komatiite. The field evidence suggests interleaving of the rock types is a

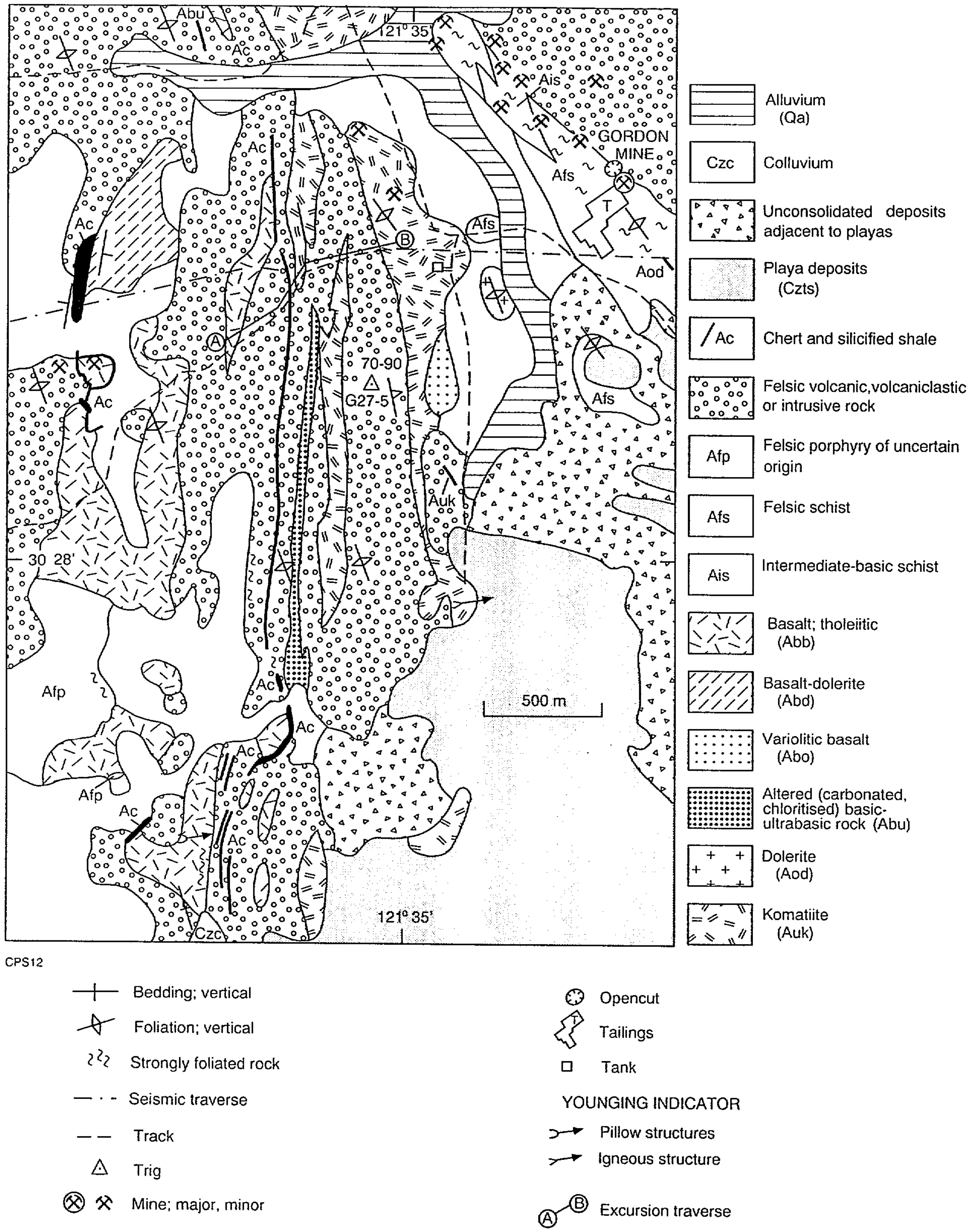

Fig. 5. Geological outcrop map of the Gordon area, showing locality 7. From Ahmat (in prep. b).

primary feature. Although the origin of many of the felsic rocks is unclear—some are clearly intrusive—their association with komatiite, basalt and chert suggest a predominantly volcanic-volcaniclastic origin. The combination of locally pillowed basalt, and the presence of chert and shale indicates subaqueous deposition. Analyses of rhyolite (114195), amygdaloidal dacite (114193; possibly silicified basalt or andesite) and basalt (110883) are shown in Table 1.

The traverse starts by examining thin basaltic zones in the host felsic rock and then proceeds to the northeast to look at a persistent chert unit which can be traced more than 3 km along strike. The chert is underlain by basalt (highly weathered) and overlain by felsic rocks. Further east, the felsic rocks are interleaved with several komatiite units which show spinifex texture in a number of places. Some 400 m east of the chert unit, the felsic zone is overlain by a 350 m thick sequence of komatiite with minor lenses of locally foliated felsic rock. Patches of high-Mg variolitic basalt occur towards the top of the komatiite.

Locality 8: Balagundi—mafic rocks

The Balagundi belt represents a mafic-dominated sequence in the central western portion of the Gindalbie Terrane. It is characterised by the predominance of tholeiitic basalt, dolerite and gabbro. Porphyritic mafic rock with very coarse plagioclase phenocrysts is known locally as "cat-rock" because its appearance is reminiscent of the coat of a native marsupial. These mafic rocks are interbedded/interleaved with numerous felsic volcanic-volcaniclastic units. The mafic rock types are closely interbedded and grade into one another over distances of metres. The intergradational nature of basalt, dolerite and gabbro, and their interleaving with felsic rocks, suggests that most of them are the products of the crystallisation of tholeiitic lava flows (Ahmat, in prep. b). Traditionally, dolerite and gabbro have been interpreted as intrusive rocks.

The first stop (Fig. 6A) examines some typical basalt and dolerite. In the area about the gate, particularly on the east side, a 30-40 m zone of porphyritic dolerite occurs within porphyritic basalt. Plagioclase phenocrysts in the dolerite are up to 1.5 cm in size and constitute up to 30% of the rock. Plagioclase phenocrysts in the basalt are mostly 2-4 mm in size and make up about 15% of the rock. About 140 m east of the gate, the porphyritic basalt grades into 'normal' basalt.

At the second stop, 6.5 km to the east southeast, the complex intergradational nature of basalt, dolerite and gabbro can be seen. These rocks are interlayered with numerous thin (1-50 m) felsic units. At the map scale, most of the mafic rock units cannot be depicted separately and are grouped under the heading Abg (basalt-dolerite-gabbro). Many of the rocks in the area are porphyritic (plagioclase-phyric). The traverse begins at a small scarp composed of highly cleaved and weathered (variously lateritised) felsic schist. Proceeding eastward, there is variously lateritised basalt-dolerite interlayered with thin (5-30 m) felsic volcanic-volcaniclastic units. Near the top of the hill, the rocks are coarser, and three separate units (?thick flows) may be present. On the eastern slope of the hill, there is a 6 m wide felsic unit followed by basalt that is porphyritic in places. In the valley to the east, there is a 40-50 m zone of felsic volcanic-volcaniclastic rock. East of this unit, the sequence consists of basalt (porphyritic in places), dolerite-gabbro, basalt, gabbro (ophitic-poikilitic in part) and porphyritic basalt.

Locality 9: Bulong Complex—komatiite

The Bulong Complex is predominantly a thick sequence of serpentinised peridotite with subordinate amounts of gabbro, pyroxenite, felsic volcanic-volcaniclastic rocks and high-Mg basalt. Although originally considered to be a differentiated ultramafic intrusive, it is now interpreted to be a volcanic complex made up of proximal to distal deposits (Ahmat, in prep. a).

The Bulong Complex occurs in the Gindalbie Terrane (Fig. 1) on the western limb of the Yindarlgooda dome. It overlies a felsic (acid to intermediate) volcanic sequence with a low-angle fault contact, and is overlain by interbedded basalt, komatiite and sedimentary rocks. The felsic unit below the Bulong komatiite has yielded a relatively imprecise U-Pb zircon age of approximately 2714 Ma (Compston & others, 1986). The Bulong Complex, over 45 km long and up to 5 km wide, shows several phases of folding and faulting, including early recumbent folds and thrusts that have stacked the sequence. Overall, the sequence youngs to the west. For example, pyroxenite-gabbro units are fractionated towards the west, and spinifex-textured komatiite and high-Mg basalt are concentrated along the west side.

The bulk of the rocks consist of serpentinised olivine cumulates (mainly olivine ortho- to meso-cumulates) but the proportion of these rocks decreases vertically and laterally. Felsic volcanic-volcaniclastic rocks occur as conformable lenses, mainly less than 100 m thick, but locally up to 500 m thick and up to 3 km long. These felsic rocks are interpreted to be products of contemporaneous volcanism. Several nickel and cobalt deposits have been recognised in laterite developed over komatiite, and there is a minor occurrence of chromite near the eastern margin (Fig. 7).

At stop A, the eastern contact of the complex is characterised by strong deformation and emplacement of quartz veins. Talc-chlorite schist is in contact with moderately foliated conglomerate containing subrounded to rounded felsic clasts up to about 1.3 m long. This conglomerate is interpreted to be the product of debris flows. The first gabbro unit lies about 200 m to the west. Rocks between the

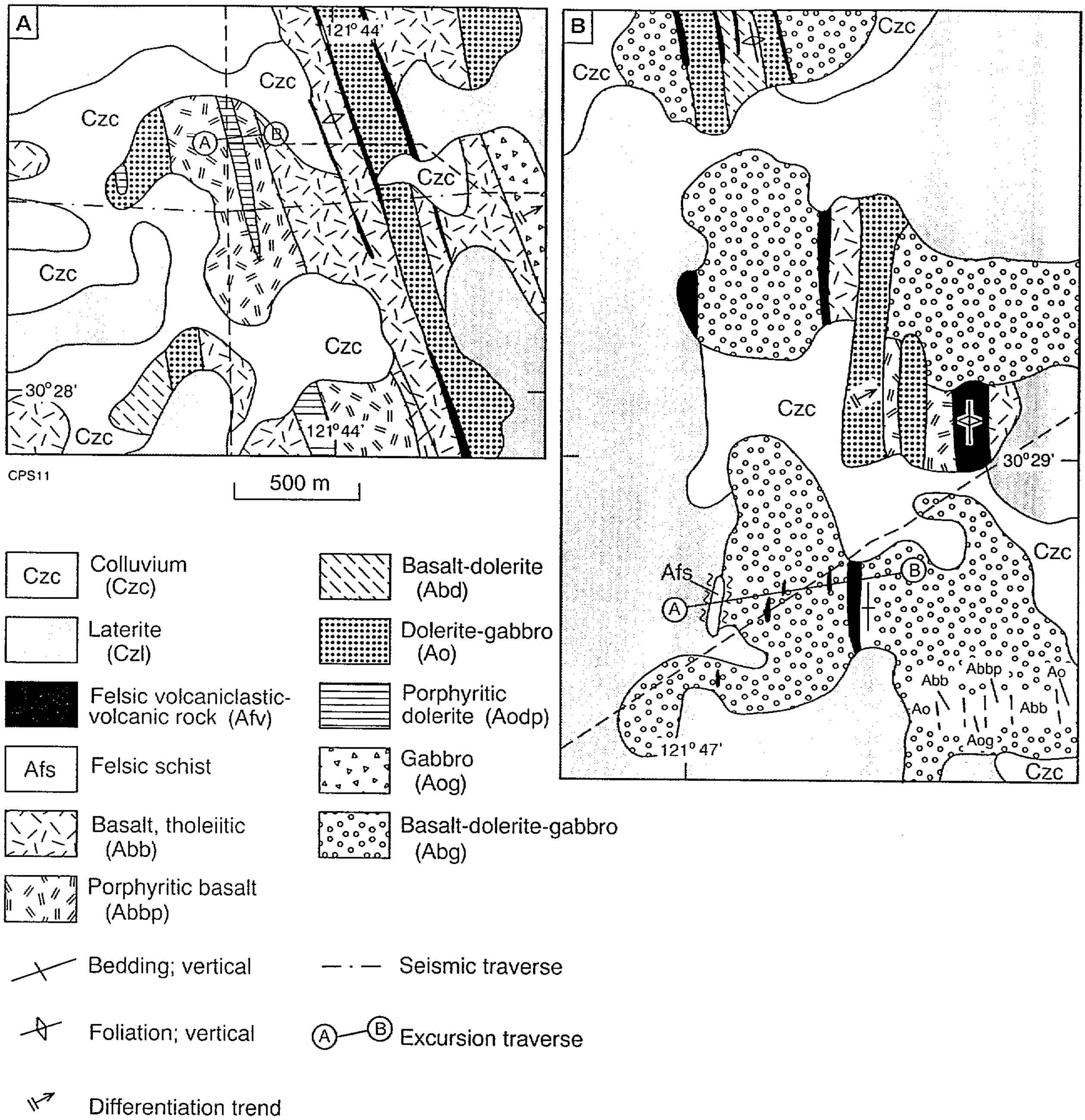

Fig. 6. Geological outcrop of part of the Balagundi mafic belt, showing stops A and B, locality 8. From Ahmat (in prep. b).

contact and the gabbro are serpentinised peridotites in which former olivine averaged about 2 mm in diameter. Peridotite is commonly poikilitic with oikocrysts of clinopyroxene and, in places, kaersutite, which are 5-10 mm in diameter. The ridge-forming gabbro, or gabbro-norite, is 5-10 m thick, and can be traced continuously to the north for about 800 m, and then further north as lenses. Pyroxenite occurs locally beneath the gabbro and there is a very thin seam of chromitite.

At stop B, a differentiated pyroxenite to gabbro sequence indicates a west-younging trend. Further west, there are felsic volcanic rocks, including fragmental varieties.

Stop C is near the western side of the complex, and shows the extrusive nature of the rocks with intercalated komatiite and high-Mg basalt. Most komatiite is olivine cumulate, but platy spinifex textures are found in a few places. High-Mg basalt comprises spinifex-textured and variolitic types. About 200 m to the southwest, good examples of 'stringy-beef' spinifex-textured high-Mg basalt contain amphibole pseudomorphs after acicular pyroxene crystals up to 10 cm long.

Locality 10: Penny Dam Conglomerate

The Penny Dam Conglomerate overlies the Emu Fault, which separates the Gindalbie

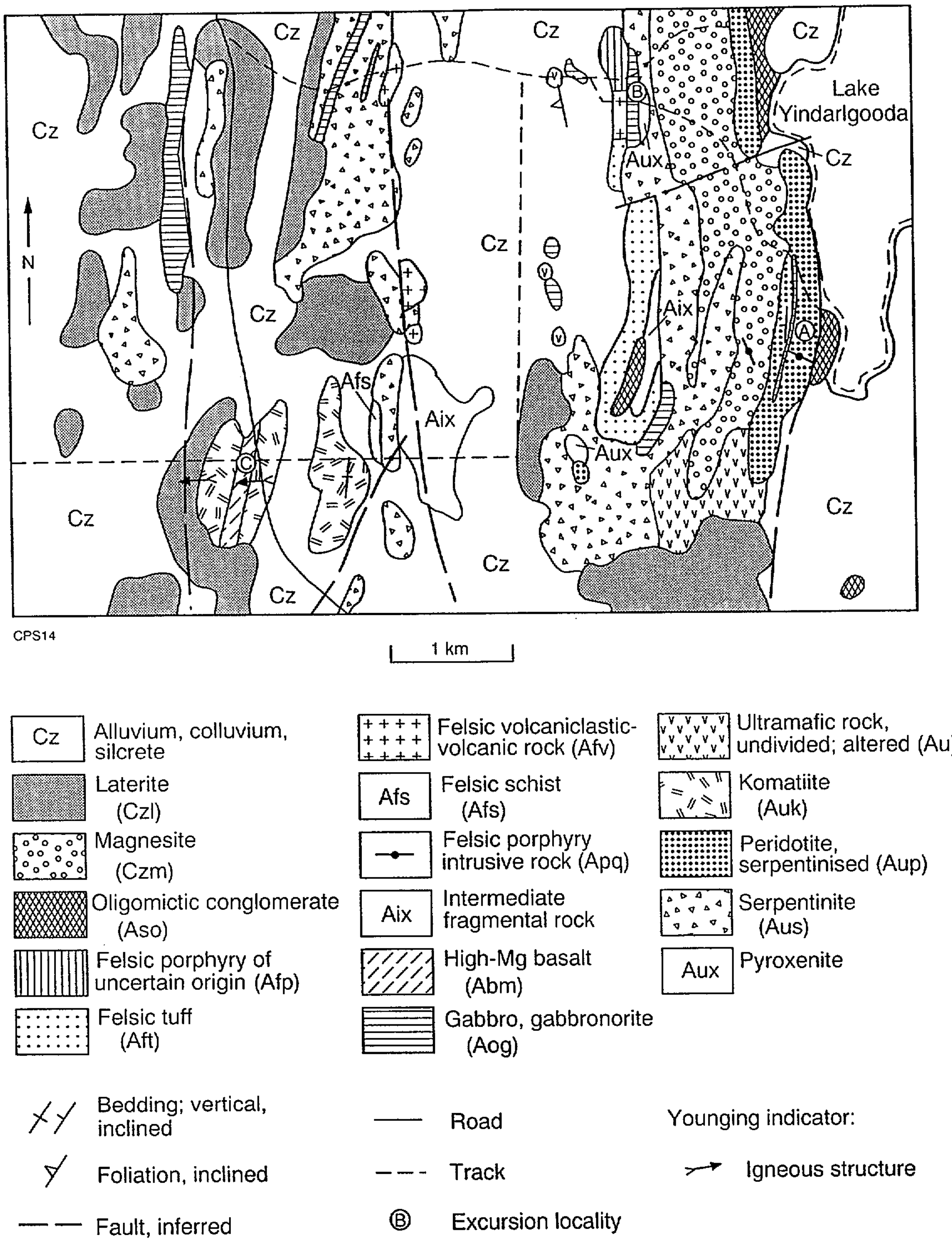

Fig. 7. Geological outcrop map of central part of the Bulong Complex. From Ahmat (in prep. a).

Terrane from the Jubilee domain (Figs. 1, 8). It forms a linear belt of clastic rocks striking southeast for over 180 km, including conglomerates which crop out over a strike length of some 45 km. Towards the south, the conglomerate may be transitional to greywacke with interleaved BIF, in a unit known as the Mount Belches beds. The conglomerate contains the regional upright foliation and is carbonated over large areas. Conglomerate deposition therefore predated regional shortening.

The conglomerates range from clast-supported to matrix-supported types and contain clasts that are generally rounded and up to 20 cm long. Most rocks are cobble conglomerates and there are subordinate pebble conglomerates and coarse-grained sandstones. Clast types include acid-intermediate volcanic rocks, basalt (mainly high-Mg type), dolerite, sedimentary clastic rocks, gabbro, chert and quartz. Many clasts appear to faceted and/or wedge-shaped, suggesting a possible glacial origin (J.S. Myers, personal communication, 1989).

At Tabletop Hill, strongly deformed metasedimentary rocks are exposed in a face of a prominent hill. These rocks overlie the more con-

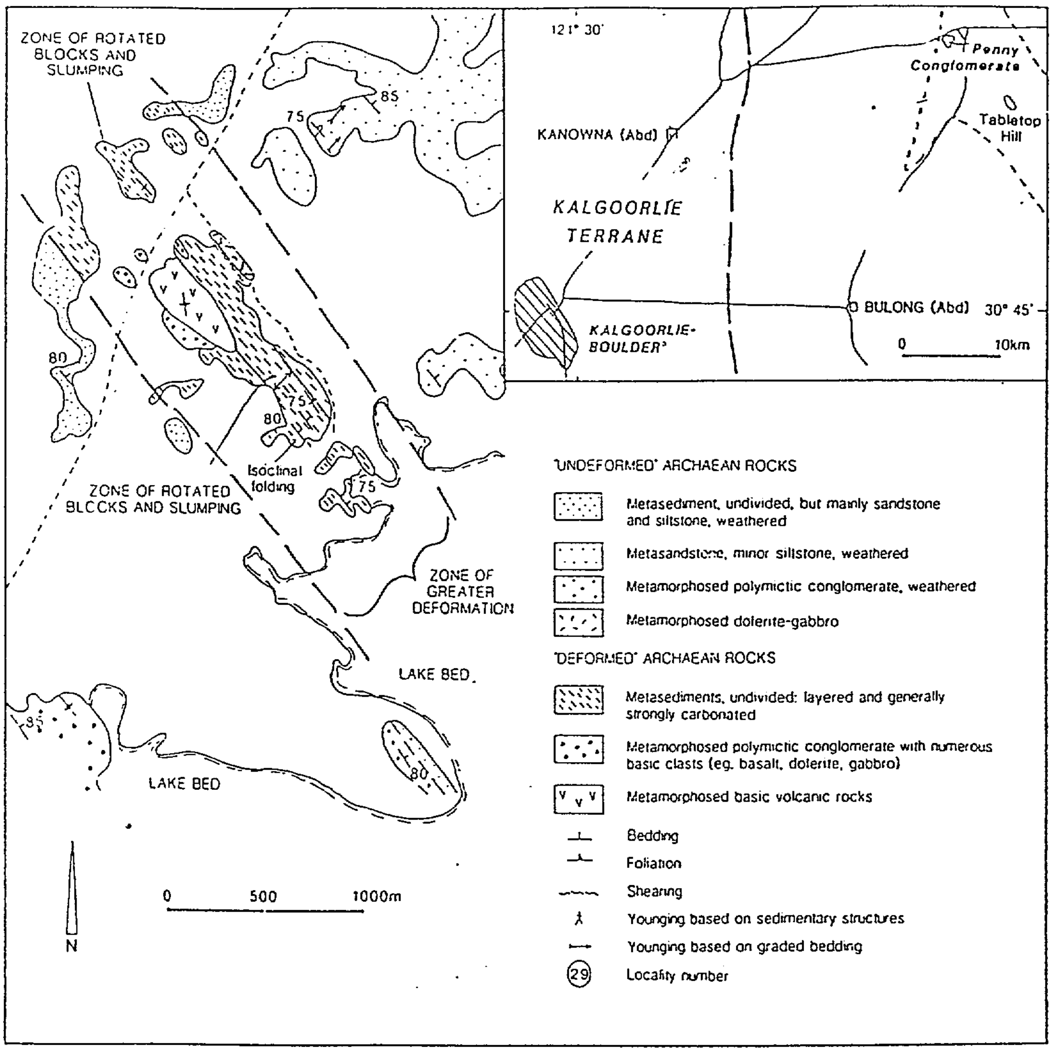

Fig. 8. Geological sketch map of the Tabletop Hill area. Insert shows location of Penny Dam Conglomerate and Tabletop Hill stops.

glomeratic zones. Associated with these metasedimentary rocks are lenses of basic conglomerate and altered basic fragmental rocks. In general, basic rocks are rare in the Penny Dam Conglomerate and their presence may signify unusual conditions. Strong carbonation of sandstone, siltstone and shale (up to 40%) has obliterated many small scale primary structures, but bedding and slump folds have survived. Mesoscopic deformation features consist of isoclinal folds (possibly refolded) and discrete zones of rotated blocks. The rotated blocks are up to 20 m in size and have highly tectonised contacts with the host rock. These structures are interpreted as reflecting syndepositional tectonic processes.

Locality 11: Kalpini East—komatiite

Ultramafic and gabbroic rocks, rare high-Mg basalt, and felsic volcaniclastic and volcanic rocks lie within the lower part of the Jubilee domain (Fig. 1). At Kalpini East, a 300 m thick sequence of ultramafic, gabbroic, basaltic, and minor felsic volcanic rocks is exposed as rubbly outcrop on the southern side of an east-west road (Fig. 9). Coarsening of the gabbro to the west suggests a westerly younging direction. The felsic unit between the two pyroxenite units in the lower part of the column is possibly mylonitic, and can be traced to a similar unit to the south. The felsic unit at the top of the sequence is crystal-rich, containing abundant feldspar and subordinate quartz grains (up to 4 mm) in a felsic matrix. Quartz grains are embayed and feldspar (albite) is euhedral, weakly resorbed and fresh. The groundmass is largely recrystallised, but a few spherules are preserved. The rock can be interpreted as a glassy pyroclastic flow, or, more likely, a crystal-rich lava flow.

The succession to the top of the pyroxenite is interpreted as a cumulate-dominated komatiite lava flow differentiated to a pyroxenite. Gabbro results from *in situ* crystallisation of a residual liquid. Variolitic basalt is a rapidly cooled differentiation product of a komatiite flow. Coeval felsic

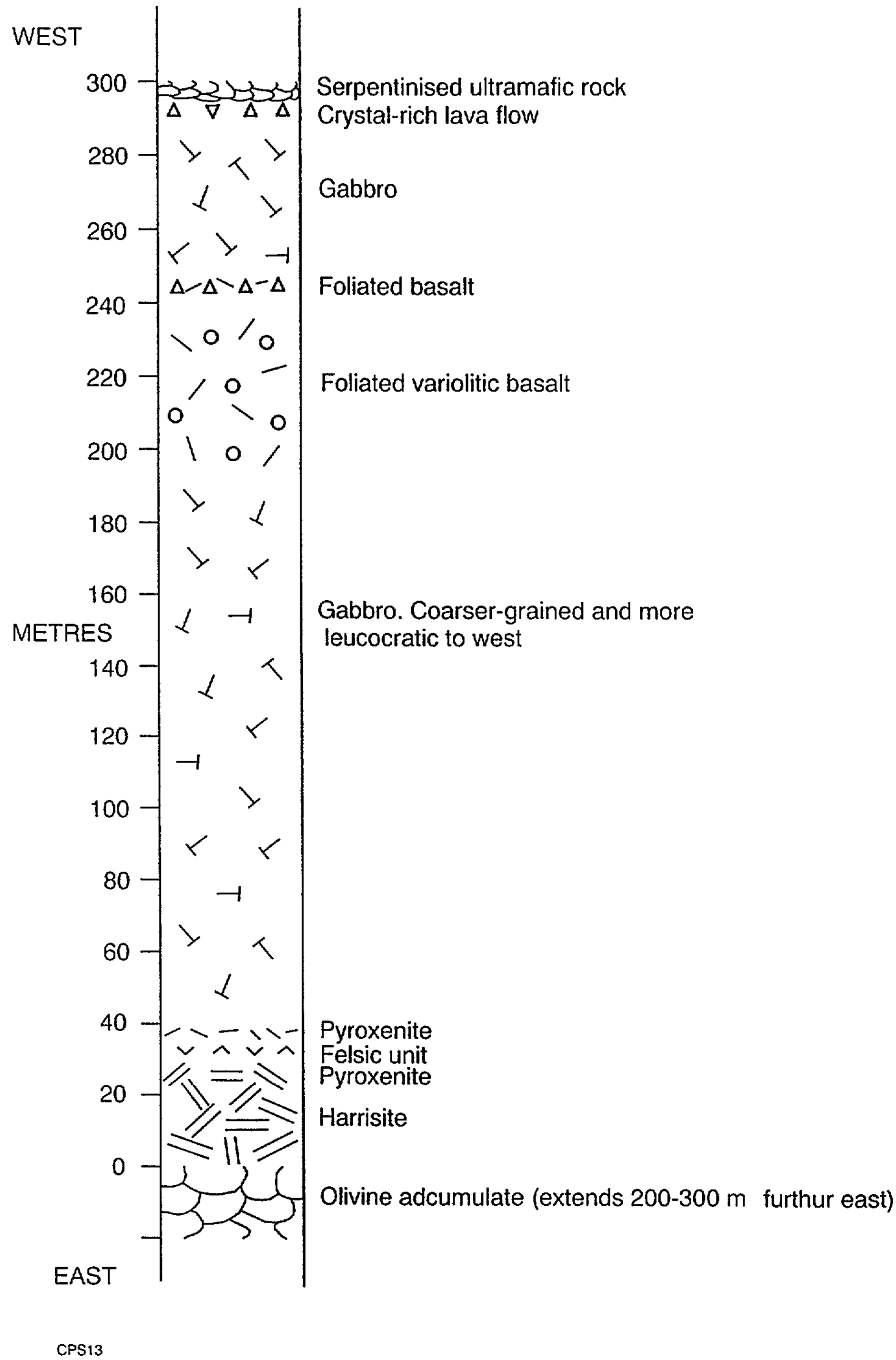

Fig. 9. Section through ultramafic sequence at Kalpini East.

volcanism is represented by the crystal-rich lava flow at the top of the sequence which is overlain by another komatiite flow. Structural repetition of the sequence may have occurred along the lower felsic schist unit and along foliated basalt above the gabbro.

Locality 12: Colour Dam—altered mafic and felsic volcanics

In the Kurnalpi domain (Fig. 1), the transition from a mafic + ultramafic volcanic sequence to a sequence of felsic volcanics which includes dolerite and strongly altered rock types, is complicated by folding and faulting. The overall structure can be described as a faulted antiform within the broad hinge of a regional syncline.

A west-to-east section exposes;

- felsic schists,
- carbonated basalt, fine-grained leucodolerite and well-foliated basaltic schist,
- felsic volcanic (including rhyolitic tuffs?) and volcaniclastic schists with fragmental textures,
- chloritoid-rich, partly fragmental chlorite-quartz

rock, with local carbonation; preserved pillows indicate basalt and hyaloclastic basalt precursors, and

- fragmental, feldspar-phyric felsic schist with dolerite-gabbro sills. The ridge to the south is dominated by chloritoid-bearing quartz-mica schist within carbonated mafic schist, and by massive quartz-andalusite rock.

To the southwest, a gossanous zone appears to be a fault zone with interleaved and strongly altered felsic volcanic-volcaniclastic, doleritic and ultramafic schists containing lenses of gossan. Gold anomalies were tested by the trial pit.

Locality 13: Gilgarna Syenite

Gilgarna Rock is one of the better exposed examples of post-deformational syenite in the Eastern Goldfields. The petrography and geochronology have been discussed by Libby (1978; 1989), Johnson & Cooper (1989) and Johnson (1991, 1992). Two textural variants, coarse- and medium-grained, are present. Analyses of each phase are shown in Table 1 (analyses 016 and 009). The two phases are in sharp contact but show no consistent spatial relationship, although Johnson & Cooper (1989) noted that the coarse-grained phase contains xenoliths of the medium-grained phase. Both phases contain mafic xenoliths (some of which are basaltic country rock), and both are cut by late stage syenitic dykes. Johnson (1992) has described well-developed rhythmic layering in part of the syenite which he attributes to the influence of an exsolved fluid phase, generated by fluorine depletion in the melt. The rhythmic layering results from cyclical variations in fluid pressure, resulting in alternating pyroxene-feldspar crystallisation.

Rb/Sr whole-rock and mineral dating (Johnson & Cooper, 1989) yielded ages of 2542 ± 14 Ma for the coarser phase, and 2627 ± 41 Ma for the medium-grained phase. These ages were interpreted to indicate intrusion of the medium-grained phase by the coarser-grained phase as a low temperature crystal mush some 85 Ma later.

Libby (1978, 1989) described felsic alkaline rocks in a broad belt between Norseman and Wiluna, including Gilgarna Rock. He noted that these rocks are characterised by alkaline pyroxene and amphibole, variable quartz contents (up to 20%), and mesoperthitic alkali feldspar.

The phases of the Gilgarna Rock syenite are mineralogically similar and appear to differ only in grain size. The coarse phase consists of interlocking anhedral grains of mesoperthite and perthite up to 5 mm in diameter (80 volume %), which show weak oscillatory zoning. These grains are slightly cloudy and a few grains have exsolved blebs of plagioclase. Subordinate albitic plagioclase has exsolved alkali feldspar (i.e. antiperthite). Weakly granoblastic quartz occupies about 10 volume %. The dominant mafic phase is euhedral, pale to deep green aegirine (up to 2.5 mm), usually associated with pockets or intergrowths of riebeckite. In late stage pockets, aegirine occurs with orange-brown titanite (up to 1 mm), calcite, anhedral biotite, and minor epidote and fluorite.

A mafic xenolith from the medium-grained phase consists of scattered prismatic euhedra of green amphibole (up to 0.5 mm), some with colourless diopsidic cores in sharp contact with the green rim. The remainder of the rock consists of intergrown perthitic feldspar, minor antiperthite, and quartz.

Locality 14: Khartoum Dam/Painted Rocks/Carosue Dam—carbonated mafic volcanic rocks, felsic volcanic rocks and sediments

This stop examines the transition from mafic volcanic rocks, mainly consisting of carbonated high-Mg basalt, to overlying felsic volcaniclastic, epiclastic, and volcanic rocks (Morris, in press) in the Mulgabbie domain (Fig. 1). This sequence lies immediately east of the Yilgangi Fault, a major regional discontinuity.

At stop A (Fig. 10), rubbly outcrop of high-Mg basalt has locally developed pillow rims and weak development of amygdaloidal texture. Carbonate spots are common, and this zone of carbonation extends to the northwest along an inferred shear zone.

At stop B (Fig. 10), conglomerate contains subrounded clasts of carbonated (but unfoliated) ultramafic rock, compositionally similar to that at stop A. The remaining clasts are largely felsic volcaniclastic fragments in a matrix of volcaniclastic sandstone. This suggests that the high-Mg basalt was laid down, carbonated, and eroded prior to deposition of the felsic volcaniclastic rocks.

At stop C (Fig. 10), a prominent multicoloured outcrop is named Painted Rocks for its distinctive chocolate brown and creamy yellow alteration. Liesegang bands are pervasively developed throughout the outcrop.

These rocks lie towards the base of the felsic sequence. Subrounded to rounded boulders up to 50 cm consist of fine-grained felsic volcanic rocks accompanied by less common angular frag-

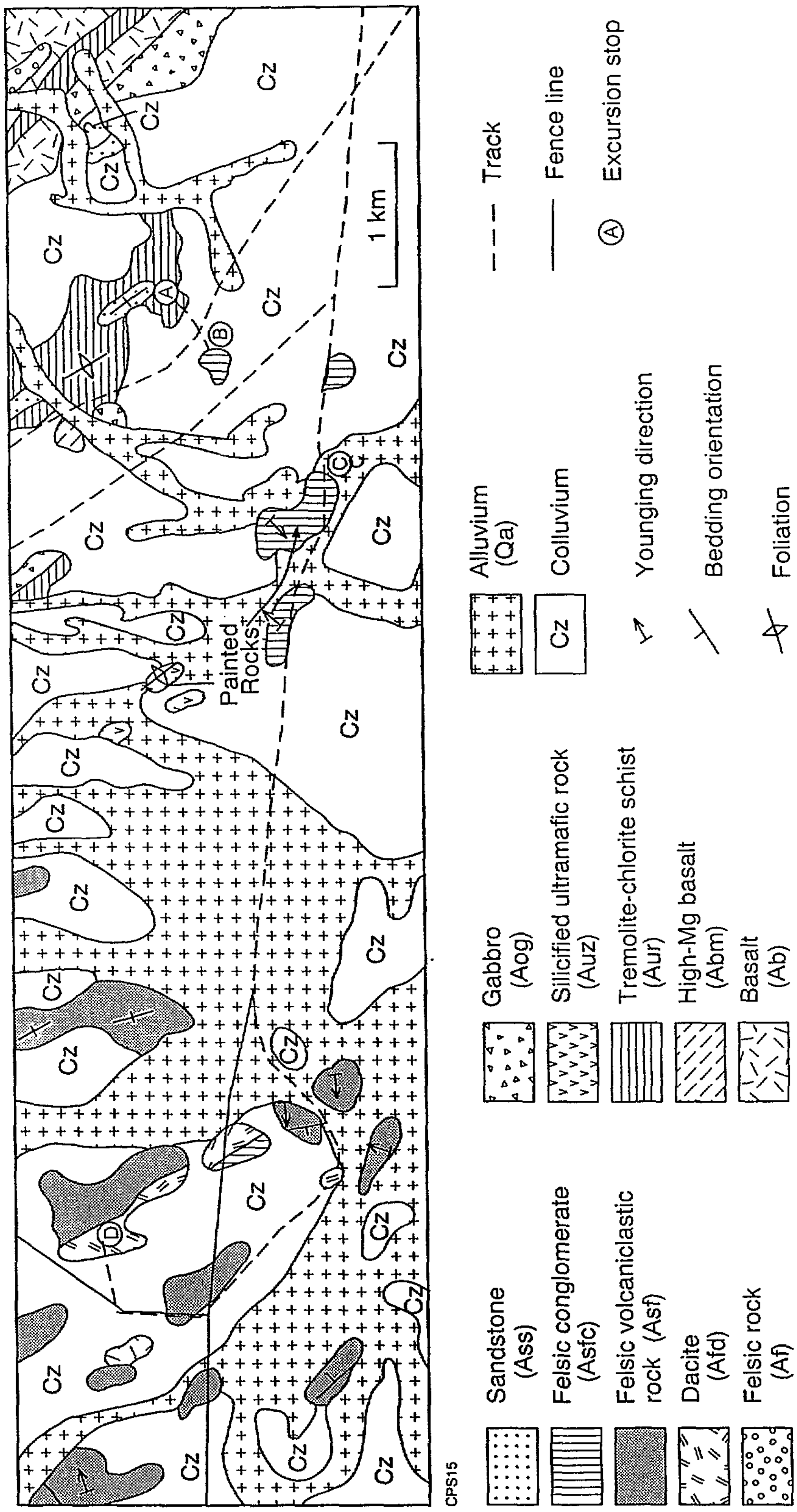

Fig. 10. Geological outcrop map of the Khartoum Dam–Painted Rocks section. From Morris (in press).

ments of mafic volcanics, 5 cm long. The matrix is a poorly sorted, medium- to coarse-grained pebbly sandstone. On the northeast side of the outcrop, crudely graded coarse-grained sandstone beds with angular felsic volcanic rock fragments form 2 m wide x 90 cm deep channels. The grading indicates southwest younging.

The poor sorting, limited clast type, gravity-dominated deposition, and coarse-grained matrix are interpreted in terms of a debris flow or lahar.

At stop D (Fig. 10) there is a largely massive, buff-coloured, locally clast-supported conglomerate. Angular fragments up to 5 cm, composed of biotite and amphibole, are scattered throughout. Crude bedding is developed locally, and there is a 10-30 m thick unit with angular clasts (usually 20 cm diameter, locally 40 cm) of leucocratic fine-grained felsic volcanic material (similar to the host), and fine-grained basalt at the base. The basalt is compositionally similar to an underlying unit that crops out to the east. In thin section, clasts comprise abundant euhedral, unzoned, and occasionally broken albitic plagioclase (20 volume %), weakly zoned and partly sericitised alkali feldspar (50%), and aggregates of biotite flakes, locally after amphibole (15%). Feldspar crystals range up to 2 mm and biotite clots reach 3 mm. The groundmass is cryptocrystalline quartz and feldspar with abundant biotite flakes and accessory epidote. Perlitic texture is locally preserved. A chemical analysis is presented in Table 1 (111903).

The poorly developed bedding, lack of flow features, brecciated base, broken crystals, lack of crystal embayments, and glassy mesostasis are consistent with deposition from a pyroclastic flow. The predominance of feldspar over quartz indicates a dacitic (rather than rhyolitic) composition.

Locality 15: Pinjin—Kirgella Rocks —a crustal section?

This west-to-east traverse shows the transition from low-mid greenschist facies to mid-upper amphibolite facies rocks adjacent to migmatitic gneiss and granite. Three informally named domains are recognized (Fig. 11),

- the Edjudina domain containing prominent BIF as well as (ultra-)mafic and felsic volcanics, metamorphosed at greenschist facies conditions. Very few reliable younging criteria have been found, and little is known about the internal structure of this domain.
- the Pinjin domain, containing well-foliated felsic, intermediate, mafic and some ultramafic schists, with subordinate BIF. Metamorphic grade increases eastwards from lower amphibolite to upper amphibolite. The greenstones are intruded by distinct, elongate granite plutons that become dominant towards the east, so that only screens and isolated 'islands' of greenstone remain within a 'sea' of granite.
- the Kirgella Gneiss domain, characterised by migmatitic granite gneiss, now surrounded by undeformed granite. On regional aeromagnetic maps, this domain resembles other high grade gneiss domains recognized elsewhere in the Eastern Goldfields (Williams and Whitaker, 1993).

The Edjudina and Pinjin domains are separated by the Pinjin Shear. To the south, this is a well-defined shear zone (up to 1 km wide) characterised by down-dip mineral lineations and west side-down movement indicators, juxtaposing mid-greenschist and mid-amphibolite facies rocks (Swager, in press). The contrast in metamorphic grade suggests substantial vertical movement and raises questions about the nature, attitude and timing of the shear on a crustal scale. At the surface, steeply west-dipping mylonitic foliations indicate an extensional, relatively late stage shear zone, presumably flattening out with depth.

The overall structure of a high grade metamorphic belt with numerous granite intrusions separating low-medium grade greenstones from migmatitic gneiss can be mapped over a strike length of 80 km (Williams & others, 1976). To the north, the medium to high grade metamorphic belt, about 10 km wide at Pinjin, narrows to about 1 km in the Celia area, resulting in a structure similar to the high grade gneiss domes with very narrow, high P-T greenstone rims documented at Leonora (Williams & others, 1990; Williams & Whitaker, 1993) and Melita (Witt, 1992). These domes have been interpreted as early metamorphic core complexes developed during extension at the time of greenstone deposition and early deformation (Williams & others, 1990) and as post-D1 and pre-D2 features (Witt, 1992).

The Pinjin Shear and other possible shears along the gneiss contact may involve relatively late extension.

Stops along the traverse are indicated on Fig. 11.

A. Variolitic and pillowed basalt with narrow hyaloclastic pillow rims is interleaved to the east with pyroxene spinifex-textured basalt. Varioles overprint acicular pyroxenes. These high-Mg basalts are deformed locally into tremolite schist.

B. Talc-chlorite schist, 30-60 m wide and partly overlain by silica caprock, is in contact to the west with well-foliated metasediments. This contact and the metasediments immediately to the west host the Harbour Lights gold mineralisation (about 16 kg Au from 500 tonnes, 1905-1908). To the east, the ultramafic schist is bounded by gabbro which locally contains two pyroxenes and minor quartz.

Rocks in the Edjudina domain (stops A & B) are at low-medium metamorphic grade, and show strain partitioning into distinct zones and/or rock types.

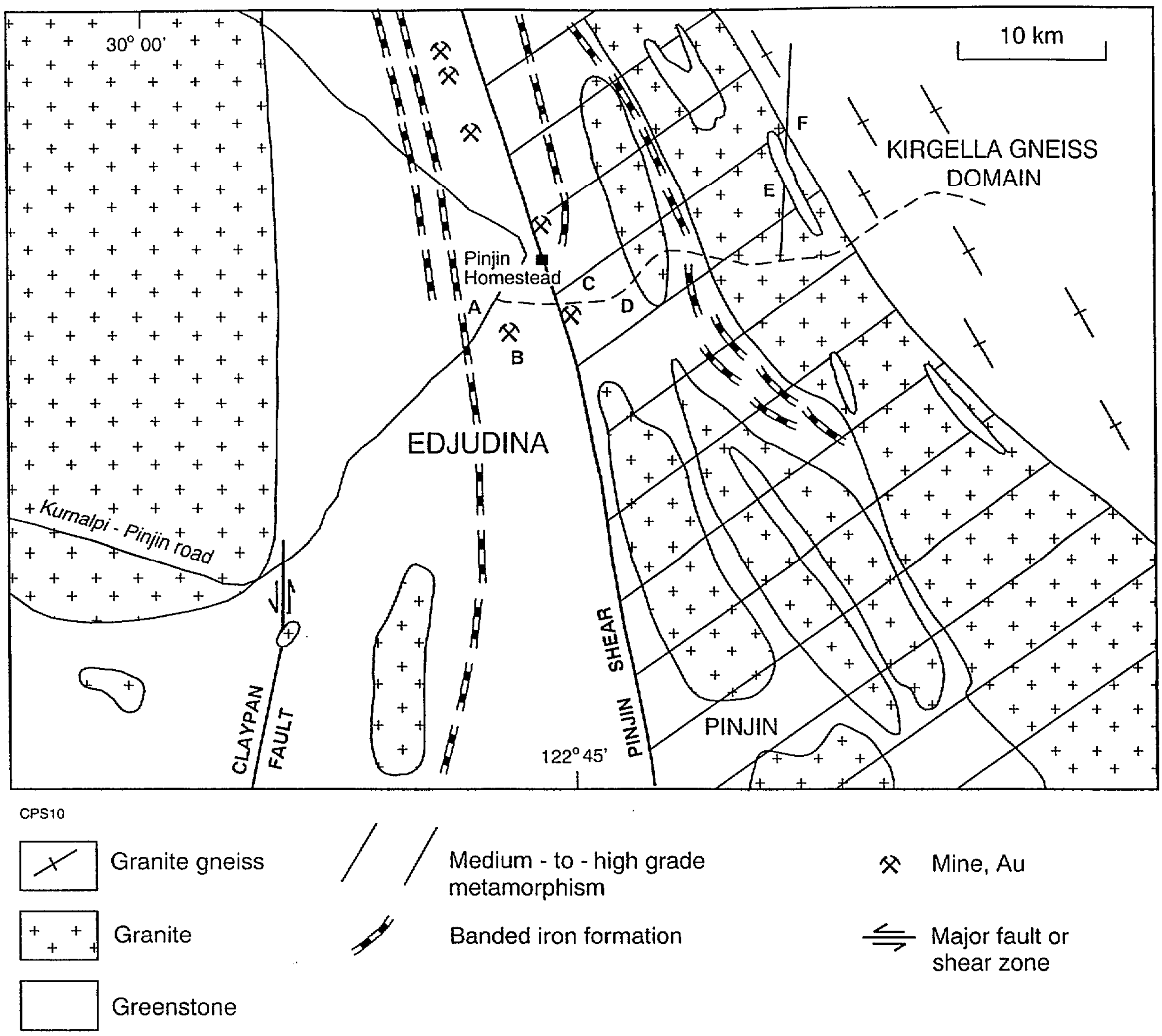

Fig. 11. Schematic map of the Pinjin area, highlighting the medium-high grade Pinjin domain adjacent to the low-medium grade Edjudina domain. Six stops along the Pinjin–Kirgella Rocks traverse are indicated.

C. Intermediate schist, with biotitic felsic schist to both east and west. These rocks are interpreted to lie within the Pinjin domain immediately east of the Pinjin Shear. They are characterised by more pervasive foliation development, with shallow to intermediate south-plunging lineations, and by upper greenschist to lower amphibolite metamorphic facies.

The intermediate schists are hornblende-biotite quartzo-feldspathic schists with variable hornblende contents and local relicts of feldspar phenocrysts or clasts. They are interleaved with felsic schist and thin amphibolite at various scales up to 1m. Prismatic and acicular hornblende is present in the fine-grained matrix, and as medium- to coarse-grained porphyroblasts. The latter have grown across, and enclosed, trails of opaques. Hornblende is also present in veins and lenses, and highly irregular aggregates. Fine- to coarse-grained garnet is found in both leuco- and melanocratic intermediate schists.

The intermediate schists, with hornblende from 5-40% and biotite 1-10%, are transitional in composition and texture to felsic schist on the one hand and mafic schist/amphibolite on the other. Some melanocratic varieties may have been derived from associated dolerite-gabbro. However, whole rock geochemistry of selected leucocratic samples have calc-alkaline, dacitic to andesitic compositions (Swager, in press).

To the west, highly carbonated feldspar-phyric biotite-quartz-feldspar schists host gold mineralisation along the Oaks-Anglo-Saxon line of workings. This line represents the easternmost mineralized structure, and is part of the Pinjin Shear. The felsic schists include bedded rocks with local fragmental and/or conglomeratic layers.

D. Interleaved banded amphibolite and felsic schist is followed to the east by a thin BIF, metadolerite and well-layered amphibolite. Further east, fine-grained felsic schists with small feldspar and/or quartz clasts have a gently south-plunging intersection lineation. They are followed by amphibolite, hornblende schist, intermediate schist and tremolite schist layers interleaved with felsic schist. Along strike to the north, very localized staurolite-garnet-andalusite-biotite assemblages suggest temperatures around 600°C. The porphyroblasts contain trails outlined by quartz, ilmenite, etc. that are continuous with and parallel to the regional foliation in the matrix, suggesting late stage mineral growth.

E. Interleaved amphibolite-foliated (leuco)granite is characteristic for the easternmost part of the Pinjin domain and its boundary with the Kirgella Gneiss domain. Amphibolite is totally recrystallized with a weakly elongate granoblastic texture of hornblende and plagioclase, with local coarser-grained, irregular patches. Along strike to the south, metamorphic clinopyroxene has grown locally at the expense of hornblende, suggesting temperatures of 700°C or more.

Foliated granite, and variably foliated medium- to coarse-grained leucogranite and pegmatoidal dykes and sills are interleaved with amphibolite.

F. Kirgella Rockhole–migmatitic banded gneiss. The gneissic banding is defined by monzogranitic layers with different biotite or K-feldspar phenocryst contents; by darker, finer-grained possibly tonalitic layers; and by early granite sills and dykes. The banding is crosscut by medium- to coarse-grained, diffuse 'pegmatoidal' veins and irregular aggregates that contain magnetite and locally deep grey quartz aggregates. These pegmatoidal patches are interpreted to have formed by partial melting of the gneiss.

The gneissic banding is folded about doubly, gently plunging fold axes with an upright axial plane foliation parallel to the regional D2 structure in the greenstones. The pegmatoidal aggregates contain this foliation, but also appear to be partly controlled by fold limb and fold hinge geometries, suggesting that high grade metamorphism and initial migmatisation occurred early during upright folding. The folded gneisses were then crosscut by late pegmatite dykes, probably at the time of widespread emplacement of monzogranite.

The early gneissic banding may have evolved during horizontal D1 deformation, and was subsequently folded during D2 shortening. However, the complex early banding may well reflect a much longer history, and the gneiss could be a remnant of sialic basement on which the greenstones were laid down or tectonically emplaced.

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Excursion 2

A field guide to the felsic igneous rocks of the northeast Eastern Goldfields Province, Western Australia: core complexes, batholiths, plutons and supracrustals

Compiled by P.R. Williams✦, M.S. Rattenbury✦ and W.K. Witt✧
Contributors: D.C. Champion✦, P.A. Morris✧, J. Sheraton✦ and S. Wyche✧

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The fieldtrip will visit a wide variety of felsic intrusive rocks, intermediate and acid extrusive igneous rocks and metamorphosed felsic rocks in the Mt Ida, Leonora, Laverton, Yundamindera, Kookynie and Pinjin areas. We will focus on the tectonic setting, structural geology, geochemistry, geochronology and geophysics of many different granite types, and their relationship to felsic volcanic centres. We will also examine two gneissic domes and their deformed margins with adjacent greenstones to discuss the relevance of extensional metamorphic core complex models to the emplacement of the domes and the geometry of the Eastern Goldfields Province. Mine visits are planned to the Sons of Gwalia and Granny Smith operations to examine mineralisation styles adjacent to different granite types and in different structural settings. Geochemical and tectonic models for the formation and evolution of the Eastern Goldfields Province will be addressed.

Introduction

P.R. Williams

The Eastern Goldfields Province (EGP) is a broad tectonic subdivision of the Archaean Yilgarn Craton of Western Australia (Gee, 1979; Fig. 1). It is a highly mineralised geological province, hosting the bulk of Australia's gold and nickel resources. It remains one of the most prospective regions of the Australian continent. It is also a notoriously poorly exposed part of the continent, and there is a need for publicly available high-density geophysical information to supplement the sparse, but increasingly detailed, geological map data. Over the previous three years, the Australian Geological Survey Organistion, through the mechanism of the National Geoscience Mapping Accord, has put substantial resources into acquistion, processing and interpretation of high-resolution geophysical data. Airborne magnetic and radiometric surveys at 400 m line spacing have been acquired over three 1:250K map sheets, and purchased over a third. Gravity data over three of these sheet areas has been collected on a 4 km grid, one jointly with the Geological Survey of Western Australia. The Geological Survey of Western Australia has purchased access to 200 m line spacing aeromagnetic data over parts of a further six 1:250K sheets, covering the main greenstone belts of the southern part of the Province.

In addition, the Australian Geological Survey Organisation has conducted a major, 230 km long seismic crustal reflection transect over the western margin of the Province. This survey has provided definitive evidence regarding the nature of the greensone basement, the geometry of the basement contact, the internal structures of the greenstones, and the nature and shape of granitic intrusions (Fig. 2). In addition, the links between crustal scale structures and the structures which can be mapped on the surface have been established—providing an insight into the relationship between mineralisation and crustal and surface structures.

Part of the regional geological mapping program has been the collection and interpretation of whole-rock geochemical and isotopic data from the vast areas of granitic (s.l.) rock, guided by the new and unexpected insights into the nature of these "granitic" areas provided by the geophysical data.

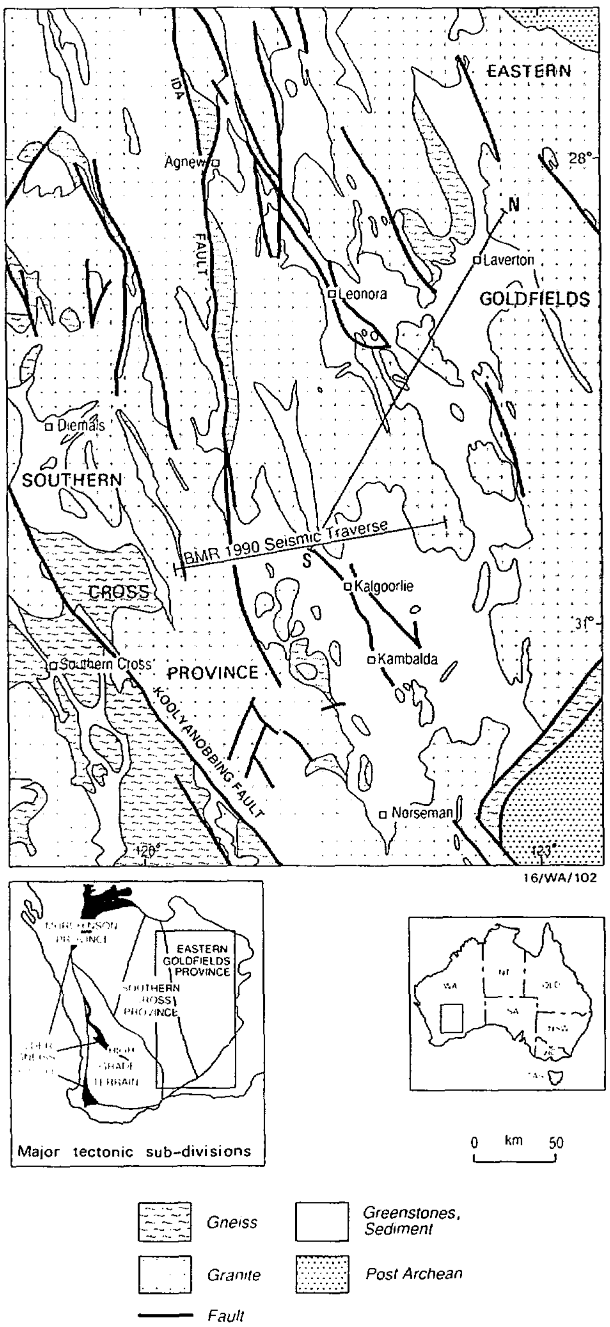

Fig. 1. The Eastern Goldfields Province of the Yilgarn Block in Western Australia. The position of the 1991 Regional Seismic Reflection Transect is shown.

This excursion and accompanying guide are designed to convey some of the current concepts being considered in the light of this vast array of new data now being made available, particularly on the origin and emplacement of the granitoids and how that has affected the greenstone belts. There is considerable controversy over the interpretation of the data—we see this as a healthy sign of the vitality of new information; the ongoing debate sparked by these new concepts will provide the basis for determining research and data collection strategies over the next decade. The development and presentation of scientific hypotheses and the testing of these against existing and new data is fundamental to the advancement of Australian science and industry—we invite your spirited participation in this process.

Geological setting of felsic magmatism

P.R. Williams

There is mounting evidence that the geological domains of the EGP and surrounding granitoids (Fig. 2) are derived from a range of crustal levels, and that the greenstones form a flat sheet which is separated by a detachment zone from the underlying felsic crust (Archibald, 1990; Goleby & others 1993; Williams & others in press). Felsic gneiss domains (from middle crustal levels) are generally marginal to the greenstone belts, and are commonly intruded by voluminous later granitic plutons and abundant minor granitic intrusions. Prior to the acquisition of the regional geophysical data, the nature and extent of the gneissic domains were poorly known, and their significance underestimated in most geological models for the EGP. Several large plutons and composite batholiths are present within the greenstone belts, and a selection of these will be visited during the excursion. Two intrusive forms have been identified. Elongate composite intrusions appear to be structurally controlled, whereas plutons with sub-circular cross-section commonly occur in low-strain zones and occupy regional anticlinal cores. A number of late stocks are also part of the felsic magmatic history, and their positions are also structurally controlled (Hallberg, 1985). Two geochemically distinct suites of felsic extrusive rocks have been identified (Hallberg & Giles, 1986), andesite-dominated volcanic centres and rhyolite-dominated centres. There is good evidence that the rhyolitic centres are extrusive equivalents of the some of the granite plutons, whereas a relationship of the andesitic rocks to plutonism has been suggested (eg Hallberg & Giles, 1986), but not as clearly established.

Stratigraphic setting

P.R. Williams

Although no definite basement to the greenstone sequences has been established, a regional stratigraphy has been identified in several regions, but particularly around Kalgoorlie and Kambalda. The lowest exposed unit is a thick basaltic succession, overlain by extensive komatiite flows.

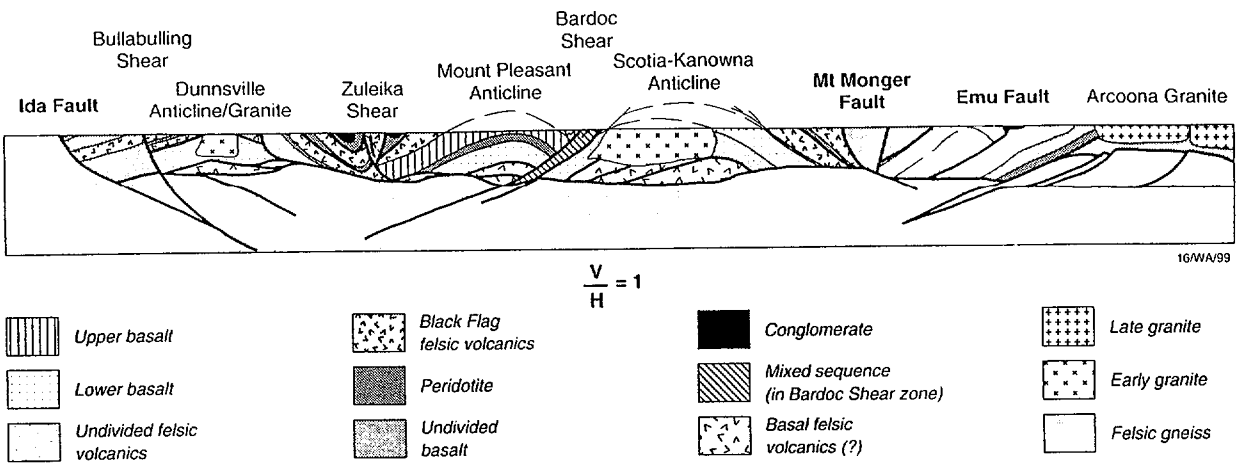

Fig. 2. Geological interpretation of the 1991 Regional Seismic Reflection Transect migrated and unmigrated data. Significant new findings were the shallow (<7 km) depth to gneissic(?) basement, a major subhorizontal décollemont at the base of the greenstone, the large scale of the Ida Fault and Bardoc Shears, and the 3-D form of some of the granite "domes" (Goleby & others 1993).

In places the komatiite is overlain by an upper basaltic succession. The upper part of the succession comprises felsic volcanic rocks and volcaniclastic sediments, in places unconformably overlain by conglomeratic sedimentary sequences. Age determinations on a variety of rock types within the Kalgoorlie region suggest that deposition of the sequence commenced just prior to 2700 Ma and continued until at least 2690 Ma (Claoué-Long & others, 1988; Campbell & Hill, 1988; Hill & others, 1989). There is speculation that felsic volcanic sequences underlie the lower basalt unit, based largely on interpretation of gravity data in conjunction with the regional seismic traverse (Goleby & others, 1993, Williams & others, in press). In addition, Hallberg (1985) and Williams & others (1993) have mapped a significant section of intermediate volcanic and volcaniclastic rocks stratigraphically below the Kalgoorlie "lower basalt" equivalent in the area east of Leonora (Rattenbury, 1993). It seems unlikely that greenstones in the northeastern Eastern Goldfields Province are older than 2735 Ma, the oldest date so far obtained from within the greenstone stratigraphy (Pidgeon & Wilde, 1990).

Stratigraphy of the northeast Goldfields

M.S. Rattenbury

Correlating stratigraphy between greenstone belts has been attempted only to a limited extent in the northern EGP. Greenstone belts from the Kalgoorlie–Kambalda region are more continuous and better known from a wealth of subsurface drilling information than those in the northern EGP. The stratigraphic succession of the Laverton and Mt Kilkenny regions has been established by Gower (1976) and Hallberg (1985), but the correlations of these regions west to the Leonora and Mt Ida stratigraphic sequences, and south into the Kalgoorlie–Kambalda region have not been demonstrated. Structural complexities such as the Keith–Kilkenny high-strain zone and large areas of intervening granite and gneiss south and west of Leonora have rendered regional stratigraphic correlation difficult. Nevertheless, regional stratigraphic correlation has been attempted in the northern EGP (Rattenbury, 1993) based on the premise that ultramafic rocks can be used as stratigraphic marker horizons. Most ultramafic rock in the EGP, including the komatiites and the olivine-rich cumulates, are considered to be extrusive flow rocks (Hill & others 1985). Komatiitic lavas have very low viscosities such that single unimpeded komatiite flows may travel over 150 km and have the potential to be important stratigraphic markers units, especially since most greenstone belts contain only one apparent stratigraphic level of ultramafic rock. Correlation of regional ultramafic marker horizons between greenstone belts has been achieved (Rattenbury, 1993) by matching associations of mafic, felsic and intermediate volcanic and sedimentary sequences above and below each ultramafic occurrence throughout the northern EGP (Fig. 3). An important link between the ultramafic rocks near Mt Kilkenny with the Kalgoorlie–Kambalda region komatiites and cumulates has been established. This has been independently confirmed by single zircon U-Pb geochronology (Claoué-Long, unpublished data) which suggests the ultramafics are the same age (within analytical error). The Mt Ida ultramafic rocks also

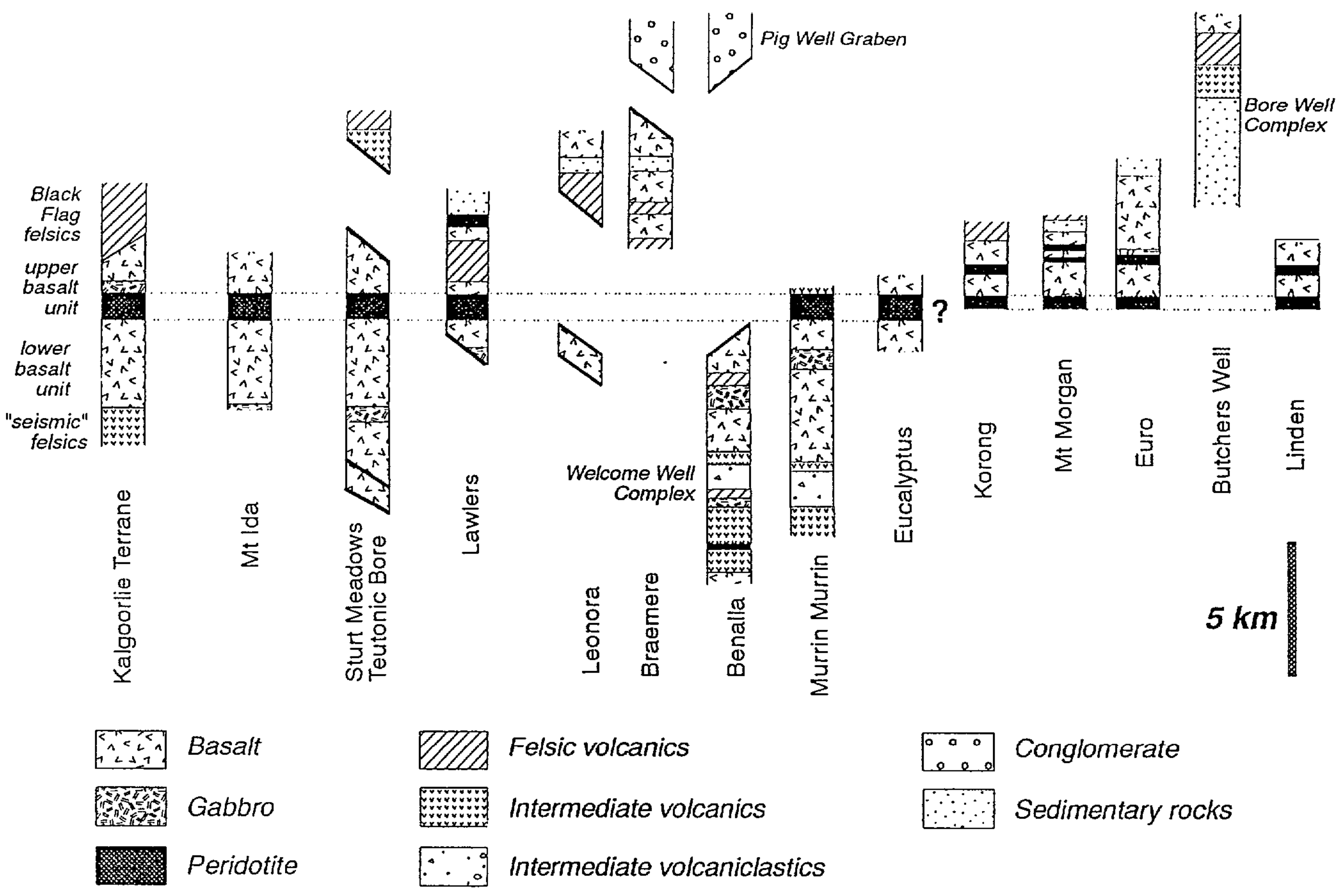

Fig. 3. Stratigraphic correlations across the northern EG, assuming a regional marker ultramafic horizon. Stratigraphic thickness is very approximate and does not account for structural thickening or excision.

correlate with the same ultramafic horizon. Correlation of the Laverton stratigraphy is complicated by multiple levels of ultramafic rocks, however, and remains ambiguous. Felsic and intermediate volcanic centres occur at least two stratigraphic levels, above and below the ultramafic marker horizon. The Welcome Well volcanic centre lies stratigraphically below the ultramafic marker near Mt Kilkenny whereas the Melita and Black Flag volcanic centres are younger than the ultramafic marker. The Bore Well and Ida Hill felsic-intermediate volcanic centres cannot yet be confidently placed into a regional stratigraphic context because of the uncertainty surrounding the relative position of the Laverton stratigraphy. The recognition of intermediate and felsic volcanic rocks older than the lowest known mafic-ultramafic sections of the Kalgoorlie Terrane stratigraphy supports the recent crustal seismic reflection/gravity traverse interpretation of basal felsic (volcanic?) rocks below the lowermost basalt (Goleby & others 1993; Williams & others in press).

Structural and metamorphic setting

P.R. Williams

The structural geological history of the EGP has been discussed by several authors (eg Archibald & others, 1981; Swager & others, 1990; Swager & Griffin, 1990a; Williams & others, 1989; Hammond & Nisbet, 1992; Williams & others, in press). Table 1 shows a summary of the structural history of the Province established in different areas. There is a lot in common between all of these proposed structural histories. All recognise an early phase of low-angle bedding parallel deformation, a later phase of upright folding, and still later strike-slip faulting.

However, there are significant differences in the details of the structural history from different regions. In the northeast Goldfields, Hammond & Nisbet (1993) propose that the early deformation is extensional, and suggest that the later upright folding is accompanied by significant high angle reverse faults which splay off a major décollement at depth. Archibald (1990) recognised two phases of early thrust deformation. Williams & Currie (1993) suggest that the earliest phase of low angle deformation in the Leonora district is extensional rather than compressional, and Williams & others (in press) have proposed that there is a major phase of extensional deformation which post-dates

Event	Study			
	Swager & Griffin 1990a (Kalgoorlie)	Williams & others 1993 (seismic line)	Hammond & Nisbet 1992 (northern)	Williams & Currie 1993 (Leonora)
D_{e1}		Basin formation, possible growth faults and half-graben development	Shear zones on gneiss/granite - greenstone margins	Shear zones on gneiss/granite - greenstone margins
D_1	Thrust faults and sequence repeats	Basal shears on greenstone, high level thrust faults	NNW directed thrusts, sequence repeats	Thrust faults and sequence repeats
D_{e2}		Extensional faulting, affecting whole of upper and middle crust, core complex emplacement.		
D_2	ENE-WSW shortening, upright folds, NNW steep cleavage	ENE-WSW shortening, upright folds, regional cleavage	ENE-WSW shortening, fault imbrication over a deep detachment	ENE-WSW shortening, upright folds, cleavage, reactivation of earlier shears
D_3	Sinistral wrench fault during regional shortening, later faults	NW-NNW sinistral faults and shears NE faults	NS dextral faults and shears, related to D_2	NS dextral shears, NNW sinistral reactivation

TABLE 1. Deformation sequence in the eastern Goldfields.

the thrust deformation, an interpretation based on restoration of the greenstone geometry from the regional seismic line north of Kalgoorlie. Clearly, more work is needed to resolve the issue of timing of regional deformation events, and the links between deformation sequences in different areas.

The metamorphic grade of the greenstone belt varies from very low grade in some areas to middle-upper amphibolite grade in narrow zones close to gneissic granites (eg Binns & others, 1976; Archibald & others, 1981). In addition, granite intrusions within the greenstone belt have relatively narrow thermal metamorphic aureoles in which post-kinematic andalusite porphyroblasts are common in appropriate lithologies. The regional metamorphic pattern was mapped by Binns & others (1976), and the timing of metamorphism in relation to the structural history discussed by Archibald & others (1981). In the Kambalda area, peak metamorphism coincided with the upright folding, and grade was controlled by proximity to nearby granite intrusions. However at Leonora, several lines of evidence, principally andalusite, chloritoid and hornblende porphyroblast relationships (Williams & others, 1990; Passchier, 1990; Vanderhor & Witt, 1992) indicate that peak metamorphism was associated with the extensional deformation and largely predated the upright folding. The grade of metamorphism drops rapidly away from the high-grade zones, and Williams & Currie (1993) suggest that peak metamorphism in the lower grade areas was later than that in the amphibolite grade domains.

Geochemistry and classification of granitoid intrusions

Granitic rocks in the southwestern goldfields

W.K. Witt

Regional mapping under the GSWA/AGSO Eastern Goldfields Province Mapping Accord, combined with evidence from commercially available aeromagnetic data, suggests that granitic rocks in the Southwest EGP (SWEGP) can be divided into three broad structural groupings (Fig. 4):

- granitoid gneiss,
- pre-regional folding granitoid (pre-RFG) complexes and
- post-regional folding granitoid (post-RFG) plutons.

Granitoid gneiss occurs mainly along the western and eastern margins of the EGP. It is intruded by, and occurs as xenoliths in post-RFG plutons. However, contacts of granitoid gneiss with pre-RFG complexes and greenstones are poorly exposed, or tectonised.

Pre-RFG complexes form elongate domes and more irregular bodies which are regionally conformable with primary layering in the greenstones. They are commonly located in the cores of F_2 anticlines and contain a spaced or pervasive northwest to north-northwest strikingregional foliation. Margins of the complexes display strong contact-parallel deformation and north- to northwest-trending lineations. They were probably em-

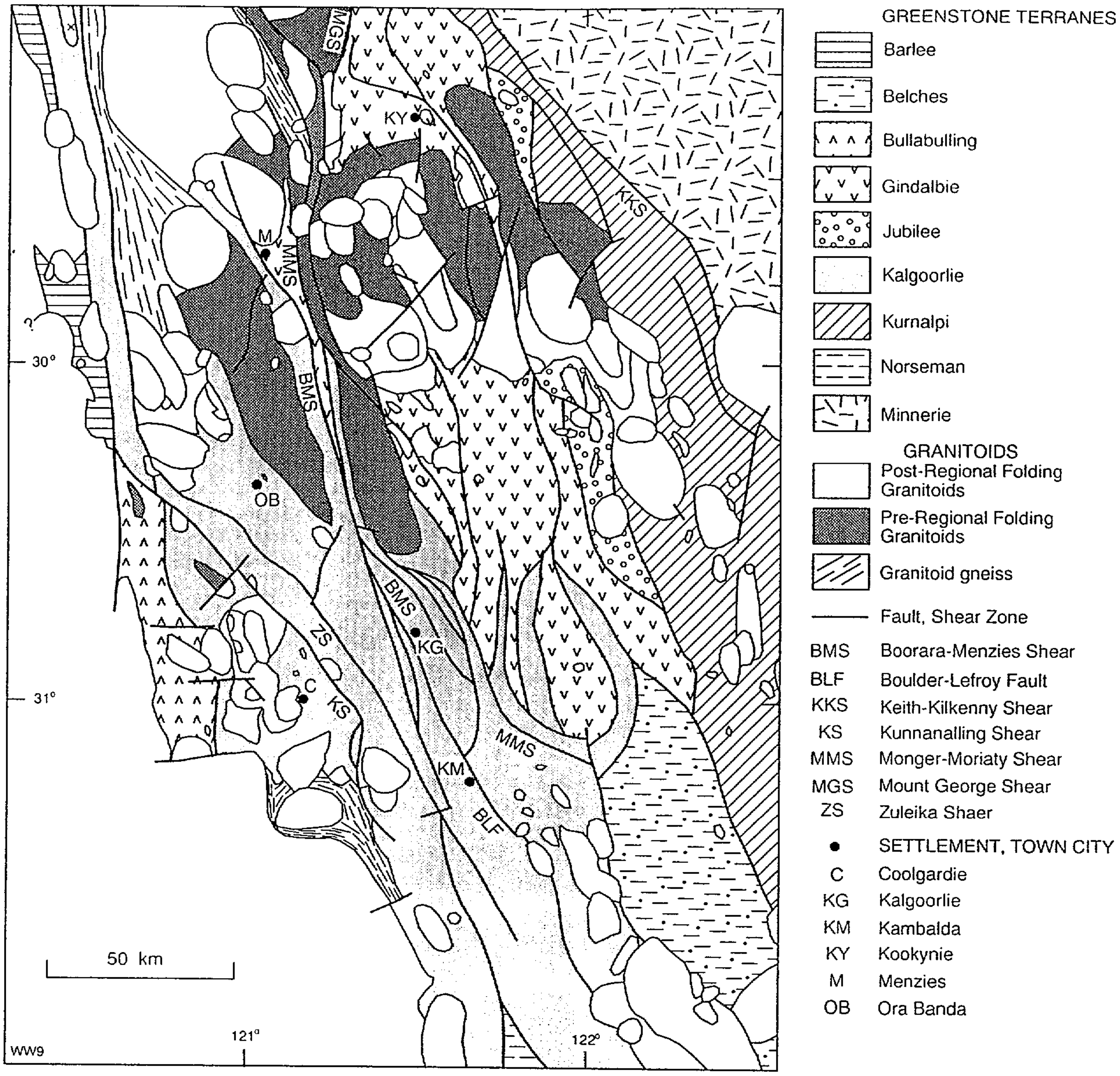

Fig. 4. Pre-regional folding granitoids, post-regional folding granitoids and greenstone terranes, Southwest Eastern Goldfields Province.

placed as composite sheet-like intrusions near the base of the exposed greenstones during stacking within the greenstone sequences. Thin high pressure metamorphic carapaces, preserved locally adjacent to the complexes, contrast with regionally extensive low pressure metamorphic assemblages and suggest broad domed uplift prior to regional folding (D_2).

Post-RFG plutons have circular to ovoid surface expressions which intrude greenstones, granitoid gneiss and pre-RFG complexes. These granitoids include syntectonic, late-tectonic and post-tectonic examples, and display variable degrees of deformation and recrystallisation. Intrusive mechanisms include diapirism, forceful emplacement by relatively brittle deformation of country rocks, and passive, piecemeal stoping. Regional metamorphic isograds are broadly concentric with respect to syntectonic intrusions.

Limited precise zircon dating in and adjacent to the SWEGP indicate ages of 2685-2690 Ma for pre-RFG complexes and 2660-2665 Ma for peak intensity of post-RFG magmatism although emplacement of granitoids continued beyond 2600 Ma (Hill & others, 1992).

The SWEGP granitoids are overwhelmingly dominated by calc-alkaline monzogranite and granodiorite. Primary mineral assemblages indicate high fO_2 magmas, and secondary minerals reflect a further increase in fO_2 during metamorphic (and deuteric?) recrystallisation. Geochemical data permit all pre-RFG, and most post-RFG samples to be assigned to one of eight suites (Table 2). All pre-RFG suites (possibly excepting

TABLE 2. Summary of main features of granitoid suites in the southwestern Eastern Goldfields Province.

Suite	*est. vol. % of granitoids*	*% SiO_2*	*Non-quartzo-feldspathic mineralogy (a)*	*Microgranitoid xenoliths, synplutonic dykes*	*Negative anomalies on chondrite-normalized spidergrams*	*Probable source rock*	*Predominant fractionation mechanism*
Post-regional folding granitoid suites							
Gilgarna	<5	54.0–67.1	Clinopyroxene (Amphibole)	Present		Granulite	Uncertain
Dairy	<5	75.3–76.7	Biotite (Hornblende, muscovite)	Not observed	Nb, Sr?, P, Ti	Monzogranite	Fractional crystallization, contamination (?)
Bali	10	71.9–76.5	Biotite (Muscovite, garnet)	Not observed	Nb, P, Ti, Y	Granodiorite	Fractional crystallization, metasomatism (?)
Woolgangie	50	70.5–75.0	Biotite (Muscovite, garnet)	Not observed	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Liberty (b)	5	66.4–71.7	Biotite Hornblende	Present	Nb, P, Ti, Y	Tonalite	Fractional crystallization
Pre-regional folding granitoid suites							
Minyma	<5	76.4–77.3	Biotite Hornblende	Not observed	Nb, Sr?, P, Ti	Monzogranite	Fractional crystallization, contamination (?)
Goongarrie	10	71.0–76.5	Biotite	Locally only	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Twin Hills	10	71.3–75.1	Biotite	Present	Nb, P, Ti, Y	Granodiorite	Fractional crystallization
Rainbow	10	66.1–71.3	Biotite Hornblende (Clinopyroxene)	Relatively common	Nb, P, Ti, Y	Tonalite	Fractional crystallization

(a) Brackets indicate mineral is present (generally in minor amounts) in some samples only

(b) The Liberty Granodiorite is described as a representative of the unassigned post-RFG plutons

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the Minyma Suite) appear to be well represented in the SWEGP. Post-RFG granitoids are volumetrically dominated by the Woolgangie Suite but also include a diverse group of miscellaneous plutons, each with its own source rock. The granitoids all have I-type, metaluminous to weakly peraluminous compositions, excepting the alkaline Gilgarna Suite which significantly post-dates (<2600 Ma) the calc-alkaline granitoids. Examples of Harker variation diagrams are shown in Fig. 5A,B. Chondrite-normalised rare earth element (REE) curves for the Rainbow and Goongarrie Suites are steeply fractionated and lack Eu anomalies. Those for the Woolgangie Suite are less fractionated and display a variable negative Eu anomaly. Dairy Suite granitoids have distinctive concave-upward, moderately fractionated REE curves.

Some suites contain relatively mafic microgranitoid xenoliths and dykes which range in composition from diorite to quartz monzonite, and display textural and structural evidence for a syn-plutonic origin. However, there is only limited evidence for magma mixing or contamination of the host granitoid by the more mafic magmas. The xenoliths are weakly alkalic, range from 50% to 68% SiO_2 and are enriched in REE, P_2O_5, F, Th, Li and Zn, relative to calc-alkaline granitoids of the SWEGP with similar SiO_2. Unlike restite-dominated suites, the xenoliths do not display a straight line relationship with the host granitoids on Harker variation diagrams.

Compositional variation within most calc-alkaline granitoid suites can be attributed mainly to fractional crystallisation of biotite, plagioclase and apatite (hornblende, K-feldspar, titanite, zircon and magnetite). Although the origin of the Minyma and Dairy Suites is less clear, available data are consistent with a combination of fractional crystallisation and variable assimilation/contamination by granitoid gneiss and greenstones. Limited data cannot resolve the significance of granitoid gneiss which may include basement to the greenstones (although unconformities and basal conglomerates have not been observed) and/or strongly deformed and metamorphosed equivalents of pre-RFG complexes.

Granitic rocks in the Leonora–Laverton region

D.C. Champion

Champion & Sheraton (1993) have classified the granitoids and gneisses of the Leonora-Laverton region into six groups using both structural and geochemical criteria. In possible order of intrusion these are:

- 1. Pre-folding (pre-regional folding group)
  a – banded gneisses
  b – pre-folding granitoids
- 2. Mafic granitoids
  a – pre-folding
  b – post-folding
- 3. HFSE-enriched granites
- 4. High-Ca post-folding granitoids (includes Woolgangie Suite)
- 5. Low-Ca post-folding granitoids (Mount Boreas Supersuite)
- 6. Syenites (= Gilgarna Suite)

Names in parentheses refer to classifications used by Witt (previous section).

The gneisses and the pre-folding granites are geochemically similar and appear to be of similar age (see below) and were treated by Champion & Sheraton (1993) as one group: the pre-folding group. Representatives from Groups 1, 4, 5 and 6 will be visited on this excursion (Stops 6, 7 and 15). Only groups 1, 4 and 5 are discussed here, Group 6 has been described by Witt in the previous section.

The pre-folding granitoids comprise an areally extensive part of the region. They are distinguished from other granitoids by the presence of gneissic layering and/or a strong foliation and commonly contain concordant zones of amphibolite, mafic schist and microgranitoid. The gneisses range from relatively homogeneous to strongly layered, and are locally migmatitic, with original igneous features largely absent. Original textures in the granitoids vary from porphyritic to equigranular, subhedral to anhedral granular. Deformational (and metamorphic) effects are evident in the development of lepidoblastic and granoblastic textures. The rocks range from biotite-rich trondhjemite to biotite leucogranodiorite and granite. They contain locally abundant pegmatite and aplite veins which both parallel and cross-cut the foliation. If the temporal framework of Hill & others (1992) applies to the northern EGP, then the pre-folding granitoids are most probably 2690-2685 Ma in age. Recent U-Pb zircon dating of gneisses in the Leonora area (L.P. Black, pers. comm.) indicate ages of about 2685 Ma, identical to those of the older granites, suggesting that gneisses are most likely temporal equivalents to the latter; additional work is needed to confirm this.

The high- and low-Ca post-folding

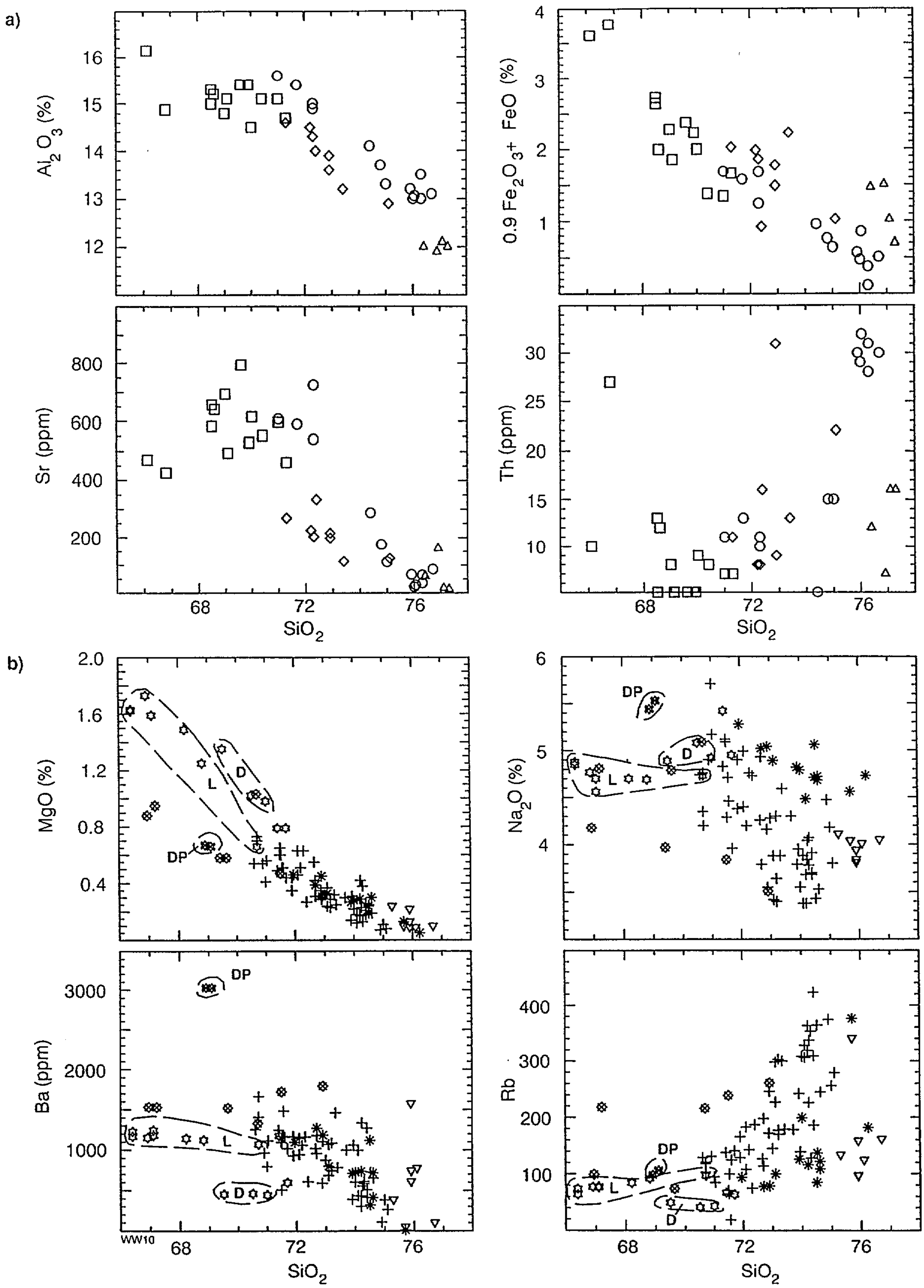

Fig. 5A. Harker variation digrams, pre-RFG suites - Rainbow (squares), Twin Hills (diamonds), Goongarrie (circles), Minyma (triangles). B. Harker variation digrams, post-RFG suites - Woolgangie (plusses), Ball (asterisks), Dairy (inverted triangles). Unassigned plutons are Liberty Granodiorite (star L), Doyle Granodiorite (D), Bonnievale Tonalite and Kambalda Trondhemite, Depot Granodiorite (star DP), and other unassigned post-RFG plutons (hatch).

granitoids are characterised by their lack of foliation, although a weak foliation is present locally. Both groups are petrographically similar, but the high-Ca group comprises sodic biotite granodiorite, trondhjemite and granite, whereas the low-Ca group is dominantly granite (syeno- and monzogranite). Textures vary from porphyritic to equigranular, and subhedral granular to irregular granoblastic. Microgranite, aplite and pegmatite dykes and patches are locally very abundant. These two groups are synomynous with the post-folding and fractionated leucoadamellite groups of Bettenay (1977). Correlation with the ages of Hill & others (1992) suggests the post-folding groups include ages of 2665 Ma and possibly younger.

The geochemistry of pre-folding granitoids, and high-Ca and low-Ca post-folding granitoids have been described in detail by Champion & Sheraton (1993). All have a narrow compositional range (68 to 76% SiO_2), are generally slightly peraluminous, are Nb depleted and all appear to be infracrustal in origin, i.e are I-type. The pre-folding granitoids are characterised by high Al_2O_3, moderate to high Na_2O, and moderate K_2O, Rb, Pb, Th, and U (Fig. 6). They are generally Sr-undepleted and Y (and HREE) depleted. The majority have strongly fractionated REE patterns and show variable LREE enrichment. The high-Ca granitoids are geochemically similar to the more potassic members of the pre-folding group, although tend to higher Th, Zr and LREE in the more mafic members (Fig. 6).

The low-Ca post-folding granites (Mount Boreas Supersuite) are geochemically distinct from all other granitoids in the region. For a given SiO_2 content, they have lower Al_2O_3, CaO (Fig. 6), and Na_2O, and higher K_2O. The most notable differences are in the trace elements; Rb, Th, U, and Pb are distinctly higher (Fig. 6), whilst Zr, La, Ce, Nd, Y are higher in the more mafic rocks, with many of the low-Ca granites being Y-undepleted. All are Sr depleted. Systematic variations in trace elements and Rb/Sr and K/Rb ratios suggest that crystal fractionation was significantly more important than in the older granitoids.

Felsic volcanism in the Eastern Goldfields

P.A. Morris

Felsic volcanic rocks in the EGP form a major part of the stratigraphic succession in the Kalgoorlie–Kambalda area, where they are the major part of the Black Flag Group, in the upper part of the sequence. In the northern part of the Goldfields, several volcanic centres have been identified, and the volcanics have less lateral continuity than does the Blag Flag Group. Giles (1982), Giles & Hallberg (1982) and Hallberg & Giles (1986) identify two geochemically distinct suites of felsic and intermediate volcanic rocks, andesite dominated and rhyolite dominated, which are associated with different intrusive events.

Volcanology

Black Flag Group

Felsic volcanic and related rocks of the Black Flag Group have been examined in drill core and outcrop between Ora Banda in the north and Love's Find (southeast of Widgiemooltha) in the south. Volcanic rocks comprise dacitic and rhyolitic lava flows and minor subaqueous (locally subaerial?) basalt. Andesitic flows and reworked tuffs form localised outcrops at White Flag Lake northwest of Kalgoorlie, and at Mt Shea south of Kalgoorlie. At the latter location, there is some evidence to support localised interdigitating of felsic volcanic rocks with the youngest phase of mafic volcanism in the Kalgoorlie Terrane.

The dacites and rhyolites occur as subaqueous lava lobes and hypabyssal intrusive equivalents. Oligomict breccias proximate to lobes are interpreted as quench-fragmented breccias derived from wastage of lobes. Current bedded deposits also show a limited clast range and are interpreted as more distal equivalents of lobe wastage, with some reworking of associated ? pyroclastic deposits. The mineralogy of deposits is quartz-feldspar. Andesites are subaerial to locally subaqueous. Associated tuffs are crystal rich and have the same mineralogy as flows, so there is evidence for coeval lava eruption and pyroclastic activity. Basalts are locally amygdaloidal and subaqueous.

Melita and Jeedamya

Much of the information on volcanology of these deposits is from Hallberg (1985) and Witt (in press). At both centres, the volcanic rocks are essentially bimodal (minor basalt and dolerite, dominantly rhyolite with subordinate dacite). The felsic volcanic rocks are scoria and ash deposits and reworked equivalents, with some felsic lava flows. Witt (in press) maintains that there is significant evidence for pyroclastic activity. The mineralogy is quartz-feldspar.

Kanowna

Volcanism in the Kanowna area reflects rapid lateral facies changes and syn-volcanic

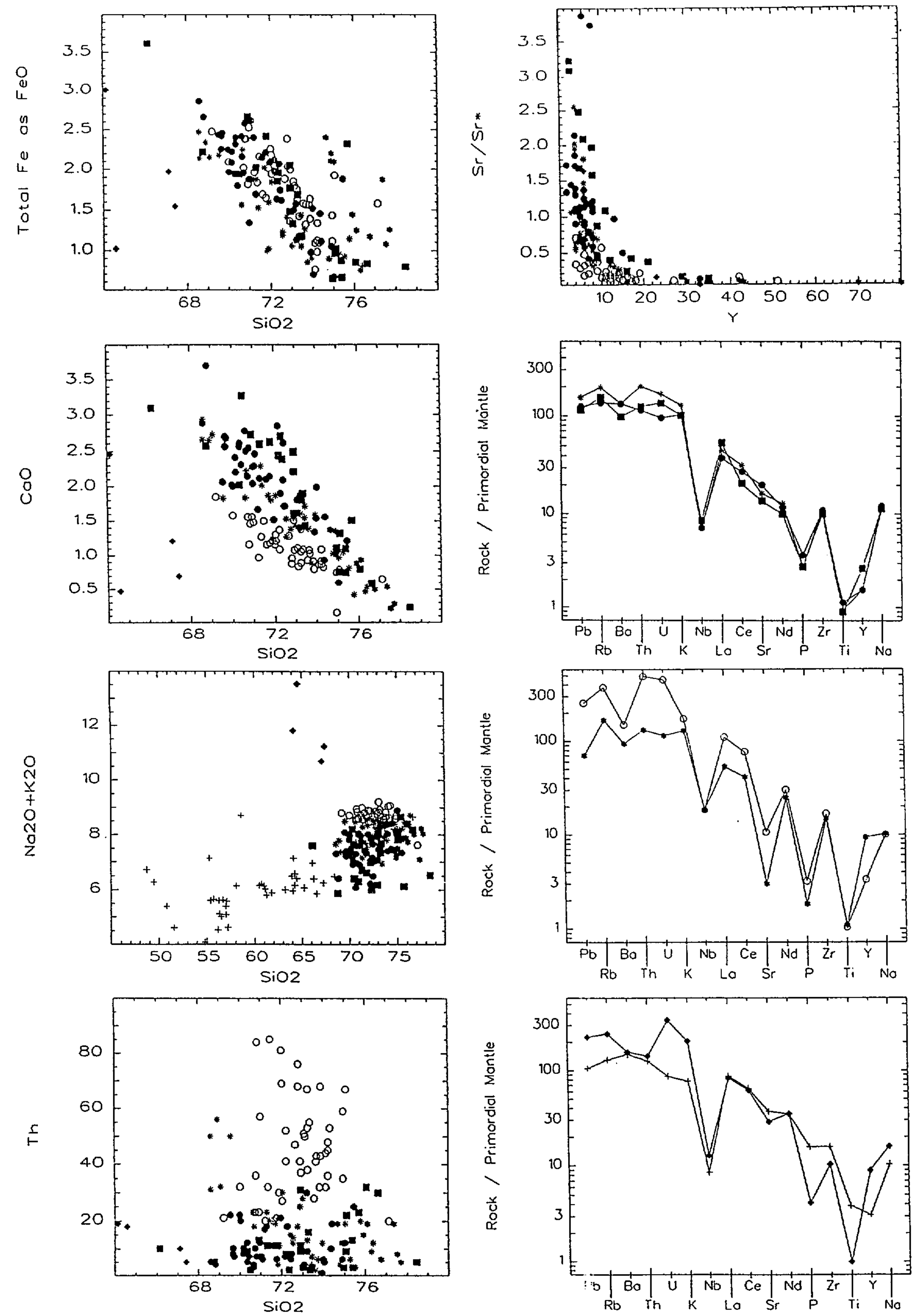

Fig. 6. Variation diagrams and multi-element primordial-matle-normalised abundance diagram (normalizing values from Sun & McDonough, 1989, and Na = 2890 ppm), for granitoids of the Leonora-Laverton region. Group averages are used in the multi-element abundance diagram (see Champion & Sheraton, 1993). Gneisses - filled circles; pre-folding granitoids - filled squares; high-Ca post-folding granitoids - asterisks; low-Ca post-folding - open circles. (Most geochemical data from AGSO, unpublished; additional data from Bettenay, 1977; Cassidy, 1992; Witt, unpublished.)

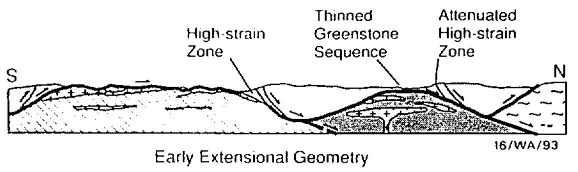

Fig. 7. Possible cross-sectional style of the Leonora–Laverton region–assuming core complex emplacement of gneiss domes (from Williams & Whitaker, 1993).

uplift and erosion. Felsic volcanic rocks comprise small volume block and ash flows (ie nueés ardente), and subaerial lava flows, although most felsic rocks are redeposited degraded ?lava flows and ?tuffs. Deposits are usually weakly polymict with felsic volcanic fragments accompanied by ultramafic and mafic fragments. Other authors (eg Taylor, 1984; Ahmat, 1990) have recorded tourmalinite beds, stromatolites and signs of large-scale mass flow. Thus there is evidence for active tectonism and hydrothermal activity during volcanism.

Based on volcanology and geochemistry, Hallberg & others (1993) have argued that the Kanowna volcanic sequence belongs with the Melita and Teutonic Bore successions, rather than the Black Flag Group.

Geochemistry

The Black Flag Group forms a geochemically cohesive suite over a wide geographic area and includes both extrusive and high-level intrusive felsic igneous rocks. It is generally less siliceous than the Melita Volcanics, and has distinct chemical characteristics that mean the Black Flag and Melita rocks are not genetically related. The Black Flag Group andesites, dacites and rhyolites have higher Sr/Y, La/Y, chondrite–normalised La/Yb, lower Nb, and lack a negative Eu anomaly compared to the Melita Volcanics. Based on available data, most Kanowna felsic volcanic rocks group with the Melita rather than the Black Flag Group volcanics. The main controls within each group seem to be the combined effects of variable degrees of partial melting of similar source materials, and fractional crystallisation. Despite their disparate chemical characteristics, both the Black Flag Group and Melita volcanics could have been derived from the same source material, a metamorphosed andesite, or a metamorphosed MORB-type basalt. Black Flag dacite can be derived by about 25% partial melting of metabasalt or about 45% partial melting of meta-andesite, in both cases with a garnet amphibolite residue. Notably, melting of neither source leaving an anhydrous (ie amphibole free) residue gives satisfactory modelling results. However, about 20% partial melting of the same meta-andesite, but leaving an anhydrous residue, would produce a composition similar to a Melita rhyolite.

Magmatism in a tectonic framework

P.R. Williams

The tectonic evolution of the EGP is intimately associate with felsic magmatism. Campbell & Hill (1988) have proposed a tectonic model whereby the diapiric emplacement of large batholiths was the main driving force for high-level basin formation and crustal deformation. They propose that the magmatism was driven by mantle plume activity. Although several authors disagree that the granite emplacement caused major regional deformation in the greenstones, the plume model is very attractive in providing adequate heat input to initiate basin formation and lower crustal anatexis. As discussed above, in the EGP there appears to be discrete granite emplacement events, separated by about 20-25 Ma. The emplacement style and to an extent the geochemistry, differs in each event and have distinctive relationships with the structural history (Witt & Swager, 1989).

Emplacement of gneiss and early granites

In an attempt to explain the structural relationships, metamorphic history and the boundary relationships common between gneiss, granite and greenstones, Williams & Currie (1993) and Williams & Whitaker (1993) have suggested that the emplacement of gneiss and granite domes may be related to regional extensional deformation. The model for emplacement suggested by Williams & Whitaker (1993) and Williams & Currie (1993) is based on rapid crustal uplift by mechanisms similar to those associated with metamorphic core complex formation in Cordilleran geology. A cross section similar to that shown in Fig. 7 is likely in this type of model. The early deformed granite bodies are most likely discontinuous sheets which were emplaced near the base of the greenstones (for example, the Laverton area, described by Williams & Whitaker, 1993), or as sheets within the gneiss. These early granites are likely to have undergone domal uplift early in the structural sequence, to account for their current shapes. A brief summary of the crustal conditions under which core complex formation and regional domal uplift may occur is therefore appropriate.

Dynamics of crustal uplift and core complex formation

Juxtaposition of high grade metamorphic rocks arising from mid-crustal levels against low grade rocks requires substantial uplift of the mid-crustal rocks. This can be achieved through either multi-stage thick-skinned thrusting (eg. Shaw & others, 1992), or thermal uplift as metamorphic core complexes. The latter uplift is common in an extensional tectonic setting (Fig. 7). In the former process, the higher grade rocks are normally sitting structurally above the lower grade rocks, and the two sequences are bounded by either thrust or high-angle reverse faults. In the second environment, the reverse is true, and the lower grade rocks lie above the higher grade rocks on (originally) shallowly-dipping mylonitic faults. In the EGP, many authors have noted that gneiss and deformed (gneissic) granite are always exposed structurally beneath the greenstones, and that the boundaries between the two are marked by mylonitic shear zones. Williams & Currie (1993) have shown that the lower grade sequences are juxtaposed against higher grade seqences over a few metres of section in the Leonora area. Consequently, the major boundary fault in that area is one of structural excision of section, and not merely an intrusive boundary. A similar boundary will be visited on this excursion at Mount Jessop.

That core complexes were emplaced in an extensional tectonic setting is now generally accepted. Extension causes the rapid uplift of lower plate material, at the same time as the lower plate undergoes deformation by ductile non-coaxial laminar flow (Lister & others, 1986). Once extension has commenced, uplift is driven by thermal effects in the crust and isostatic compensation (Sonder & England, 1989; Buck, 1991). The thermal regime of the crust prior to extension has a major effect on the yield strength of the crust, with higher heat flow reducing initial yield strength. Thus a thermal input (such as a mantle plume) will enhance crustal flow under extension and physical properties will favour core complex formation as the main response to extension (compare Buck, 1991).

There is however, considerable debate over the actual driving force of extensional processes. For example, in the Basin and Range Province two main processes have been proposed; plate interactions (eg Coney, 1980) and crustal flow due to overthickening during the Laramide Orogeny (eg Wernicke & others, 1987). In the EGP, the same difficulties are apparent (Table 1). The age of uplift of the gneiss domes and belts, relative to the compressional deformation phases, needs to be determined, and the tectonic processes leading to formation of the greenstone basins needs integration into the regional deformation history, as has been attempted by Hammond & Nisbet (1992). However, until detailed, high resolution zircon geochronology becomes available, the current models must be considered tentative.

Large plutons and batholiths

The bulk of these intrusions are subcircular in form and several have deformed margins around which the regional foliation is deflected. The form in the depth dimension is not well constrained, although one of these intrusions, the Bundarra Batholith (north of Leonora and east of Teutonic Bore) is probably relatively thin in its western margin and probably sheet-like in form (from the geophysical model, Whitaker, personal communication). Others (eg southeast of Ida Valley) coincide with large gravity lows and presumably must be thick. Some were emplaced in an active tectonic environment, and the excursion will examine the ring-dykes associated with one of these (stop 17). There is no evidence of early deformation structures in these plutons (stops 6,7) and they are considered to be late-post regional folding (Witt & Swager, 1989). Age determinations in the excursion area are sparse, but the granites have characteristics of the ~2660 Ma granites from the Norseman area (R.I. Hill, personal communication). These granites exhibit variable geochemistry with several groups defined (Witt & Davy, 1993; Champion & Sheraton, 1993) requiring a range of source rocks.

Later stocks

The small stocks and syenitic intrusions appear to be later than the large plutons, and to be structurally controlled to the extent that they occur on major tectonic lineaments. One of these will be visited on the excursion (stop 15).

A sequence of tectonic events

The history of tectonic events suggested below is a summary of magmatic development within a structural and tectonic framework of the EGP. Many features of this framework remain to be tested rigorously, particularly the geochronology, and the framework must be considered tentative. However, it does provide a focus for discussion during the excursion, and should lead to additional research to test the hypotheses.

1: Mantle activity to provide initial impetus for basin formation. This may be a mantle plume (Campbell & Hill, 1988), just prior to 2700 Ma.

2: Asymmetrical rifting and uplift of rocks to the west of the EGP above an initial shallowly dipping detachment (see Hammmond & Nisbet, 1992; 1993). Voluminous mafic volcanism was deposited as the rift succession in large scale half-grabens. Major structures developed at this stage later acted as terrane boundaries (eg Mt Monger Fault). This model allows the accumulation of the several km of greenstone stratigraphy, not normally possible in a basin formed solely by crustal down-warping. Deposition of the bulk of the greenstone succession was completed by 2690 Ma (age of the Upper Basalt).

3: Active rifting ceased, and was rapidly followed by thrust faulting and stacking of the stratigraphy. Emplacement of voluminous granite magma took place at this stage (stops 3,6) (ca 2680 Ma), and represents massive re-cycling of the lower crust, probably in response to the thermal input from the mantle some 20 Ma earlier (see Campbell & Hill, 1988). Age constraints on gneiss in the Leonora area (L.P. Black, personal communication) suggest that emplacement took place at a range of levels in the crust, from as deep as 20 km (upper amphibolite) to the lower parts of the newly deposited greenstone stratigraphy. These early granites were probably emplaced as sheets and small elongate flattened plugs (Goleby & others, 1993).

4: The renewed instability of the crust as a result of thickening, granite intrusion and thermal weakening of the lower crust resulted in renewed extensional deformation. This event largely re-activated the earlier extensional faults and half-graben margins, and caused normal faulting in the overlying greenstone stratigraphy. The extension caused uplift of the basin margins, which were largely composed of granite gneiss of the immediately preceding igneous event, and also caused the compressed metamorphic gradients observed on the greenstone margins (stops 8, 10, 16). Several of the early granite sheets were uplifted in a similar way, as metamorphic core complexes within the greenstone belt. These core complexes commonly contain internal blocks or separate regions of banded gneiss.

5: Initiation of this second extensional phase probably resulted in a second rapid heat input from mantle asthenosphere, and eventual remelting of the lower crust. This occurred at about 2660 Ma (a further ~20 Ma after extension) and also probably caused flow in the lower crust to compensate for extensional thinning, explaining the lack of deflection on the reflection Moho during this later extension event. Geochemical evidence (Champion & Sheraton, 1993) suggests that granitoids emplaced in this event arose from a variety of crustal sources, including the earlier intrusives (stops 1, 7, 17, 18). Some of these phases are located within distinct structural zones (stop 11).

6: Compressional orogeny followed the second extensional event, and caused significant reactivation of the extensional faults as reverse-slip structures, steepening of the structures, and tightening of the extensional anticlines. Strain was markedly partitioned into zones between the anticlines, which were largely areas of earlier extensional and thrust faulting. Structural evidence suggests that the main compressional phase belongs to this penultimate stage and largely pre-dated the second phase of granite emplacement.

7: Continued compression after granite emplacement resulted in the formation of strike-slip movement on suitable oriented earlier fault structures. Late magmatism was located in the late movement zones.

The excursion stops (see Fig. 8):

Stop 1. Depot Granodiorite, at Depot Rocks (W.K. Witt)

The Depot Granodiorite is one of several ovoid, post-regional folding plutons which were emplaced along the relatively high metamorphic grade, western margin of the Kalgoorlie Terrane. This group was classified as post-D_2 to syn-D_3 diapirs by Witt & Swager (1989). The coarse-grained Depot Granodiorite (locally tonalitic) contains 5-10% hornblende, and accessory magnetite, titanite, apatite, zircon and allanite. Relatively fine-grained, and mafic xenoliths, up to 1 m across, and irregular to dyke-like pegmatoidal segregations are locally common. Both have similar mineral assemblages to that of the host granodiorite.

Unusual features include the absence of primary biotite, and a granoblastic fabric with widespread 120° triple points. The composition of this granitoid (analysis 1, Table 3) is also unusual, and cannot be assigned to any of the SWEGP suites. Compared to other SWEGP granitoids with similar SiO_2, the Depot Granodiorite has low TiO_2, MgO, CaO, V and Zn, high Na_2O, K_2O and Sr, and very high Ba (Fig. 5B). Chondrite-normalised REE curves are steeply fractionated with a weak or no Eu anomaly.

McCulloch & others (1983) obtained Rb-Sr and Sm-Nd whole-rock ages of approximately 2800 Ma for xenoliths of granitoid gneiss in

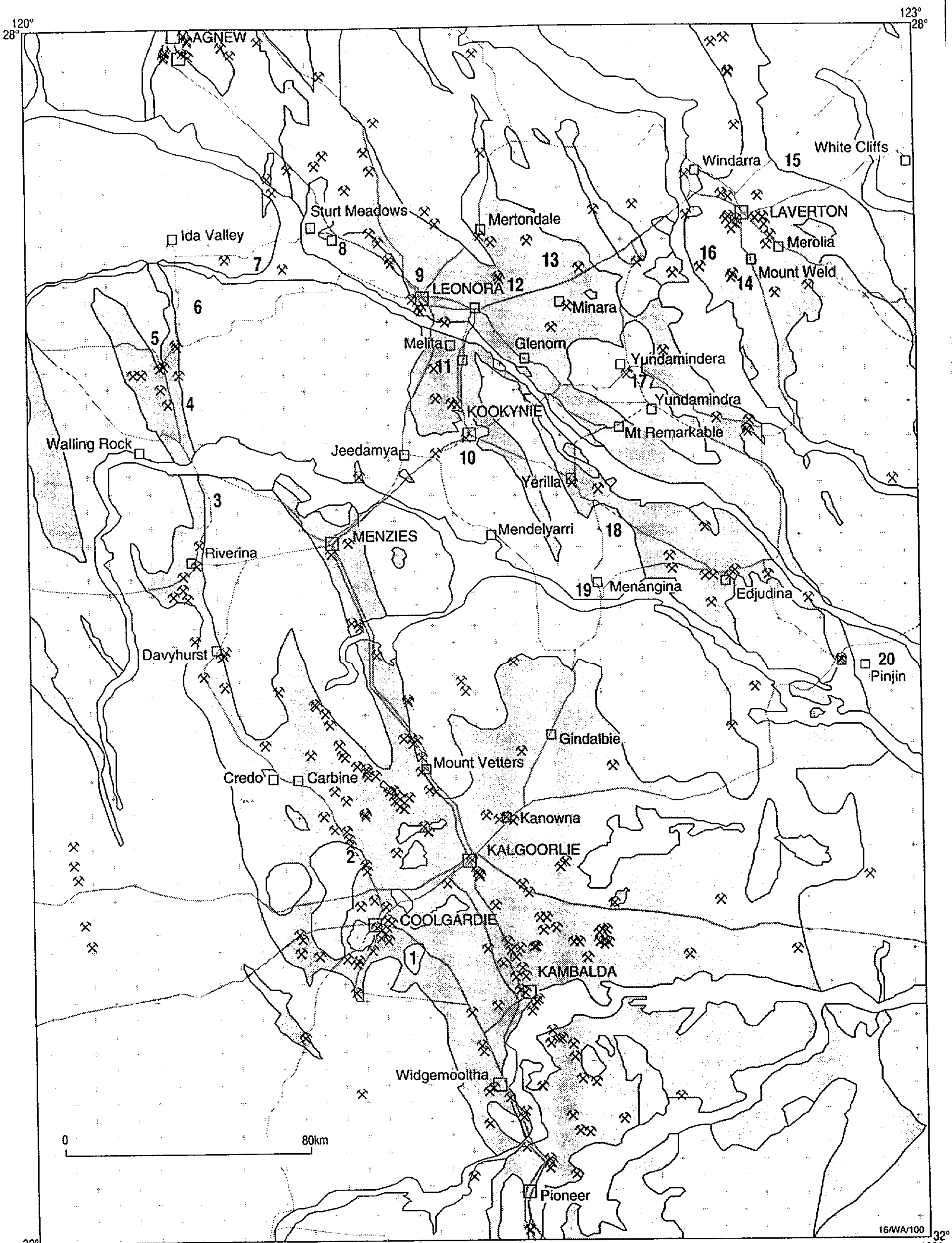

Fig. 8. Field excursion locality map of the Eastern Goldfields region, showing simplified Archaean granite/gneiss and greenstone, and Cainozoic lake geology, major and minor roads, towns and homesteads. Excursion stop numbers are shown and refer to numbered text in this guide.

the Depot Granodiorite (not exposed at the excursion locality), similar to the age of zircon xenocrysts in other, temporally equivalent plutons along the western margin of the Kalgoorlie Terrane (Hill & others, 1992).

Stop 2. Bali Monzogranite, at Kunanalling (W.K. Witt)

The Bali Monzogranite is a multiple intrusion of medium-to coarse-grained, equigranular to porphyritic biotite monzogranite, locally with

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	68.90	74.60	73.05	76.05	69.00	68.60	60.10	70.60	63.30	60.10	72.40
TiO_2	0.18	0.11	0.11	0.06	0.32	0.33	0.64	0.27	0.45	0.54	0.18
Al_2O_3	15.70	14.20	14.44	13.06	14.80	15.20	14.80	14.90	13.40	14.50	14.20
Fe_2O_3	1.30	0.47	0.40	0.66	0.97	1.21	2.26	1.03	1.56	2.07	0.50
FeO	0.53	0.43	0.45	0.26	1.40	0.90	3.23	0.75	3.37	3.92	0.43
MnO	0.07	0.05	0.17	0.03	0.05	<0.05	0.13	<0.05	0.13	0.17	<0.05
MgO	0.67	0.30	0.17	0.09	1.25	0.71	3.07	0.66	4.02	4.73	0.27
CaO	1.69	1.31	1.41	0.80	2.94	2.38	5.01	2.05	4.50	5.47	1.17
Na_2O	5.44	4.72	4.90	3.85	5.16	5.13	4.49	5.01	4.27	4.92	4.73
K_2O	3.93	3.30	3.46	4.44	2.72	3.57	4.35	3.94	3.17	1.38	4.18
P_2O_5	0.09	0.03	0.04	0.01	0.11	0.11	0.50	0.09	0.20	0.19	<0.05
CO_2	0.15	0.21	-	-	0.31	0.35	0.12	0.10	0.11	0.14	0.20
LOI	0.74	0.83	0.27	0.35	0.78	1.07	0.74	0.47	0.83	1.41	0.89
Ba	3027	414	1079	94	874	1069	1343	968	754	254	611
Ce	74	28	25	24	53	79	160	70	65	48	39
Cr	12	<10	7	3	26	43	32	10	241	194	12
Cu	<2	4	-	2	6	7	42	6	76	38	9
F	423	269	-	-	447	713	1100	512	2000	2160	435
Ga	19	22	3	17	19	18	17	18	20	23	21
La	48	18	8	7	28	43	79	42	39	22	21
Li	22	53	16	22	61	41	41	43	74	104	61
Nb	<10	<10	-	13	<10	10	12	10	<10	<10	<10
Ni	8	<4	6	3	23	11	23	9	86	103	32
Pb	51	22	57	57	25	27	33	29	25	22	34
Rb	98	122	95	242	90	128	145	143	137	68	187
Sc	2	2	6	2	5	3	12	3	13	17	2
Sr	1212	273	246	29	694	641	1046	502	582	558	212
Th	16	11	-	32	8	12	18	16	5	6	17
U	17	<5	8	8	5	3	3	2	5	3	5
V	23	4	7	3	36	30	107	20	79	105	13
Zn	43	42	28	21	56	59	87	52	130	165	41
Zr	172	80	57	67	145	203	276	185	149	172	112

1. Depot Granodiorite (sample 98276);
2. Bali Monzogranite (sample 98260);
3. Granitoid gneiss (sample 82167, data of Bettenay, 1977);
4. Copperfield Granodiorite (sample 90967150, M. Rattenbury, AGSO ROCKCHEM database);
5. Rainbow Suite monzogranite (sample 101381);
6. Rainbow Suite monzogranite (sample 101384);
7. Clinopyroxene-hornblende monzonite dyke in Rainbow Suite monzogranite (sample 101383);
8. Biotite-hornblende quartz monzonite dyke in Rainbow Suite monzogranite (sample 101382);
9. Biotite-hornblende quartz monzonite xenolith in Rainbow Suite monzogranite (sample 101379);
10. Biotite-hornblende monzodiorite xenolith in Rainbow Suite monzogranite (sample 101380);
11. Menangina Monzogranite (sample 101346).

TABLE 3. Selected granitoid analyses, southwest Eastern Goldfields Province.

muscovite and garnet. Phenocrysts are K-feldspar and accessory minerals are magnetite, ilmenite, apatite and zircon.

The Bali Monzogranite intrudes a F_2 fold axis but is deformed by the D_3 Kunanalling Shear Zone, on its northeast margin, not far from the excursion locality. Contact zones (where not overprinted by D_3) are characterised by intense ductile deformation and down-dip lineations. However, the amount of deformation and recrystallisation decreases towards the interior of the intrusion(s). The Bali Monzogranite is a typical example of the post-D_2 to syn-D_3 diapirs of Witt & Swager (1989), which occur along the western margin of the Kalgoorlie Terrane.

The Bali Monzogranite is a member of the Bali Suite. Granitoids of the Bali Suite are petrographically similar to those of the Woolgangie Suite, and span a similar SiO_2 range (72-76.5%). However, relative to the Woolgangie Suite, they have higher Al_2O_3, Na_2O and Sr, and lower K_2O, Rb, Th and U (Fig. 5B). An analysis of Bali Monzogranite at Stop 2 is given in Table 3 (analysis 2).

Regional metamorphic isograds are concentrically disposed with respect to Bali Suite plutons, and gold deposits close to the margins of these intrusions have relatively high temperature (450°C, approximately) alteration assemblages. Witt (1991) suggested that the plutons acted as centres of heat and fluid flux within a large-scale, synmetamorphic hydrothermal system. Some of the geochemical characteristics of this group of intrusions may have been caused by metasomatic processes during this hydrothermal event.

Stop 3. Riverina Gneiss, 18 Mile Well (S. Wyche)

This locality is representative of quartz-feldspar (± biotite) gneiss which occurs in a strip about 150 km long and 20 km wide extending from south of Riverina Homestead in the south to the Maroon Range in the north. It lies to the east of the Zuleika Shear, a complex zone of attenuation and stratigraphic mismatch which is more than 1 km wide in places. The Zuleika Shear is a major structure within the Kalgoorlie Terrane of Swager & others (1990b) and can be traced for more than 300 km to the south.

The gneiss displays compositional banding, folding and cutout structures which indicate a complex deformational history and may contain features which predate the structural history of the region as represented in the greenstone sequences.

Compositional banding on a scale of less than 1 cm to several tens of cms is defined by the relative abundance of biotite. The more mafic bands contain subordinate epidote. Also present are bands which contain numerous feldspar porphyroclasts, some up to 5 cm across (Fig. 9A). Some of the coarse porphyroclast-rich bands are deformed pegmatites but thicker bands containing finer porphyroclasts may be derived from porphyritic granite. There are scattered patches of poorly outcropping epidote-rich amphibolite in some of the recessive areas between outcrops of gneiss.

Tight folds with well developed axial plane foliation are best displayed by pegmatites folded with the gneiss (Fig. 9B). Good exposure of these folds can be seen at a blast site about 280 m east of the road and 100 m north of the fence line. here one can also see the subhorizontal mineral lineation.

Near the greenstone contact, the compositional banding has been overprinted by a slightly discordant mylonitic fabric related to the Zuleika Shear.

Stop 4. Ballard Shear zone near Dry Well (M.S. Rattenbury)

The Ballard Shear is a major D_3 strike-slip ductile shear zone, which has juxtaposed the Mt Ida greenstone belt mafic-ultramafic volcanics against quartzofeldspathic gneisses and intercalated amphibolitic layers (Fig. 10). The shear zone is characterised by enhanced foliation planarity and intensity within the gneisses towards the contact with the mafic-ultramafic metavolcanics, accompanied by some reduction in mineral grainsize typical of mylonitic deformation (Fig. 11A,B). The gneiss/mylonite has an overall very steeply west-dipping foliation, and a well developed subhorizontal to gently south-plunging stretching lineation defined by quartz and mica. Composite planar fabrics indicate considerable simple shear, although few asymmetric microstructural criteria have been found. The curvature and attenuation of the eastern limb of the Kurrajong Anticline, the drag of the gneiss layering into the shear zone, and the slight anticlockwise rotation of the Kurrajong Anticline axial trace into the Ballard Shear suggest sinistral movement of the shear zone (Fig. 10).

The original spatial and age relationships between the gneisses and the mafic-ultramafic volcanics remains uncertain, however. There is little evidence for significant dip-slip movement across the Ballard Shear. Steeply plunging mineral lineations are not apparent within the Ballard Shear zone, although steeply stretching lineations do occur within the gneisses 5 km east of the Ballard Shear. Penetrative D_3 ductile strike-slip may have obliterated any earlier fabric in the Ballard Shear zone, however. Contrasts in metamorphic grade between the gneisses and the metavolcanics cannot be easily constrained because of a lack of reliable geobarometric mineral assemblages. Brittle small displacement fractures within the gneisses east of the Ballard Shear identified from aeromagnetic interpretation have a Reidel shear geometry consistent with minor dextral D_4 movement (Fig. 10,11B).

The gneiss is dominated by quartz-feldspar-biotite, with thin continuous interlayered hornblende-rich amphibolite bands up to 5 m thick. Detailed aeromagnetics across the gneiss reveals the layers maintain constant thickness over considerable strike length and are disrupted only by small displacement east-trending fractures. The mineralogy of the gneiss is dominated by quartz with ortho-

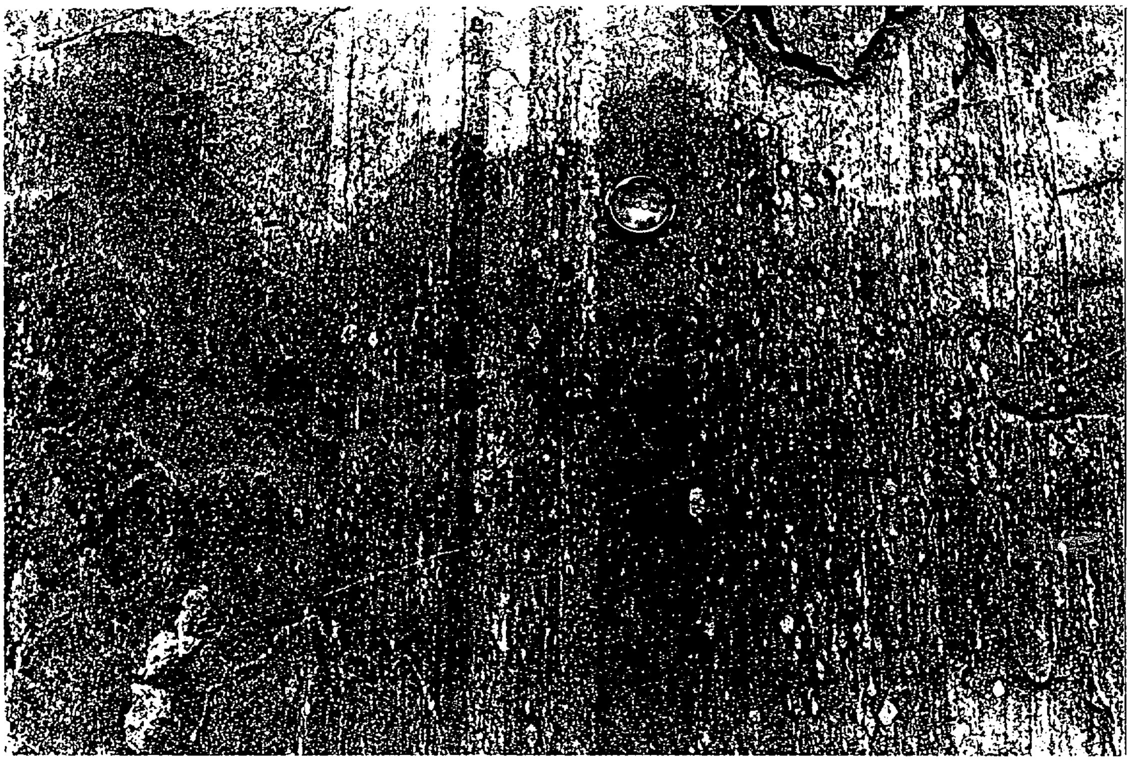

Fig. 9A. Mylonitised Riverina gneiss from near 18 Mile Well, showing compositional banding and well-developed feldspar porphyroclasts.

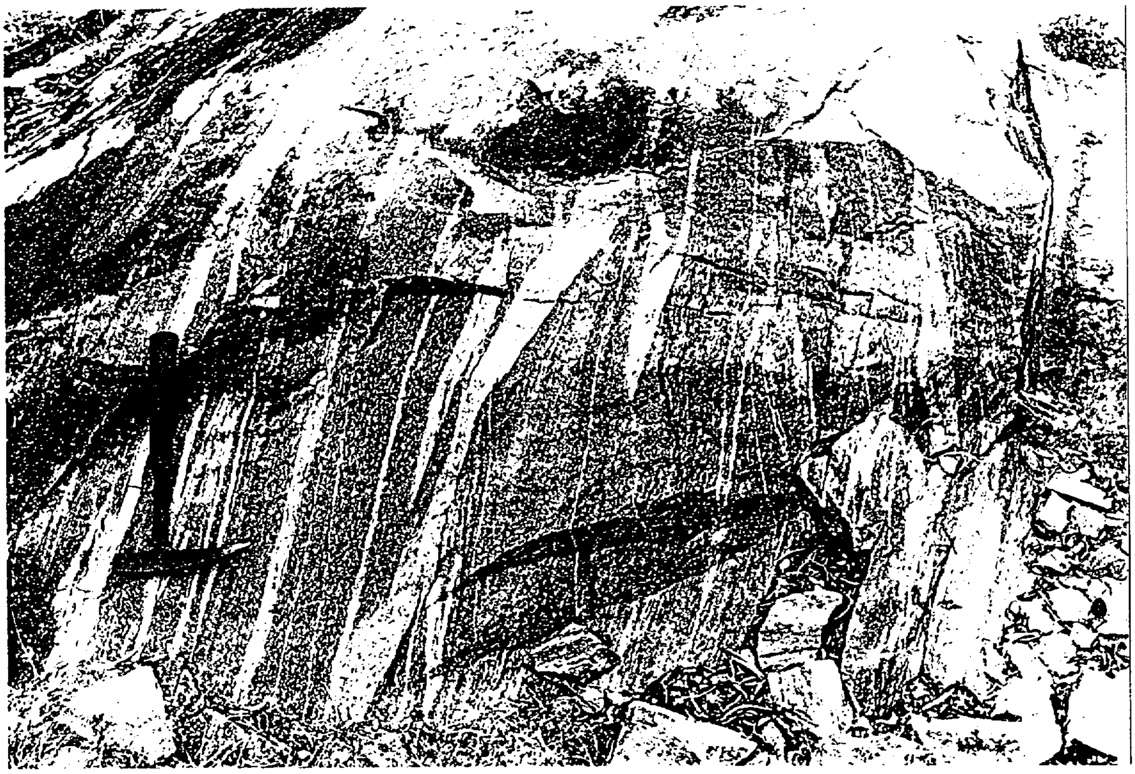

Fig. 9B. Tightly folded pegmatite within Riverina gneiss near 18 Mile Well.

clase, oligoclase, biotite and muscovite. One gneiss sample collected near the southern boundary of the Ballard 1:100K sheet contains the pelitic assemblage garnet-biotite-staurolite-K feldspar-quartz suggesting these rocks reached mid-amphibolite facies grade. Rutile needles in quartz are also indicative of high temperatures. Larger microcline grains are commonly surrounded by equidimensional sub-

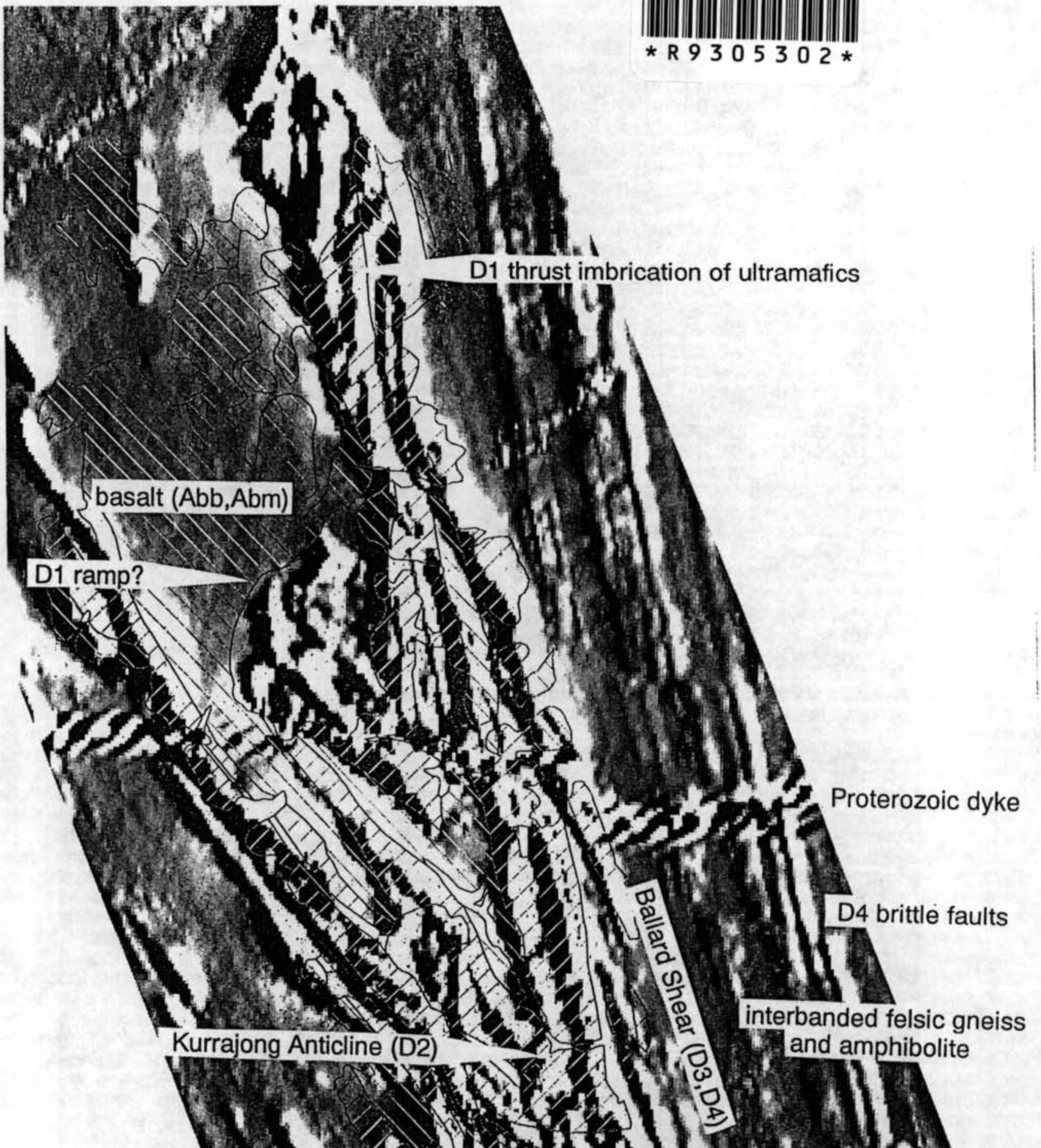

Fig. 10. The Ballard Shear zone near Dry Well. The aeromagnetic image is from open-file 100 m line-spacing data acquired for Shell in 1985. The gneisses show well developed and remarkably consistent banding defined by less magnetic amphibolite-rich bands alternating with quartzo-felspathic bands. The Kurrajong Anticline hinge region to the west of the shear is highlighted by highly magnetic komatiite and olivine cumulate volcanics interlayered and thrust-imbricated with poorly magnetic basalt.

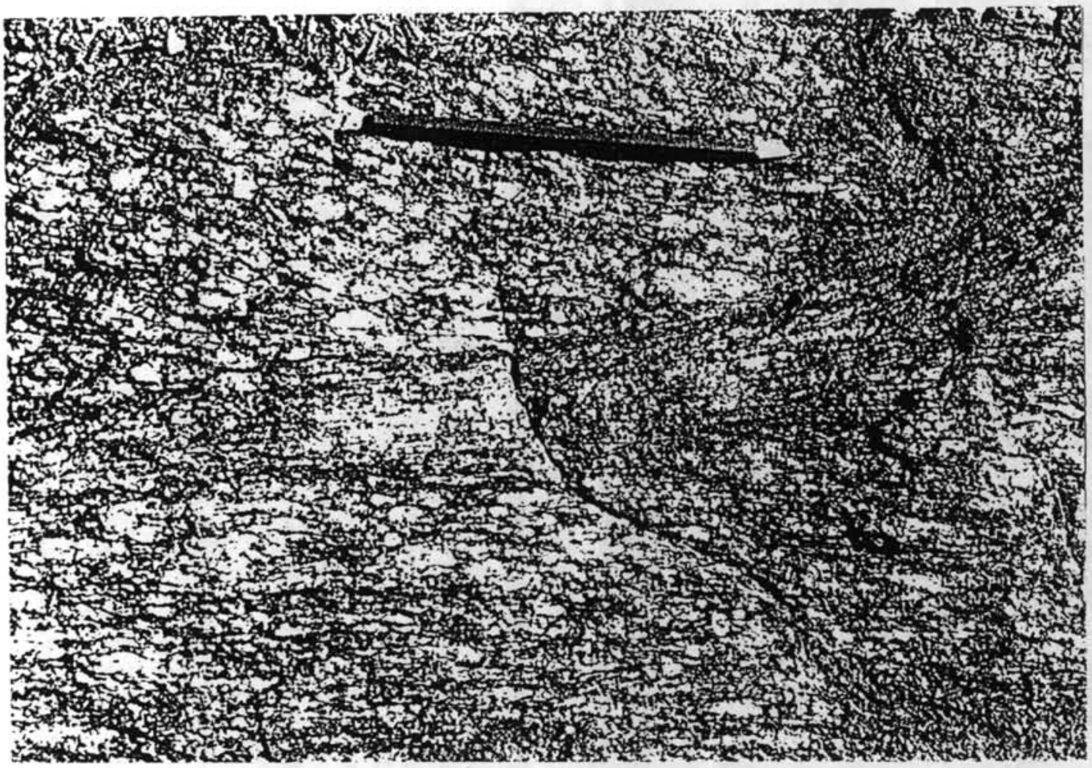

Fig. 11A. Mylonitic shear zone cutting less deformed, segregated gneiss.

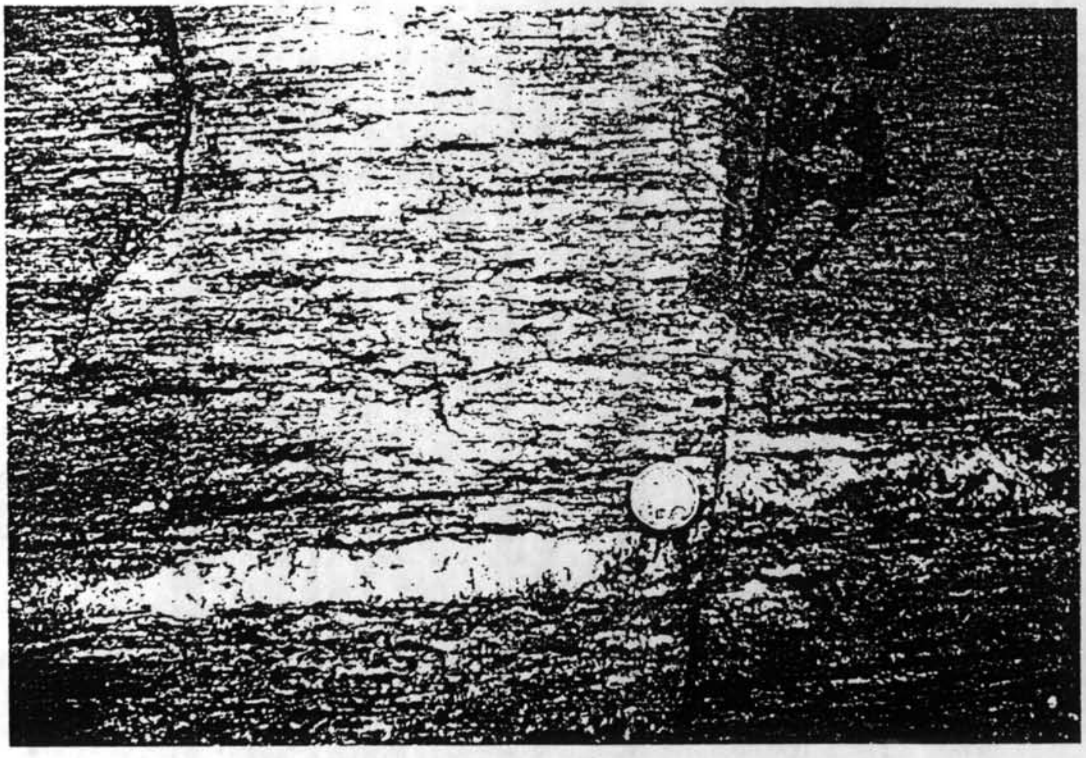

Fig. 11B. Late D4 fracture offsetting highly strained, mylonitic gneiss.

grains between 100-400 microns diameter within the Ballard Shear zone. The subgrains typically develop from dynamic recrystallisation of microcline during ductile high strain of the gneiss. Oligoclase porphyroclasts in some gneiss samples show bending and kinking of twin planes indicative of moderately high temperatures during high strain deformation. Cross-cutting quartz-muscovite shear bands suggest ductile high strain occurred after peak metamorphism and early foliation development, but the garnet and staurolite porphyroblasts are not significantly altered or retrogressed.

The Ballard Shear appears to have limited associated mineralisation. The Golden Ridge workings (36 kg at 20 g/t) and Madhatter (4 kg at 31 g/t) occur in subparallel subsidary shears to the Ballard Shear which crops out 50-200 m to the east.

Stop 5. Copperfield granite (M.S. Rattenbury)

The Copperfield granite occurs in the core of the Kurrajong Anticline (Fig. 12). The granite slightly transgresses greenstone belt stratigraphy which suggests an intrusive relationship. The contact, however, is strongly deformed. The granite has a very well developed, pervasive stretching lineation, particularly around the pluton margins. The granite also has a weakly developed foliation which is subparallel to the boundary with the mafic-ultramafic volcanics around the Kurrajong Anticline. The contact between the mafic metavolcanics and the lineated Copperfield granite is strongly sheared but the fabric intensity diminishes southwards and eastwards into the mafic-ultramafic volcanics indicating penetrative ductile deformation is localised in the lower part of the stratigraphy. The metavolcanics are pervasively lineated east of the Copperfield Granite, and have been crenulated by the D_2 upright fold axial planar cleavage.

The granite lineation is formed by ribbons of relatively large unstrained quartz grains up to 2 mm long separated by 1-3 mm plagioclase grains and .3-.8 mm microcline. The plagioclase is typically unstrained with muscovite inclusions. The microcline occurs as subgrains with small mismatches in twin boundary orientations across grain boundaries. Dark green-brown biotite is predominant mafic mineral present, with minor magnetite, apatite. Dynamic recrystallisation of microcline is indicative of high temperatures during significant strain. The weak foliation within the granite and the foliation within the greenstone belt folded with the anticline suggests the deformation predated D_2 upright folding, despite the occurrence of the stretching lineation direction sub-parallel to the Kurrajong Anticline fold axis. The fabric was probably imposed during major layer-parallel deformation.

The region has in the past been a significant gold producer, with major production occurring at the Timoni mine (7486 kg Au at an average grade of 55 g/t). Numerous mines occur around the margins of the deformed Copperfield Granite in mafic and ultramafic metavolcanic rocks including Timoni, Forest Belle/Boudie Rat (201 kg at 18 g/t), Ida (136 kg at 36 g/t), and Golden Vale (41 kg at 17 g/t) mines.

Stop 6. Wilbah banded gneiss and amphibolite, and low-Ca intrusive (3 stops) (D.C. Champion)

This area provides excellent examples of banded gneiss, the major rocktype in the area, and low-Ca post-folding granitoids which intrude the gneiss. The gneiss forms part of a large belt continuous with the Riverina Gneiss and extending further north (Williams & others, 1993). Recent U-Pb zircon SHRIMP ion-microprobe ages are from gneisses in this region. These indicate ages around 2685 Ma (L.P. Black, pers. comm.) which are similar to those reported by Hill & others (1992) for pre-folding granitoids to the south, suggesting that the gneisses may represent higher-grade equivalents; more work in needed, however, to confirm these gneiss ages.

Stop 6a. 258650E, 6800480N, approx. 1 km east of Lawlers–Mt Ida road

This stop looks at the Mars Bore granite, a member of the low-Ca post-folding group, that intrudes the banded gneiss. The granite outcrops, with an east-west extent of at least 1 km, as small boulders to low platforms of generally homogeneous, white medium to medium-coarse grained, generally equigranular biotite granite (in fresh outcrop). Very sparse phenocrysts (<1%) of white subhedral feldspar to 1.5 cm and anhedral clear quartz to 1 cm are locally present. There is no obvious foliation and the granite is moderately jointed. Pegmatite dykes (to 15 cm) are relatively common and randomly orientated. Aplites are absent, as are enclaves. Local quartz veins (<10 cm) are also present. The granite has a high radiometric response (1500-1900 counts per second), a characteristic of the low-Ca group, and is magnetic (300-450 x 10^{-5} SI units), although the latter appears to vary with degree of weathering. The granite is geochemically homogenous; it is felsic (73-74% SiO_2) and moderately fractionated, and is typical of the low-Ca group granites (compare with the high-Ca Blue Well and Union Jack granites in Table 5).

Stop 6b. 267000E, 6801300N—Gneiss with amphibolite bands

Stop 6c. 257950E, 6808880N, east of Lawlers-Mt Ida road. Large platforms of banded gneiss

The gneisses vary from relatively homogeneous to strongly banded, and locally migmatitic, at scales from millimetres to tens of metres, with banding defined by compositional and grainsize differences (fine to coarse). The former are due chiefly to varying biotite content (<2% to >30%),

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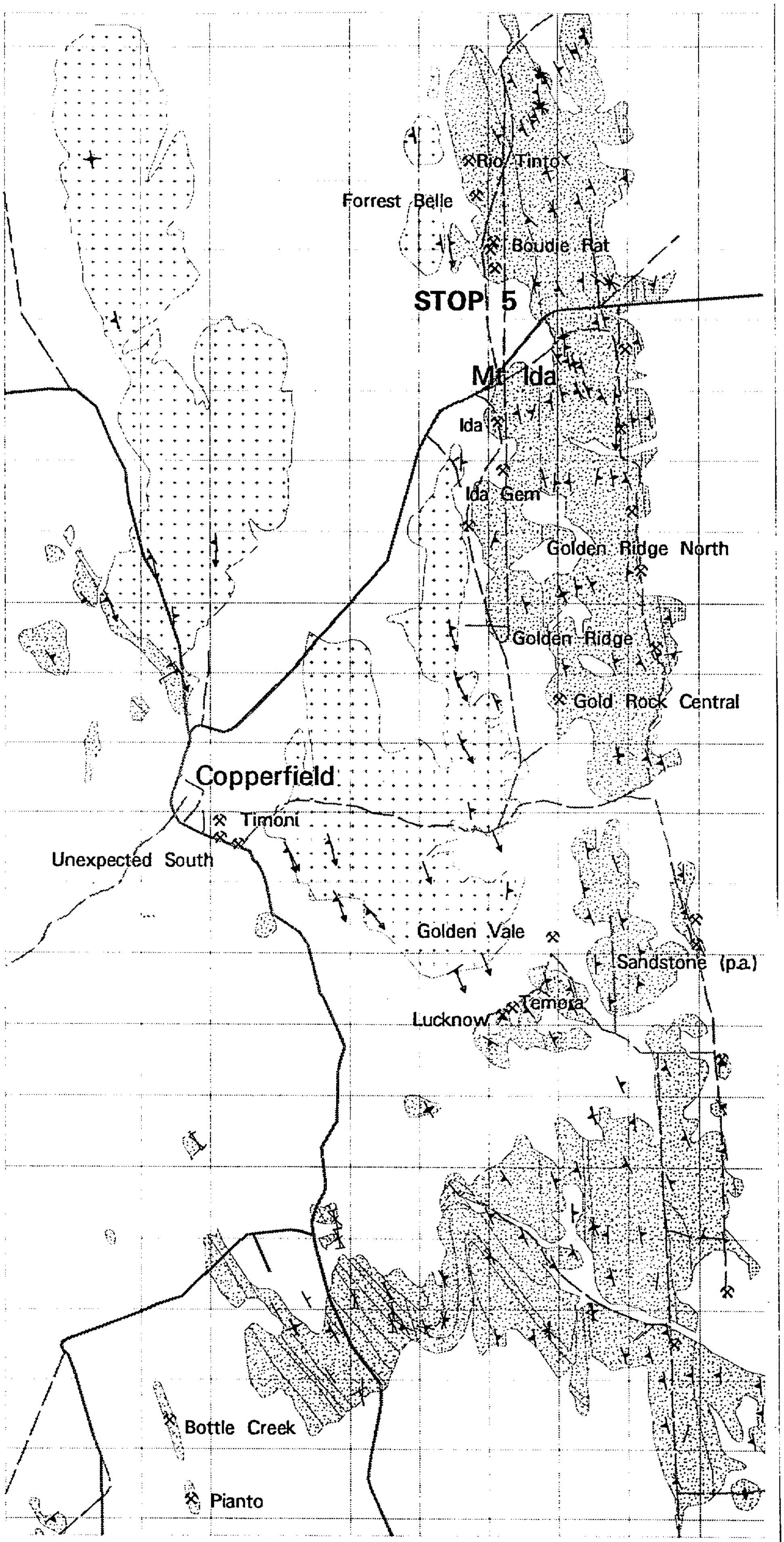


Fig. 12. Basement geology and mine locations around the Mt Ida - Copperfield area, showing the surface extent and structural fabric of the Copperfield granite, the adjacent mafic-ultramafic volcanics, and the Riverina gneiss to the east. The Copperfield granite occurs in the core of the south-plunging Kurrajong Anticline and the granite-greenstone boundary is a highly strained ductile shear zone.

but also include the presence of subhedral feldspar porphyroclasts (up to 1-4 cm and aligned with the foliation) and leucogranitic bands. Locally the banding shows evidence of tight refolding. Mineralogically, the gneisses comprise plagioclase, biotite, quartz and alkali-feldspar, with compositions ranging from biotite-rich trondhjemites to leucogranodiorites and adamellites. Accessory minerals present include opaques, zircon, apatite ± garnet ± sphene ± allanite?, with secondary sericite, muscovite, ± epidote ± calcite ± sphene ± chlorite. Deformational (and metamorphic) effects are evident in the gneissic foliation, development of lepidiloblastic and granoblastic textures, the common presence of tartan twinning, variable perthite development in alkali feldspar and common occurrence of myrmekite. Original igneous features are suggested in plagioclases containing oscillatory zoning. The gneisses contain locally abundant pegmatite and aplite veins which both parallel and cross-cut the gneissic foliation. Concordant amphibolite and mafic schist zones up to a few metres in width are locally present, which in places contain trondhjemitic sweats. The gneisses are variably magnetic (100-800 x 10^{-5} SI units) with a low to moderate radiometric response (400-1000 counts per second). The gneisses in this region exhibit a range of compositions (69-74% SiO_2) and are typically geochemically heterogeneous (Fig. 6), in particular with regard to the LILE, e.g. K_2O, Th (Table 5).

The amphibolite and presence of partial melts indicates the gneisses have undergone high-grade metamorphism with temperatures of 650-700°C. Unpublished geobarometry and geothermometry on garnet-bearing amphibolites from this region indicate pressures up to 800 MPa and temperatures of 700°C (M. Duggan, personal communication). Clearly the gneisses have undergone considerable uplift to their present position, presumably before emplacement of the Mars Bore granite.

Stop 7. Late high-Ca intrusives—Blue Well area (D.C. Champion)

This stop examines two typical members (Union Jack and Blue Well granites) of the high-Ca post-folding group, the other major post-folding type in the Laverton–Leonora region (compare low-Ca granite at Stop 6).

The Blue Well granite is compositionally homogeneous, but varies from grey to blue-grey medium equigranular biotite granite to grey fine-medium very sparsely feldspar-quartz porphyritic biotite granite. Phenocrysts, where present, occur as white euhedral to subhedral feldspars to 2 cm (commonly smaller) and clear anhedral quartz grains to 5 mm. Biotite contents are generally similar in all outcrops, averaging 5%. The granite contains uncommon aplite and pegmatite dykes (1-10 cm) and very sparse ovoid to elliptical biotite-rich enclaves to 5 cm. The granite is non-foliated with moderate jointing. It has moderate to high radiometric response (1000-1400 counts per second) and is variably magnetic (100-1100 x 10^{-5} SI units). The Blue Well granite appears to intrude the Union Jack granite, with good contact relationships evident in a few places (Stop 7b below and to the north), despite the former being slightly more mafic than the Union Jack granite (Table 5). The Blue Well granite is an example of a mafic high-Ca granite with elevated Th, Zr and LREE and as such is clearly geochemically distinct from the pre-folding group (Fig. 6, Table 5).

The Union Jack granite outcrops as grey-white to white-pink sparsely feldspar-quartz porphyritic medium to medium-coarse grained granite. Feldspar phenocrysts are subhedral, pink and white, up to 1-3 cm (locally to 6 cm) and are characteristic of this unit, being very distinctive on weathered surfaces. Quartz phenocrysts are of a similar size. Biotite (approx. 2%) is present as irregular flakes from 2-6 mm. The granite is unfoliated although in one locality (7a) contains sub-parallel thin (1-2 cm) biotite-richer (5%) bands. The granite is variably magnetic (100-1000 x 10^{-5} SI units) and has a moderate to high radiometric response (600-1500 counts per second). Both pegmatite dykes (2-20 cm) and patches (<0.5m) and aplite dykes (<2 m) are locally common and exhibit a random orientation. Dykes (2-5 m) of fine to fine-medium biotite microgranite are locally present (e.g at 289440, 6816070). The Union Jack is geochemically more felsic and more heterogeneous (72-75% SiO_2) than the Blue Well granite. Comparison of the Blue Well and Union Jack granites with the Mars Bore (and Extension) granite clearly shows the geochemical differences between the high- and low-Ca groups, e.g. compare CaO, K_2O, and Rb in Table 5.

Stop 7a. 282982E, 6819748N, south side of Ida Valley Road, approx. 3.5 km from Red Well

Contact between the Blue Well and Union Jack granites. At this site the former crops out as very fresh tors and whalebacks to 10 m and appears to be the only rock type present. However, the Union Jack granite crops out as small isolated boulders and as low to flat boulders and pavements. It is generally moderately weathered but readily recog-

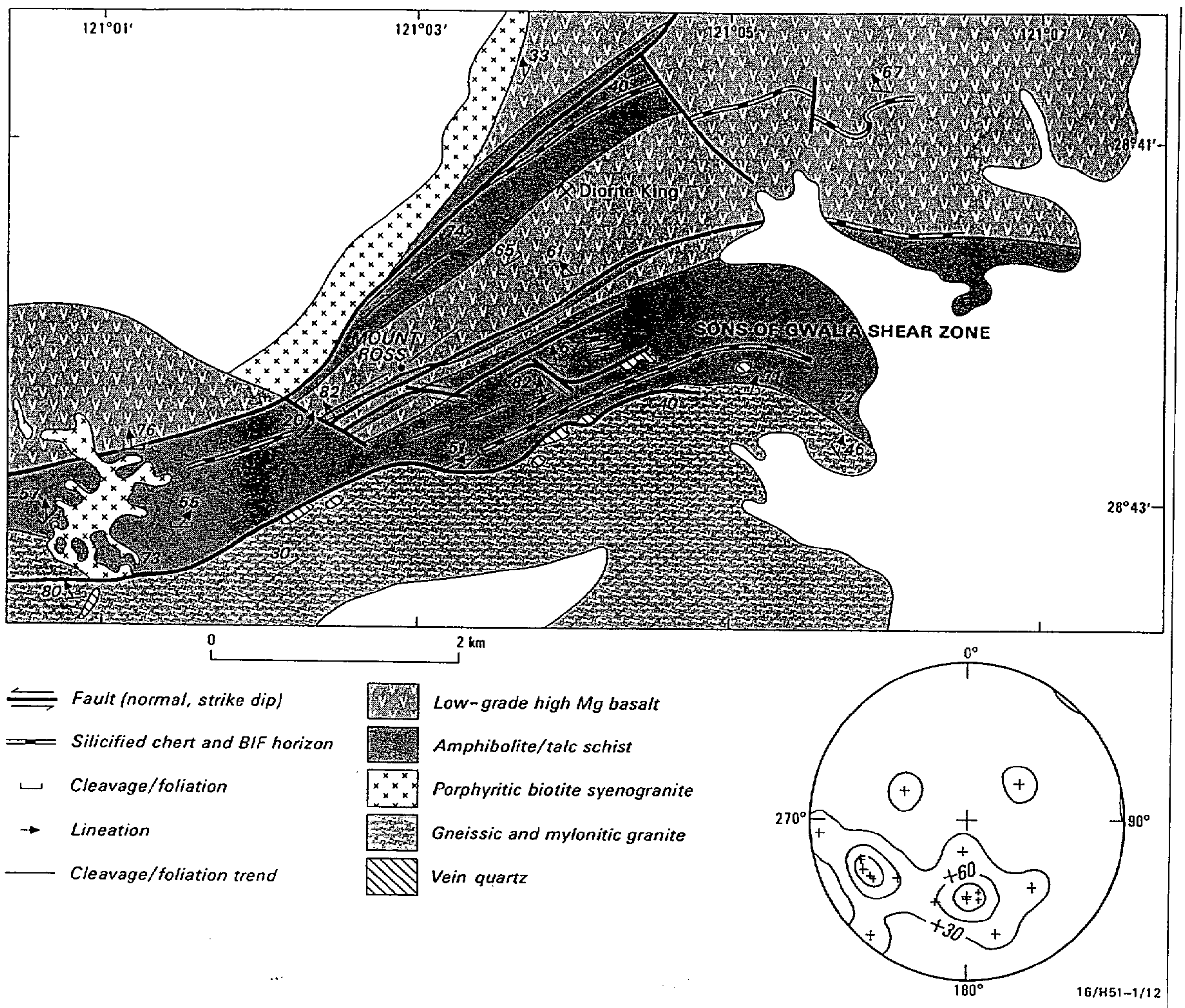


Fig. 13A. The Sons of Gwalia Shear Zone in the Mt Ross area.

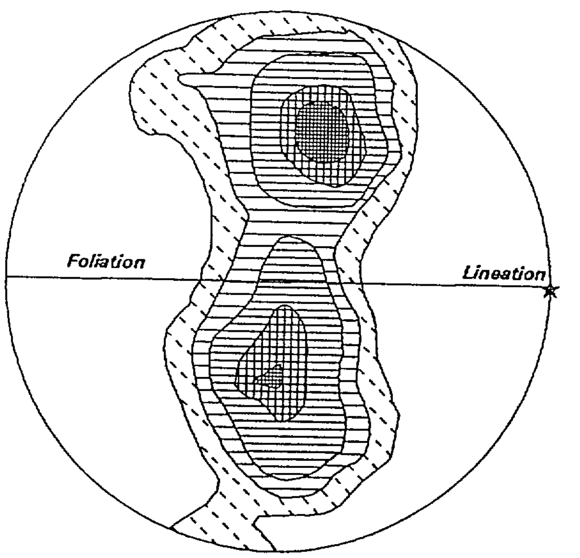


Fig. 13B. Quartz optic axes from the Sons of Gwalia Shear Zone showing an asymmetric girdle indicating normal movement.

nised by its feldspar phenocrysts. Although no actual contact is observed, the Blue Well granite appears to form a sill or sheet like body in the Union Jack granite.

Stop 7b. 288020E, 6815370N, west of Lake Raeside

This outcrop exhibits similar relationships as seen at Stop 7a, comprising a small hill of moderate to large boulders/tors of Blue Well granite, with the Union Jack granite cropping out as generally moderately weathered low/flat boulders. A good contact between the two is clearly evident with chilling of the Blue Well granite. The contact is irregular, varying from predominantly horizontal to vertical. The outcrop behaviour of the Blue Well granite is interesting in that many of the boulders appear as if they have sunk into the ground, presumably due to the decomposition of the Union Jack granite. To the east of this site are abundant excellent outcrops of the Union Jack granite. Outcrop of the latter is also found further to the west.

Stop 8. Granite-greenstone margin—Mount Ross area (P.R. Williams)

Williams & others (1989) discussed the regional deformation pattern in the Leonora area and established that the Sons of Gwalia Shear Zone was a distinctive arcuate, high-grade shear which broadly follows the boundary of the Raeside Gneiss (Fig.13A). Deformation in the shear zone was shown to be earlier than the upright folding, which is in turn earlier than north-northwest trending strike-slip faults. Detailed mapping of westerly exposures of the Sons of Gwalia Shear Zone further constrains the nature of the structure. In the Mount Ross area, the boundary between amphibolite and gneiss is strongly sheared. A well-developed planar structure parallel to the boundary is present within both the amphibolite and gneiss. In the amphibolite, the intensity of the foliation decreases away from the boundary, from a penetrative foliatian within 200 m of the contact to a decreasing number of anastomosing shears up to 700 m from the gneiss margin. At the margin, tectonic slices of amphibolite and ultramafic rocks between 0.5 m and 5 m thick and several metres long are interleaved with the gneiss.

The foliation contains a strong mineral elongation lineation, especially close to the contact. In amphibolite, the lineation is defined by amphibole laths; in the gneiss by the alignment of quartz grains and pressure shadows around feldspar phenocrysts. In the gneiss, numerous examples of S-C fabric and asymmetric pressure shadows are present around feldspar porphyroclasts some of which show extensional rotational fractures. Both textures are definitive of normal movement on the shear surfaces. Quartz optic axes within the gneiss adjacent to the boundary define a single asymmetrical girdle indicating normal (top-side north) movement (Fig.13B) and a moderately high metamorphic grade during deformation. Within the amphibolite, discontinuous faults with a strong down-dip linear fabric and distinctive silicic fault fill (silicified ultramafic rock?) are offset by dextral strike slip segments. Within the amphibolite rare, irregular leucocratic feldspar-rich patches have have been observed. These have a granophyric texture, and form thin sweats and veins often surrounding patches of deformed amphibolite. The patches are interpreted as the product of local melting of the amphibolite after the main deformation, and indicates the amphibolite margin also reached a high metamorphic grade. The zone of melting is in close proximity to the small granite pluton, which may have caused a sharp local temperature rise after the cessation of deformation.

The foliation in the gneissic granite is folded about a north plunging axis, at a high angle to the stretching lineation, confirming that the mylonitic foliation within the western exposures of the Sons of Gwalia shear zone pre-dates upright regional ENE-WSW shortening. The timing relationship is the same as that from around Leonora. Schistosity in the amphibolite is also folded on a mesoscopic scale by fold events which post-date the shear fabric. East of Mount Ross, in the Auckland area, S-C fabric developed in chlorite schist also clearly indicate top-side-north sense of movement.

In the Mount Ross area the upper plate is intruded by a large number of feldspar- and quartz feldspar porphyry dykes ranging from 1 m to 3 m wide. Dykes may be either concordant to foliation or markedly discordant, and are either unfoliated or carry a weak foliation with marked mineral elongation lineation, particularly on their margins. The intensity of dykes reduces rapidly away from the margin. In the western area, a small pluton of undeformed feldspar phyric leucocratic biotite granite may be co-magmatic with the dykes, as several of the dykes can be traced into the pluton margins without appearing to cross-cut the granite. This relationship produces the ameoboid character of the granite pluton.

The porphyry dykes do not extend into the structurally underlying granite or gneiss. At Mount Ross, a discordant dyke has been truncated by the major granite-greenstone boundary fault, but is essentially undeformed, even at the fault. These relationships suggest that porphyry emplacement took place during the formation of the Sons of Gwalia Shear, over a significant time period, commencing during ductile deformation in the shear zone, and continuing when the deformation regime had become brittle. Large quartz blows along the trace of the gneiss-amphibolite boundary also indicate that late brittle movement took place, and that the brittle fault was located at the lithological boundary.

The microstructure of amphibolites is consistent with overprinting of high grade ductile fabrics with brittle structures. The amphibolite is characterized by acicular hornblende needles defining a strong planar fabric which is in places overgrown by randomly oriented amphibole laths with similar optical characteristics to the earlier syn-deformation amphibole. The rocks are cut by late clinozoisite and prehnite veins, but show no other signs of retrogression. The metamorphic grade drops rapidly to the north (Fig. 13A), where the rocks are weakly deformed to undeformed, greenschist grade, pillowed basalts cut by thin feldspar (quartz) porphyry dykes. The rocks in both amphibolite and greenschist facies rocks dip approximately 30° north, sub-parallel to the normal faults.

Stop 9. Sons of Gwalia open pit (Sheldon Coates)

The Sons of Gwalia deposit was discovered in 1897 by prospectors and worked as an underground mine until 1963, up to when it had produced 2.5 million ounces of gold. The underground workings extended 1500 m down plunge and 1000 m vertically. Since 1984, and open cut mine has produced over 500 000 ounces of gold down to a depth of 110 m, with a total planned depth of 280 m.

Regional setting

The orebody lies within a sequence of mafic volcanics consisting of tholeiitic pillow basalts and minor interflow sediments. The mine sequence is underlain by ultramafic rocks which have been intruded by a granite batholith, made up largely of monzogranite. There is no thermal aureole visible, and the granite may have intruded in an extensional regime. The mafic and ultramafic rocks are variably sheared and comprise the Sons of Gwalia Shear Zone.

Two gabbro intrusions lie adjacent to the deposit to the northwest and south, and may have been a factor in localising the mineralisation of the orebody within the shear zone (Fig. 14A).

Mine geology

The orebody is situated within a mylonite zone, bounded on the hangingwall and footwall by east-facing pillow basalts which become increasingly sheared as the mineralisation zone is approached. The ore zone is U-shaped in plan and open to the north. The foliation dips 45° to the east, and plunges 70° to the south. A strong mineral lineation is parallel to the plunge of the ore zone, as are small isoclinal fold axes, boudin axes and ore lenses. Small Z-folds are common and indicated by quartz-carbonate veins, and confirm the dominant dextral movement direction. Other kinematic indicators, such as S-C fabrics and asymmetric pressure shadows, confirm that the sense of movement is dominantly dextral (east-side-down). Pillow basalts in the hangingwall and footwall both indicate the succession is younging to the east.

Mineralisation

The mineralising fluid was probably derived by thermal metamorphism of the volcanic pile by granite intrusion and was channelled up the dilatant shear zone, causing K-metasomatism, and carbonate addition as a number of generations of quartz-carbonate veins. The major ore type is chlorite sericite schist ± fuchsite ± albite and with numerous quartz-carbonate veins which are folded, boudinaged and sheared out.

The south end of the deposit consists of massive quartz-carbonate with relict foliation, and abruptly changes to highly sheared basalt becoming moderately sheared, barren basalt only a few metres to the south. The area between Main Lode and West Lode is chlorite schist with little quartz-carbonate veining and contains only anomalous gold levels (Fig. 14B,14C).

Pyrite is the major sulphide present, with trace amounts of chalcopyrite, gerdorffite and arsenopyrite. Scheelite also occurs throughout the mineralised zone in small quantities. Gold occurs in free form and also as small particles within the pyrite. Based on fluid inclusion data, mineralisation formed at 380°C from a fluid with H_2O/CO_2 of 19, while the muscovite-biotite-chlorite geobarometer indicates a formation pressure of 2.2 kbars.

Stop 10. The high-grade metamorphic zone at Mount Jessop, Morapoi station (W.K. Witt)

At Mount Jessop, near Morapoi station homestead, high-grade metamorphic rocks are exposed adjacent to the pre-regional folding Mulliberry granitoid complex. The contact between the Mulliberry granitoid complex (mainly biotite monzogranite and granodiorite, chemical analyses not available) and the overlying greenstones is a zone of strong contact-parallel (D_1) deformation and interleaving between greenstones and granitoids. Lineations (L_1) trend in a north to northwest direction. The contact-parallel foliation (S_1) trends northeast at Mount Jessop, and is locally overprinted by an upright north to north-northwest (S_2) foliation.

The high-grade metamorphic carapace adjacent to the Mulliberry granitoid complex is approximately 500 m wide and contains pods of mafic gneiss within metasedimentary schist. Mafic gneiss consists of a clinopyroxene-hornblende-plagioclase (andesine) assemblage whereas the metasediments contain quartz, plagioclase and biotite. The gneissic banding in the mafic rocks, and the dominant schistosity in the metasediments are both S_1. Both rock types display partial melting structures. Melt veins

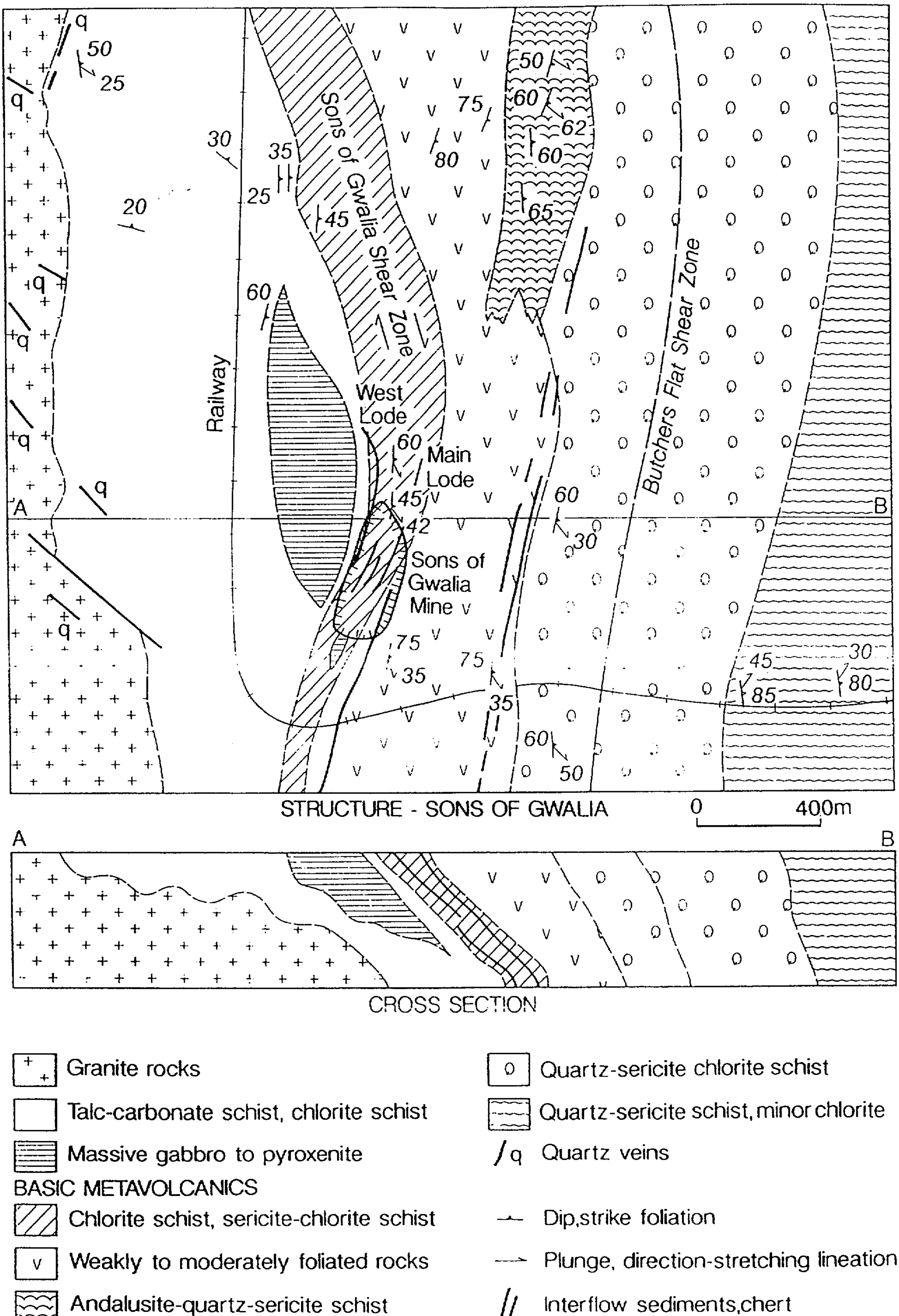
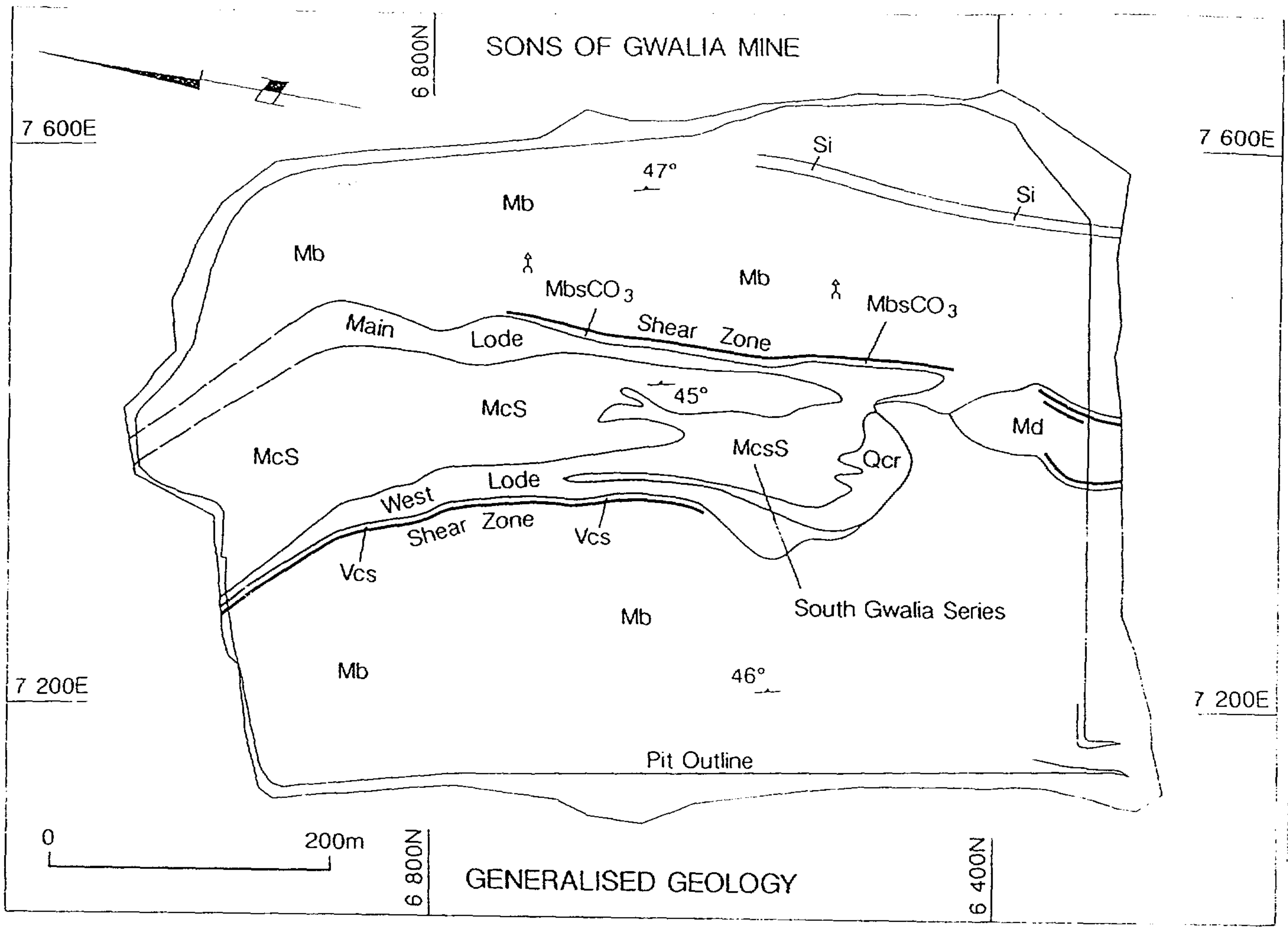


Fig. 14A. Structural map of the Sons of Gwalia Mine.



Mb	Basalt with pillows, anastomising shears around less deformed lenses.
Si	Gwalia slate - highly sheared sediment with sheared basalt.
$MbsCO_3$	Carbonated basaltic schist on east edge of mine lode
Vcs	Chlorite talc schist 1-3m wide. Footwall of mineralisation.
Md	Mafic dyke, largely massive, fine/med. grained. Slightly sheared at margins.
McsS	Chlorite sericite schist ± fuchsite. Variable stringers and boudins of quartz carbonate. Minor pyrite.
Mcs	Chlorite schist, minor quartz carbonate veinlets. Minor pyrite, barren.
Qcr	Quartz-carbonate rock, massive, relict foliation.
46°	Strike and dip of foliation.
⋏	Facing of pillow basalts.

Fig. 14B. Mineralisation lodes from the Sons of Gwalia Mine.

are mostly parallel to, but locally transgress, S_1. Partial melts are dioritic to trondjhemitic in mafic gneiss, and granitic to pegmatitic in metasedimentary schist. Metamorphic assemblages and evidence for partial melting indicate peak metamorphic (M_1) conditions of 650-750°C and 500 MPa.

The above fabrics and metamorphic conditions contrast with those in overlying mafic rocks to the northwest where low strain domains are widely preserved in dolerite, quartz dolerite and anorthositic gabbro. These mafic rocks contain plagioclase, tremolite-actinolite and chlorite, typical of the more widespread greenschist facies (M_2) metamorphism. The contact between M_1 and M_2 assemblages, although not exposed, is interpreted to be a bedding-parallel zone of extension related to doming of the granitoid complex, prior to regional folding (F_2).

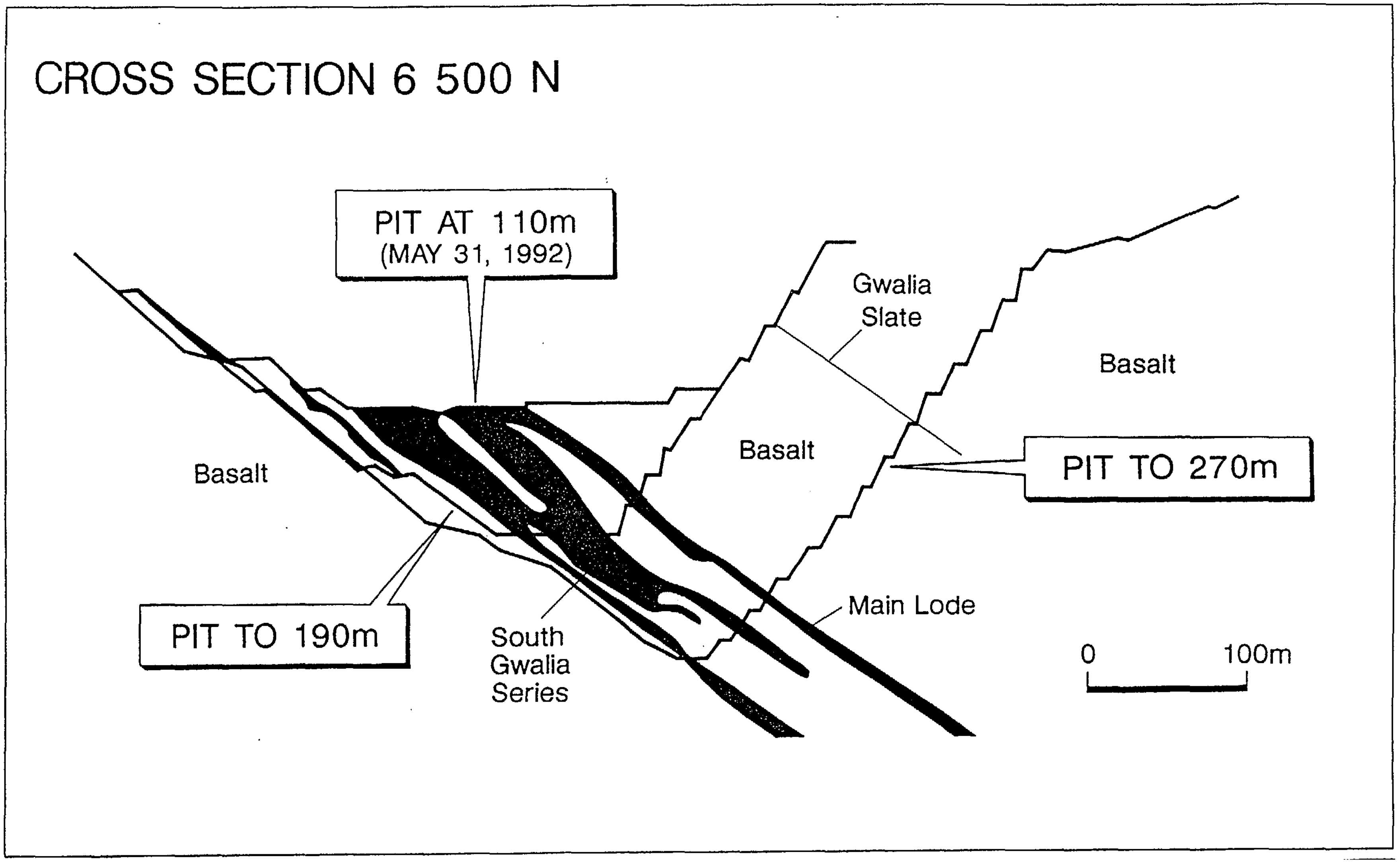


Fig. 14C. Cross section through the Sons of Gwalia Mine lodes.

Stop 11. Melita Rhyolite at Melita railway siding (W.K. Witt)

The Melita Rhyolite is part of a bimodal volcanic association which occurs within a north-trending zone of rhyolitic volcanism, between the Kalgoorlie Terrane to the west, and the Gindalbie, Jubilee and Kurnalpi Terranes to the east. Rhyolitic volcanic rocks in this zone are mildly peralkaline and enriched in Nb, Y, Zr, K, Rb and REE, compared with rhyolite in andesite-dominated calc-alkaline complexes in the EGP (Hallberg & others, 1993).

Pyroclastic flow deposits of the Melita Rhyolite are exposed near the Melita railway siding, 30 km north of Kookynie. The Melita Rhyolite consists mainly of crystal-vitric tuff, lapilli-tuff and pyroclastic breccia, with minor ash-tuff and dacitic rocks. The poorly sorted and unbedded nature of most fragmental rocks suggest they are pyroclastic flow deposits. Felsic volcanic rocks are interbedded with pillowed basalt and basaltic andesite, locally with abundant vesicles indicating shallow water deposition. However, rhyolitic volcanic centres were probably emergent. There is a general increase in clast size and proportion of pyroclastic breccia, from the south and southwest towards Melita railway siding, suggesting proximity to a volcanic centre.

At the excursion locality, coarse pyroclastic breccia forms prominent outcrops east of the railway line. Up to 50% angular clasts (30 cm) of devitrified rhyolite and crystal fragments (2 mm) of quartz, K-feldspar and albite occur within a very fine-grained, quartzofeldspathic matrix. Locally, a flow foliation sweeps around crystal and vitric clasts. A thin unit of finely bedded, glassy ash-tuff can be observed west of the railway line. It was probably deposited as an air-fall tuff, but low-angle cross-bedding and flame structures indicate subaqueous deposition, and suggest limited sedimentary reworking.

Stop 12. Calc-alkaline lamprophyre intrusions—Pub Well (P.R. Williams/K. Currie)

In the region between Eulaminna Siding through to Monger Bore in the north, a large number of lamprophyric and feldspar-phyric dykes and minor intrusion have been identified (Fig. 15) over a number of years (Miles, 1945; Hallberg, 1985; Rock & others 1988; Williams & others, 1993). Observations on over 80 of these occurrences during a recent mapping program have led to the suggestion that the majority of these intrusions are related to the mafic magmatism which produced the voluminous mafic sills in the area. The stratigraphy around the Benalla Anticline, on the Minerie 1:100K sheet, is strongly disrupted by the emplacement of differentiated dolerite/gabbro sills and discordant sheets (see Welcome Well area). Some of these sills are of the porphyritic "cat-rock" variety.

In this area, lamprophyres are strongly spatially associated with the mafic sills, particularly with "cat-rock". Currie (in Williams & others, 1993) found no occurrences of lamprophyre more than 100 m from another mafic body. Typically the lamprophyre occurs within a mafic body, but several examples of intrusions into host rock have been noted. The lamprophyre intrusions are typically termed dykes, but a range of intrusive forms has been observed. Elliptical forms, pod-like masses, sills and U-shaped bodies are present. They range in thickness between 6 cm and 2 m, and range from 10 to 1000 m long. However, most examples are under 50 m in length. The boundaries are usually sharp, but in mafic host rocks tectonised chloritic alteration zones are common at the dyke margins. Dyke offsets at the lithological contact between mafic sills and host rocks are due to syn-intrusive faults. Dykes with lenticular shapes at the boundaries of the mafic sills, and pipe-like shapes with dyke offshoots were also observed.

Feldspar-phyric bodies resemble the lamprophyres in form, mineralogy, and colour index. There is no sharp distinction between the two, since many lamprophyre dykes contain plagioclase in their groundmass, and such dykes pass gradationally along strike to plagioclase-phyric varieties within a few metres. Petrographically, four categories of intrusions can be defined—

- feldspar-phyric dykes (plagioclase-pyroxene porphyries)
- mica-bearing lamprophyres
- pyroxene-bearing lamprophyres
- plagioclase-bearing lamprophyres

Average analyses of these groups is shown in Table 4, along with the average host differentiated sill composition. The analyses show typical calc-alkaline and sub-alkaline affinity, although some of the mafic sills are tholeiitic. There is no split on geochemical discrimination diagrams between feldspar-phyric dykes and lamprophyres; in fact a continuous trend in composition from the most mafic rocks of the sills to the most siliceous plagioclase-bearing lamprophyres is implied (Fig 16). The trace element data suggest derivation of all the mafic rocks from a similar mantle source (Zr/Hf =35; Y/Nb =4-10). Differing compositions could be explained by fractionation of differing proportions

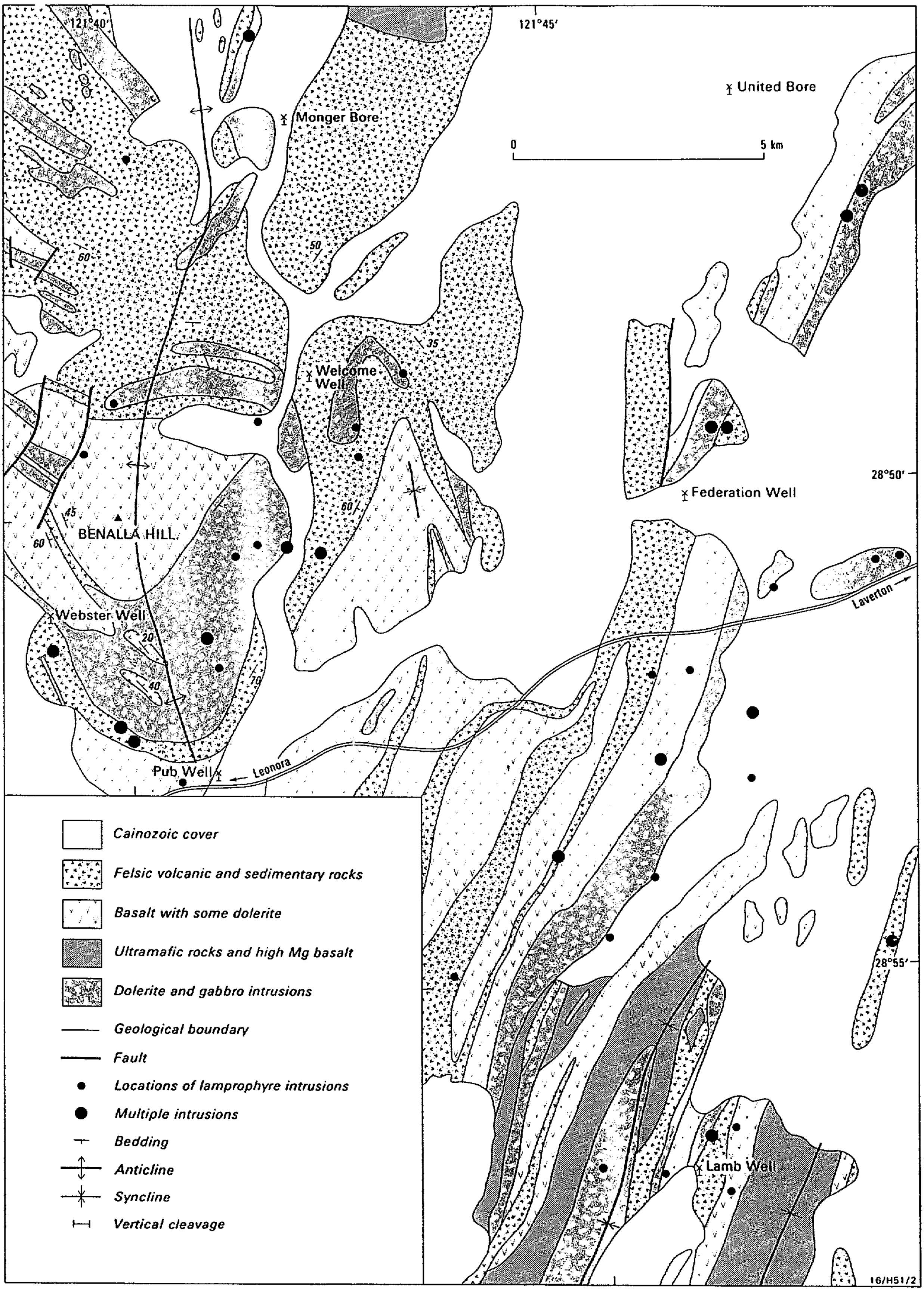


Fig. 15. Lamprophyres in the vicinity of Pub Well.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	53.01	57.63	67.12	77.38	47.61	51.50	49.28	61.04	75.17	65.34	73.77
TiO_2	0.76	1.05	0.59	0.33	1.04	0.81	0.69	0.66	0.15	0.59	0.16
Al_2O_3	17.70	16.07	15.78	12.95	14.56	12.80	12.36	14.30	12.76	15.21	13.81
Fe_2O_3	7.28	8.45	3.46	1.55	3.44	3.50	2.15	3.01	0.97	1.64	0.72
FeO					7.30	3.82	5.36	2.64	1.38	2.87	0.91
MnO	0.10	0.13	0.06	0.03	0.16	0.09	0.12	0.06	0.05	0.06	0.03
MgO	5.99	5.31	1.92	0.22	5.80	5.77	7.64	4.00	0.18	1.88	0.33
CaO	9.64	5.69	5.08	0.50	11.18	8.60	8.63	3.93	1.76	4.55	1.78
Na_2O	4.92	3.41	5.57	6.84	2.24	3.19	3.11	4.08	4.24	4.35	4.50
K_2O	0.49	2.37	0.68	0.33	0.29	0.52	0.71	1.68	1.88	1.27	2.59
P_2O_5	0.36	0.17	0.12	0.05	0.24	0.44	0.44	0.34	0.02	0.14	0.05
H_2O^+					3.52	3.78	3.38	2.68			
H_2O^-					0.12	0.16	0.13	0.31			
CO_2					1.86	4.69	5.17	0.93			
S					0.20	0.18	0.26	0.15		0.16	
LOI	3.70	2.77	2.00	1.32					0.73	1.48	0.93
TOTAL									99.45	99.67	99.74
Ba	270	1275	271	362	148	195	635	404	498	350	629
Ce	55	27	18	14.3	44	72	70	82	103	39	55
Cr	800	336	101	16	269	353	551	196	7	46	6
Cu					82	57	63	29	<1	14	3
Ga					18	16	15	18	19	19	19
La					22	30	33	45	54	21	27
Li					6	14	17	20	41	28	25
Nb	6.1	7	4.5	3.1	3	4	4	6	10	7	7
Nd	34	11	9	3.6	24	42	40	40	57	16	20
Ni	317	140	51	12	72	51	114	75	<1	22	4
Pb					2	10	8	7	6	6	15
Rb	24	54	12	26	6	5	10	31	42	35	85
Sc	28	21	14	5.6	36	25	27	14	7	13	3
Sr	421	586	294	251	223	366	443	424	147	287	367
V	197	158	99	49	252	175	185	101	<2	84	14
Y	23	20	9.4	2.9	28	23	21	16	67	14	10
Zn					96	86	94	66	63	68	47
Zr	111	125	121	91	100	139	131	182	178	140	108

1. Porphyritic basalt-andesite - Welcome Well Complex from Giles and Hallberg (1982)
2. Porphyritic andesite - Welcome Well Complex from Giles and Hallberg (1982)
3. Dacite - Welcome Well Complex from Giles and Hallberg (1982)
4. Porphyritic rhyolite- Welcome Well Complex from Giles and Hallberg (1982)
5. Average of 7 analyses of differentiated and porphyritic gabbroic sills - AGSO ROCKCHEM database (Currie and Williams, in prep).
6. Average of 6 analyses of feldspar-phyric mafic dykes, Benalla Hill area - AGSO ROCKCHEM database (Currie and Williams, in prep).
7. Average of 11 analyses of mica (chlorite) lamprophyres, Benalla Hill area - AGSO ROCKCHEM database (Currie and Williams, in prep).
8. Average of 6 analyses of plagioclase-bearing lamprophyres, Benalla Hill area - AGSO ROCKCHEM database (Currie and Williams, in prep).
9. Monzogranite from north of Yundamindera - AGSO ROCKCHEM database (Sample # 92967022).
10. Average of 4 analyses of tonalite, Yundamindera area - AGSO ROCKCHEM database.
11. Average of 4 analyses of monzogranite, Yundamindera area - AGSO ROCKCHEM database.

TABLE 4. Selected analyses from the Welcome Well volcanic centre and calcalkaline mafic intrusives, and from the Yundamindera granitoids.

of the same minerals from a hypothetical parental magma, and modelling of fractionation of measured compositions of phenocryst phases is consistent with this suggestion.

Probably the best evidence is the intimate association of the lamprophyric rocks with the gabbroic intrusions, and the unusual intrusive forms, combined with the similarity of their geochemical characteristics. These features are readily explained if the gabbros and lamprophyres are tapping a similar source and fed through the same crustal conduit, but is a strange coincidence if the lam-

	A	B	C	D	E	F	G	H
SiO_2	72.25	71.64	73.20	72.52	72.80	75.03	65.80	60.98
TiO_2	0.22	0.24	0.19	0.20	0.22	0.23	0.21	0.81
Al_2O_3	14.59	14.90	14.10	14.50	13.87	12.56	17.08	15.44
Fe_2O_3	0.61	0.59	0.62	0.61	0.72	0.72	1.47	2.13
FeO	1.26	1.38	1.09	0.92	1.10	1.45	0.56	2.91
MnO	0.03	0.03	0.03	0.02	0.03	0.03	0.15	0.08
MgO	0.50	0.54	0.44	0.40	0.32	0.25	0.51	2.79
CaO	2.00	2.09	1.87	1.60	1.10	1.07	1.21	4.97
Na_2O	4.58	4.68	4.43	4.41	3.88	3.96	6.18	4.01
K_2O	2.81	2.83	2.80	3.59	4.79	3.54	5.64	2.13
P_2O_5	0.07	0.08	0.06	0.06	0.07	0.04	0.09	0.34
Ba	824	920	676	932	1028	648	1077	1018
Rb	90.5	85.5	98	123	234	105	153	81.5
Sr	367	419	287	343	223	63	595	767
Pb	24	25	23	31	51	14	45	21
Th	11	10.5	11.5	18.5	45	12	13	11.5
U	2.4	2.1	3	3.7	9.9	2.5	7.5	1.9
Zr	116	120	110	123	186	165	113	174
Nb	5.5	5	6	5	13	13	9	6
Y	9	7	12	7	15	42	40	14
La	24.3	26.7	19.4	31.7	76.6	37.2	57.8	60.9
Ce	45.8	49.6	37.6	58.1	138.9	74.1	111.5	117.4
Nd	15.1	15.9	13.4	17.4	40.6	33.3	46.7	46.3
Sc	4	4	4	3	3	5	5	13
V	19	21	16	14	12	10	22	101
Ni	6	6	6	6	5	5	5	32
Cu	7	6	9	10	5	4	6	25
Zn	37	40	32	37	44	32	51	81
Ga	19.4	20.2	18	19.7	20.8	15.9	21.5	20.3
K/Rb	258	275	237	242	170	280	306	217
Sr/Sr*	0.96	1.02	0.90	0.73	0.20	0.09	0.59	0.74
$(Ce/Y)_N$	12.7	17.7	7.8	20.8	23.2	4.1	7.0	21.0

A – average of Group 1 (pre-folding group), 69 samples
B – average of Group 1 gneisses, 42 samples
C – average of Group 1 granitoids, 27 samples
D – average of Group 4 (high-Ca post-folding granitoids), 34 samples
E – average of Group 5 (low-Ca post-folding granitoids), 45 samples
F – average of Group 3 (HFSE-enriched granitoids), 10 samples
G – average of Group 6 (syenites), 4 samples.
H – average of Group 2 (mafic granitoids), 41 samples.
K/Rb, Sr/Sr* and $(Ce/Y)_N$ ratios calculated from averages. (Most geochemical data from AGSO, unpublished; additional geochemical data from Bettenay, 1977; Cassidy, 1992; Witt, unpublished.)

TABLE 5. Averages of gneiss and granitoid groups in the Leonora–Laverton region.

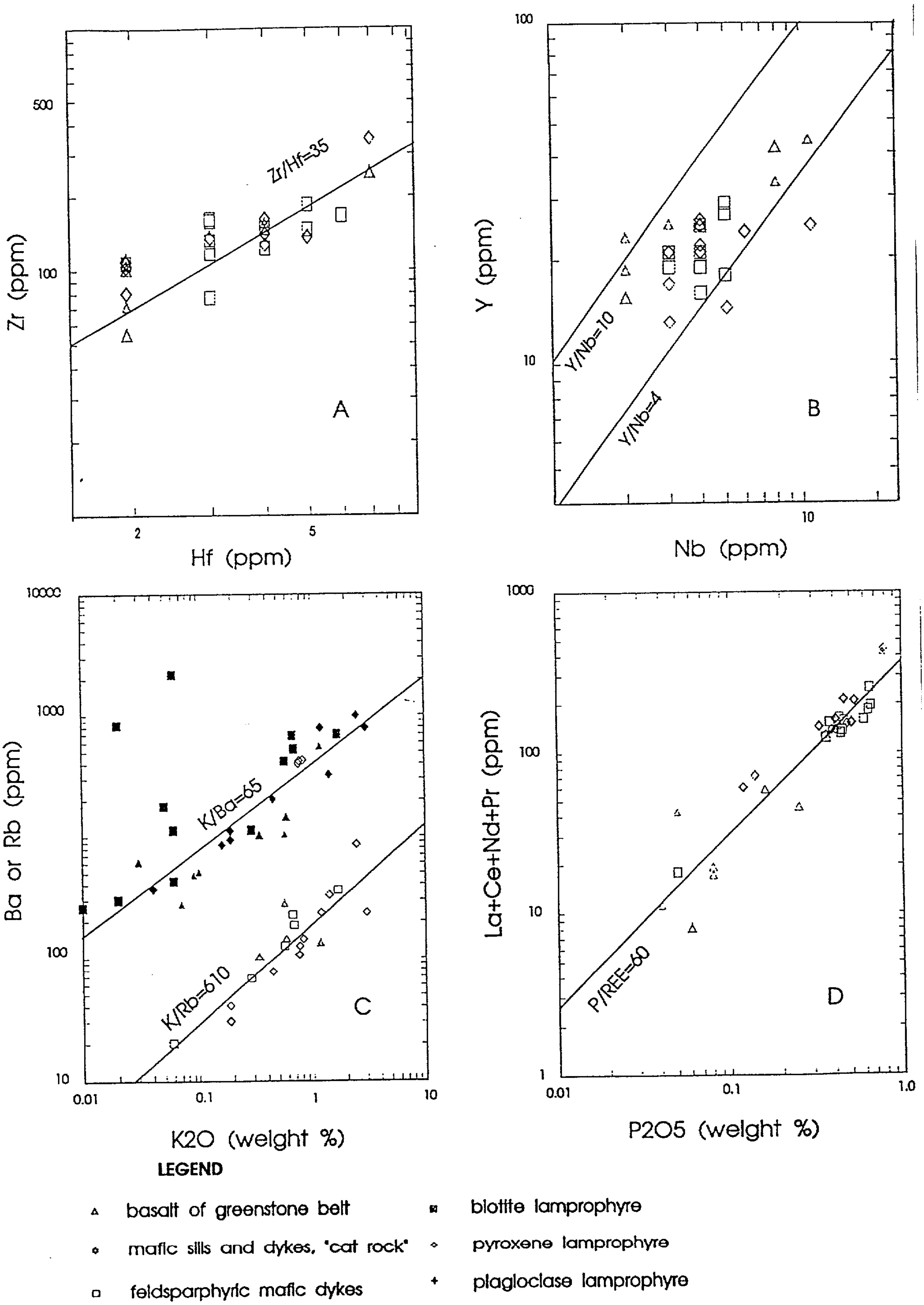


Fig. 16. Geochemistry of the Pub Well lamprophyres.

prophyres are tapping a separate mantle melt. The coincidence is reinforced by fact that the intrusive region is away from any of the major through-going structures of the NE Goldfields, and situated in one of the largest low-strain domains in the region.

Currie & Williams (1993) argue that the lamprophyric magma formed by local hydration and carbonation of mafic magma at crustal depths. The lack of plagioclase phenocrysts can be ascribed to stabilisation of amphibole, rather than plagioclase, at the depth of crystallisation. Plagioclase-pyroxene porphyry could result from repeated degassing and recharge of the magma (possibly associated with volcanic eruption) at water fugacity too low to stabilise amphibole. The irregular, locally brecciated and tectonised forms of the minor mafic bodies are a natural consequence of the rise of volatile-rich magma to levels where exsolution of volatile phases occurred. According to this model, lamprophyres and related porphyries form a late, highly differentiated phase of the major Archaean mafic magmatism which formed the greenstone belts in this region.

The excursion stop demonstrates the unusual form of intrusion of one of the many bodies in the area. The area is on the upper contact between a dolerite sill and felsic volcanics. From the ridge top looking north, the sill-like form of the dolerite/gabbro bodies is clearly visible in the form of a stepped "cuesta" landform. The dip slopes, dipping east here are sill tops; the steps or nicks in the hillside are concordant felsic volcanic horizons of the upper portion of the Welcome Well Complex. Three examples of lamprophyre are exposed. A pipe-like, discordant intrusion of biotite (chlorite) lamprophyre is apparently disconnected from the upper part of the dolerite sill. However, a connection at depth may be implied by the presence of short dyke of similar material within the upper part of sill, just to the north. On the northern side of ridge, a third exposure of lamprophyre has been observed in the form of a short, discordant dyke. It is this almost random, irregular nature of intrusions which gives the strong impression of their relationship to the surrounding differentiated sill, and the unlikely possibility of emplacement in mantle-tapping fractures.

Stop 13. Welcome Well mafic and intermediate metavolcanic stratigraphy (P.R. Williams & J. Sheraton)

The Welcome Well Complex (Giles & Hallberg, 1982) is an example of the emergent andesitic volcanic centres which are present in the northeastern Goldfields. The centres are widely spaced and discrete. They include the Spring Well Complex (Giles, 1982), Ida Hill Complex (Giles, 1981) and Bore Well Complex (Giles, 1981). Rocks in the Welcome Well Complex are andesitic lavas and agglomerate overlain by a black shale/sediment horizon followed by a succession dominated by volcaniclastic breccia and feldspathic sandstone. The succession is shown in Fig. 3; the map is taken from Williams & others (1993).

The andesitic volcanics show slight to moderate Y (and by analogy HREE) depletion, but an overall lack of Sr depletion, consistent with derivation from a plagioclase-poor source, probably in the mantle. Relatively unfractionated REE patterns $(Ce/N)_N$ mostly 3-8) argue against residual garnet and probably amphibole.

Giles (1982) and Giles & Hallberg (1982) propose fractionation of a primary mantle-derived mafic magma involving separation of amphibole and plagioclase and lesser amounts of clinopyroxene, Ti-magnetite and apatite. Some degree of fractionation is likely, but the amounts of amphibole and plagioclase separation possible are severely restricted by the lack of major Y and Sr depletion respectively. Hence, the parent magma was probably much less sileous than the more mafic basaltic and basaltic andesite volcanics, some of which have quite high Cr (≅ 600g/t) and Ni (280 g/t). Partial melting of an intermediate crustal source (dioritic or tonalitic gneiss) is precluded by the lack of negative Sr anomalies in the volcanics.

There is a broad similarity in composition to some of the less siliceous pre-folding intrusives, such as the Lawlers Tonalite. However, the andesitic volcanics tend to be lower in K, Ba, Rb, Sr, Ce and Zr, but higher in Cr and Ni, suggesting derivation from a distinct, less enriched mafic source, or higher degrees of melting of a similar source. The sodic rhyolites are relatively low in K and Rb, but have high Na and Sr, precluding extensive fractionation of an andesitic magma. Similar features in many felsic gneisses and pre- to syn-folding granitoids (which, however, are rarely so depleted in K and Rb) are thought to reflect partial melting of a mafic source. However, felsic volcanic rocks commonly show evidence for late- or post-magmatic redistribution of more mobile elements (particularly alkalis), so these features may not necessarily be primary.

The Welcome Well Complex occurs in the lower part of the statigraphic succession in the Minerie area (Fig. 17). The rocks are beneath the major ultramafic horizon present in the Mount Kilkenny area, and this ultramafic is now considered to be the same age as and hence correlated with the

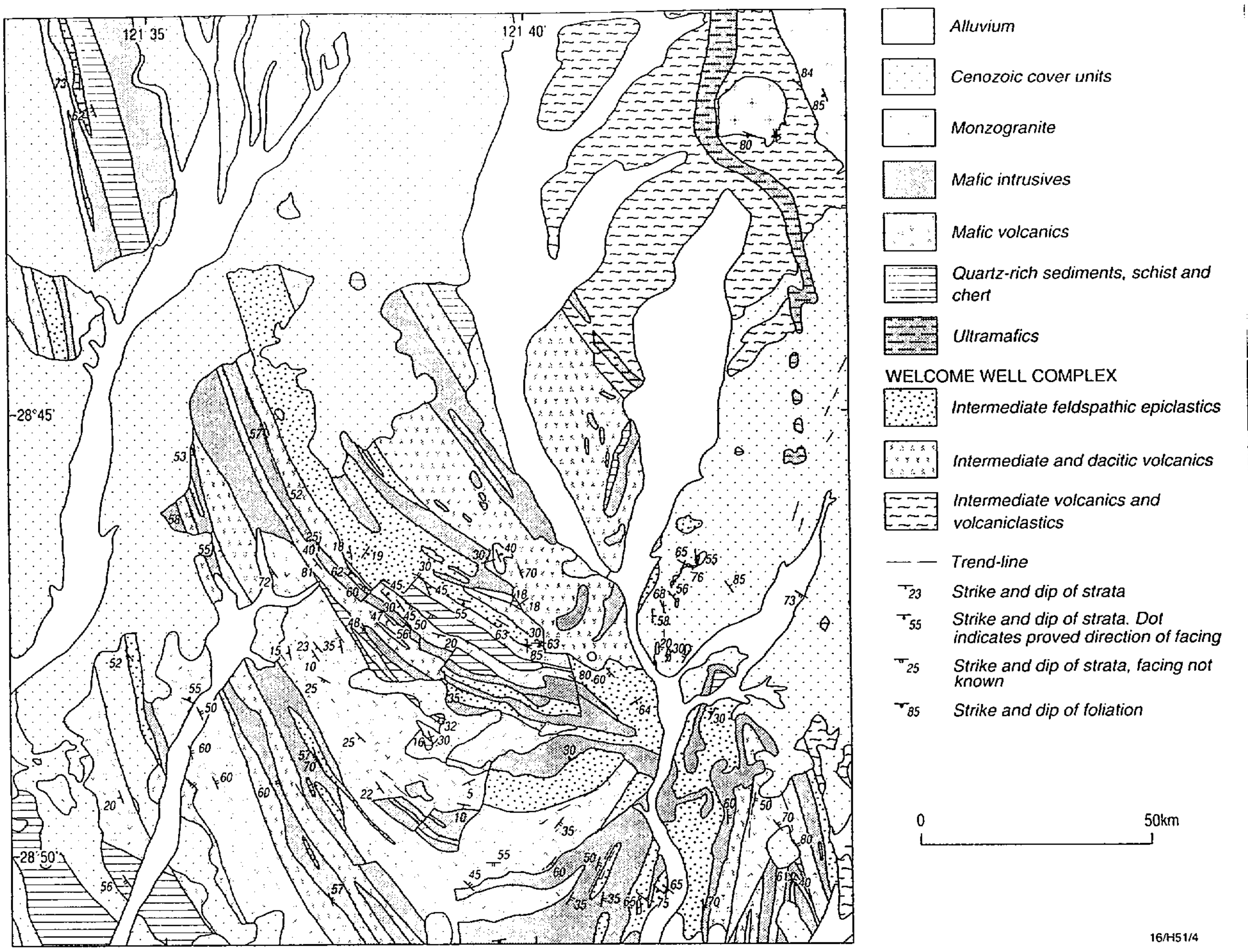


Fig. 17. The Welcome Well Complex in the Minerie area.

Kambalda komatiite sequence (Claoué-Long, personnel communication). There is a lower ultramafic horizon within the andesitic rocks of the Complex, which suggests contemporaneous komatiitic and andesitic volcanism. The basaltic sequence above the Complex consists of distinctive tholeiitic pillow lava separate by rhyolitic felsic volcanics or tuffs.

The close association of felsic volcanics, andesites derived from differentiation from basalt and tholeiitic basalts, together with the discrete nature of the andesitic centres argues against a subduction-related origin for the rocks, and extensional processes associated with basin formation above a mantle heat source (such as a mantle plume) may present a better tectonic model for the generation of the andesitic rocks.

The excursion stop examines the coarse epiclastic breccias and their surrounding rocks to the southeast of Welcome Well. The breccias are composed of pale-coloured fine-grained volcanic clasts ranging in size up to 0.5 m set in a plagioclase-phyric volcanic or volcaniclastic groundmass. The breccia outcrops stand out above the alluvial plain, but at the edges of the outcrops, fine-grained, strongly foliated rocks suggest that the breccia outcrops represent original discrete debris flow lobes surrounded by finer-grained detritus. The margins of the clasts have a welded appearance with the matrix, suggesting that the breccias were still hot when deposited. They are thus proximal to a volcanic vent.

Where the road to the south of the breccia outcrops crosses the ridge, good exposures of intrusive porphyritic gabbro show the characteristics of "cat rock". The porphyritic intrusives are spectacular, but form only the minority of the intrusive gabbro and dolerite bodies. In this area, the gabbro is discordant with stratigraphy, but most intrusions are thick, concordant sills.

Stop 14. The Granny Smith gold deposit (V.J. Ojala & S. Hunt)

The Granny Smith gold deposits are situated 250 km NE of Kalgoorlie and 23 km south of Laverton at lat. 28°48' south, long 122°25' east in the Laverton–Leonora area of the north EGP (Fig. 18). The mines are a joint venture between Placer (Granny Smith) Pty Limited (60%), a wholly owned subsidiary of Placer Pacific Limited, and Delta Gold NL (40%). Granny Smith is a relatively new discovery: the area was staked in 1979 by prospector Ray

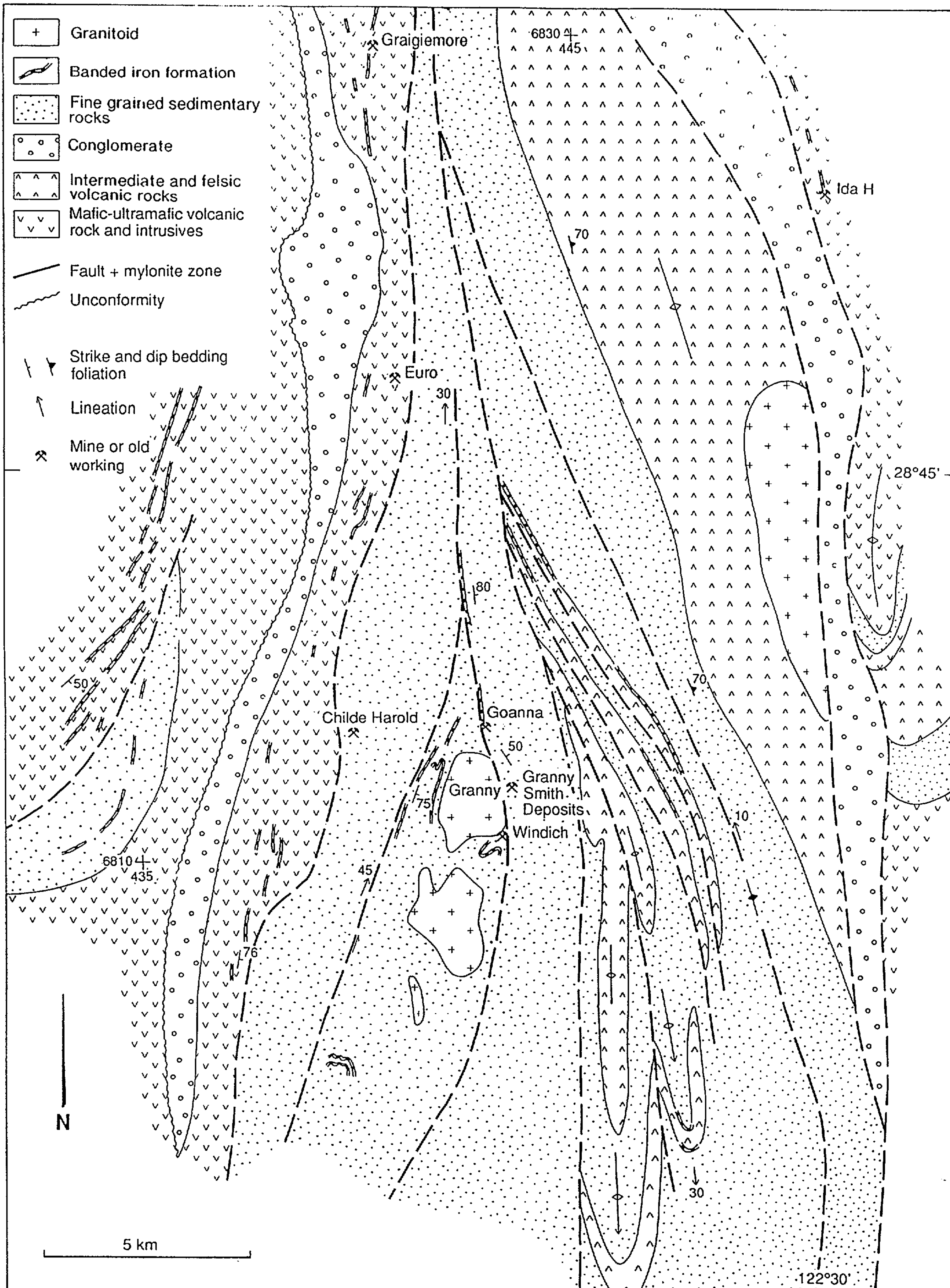


Fig. 18. Geological sketch map of the area surrounding the Granny Smith deposits showing the location of the Granny Smith Granodiorite in the structural corridor between areas of contrasting structural trend.

Smith whose wife Lorraine had recently become a "Granny", and hence the property name. Mine production commenced in 1990 after 10 years of exploration, and the development plan of the mine was based on proven and probable reserves of 21 Mt with an average grade of 1.7 g/t in three deposits.

Regional geology

The Granny Smith deposit is located within a succession of sedimentary and felsic to intermediate volcanic and volcaniclastic rocks within the Murrin-Margaret sector of Hallberg (1985) on the eastern limb of the Margaret anticline. Hall & Holyland (1990) termed this zone "a structural corridor" between areas of different structural orientations (Fig. 18). Mafic rocks dominate the western side of the structural corridor, and sedimentary rocks and felsic to intermediate volcanic rocks dominate the eastern side. Hall & Holyland (1990) suggested that the corridor contains several strike-slip faults. However, recent mapping suggest that the corridor consist of small-scale thrust stacking, and that brittle faults, including the mineralised structures, are mainly reactivated reverse faults.

Local geology

Sedimentary rocks

Sedimentary rocks in the Granny Smith area (Fig. 19) consist of banded iron formation (BIF), chert, argillite, arenite, lithic greywacke and conglomerate. Most of the sedimentary sequence consists of laminated argillites, in which silty laminae alternate with mud laminae and lithic greywackes deposited from turbidity currents. Thin layers of chert occur throughout the stratigraphy. Among these rocks, there are coarser grained sedimentary rocks, including immature matrix-supported conglomerates. Poor sorting and angular clasts, which are mainly of volcanic origin, indicate close proximity to volcanism.

Granitoid

The Granny Smith Granodiorite is a small, elongate (about 2 km x 5 km), zoned calc-alkaline pluton which has porphyritic and more mafic margins, and which has intruded, together with marginal porphyry dykes, into the structural corridor after the main folding event. The composition of the intrusive rocks varies from diorite, commonly containing clinopyroxene, to hornblende-biotite granodiorite which forms the major part of the intrusion. Pegmatitic aplite veins represent the most fractionated part. All intrusive phases show some degree of deuteric alteration which has resulted in small amounts of sericite, saussurite and chlorite. Variable mineral composition of the pluton is reflected in its geochemistry, which shows quite large variations in major element compositions. However, Rb, Sr and Ba do not show strong fractionation, except for the aplitic pegmatite dykes, and there is a gap in compositions between pegmatites and the main granodiorite (Fig. 20). The mineral assemblage and geochemical features (presence of hornblende + magnetite + titanite; a wide range in SiO_2 and metaluminous compositions) indicate similarities to Phanerozoic I-type granitoids. These are common characteristics of syn to late-tectonic calc-alkaline internal granitoid plutons (Cassidy, 1992) Biotite crystallisation before hornblende, together with clinopyroxene, suggest that the intrusion crystallised from a hot, dry magma that would have been capable of intruding to a high crustal level (compare Wones, 1981; Hyndman, 1981). Intrusive breccias and miarolitic cavities also indicate high level intrusion. The pluton is surrounded by a 200-300 m wide contact metamorphic aureole that is zoned, progressively from the granitoid contact outwards, with a several metres wide hornfelsed margin in which no sedimentary textures have been preserved, an andalusite-bearing slate, and finally a slate with mica spots. Preservation of sedimentary structures in spotted zones is exceptionally good. The contact aureole also indicates a high level of emplacement.

Structure

The Granny Smith gold mineralisation is located along a norht-south striking deformation zone that partly follows the contact between granitoid and sedimentary rocks. The mineralisation-related deformation and alteration is late in the structural history. It is brittle in the granitoid and brittle-ductile in the sedimentary rocks. The movement sense of the faults in the deformation zone is reverse, but total displacement during the mineralisation is unknown. In the granitoid, offset of the individual vein-filled mineralised faults, measured from displaced aplite veins, is on a centimetre to decimetre scale. Offset of a folded BIF horizon in the northernmost Goanna deposit is interpreted from drilling and geophysical data to be about 900 m. Rocks on both sides of the fault have been contact metamorphosed near the granitoid. Therefore, most of the displacement along this reverse fault probably occurred during the folding and related faulting event, before the intrusion of the granitoid.

Gold mineralisation

Economic gold grades occur in three deposits (Goanna, Granny and Windich) along the

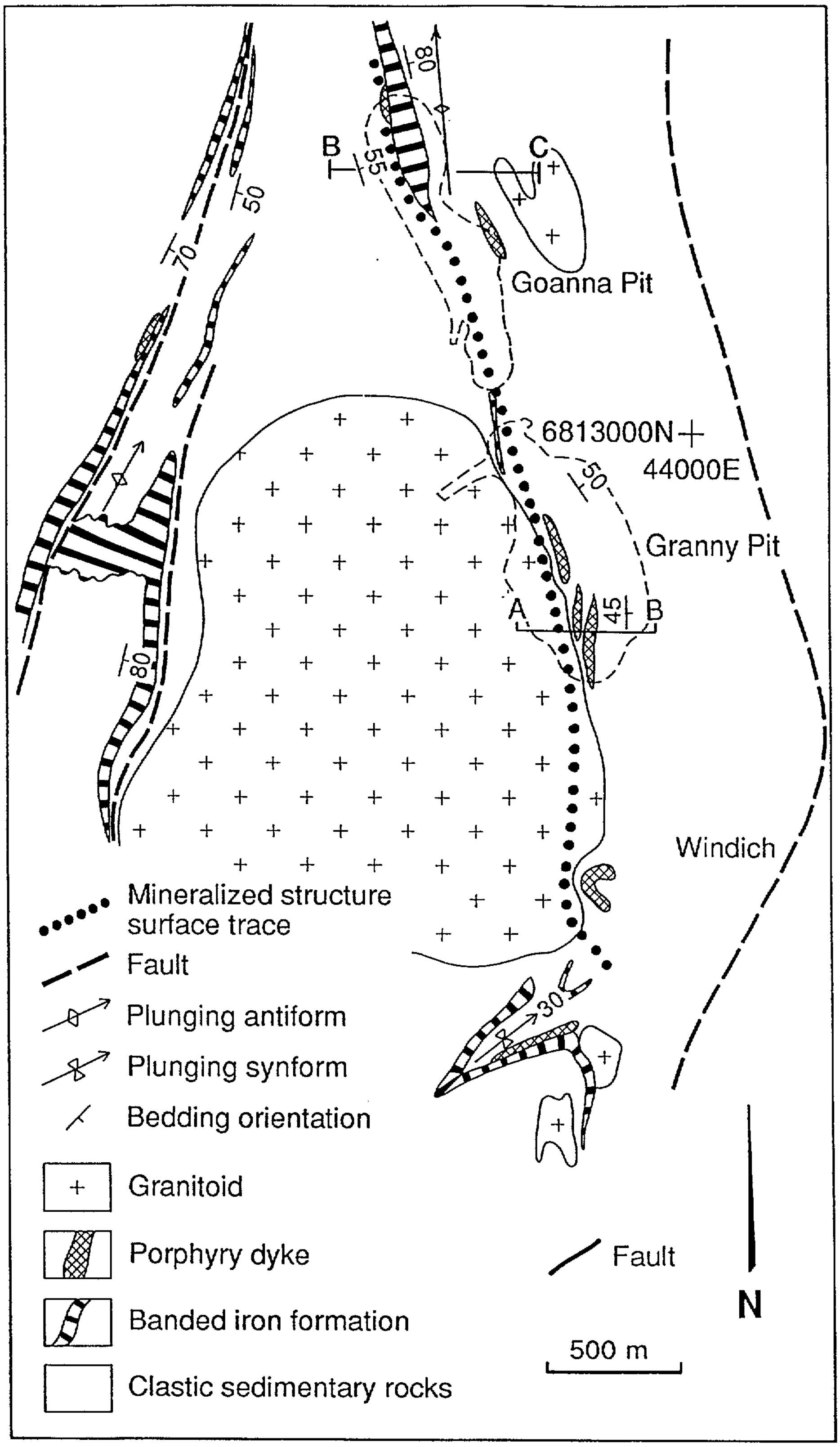


Fig. 19. Geological map of the Granny Smith gold deposits showing the relation of the deposits to the granitoid and the surface trace of the mineralised deformation zone.

mineralised deformation zone (Fig. 19). At the northernmost Goanna deposit, gold mineralisation is hosted by sedimentary rocks. The mineralisation is about 5 m thick and it is in a reactivated reverse fault (dip about 50°east) which has cut the western limb of an anticlinal fold defined by the BIF horizon (Fig. 21A). At the Granny and southernmost Windich deposits, the mineralisation is largely controlled by the contact between the granitoid and sedimentary rocks (Fig. 21B). The mineralisation follows the contact where it is at shallow and moderate dips (2°east). However, where the dip of the contact

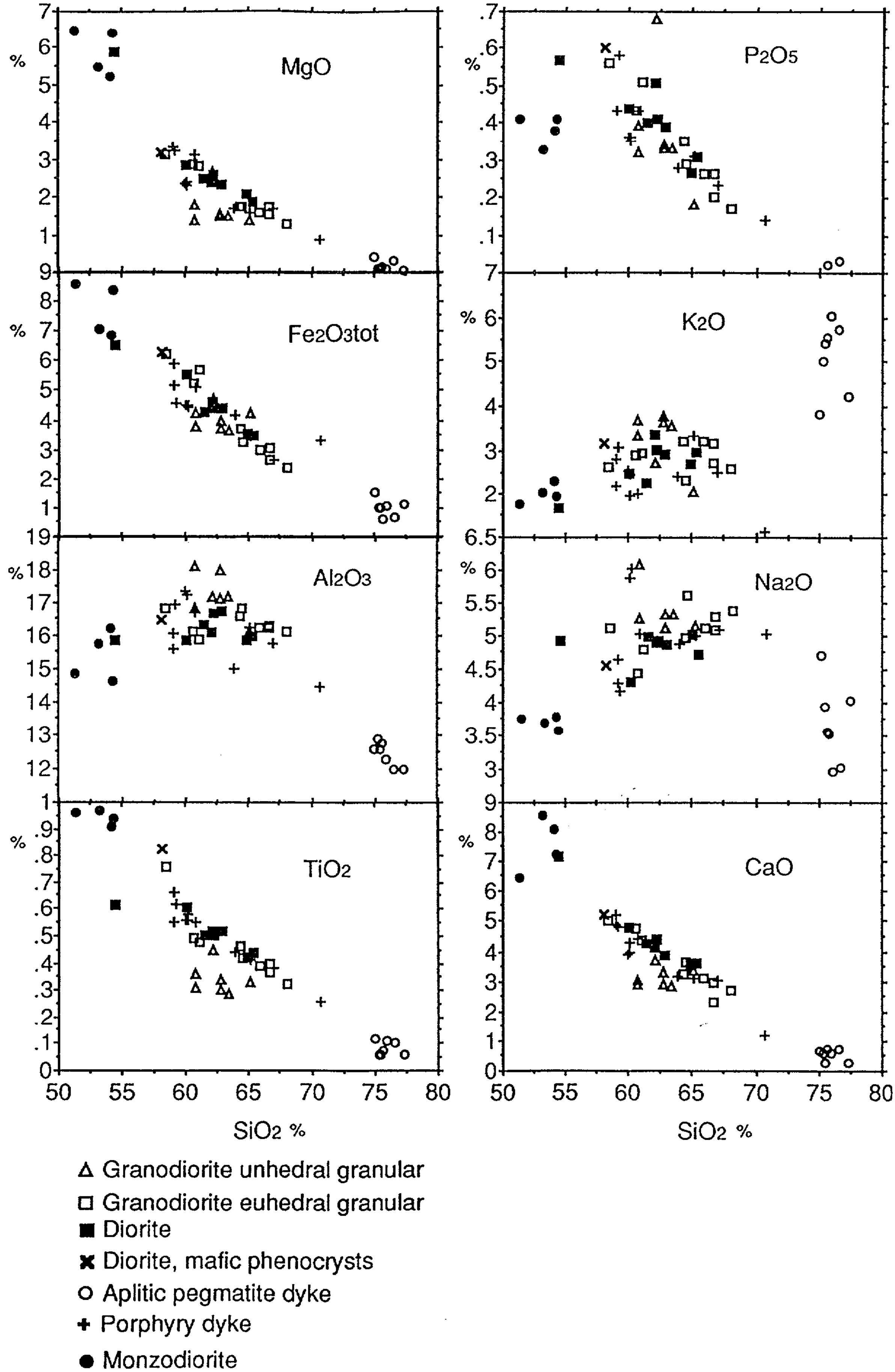


Fig. 20. Harker variation diagrams for the Granny Smith Granodiorite.

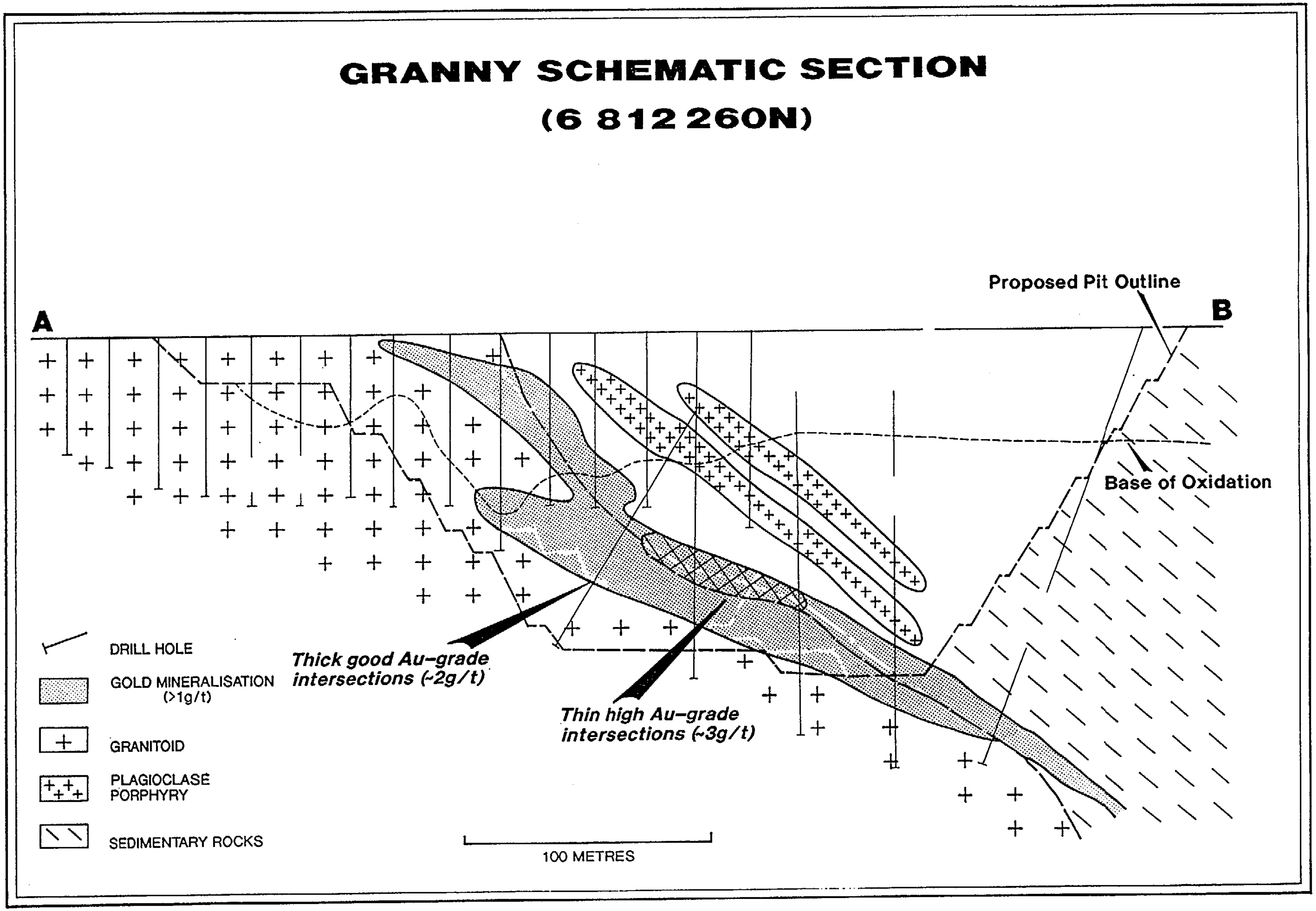


Fig. 21A. Schematic section of the Granny deposit showing the relation to the granitoid contact. Location of the section shown on Fig. 2.

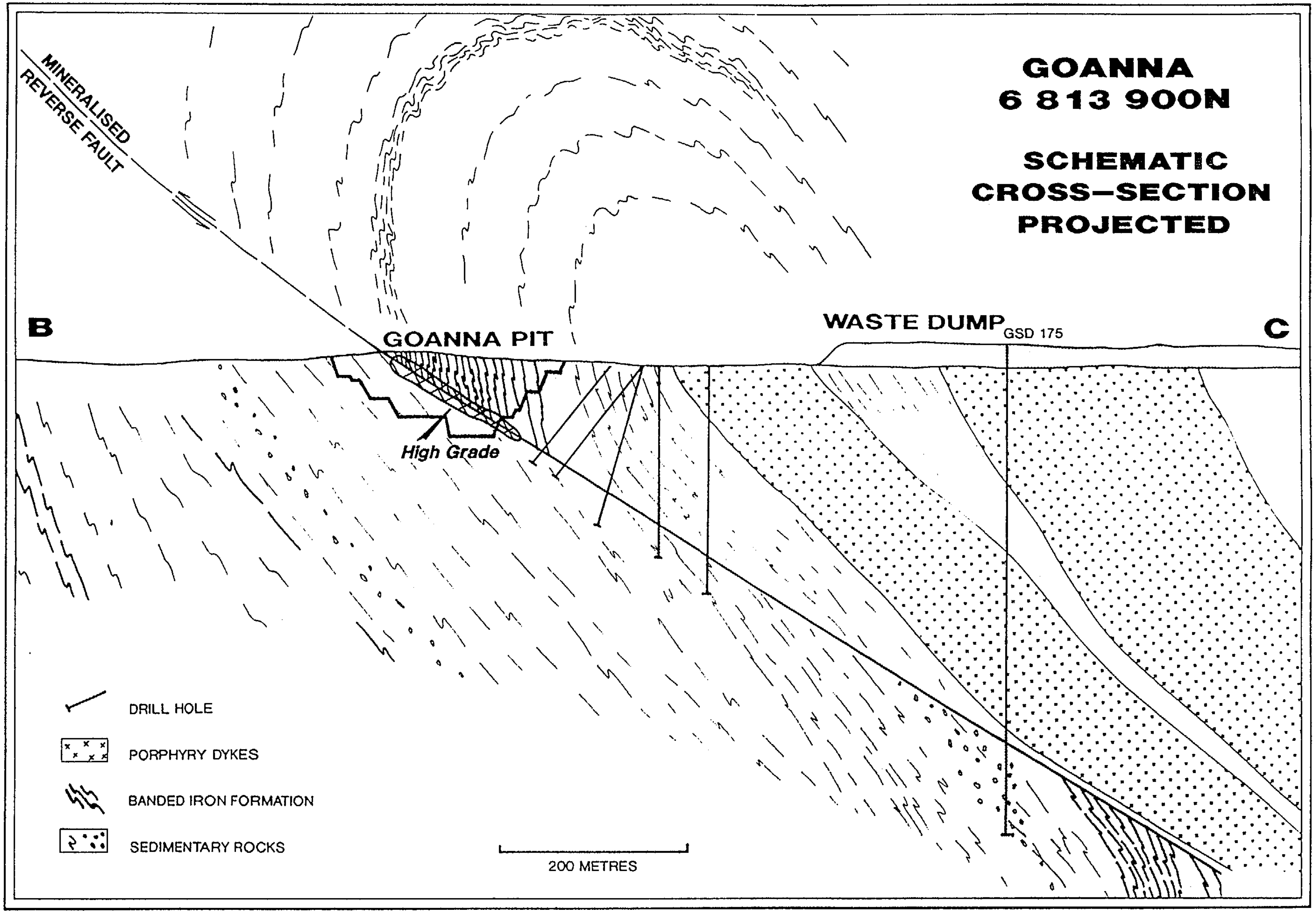


Fig. 21B. Schematic section of the Goanna deposit. Location of the section shown on Fig. 2.

is steeper, the mineralisation occurs both in the granitoid and in the sedimentary rock, in which it roughly follows bedding. The highest gold grades are in the sedimentary rocks just above or at the shallowly dipping irregular contact. The dip of the mineralisation shallows towards the centre of the granitoid pluton. In the granitoid and in much of the hornfelsed sedimentary rocks, the gold mineralisation is in a conjugate network of thin (millimetre-scale) carbonate-quartz breccia veins and their alteration halos. Within the granitoid, this veining is concentrated in an up to 40 m thick subhorizontal zone. The veins generally contain more wall rock than carbonate-quartz vein infill, and commonly display minor movement. Variations in the vein orientations, and therefore in the inferred orientation of the local stress field, are greatest within the Granny deposit where the granitoid contact is also most irregular and best mineralised, and differences of up to 90° occur in the orientations of the conjugate vein-set maxima on a stereonet. Conjugate vein sets occur at scales from millimetres to tens of metres. The gold mineralisation consist of two main alteration stages: hematite alteration and sericite-carbonate (ankerite) alteration. Hematite alteration occurs only in the granitoid, where it is more widespread and more pervasive than sericite-carbonate alteration. Gold grades of hematite alteration rarely exceed 1 g/t . Sericite-carbonate alteration ("bleaching") represents the main mineralising phase, which is more fracture and deformation controlled and overprints hematite alteration. Distal alteration is typified by the breakdown of clinopyroxene and amphibole and the development of retrograde sericite-carbonate ± biotite ± chlorite alteration, whereas the proximal alteration zone is defined by more intense ankerite-sericite-silica-pyrite ± rutile alteration. Gold grade is strongly correlated with intensity of associated pyrite alteration. Pyrite is the main sulphide phase, and pyrrhotite, chalcopyrite, sphalerite and arsenopyrite are common but minor sulphides. Galena and Au-, Ag- and Pb-tellurides occur in late-stage quartz-carbonate veins. Native gold occurs as inclusions and on the grain boundaries of sulphides, and as individual grains and clusters in alteration halos and veins.

Fluid inclusions, interpretated to be trapped during the gold mineralisation, are low salinity (0-8 eq.wt% NaCl) CO_2-H_2O-NaCl ± CH_4 inclusions with variable liquid/vapour ratio. Liquid–vapour homogenisation temperatures of these inclusions vary from 150°C to 460°C (mean 325°C). CO_2-H_2O-NaCl ± CH_4 inclusions in the quartz veins from the proximal alteration zone have higher XCO_2 and lower salinities than inclusions in the quartz veins from the distal alteration zones. Calculated pressure at the time of trapping ranges from 0.5 kb to 2 kb. Nahcolite (Ts = 80-250°C, mean 160°C) is the most common daughter mineral; other carbonate minerals are also identified, but they are rare. Petrographical and compositional data suggest that the proximal high XCO_2 of the fluid is a result of phase separation at depth, and that this fluid has been mixed with a cooler, relatively saline (5-10 wt. % NaCl eq.) aqueous fluid. The high level emplacement of the granitoid, but the CO_2 - and CH_4-rich (deep-level) nature of the fluids trapped in the proximal quartz veins in combination, suggest that the source of the ore fluid was not the exposed granitic pluton. Rather, as indicated by conjugate vein orientations within the granitoid, the localisation of the mineralisation in and around the granitoid was due to stress heterogeneities which were controlled by its anomalous geometry within the enclosing greenstone sequence The fluid was most likely derived from a deeper source, possibly a deeper granitic body.

Stop 15. Syenite and low-Ca granite—Laverton Tectonic Lineament (P.R. Williams/D.C. Champion)

Syenite and associated potassic syenogranite and alkali feldspar granite are a relatively minor but widespread component of the intrusive suite. They intruded late in the tectonic and magmatic history, but are strongly structurally controlled in their distribution (Libby, 1978; Hallberg, 1985). They have been recognised by Witt & Davy (1993) and Champion & Sheraton (1993) as a distinct geochemical suite (Gilgarna Suite).

A number of syenite intrusions are present on the eastern side of the Laverton "lineament". They stand out clearly on airborne radiometric images and form markedly elongate, almost linear plutons. The excursion stop is at one of these intrusions. The rocks vary from medium to coarse-grained varieties, and the composition from syenite to quartz syenite. The coarse-grained rocks have tabular K-feldspar crystals in a cumulate-like aggregate with interstitial finer-grained biotite, feldspar and varying small amounts of quartz. The biotite is in small flakes and comprises about 5% of the rock. The medium to fine-grained syenite is equigranular with only minor quartz, although the grainsize is variable and quartz is more abundant in coarser-grained patches. The syenite is not foliated, but is cut by thin (1 mm) mylonite zones with sinistral offset, and one

0.5 m wide shear zone striking NNW has been observed.

North of the syenite body, the Extension Tank granite is a pink-grey sparsely porphyritic medium-grained biotite granite. Feldspar phenocrysts are pink and subhedral up to 1.5 cm in size. The granite is not foliated. It is magnetic (450-850 x 10^{-5} S.I. units) and has a high radiometric response (1400 counts per second). Although the Extension Tank granite is one of the more mafic low-Ca granites, the characteristic low CaO and high K_2O, Rb, Th, U, Zr and LREE are still evident (Table 5).

The syenite is geochemically distinct from the Extension Tank granite, being considerably more mafic with markedly higher total alkalis (Table 5, anal. 8). The latter is a characteristic of all the syenitic rocks in the region (Witt & Davy, 1993; Champion & Sheraton, 1993). Other geochemical characteristics of the syenite include low TiO_2, MgO and CaO (Table 5).

Stop 16. Deformed porphyry dykes in amphibolite—Hawks Nest: Structural relationships on the margins of the Laverton Dome (P.R. Williams).

The rocks at Hawk's Nest are foliated amphibolite intruded by a number of feldspar and quartz feldspar porphyry dykes. The area is at the southern margin of the Laverton magnetic domain of Williams & Whitaker (1993). This domain is a region of medium-high grade gneissic and granitic rocks northeast of Laverton (Fig. 22A). Rocks at the margin of the Laverton magnetic domain are strongly sheared intercalated felsic porphyry and amphibolite, the margin forming a major regional mylonite zone which affects the surrounding greenstones. Internally, the magnetic domain comprises a composite body of gneissic granite, porphyritic granite and late, undeformed porphyry dykes and pegmatites (Fig. 22B). Gower (1976) has indicated that the margins between the porphyritic granite and migmatitic gneiss within the Laverton magnetic domain are transitional, implying that the bulk of the granitic rocks in the dome are of high metamorphic grade.

The gneiss and granite of the Laverton domain are bounded to the south and southeast margin by amphibolite intercalated with deformed quartz feldspar porphyry The margin is very similar in character to the margin of the Raeside Batholith. The pattern of mineral lineations and movement vectors on mylonite around the Laverton magnetic domain have not yet been established.

Age relationships in the Laverton magnetic domain indicate that significant components of the dome were emplaced early in the structural history. Several sheets of gneissic granite are strongly foliated, in places with two distinct foliations developed. There is a strong foliation in the mafic rocks adjacent to the domain, parallel to the strike of the contact, and that foliation is folded by the upright folding event which produced the regional Margaret Anticline (a D_2 regional fold, Gower, 1976). Thus the regional S1 and S2 are present in both the amphibolite enclaves and the granite. At Mount Gooses the earlier foliation is oriented east-west and dips to the south, and porphyry dykes in the amphibolite structurally overlying the granitic complex are also deformed in a non-coaxial (shear) event parallel to the early shallowly dipping east-west foliation.

Linear wedge-shaped apophyses and aligned enclaves of amphibolite extend into the Laverton domain in a northwesterly direction from its southern margin. A small body of dominantly fine-grained strongly deformed porphyry forms an outlier of the main granitic complex. The porphyry has a gently dipping concordant roof zone with a strong cleavage parallel to the margin. Greenstones adjacent to the porphyry are strongly lineated amphibolite intruded by abundant quartz and quartz-feldspar porphyry dykes. The dykes are also strongly deformed, particularly where oriented parallel to the external foliation. Asymmetric pressure shadows developed around feldspar phenocrysts suggest that the movement direction was top-side-north. To the north of the porphyry body the amphibolite shows excellent evidence of two phases of deformation. The strong foliation defined by aligned amphibole laths is folded into upright shallowly plunging east-verging folds which are parasitic on the regional Mount Margaret Anticline. There is a persistent crenulation cleavage in the amphibolite belt which is oriented parallel to the axial surface of the regional D_2 anticline. The amphibolite and banded iron formations in the Windarra and Windarra South areas (Fig. 22A), are concordant remnants of the upper plate to the granitic complex (Williams & Whitaker, 1993). The evidence suggests that the upper surface of the dome is a concordant sheet. There is no evidence of stoping and no piercement structures as would be expected with diapiric emplacement. A model of the dome shape is shown in Fig. 22B. The apophyses are likely to be original features of the dome emplacement, not infolded during D_2, because the synclinal axes of the amphibolite lying between the porphyry outlier and the main complex is at a high angle to and over-

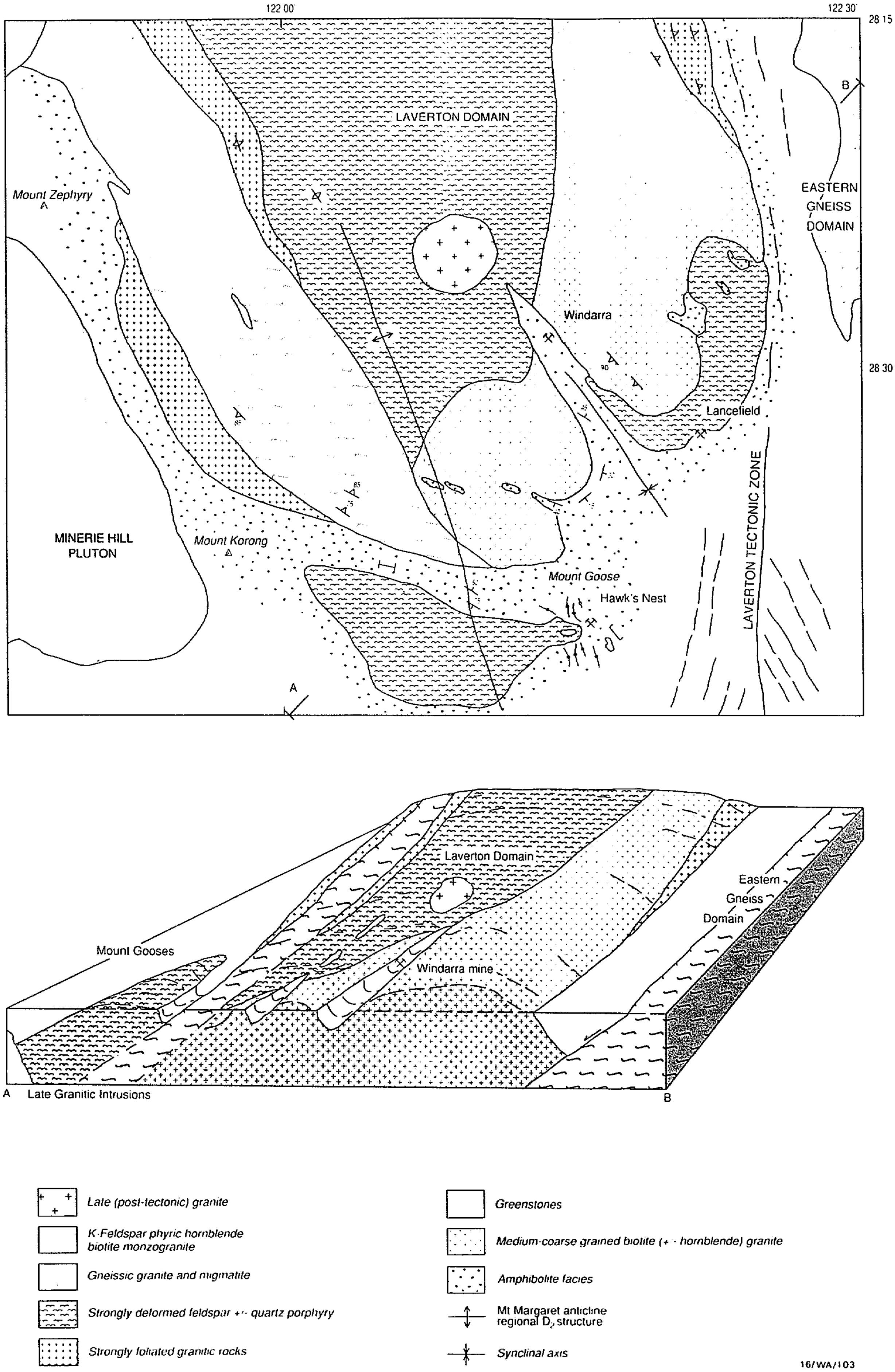


Fig. 22A. Details of the geology of granitic "intrusions" in the Laverton magnetic domain between Mt Korong and Windarra. B. Schematic block diagram of southern part of the Laverton Dome showing the structural position of the greenstone apophyses and their interpretation as "mega-mullions" in the roof zone of the dome.

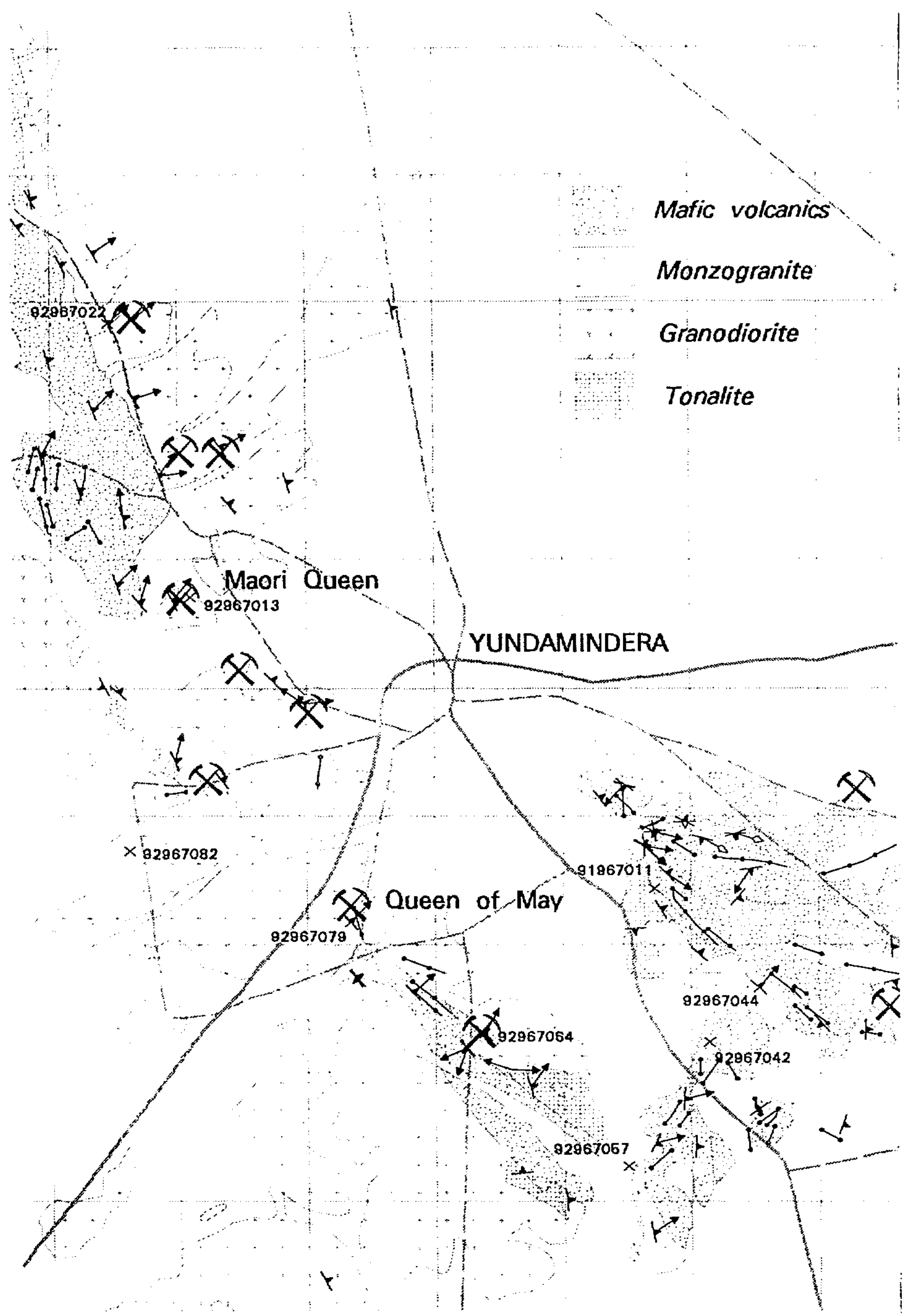


Fig. 23. Granitoid plutons and regional deformation of the Yundamindra region (area A in Fig. 24). Penetrative deformation in the granite and marginal mafic-ultramafic metavolcanics is associated with pluton emplacement during regional extensional deformation.

printed by the regional D_2 anticline. The regional D_2 overprint may, however, have steepened the dips on the earlier NW trending structures, as these would have remained in the flattening field of D_2 strain. The apophyses are therefore interpreted as remnants of upper plate greenstones between lobes of the Laverton dome with slightly different uplift rate. The elongation direction of the apophyses may define the regional extension direction during dome emplacement.

Stop 17. Yundamindera magnetic syn-late D_2 granite, intrusive relationships (M.S. Rattenbury)

The Yundamindera region (Fig. 23) has a spectrum of typical Archaean Eastern Goldfields granitoids, including voluminous granite, granodiorite, tonalite and syenite (Hallberg & Wilson, 1983; Hallberg, 1985; Rattenbury & Swager, in prep). Collectively the Redcastle, Danjo, and Maori Queen plutons at Yundamindera and the Pindinnus and Colindina plutons farther south form an irregular 2000 km^2 north-trending block which separates greenstone stratigraphy to the east and west (Fig. 24). Mafic and ultramafic metavolcanics occur in what has previously been mapped as a south-closing fold structure, the Eucalyptus Anticline. The western limb has a surface expression which extends over 20 km to the northwest, ranging in width from 0-5 km. The width variation is due to embayment by granitic plutons from the northeast and southwest, complicated by later thrust and strike-slip faulting. The Yundamindera region has a penetrative linear and/or planar deformation developed, particularly near the contact between mafic metavolcanics and intrusive granite. The deformed Maori Queen tonalite and granodiorite occur as small intrusions which are mostly confined within the mafic and ultramafic metavolcanics at the boundary between the large Danjo and Redcastle plutons. The deformed Danjo granodiorite has distinctive arcuate magnetic zoning and gravity measurements suggest this pluton has a relatively thin, flat-lying sheet-like form. The undeformed Redcastle monzogranite is a large subcircular (~20 km diameter) pluton with a prominent magnetic rim and a large negative gravity anomaly.

The granitoids can be subdivided geochemically into the deformed and relatively sodic tonalite and granodiorite, and the unfoliated monzogranite (high-Ca group of Champion & Sheraton 1993, eg 92967079.2). Most analysed granitoids samples are depleted in Y (and heavy rare-earth elements, HREE), but not Sr, and may have been formed by large-scale remelting (remagmatisation) of older tonalitic to granodioritic crust derived, in turn, by melting of a plagioclase-poor (eclogitic?) source. Such a two-stage model, as favoured by Wyborn (1993) and Champion & Sheraton (1993), explains the widespread occurrence of inherited zircons, implying derivation from older felsic crust, in many Eastern Goldfields Province granitoids. Some granitoids, however, like the less siliceous Maori Queen tonalite (eg 92967079.1) which have relatively low large-ion lithophile elements (K,Rb,Th and U) and LREE, may well have been derived by direct melting of a mafic source, although isotopic data will be neccessary to confirm this. The Danjo granodiorite (eg 92967022) differs from most other granitoids in the area by showing marked Sr depletion, and having relatively high Zr, Y and LREE. These features are consistent with partial melting of felsic crustal rocks (ie residual plagioclase), possibly combined with significant crystal fractionation.

Another feature of the Yundamindera region is the large number of quartzofeldspathic porphyry dikes which intrude both granite and greenstone. The wide geographical distribution of dikes from the Yundamindera region suggests the granite complex roof was close to the present erosion surface, and some of the numerous scattered irregular mafic volcanic pods mapped within the granite are probably roof pendants. Granite porphyry dikes from an area south of Murphy Well are concentrically arranged around two partially closed elliptical centres (Fig. 25). The Murphy Well ring-dike geometry is interpreted to have initiated from cylindrical or domal cupolas on an irregular subsur-

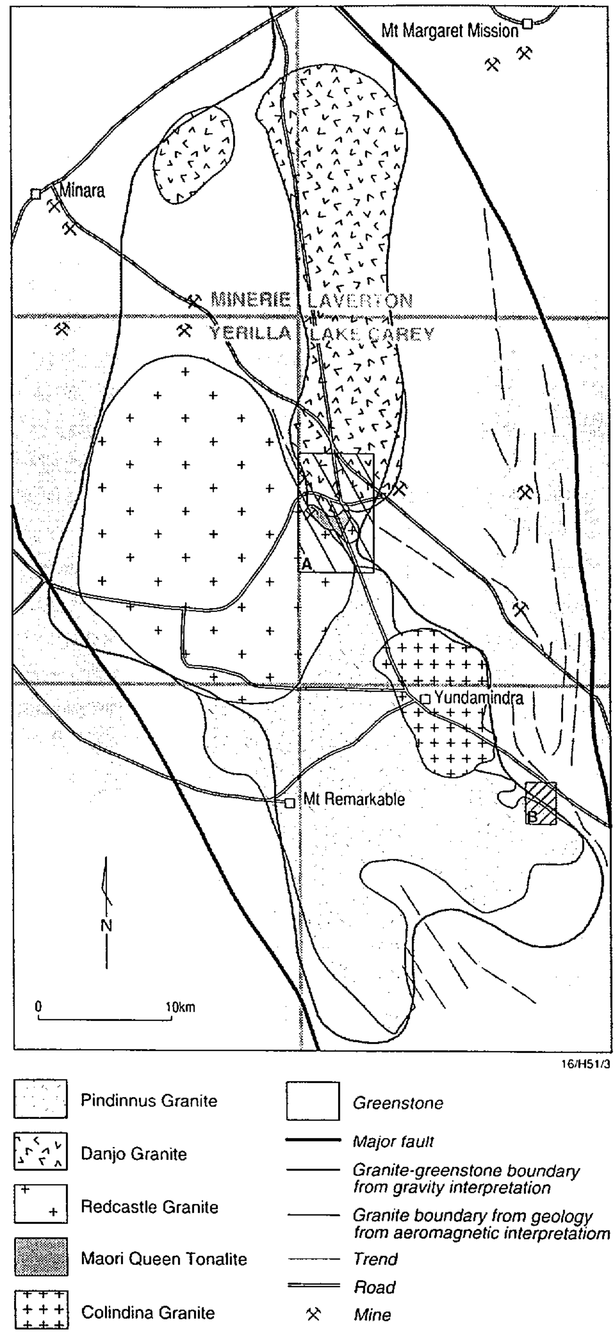


Fig. 24. The Pindinnus, Redcastle, Danjo and Colindina plutons in the wider Yundamindera region form an irregular 2000 km^2 north-trending block which separates greenstone stratigraphy to the east and west

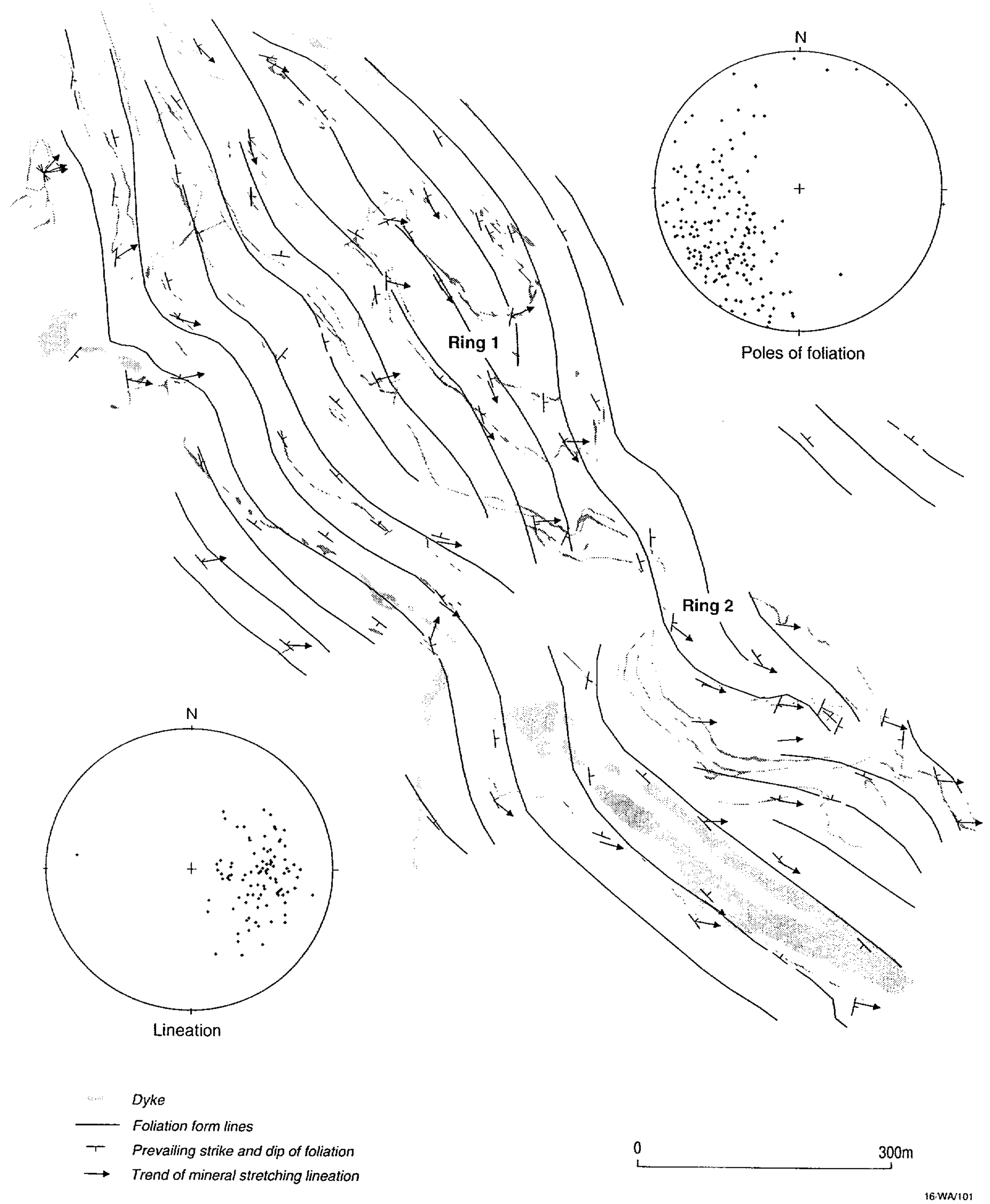


Fig. 25. Granite porphyry ring-dikes intruding mafic metavolcanic rocks south of Murphy Well (area B of Fig. 24). Two concentrically arranged rings are apparent and are interpreted to have intruded from a near-surface granite cupola. Foliation form trends (lines) and east-plunging stretching lineations (arrows) suggest intrusion of the dikes occurred during extensional deformation. Stereonets are equal area and lower hemisphere projections.

face granite topography. The dikes and surrounding mafic schists are penetratively foliated with a strong stretching lineation developed, except for one concentric ring of undeformed granite dikes. The deformed and undeformed ring-dikes are interpreted to have intruded during the final stages of movement within an extensional shear zone. Foliation trajectory maps show cusp-like trends indicative of higher strain have developed between the ring-dike centres. The cusps resemble large scale boudinage necking. The Murphy Well ring-dike structure forms part of the upper surface of the Pindinnus composite pluton which extends over an area of about 800 km^2. The earlier phases of the granite are characterised by a penetrative foliation dipping moderately east to northeast and/or a stretching lineation plunge moderately east to northeast. Amphibolite blocks up to several square kilometres area occur throughout, some of which have subparallel structural fabrics to the surrounding granite; others show some rotation. The blocks with subparallel fabrics may be "attached" remnants of the greenstone carapace overlying the granite, whereas the blocks which show apparent rotation are probably roof pendants which have detached from the carapace. The structural fabrics from both amphibolite and granite suggest a regional east side to the east extensional movement during pluton intrusion.

Stop 18. Birthday complex granitoids of the Rainbow Suite, Cement Well (W.K. Witt)

At this locality, hornblende-biotite granodiorite and monzogranite, locally containing tabular K-feldspar phenocrysts, belong to the Rainbow Suite. The composite nature of the Birthday complex is indicated by an intrusive contact between relatively coarse-grained granodiorite and finer-grained, relatively leucocratic monzogranite. Features characteristic of the Rainbow Suite include a relatively high modal ferromagnesian mineral content (5-15%, including hornblende), and the widespread presence of synplutonic dykes and rounded, relatively mafic xenoliths. However, the northwest to north-northwest-trending regional S_2 foliation is weakly developed or absent at this locality, except in synplutonic dykes.

Rounded, relatively mafic clots and xenoliths, up to 1 metre across, are abundant and compositionally diverse, ranging from hornblende (clinopyroxene, biotite, quartz) monzonite to monzodiorite. Mesocratic xenoliths commonly contain smaller, darker enclaves and mafic mineral clots. Dykes (some synplutonic) are compositionally similar to the rounded xenoliths, contain more mafic xenoliths and have cuspate margins. Both dykes and xenoliths are back-veined by the host granitoids.

Rainbow Suite granitoids range from 66-71.5% SiO_2. Alkalis increase, and TiO_2, FeO*, MgO, P_2O_5, V and Zn decrease with increasing SiO_2. Chondrite-normalised REE patterns are steeply fractionated with no Eu anomaly. Xenoliths range from 50% to 64% SiO_2, but dykes extend to 74.5% SiO_2. They have similar REE patterns to the host granitoids but are relatively enriched, particularly in LREE. The dykes and xenoliths are scattered on Harker variation diagrams and do not display a straight line relationship with host granitoids (compare with restite-dominated suites, White & Chappell, 1977). Analyses of granitoids from Stop 18 are given in Table 3 (analyses 5-10).

Stop 19. Lunch time stop, (time permitting) Menagina Monzogranite, at Menangina Rocks (W.K. Witt)

The Menangina Monzogranite is an ovoid pluton (approximately 10 x 5 km) which has intruded the Birthday complex. Aeromagnetic data suggest it is concentrically zoned but exposures in magnetically distinct zones are petrographically similar. The intrusion is a medium- to coarse-grained, relatively leucocratic biotite monzogranite, locally with tabular K-feldspar phenocrysts (<2 cm). In contrast to the last locality, it is characterised by petrographic homogeneity, although aplitic veins and pegmatitic segregations are common in some exposures.

The Menangina Monzogranite is a member of the post-regional folding Woolgangie Suite, the volumetrically dominant post-RFG suite in the SWEGP. The SiO_2 content of the Woolgangie Suite ranges from 70.5% to 75.0%. K_2O, Rb, Th, U, Nb, Y and Li increase, and TiO_2, Al_2O_3, FeO*, MgO, CaO, Na_2O, P_2O_5, Ba, Sr, Zr and V decrease, with increasing SiO_2. LREE contents are similar to those of the Rainbow Suite, but chondrite-normalised plots are less fractionated, and most samples generate a distinct Eu anomaly. An analyses of Menangina Monzogranite at this locality is given in Table 3 (analysis 11).

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Excursion 3

The regolith and its exploration and economic significance

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The importance of regolith in mineral exploration

by R.R. Anand and R.E. Smith

On the Yilgarn Craton, it is interpreted that the combined effects of prolonged deep weathering under warm, humid conditions followed by differential erosion and physical and chemical modification, particularly under arid or semi-arid conditions, have led to a great variety of materials exposed on the land surface and to intricate regolith-landform relationships. For an exploration programme, it is important to understand the regolith-landform relationships in the wide variety of terrain types which have resulted from this complex geomorphic settings and regolith evolution, for two reasons:

- (i) to design and execute the sampling programme properly;
- (ii) to present and interpret the data properly.

Both of these tasks need to include a knowledge of regolith and landscape evolution, weathering, and dispersion processes.

For geochemical and geophysical exploration regolith–landform control is provided by regolith–landform mapping, establishing the regolith stratigraphy within these mapped units, and synthesizing a regolith-landform model. An overall flow chart for carrying out regolith mapping is shown in Fig.1. Different geochemical thresholds usually apply to different sampling media and hence to different regolith-landform mapping units. One purpose for producing a regolith–landform map is to delineate areas or units within which data may be treated uniformly. Regolith–landform maps also identify and delineate areas characterised by complex surficial relationships which may require specialised exploration approaches in contrast with areas which require, for example, straight-forward soil sampling. For these reasons it may be very useful to consider regolith-landform relationships in interpretative terms, that is, *residual, erosional* and *depositional regolith–landform regimes* (Anand, & others, 1989). *Residual regimes* are mappable areas characterised by widespread preservation of lateritic residuum. Conceptually, they are relics of an ancient weathered landsurface. *Erosional regimes* are those areas where erosion has removed the lateritic residuum to the level where the mottled zone, saprolite, or fresh bedrock are either exposed, concealed beneath soil, or beneath thin locally derived, associated sediments. *Depositional regimes* are areas characterised by widespread sediments which can be many metres thick. The boundary between residual and depositional regimes can be gradational or sharp. The substrate can range from stripped surfaces to complete weathering profile. It is now recognized that, in some regions, extensive areas in depositional regimes can be underlain by complete or near-complete lateritic weathering profiles (Anand & others, 1991).

Commonly, residual, erosional, and depositional regimes must be subdivided into regolith-landform mapping units. The extent of subdivision will, of course, depend upon the mapping scale. The more detailed the scale becomes, the more the mapping units become regolith- rather than landform-based, and vice versa.

If the broad *regolith–landform regimes* are mapped in an area, it usually becomes clear which geochemical sampling media to use. Where the lateritic horizon is preserved, duricrust, pisoliths and nodules form an ideal sampling medium for seeking widespread dispersion haloes for Au and

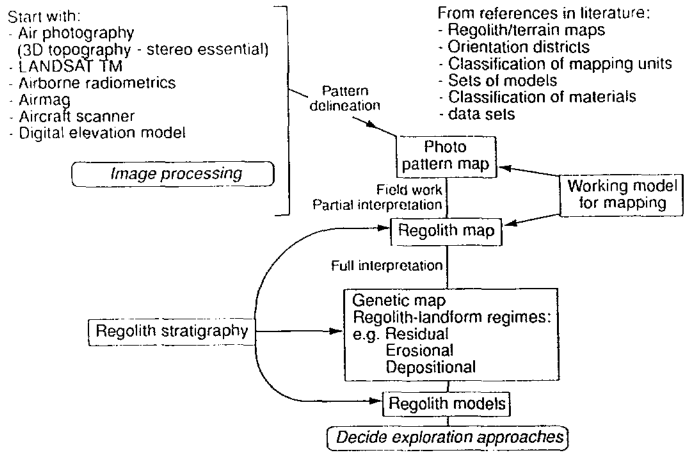

Fig. 1. General flow chart for regolith mapping.

base metals exploration. These may be collected from the surface or near surface in residual regimes or by drilling in depositional regimes (Anand & others, 1991; Smith & others, 1992). In depositional areas, seeking geochemical haloes in buried residual laterite and ferruginous saprolite can be of great advantage in exploration. This requires accurate, subsurface sampling of the lateritic materials and knowledge of the regolith stratigraphy. In drilling to sample buried laterite, it is important to recognise and distinguish between the transported lateritic debris and residual laterite. Where the profile is truncated, ferruginous saprolite iron segregations and soils are suitable sampling media in erosional regimes (Anand & others, 1991).

Regolith–landform evolution and geochemical dispersion in regolith, Kalgoorlie region

by R.R. Anand (unless otherwise indicated)

The purpose of this section is to describe those aspects of the evolution of regolith and landscape that are important to the mineral exploration in the Kalgoorlie region. This region is an integral part of the array of weathering terrains in the Yilgarn Craton. Thus, in common with other terrains the evidence of deep weathering is widespread. However, details of weathering, including laterite formation and modification since development by erosion, deposition and secondary enrichment is significantly different from other areas of the Yilgarn such as the Leonora–Wiluna region. Consequently, Kalgoorlie region requires a different exploration approach in terms of sampling media compared to the Leonora–Wiluna region.

Regional geology and geomorphology

The climate of the Kalgoorlie region is semi-arid with a mediterranean (winter rainfall maximum) tendency; hot summers alternate with cool to mild winters. The vegetation is a mosaic of predominantly eucalypt woodlands, becoming open with a saltbush and bluebush understorey on the more calcareous soils.

The Kalgoorlie region covers a number of geological provinces and major structural elements. Granite-greenstones of the Kalgoorlie region form the southern part of the Eastern Goldfields Province in the Yilgarn Craton of Western Australia. The greenstones, which host rich deposits of nickel and gold, comprise metamorphosed mafic volcanic and intrusive rocks, felsic volcanic rocks and sedimentary rocks which crop out in highly deformed linear belts intruded by, and separated by, variably deformed and metamorphosed granitoid. In the Kalgoorlie region, systematic regional mapping at 1:100 000 scale by the Geological Survey of Western Australia (GSWA) has delineated a number of structural and stratigraphic domains with similar geological histories (Swager & others, 1990). These are: the Kalgoorlie, Callion, Norseman, Kurnalpi and Menzies Terranes.

The Kalgoorlie Terrane is divided into four major domains (Coolgardie, Ora Banda, Kambalda, Boorara) and two smaller domains (Bullabulling, Parker). The domains are separated by shear zones that include dismembered and attenuated elements of the stratigraphy. Despite these structural breaks, a similar regional stratigraphic succession (with some variations) and a common deformation history are recognized throughout. Callion and Norseman Terranes lack significant komatiite and contain extensive BIF units which have not been found in Kalgoorlie Terrane. The Kurnalpi Terrane contains komatiite but is dominated to the east by mafic and acid to intermediate volcanic rocks.

The Kalgoorlie region is characterised by an interior drainage in enclosed basin and is within the Salinaland Division of Justson (1934).

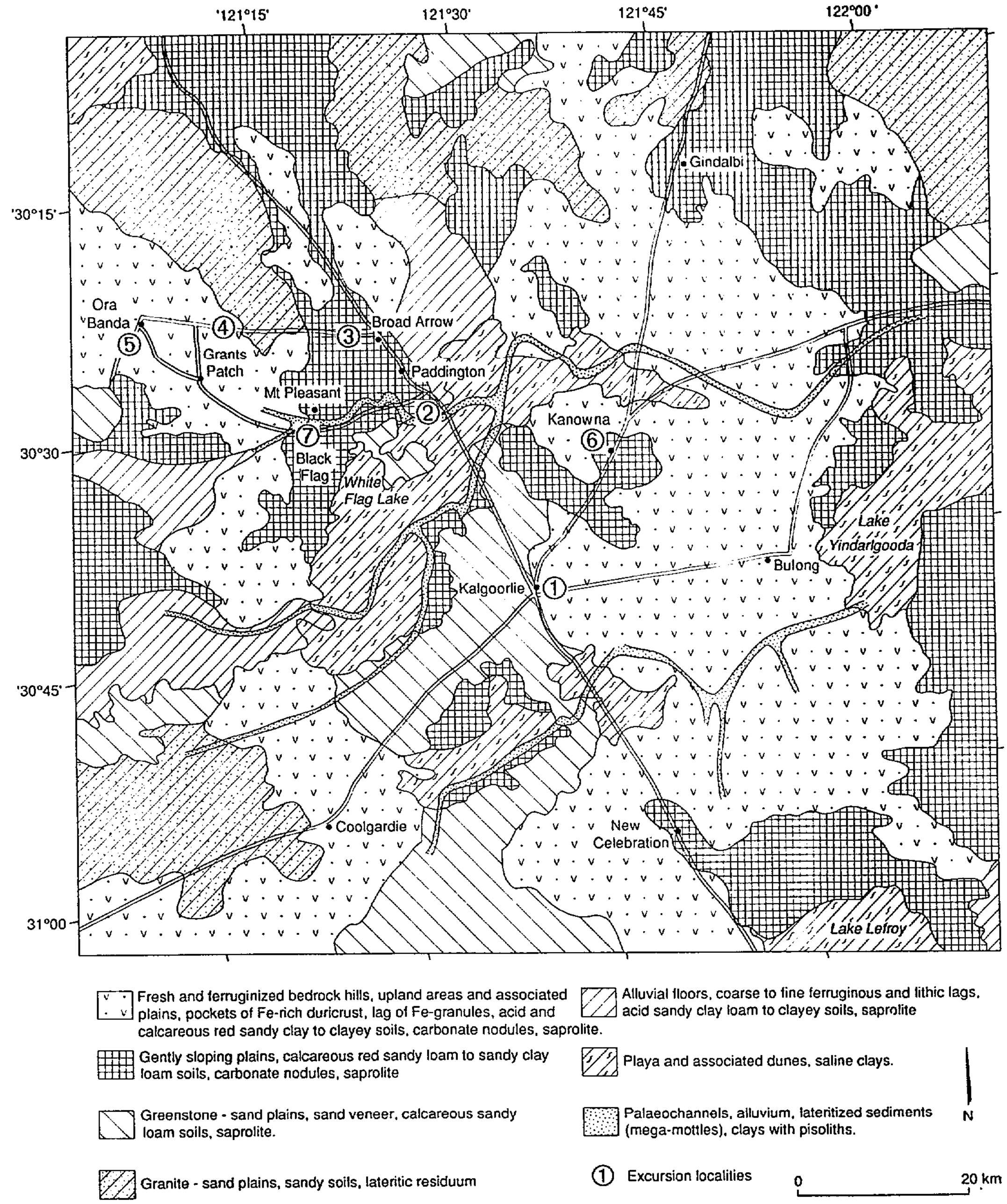

Fig.2. Generalised regolith–landform modules of the Kalgoorlie region. The excursion localities are also shown.

The area is one of gently undulating, subdued relief broken by greenstone strike ridges, granite mound and low breakaways. Landforms largely reflect the underlying geology. Thus the greenstone belts, which generally trend north-northwest, are associated with series of strike ridges, low hills and broken slopes rising above the general level of the gently undulating landscape. The terrain decreases in altitude away from greenstone ridges towards broad, colluvium filled valleys. Numerous playa lakes occupy the lower areas.

Some drainage features have extensively dissected a zone peripheral to the playas while discontinuous breakaways are associated with both greenstone and granite terrain.

Regolith–landform distribution and stratigraphy

The Kalgoorlie region can be subdivided into seven broad regolith-landform modules: *upland areas with hills, stripped plains, greenstone-sandplains, granite-sandplains, broad alluvial floors, playas* and *associated dunes,* and *paleochannels* (Fig.2). The regolith stratigraphy for the Kalgoorlie region is summarised in Fig.3 and profiles typical of crest, low hills, plains and paleochannel environments are shown in Fig.4.

1. Upland areas including bedrock hills

Upland areas comprise broad crests, and long gentle slopes including backslopes of

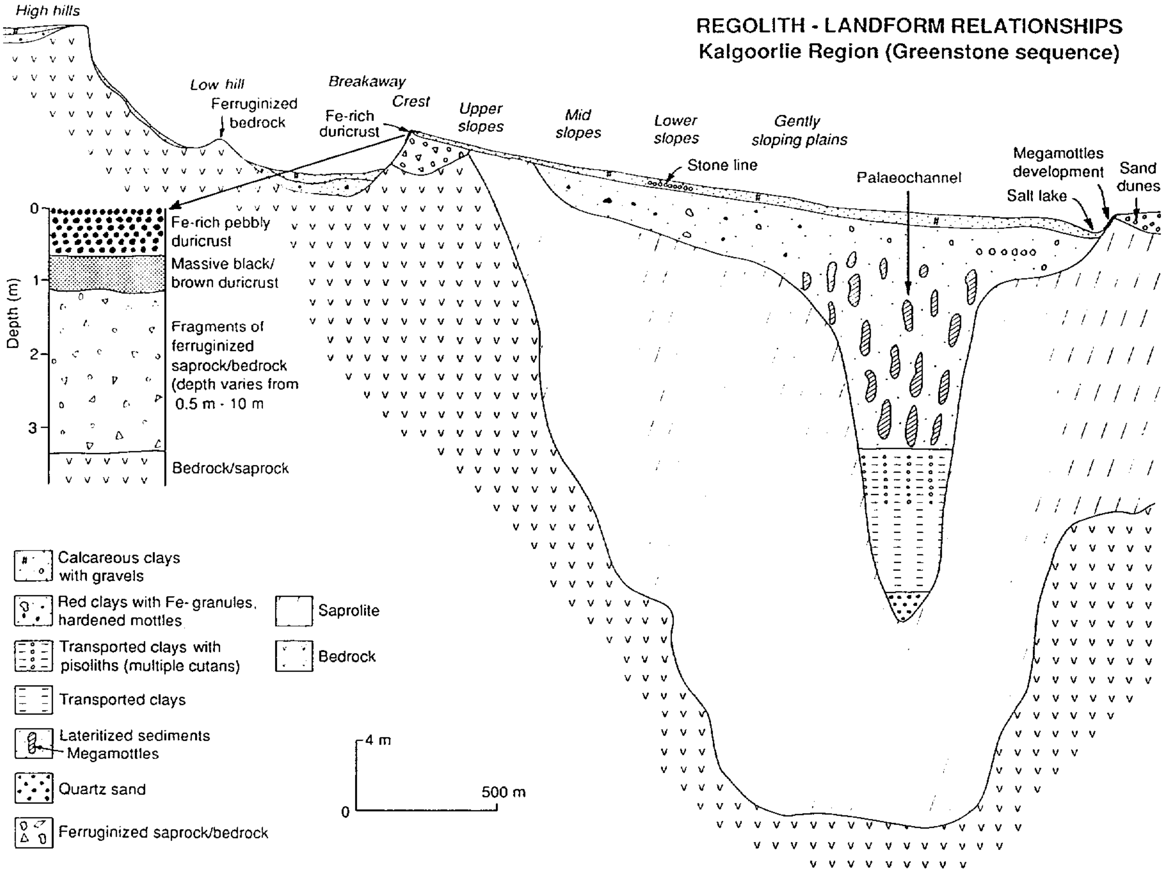

Fig. 3. Schematic cross section for the Kalgoorlie region showing regolith stratigraphy and landforms.

breakaways and gently sloping plains that forms a downslope continuum with backslopes.

The *high hills* generally flanked by the steep slopes rise above the relics of lateritized surface and have exposure of fresh bedrock. Some shallow stony calcareous soils (<50 cm) occur. On *steep slopes* scattered outcrops and cobbles of saprock on the upper slopes outcrop through a shallow, stoney, sandy clay to sandy clay loam that have powdery and nodular carbonates.

Low hills are characterised by fresh and ferruginized bedrock. Soil formation is quite common on low hills. Typically these gently undulating hills have well developed calcareous red sandy clay loam soils which can be underlain by acid red clay. The total thickness of soils vary from 30 cm to 100 cm and black ferruginous granules are common. Bedrock or saprolite forms a general substrate.

Iron rich duricrusts (>70% Fe_2O_3) and brown duricrusts (<50% Fe_2O_3) usually occur as large slabs and blocks on small broad convex crests on low rises. The crests are generally small. A mixed lag of lateritic nodules and ferruginized lithic fragments is over a shallow (10-30 cm) reddish brown sandy clay loam to clay soil. The duricrust and lateritic nodules are commonly infused with carbonates which is clearly visible where the lag-covered surface is slightly disturbed. The thickness of duricrust ranges from 0.5 to 2 m and is underlain either by ferruginous bedrock/saprock or deep saprolites. The weathered profiles are generally shallow and range in thickness from 0.5-10 m but may exceed 50 m. Backslopes that trend down from the crests are mantled by a lag of yellowish brown to black nodules and ferruginized lithic fragments. The ferruginised lithic fragments are coarse upslope, on the fringes of the duricrust-capped crests, and become finer downslope. Lag on the upper slopes also contain an appreciable amount of fragments of Fe-rich duricrust. The soils are acid, sand clay to sandy clay loam, over a weakly to strongly developed hardpan at about 15 cm depth, although carbonates generally occur within 20 cm of the surface. The soils contain moderate to large amounts of <1 mm quartz, particularly between a depth of 0-50 cm. The carbonates may continue to a depth of about 1 m which may then merge with acid red soils. Saprolite or bedrock generally appear below 2 or 3 m. In addition, there are scattered pockets of cracking red clay (overlying bedrock) which have a finely patterned micro-relief (gilgai).

Gently sloping plains that form a downslope continuum with backslopes are extensively mantled by fine black ferruginous lag and this generally overlies acid red sandy clay loam with

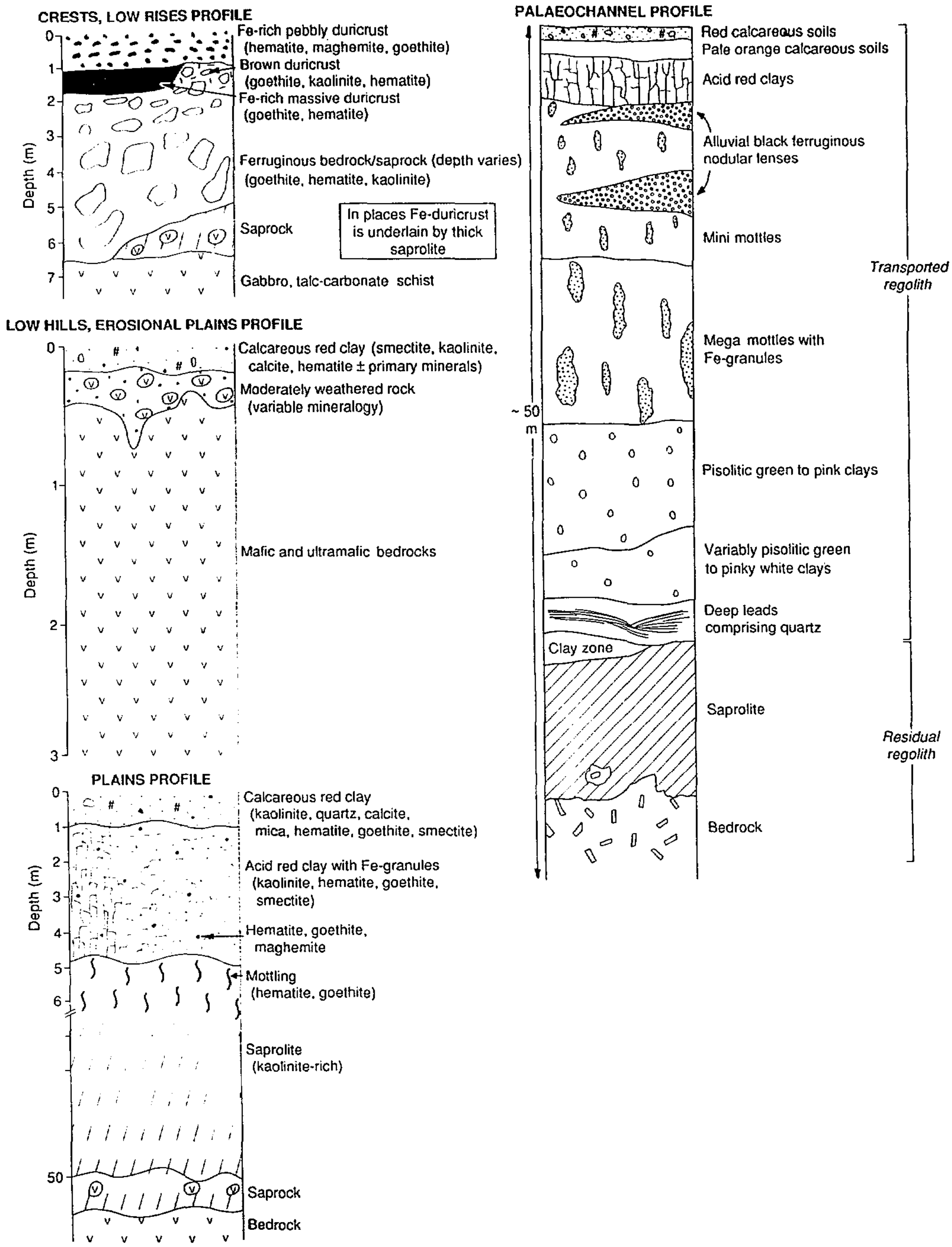

Fig. 4. Regolith profiles typical of crests, low hills, plains and paleochannel environments.

mildly developed hardpan at a depth of 30 cm. Calcium carbonate in several forms (powdery, nodular, stringers) occur within 15-100 cm depth. The calcareous soils are extensively underlain by 2-5 m thick zone of plastic uniform red clays. These soils appear to be largely residual in nature. Ferruginous granules and mottles are commonly present.

2. Stripped plains

Stripped plains that are peripheral to playa system show active drainage. These plains are occupied by calcareous soils containing abundant carbonate nodules. The soils overlie bedrock or saprolite. Little lag is associated with these areas.

3. Greenstone-sand plains

Greenstone-sand plains associated with playas are flat and are characterised by sandy soils and have a quartz lag. At depth, calcareous soils can occur. A zone of clayey alluvium of varying thicknesses (3-10 m) is beneath the soils.

4. Granite-sand plains

The lateritic profiles are developed on free drainage surface of low relief. Here a layer of yellow non-calcareous sand overlies a layer of lateritic pisoliths and nodules. However, pockets of carbonates and round pisoliths can occur.

5. Alluvial floors

Alluvial floors have clearly defined but minor channels. Red brown to light brown clays occur extensively and generally have coarse to fine ferruginous and lithic lags. Ferruginous granules commonly present in soils. Alluvium of varying thicknesses (up to 10 m) including lacustrine clays underlies the calcareous clays.

6. Playas

Playas are characterised by the saline, dark to pale brown fine clays and muds. The clays can be underlain by varying thicknesses of lacustrine clays which in turn overlie saprolite or bedrock. In places bedrock or saprolite occurs close to the surface. Gypsiferous and quartz-rich clayey sands border the salt lakes and playa system.

Clays with mega-mottles are characteristic features of edge of lakes and these can also occur as low rises within lakes.

7. Paleochannels

Paleochannels generally occur in the lower parts of the landscape. They are characterised by greater thicknesses of alluvium which is underlain by Archaean saprolite. The development of mega-mottled clay zone and spherical pisoliths in underlying grey kaolinitic clays are typical features of paleochannel environments. Profiles over these areas generally comprise 20 to 50 cm of red to brown calcareous clay soils with polymictic lag of abundant black ferruginous granules, and lithic fragments. The soils overlie plastic red clays of varying thicknesses. The plastic clays commonly contain black ferruginous granules. The clast components observed within the unit may occur as horizontally elongate lenses. Bleaching and pseudomottle development within the basal Fe-rich clays of the unit marks the transition into the mottled zone.

The mottled zone is characterised by increased bleaching and development of evenly-spaced irregular, hematite-goethite rich, 10 cm to several metres long mottles or septa. Abundant ferruginous granules may occur within the mottles. The creamy white bleached clays become more prominent with increasing depth and may develop an elongate, columnar cracking structure exposing root systems, commonly sheathed by Fe-rich accumulations. The transition from the mega-mottled zone to the underlying pisolitic clay is marked by the gradual decrease of mottles until the clays are totally bleached.

The pisolitic clay horizon is characterised by the presence of sub to well rounded pisoliths with greenish brown to grey cutans, in a matrix of pink-whitish to grey clays with minor detrital quartz. The underlying unit comprised of angular to sub-angular quartz-rich alluvial sediments forms the deep leads. The *in situ* saprolite forms the lowest unit of the weathering profile. Primary textures are generally preserved within the saprolite.

Characteristics of regolith

by R.R. Anand and C. Phang

Ferruginous materials

A wide variety of ferruginous materials occur in the Kalgoorlie region. They occur as crust or as lag and as gravel component in soils, colluvium and alluvium. Important patterns of geochemical dispersion from mineral deposits can be preferentially contained or preserved within these ferruginous materials. Consequently, understanding the characteristics and evolution of these materials, their internal and external characteristics (mineralogy and chemistry) is very relevant to both research into geophysical and geochemical exploration methods. This section presents their salient features as well as clarifying the relationship between some of the main types of ferruginous materials. Their evolutionary pathways are summarised.

For the purpose of geochemical exploration, four types of ferruginous materials are recognized, based upon their mesoscopic and chemical characteristics as well as their position in the regolith stratigraphy, and the regolith-landform framework as well as their chemical characteristics. The materials considered are the Fe-rich black duricrusts, the brown duricrusts, the yellowish brown nodules, the ferruginous granules and the mega-mottles.

Fe-rich black duricrusts

The Fe-rich duricrusts are hard ferruginous crust, reaching several metres in thickness and comprising several secondary structures (nodular, pisolitic), are sporadically distributed throughout the Kalgoorlie region. The outersurfaces of duricrusts may have a pebbly appearance. These occur at surface and are typically 0.5-2 m thick. They are largely pedogenic in origin and result, from the weathering of Fe-rich mafic and ultramafic rocks.

These duricrusts comprise dark reddish brown to reddish black nodules and pisoliths set in a fine grained, sparse, reddish brown matrix. The ratio of nodules to matrix ranges from 60:40 to 80:20; most samples examined having a ratio close to

	Gabbro/Basalt N=3	Fe-rich duricrusts developed from gabbro/basalt N=3	Talc-carbonate schist N=5	Fe-rich duricrusts developed from talc-carbonate schist N=5
SiO_2%	47.9	4.9	53.9	7.8
Al_2O_3%	16.2	7.5	4.3	7.6
Fe_2O_3%	7.3	74.4	13.4	73.1
MgO%	8.86	0.11	16.90	0.14
CaO%	14.40	0.16	0.30	0.12
Na_2O%	1.25	0.01	0.11	0.01
K_2O%	0.09	-	-	-
TiO_2%	0.48	4.22	0.27	2.01
LOI%	2.47	6.21	9.92	6.59
Mn ppm	983	339	330	411
Cr ppm	289	831	3370	18760
V ppm	178	2125	79	802
Cu ppm	76	42	26	25
Zn ppm	40	15	58	30
Ni ppm	136	48	2160	566
Co ppm	37	38	185	149
As ppm	6	12	10	16
Mo ppm	3	9	1	6

TABLE. 1. Characteristics of fe-rich duricrusts developed from gabbro and talc-carbonate schist.

80:20. The boundary between nodules and matrix is generally not well defined and nodules show weak or no development of macroscopic cutans. There are small vermiform voids, to 3 mm in diameter in the matrix, generally lined with yellow goethite. In places the matrix is porous and white, cryptocrystalline silica occupies some of the small voids. Many of the nodules of the duricrust contain lithorelics. The centre of the nodules may show the pseudomorphs after primary minerals (e.g. olivine) but much of the nodules fabric appears to have been destroyed by massive to slightly porous Fe-oxides. In polished sections of some samples, pseudomorphed wood fragments are conspicuous and occur in finely crystalline matrix of hematite and goethite. In the nodules, many pieces of wood are replaced by Fe-oxides so completely, that in sections cell structure can readily be seen. Similar cell structures have been observed in the oolitic Fe-rich duricrusts of the Lawlers district (Anand & others, 1991).

Hematite, goethite and maghemite are the major minerals present in duricrusts. Kaolinite is either absent or present in small amounts. Small amounts of talc and chromite are generally present in ultramafic derived duricrusts. Nodules and pisoliths are generally magnetic because of the presence of maghemite which may occur around the margins or within the cores of nodules and pisoliths.

The chemical compositions of duricrusts derived from gabbro and talc-carbonate schists is given in Table 1. There is no difference in major element compositions between the duricrusts derived from the weathering of gabbro and talc-carbonate schist. These are characterised by high concentrations of Fe_2O_3 (>70% Fe_2O_3) and very low concentrations of SiO_2 and Al_2O_3. However, the distribution of the trace elements is controlled by the nature of the bedrock. The duricrusts formed from the weathering of talc-carbonate schist show high values of Cr, Ni, and Co. This is reverse for duricrusts derived from the weathering of gabbro.

Brown duricrusts and loose nodules

These are weathering crusts composed of goethite, hematite, and kaolinite. Irregular, vermiform voids (2-10 mm) are generally lined with pale yellow-brown goethite and kaolinite. Some of these are filled with clay having an incipient pisolitic structure. A sandy clay matrix (30-60 vol%) is generally yellowish brown to dark red and is predominantly kaolinite, goethite and quartz. Nodules and pisoliths are red to reddish brown and generally have a goethite-kaolinite rich cutans. In polished sections, the central parts of nodules may show the preservation of relic fabric. The duricrust is comparatively rich in kaolinite and goethite, poor in hematite. These are relatively low in Fe_2O_3 (<50% Fe_2O_3) and higher in Al_2O_3 and SiO_2. The compositions of these duricrusts generally reflect the underlying lithologies.

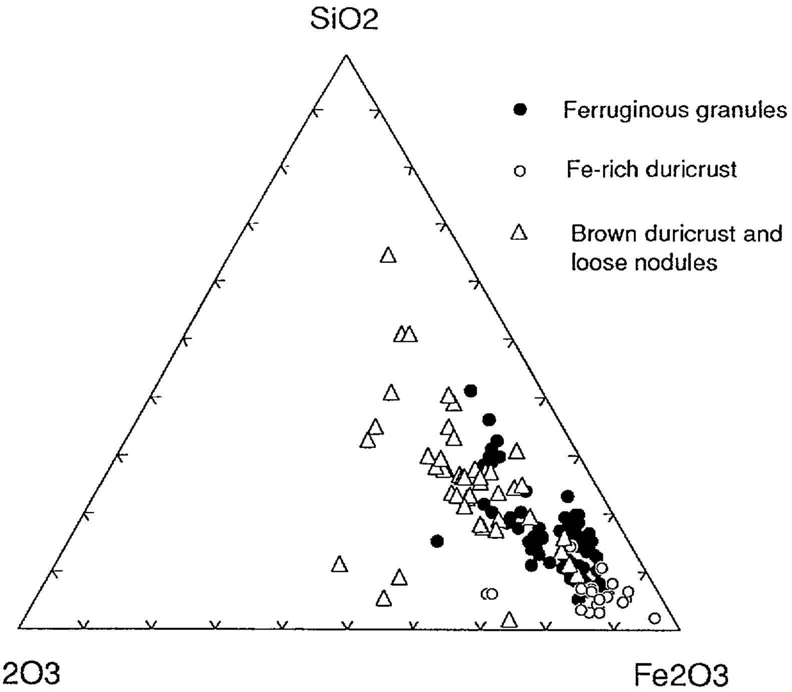

Fig. 5. Triangular diagram showing compositions of ferruginous materials, in terms of SiO_2, Al_2O_3 and Fe_2O_3.

Ferruginous granules

Ferruginous granules occur in soils or as lags. They are black, silver to earthy grey, sub to well-rounded and vary in size from 0.5 to 10 mm in diameter. Typically the granules have an earthy to sub-metallic lustre and occasionally have thin earthy cutans. They can be either magnetic or non-magnetic.

The granules largely consist of hematite and maghemite, with variable quantities of goethite, kaolinite and quartz. The quartz occurs as angular to well-rounded grains commonly incorporated into the structure, or forming the nucleus. Numerous black pits and voids are present within the granules often highlighting relict textures such as fossilised cellulose or providing pathways that have initiated partial or total hematite replacement of clays.

Petrographic examination reveal several types of internal fabrics. The non-magnetic granules show progressive replacement of clays by hematite forming essentially massive granules. Some granules show the preservation of relic rock fabrics and pseudomorphs after rock forming minerals preserved within the internal fabric of the granules. Some granules represent ferruginized cellulose fragments, which are clearly identifiable by the intricate preservation of individual cell walls now totally replaced by hematite. A large proportion of the granules have a concentric outershell developed around a nucleus. Quartz fragments are commonly incorporated into the concentric bands indicating multiple periods of development.

Granules comprised mainly of Fe_2O_3 (>70%), SiO_2 (10-15%) and Al_2O_3 (2-7%) which when combined account for 95% of the total granule composition.

Mega–mottles

The mega-mottles are brown to reddish brown, irregular Fe accumulations (up to several metres) containing smaller (<10 mm) sub-angular metallic granules. The mottles have a dull earthy lustre and have a gradational to abrupt boundary with the surrounding bleached clays. Root systems surrounded by a sheath of bleached clays are common and appear to show a close spatial relationship to zones of Fe accumulation. The bleaching extends down cracks in some instances, and also down root channels. Mega-mottles are characterised by kaolinite, hematite and quartz.

Silicon–Aluminium–Iron relationships–ferruginous materials

The Si-Al-Fe relationships of the Fe-rich duricrusts, brown duricrusts and loose brown nodules, and ferruginous granules are shown in the ternary diagram (Fig.5). The compositional fields of Fe-rich duricrusts and ferruginous granules lie close to each other. The Fe-rich duricrusts have a relatively restricted compositional range and there is a tendency for a higher concentration of Fe in the Fe-rich duricrusts relative to ferruginous granules. Brown duricrusts and nodules have a wide compositional field reflecting variation in the Al and Si contents.

Soils

The major regolith units of the deep weathered profile forms distinctive soil parent materials, either when exposed *in situ* or as transported sediments. The soil patterns depend partly on the degree of stripping of the weathered mantle, on the lithology and partly on the spread of weathering and erosional products across the various slope elements. The following soil sequences in greenstone terrain in Kalgoorlie region illustrate these relationships.

Gravelly soils occur on areas dominated by duricrust. These are generally brown to reddish brown, friable sandy loams to sandy clay loams. Soils are up to 30 cm thick and are generally residual derived from the weathering of duricrust. The dominant gravel component of these soils consist of lateritic nodules and pisoliths. The soils largely consist of kaolinite, quartz and goethite.

Calcareous red sandy clay to clay and shallow stony soils occupy the erosional areas. These soils show a close association with weathered or sub-cropping mafic/ultramafic rocks and appear to result from in situ weathering of rocks. The gravel fraction being dominated by 1 to 5 mm shiny, black, ferruginous granules and lithorelics. Lateritic nodules and pisoliths are typically absent. The calcareous red earths are dominated by kaolinite, calcite, smectite and mixed layer minerals with small amounts of goethite, hematite, quartz and dolomite.

Soils in the depositional regimes are generally calcareous sandy clay loams to clays developed in colluvium and alluvium. The most common substrate to the calcareous red clay is non-calcareous, dark red brown clays which generally merges with mafic/ultramafic saprolite at a depth of 2 to 5 m. These soils are generally plastic, and uniformly Fe-stained and may contain ferruginous granules.

Regolith evolution

The regolith-landform relationships and regolith stratigraphies indicate a polyphase, multiprocess history. Many of the regolith types resulting from this complex array of processes, have a distinctive pattern. In Kalgoorlie region, the processes of regolith evolution, particularly deep weathering, laterite formation and modification of the deeply weathered regolith in response to the change from a humid to an arid climate are markedly different from those of the Leonora–Wiluna region. These are shown in Fig. 6 and are discussed below.

Lateritic weathering processes

In the Kalgoorlie region the effects of past weathering is widespread as evidenced by deep kaolinization of basement rock however, laterite is limited in extent and size. This would be due to two reasons. Firstly it may be that the laterites had never developed. Perhaps extensive sheets of laterite may not have existed over large areas, but duricrust, red soils and mottled zones may have developed in specific sites in response to geology and local environments. This is in contrast to the Leonora–Wiluna region where laterite formed a continuous blanket deposit. Indeed, buried residual laterite profiles are also widespread beneath an overlay of colluvium and alluvium (Anand & others, 1991).

The weathered profiles are thinner and less continuous in the upland areas. The profiles are comparatively thicker on valleys and plains where it generally exceeds 50 m. Ferruginisation is much less common in these areas. The formation of deep saprolite is favoured on stable, subdued landsurfaces (Mabbutt, 1980). Variation in the depth of weathering, tend to be geologically controlled and may give little evidence of the form and position of any associated originating landsurfaces.

Fe–rich duricrusts

Genesis of Fe-rich duricrusts are explained by two mechanisms. Firstly lateritic processes have produced the Fe-rich duricrust by the *in situ* weathering of mafic and ultramafic rocks, resulting in a relative accumulation of Fe. Alternatively, the Fe-rich duricrusts have been produced by the absolute accumulation in valley floors followed by relief inversion in response to drainage incision. Examples of the latter category are rare. These two mechanisms are now discussed.

In situ weathering

The general preservation of Fe-rich duricrusts over mafic (e.g. gabbro, basalt) and ultramafic rocks (e.g. talc-carbonate schist, pyroxenite) suggests that these duricrusts appear to be closely associated with the weathering of Fe-rich lithologies. These are formed by the intense infusion of Fe into saprock without forming a thick saprolite. Weathering of the Fe-rich mafic and ultramafic rocks has produced a shallow profile which consists of rock, saprock, ferruginous saprock and Fe-rich duricrust. These horizons tend to merge one with another. Deep clay-rich saprolites are not common beneath the duricrusts. Primary minerals weather into secondary products which in turn transformed, into new products, amongst which hematite, goethite

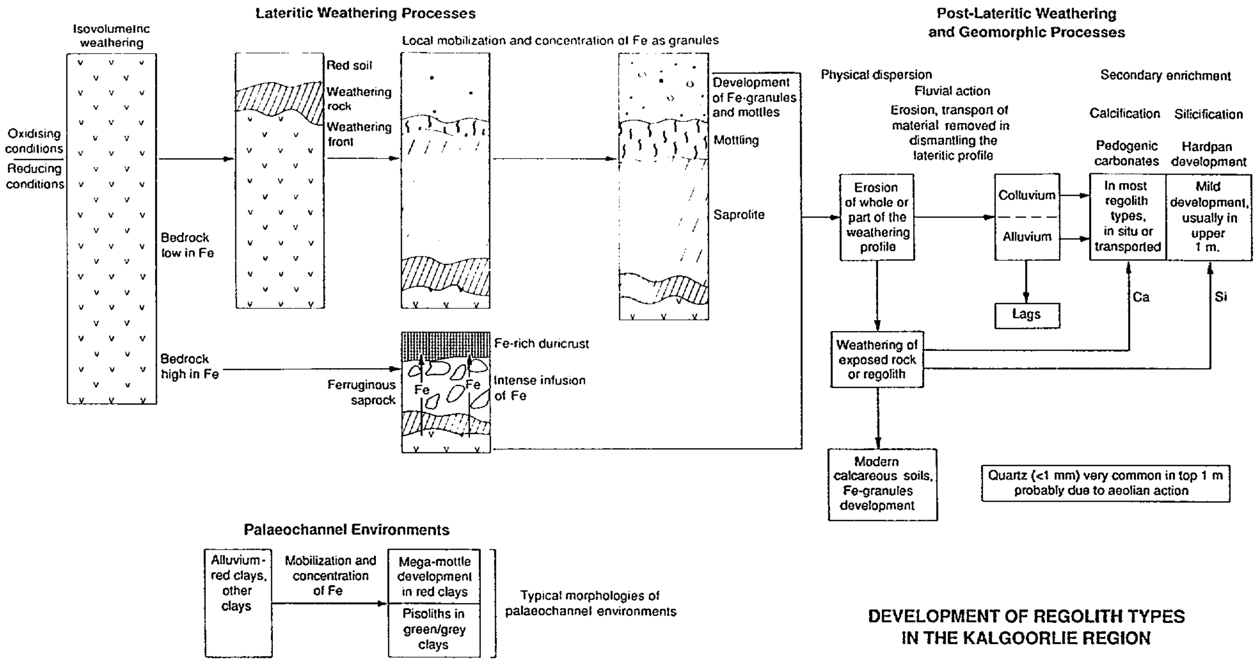

Fig. 6. Schematic diagram showing an inferred genetic relationship between the major regolith types in the Kalgoorlie region.

and maghemite are the most abundant. It appears that kaolinite formed from the weathering of primary minerals may have been replaced by Fe-oxides by epigenetic reactions suggested by Didier (1983).

The geochemical data suggest that these Fe-rich duricrusts do have a geochemical affinity with mafic and ultramafic Fe-rich bedrocks. The concentration of Cr, Co and Ni can be used to discriminate the duricrusts derived from the weathering of mafic and ultramafic rocks. Those rich in Cr, Ni and Co are derived from the weathering of ultramafic rocks, where those containing relatively-low levels of these elements are likely to have a mafic origin.

Relief Inversion

Field relationships and petrographic data of some duricrust samples (e.g. 2 km south of Ora Banda) suggest that low hill duricrusts are remnants of what was once an ancient lower surface or depression, into which sediments accumulated. South of Ora Banda, 1 m thick Fe-rich duricrust has developed on surficial sediments which is underlain by lenses of coarse to fine pisoliths (Fig.7). This is underlain by ferruginous saprolite and clay-rich horizon consisting of boulders of Fe-rich duricrusts and lenses of polymictic gravels. In some cases, the duricrust rests directly on fresh bedrock. The depressions became favoured sites for the precipitation of Fe-oxides from groundwater. In this regard, low hills and their duricrusts could be an expression of a complex series of erosional, aggradation, and weathering events. Relief inversion may have occurred and duricrust covered depressions may have become hills and ridges. Examples of relief inversion have been provided in the literature, some including laterites which occur as long sinuous ridges and may have formed as valley laterites (Goudie 1973; Ollier & others, 1988).

Iron may have been derived by weathering processes from ancient upland positions and transported laterally to valley floors. The dissolved ferrous iron is subsequently precipitated and oxidized or oxidised and precipitated. In general, goethite and hematite form where oxidation precedes hydrolysis, when hydrolysis and precipitation occur before oxidation lepidocrocite and maghemite may occur (Taylor & Schwertmann, 1974). These possible processes would result in the formation of Fe-rich duricrust. The valley floors capped with Fe-rich duricrust are the most indurated, and as they are then resistant to erosion, softer upland and valley side materials are eroded, leaving the former valleys as the ridges and hills.

Red soils and ferruginous granules

Red soils are very common on the greenstones. Detailed investigations show that these red soils are derived from the weathering of underlying rocks and may have even once blanketed the landsurface.

The non-calcareous nature and very low level of smectite in these soils suggest that they

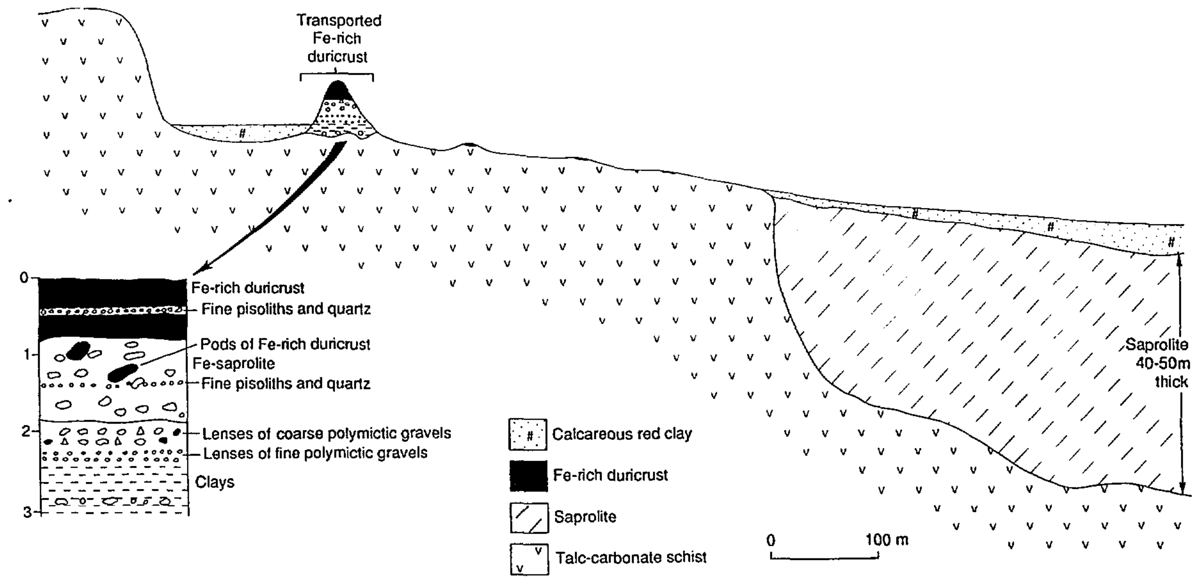

Fig. 7. The development of Fe-rich duricrust by absolute accumulation of Fe and relief inversion (see explanation in text).

have formed under generally mild to warm conditions, free drainage, and sub-humid to humid climates with alternating wet and dry periods. These are the conditions necessary for leaching of bases and the formation of kaolinitic clays that are acid and unsaturated with bases. Some Fe released on weathering has been mobilised and segregated as granules and mottles. Granules which show the preservation of rock fabrics are formed by the ferruginisation of the saprolite or saprock.

Post-lateritic weathering

Figure 6 depicts the effects of post-lateritic weathering upon areas where erosion has removed the red soils or laterite. Whilst the underlying lithologies are best exposed in the erosional area even the broad smooth crests and backslopes frequently show the result of mild to strong stripping. The regolith types contain useful traces of underlying lithologies.

Modern calcareous soils and carbonates

After erosion, weathering of bedrock and saprolite continues to produce calcareous red clays. These soils have a much more immature weathering status based upon the presence of fresh primary minerals and recognisable pseudomorphs after primary minerals. Smectites in these soils are the product of the weathering of mafic and ultramafic lithologies during an arid climate in which they now occur. In arid climates, pedogenic processes, such as the leaching of bases, do not occur due to lack of a leaching regime.

Carbonates are generally redistributed into massive, nodular or laminar calcrete. Erosion and stripping of the upper, more weathered, parts of the regolith, appear to be important factors influencing the gross distribution of calcium carbonate in the Kalgoorlie region. Weathering of rocks provides Ca and Mg-rich solutions that infuse the upper parts of the regolith.

The carbonates in the depositional areas are associated with an irregular weathering front, protruding through the more weathered parts of the regolith. Upon weathering, these could be a source of Ca-rich solutions that would infuse the upper parts of the regolith. Alternatively, the carbonates may have been derived by lateral transportation and redeposition of weathered fragments of calcrete derived from the erosional areas which are then dissolved and precipitated at the top of the profile.

Calcareous clays contain varying amounts of fine quartz particularly in top 1 m which appears to be aeolian in origin. This has been probably re-worked by colluvial processes and affected by chemical leaching and precipitation.

Geochemical dispersion in regolith

In Leonora–Wiluna region, where the lateritic residuum is widely preserved, pisoliths and nodules, duricrust and ferruginous saprolite form an ideal sampling medium for seeking widespread dispersion haloes for Au and base metal exploration. These may be collected from the surface in residual areas or by drilling for buried laterite in depositional areas (Anand & others, 1991; Smith & others, 1992).

In Kalgoorlie region where the laterite is patchy, an alternative sampling media is required. For Au exploration in the Kalgoorlie region, Au en-

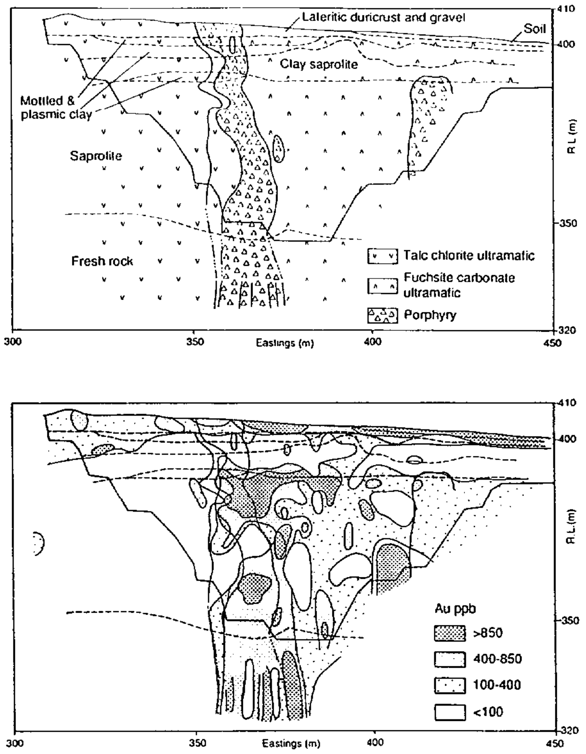

Fig. 8. Geological and regolith cross section across the Mystery Zone, Mt. Percy, showing the distribution of Au (after Butt and others, 1991).

richments in calcareous soils, ferruginous granules in soils and mottles are of specific importance. These materials, which generally occur in the top 1-2 m of the profile, is the preferred sample medium, even in areas of transported cover, and gives superjacent anomalies to concealed mineralisation.

The Au anomaly is present in the carbonate horizon in both residual and transported material. Deeper sampling (2-6 m) gives no useful response (Butt & others, 1991). The enrichment is thought to be due to active cycling of Ca and Au via vegetation, driven by evapotransportation. Only Au appears to have enriched in the carbonates and, indeed, base metal concentrations tend to be depressed by dilution. Typical results from the Mt Percy and Panglo deposits, are shown in Figs 8 and 9. Some of these aspects of sampling are given by Butt & others (1991).

Excursion localities

by R.R. Anand and T.J. Munday

The excursion localities are shown on Fig. 11. Localities 1 to 7 illustrate aspects of the regolith of the Kalgoorlie region and their significance to exploration has been indicated above where appropriate.

Locality 1: Mt Percy gold mine

The visit to Mt Percy will include a traverse along the west and northern walls of the Mystery pit. The Fe-rich duricrust and in places, theupper part of the mottled zone and some porphyry saprolite are visible in the bench wall. The landsurface is lower to the north as the massive duricrust gives way to lateritic gravels and calcareous gravelly soils.

Mt Percy is situated in the upper parts of a landscape, that has relatively low relief (i.e. a few tens of meters). The elevation is probably due to the armouring effect of the lateritic duricrust, here developed most strongly over the Hannan's Lake Serpentinite. As a consequence, an almost complete lateritic regolith 50-70 m thick, is present over most of the area. The duricrust is developed most strongly over the talc chlorite carbonate rocks and the Golden Mile Dolerite, and these form the highest points at the south end of the Mystery Pit and Mt Percy, upon which the Mt Percy water-tank is situated. The regolith is the host to secondary Au mineralisation within both the lateritic duricrust and the saprolite (Fig. 8).

Locality 2: Panglo gold mine

The Panglo Gold Mine occurs 5 km south-east of the Paddington mine, within steeply west-dipping carbonaceous shales and mafic to ultramafic volcanics, within a major shear zone. mineralisation occurs as a relatively flat-lying body at a depth of 35 m below the surface.

The profile is developed upon transported material filling a Tertiary paleochannel. The paleochannel fill consists primarily of a sediment of pisoliths and nodules, which include fragments of amphibolite. Drilling indicates the paleochannel to be 10 m thick and is comprised of gravels overlying mottled clays. These lie on clay-rich saprolite several tens of m thick, derived from the weathering of mafic volcanics. There is some Au (0.1 to 1 ppm) at the boundary between the clay-rich mottles in the paleochannel and the clay-rich saprolite, which probably indicates enrichment at the old land surface, pre-dating the Tertiary. Economic grades of Au (>3 ppm) occur as a supergene deposit within the saprolite at about 40 m.

There is a very strong association between Au and the alkaline earth elements Ca, Mg, and Sr throughout the profile (Fig.9). The lowest Au concentration (<0.01 ppm) occurs at the base of the profile. Peak concentrations of Au (0.26 ppm) and

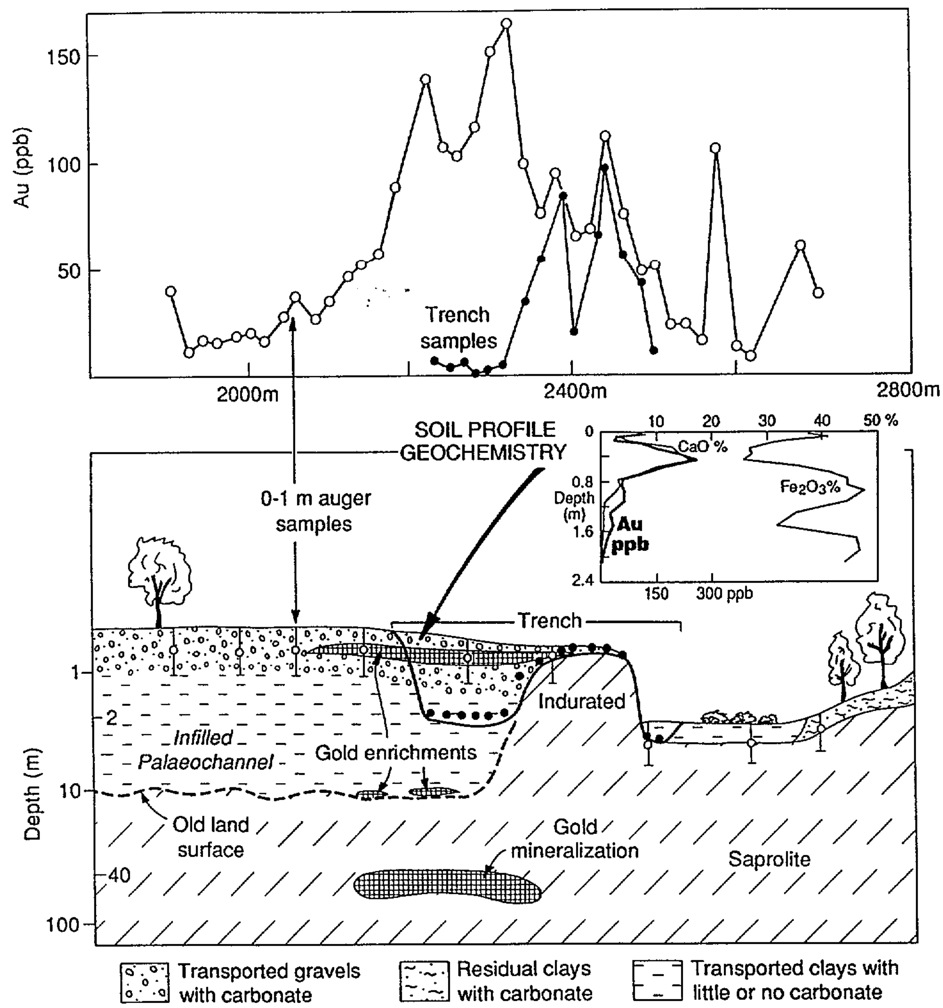

Fig. 9. Landscape section across part of the Panglo Au deposit, north of Kalgoorlie, illustrating the importance of sampling soil carbonate horizons in Au in exploration. Shallow carbonate-rich samples from the trench give a significant response to buried mineralisation, whereas deep, carbonate-poor samples have background Au contents (after Lintern & Scott, 1990).

the alkaline earth elements (e.g. 16% CaO) occurs at 45 cm depth.

Locality 3: Bardoc quarry

This stop is to demonstrate the complex array of regolith types developed within a small area. Features to be examined include the development of Fe-rich duricrust, calcified partially indurated lateritic nodules, ferruginous saprock/bedrock and calcareous soils. Fresh gabbro is exposed on the crest.

Locality 4: Lady Evlyn

The pattern of regolith types relates closely to bedrock geology, landforms and to the varying degrees of erosional and depositional modification of the deeply weathered mantle. The location comprises breakaway, pediments, crest and backslopes of the breakaway. Talc-carbonate schist is exposed on the breakaway.

Locality 5: Ora Banda

This stop is to demonstrate that some of the Fe-rich duricrusts are transported and are formed by the absolute accumulation in the valley floors followed by the processes of relief inversion. This is described in detail (this excursion).

Locality 6: Kanowna Deposits

The NLP9 Pit is located within the GNJV deep lead Au and Kanowna–Belle tenement area and provides an excellent exposure of paleochannel profiles. A study of the regolith stratigraphy shows that there is a preferential development of the lateritic weathering profile within transported sediments. This is evidenced by the accentuated development of the mottled zone within alluvial detritus filling the deeply incised paleochannels present within the area. The regolith is the host to secondary Au mineralisation within the calcareous soil, mottles and ferruginous granules.

Locality 7: Black Flag

Breakaway provides an excellent exposure of the regolith stratigraphy in the salt lake environments. Both residual and transported regolith will be examined.

Regolith–landform evolution and geochemical dispersion in regolith, Lawlers district

by R.R. Anand

The Lawlers district, an area of some 500 km^2, contains truncated laterite profiles on uplands and lateritic residuum buried under thick transported sequences, marked by extensive plains. The Lawlers district is an example of some important exploration problems in the Yilgarn Craton and particularly in the Leonora–Wiluna region.

The Lawlers district lies some 300 km north of Kalgoorlie. It has a hot, arid climate with an erratic median annual rainfall of approximately 200 mm. The area is characterised by sparse, low acacia woodlands with dominant mulga (*Acacia aneura*).

Regional and local geology

Locality map.The Lawlers district lies within the Agnew supracrustal belt of the Archaean Yilgarn Craton. The Lawlers greenstone sequence is up to 3 km thick and consists of interlayered high-Mg basalt, ultramafic rocks, gabbro and differentiated gabbro-pyroxenite-peridotite sills, thin, fine-grained sedimentary and silicic, volcanogenic layers (Platt & others, 1978). Some ultramafic units show spinifex textures. The gabbroic sills are up to 300 m thick; they are concordant to the stratigraphy and are laterally very extensive. Volcanic and sedimentary units are interlayered with sills throughout the sequence which is also intruded by tonalite. The most prominent structural feature in the area, is a major north plunging upright fold, the Lawlers Anticline (Fig. 10). A later leucogranite has been mapped in the area cutting both the tonalite and greenstones.

The Lawlers greenstone sequence is overlain on the west side of the Lawlers Anticline by the Scotty Creek sedimentary sequence (Fig. 10). This is about 1500 m thick and consists of a basal conglomerate derived from mafic and ultramafic units within the Lawlers greenstone sequence (Platt & others, 1978).

Gold deposits in the Lawlers district fall into the three broad categories. These are: disseminated Au within alteration haloes quartz vein systems in shear zones (e.g. Great Eastern, McCaffery, Weight Hill, North Pit, and Turrett); altered and sulphidic shoots with little or no quartz in major shear zones (e.g. Emu, Redeemer); and quartz stockworks and ladder veins in metasediments (e.g. Genesis).

Gold from any of the primary categories has been redistributed and concentrated by secondary weathering into the saprolite and, to places, in the overlying lateritic residuum. This secondary Au mineralisation forms a new category. It is important as it forms low to medium tonnages of low-grade Au resources which are easily mined and processed, examples are the laterite ore at North Pit, Turrett and Waroonga.

Regolith–landform relationships

The Lawlers district is situated on the Great Plateau of Western Australia (Jutson, 1934). It is a broadly-undulating terrain with scattered belts of hills providing some local relief. More detailed relief variation, such as at breakaway scarps, is the result of differential stripping of an extensive deeply-weathered mantle and by localised deposition of detritus resulting from this process.

This district straddles a divide between the Lake Raeside drainage to the south and that of Lake Miranda and Lake Darlot to the north. For much of its length, the northwest-oriented divide comprises the crests of prominent breakaways, the Agnew Bluff. Extensive erosional tracts extending south from these breakaways are first dominated by hill belts. These hill belts give way, southwards, to gently-sloping pediments, thinly mantled by debris from the immediate hinterland.

By way of contrast, north of the divide the topography is dominated by long, very gentle, smooth slopes. Many of these have their origin on the broadly-convex laterite-mantled crests, immediately above the Agnew breakaway and gradually merge down to broad alluvial floors of tributary valleys, and thence to the main drainage sumps of Lake Darlot and Lake Miranda. Alluvial floors, often associated with a complex of minor meandering channels, are little incised below the main alluvial plain and the drainage often terminates on sandplain tracts over granitic rocks.

The surface distribution of regolith units

R.R. Anand and R.E. Smith

Figure 11 shows the distribution of regolith-landform units for the Lawlers district. The broad regolith-landform units which have been rec-

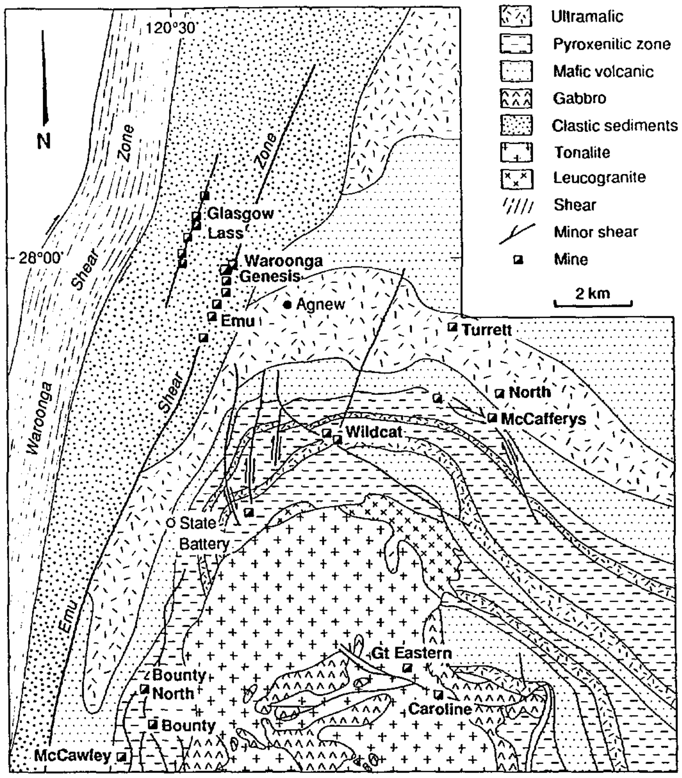

Fig. 10. Detailed geology in the vicinity of Agnew and Lawlers. (Modified after Aoukar & Whelan, 1990).

ognized in the Lawlers district are given in Table 2 together with their main characteristics. Variations in regolith at Lawlers can be explained in terms of erosional and depositional regimes that modified a relatively stable, weathered land surface, scattered remnants of which form residual regimes (Anand & others, 1991).

Residual regimes are areas characterised by widespread preservation of lateritic residuum which constitute about 15% of the surface landscape. Unit 1 in the residual regime is mantled by Fe-rich black pisolitic-nodular lateritic duricrust, yellowish brown duricrust and lateritic nodules and pisoliths. This unit generally merges downslope into colluvium, Unit 6. *Erosional regimes* comprise terrain within which varying degrees of erosion of the weathering profile has occurred, and has removed the lateritic residuum to the level where the ferruginous saprolite, mottled zone, saprolite, or fresh bedrock are either exposed, concealed beneath soils, or beneath locally derived patchy sediments. Units in the erosional regimes are dominated by largely residual soils on bedrock and saprolite, lag derived from bodies of iron segregations, ferruginous saprolite, saprolite, and vein quartz. *Depositional regimes* include colluvial and alluvial outwash plains (Units 6 and 7). These form widespread regolith-landform units which account for about 40% of the mapped area. The origin of the sediments may range from local to distal and the thickness of which can reach tens of metres. These depositional units commonly conceal extensive areas of complete or nearly complete lateritic weathering profiles.

Regolith stratigraphy

Although regolith mapping indicated a general relationship between the surface regolith types and landforms, drill spoil and open pits examined during this phase, showed changes in the regolith which were not evident on the surface. A more complete picture of the regolith, including stratigraphic relationships are needed to formulate a rational sampling strategy for mineral exploration in this type of weathered terrain. Detailed observations were made at a number of type locations including McCaffery, North, Turrett, Meatoa, Waroonga and Genesis gold deposits.

McCaffery–North–Turrett pits

McCaffery-North-Turrett pits are located on the backslopes of the breakaway and colluvial outwash plains. Here, bedrocks are generally weathered to 30-80 m depth. In the *McCaffery-North Pit* area, an extensive, but somewhat discontinuous, horizon of essentially-residual laterite is unconformably overlain by a varying thickness of colluvium, which itself has components derived by partial or complete stripping of lateritic residuum and ferruginous saprolite (see Fig. 17).

Colluvial outwash plains, sloping at approximately 1°, extend eastwards from a breakaway scarp, towards a southeast-draining braided

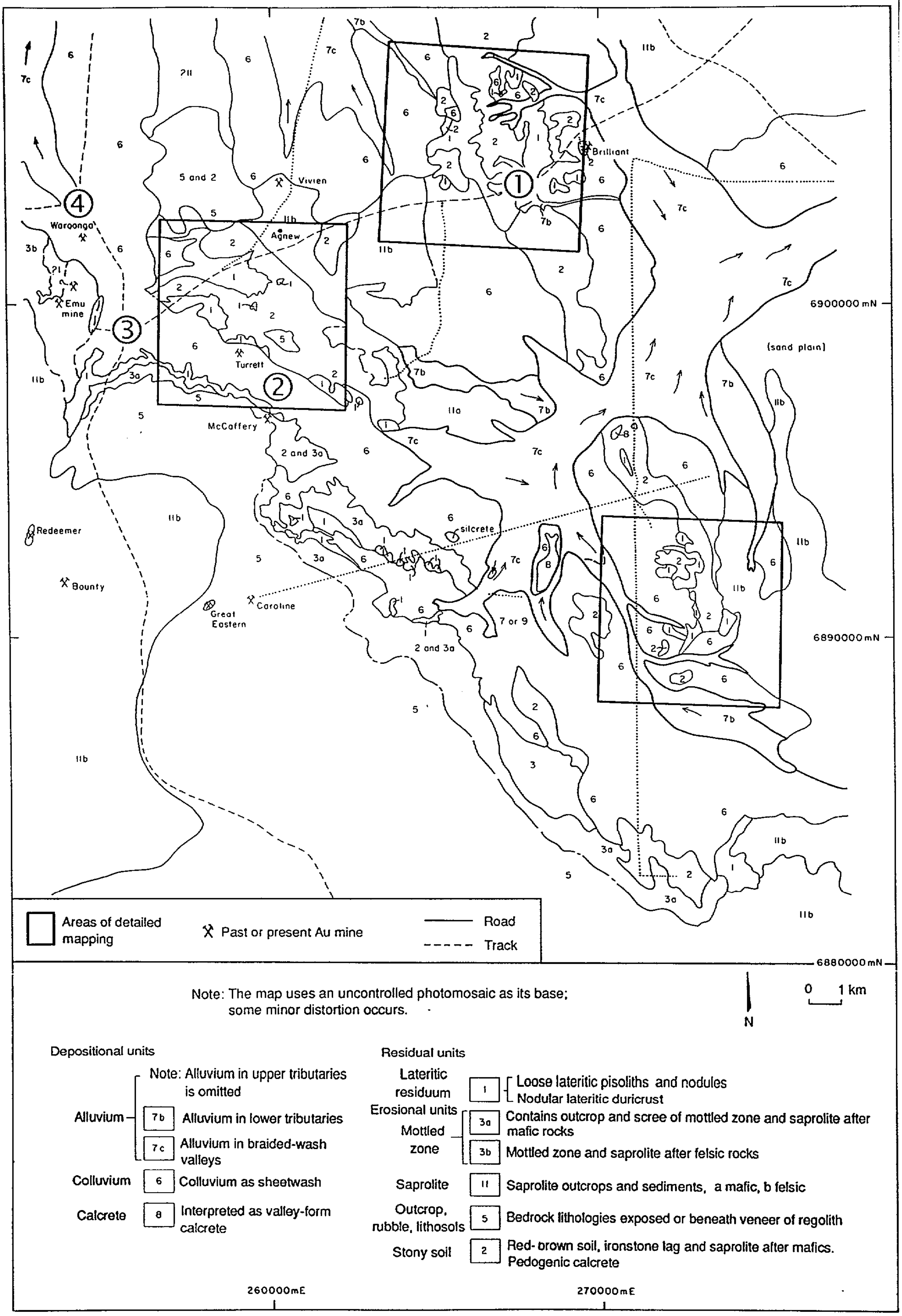

Fig. 11. Map showing the surface distribution of regolith–landform units for the Lawlers distict. The excursion localities are also shown.

TYPE OF REGIME	RESIDUAL REGIMES	EROSIONAL REGIMES	DEPOSITIONAL REGIMES
REGOLITH-LANDFORM MAPPING UNIT	(2 units)	(6 units)	(6 units)
LANDFORM	Crests and backslopes	Breakaway, pediment slopes, low hills	Slopes, valleys, major and minor drainages
VEGETATION	Mulga	Mulga	Mulga and shrubs
LAG	Lateritic nodules, pisoliths	Iron segregations, Fe-saprolite, saprolite, quartz	Mixed ferruginous granules, quartz, lithic fragments
SOILS	Sandy loam to sandy-clay loam	Sandy-clay loam to light clay	Light clay
ALLUVIUM	-	-	Extensive
COLLUVIUM	Minor	Minor	Extensive
HARDPAN	Minor to absent	-	Extensive
CALCRETE/CARBONATES	-	Pedogenic carbonate	Calcreted drainage lines
LATERITIC RESIDUUM	**Nodular duricrust, Fe-rich nodular duricrust**	-	**Commonly beneath colluvium and alluvium**
FERRUGINOUS SAPROLITE	Present	Present	Present
SAPROLITE	Multicoloured clay-rich mafic/ultramafic saprolite	Granitic/mafic/ultramafic saprolite	Multicoloured clay-rich mafic/ultramafic saprolite
BEDROCK	Mafic, ultramafic	Felsic, mafic, ultramafic	Mafic, ultramafic

TABLE 2. Summary of regolith stratigraphy and characteristics of regolith units: Lawlers district.

fluvial system. The plains in the North Pit area, as elsewhere in the Lawlers tenements, have a loose surface veneer of mixed lithic and lateritic debris. This surface veneer typically overlies a layer (up to 4 m in thickness, but typically 0.5-2 m) of unconsolidated, coarse, polymictic gravels with very crude bedding in the few exposures and some imbrication of the larger flattened clasts. The coarse, near-surface deposits of polymictic gravels fine downwards into thick deposits of loams, sandy loams, and puggy grey-white and white clays interstratified with more gravel-rich intervals which may include one or two intervals of transported lateritic nodules and pisoliths. Drilling has established that the total colluvial sequence exceeds 10 m in thickness and may reach about 40 m.

Authigenic *hardpanisation* affects much of the colluvial profile and reaches a maximum development in the near-surface, more coarsely-clastic gravels. Near surface, hardpan exhibits a sub-horizontal lamination or inter-clastic "pseudo-foliation" or parting and the colour is brownish changing to a characteristic brick-red with depth. The hardpan matrix is characteristically porous, and unctuous to the tongue. Deposits of glassy, botryoidal opal (hyalite variety), and films of black Mn oxide are present in pores or along cleats in the upper half of the hardpanised profile. In detail, hardpanisation is not stratigraphically controlled, but transgresses lithologic contacts and locally extends down through colluvium into the underlying residual loose nodular laterite.

The top of the residual laterite profile is composed of a layer of lateritic residuum averaging some 3 to 8 m in thickness. It consists of layer of loose pisoliths and nodules which may be underlain by a layer of nodular duricrust. The laterite residuum, in turn, is underlain by a zone of ferruginous saprolite characterised by bodies of iron segregations. Ferruginous saprolite forms a blanket deposit, up to several metres thick, in many areas, in the Lawlers district, and is preferentially developed over mafic and ultramafic lithologies. Ferruginous saprolite grades downwards into a thick saprolite zone, which extends to vertical depths of 50 to 70 m.

In general terms, stratigraphic sequences observed in eastern and western walls of *Turrett Pit* are similar to those of North Pit (Fig.12). However, the colluvium is shallow and reaches a maximum thickness of only 6 m and bodies of *iron segregations* are relatively more abundant. In the western wall of Turrett Pit, gravelly colluvium (3 m) overlies the 6-7 m thick pisolitic lateritic residuum. At depth, lateritic residuum merges into yellowish-brown collapsed ferruginous saprolite.

Waroonga-Genesis pits

The deposits are located within the Scotty Creek Sequence of metasedimentary rocks and thus contrasts with the dominantly mafic/ultramafic settings of the McCaffery, North Pit, Turrett, and Meatoa areas. Scotty Creek metasediments consist mainly of a series of very fine grained, psammitic units within which a 15 m thick coarser unit occurs, which hosts the orebody. Weathering is most advanced in the vicinity of the orebody, although its resistant nature results in its persistence, unaltered, through the saprock horizon. Immediately adjacent to the orebody, the stratigraphy of the southern wall comprises fresh bedrock (7 m), saprock (17 m), saprolite (16 m), mottled zone (6 m) and transported overburden (6 m).

In Waroonga, weak development of lateritic residuum (in terms of thickness) and the lack of iron segregations may be related to the na-

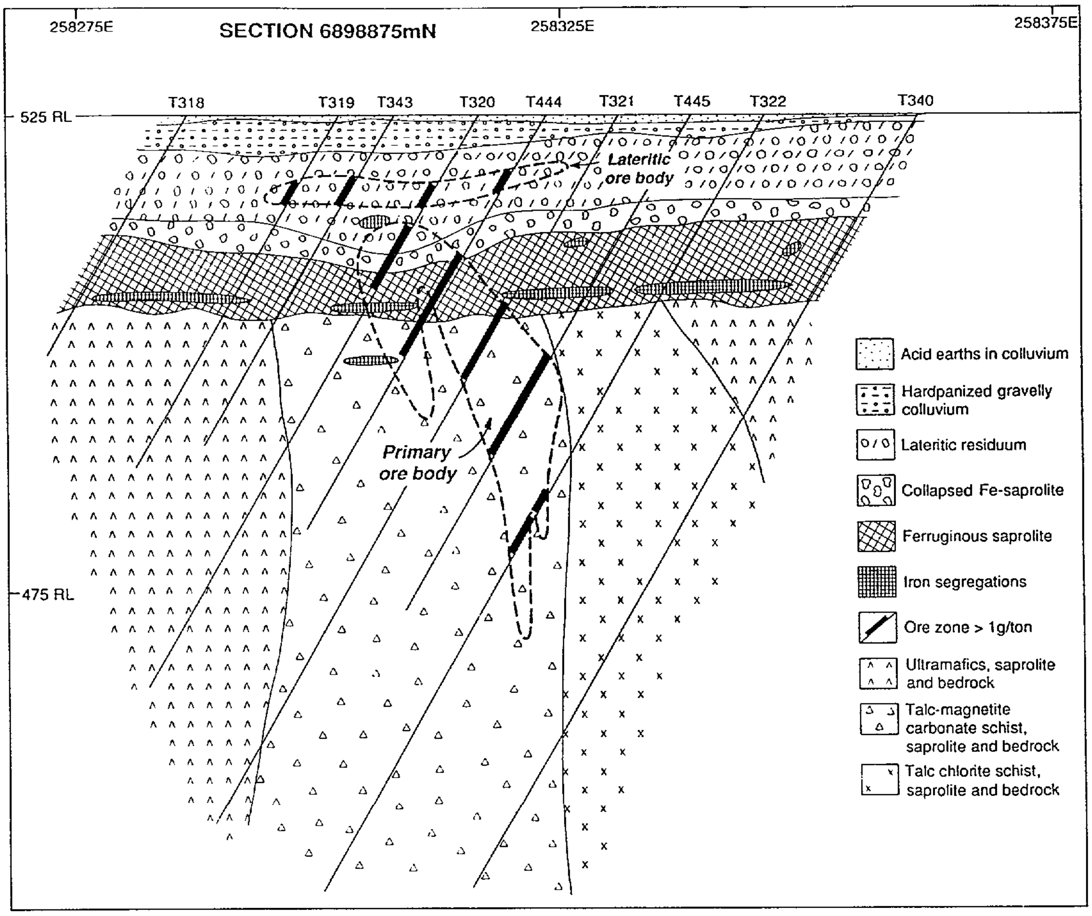

Fig. 12. Diagrammatic cross section along line 6898875N in the Turrett Pit showing regolith stratigraphy.

ture of the underlying lithology. The Waroonga Pit is sited within the Scotty Creek Sedimentary Sequence comprising feldspathic sandstone, chert, and conglomerate of mafic and ultramafic origin (Partington, 1986). In contrast, lateritic residuum over mafic and ultramafic rocks at North Pit and Turrett Pit is relatively much thicker and ferruginous.

In Genesis Pit, the top of the residual saprolite profile has been incised by Permian glaciofluvial channels. The saprolite and part of the mottled zone are developed in Archaean rocks but the upper mottled zone and lateritic horizon are developed in Permian clays. These, in turn, are overlain unconformably by various colluvial/alluvial horizons, including upper layers of lateritic gravel and silt, silicified to hardpan. A small, rare wedge of paleosol occurs between mottled Permian clays and the colluvium/alluvium.

Synthesis of regolith development

The development of the regolith of the Lawlers district can be related to processes of deep lateritic weathering, subsequent erosion, deposition and modification through leaching and cementation. The processes responsible for the formation of the regolith at Lawlers are briefly described below. The contribution of these processes to the regolith types is presented schematically in Figs. 13 and 14 and are described below.

Weathering and laterite formation

A generalized evolution sequence of the weathering developed from mafic, ultramafic and felsic bedrocks is shown in Fig. 13. The left hand side of the Fig. shows a profile commonly developed from mafic and some ultramafic bedrocks, with a characteristic ferruginous saprolite, that on the right hand side shows a profile with a strongly developed mottled zone common on meta-sediments and felsic bedrocks. Figure 14 is a detailed block diagram showing the transition from ferruginous saprolite to lateritic residuum, based mainly on observations at the McCaffery Pit.

At the base of the profile, at the lower saprolite, saprock zones, and at the saprock/fresh rock interface the primary minerals weather to assemblages of halloysite/kaolinite, smectite, and goethite depending upon the nature of the primary minerals and internal drainage. Rock structures, including millimetre scale patterns, can be well preserved resulting in thick saprolite zones. Higher in the weathering profile, primary textures on a large

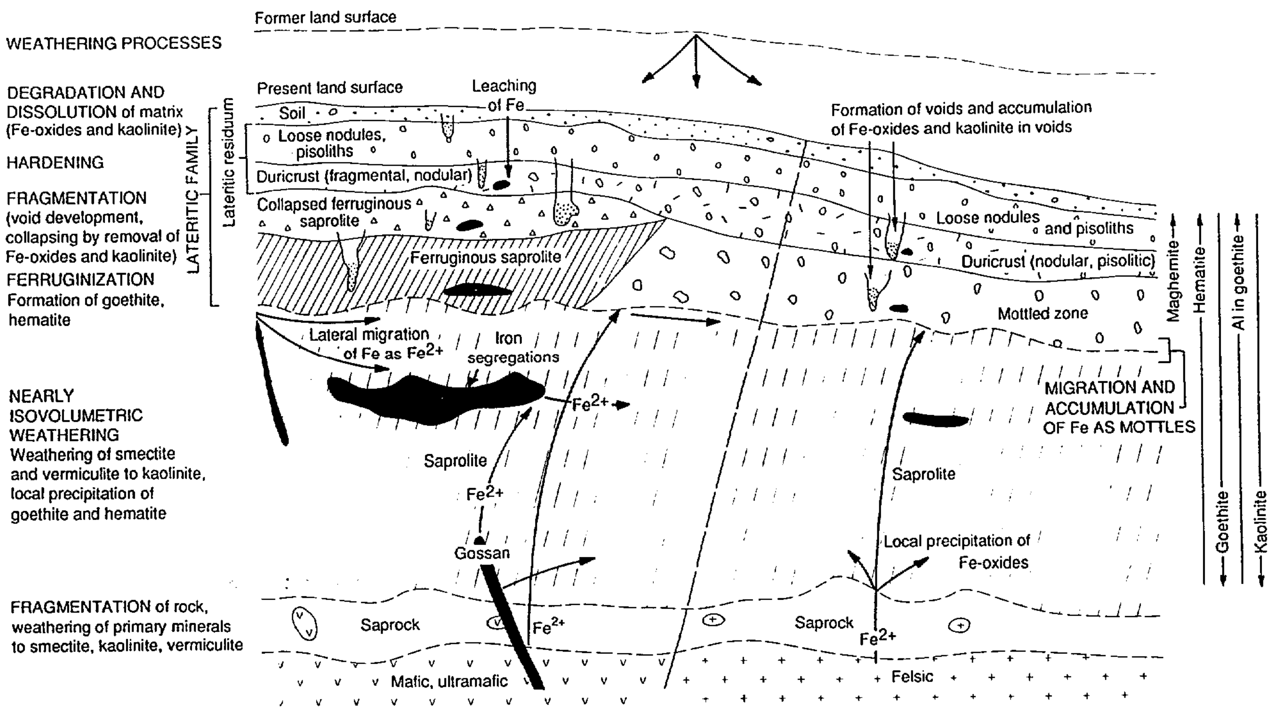

Fig. 13. A schematic diagram of the differences in the nature of the weathering mantle developed from mafic, ultramafic and felsic bedrocks.

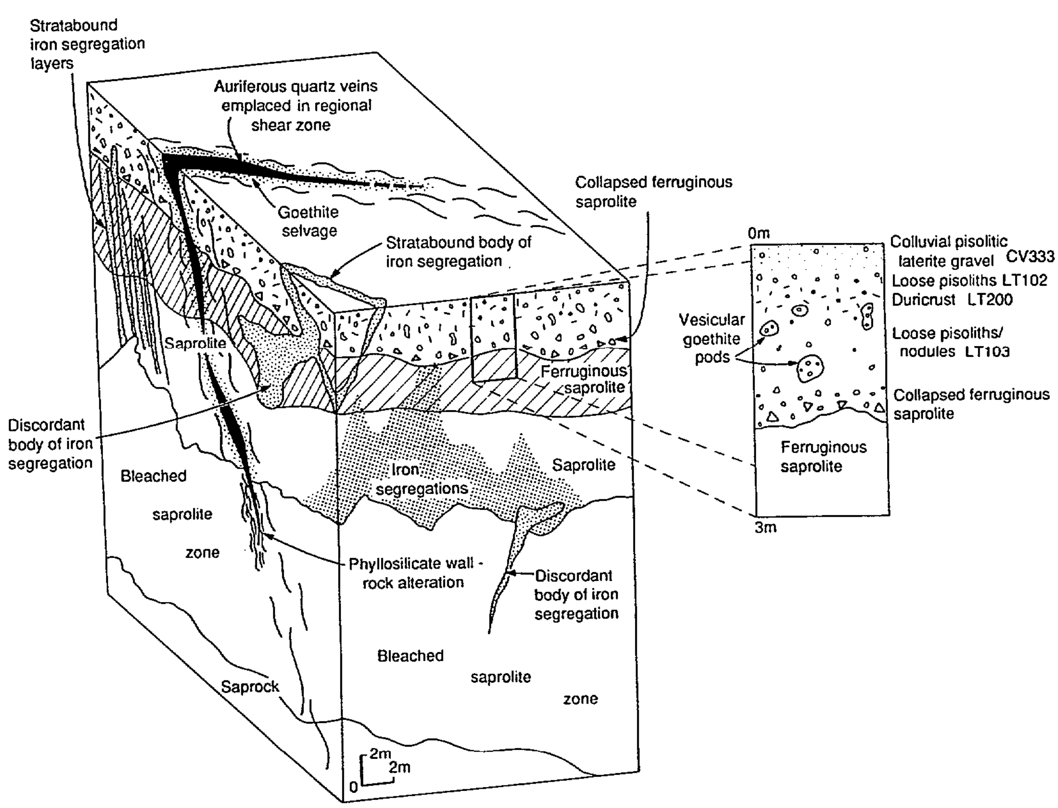

Fig. 14. Detailed block diagram showing field relationships for several categories of lateritic materials and iron segregations.

scale are destroyed. This commonly occurs close to the water table, which is a site of considerable chemical activity, particularly for elements such as Fe and Mn. The major characteristics of the mineralogy are presence of large amounts of goethite in the upper part of the profile, with hematite and maghemite increasing in proportion towards the surface. Smectite occurs throughout the profile except at the surface. Bands of iron segregations which are commonly observed within the upper part of a profile are dominated by goethite with sub-ordinate amounts of hematite.

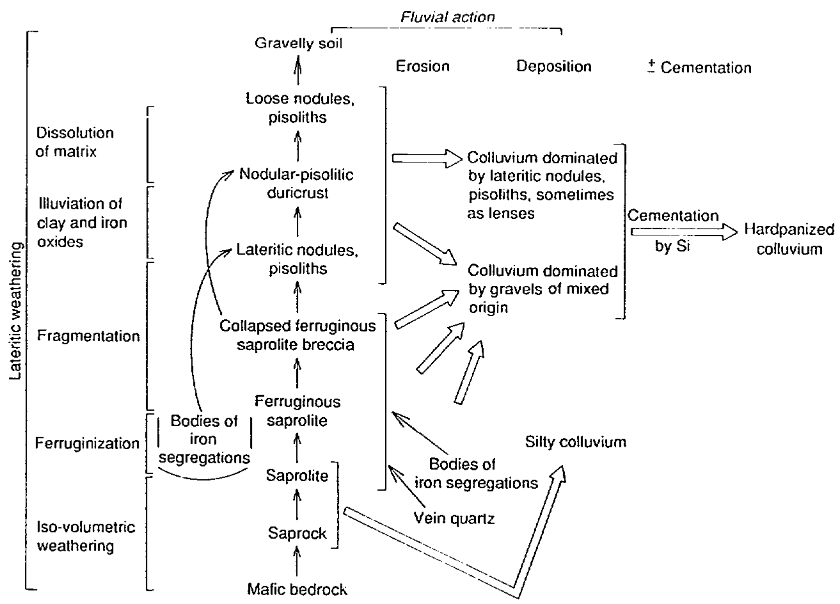

Fig. 15. Schematic facies relationship diagram for the formation of lateritic residuum and its subsequent dismantling.

Quartz and resistant minerals such as talc and chromite survive through much of the laterite and help identify the bedrock. Iron and some trace elements in lateritic residuum also reflect the composition of the underlying bedrock. Laterites formed from metasediments are low in Fe due to the small abundances of original Fe. Laterites derived from ultramafic rocks are slightly Al poor but richer in Fe than those from mafic rocks. The ultramafic laterites are, however, richer in Co, Ni, Cr, which may be used to distinguish mafic from ultramafic-derived laterites.

Many nodules and pisoliths develop by fragmentation of ferruginous saprolite (Fig. 13). Ferruginous saprolite is a yellowish-brown, indurated mass which was produced by the infusion of Fe-oxides into clay-rich saprolite. Fragments of ferruginous saprolite are broken down into small nodules with a yellowish-brown/olive-green cutan. Cutans would form by deposition of Fe and Al around the nucleus.

Modification of weathering profile

A number of processes have continued since the formation of the lateritic weathering profiles. These include dehydration and hardening of the lateritic residuum; erosion of the whole or part of the weathering profile; deposition of detritus generated from this erosion; weathering of the newly exposed regolith; silicification and calcification of both transported and residual regolith; leaching of the upper regolith; and chemical and mineralogical changes in the upper regolith. These processes may be related to a change to a drier climate for the inland Yilgarn; a change which has probably taken place since the mid-Miocene.

Dismantling of lateritic residuum leads to the deposition of colluvial/alluvial units rich in lateritic nodules and pisoliths (Fig. 15). In contrast colluvial/alluvial units derived from ferruginous saprolite, saprolite, and lateritic residuum are dominated by polymictic gravels. All of the colluvial/alluvial units can be further modified by cementation resulting in hardpan.

Erosion has affected some parts of the landscape, while other parts such as laterite capped crests and back slopes, remain relatively unchanged. Materials removed from the erosional areas have been deposited on lower slopes with consequent burial of deeply-weathered profiles and the reduction of relief.

The distribution of lateritic residuum, as a product of long continued weathering at or near the landsurface, can be seen as an indicator of the nature of the relief of the area prior to its modification by erosion and burial. The widespread lateritic residuum, either as extensive sheets or as scattered pockets in a variety of topographic situations, suggests that it once formed a somewhat continuous surface in the Lawlers area.

Formation of hardpan and calcrete

Bettenay & Churchward (1974) suggested that hardpan is developed in colluvium and alluvium on surfaces either carved out of, or enveloping the lower parts of the laterite mantled landscape. Recent work has shown that hardpanisation (cementation by Si, Al, Fe) have not only affected colluvium and alluvium but also lateritic residuum

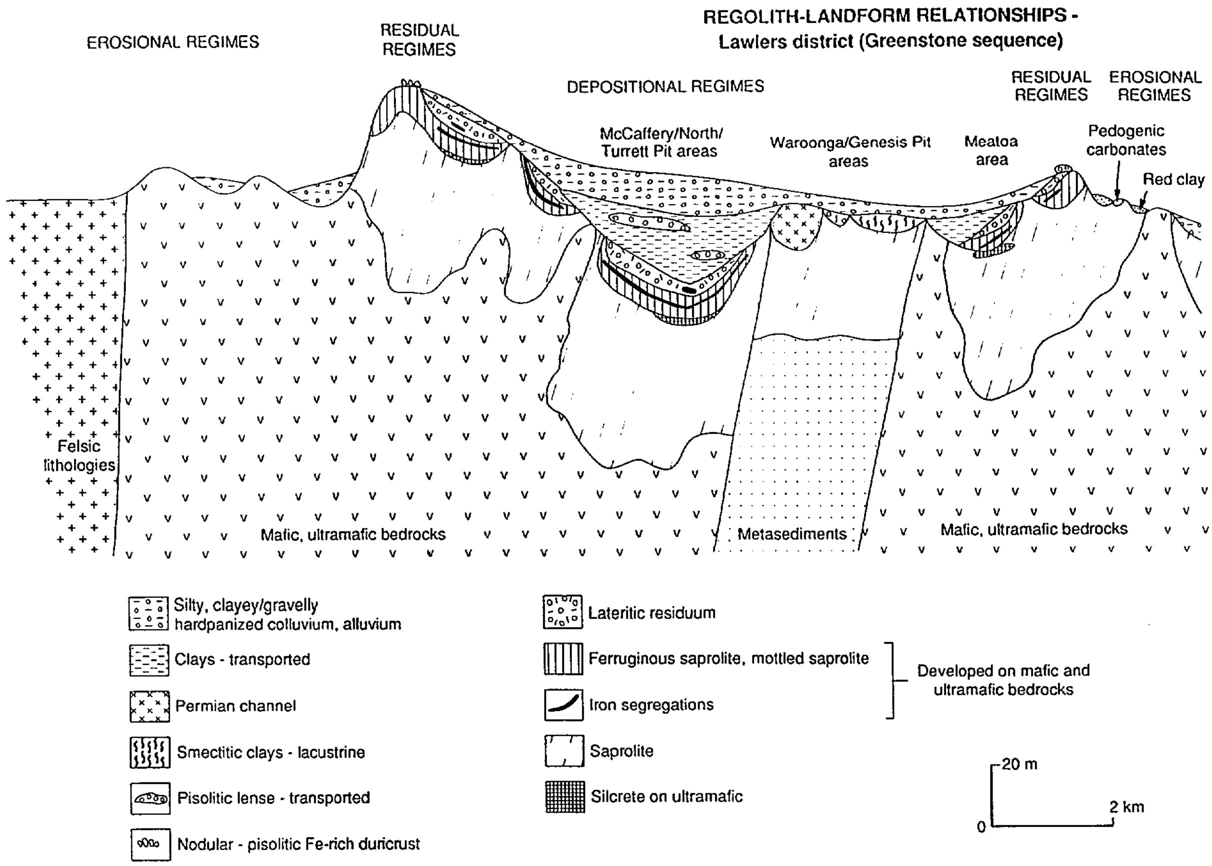

Fig. 16. Schematic cross section for the Lawlers distict showing regolith stratigraphy and landforms.

and in places, upper saprolite (Anand & others, 1989, 1991). Hardpanisation commonly occurs within the top few upper metres of the regolith, particularly in wide past or present depressions. Well-developed hardpans are uncommon in erosional regimes which include active pediments and steep slopes. This suggests that land-surface stability is a prerequisite for hardpanisation. Widespread hardpanisation of many regolith units indicates mobilization and deposition of silica in the upper regolith. hardpanisation appears to have resulted from periodic waterlogging of the sediments and locally-underlying regolith followed by dessication under semi-arid to arid conditions.

There can also be extensive chemical modification of lateritic duricrust, including precipitation of carbonates and silica. In some locations, the matrix, nodules, and pisoliths appear to have been replaced and/or displaced by carbonates and silica, with consequent formation of calcareous and siliceous duricrusts. If the process was taken to completion, calcrete and silcrete would result.

Origin of lags

The general distribution of lag gravels can be understood in terms of regolith-landform relationships. In the erosional regimes, coarse black lags of iron segregations, or lags of fragments of ferruginous saprolite (where stripping is less extensive), appear to be largely the result of present-day in situ weathering of the landscape. In the same sense, lateritic lag comprising nodules and pisoliths is the in situ product of present-day weathering of lateritic duricrust. These lags may have been concentrated at the surface by a variety of processes including deflation, removal of matrix, burrowing action of termites, ants, and rabbits, etc.; these processes have been discussed in detail by Mabbutt (1980) and Carver & others. (1987). These in situ lags have been further subjected to physical and chemical weathering and dispersion processes. Lateral dispersion of these lags by the action of water has resulted in a layer of fine lag comprising a variety of clasts on the colluvial outwash plains.

Generalised regolith–landform model

Figure 16 is a schematic cross section showing regolith-landform relationships for the Lawlers district. This figure is based upon the regolith-landform assessment throughout the Lawlers district coupled with the detailed study at McCaffery-North Pit, Turrett Pit, Waroonga Pit, and Meatoa areas. The dominant features are a residual lateritic weathering profile that undulates over the landscape, erosion partly dismantling the lateritic residuum and ferruginous saprolite, cutting into the saprolite, and the resulting debris being deposited as colluvium and alluvium in areas of low relief. From

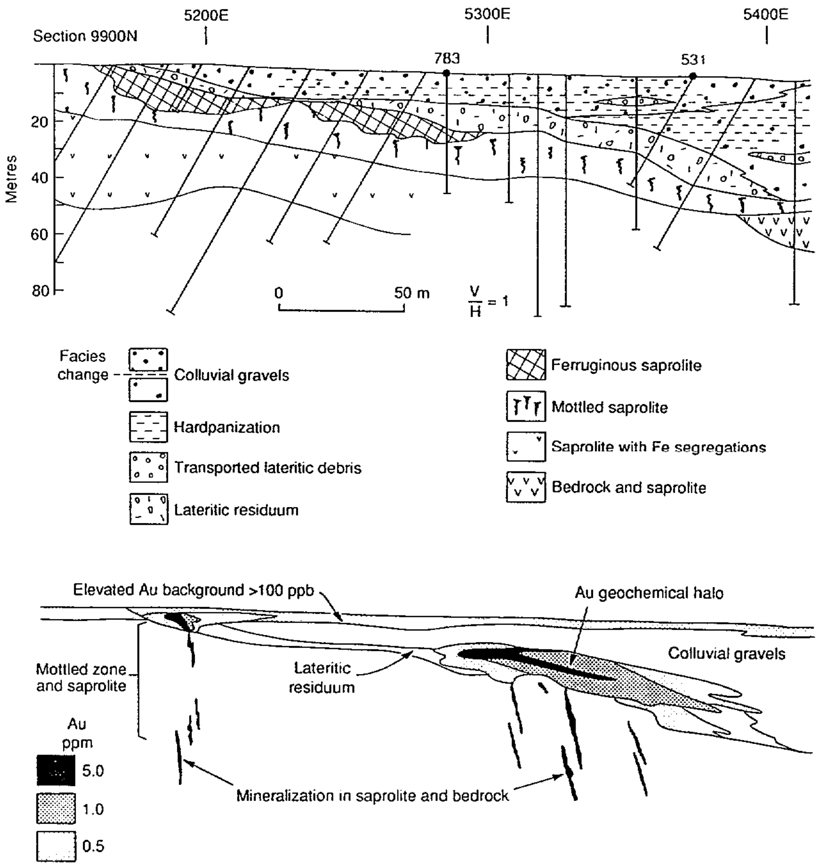

Fig. 17. Diagrammatic cross section along line 9900N in the North Pit showing regolith stratigraphy and dispersion of Au in lateritic residuum.

this study, together with the application work of Geochemex (Butler & others, 1989), it is now well established that the buried residual laterite profiles are widespread beneath the sediments. Their distribution is however, erratic and difficult to predict because of the partial stripping of the old surface.

Geochemical dispersion—North, Turrett and McCaffery deposits

Laterite geochemical techniques are widely used in Australia for initial mineral exploration and for follow-up work. Laterites have been found to contain relatively low-order anomalies of kilometre scale which are far greater in area than the equivalent anomalies found in fresh rock or saprolite. The act of hydromorphic and mechanical dispersion has tended to smooth much of the local chemical and mineralogical variation, making recognition of this low-order haloes generally easier (Smith & Perdrix, 1983; Smith, 1989; Anand & Smith, 1992; Smith & others, 1992).

Where the lateritic horizon is preserved, duricrust, pisoliths and nodules form an ideal sampling medium for seeking widespread dispersion haloes for Au and base metals exploration. These may be collected from surface or near-surface in residual regimes or by drilling in depositional regimes. Drilling for buried geochemical haloes in laterite and ferruginous saprolite can be a particularly effective method of exploring sediment-covered areas because the laterite dispersion haloes are much larger than the ore deposit targets (Anand & others, 1991; Smith & others, 1992). This requires accurate, sub-surface sampling of the lateritic materials and knowledge of the regolith stratigraphy. In drilling to sample buried laterite, it is important to recognise and distinguish between the transported lateritic debris and residual laterite.

North and Turrett Pits within Lawlers district demonstrate the effectiveness of drilling for buried geochemical haloes in laterite and ferruginous saprolite (Figs. 17 & 18). The areas are dominated by gravel-strewn colluvial outwash plains. An extensive, but discontinuous, horizon of essentially-residual laterite is overlain unconformably by a varying thickness (5-30 m) of colluvium. The colluvium contains components derived by partial or complete stripping of lateritic residuum and ferruginous saprolite elsewhere. Detailed field relationships and regolith stratigraphy of the North and Turrett Pit areas are discussed in earlier sections.

Prior to mining at North Pit, lateritic and saprolitic Au resources lay beneath 10 to 20 m of hardpanized colluvium. The bedrock mineralisa-

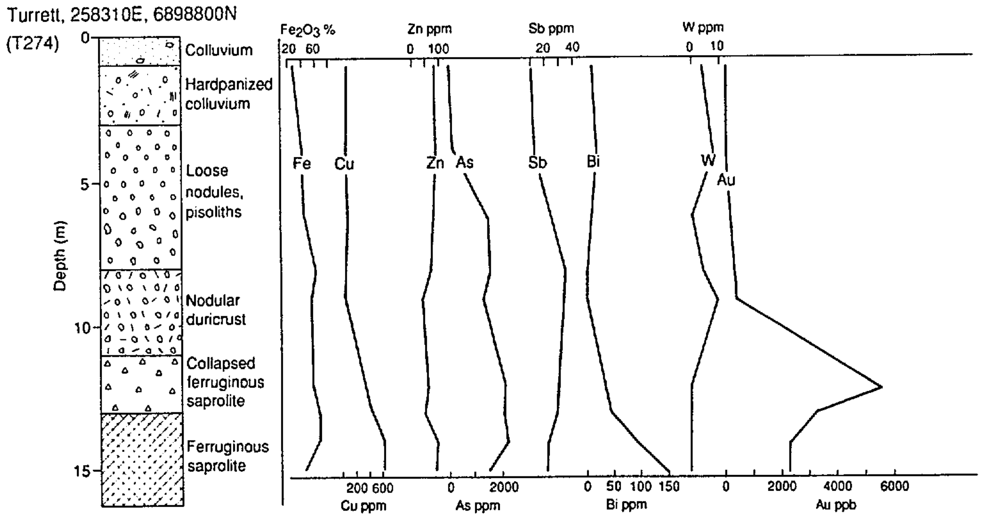

Fig. 18. Vertical profile showing the regolith stratigraphy and geochemistry of the regolith units intersected in the drill hole–T274, Turrett Pit area.

tion continues to the south within the McCaffery Pit. Gold from this source has been redistributed and concentrated by secondary weathering effects into the saprolite and, in places, into the overlying lateritic residuum.

Samples of specific units within vertical profiles were taken from drill spoil. Residual lateritic pisoliths/nodules of lateritic residuum typically have 1-2-mm thick yellowish-brown/greenish cutans around black/red nuclei. Pisoliths are rounded to sub-rounded and are 5-20 mm in diameter. The presence of cutans may be used to recognise nodules derived from the breakdown of lateritic residuum. Fragments of ferruginous saprolite differ from lateritic residuum in having a yellow-brown colour, irregular shape, and are non-magnetic with incipient nodular structure. The gravel fraction from colluvium displays features that are indicative of an inherited, transported origin. Iron segregations can be recognized by their irregular, black, non-magnetic and pitted surface properties.

Iron segregations differ from lateritic residuum by having abundant goethite and less hematite and kaolinite. Maghemite is typically absent in iron segregations. Lateritic residuum can be distinguished from ferruginous saprolite by having abundant hematite and less kaolinite. Colluvium differs from other groups in having abundant quartz, kaolinite, and some heavy minerals.

The results showed that the North and Turrett Pit Au deposits forms the high-grade part of a chalcophile multi-element geochemical anomaly. Anomalous and ore-grade Au values in lateritic residuum and ferruginous saprolite are accompanied by anomalous levels of As, W, Sb, Bi, Cu and Ag (Figs. 17 & 18). Gold in lateritic nodules from the North Pit occurs as grains (<15μm in diameter), in cracks, and as relatively large, dendritic grains (which reach 70 μm in diameter), attached to the surface of goethite. Both occurrences of Au appear to be secondary and are almost free from Ag.

Iron segregations

The iron segregations are suitable sampling medium for geochemical exploration in areas where lateritic residuum is stripped. Samples of iron segregations collected from surface over an area of 1.5 km by 0.5 km, and from pit walls, document the multi-element characteristics of McCaffery-North Pit Au deposits including dispersion during lateritic weathering of the hosting mafic and ultramafic lithologies. The mineralisation is depicted by a multi-element anomaly in Au, As, Cu, Zn, W, Mn and to some extent in Bi, Ag and Sb (Fig. 19). The ore-related elements in iron segregations, with the exception of Mn and Zn, are similar in abundances to those in the lateritic nodules and pisoliths. Gold has however, a relatively low abundance. The geochemical pattern for Au is consistent over the 200 to 300 m width of the anomaly for a strike length in excess of 700 m. A background for Au between 3-5 ppb with a threshold of 10 to 20 ppb would seem appropriate in reconnaissance exploration.

Conclusions and implications for exploration

Extensive areas of complete laterite profiles occur buried beneath widespread alluvial and colluvial plains. The extent of buried laterites are in marked contrast with the restricted area of lateritic residuum exposed at surface, the latter being about 15% of the total area. Exploration beneath

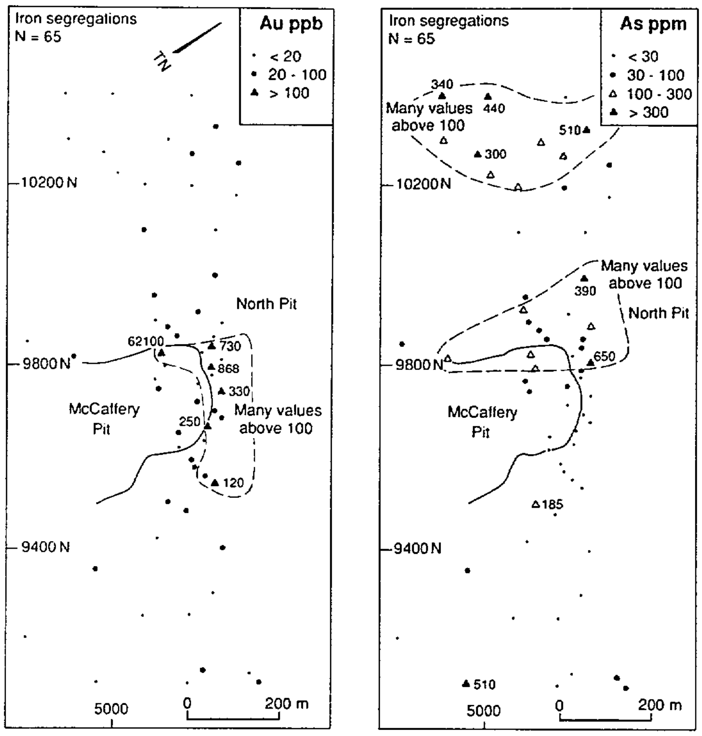

Fig. 19. Maps of the distribution of Au and As in iron segregations, McCaffery–North Pit areas.

the plains at Lawlers carried out by Forsayth and Geochemex, with research support by CSIRO, has clearly demonstrated the effectiveness of drilling for buried geochemical haloes in laterite and ferruginous saprolite.

Broad Au anomalies and anomalous concentrations of other ore-associated elements such as As, Cu, Bi, Sb, and W are effective indications of primary and supergene Au mineralisation in the lateritic residuum and ferruginous saprolite at North and Turrett Pits. Compared with lateritic residuum, the ferruginous saprolite is less weathered and is closer in geochemical characteristics to the mineralisation.

The iron segregations, and the lag derived therefrom, are appropriate sampling media in partly truncated areas of the Lawlers district, in lieu of lateritic residuum and ferruginous saprolite. Elevated levels of Au, As, Cu and, to some extent Bi and Sb, anomalous geochemical associations in the iron segregations. The colluvium and hardpanized colluvium are also anomalous in Au while As and Sb have only moderate abundances in the near-surface colluvium.

Excursion localities

Locality 1: Brilliant Area

This stop is to demonstrate an example of regolith in an erosional regime. The ferruginous cobbles occur largely on erosional areas in the Lawlers district and appear to have been derived from the breakdown of iron segregation bodies. The iron segregations, several metres across, commonly occur within the ferruginous saprolite/saprolite horizons in a weathering profile. Ferruginous cobbles are black, generally non-magnetic and many of them are dominated by goethite. The internal surfaces of ferruginous cobbles may show the goethite pseudomorphs after pyrite and pyrrhotite. Ferruginous cobbles are high in Fe (71% Fe_2O_3), Mn (3000 ppm), Zn (380 ppm), Cu (157 ppm), and Co (91 ppm)—mean values of 76 samples.

The iron segregations, and the lag derived therefrom, are appropriate sampling media in partly truncated areas of the Lawlers district, in lieu of lateritic residuum and ferruginous saprolite.

Locality 2: North and Turrett Pits

An extensive horizon of residual laterite occurs beneath varying thicknesses of sediments. Regolith stratigraphy in the North Pit also provides a classic example of strongly developed mottling in a cover sequence which overlies a complete lateritic profile. This mottling may be confused with mottling developed through the lateritic weathering of Archaean bedrock. Detailed field relationships and geochemical dispersion in the regolith are covered in earlier sections.

Locality 3: Agnew Gravel Pit

This stop is to demonstrate the differences in the regolith types between residual (crest, backslopes) and erosional regimes (breakaway, pediment slopes). A wide range of ferruginous materials occur within these regimes. Lateritic duricrust and loose pisoliths and nodules occur on residual regimes while ferruginous saprolite, mottled saprolite and iron segregations occur on erosional regimes. Implications to exploration will be discussed.

Locality 4: Waroonga–Genesis Pits

The deposits are located within the Scotty Creek Sequence of metasedimentary rocks and thus contrasts with the dominantly mafic/ultramafic settings of the McCaffery, North and Turrett Pits. Immediately adjacent to the orebody, the stratigraphy of the southern wall comprises fresh bedrock (7 m), saprock 17 m), saprolite (16 m), mottled zone (6 m) and transported overburden (6 m). In Genesis Pit, the top of the residual saprolite profile has been incised by Permian glaciofluvial channels. Detailed field relationships are discussed in earlier sections.

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Excursion 4

Gold mineralisation at various regional metamorphic grades

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Introduction: objectives and scope of the excursion

J. Ridley

This excursion will visit lode-gold deposits in the Southern Cross greenstone belt and the Kalgoorlie Terrane of the Norseman–Wiluna greenstone belt, with the emphasis of the excursion being to illustrate the variety of styles of mineralisation that have been recognised, both with respect to ore and wallrock alteration mineralogy and to structural setting. The variety is largely controlled by hostrock metamorphic grade, and four areas are to be visited, which between them cover most of the spectrum of metamorphic grade in the southern half of the Yilgarn Block. The areas (Fig. I.1, and in more detail in Figs. II.1 & II.4) and the dominant metamorphic grade of each are:

Southern Cross–Bullfinch:	middle-amphibolite facies
Coolgardie Goldfield:	lower-amphibolite facies
Kambalda–New Celebration:	upper-greenschist facies
Kanowna–Mount Pleasant:	lower- to sub-greenschist facies

Although metamorphic grade is an important control on structural style of mineralisation, deposits in rocks of a specific metamorphic grade have a range in structural styles, and aspects of this variability will also be illustrated during the excursion.

The recognition (re-recognition?) that lode-gold deposits occur across a wide range of metamorphic settings, and that the characteristics of the deposits are functions of metamorphic grade, has led to significant reassessment of models for the formation of this type of deposit. A number of lines of evidence lead to the conclusion that mineralisation generally occurred broadly syn-metamorphically, whatever the peak metamorphic conditions of the hostrocks. The deposits thus formed under a wide range of pressure and temperature conditions—there is a 'continuum' in the pressure–temperature conditions of formation of lode-gold deposits. An overview of the arguments for broadly syn-metamorphic mineralisation, and for the model of a genetic 'crustal continuum' of lode-gold deposits, together with a brief coverage of some important implications of the model is given in the Part One of this guide.

Part Two of this guide gives brief descriptions of the regional geology of each of the areas to be visited, and descriptions of the geology of most of the mines to be visited in each area. A summary of the geology and mineralisation of the Yilgarn Block and the Eastern Goldfields as a whole is not specifically given. The reader is referred rather to individual Geological Survey of Western Australia publications (Keats, 1989; Griffin, 1990; Swager

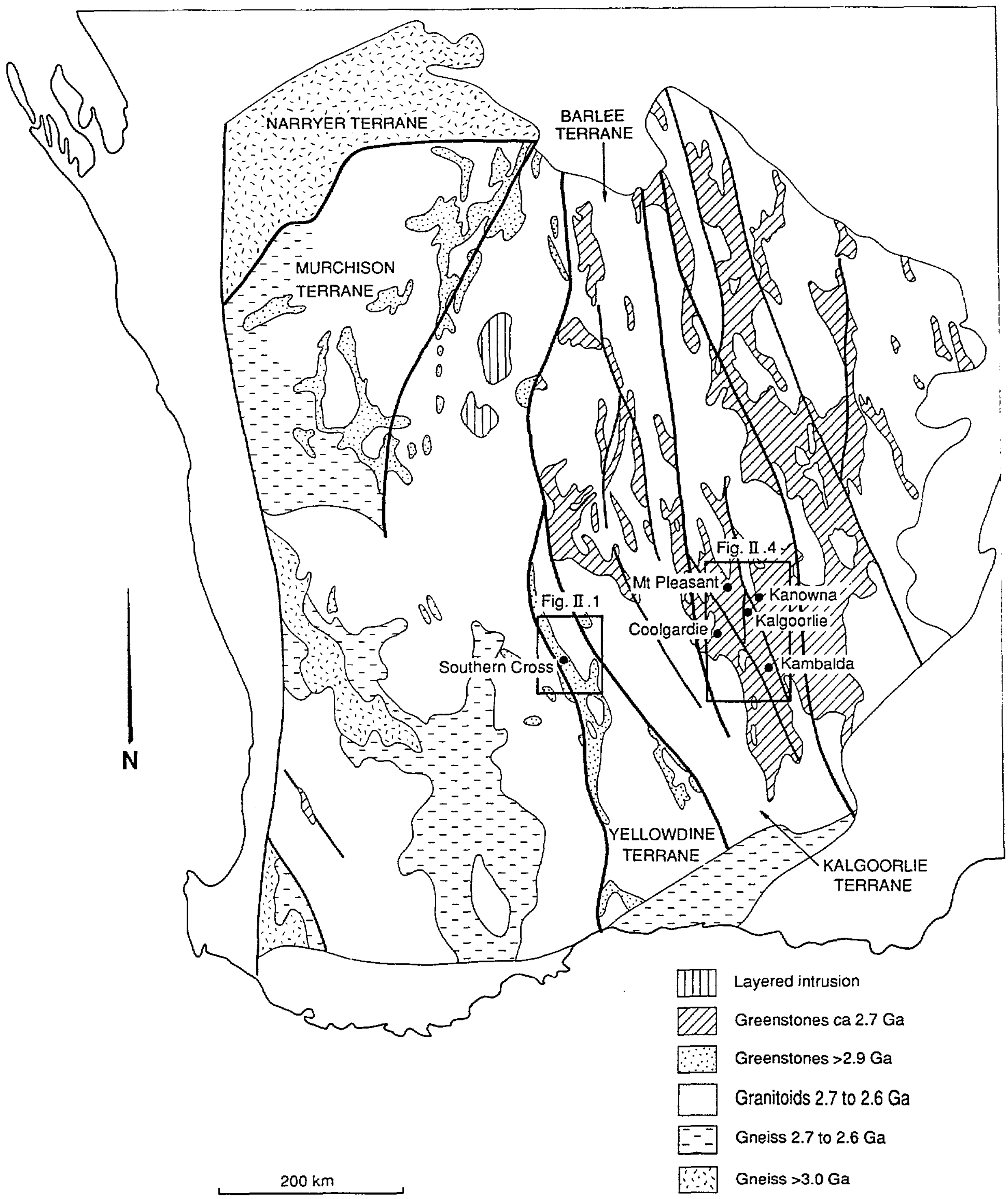

Fig. I.1. The Yilgarn Block, Western Australia, showing the major geological units. The outlined areas are to be visited in this excursion, and are covered in more detailed maps in Figs. II.1 & II.4.

& Griffin, 1990; Hunter, in press; Ahmat, in press), and the summary of much of this work in Swager & others (1992), for descriptions of lithological successions and structural geology, to Binns & others (1976) and Ahmat (1986) for metamorphic isograd maps, to Goleby & others (1993) for geophysical data on greenstone-belt structure, to Campbell & Hill (1988), Barley & others (1989), Myers (1992), and Williams & Whitaker (1993) for various models for the tectonic evolution, and to Ho & others (1990) and Witt (1993) for general descriptions of gold mineralisation in the region.

Part I: An integrated model for genesis of Archaean gold mineralisation within the Yilgarn Block, Western Australia

D.I. Groves

Lode-gold deposits are widespread in Archaean granitoid-greenstone terranes (e.g. Colvine, 1989; Foster, 1989), and similar deposits occur in the Phanerozoic Cordilleran terranes of North America (e.g. Nesbitt & others, 1986). Following early controversy over syngenetic as opposed to epigenetic models for these deposits, there has been general acceptance of an epigenetic origin, with dominant structural and host-rock controls, even for BIF-hosted deposits, and major controversy has shifted to the timing and crustal levels at which mineralisation took place and to the ultimate source of the ore fluids and ore solutes that formed the deposits.

Although most of the lode-gold deposits in the Yilgarn Block represent the so-called "mesothermal" deposits hosted in greenschist-facies host rocks, there has been a growing realisation that significant deposits may occur in sub-greenschist facies and amphibolite- to granulite-facies host rocks (e.g. Barnicoat & others, 1991; Witt, 1991). Here a concise review of the characteristics of the deposits in different metamorphic settings (summarised in Figs. I.2 & I.3) is presented, demonstrating that they represent a genetic group, showing evidence that they were formed at (broadly) the P–T conditions indicated by either (or both) metamorphic or metasomatic-alteration assemblages in host rocks—hence syn-metamorphically, and briefly discussing the implications for genetic models, particularly the sources of ore fluids and solutes.

Lode-gold deposits: a coherent genetic group

As discussed by numerous authors, the great majority lode-gold deposits, both in the Yilgarn Block and in Archaean cratons world-wide, have a large number of features (albeit dominated by data from deposits in greenschist facies environments) in common. The deposits are epigenetic and structurally controlled, generally in late (commonly reactivated?) shear zones. They have consistent enrichments in Au (normally 10^3-10^4 times background), Ag, As, and W, with variable enrichments in Bi, Sb, Te, and B, and minor enrichments in Cu, Zn, and Pb. The alteration assemblages, although varying in mineralogy with metamorphic setting (Fig. I.3), are characteristically enriched in CO_2, S, K (and other LILE), plus the ore metals, and there is commonly volume increase or conservation in proximal alteration zones. Lateral alteration zoning is characteristically on the scale of centimetres to tens of metres, whereas vertical zonation, where recognised in the Western Australian deposits, is normally more subtle and on the scale of hundreds of metres (e.g. Mikucki & others, 1990): though 'telescoped' alteration may be present in sub-greenschist facies ore environments (Hagemann & others, submitted). In addition, as determined from fluid inclusion studies, a low-salinity, H_2O-CO_2-CH_4 fluid is important at all deposits, albeit with variable H_2O:CO_2:CH_4 ratios for different deposits, but generally an XCO_2 of 0.1 to 0.2 before phase-separation or mixing with other fluids (see Groves & others, 1992, table 1, for summary). Thus, available evidence supports the assertion that most of the lode-gold deposits can be classed as a single genetic group.

Lode-gold deposits: formation within a restricted time interval

Available relative and absolute geochronological evidence supports broadly contemporaneous gold mineralisation in the late Archaean throughout the Yilgarn Block. The lack of significant temperature differences between fluid and wallrock, the general lack of 'telescoped' vertical zonation of wallrock alteration, and the gross correlation between mineral assemblages of proximal metasomatic wallrock alteration and regional-scale metamorphism (Fig. I.3) indicate the infiltration of ore fluids into heated host rocks. This appears to implicate the formation of gold deposits during the regional metamorphic event recorded in the greenstone belts. More importantly, the three published precise ages on mineralisation, for a greenschist-amphibolite transition setting at Kambalda in the Eastern Goldfields (Clark & others, 1989), a granulite-hosted deposit at Griffins Find in the Southern Cross Province (Barnicoat & others, 1991), and a lower-amphibolite facies setting at Reedys in the Murchison Province (Wang & others, submitted) are within error at approx. 2.63 Ga despite their wide geographic spread and contrasting settings. In addition, Pb model ages on least-radiogenic ore-related sulfides are essentially within error (± 30 Ma) of each other over the entire Yilgarn Block (McNaughton & others, 1990), supporting the majority of field evidence which suggests late structural timing of gold mineralisation (e.g. Witt, 1993).

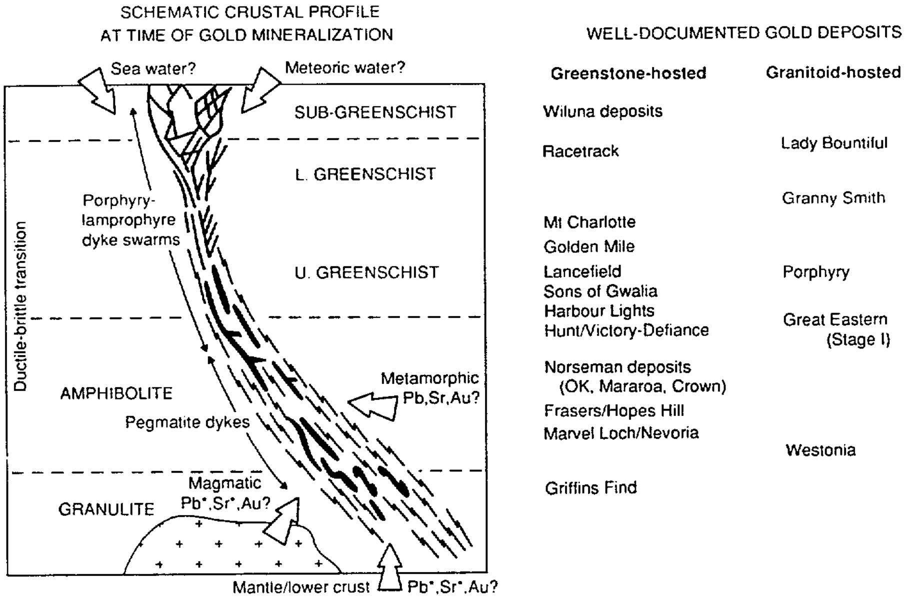

Fig. I.2. Schematic reconstruction of a hypothetical, continuous hydrothermal system extending over a crustal depth range of 25 km, showing potential fluid and radiogenic isotope sources (adapted from Colvine, 1989; Foster, 1989; Barnicoat & others, 1991; Groves & others, 1992). Note that the continuous section is derived from the study of deposits in a number of discrete areas, each of which can be viewed as showing a specific section of the vertical profile. It is not implied that a series of deposits will occur in the same vertical plane from the top to the bottom of the system in any one area.

Lode-gold deposits: formation at a variety of crustal depths

The extremes of hostrock metamorphic grade yet recognised are from the sub-greenschist facies (e.g. Wiluna, Hagemann, submitted) at approx. 200°C and 100 MPa, to the lower-granulite facies (Griffins Find, Barnicoat & others, 1991) at approx. 700°C at 500 MPa. If the lode-gold deposits are a coherent genetic group, they potentially represent a continuum spanning a depth range within the crust from less than 5 km (Wiluna) to greater than 20 km (Griffins Find). Evidence is presented, in summary form below, to illustrate that the deposits show a number of parameters consistent with formation at variable crustal depths.

The deposits show a gross trend in structural style (Fig. I.3) from more brittle structures in sub-greenschist facies domains (e.g. Mount Pleasant area) through brittle to brittle-ductile hosting structures in greenschist facies domains (e.g. Kambalda, New Celebration), to ductile-hosting structures in amphibolite (e.g. Southern Cross area) to lower-granulite facies. As shown in Fig. I.3, deposit styles show progressively fewer breccias and transgressive quartz-vein sets and generally more foliation-parallel quartz veins and shear-zone replacements with increasing metamorphic grade: similar trends are discussed by Witt (1993). Quartz vein textures show a grossly parallel trend (Fig. I.3) from plumose, comb, and cockade textures and vugh fillings at the lowermost metamorphic grades through bucky or laminated quartz with partial annealing textures at intermediate grades, to coarse grained veins with granoblastic textures at the highest metamorphic grades.

As shown schematically in Fig. I.3, wallrock alteration assemblages in the ore (proximal) zone of mafic/ultramafic-hosted deposits (the best-studied major group) also vary systematically with the metamorphic grade of the enclosing rocks (Mueller & Groves, 1991; Witt, 1991). At sub-greenschist to mid-greenschist grades, low P-T assemblages, such as ankerite/dolomite-white mica-chlorite are common (Kanowna, Mount Pleasant, and see e.g. Phillips, 1986), whereas ankerite/dolomite-white mica-biotite (phlogopite)-chlorite±albite assemblages occur at mid-greenschist to the greenschist-amphibolite transition facies (Kambalda, New Celebration, e.g. Clark & others, 1989). At low-to mid-amphibolite grade, amphibole-biotite-plagioclase assemblages are dominant (Coolgardie Goldfield, and e.g. Golding & Wilson, 1982), in contrast to garnet-diopside-biotite-K feldspar assemblages at mid-amphibolite to lower granulite grade (Southern Cross, e.g. Barnicoat & others, 1991). The opaque mineralogy of the gold deposits shows a broadly complementary trend from S-rich assemblages dominated by pyrite (± arsenopyrite ± pyrrhotite) at low metamorphic grades, through pyrrhotite (± arsenopyrite) dominated assemblages, to

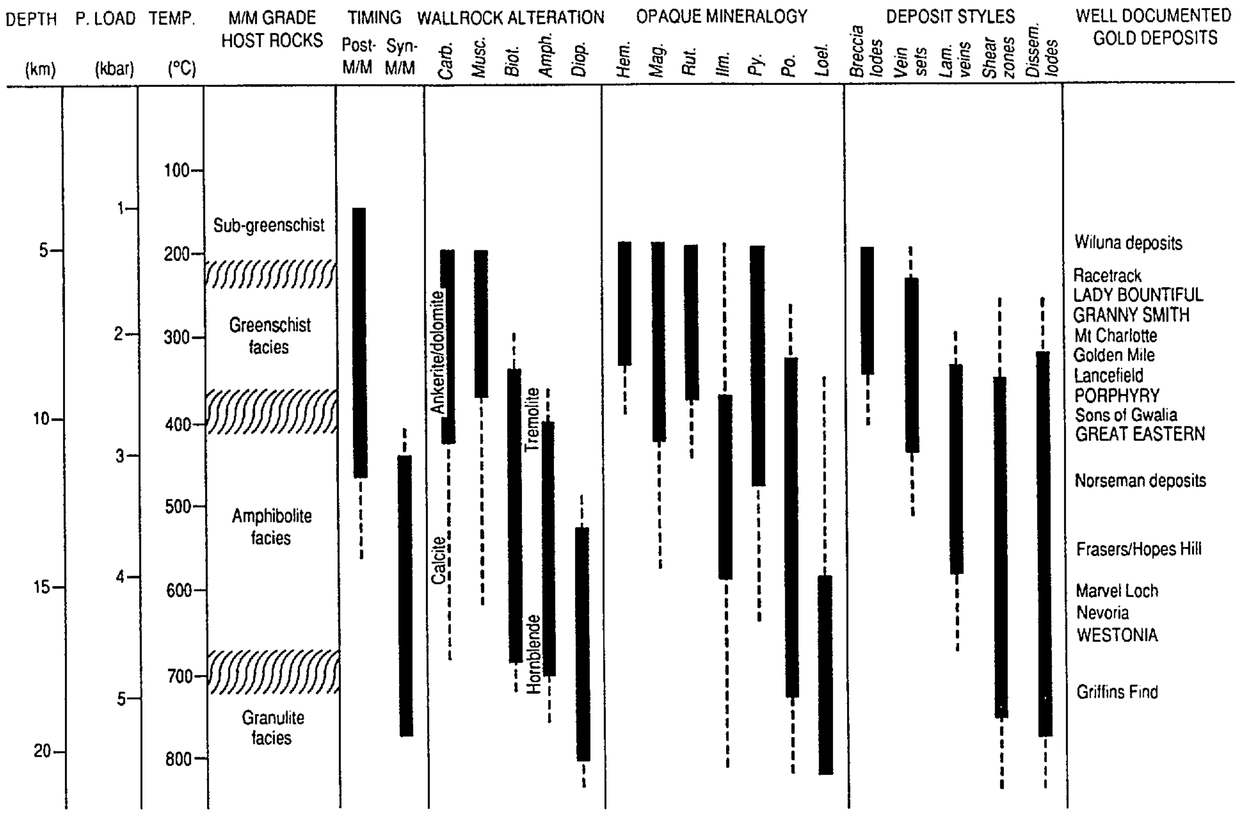

Fig. I.3. Summary of various features of late-Archaean lode-gold deposits over the crustal continuum of their deposition. The P–T–depth conditions indicated correspond to the conditions at the time of gold mineralisation, not necessarily those at the peak of metamorphism. The metamorphic grades shown are for peak metamorphic conditions of the host rocks to mineralisation. A geothermal gradient of 40°C/km is assumed. The characteristics shown are based on a small number of well-documented examples and are, of necessity, generalised. Alteration minerals are listed individually for simplicity, although it is recognised that wallrock alteration assemblages are the critical features characterizing the different P–T–XCO_2 conditions of alteration. Typical examples of well-documented gold deposits are listed, with granitoid-hosted deposits in capitals. Abbreviations used: i) timing, m/m = metamorphism, ii) wallrock alteration, amph = amphibole, biot = biotite, diop = diopside, musc = white mica, iii) opaque mineralogy, hem = hematite, ilm = ilmenite, loel = loellingite, mag = magnetite, po = pyrrhotite, py = pyrite, rut = rutile, (arsenopyrite is present at all crustal levels and is not shown), iv) deposit styles, dissem = disseminated (or shear-parallel veins), lam = laminated. Diagram designed by K.F. Cassidy and D.I. Groves, based on Groves & others (1992).

pyrrhotite-arsenopyrite (± loellingite) assemblages at high metamorphic grade. Tellurides, stibnite, tetrahedrite, and sulfosalts are more abundant in the deposits from low metamorphic grade environments and electrum may locally be present in place of gold (Racetrack, Mount Pleasant, Gebre-Mariam & others, submitted; Hagemann & others, submitted). Perring & others (1991) also show that Bi and Cu contents of bulk-ore samples are higher in high-grade environments whereas Ag, Sb, Pb, and S appear relatively enriched in ores from lower-grade domains, albeit from a restricted data set.

As noted above, vertical zonation of wallrock alteration is not commonly recorded from individual lode-gold deposits, although Mikucki & others (1990) discuss upwards vertical transitions from pyrrhotite- to pyrite-dominated assemblages at Mt Charlotte, and from biotite (± white mica) to white mica (± chlorite) assemblages over a vertical profile of about 1 km at Sons of Gwalia.

Lode-gold deposits: Syn-metamorphic timing in deeper crustal settings

As discussed by many authors, most lode-gold deposits in greenschist to lowermost amphibolite-facies domains have wallrock alteration assemblages that overprint metamorphic assemblages, and in some well-documented examples (e.g. in the Kambalda region: Clark & others, 1989) the temperatures of mineralisation clearly indicate post-peak metamorphic timing, though are still broadly syn-metamorphic.

There are as yet few *detailed* published studies of amphibolite-hosted lode-gold deposits in Western Australia, although Barnicoat & others (1991) and Mueller & Groves (1991) do review the critical evidence available. Petrological and mineralogical studies of wallrock alteration, and the structures and textures of mineralised veins, have been used to support a broadly syn-metamorphic timing for these deposits. Some deposits are considered to be pre-peak metamorphic (e.g. Big Bell; Phillips, 1985), but this interpretation is controversial (Wilkins, 1993). Critical evidence observed in a number of different deposits for syn-metamorphic timing includes:

- i) the high thermodynamic variance (low number of phases) of the high P-T alteration assemblages, indicating an open metasomatic system at those conditions,
- ii) fine oscillatory zoning in vein minerals (e.g. diopside), indicating growth most likely into fluid-filled space, and
- iii) the variable textures of the quartz and diopside veins from deformed and annealed grains through to coarse grained, undeformed crystals with some undeformed alteration phases (e.g. amphibole) aligned perpendicular to the vein walls, implying alteration was progressive during deformation at high temperatures.

An integrated genetic model for lode-gold deposit: a mid- to upper "crustal continuum"

The evidence presented above supports the concept that the majority of the late-Archaean lode-gold deposits do represent a single genetic group, and that these formed from a similar, but evolving, ore fluid at a variety of crustal depths. This is the basis for the 'crustal continuum' model, shown schematically in Fig. I.2. Some implications of the model and its acceptance are briefly outlined below.

Scale of hydrothermal circulation systems

A major implication of the model is that the scale of the hydrothermal systems was very large, and that the fluid conduits were potentially very long. This is compatible with the regional-scale association of many of the lode-gold deposits with crustal-scale deformation zones, commonly in association with swarms of lamprophyres and felsic porphyries considered derived from mantle and lower crustal depths, respectively, although many individual gold deposits occur in second- or third-order structures (e.g. Eisenlohr & others, 1989), and some deposits may show no obvious relationships to crustal-scale structures (Witt, 1993).

Fluid and solute source

The interpretation that the lode-gold deposits were deposited over the entire range of crustal depths represented by exposed Archaean greenstone belts, and that some were formed in amphibolite-granulite facies domains only a few hundred metres from synkinematic granitoid domes, effectively rules out metamorphic devolatilisation of greenstones alone (e.g. Phillips & Groves, 1983, Groves & Phillips, 1987) as the fluid and solute source: there is no seismic evidence for greenstone belts within the felsic crust underlying exposed belts in the Yilgarn Block (Goleby & others, 1993). Similarly, models involving *in situ* release of fluids from high-level felsic intrusions are unlikely given that they are only abundant in mine environments representing high crustal levels. Pegmatites are the dominant felsic intrusive phases in higher metamorphic-grade environments, but normally post-date gold mineralisation.

Although stable isotope data (e.g. Golding & others, 1989) are compatible with a variety of sources, including greenstone belts, for some components of the ore fluids that infiltrated to relatively high crustal levels, there is growing evidence from Pb- (Browning & others, 1987; McNaughton & others, 1990) and Sr- (Mueller & others, 1991) radiogenic isotope data for involvement of fluids and solutes from the underlying felsic crust and/or granitoids derived from it. Of particular importance is the observation that there is regional scale variation in the Pb-isotopic compositions of ore-related sulfides, and that there is a complementary variation between these compositions and the initial Pb-isotopic ratios of neighbouring crustally derived rocks, implying derivation of Pb in ore fluids from the crustal segment underlying the deposits (McNaughton & others, 1990). Ridley (1990) argues that the wallrock alteration assemblages in gold deposits are consistent with formation from a fluid of a composition that best fits equilibration with, or derivation from, a rock of broadly granitic composition.

Thus, the majority of radiogenic isotope and thermodynamic data favour either derivation of the deeply sourced ore fluid from granitic magmas or equilibration of a fluid derived from even deeper levels (e.g. subduction zone or overlying wedge; Barley & others, 1989) with granitoids, but cannot distinguish between these two possibilities. Magmas crystallizing at mid-crustal depths may evolve low-salinity fluids without the extensive release of mechanical energy. To date, granitoids of an appropriate age have been identified dominantly in the higher-grade Western Gneiss Terrane and adjacent Southern Cross Province, in areas remote from mineralisation (Hill & others, 1992). Granites of the appropriate age intimately associated with mineralisation have been perhaps recognised in the Murchison Province (Wang & others, submitted). For a lower crustal- or mantle-derived fluid, a potential problem is its transfer through a crust at temperatures above the granite water-saturated solidus without causing partial melting with incorporation of the fluid into a melt (e.g. Ridley, 1990).

It should be emphasised that, although the primary, deeply-sourced ore fluid (the fluid common to all deposits) is interpreted to be largely derived from, or to have interacted with, granitic rocks below the greenstone belts, some stable isotope data implicate other sources for at least part of the fluid components. This would be expected from a crustal-scale hydrothermal system in which deeply sourced, ore fluids infiltrated the upper granitic crust and greenstone belts on their passage to dominantly greenstone-belt depositional sites.

Involvement of surface water

The possibility that either meteoric water or sea-water was a component of the upper-level hydrothermal system is raised by the recognition that some deposits are hosted by brittle structures and are sited in lower- or sub-greenschist settings. Both Gebre-Mariam & others (submitted) and Hagemann & others (submitted) provide stable isotope evidence for the involvement of surface waters in the upper levels of the proposed giant hydrothermal systems, but evidence is lacking for their presence at deeper levels. This may have implications for the geochemistry and mineralogy of deposits formed at these relatively high crustal levels.

Tectonic settings of mineralisation

Constraints on the tectonic setting of mineralisation may be available from its timing relative to the major regional metamorphic event at different levels of the crust. The available absolute-age data on gold deposits, combined with Pb model-age data, suggest that mineralisation was synchronous across the Yilgarn Block, yet it was apparently post-peak metamorphism, at least for many deposits, at relatively high crustal levels (<low-amphibolite grade domains), but syn-peak metamorphism at deeper crustal levels (>low-amphibolite grade domains). This suggests that peak metamorphism was diachronous within the greenstone terranes across the Yilgarn Block. It is possible to explain the earlier timing of peak metamorphism at upper crustal levels if crustal thickening occurred through structural (thrust) repetition (England & Thompson, 1984), but there is no evidence preserved of medium- to high-pressure metamorphic assemblages that might be expected in an overthrust terrain. It is possible that the presently preserved metamorphic assemblages record only the highest T portion of the P-T path due to the late domal emplacement of voluminous granitoids into the terrain. Alternatively, the terranes may be recording two (or more) metamorphic events, an early sea-floor metamorphism and/or regional metamorphism related to the same thermal event that induced the uprise of the voluminous anatectic granitoids. If so, gold mineralisation was related to the second, granitoid-related metamorphic event.

The gold mineralizing event is clearly an integral part of the late-tectonic evolution of the granitoid-greenstone belts, but lack of a comprehensive understanding of this tectonism currently limits complete resolution of the genesis of the late-Archaean lode-gold deposits. In Archaean terranes, it may always be difficult to define the precise mechanism(s) which triggered craton-wide gold mineralisation, and analogies may have to be made with more recent examples. For example, Goldfarb & others (1991) have shown that extensive Eocene gold mineralisation in Alaska coincided with a change in plate motion which caused a shift from convergent to partly transcurrent tectonics, and such a change may be evident in the structural record of the Archaean granitoid-greenstone terranes, for example, in the reactivation of earlier structures and/or the change from one structural regime to another during mineralisation.

Part II: Descriptions of individual gold deposits and their regional settings

Maps showing the deposits and major features of the areas to be visited are Fig. II.1 (Southern Cross) and Fig. II.4 (Coolgardie, Kambalda, New Celebration, Kanowna and Mount Pleasant). Figure II.4 also shows the approximate position of metamorphic isograds in this segment of the Norseman–Wiluna greenstone belt.

Gold mineralisation in the Southern Cross greenstone belt, Yilgarn Block, Western Australia

E.J.M. Bloem, H.J. Dalstra and N.M. Edwards

The Southern Cross greenstone belt between Marvel Loch and Bullfinch (Fig. II.1) is a narrow, highly deformed greenstone band. To the east is the Ghooli Dome, a granitic diapiric intrusion, deformed along its eastern and western margins: to the west the Rankin Dome. The greenstone belt comprises dominantly tholeiitic and high-Mg basalts and komatiites together with banded iron formations overlain by younger sequences of terrigenous sediments. Quartz-rich sandstones, possibly unconformable on adjacent granitoid, locally occupy the base of the succession (Gee & others, 1982).

Regional structural and metamorphic geology of the Southern Cross greenstone belt

The Southern Cross greenstone belt has been affected by overlapping metamorphic, deformational, and granitoid emplacement events. Although the structures in the area can be explained by a progressive deformation event (Bloem & others, submitted), a subdivision of this event into substages D_1, D_2 and D_3 is made:

- D_1: upright folding.
- D_2: an early dominantly east-west flattening stage and a late dominantly shearing stage.
- D_3: ongoing dextral shearing, oblique (reverse/thrust-dextral) shearing and brittle faulting and kinking, during retrograde metamorphism.

A regional scale D_2 shear zone, the Fraser's-Corinthia shear zone, runs along the eastern contact of the greenstone belt north and south of Southern Cross. Within this shear zone, rocks are strongly foliated and in part mylonitic over 500 m to 1 km across strike width. Folded quartz veins, both sub-horizontally and sub-vertically boudinaged quartz-veins, boudinaged banded iron formation (BIF) and boudinaged aplitic dikes at Hopes Hill, and quartz c-axes indicate a strong flattening component perpendicular to the granitoid-greenstone boundary (Bloem & Ridley, 1991). The strong flattening component is considered related to syn-tectonic diapiric intrusion of surrounding granitoids. Despite the dominant flattening, rotated porphyroblasts and a displaced aplite dike at Corinthia suggest an overall sinistral movement along the Fraser's–Corinthia shear zone.

Low to mid-amphibolite facies metamorphism accompanied D_1 and D_2 deformation (Bloem & others, 1992). The presence of andalusite around Southern Cross (Ahmat, 1986), geothermometry based on garnet-biotite at Golden Pig and Hopes Hill, garnet-cordierite from Hopes Hill, and amphibole-plagioclase from Hopes Hill, Corinthia, Polaris South and Fraser's, and fluid inclusion isochores yield consistent P-T estimates of 530-580°C and 300 to 400 MPa for peak metamorphism around Southern Cross. It is also evident that metamorphic temperatures decrease from south to north: peak metamorphic conditions at Corinthia were, based on garnet-biotite and garnet-cordierite geothermometry, roughly 500°C. Metamorphic assemblages at Copperhead indicate metamorphic temperatures less than 500°C.

Gold mineralisation in the Southern Cross greenstone belt

For a summary of the characteristics in the major deposits in the Southern Cross to Bullfinch segment of the Southern Cross greenstone belt see Table II.1.

Lode-gold deposits in this belt occur predominantly within the volcanic-dominated greenstone sequences, the majority of significant deposits being along the eastern margin of the belt, particularly within the Fraser's–Corinthia shear zone. Within the belt as a whole two major types of structural setting are recognised for lode-gold deposits and associated alteration envelopes: fold-hinge zones (e.g. Copperhead and Golden Pig deposits) and shear-zone dominated (e.g. Polaris South, Fraser's, Hopes Hill and Corinthia). Within fold-related gold deposits, the most common host rocks are Banded Iron Formation (BIF), within shear zone dominated deposits, host rocks are variable, but predominantly mafic and ultramafic vol-

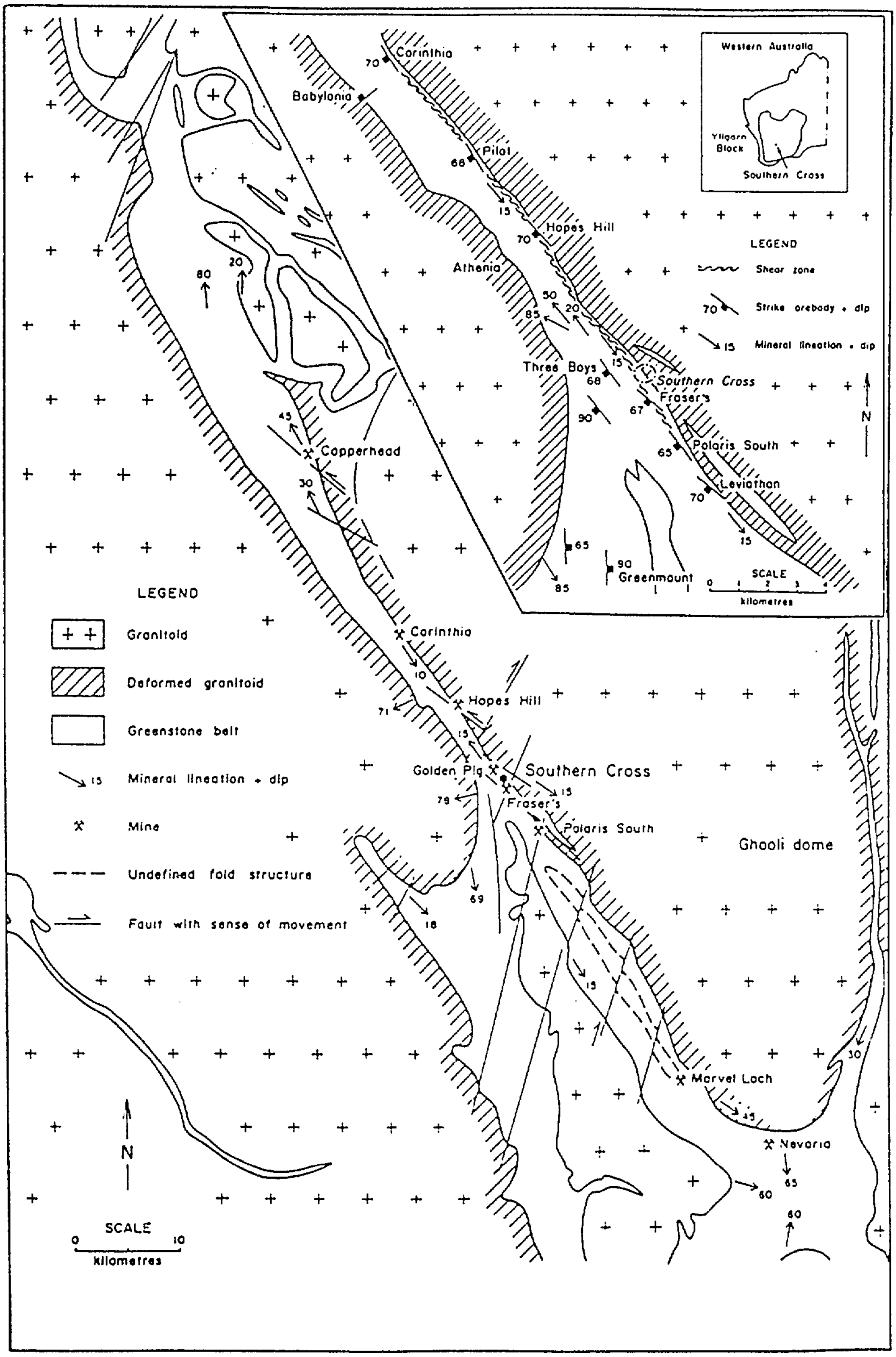

Fig. II.1. Overview of the Southern Cross greenstone belt. The inset shows the Fraser's-Corinthia shear zone in the area around Southern Cross, and the dip and strike of the lodes in the main lode-gold deposits.

canic rocks, but include graphitic micaceous schists at Transvaal.

Gold mineralisation occurred predominantly during D_2. Mineralisation along the Fraser's–Corinthia shear zone for instance is controlled by subtle variations in the strike of the shear zone, and occurs in *en echelon* quartz veins, with lodes subparallel to the S_2 foliation and shoots parallel to the generally shallowly plunging L_2 mineral lineation. At Fraser's, lodes both follow, and are cut by extensional crenulation cleavages (ECC's, e.g. Platt & Vissers, 1980), which formed late within the D_2 de-

Deposit	Production	Host lithologies	Dominant structure	Alteration assemblages	Ore minerals
Copperhead	24.5 t Au	dolerite, BIF	tight folds	distal: bio-chl-act proximal: qtz-dol-cal	py-po-gn-cpy -Au
Corinthia	2.5 t Au	Tholeiitic & komatiitic basalts, BIF	sinistral strike slip + reverse 320°/70°	distal: act-bio-po proximal: trem-cal-qtz±pl±ap	po-cpy-py± apy±mo±sch ±Au
Hopes Hill	4.5 t Au	Tholeiitic & komatiitic basalts, sedimentary rocks	sinistral strike slip + reverse 320°/70°	distal: tsch-bio-po proximal: dio-cal-qtz±pl±ap	py-po-cpy± apy±sch
Fraser's	12.0 t Au	Tholeiitic & komatiitic basalts	dextral-reverse oblique-slip 330°?65°	distal: act-bio-po proximal: dio-cal-qtz±pl	py-po-cpy-gn -sch±apy-Au
Polaris South	4.0 t Au	Tholeiitic & komatiitic basalts	unknown 330°?70°	distal: act-bio-po proximal: dio-cal±qtz	py-po-cpy± apy±Au

Abbreviations: Alteration minerals: act=actinolite; ap=apatite; bio=biotite; cal=calcite; dio=diopside; pl=plagioclase; qtz=quartz; trem=tremolite; tsch=tschermakitic hornblende

Ore minerals: apy=arsenopyrite; Au=native gold; cpy=chalcopyrite; gn=galena; mo=molybdenite; po=pyrrhotite; py=pyrite; sch=scheelite

Note that host lithologies are metamorphosed to upper greenschist-amphibolite facies

TABLE II.1. Characteristics of major lode-gold deposits in the Southern Cross–Bullfinch area.

formation of the shear zone. Extensive calcite-diopside-quartz and biotite-pyrrhotite alteration occurred during gold deposition (D_2), indicating similar to slightly lower temperatures during gold deposition as for peak metamorphism (Mueller, 1988; Bloem & others, submitted).

Polaris South gold deposit

E.J.M. Bloem, P. Woodman and N.M. Edwards

Polaris South is located along strike to the south-east of Fraser's (described in Dale & Thomas, 1990; Barnicoat & others, 1991), and is hosted by the same sequence of mafic and ultramafic rocks with minor sedimentary intercalations. The granitoid-greenstone contact is located about 250 m to the east. Metamorphic grade is of lower-amphibolite facies. Gold mineralisation is associated with extensive pyroxene-calcite-sulfide alteration (compare with Wilson, 1953; Mueller, 1988), which is syn- to post- peak-metamorphic and associated deformation, indicated by microstructural evidence for timing of alteration mineral growth, similar metamorphic and metasomatic temperatures, and the high thermodynamic variance (low number of phases). Only minor quartz veins are present.

Lithologies and metamorphism

A cross-section of the deposit is shown in Figure II.2. Polaris South is located entirely within greenstones. The Units shown in Figure II.2 have, based on hand specimen descriptions together with trace element analysis, the following characteristics:

- Units 1 & 4: tremolite-chlorite schists (komatiitic basalt)
- Unit 2a: para-amphibolite (sedimentary units with channel-structures?: younging to the east)
- Unit 2b: actinolite schist
- Units 3, 5, 6, 8, 9, 10 & 11: actinolite schist (tholeiitic basalt)

Along the hanging wall, unaltered banded iron formation is present.

Amphibolite-facies metamorphism affected all host rocks. Geothermobarometry performed in the area around Southern Cross, including amphibole-plagioclase geothermometry at Polaris South, suggest peak metamorphic temperatures around 550°C.

Structures

The main foliation dips 65° southwest, and a mineral lineation plunges shallowly south. The host rocks and main foliation are subparallel to the strike of the ore-body. Ore-shoots are subparallel to mineral lineations and have a consistent down-plunge continuation.

Alteration and associated gold-mineralisation

Two distinct alteration zones with associated gold-mineralisation are present at approximately 35 m apart. The western alteration zone is approximately 15 m across, the eastern about 25 m.

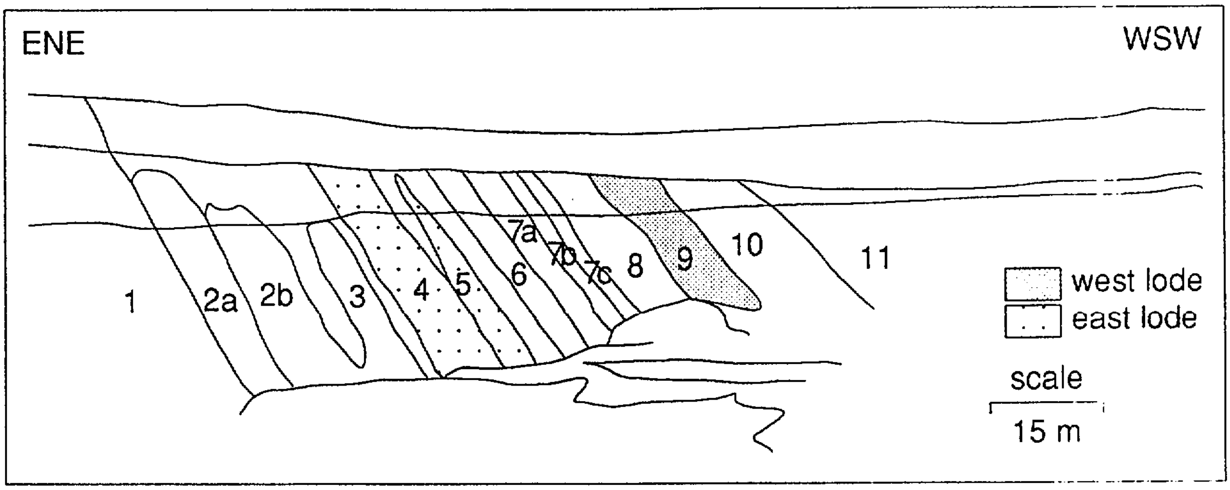

Fig. II.2. Cross-section of the upper-part of Polaris South open cut viewed to the southeast. The east-lode is located on the boundary of mafic (Unit 5) and ultramafic (Unit 4) schists. The west lode is located entirely within mafic schists (Unit 9).

The western alteration zone is hosted by mafic and ultramafic rocks (Units 4 & 5), the eastern zone is entirely hosted by mafic schists (Units 9 & 10). Gold mineralisation is directly associated with diopside-calcite-quartz-pyrite-pyrrhotite veining and wallrock sulfidation.

The mafic units (Units 5, 9 & 10) are extensively altered, characterized by diopside-calcite ± quartz ± plagioclase ± apatite ± titanite and massive pyrite-pyrrhotite ± quartz veining, together with alteration haloes of biotite-pyrrhotite several cms into the host rocks. Veins vary in size (0.1-50 cm width). Unit 2 exhibits minor biotite-pyrrhotite veining.

Altered ultramafic rocks (Unit 4) are characterized by extensive silicification. Diopside-calcite-quartz ± pyrrhotite ± pyrite veining is present, with inner alteration haloes of diopside-tremolite and outer alteration haloes of sericite-pyrrhotite extending several cms into the host rock, and overgrowing metamorphic chlorite. Carbonatization of ultramafic host rocks is also present (Unit 4).

Equilibrium between tremolite-calcite-quartz-diopside suggests temperatures during alteration and associated gold-mineralisation around 500°C, just below or close to peak metamorphic temperatures.

The Copperhead gold deposit

H.J. Dalstra

The Copperhead gold deposit is located approximately 1 km east of Bullfinch in the Southern Cross greenstone belt, approximately 150 m from the granitoid-greenstone contact (see Carter & Grayson, 1990). Total production from both open-pit and underground mining in the period between 1910 and 1960 was 20 tonnes of gold. Rejuvenated open-pit mining by Burmine Ltd from July 1989 has produced over 3.5 tonnes of gold. The Copperhead deposit is the largest gold producer in the Southern Cross greenstone belt.

Two major orebodies have been mined, historically referred to as the "Northern Series" and "Southern Series" orebodies (Fig. II.3). These two ore environments are separated by a weakly mineralised area which is historically referred to as the "Saddle Area". Mineralisation in the Southern Series is hosted by two units of Banded Iron Formation (BIF) which are metasomatised into massive quartz-actinolite-pyrite-chlorite-magnetite ± siderite ± marcasite ± native gold rocks (Fig. II.3). Mineralisation in the Northern Series is hosted by predominantly coarse grained mafic rocks (metadolerite) which are metasomatised into actinolite-plagioclase - dolomite-calcite-biotite-chlorite-pyrite-pyrrhotite ± galena ± native gold rock (historically referred to as the dolomite lode). Very high gold grades in the Northern Series occur in thin discontinuous BIF levels adjacent to the main dolomite lode with similar metasomatic imprints as the BIF's of the Southern Series. Mineralisation in BIF occurs throughout the rocks in disseminated sulfides which replace magnetite. Mineralisation in the mafic host rocks is hosted by meso-scale veins with varying orientations and in disseminated sulfides in the host rock itself. Alteration assemblages and metamorphic mineral assemblages indicate peak metamorphic conditions in the lower-amphibolite facies and slightly retrograde conditions during gold mineralisation (below 500°C).

Structural setting

The Copperhead deposit is located in the core of a regional, map scale D_1 synform in an area of relatively low strain. The major ore shoots

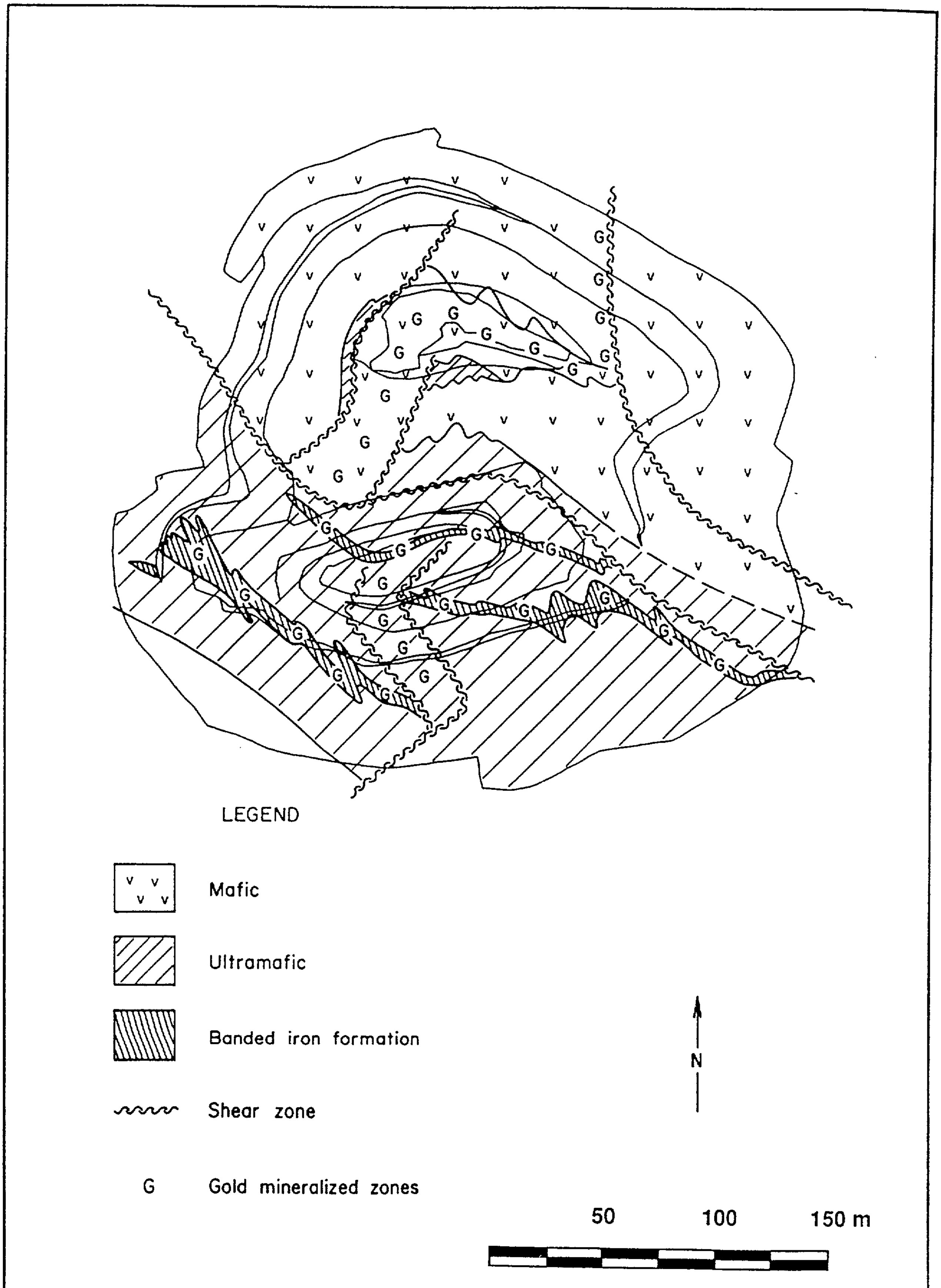

Fig. II.3. Simplified geological map of the Copperhead open pit, showing the major lithological units, structures, and locations of the important orebodies.

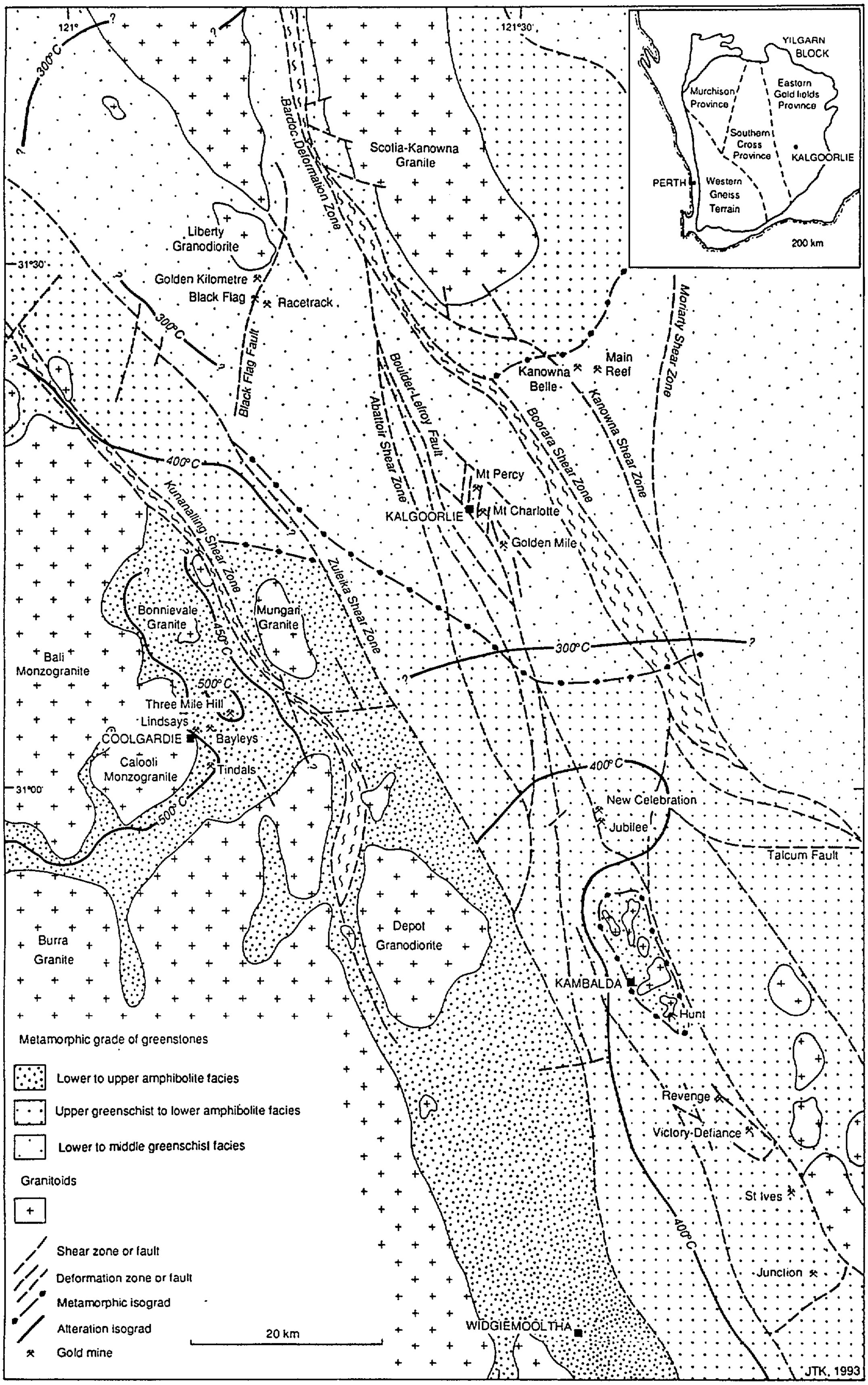

Fig. II.4. Metamorphic and tectonic map of the Coolgardie-Kalgoorlie-Kambalda segment of the Norseman-Wiluna greenstone belt. Independent isograds are shown for the peak conditions of regional metamorphism and for the temperature of gold-related alteration determined at each gold deposit, though note that there is a broad parallelism of the two isograd sets. Metamorphic and alteration data from the work of Binns & others (1976), Witt (1991) and Knight & others (1993). Figure from Knight (in prep, 1993).

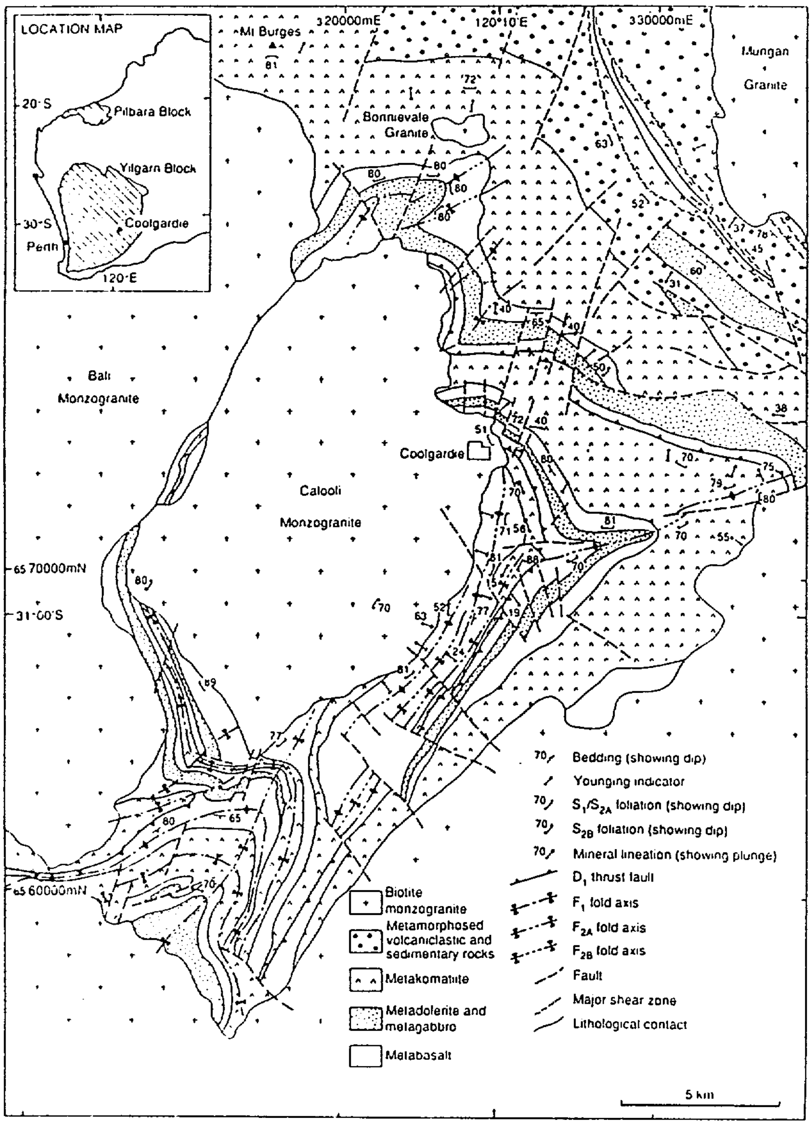

Fig. II.5. Interpretive geology of the Coolgardie Goldfield.

plunge subparallel to the D_1 fold axes (311/41) and the mineral and stretching lineations (283/48). Ore shoots occur en-echelon in D_1 drag folds on the major synform. Later (D_2) ductile northwest-trending shear zones follow the limbs of D_1 folds, and are host to minor, but high grade mineralisation. Shear indicators and en-echelon quartz veins indicate dextral-normal movement sense on these shear zones.

Gold mineralisation was reactivated in northeast-trending brittle-ductile reverse D_3 faults which cross-cut the two lode systems. Remobilisation of the gold along these faults resulted in significant amounts of mineralisation in the Saddle Area. These faults are only mineralised in the mine environment.

Discussion

Gold mineralisation in the Copperhead deposit was an integral part of the regional folding and shearing event. Mineralisation took place late in D_1 and possibly during tightening of D_1 folds during D_2 shearing. The strong lithological control on mineralisation in addition to the structural controls suggests that fluid-wallrock reactions played an important role in depositing gold in previously prepared structural sites.

The high-temperature Archaean lode-gold deposits of the Coolgardie area

J.T. Knight and P. Batten

Regional setting

The amphibolite-facies Coolgardie Goldfield is located at the western margin of the approx. 2700-2690 Ma volcano-sedimentary sequence of the Norseman–Wiluna Belt, 560 km east of Perth and (<40km southwest of the giant greenschist-fa-

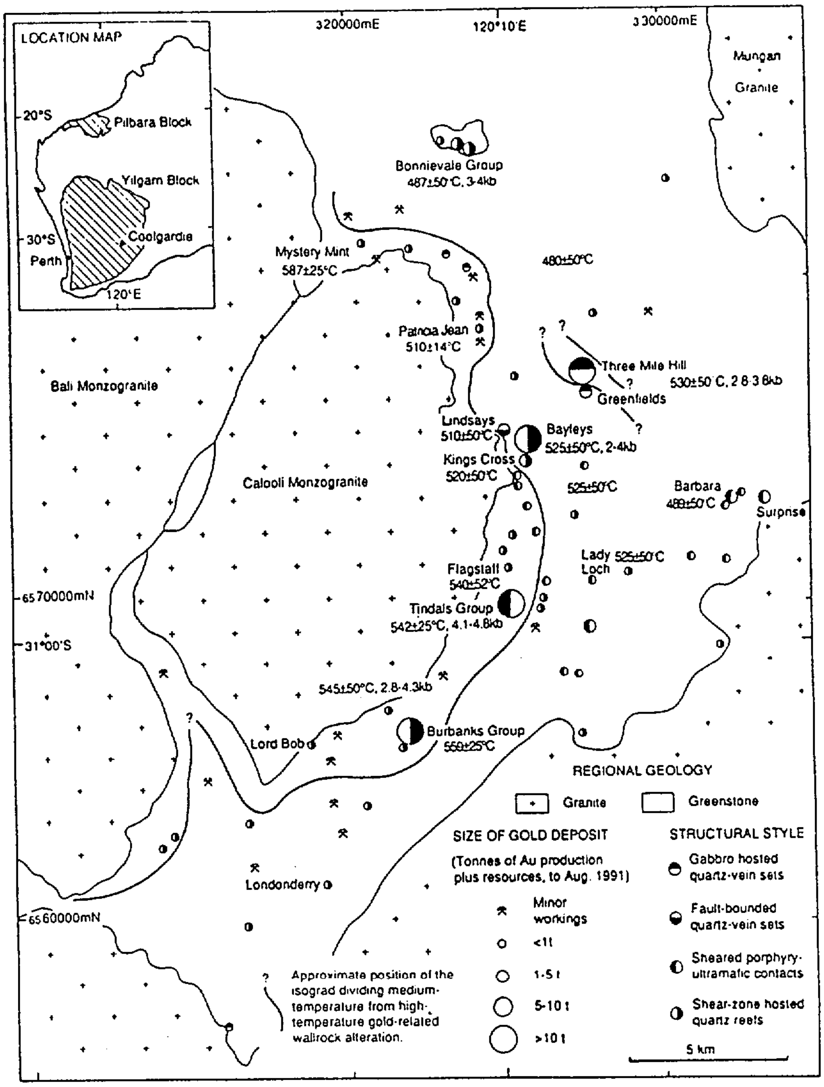

Fig. II.6. Structural style and production data for significant deposits of the Coolgardie Goldfield. Also shown is the position of an isograd (the garnet-in isograd), which separates high- and medium-temperature gold-related wallrock alteration assemblages.

cies lode-gold deposits at Kalgoorlie. The Goldfield covers 900 km^2 (Figs. II.5 and II.6), was discovered in 1892, and has since produced >50 t Au and 0.25 t Ag.

The Coolgardie Goldfield lies in the Coolgardie Domain of the Kalgoorlie Terrane, Eastern Goldfields Province (terminology after Swager & others, 1992). At Coolgardie, the stratigraphic sequence consists of a lower pillowed low- to high-Mg basalt unit, overlain by a porphyritic basalt horizon and a thick sequence of spinifex-textured komatiites. At the top of the succession is a series of felsic volcanic and sedimentary rocks. The lower basalt unit has been intruded by a synvolcanic differentiated gabbro sill, and thin interflow sedimentary rocks occur throughout the mafic-ultramafic units. The sequence at Coolgardie has been intruded by a suite of felsic and mafic porphyries, and is bounded to the west by the syn-tectonic Bali and Calooli Monzogranites, to the east by the post-tectonic Mungari Granite, and to the south by the Burra Granite. Significant gold mineralisation is hosted by all rock types in the greenstone belt, but is concentrated in the lower part of the sequence.

Country rocks at Coolgardie have been metamorphosed to the low- to mid-amphibolite facies. In mafic rocks, the typical equilibrium assemblage is hornblende-plagioclase (An>35)-ilmenite, and in ultramafic rocks the assemblage consists of tremolite-chlorite-talc-carbonate, with minor anthophyllite and forsterite. Silicate geothermometry indicates that peak metamorphic temperatures reached 480°C in the east of the Goldfield. Metamorphic grade increases westwards towards the Calooli Monzogranite, with temperatures of 525°C attained in the centre of the Goldfield, and maximum peak-metamorphic conditions of 545°C and 280-340 MPa recorded proximal to the western granitoid-greenstone contact (Fig. II.5).

The repetition of the lower part of the stratigraphy across the Coolgardie area (Fig. II.5), together with the presence of a layer-parallel fabric and consistent northeast-younging across the central and northern part of the region, is interpreted to be the result of D_1 low-angle thrusting. Four different sets of post-D_1 structures occur in the Coolgardie Goldfield. These are:

- north- to northeast-trending, doubly-plunging, tight to isoclinal folds,
- northeast- to east-trending, steeply-plunging folds,
- northeast- and northwest-striking brittle-ductile shear zones, and
- east-striking sinistral brittle-ductile shear zones.

Post-D_1 structures tend to be domainal with respect to the western granitoid bodies, have associated fabrics defined by peak metamorphic minerals (and therefore formed under similar P-T conditions), and have a broadly constant orientation of the regional stress field inferred from each set of structures; features which indicate that these structures formed during a single progressive deformational event.

Gold deposits of the Coolgardie camp

Archaean lode-gold deposits in the Coolgardie Goldfield occur as laminated quartz reefs (Bayleys, Kings Cross), narrow brittle-ductile shear zones sited along porphyry-ultramafic rock contacts (Tindals), fault-bounded quartz vein sets (Lindsays), and gabbro-hosted quartz vein sets (Three Mile Hill). They are located in each of the four sets of post-D_1 structures. In deposits associated with structures of each deformation event, textural evidence, which includes:

- a correlation between the intensity of strain and the degree of development of hydrothermal alteration,
- the definition of fabrics by hydrothermal silicate and sulfide minerals,
- ore-shoots which plunge parallel to stretching lineations, and
- the preservation of auriferous veins, sulfide minerals and alteration haloes with varying degrees of deformation, indicates that mineralisation was syndeformational.

Two different styles of gold-related wallrock alteration can be recognised at Coolgardie. These can be classified into:

- a high-temperature group consisting of garnet-hornblende-plagioclase-calcite-chlorite-K feldspar, with pyrrhotite and minor sphalerite, and
- a medium-temperature group characterised by calcic amphibole-biotite-plagioclase and calcite, with abundant arsenopyrite and pyrrhotite.

The medium-temperature group formed at temperatures of 480-520°C in the central and eastern margins of the Goldfield. In contrast, the high-temperature group formed at 520-590°C at the western margin of the Goldfield. The spatial distribution of these two wallrock alteration styles is controlled by plan-view distance from the western granitoids, with the high-temperature group located more proximal to the granitoid contact (Fig. II.6). Equilibrium textural relationships between high-temperature silicate phases, sulfide minerals, and native gold, the low number of silicate minerals in proximal alteration zones, and stable isotopic evidence discussed elsewhere (Knight & others, 1993), indicate that the deposits of the Coolgardie Goldfield formed in an open-system, at, or near to, peak metamorphic conditions. Furthermore, the correlation between the temperature of mineralisation and distance from the western granitoids suggests that gold deposition was broadly synchronous with granitoid emplacement (compare with Witt, 1991).

The object of this part of the excursion is to examine the different structural and wallrock alteration styles of amphibolite-facies gold deposits in the Coolgardie camp, and to compare and contrast these deposits both with the higher temperature deposits in the Southern Cross greenstone belt and with the greenschist-facies deposits at Kambalda, Mt Pleasant, and Kanowna Belle. The Coolgardie deposits represent the highest temperature gold deposits exposed in the Mt Pleasant–Kambalda–Coolgardie area: the characteristics of individual deposits are summarised in Table II.2.

Bayleys

The Bayleys deposit is located 1.5 km north-northeast of Coolgardie, was discovered in 1892, and has since produced about 10 t of gold from underground mining operations (see N. Swager, 1990). The mine stratigraphy consists of a steeply northeast-dipping, fine-grained pillowed basalt unit (hornblende-plagioclase-ilmenite rock) overlain by a thin (<5m) discontinuous black shale layer and fine to medium grained tremolite-chlorite-talc-carbonate schists (metamorphosed komatiites). Quartz-feldspar porphyry sills (<10m thick) have intruded the sequence along the black shale horizon. Peak metamorphic conditions in unaltered wallrocks at Bayleys reached the low amphibolite facies (525°C, 300 MPa).

Mineralisation at Bayleys is hosted by thin (<2m, average thickness 0.5-1 m) but continu-

DEPOSIT	PRODUCTION	HOST ROCKS (METAMORPHIC GRADE OF HOST ROCKS)	STRUCTURAL CONTROLS	PRINCIPAL PROXIMAL ALTERATION MINERALS	ORE MINERALOGY	P-T CONDITIONS OF MINERALISATION
BAYLEYS	558,551 t ore @ 15.58g/t, 8700 kg Au (to April 1991)	Quartz-feldspar porphyries, black shale, komatiites and pillowed basalts (525°C, 300MPa)	Laminated quartz reefs sited in steeply dipping brittle-ductile shear zones trending 320°.	Magnesio hornblende-plagioclase-calcite-quartz-biotite-titanite-Mg chlorite-talc	Sulphides: arsenopyrite-pyrrhotite-chalcopyrite-galena Oxides: scheelite	525°C, 300 MPa (silicate and sulphide geothermometry)
KINGS CROSS	216,415t ore @ 5.08g/t, 1099kg Au (to April 1991)	Pillowed high-Mg basalts (525°C, 300MPa)	Continuous laminated quartz reef sited in an oblique-reverse brittle-ductile shear zone trending 70°/190°	Magnesio hornblende-plagioclase-biotite-calcite-quartz	Sulphides: arsenopyrite-pyrrhotite-sphalerite-chalcopyrite Oxides: scheelite	520°C (silicate and sulphide geothermometry)
LINDSAYS	326,435 t ore @ 3.78g/t, 1234 kg Au (to April 1991)	Pillowed basalts and minor interflow sedimentary rocks (520°C, 300MPa)	Discontinuous northeast- and northwest-trending quartz veins sited in narrow brittle-ductile shear zones, bounded by two steeply dipping northeast-trending dextral shear zones.	Magnesio-actinolitic hornblende-plagioclase-quartz-biotite-calcite-titanite	Sulphides: arsenopyrite-pyrrhotite-chalcopyrite Oxides: scheelite-ilmenite	510°C (silicate and sulphide geothermometry)
THREE MILE HILL	1,850,000 t ore @ 2.09 g/t, 3877 kg Au (to May 1993). RESERVES: 2,180,000 t ore @ 2.9g/t.	Differentiated gabbro sill (510°C, 300MPa)	Shallowly (<30°) north west-dipping brittle quartz veins sited on the limbs of a major northeast-trending fold	Ferro hornblende-tschermakite-plagioclase-quartz-calcite-almandine garnet-Fe chlorite-biotite	Sulphides: arsenopyrite-pyrrhotite-chalcopyrite-galena. Oxides: scheelite-ilmenite	530°C, 330 MPa (silicate and sulphide geothermobarometry, fluid inclusions)
TINDALS	917,678 t ore @ 4.74 g/t, 4350 kg Au (to May 1993)	Komatiites intruded by dolerite, gabbro and quartz-feldspar porphyry sills (545°C, 360MPa)	Narrow (<20m) oblique-dextral brittle-ductile shear zones located along subvertically-dipping, north-striking sill-komatiite contacts	Ferro hornblende-plagioclase-calcite-almandine garnet-quartz	Sulphides: pyrrhotite-sphalerite-chalcopyrite-pyrite. Oxides: scheelite-magnetite-ilmenite	542°C, 360 MPa. (silicate and sulphide geothermobarometry)

Note. Standard error on temperature calculations quoted in the text and this table is 50°C, and 100 MPa for pressure estimates.

TABLE II.2. Production and geological characteristics of significant mines in the Coolgardie Goldfield. Production data obtained from unpublished company reports.

ous, laminated to bucky quartz reefs sited in steeply (>70°) northeast-dipping, brittle-ductile shear zones which are developed parallel to stratigraphy along black shale horizons. Microstructures and a well-developed L-S tectonite fabric within the shear zone indicate oblique-reverse movement. Mineralised quartz reefs parallel the shear-zone schistosity, are boudinaged along strike and down-dip, and are locally folded about northwest-trending axes.

The reefs are characterised by bucky to laminated quartz with stylolites. Individual laminae are defined by inclusions of wallrock (normally graphite), sulfides (arsenopyrite, pyrrhotite, and sphalerite), and hydrothermal silicates (amphibole, biotite, and chlorite); native gold grains are preferentially sited along these laminae. Proximal alteration at Bayleys consists of rhythmically banded amphibole-biotite-calcite-plagioclase-quartz-titanite rock, with centimetre-scale zones alternately rich in biotite and amphibole. The main sulfide minerals are pyrrhotite and arsenopyrite, with minor sphalerite, galena, and chalcopyrite. Scheelite is a common accessory mineral. Medial and distal alteration zones are poorly developed or absent, and the total width of the alteration halo is normally <10 m. The P-T conditions of mineralisation, 525°C, 300 MPa, indicate that gold deposition was synchronous with peak metamorphism.

The Bayleys reefs are cross-cut by several steeply (70°) west-dipping, northeast-striking, oblique-reverse, brittle-ductile shear zones, which have plan-view dextral offsets of tens of metres. One of these faults, the Kings Cross Fault, is the host to a shear foliation-parallel, boudinaged and laminated auriferous quartz reef, which is developed within the lower basalt unit. The Kings Cross orebody has similar alteration and sulfide minerals as Bayleys, and therefore, formed under the same metamorphic conditions.

Lindsays

Lindsays open pit is located 1.5 km north of Coolgardie and 1 km west of Bayleys and Kings Cross. The deposit is hosted by fine grained, massive pillowed basalts, which contain the metamorphic assemblage magnesio hornblende-plagioclase (An28-35)-ilmenite, indicative of the low amphibolite facies (520°C). Thin (<10m), boudinaged and strongly foliated black pyritic shale units, which occur in the southern part of the pit, dip 70-80° to the northeast and represent interflow sedimentary rocks. Gold mineralisation at Lindsays is spatially controlled by two major northeast-trending shear zones, the Lindsays and Hillside Faults, which have apparent dextral offsets of 200 m and 500 m, respectively. Native gold occurs in 0.1-0.5 m thick, laminated to bucky quartz veins sited in multiple, narrow brittle-ductile shear zones, which are bounded by the unmineralised Lindsays and Hillside Faults. Individual shear zones have intense, but highly localised, fabrics, which parallel vein margins. Unstrained and visibly unaltered basalt occurs between the mineralised shears.

The orientation of the mineralised structures is highly variable, and individual veins trend parallel, sub-parallel, and oblique to the Lindsays and Hillside Faults. However, the main conjugate set of veins dips at moderate to steep angles to the northwest and northeast and strike at acute angles with respect to the northeast-trending, bounding shear zones. The main mineralised structure at Lindsays, the Queens Reef, which dips 70° east and strikes north-south, is a 0.5-0.7 m thick boudinaged and laminated quartz reef located in a brittle-ductile shear zone, with well developed shear fabrics and microstructures which indicate oblique-dextral movement.

At Lindsays, gold occurs in quartz-calcite veins and is associated with coarse euhedral arsenopyrite, massive pyrrhotite, minor chalcopyrite, and minor coarse-grained scheelite. The main silicate gangue minerals are magnesio hornblende, biotite, plagioclase, titanite, and epidote. Quartz veins are commonly rimmed by monomineralic amphibole and calcite and have narrow, laterally-zoned proximal alteration haloes comprising banded amphibole-biotite-plagioclase-calcite-arsenopyrite-pyrrhotite-ilmenite rock, with rare gold. Arsenopyrite commonly defines a vein-parallel foliation and steeply pitching lineation, suggesting syndeformational mineralisation. Medial and distal alteration zones are poorly developed or absent. Where present, these zones are defined by a coarsening of grain size of amphibole and plagioclase, the presence of minor arsenopyrite and biotite, and the replacement of metamorphic ilmenite by pyrrhotite. Silicate and sulfide geothermometry combined with textural evidence, and the low thermodynamic variance of the alteration assemblages, suggests that gold mineralisation was syn-peak metamorphic, and occurred at 510°C.

The Lindsays orebody is cross cut by a set of east-trending, oblique-sinistral brittle-ductile shear zones, which have apparent plan-view offsets of 10-15 m. The largest of these, the Departure Fault, crosses the centre of the pit.

Three Mile Hill

The Three Mile Hill Sill is a 500 m thick differentiated, tholeiitic gabbro sill, which can be traced for 20 km across the northern and central parts of the Coolgardie Goldfield. The sill was intruded prior to deformation within the lower basalt unit, and has been subsequently structurally repeated across the Goldfield by the early thrusting (Fig II.5). The central quartz-rich, granophyric section of the sill, which has the highest Fe/(Fe+Mg) ratio, is host to significant gold mineralisation, including the Greenfields, Patricia Jean, and Mystery Mint deposits. The geology of the largest deposit hosted by this sill, Three Mile Hill, is described below.

At Three Mile Hill, the northwest-trending, subvertically-dipping gabbro body has been divided into mineralised gabbro (G2) and unmineralised gabbro (G3) on the basis of modal mineralogy and grain size (Middleton, 1990). The contact between the two, which is sharp on the northeastern side of the pit but gradational towards the southwest, dips steeply to the northeast. The upper contact between G3 gabbro and the overlying basalt unit, which is exposed in the northwest of the pit, is marked by a thin (<10m) black shale horizon intruded by a quartz-feldspar porphyry. The G2 gabbro unit is 100-150 m thick and, where unmineralised, is generally massive, homogeneous, and consists of the equilibrium assemblage ferro hornblende-plagioclase (An18-30)-ilmenite-quartz with minor garnet. Peak metamorphic temperatures reached the low amphibolite facies (510-530°C).

Three Mile Hill mine is located on the eastern limb of a major northeast-trending, steeply southwest-plunging open anticline. Mineralisation is confined to the G2 gabbro (and can therefore be classified as stratabound), and sited in narrow (<0.5 m), strike continuous (50-100 m) brittle bucky quartz-calcite-amphibole-arsenopyrite-pyrrhotite veins and their associated alteration haloes, which dip shallowly (<30°) to the northwest. Arsenopyrite, the dominant sulfide, is commonly coarse-grained, euhedral and associated with native gold; pyrrhotite is typically coarse grained and massive. Accessory ore minerals include scheelite, chalcopyrite, and galena. Vein silicate minerals include plagioclase-amphibole-titanite and minor biotite. Mineralised veins in the G2 gabbro are mainly undeformed, except they are cross-cut by a set of steeply dipping (60-80°), northeast-trending brittle-ductile shear zones.

Wallrock alteration can be divided into three zones:

- (i) Proximal alteration, characterised by intense bleaching, consists of plagioclase (An0-3), hornblende-calcite-quartz-arsenopyrite-pyrrhotite, with minor almandine garnet, titanite, biotite, and rare native gold. Auriferous quartz veins are commonly rimmed by monomineralic calcite and/or arsenopyrite and pyrrhotite.

- (ii) Medial alteration is characterised by moderate bleaching and a similar assemblage to that which occurs in the proximal alteration zone, except sulfides are less abundant and hornblende is the main silicate phase.
- (iii) Distal alteration appears weakly bleached, contains trace calcite, biotite, arsenopyrite and pyrrhotite, but mainly consists of minerals characteristic of unaltered G2 gabbro.

The transition from unaltered G2 gabbro to a gold-bearing quartz vein can occur on the scale of 10 cm; distal and proximal alteration haloes are often weakly developed or absent. Geothermobarometry and analysis of fluid inclusions in gold-related quartz indicates that gold mineralisation was peak-metamorphic and occurred at about 530°C and 330 MPa. Gold mineralisation at Three Mile Hill is structurally similar to deposits located in other differentiated mafic sills in the Kalgoorlie district (compare with Witt, 1993). However, it has the highest temperature mineralisation of the known deposits hosted by these sills.

Tindals

The Tindals deposit, located 3.5 km south of Coolgardie, was discovered in 1897, and mined underground to 230 m depth until 1944 and by open cut methods from 1986 to 1988 and 1991 to present day (McCormick & Hanna, 1990). Total production is 4.35 t of gold at an average grade of 4.74 g/t. At the Tindals Group, mineralisation is hosted by a series of komatiites, with locally preserved spinifex textures, which are intruded by a suite of metamorphosed quartz-feldspar porphyry and dolerite sills. The intrusions vary in width from 2-40 m, were emplaced along flow boundaries and early foliation planes, and have been subsequently tightly folded about north- to northeast-trending axes. Fold hinges plunge steeply to the north and south, and the sills have been boudinaged along strike and down-dip. The sill-ultramafic rock contacts are steeply dipping (>60°), strongly foliated, and have a steeply-pitching mineral lineation defined by tremolite. Microstructures indicate oblique-reverse movement along these contacts. In unaltered ultramafic rocks, the metamorphic assemblage is tremolite-chlorite-talc-carbonate-magnetite, with rare forsterite, and in the dolerite sills, the assemblage is hornblende-plagioclase-ilmenite, with rare garnets. Peak metamorphic conditions at Tindals reached 545°C and 360 MPa.

Mineralisation at Tindals occurs in extensive brittle to brittle-ductile fractures within the intrusive bodies, with multiple generations of centimetre-scale quartz-calcite veinlets concentrated along contacts, running subparallel and oblique to the main north-south-trending foliation. There is a broad correlation between the intensity of strain, indicated by the degree of development of deformational fabrics, and the intensity of hydrothermal alteration. Gold mineralisation, and its associated wallrock alteration, is concentrated within granophyric, quartz-rich zones of the sills and along sill-ultramafic rock contact zones. Gold occurs in quartz-calcite veinlets, which have narrow alteration zones comprising quartz-albite-calcite-ferro hornblende-Mg chlorite, with minor biotite and garnet. The main sulfide is pyrrhotite, with minor pyrite, chalcopyrite, and sphalerite; scheelite, ilmenite, and accessory magnetite are the main oxide phases. Gold occurs as free grains associated with pyrrhotite, sphalerite, and silicate gangue-minerals. Silicate and sulfide geothermobarometry indicates that mineralisation occurred at 542°C, at a pressure of about 400 MPa, similar P-T conditions to those attained during peak metamorphism.

The gold deposits of the New Celebration—Kambalda district

D.I. Groves

Specific guides to the gold deposits visited on the field excursion will be handed out at the mine sites. The following descriptions of the regional setting and deposit styles are taken from Roberts (for Kambalda) and Cullen and Norris (for New Celebration), both in Groves (1990). Other descriptions of the geological setting are given in Groves & others (1988), and of the individual mining camps by Norris (1990, New Celebration), and Roberts & Elias (1990, Kambalda–St Ives). The district is shown in Fig. II.4.

Regional setting

The New Celebration–Kambalda district, together with Kalgoorlie, lies in the Kambalda Domain of the Kalgoorlie Terrane within the Norseman–Wiluna Belt (terminology after Swager & others, 1992). Stratigraphy can thus be broadly correlated from Kalgoorlie to the Kambalda district but has some minor differences compared to that at Coolgardie. The approx. 2.7 Ga (Claoué-Long & others, 1988) Archaean stratigraphy reflects green-

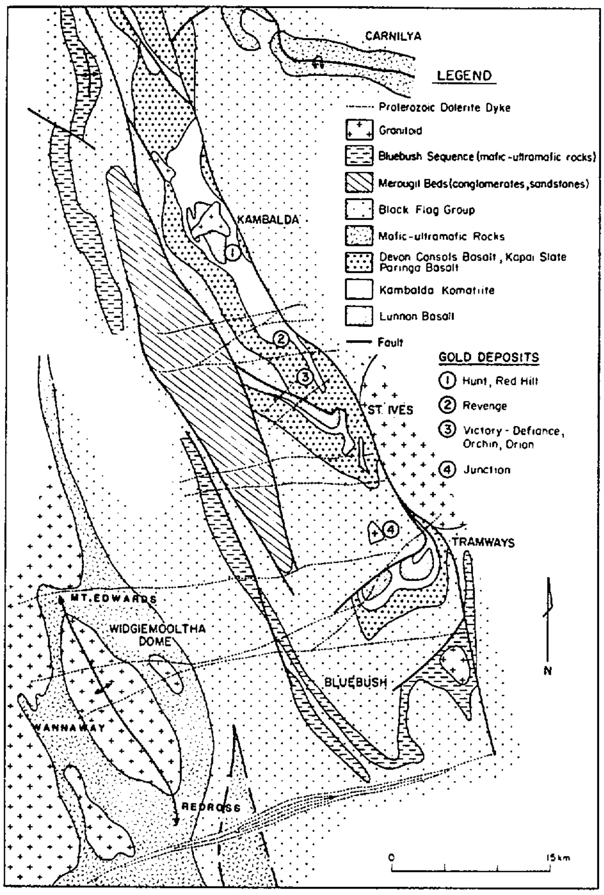

Fig. II.7. Regional geological map of the Kambalda area (from Groves & others, 1988).

stone evolution from tholeiitic basalt, through komatiite and high-MgO basalt, to sequences of felsic volcanic-volcaniclastic and clastic sedimentary sequences. Thick layered mafic-ultramafic sills intrude the high-MgO basalt sequences, and are the host for the giant Kalgoorlie (Golden Mile and Mt Charlotte) deposits as well as many of the deposits in the Kambalda–St Ives–Tramways district and at Pernatty in the New Celebration district: almost 1300 tonnes of gold have been produced from deposits in these sills (Witt, 1993).

The greenstone belt trends north-northwest, with elongate segments of the stratigraphic succession largely bounded by major northwest- to north-northwest-trending shear zones (see Fig. II.4). From an economic viewpoint, the most important of these is the Boulder–Lefroy Fault, which is spatially associated with gold mineralisation at Kalgoorlie, New Celebration, and Kambalda-St Ives–Tramways where the fault bends into a northwest orientation from its north-northwest regional trend. There is debate about the precise deformation sequence in the belt (compare Archibald & others, 1978; Gresham & Loftus-Hills, 1981; Swager, 1989; Swager & Griffin, 1990), such that D_1, D_2, D_3 and D_4 have different connotations in different schemes. However, most authors invoke one or more phases of subhorizontal thrusting and recumbent folding (D_1 of Witt, 1993), followed by a phase of upright regional folding about north- northwest-trending, shallowly plunging fold axes (D_2 of Witt, 1993), either accompanied or followed by a phase of continued regional shortening and sinistral strike-slip to oblique-slip movement on north-northwest-trending shear zones (D_3 of Witt, 1993). Dextral movements on reactivated north- northwest-trending shear zones and development of north- to north-northeast-trending dextral faults are considered the final major late-Archaean structures to evolve in the district (Witt, 1993).

The granitoids have been studied most recently by Witt & Swager (1989) who suggest that they were emplaced during the main phase of upright folding and during the sinistral strike-slip shearing event. There is a broad relationship between higher metamorphic grade domains and the occurrence of syn-deformational granitoid domes exposed in the cores of regional synclines, and regional metamorphism is generally accepted as being synchronous with regional compression at approx. 2.66 Ga, the age of the syn-metamorphic Kambalda granodiorite dome (Compston & others, 1985). The greenstones are floored by granitoids at relatively shallow depth (<10km) as indicated by gravity surveys (Archibald & others, 1978) and seismic reflection surveys (Goleby & others, 1993).

Kambalda Goldfield

The Kambalda Goldfield includes the area between Kambalda and Tramways to the west of the Boulder–Lefroy Fault (Fig. II.7), in an area of transitional greenschist-amphibolite metamorphic grade. In this goldfield, all lithological units in the stratigraphic succession host some gold mineralisation, and there is commonly a close spatial association of mineralisation with felsic porphyry-lamprophyre complexes. However, the thick mafic-ultramafic synvolcanic sills are the best mineralised units, with Witt (1993) estimating 31.5 tonnes of contained gold from the Defiance, Revenge, and North Orchin deposits in the Defiance Dolerite, 32 tonnes of contained gold from the Junction deposit in the Junction Dolerite, and 18 tonnes of contained gold in the Cave Rock deposit in an unassigned dolerite sill: estimates in Roberts (1988) are somewhat higher. The other main host rocks are iron-rich cherty units, for example at Victory. Deposits are mined both from open pit and from underground.

The gold deposits are interpreted to lie in second- and third- order splays off the Lefroy

Fault, several of them essentially flat-lying with the deposits occurring as quartz-vein arrays, breccia zones, and/or central, quartz-rich, mylonitic zones in shear zones: these deposit styles are well illustrated by Clark & others (1986), Roberts & Elias (1990), and Witt (1993). They typify the variety of structures developed at the brittle-ductile transition. All mineralised zones have metasomatic alteration haloes with the alteration minerals overprinting regional metamorphic assemblages (Phillips & Groves, 1984; Clark & others 1986; 1989). The alteration zones result from progressive carbonation and alkali metamorphism, with an outer chlorite-calcite zone enveloping a biotite-ankerite zone with an ankerite-albite-pyrite zone adjacent to a quartz vein, breccia, or high-strain zone within a shear zone. Gold is generally best developed within the pyritic zone, presumably as a result of sulfidation reactions between a low-salinity, H_2O-CO_2 fluid carrying gold as a thiosulfide complex and the Fe-rich (and high FeO/FeO + MgO) wallrocks (Phillips & Groves, 1984; Clark & others, 1989). The late structural timing of gold mineralisation is confirmed by a U-Pb in rutile age of 2627 ± 7 Ma for the wallrock alteration associated with the Victory–Defiance deposit.

New Celebration District

The Hampton-Boulder and Celebration gold deposits occur in, or immediately adjacent to, the Boulder–Lefroy Fault (Fig. II.4, II.8), in an upper greenschist facies metamorphic domain. At the site of the open pits, the zone of intense shearing and high-strain fabrics is over 100 m wide and subvertical in attitude. The shear zone truncates a tight, steeply north-plunging anticline, the Celebration Anticline, with stratigraphic sequences to the east being equivalent to the Kalgoorlie sequence whereas the sequences to the west are poorly exposed (Fig. II.8).

In the Hampton–Boulder ore zones, the mineralisation (>20 t contained Au) is controlled by the distribution of >600 m long by up to 80 m thick quartz-feldspar porphyry body, known locally at the Hampton–Boulder Porphyry. This porphyry, which contains corroded phenocrysts of quartz and albite, dips steeply west and divides a mainly mafic hangingwall sequence from an ultramafic sequence containing thinner felsic porphyry bodies in the footwall. Lamprophyre bodies are also present. Major mineralisation is related to stockworks of quartz-carbonate-pyrite micro-veinlets along the hangingwall and footwall contacts of the brittle felsic porphyry bodies, particularly the Hampton–Boulder Porphyry, producing a series of tabular, steeply

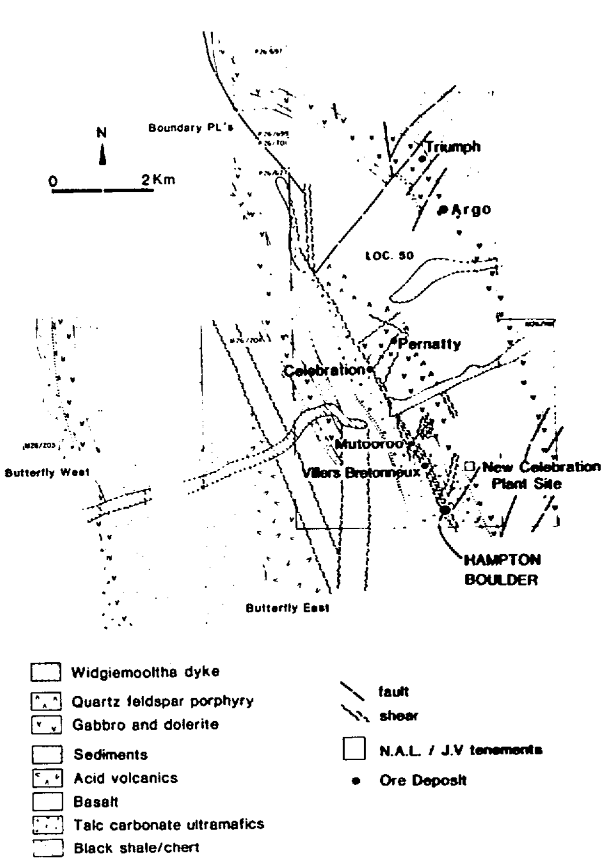

Fig. II.8. Regional geological map showing the location of the Hampton–Boulder gold deposit and other mineralisation in the New Celebration area (from Groves & others, 1988).

west-dipping ore zones in which there are steeply plunging higher-grade ore-shoots. There is pervasive alteration of the porphyry, mainly sericitisation and silicification, with visible gold occurring as microscopic (50 μm diameter grains) in and along the grain boundaries of pyrite. Calcite alteration of the volcanic wallrock is widespread, but economic gold mineralisation is only associated with localized intense quartz-ankerite-pyrite alteration of footwall ultramafic rocks.

The Pernatty deposit (8 t contained Au: Witt, 1993) occurs in shear structures cutting the granophyric quartz-gabbro phase of the differentiated Pernatty Gabbro sill which is also cut by late-stage felsic porphyry and lamprophyre intrusions. Mineralisation occurs within a northeast-trending, steeply north-dipping shear zone (Pernatty Shear), in an east-trending, steeply north-dipping quartz-filled extensional structure (Annamax Zone), and in a complex zone at the intersection of these structures. Wallrock alteration includes silicification, sulfidation and potassic alteration, and Norris (1990) records K-feldspar, biotite, and pyrite as the ore-related alteration assemblage. Gold occurs both within the veins and in their immediate alteration haloes.

Archaean lode gold deposits of the Kanowna Region

A. Ross

The ghost town of Kanowna lies 20 km to the northeast of Kalgoorlie. Gold was first discovered in the Kanowna region in 1893, less than twelve months after its discovery at Kalgoorlie. By 1918, the Kanowna region had produced over 500 000 oz of gold from both alluvial and bedrock sources (Maitland, 1919). Today, just a few kilometres southwest of the old Kanowna townsite, the newly discovered Kanowna Belle gold deposit boasts measured and indicated resources of 2.6 M oz of gold and is open at depth. The following is a summary of the geology, alteration and mineralisation in the Kanowna district, followed by a brief summary of example historical mines and the Kanowna Belle gold deposit.

Regional setting

The gold deposits of the Kanowna district are located within greenschist-facies rocks of the Boorara Domain, Kalgoorlie Terrane of the Archaean Norseman–Wiluna belt. The stratigraphic succession of the Boorara Domain is a lower basalt unit (Scotia Basalt), Big Blow Chert, a komatiite unit (Highway Ultramafics), a discontinuous upper basalt unit, and a felsic volcanic and sedimentary package (Witt, 1990). This upper felsic succession is the Gindalbie Formation as defined by Williams (1970) and is currently correlated with the Black Flag Group of the Ora Banda, Kambalda and Coolgardie Domains. It is this formation that hosts gold mineralisation in the Kanowna district. Stratigraphic subdivision of the Gindalbie Formation in the Kanowna area was attempted by Taylor (1984) but, structural complexities precluded stratigraphic correlations over significant areas.

The structural interpretation map of Kanowna 1:100 000 (Ahmat & Swager, 1992) shows the Kanowna district to be a structural subdomain bounded by the Kanowna shear to the west and the Mt Monger fault to the east. The domain itself is dominated by a monzogranite-cored, southeast-plunging Scotia–Kanowna anticline with the Kanowna gold deposits located on its eastern limb, or on smaller parasitic folds (Grigson, 1981). Earlier thrust faults are folded by the anticline and the rocks are overprinted by an upright foliation striking between 120° and 180°. The structural framework of the Kalgoorlie Terrane by Swager (1989) recognised four deformation events. At Kanowna, the early faults formed during D_1 deformation and resulted in repetition of basalt and ultramafic units in the region. The Scotia–Kanowna anticline is a large upright, regional D_2 fold (Witt, 1990) and the D_3 event is responsible for the ubiquitous steeply dipping to upright foliation. D_4 has not been recognised in the Kanowna area. North-south structural features have been noted, but poor exposure inhibits further interpretation.

Metamorphic grade in the Boorara Domain is lower greenschist facies in the south, but increases to amphibolite facies to the north (Binns & others, 1976). In the region of Kanowna, lower-greenschist-facies metamorphism is indicated by the mineral assemblage: albite-chlorite-actinolite-clinozoisite in metabasalts (Taylor, 1984). Higher metamorphic grade is represented by andalusite in felsic schists 12 km northeast of Kanowna townsite (Taylor, 1984) and mineral compositions of plagioclase (An 22-33: oligoclase to andesine) and amphibole (>9.5 wt % Al_2O_3: hornblende) east of Lindsay gold mine, approximately 25 km north of Kanowna townsite (Hack, 1972).

Gold Deposits of the Kanowna District

Lode-gold deposits in the Kanowna district are hosted by a variety of rock types (Table II.3). These include komatiites, high-Mg basalts, polymict conglomerate, felsic conglomerate, finer-grained epiclastic rocks and intrusive porphyries. No rock type is preferentially mineralised and a rock type that bounds mineralisation at one mine may host mineralisation at another. The control on mineralisation is an interplay of both structure and rheology.

Ho (1984) divided the Kanowna deposits into three distinct styles using the major mineralised structure and rock type. The structural styles are:

- laminated quartz veins
- quartz stockworks and vein arrays
- mineralised alteration haloes in shear zones with subordinate quartz.

In addition to quartz stockworks and vein arrays, hydrothermal breccias (Kanowna Belle, Bonnie Charlie) occur.

Low temperature alteration minerals found in the Kanowna gold deposits include Cr-mica, white mica, ankerite, calcite, albite, and quartz. Variation in proximal alteration minerals between deposits can be accounted for by bulk chemical composition and does not require multiple ore fluids or different pressure and temperature conditions of mineralisation. Adjacent to major fluid

DEPOSIT	PRODUCTION	HOST ROCKS	STRUCTURAL CONTROLS	PROXIMAL ALTERATION MINERALS	ORE MINERALOGY
KANOWNA BELLE	–	Feldspar porphyry, conglomerates, pebbly quartz sandstones, minor basalt	Hangingwall alteration halo of southeast dipping brittle-ductile shear zone, alteration haloes to subsidiary hangingwall mylonite shears and associated quartz - pyrite breccias and veins, horizontal quartz veins	Muscovite - ankerite-quartz - fuchsite - albite	**Sulfides:** pyrite, minor pyrrhotite, chalcopyrite, late arsenopyrite **Oxides:** rutile
ROBINSONS [1]	46 605 t ore @ 20 g/t, 932 Kg Au (to 1935)	Komatiite flows. Spinifex textured Mg basalt - pyroxenite	Series of narrow quartz veins. Five main branching lodes trending 060°, general dip of main reef 45° SE, northerly plunge.	carbonate, fuchsite, quartz	**Sulfides:** pyrite. **Oxides:** none reported
LAST CHANCE[1]	27 918 t ore @ 11.25 g/t, 314 Kg(to 1935)	Footwall felsic epiclastic rocks, hangingwall komatiites	East - west, 70° south dipping re-activated shear with internal quartz veining. Shear separates ultramafic and felsic metasedimentary rocks.	carbonate, fuchsite, muscovite, silica	**Sulfides:** pyrite, rare galena, sphalerite, chalcopyrite **Oxides:** none reported
BALLARAT [1]	14 399 t ore @ 14.6 g/t, 210 Kg Au (to 1935)	Felsic epiclastic rocks	Narrow (<0.5 m) wide, north -northwest trending, 70° east dipping quartz vein.		
RED HILL [2]	43 374 t ore @ 34.7 g/t, 1505 Kg Au [1]	Dacitic porphyry bounded by polymict conglomerate	Vertical stacking of sub-horizontal quartz veins containing free gold. Veins are massive with occasional vugs. Slickensides on fractures suggest reverse movement.	Carbonate, white mica, albite **Press.-Temp :** 280° - 320°C, ca 100-135 MPa (Fluid Inclusions)	**Sulfides:** galena, minor pyrite. Pyrite in un-mineralised wallrock **Oxides:** none reported
KANOWNA MAIN REEF [2]	354 520 t ore @ 17.6 g/t, 6241 Kg Au (to 1919)[4]	Polymict conglomerate bounded by intrusive porphyry	Steeply dipping (40° - 70°) east dipping auriferous quartz veins within north to northeast trending shear zones. Occasional flat lying quartz veins in porphyry	Carbonate, fuchsite **Press.-Temp:** 250°-325°C,90-100 MPa (Fluid Incl.)	**Sulfides:** pyrite, galena **Oxides:** none reported
BONNIE CHARLIE / FEDERAL[3,1]	3160 t at 6.9 g/t, 21.8 Kg Au	Hangingwall polymict conglomerate, footwall sedimentary grits	Shear hosted quartz reef dipping 50° ESE, east - west striking, north dipping auriferous quartz veins in sedimentary rocks	carbonate, fuchsite, silica, sericite, pyrite	**Sulfides:** none reported **Oxides:** none reported

1. Peachey (1993), 2. Grigson (1981), 3. Mees (1991), 4. Maitland (1919).

TABLE II.3. Production and geological characteristics of selective bedrock mines in the Kanowna district

pathways (e.g. faults and shears), high fluid/rock ratios mean that carbonates are ubiquitous independent of original rock type.

The Red Hill deposits

The Red Hill area refers to the dacitic boss 1.4 km north of Kanowna townsite (Fig. II.9). A number of shafts were worked in this area including the Gentle Polly, Kintore and Kanowna mines. The average grade and tonnage of these mines was 43,379 t of ore at 38.2 g/t Au (Western Australia Department of Mines, 1954, List of Cancelled Gold Mining Leases, reprinted 1980). Today, only the Gentle Polly mine is accessible. The following information is a summary of work on Red Hill by Grigson (1981), and Ho (1984; 1986).

Two rock types occur at Red Hill; dacitic porphyry and polymict conglomerate. Peak metamorphic conditions are not known, but regional work suggests that metamorphism was of greenschist facies or lower. Textures show the replacement of chloritised biotite by alteration minerals, though this biotite may have been a magmatic, not a metamorphic mineral. Similarly, biotite in the polymict conglomerate may be attributed to contact metamorphism.

Mineralisation at Red Hill occurs in sub-horizontal veins arrays within the dacitic porphyry. The veins are massive with a few large vughs, and average between 5 and 30 cm thick with bifurcations and amalgamations being common. Veins taper and terminate towards the edge of the porphyry. Gold mineralisation occurs as free gold in the veins with minor pyrite and galena. Minor gold is associated with pyrite at veins margins. The alteration assemblage at Red Hill is pyrite-ankerite-muscovite-albite with occasional calcite. Chloritised biotite is replaced by pyrite and carbonate, giving the rock a dull-grey colour.

The mechanism favoured for gold deposition at Red Hill is a change in oxidation state of the ore fluid due to interaction with a relatively oxidising porphyry. This mechanism is supported by a change in the oxidation state of iron in the alteration zones. Fluid inclusion studies show that the ore fluid was a homogeneous, low salinity, carbon dioxide-rich fluid. Trapping temperatures were 280°-320°C at pressure of 100-135 MPa.

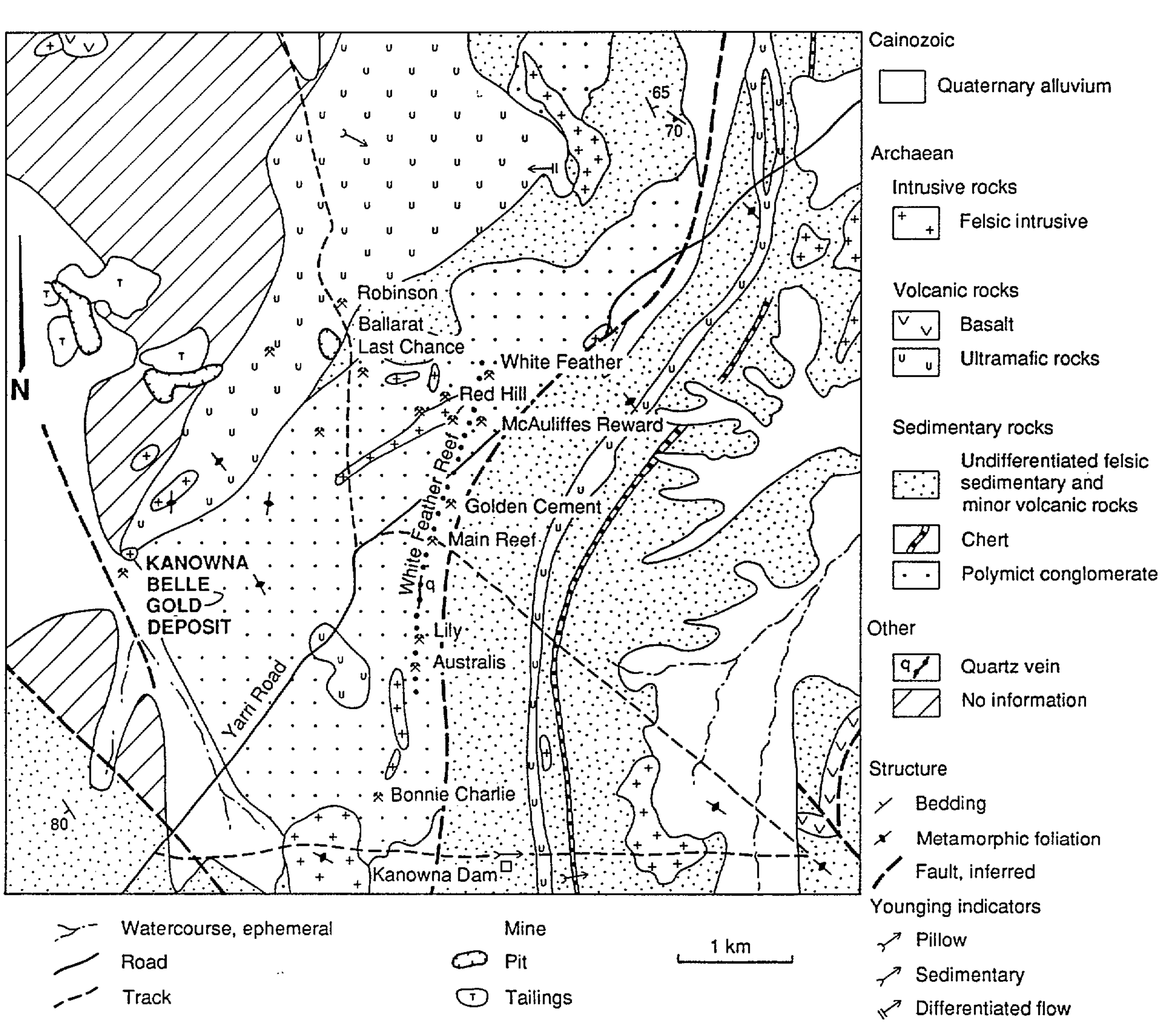

Fig. II.9. Schematic geology and gold deposit location map of the Kanowna district, Western Australia (modified from Taylor, 1984; Ahmat, in press; Peachey, 1991).

Kanowna Main Reef

The Kanowna Main Reef is a north-northeast trending arcuate vein system that is developed over several kilometres. Major mines operated on the Reef include Lily Australis, Main Reef, Golden Cement, McAuliffe's Reward/White Feather Reward and North White Feather (Fig. II.9). As of 1919, gold production had reached 354 520 t ore at 17.6 g/t Au (Maitland, 1919). The Kanowna Main Reef was studied by Grigson (1981), Ho (1984; 1986). The following is a summary of that work.

Two rock types are exposed along the Kanowna Main Reef; polymict conglomerate and intrusive porphyry. Metamorphic grade is greenschist facies or lower. No direct evidence suggests that mineralisation is later than peak metamorphism, but veins similar to those at Red Hill occur in the Main Reef Mine and, at this locality, the Kanowna Main Reef veins enclose the Red Hill style veins (auriferous, porphyry-hosted, flat-lying veins). This would suggest that mineralisation at the Kanowna Main Reef was slightly later than at Red Hill.

Kanowna Main Reef consists of one principal reef, hosted by polymict conglomerate, containing anastomosing and bifurcating quartz veins. The reef has a strike length of greater than 3 km and a vertical depth extent of more than 350 m. Vein thicknesses are generally between 0.5 and 2 m. Internal vein fabrics range from massive quartz with local ankerite and calcite to laminated quartz with laminations defined by chlorite-talc-ankerite-calcite. In many places the intrusive porphyry acts as a bounding feature to the vein system. Alteration at Kanowna Main Reef is lithology-dependent with the exception of carbonate which is pervasive and extensive. Alteration minerals include ankerite-calcite-white mica-Cr mica and pyrite. Mafic clasts show preferential pyrite-carbonate alteration and ultramafic components are predominantly altered to Cr-mica and carbonate.

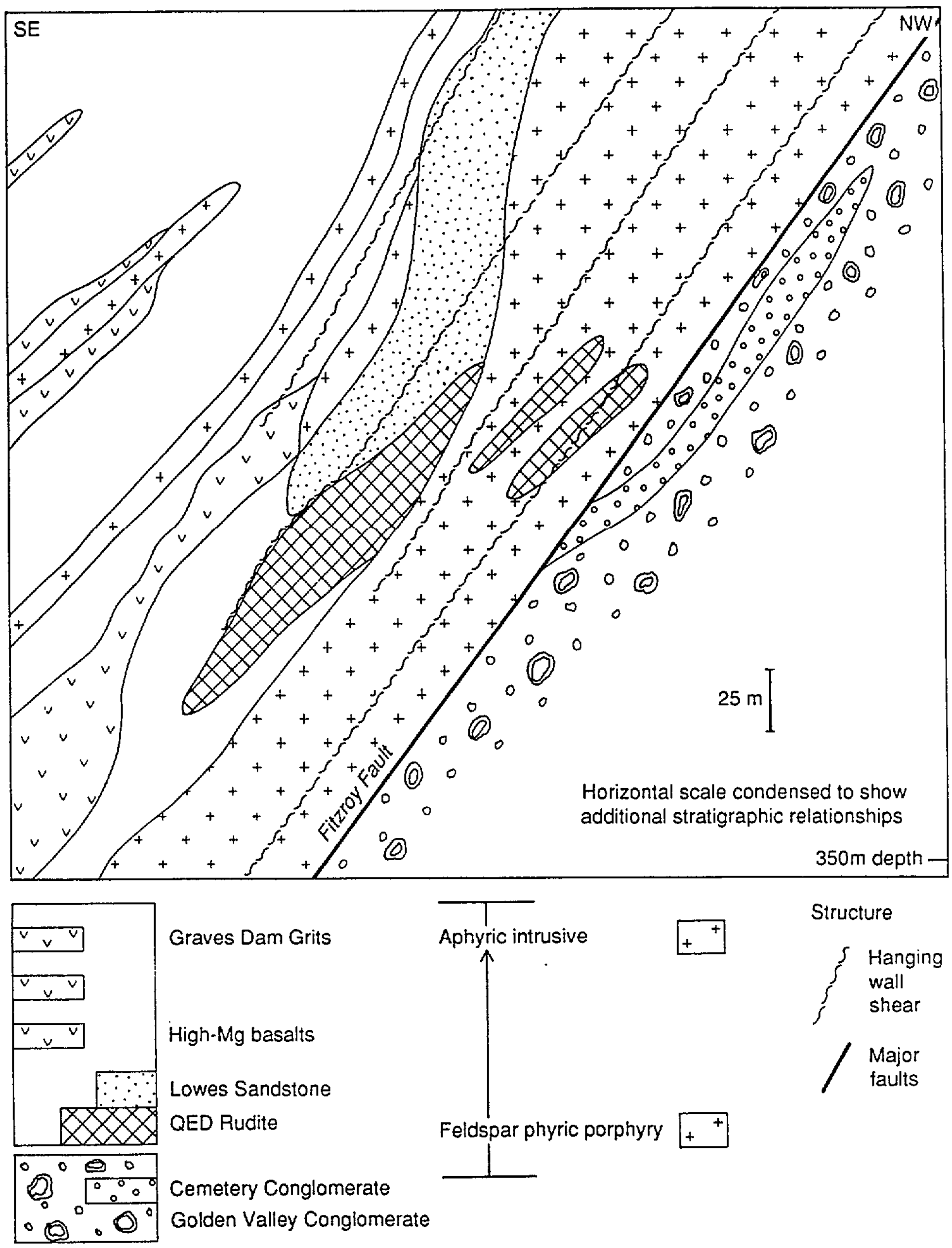

Fig. II.10. Schematic cross section and mine stratigraphy of the Kanowna Belle Gold Mine.

The Kanowna Main Reef is interpreted to be a vein system emplaced along a pre-existing fault or shear zone. Internal vein fabrics and large vughs suggest hydraulic fracturing. Gold deposition is attributed to loss of H_2S and a reduction in sulfur activity during boiling. This mechanism is supported by fluid-inclusion data where two sets of primary inclusions give evidence of boiling. Trapping temperatures were between 250°-325°C at pressure of 90-130 MPa.

The Kanowna Belle deposit

The Kanowna Belle deposit is a sedimentary and porphyry hosted gold deposit with a measured and indicated resource of 2.6 M oz: a further 0.68 M oz is inferred (Definitive Feasibility Study, 1992). Ore is encountered at approximately 30 m depth and continues in excess of 800 m. An open pit mine life of 7 years will result in 6 750 000 tonnes of ore being mined to a depth of 200 m. The deeper ore will be mined by underground mining methods and will extend the overall mine life to greater than 13 years. The following section is based on the contributor's PhD studies on the alteration aspects of the Kanowna Belle deposit.

In the upper part of the Kanowna Belle deposit (Fig. II.10), six units have been recognised in the mine area and are named here using minesite terminology. A mafic-rich conglomerate (Golden Valley Conglomerate) and a lens of feldspar-rich felsic conglomerate (Cemetery Conglomerate) occur beneath the Fitzroy Fault. In the hangingwall of this fault, a cobble to pebble clast-supported felsic conglomerate to breccia (QED Rudite), a quartz-rich pebbly-grit unit (Grave Dam Grits) which grades locally into the QED Rudite, and a spatially restricted, highly altered feldspar-quartz sandstone unit (Lowes Sandstone) occur. High-Mg basalts occur to the south and a feldspar-phyric to aphyric porphyry intrudes the entire sedimentary sequence (Kanowna Belle Porphyry).

The Kanowna Belle deposit has an asymmetric alteration envelope consisting of three principal zones; a peripheral chlorite-calcite zone, a thick sericite-carbonate-pyrite-fuchsite zone and a spatially restricted quartz-albite-pyrite zone. Alteration assemblages are locally overprinted by hydrothermal fracturing and carbonate deposition. Above 350 m depth, the inner two zones are generally restricted to the hangingwall of the main fault.

Mineralisation at Kanowna Belle has a strong structural control. The most prominent feature is the Fitzroy Fault zone/Fitzroy Fault gouge. The fault zone is a mineralised brittle-ductile shear with zones of schistosity and brecciation. Within this fault zone is a small, but continuous fault gouge, commonly referred to as the Fitzroy Fault or simply the "pug zone". This fault gouge strikes northeast and dips 60° southeast. In the upper part of the deposit, the majority of mineralisation occurs above this gouge. Smaller shears occur in the hangingwall of the deposit and these shears appear to be responsible for hangingwall ore shoots above the pervasive blanket of Fitzroy mineralisation.

Gold at Kanowna Belle occurs with pyrite in alteration haloes around the Fitzroy Fault zone and hangingwall shears. Gold also occurs in hydrothermal quartz breccias, sericite-pyrite veinlets, and pyritic quartz stockworks. Occasionally free gold occurs in late, flat-lying quartz veins.

The Kanowna Belle deposit formed either synchronous with peak metamorphism or shortly afterwards. Mineralised veins both exploit the D_3 regional foliation and cross cut it. A late chlorite overprint occurs on the margins of the deposit, but this chlorite may be related to late shears, peripheral alteration or regional metamorphism. Biotite occurs locally in both the footwall and the hangingwall of the deposit, but its origin may be primary magmatic, contact metamorphic, or regional metamorphic. No fluid-inclusion studies have been completed on Kanowna Belle, but structural and alteration styles are similar to both Red Hill and Kanowna Main Reef. It is likely that the pressure and temperature constraints on mineralisation were similar, as were the mechanisms for gold deposition.

Lode-Gold deposits of the Mount Pleasant Area

M. Gebre–Mariam

The Mt Pleasant area is located 35 km northwest of Kalgoorlie, in the Norseman–Wiluna Belt, Yilgarn Block. The lode gold deposits of the region have to date produced approximately 30 tonnes of Au (Witt, 1993). Gold mineralisation is hosted by a variety of lithologies. Deposits in basalts include Racetrack, Royal Standard, and Black Flag; in layered mafic sills at Golden Kilometre and Lady Bountiful; and in granitoid at Lady Bountiful. The characteristics of the deposits are summarized in Table II.4.

Regional setting

The Mt Pleasant area forms the southern portion of the Ora Banda Domain (Swager & others, 1990). The supracrustal succession of the Ora Banda Domain is broadly comparable with sequences at Kalgoorlie (Travis & others, 1971) and Kambalda (Roberts, 1988), and is dated at 2704 ± 8 Ma (Pidgeon, 1986), essentially the same age as the Kambalda greenstones (2702 ± 4 Ma; Claoué-Long & others, 1988). It is dominated by mafic to ultramafic lavas and high-level intrusive equivalents of the mafic lavas. The sequence is approximately 10 km thick (Witt, 1990). This is much thicker than the greenstone succession at Kalgoorlie or Kambalda, a difference partly attributed to a larger proportion of intrusions, and partly to lesser structural attenuation than in the Kalgoorlie or Kambalda areas. In the Mount Pleasant area, the upper part of the Ora Banda Sequence (Fig. II.11a) includes the Bent Tree Basalt (flow basalt), Victorious Basalt (porphyritic basalt) and Black Flag Group (felsic to intermediate volcanics and epiclastic sedimentary rocks). Intruding the sequence are the Mt Ellis (layered, pyroxenite to quartz-gabbro) and Mt Pleasant (layered, peridotite to quartz-gabbro) Sills, the Liberty Granodiorite, and felsic porphyries. Upright D_2 folding and D_3 transcurrent faulting are the dominant regional-scale deformation events in the area (Witt, 1990). Late north-northeast-trending, dextral strike-slip D_4 faults have disrupted the greenstone sequence. In general, the rocks are unstrained, and there is no pervasive or spaced fabric except in discrete planar zones of high strain, which are characterised by pervasive foliation and destruction of primary textures. Massive undeformed mafic to ultramafic rocks, with well-preserved igneous structures and textures, including cumulate textures in layered intrusions, and pillows and varioles in ba-

Deposit	Production/ Reserves	Host lithologies	Dominant structure	Alteration assemblages	Ore minerals
Golden Kilometre	16.6 t Au	Mt Pleasant Sill	sinistral strike slip and oblique slip (dextral-reverse) 085°/80° north & 060°/75° north west	distal: chl-cal proximal: musc-ank	py-po-cpy-gn-sph-sch-apy-flu
Racetrack	12.6 t Au®	Porphyritic basalt	normal fault 050-060°/40-60° north west	distal: chl-cal proximal: musc-ank-dol-cal	py-apy-cpy-sph-gn-tet-fre-ten-fah
Lady Bountiful	11.4 t Au	Liberty Granodiorite & Mt Pleasant Sill	sinistral strike slip main lode: 090°/65-80° north tension veins: 040-060°/65-80° north west	distal: kfs-musc-chl-bio-hem-musc proximal: musc-alb-chl-rut	py-po-cpy-gn-tell-sph-ch-flu
Royal Standard	1.5 t Au	Porphyritic basalt	dextral strike slip 010°/80° west	distal: chl-musc-cal proximal: musc-ank-sid	py-po-cpy-gn-sph-apy
Black Flag	0.5 t Au	Bent Tree Basalt	dextral strike slip north south to north north east trending	chl-musc-sil	sph-gn-py

Abbreviations: Alteration minerals: ank - ankerite; alb - albite; bio - biotite; cal - calcite; chl - chlorite; hem - hematite; kfs - K-feldspar; musc - muscovite.
Ore minerals: apy - arsenopyrite; cpy - chalcopyrite; fah - fahlore; flu - fluorite; fre - freibergite; gn - galena; po - pyrrhotite; py - pyrite; sch - scheelite; sph - sphalerite; tell - tellurides (Au-Ag-Bi-Pb); ten - tennantite; tet - tetrahedrite.

® includes West Racetrack, Racetrack and East Racetrack oxide and Racetrack primary.

TABLE II.4. Characteristics of gold deposits in the Mt Pleasant area.

salts, occur over a wide area. Metamorphism is characterised by a high degree of primary textural preservation, and ranges from low greenschist to mid-greenschist facies (Fig. II.4).

Gold deposits in the Mount Pleasant area

In the Mt Pleasant area, gold deposits are hosted by a variety of lithologies: mafic layered sills, tholeiitic basalt, and granitoid that have been metamorphosed up to the greenschist facies. Gold mineralisation is concentrated in brittle and brittle-ductile strike-slip faults. The orientations and associated sense of displacement of mineralized structures suggest that they are spatially controlled by a NNE-trending, dextral strike-slip fault system that formed during D_4.

In terms of the distribution of metamorphic and alteration isograds, the Mt Pleasant area has the lowest grade metamorphic and alteration assemblages in the region in the Ora Banda–Kalgoorlie–CoolgardieKambalda region (Fig. II.4).

Racetrack deposit

The Racetrack deposit (Fig. II.11a), discovered in 1987 by 20 m x 20 m grid As soil geochemistry, is hosted by porphyritic basalt of the Ora Banda Sequence. In the mine environment, the stratigraphy is dominated by the host porphyritic basalt with minor intrusions, andesites, felsic and intermediate porphyries and dolerite (Fig. II.11b). The porphyritic basalt, locally known as 'cat rock', is a massive to pillowed, coarsely plagioclase-phyric tholeiitic basalt, locally with a coarse-grained doleritic groundmass. Regionally, the deposit is on a splay fault between two parallel dextral strike-slip faults: the Black Flag and Royal Standard Faults. The splay fault is interpreted as an extensional (T), normal fault zone subsidiary to these strike-slip faults.

Gold mineralisation occurs in two types of reefs: quartz-breccia, and narrow shear zones with foliation-parallel quartz veins. The breccias, hosted by a 060°/40° to 60° north west (strike/dip) fault zone, are related to brittle fault deformation, whereas the shear zones, trending 050°/60° north west display brittle-ductile deformation. Subtle changes in the strike and/or dip of the ore-hosting zone are associated with a lateral variation from high-grade to sub-economic mineralisation, and also with a change in reef style. There is an example in the central part of the open pit where a 060°/60° northwest fault zone bends to a 050°/40° northwest zone, and the mineralisation style changes sympathetically from a quartz-breccia to a narrow (<0.4 m) shear-zone lacking quartz veins: along strike, the mineralisation dies out (Fig. II.11b). Most gold production comes from three discrete breccia zones. Mineralisation in the 060°-trending structures occurs in both strained and unstrained host-rock (with well-preserved primary igneous textures), in strongly altered and mineralised breccia clasts, and in the quartz matrix. In the shear zones, mineralisation occurs in strongly altered and

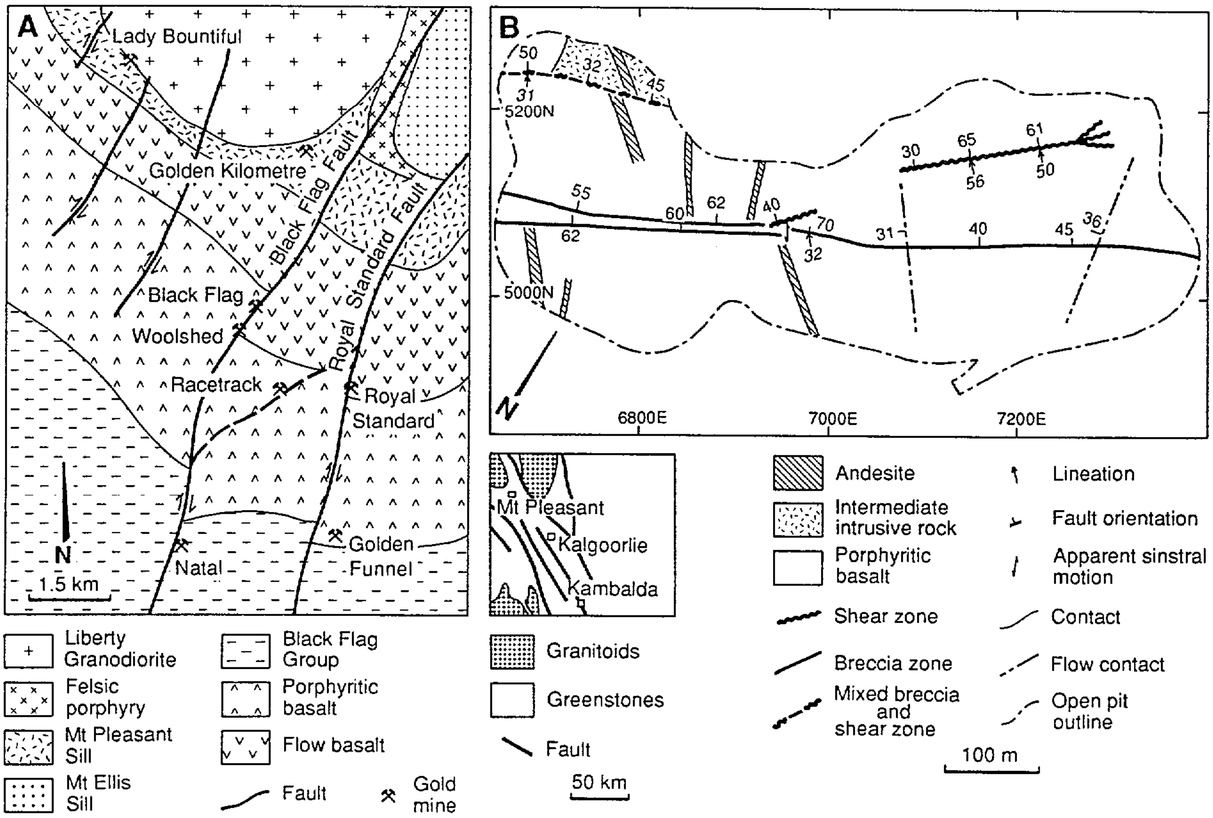

Fig. II.11. (a) Geological map of the Mt Pleasant area, (b) Geological map of the Racetrack deposit

foliated zones which have very thin (few mm to 2 cm) quartz veinlets subparallel to the foliation. The veinlets are locally boudinaged or occur as lenses. Economic mineralisation dies out to the west where the shear zone flattens, and to the east where it terminates in a horsetail splay.

Three distinct and successive stages of hydrothermal activity and late quartz-carbonate veining resulted in multiple veining and/or breccia-tion phases. Sulfide mineralisation occurred throughout the paragenetic sequence and in the late veins. Gold mineralisation was restricted to the first two stages. Stage I mineralisation occurs, in both the 050°- and 060°-trending structures, as zones of intense wallrock alteration associated with silicified domains consisting of microcrystalline to crystalline quartz. Within the ore zone, alteration is characterized by intense bleaching, silicification, sericitisation, and carbonatisation. Alteration assemblages are laterally zoned, with chlorite-calcite-epidote assemblages forming the outer fringe of mineralisation. Ore minerals include arsenopyrite, pyrite, chalcopyrite, Fe-poor sphalerite, tetrahedrite, tennantite, fahlore, gold, and electrum. Stage II represents a period of intense fracturing, veining, and brecciation of earlier Stage I mineralisation, and is spatially restricted to the Stage I conduit structures. The breccia matrix is completely cemented by hydrothermal minerals which display open-space growth textures. Quartz crystals predominate, and show comb, rosette, plumose, and banded textures. Typical ore minerals include freibergite, tetrahedrite, tennantite, galena, arsenopyrite, pyrite, chalcopyrite, sphalerite, gold, and electrum. Minor cassiterite also occurs. Stage III represents a second phase of intense fracturing, veining, and brecciation of Stage I and II assemblages by fine-grained carbonate. Spatially, this stage is restricted to the western part of the mine area. The brecciation is pervasive, and massive addition of carbonate, in places, has diluted the ore grade. Minor sulfides which occur in this stage include pyrite, arsenopyrite, and chalcopyrite.

Flat to gently northwest-dipping, buck-textured quartz-carbonate veins which cross-cut Stages I, II, and III are widespread within and outside the mine area. The veins show cross-cutting relationships with post-ore faults, which suggest that they are late and not related to the main pulse of hydrothermal activity which formed the mineralisation.

In summary, the Archaean Racetrack Au-Ag deposit, sited in a predominantly brittle, strike-slip fault system and hosted by porphyritic basalt metamorphosed at low-greenschist conditions, shows several features that suggest mineralisation formed in a shallow, near-surface environ-

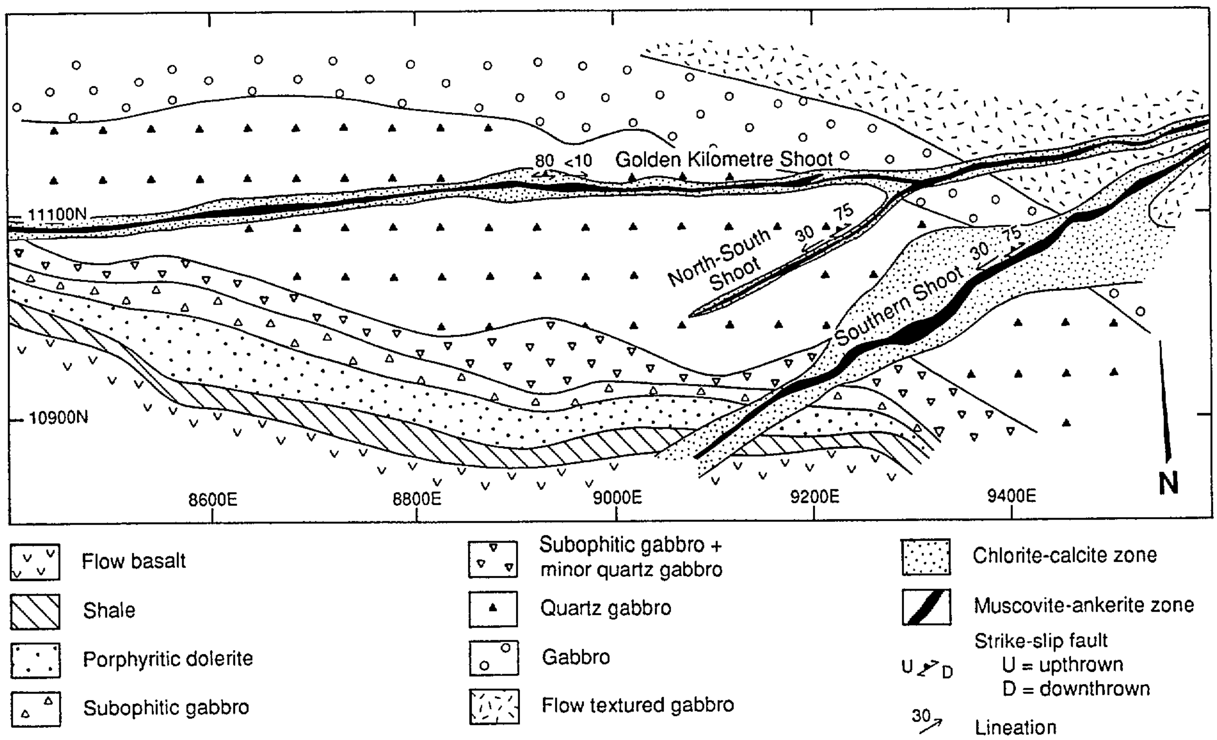

Fig. II.11 (c) Geological map of the Golden Kilometre deposit at 900 m RL, modified from unpublished company data.

ment. These include: i) the predominantly brittle nature of the ore-hosting structures, ii) vein textures indicative of open-space fill, and iii) ore mineral assemblages similar to epithermal deposits. The deposit is interpreted to represent the upper crustal end-member of the Archaean lode-gold depositional continuum of Groves & others (1992).

Golden Kilometre

The Golden Kilometre deposit (Fig. II.11c) is hosted by the quartz gabbro zone of the Mt Pleasant Sill. This layered and differentiated mafic-ultramafic intrusion ranges from peridotite at the base to granophyric quartz-gabbro about 50 m below the top (Witt, 1990). In the mine environment the stratigraphy is dominated by the host sill and basalt, with the contact defined by a shale horizon. The upper, differentiated iron-rich granophyric zone of the sill is the preferred host rock to gold mineralisation at several localities in the Mt Pleasant-Ora Banda area. Economic mineralisation at Golden Kilometre is largely restricted to the quartz-gabbro zone of the sill, with minor amounts in the bordering units (subophitic gabbro and gabbro). The quartz-gabbro unit represents the most fractionated rock within the intrusion, and is the most Fe-rich rock in the greenstone succession. The preferential development of ore in this unit is considered due to the physical and chemical characteristics of the unit. The greater quartz content has rendered it more amenable than other units to brittle fracturing during faulting and veining, thus enhancing permeability to gold-bearing fluids which reacted with the unit due to its favourable Fe-rich chemistry.

Gold mineralisation at Golden Kilometre is controlled by lower-order brittle-ductile strike-slip faults associated with regional strike-slip faults. The deposit comprises a system of laminated quartz veins and related altered wallrock, and minor breccia zones. The major quartz veins, up to 1 m thick, are generally laminated, and contain narrow ribbons of pyritized wallrock. Gold mineralisation occurs in three discrete shoots: Golden Kilometre (085°/80° north), Southern, and North-South shoots (060°/75° north west). Mineralisation on the Golden Kilometre shoot is along a main D-fault, with minor ore shoots in the Riedel and tension gash orientations. The main shoot varies from 2 m to 6 m thick and splays and anastomoses along Riedel and extensional directions. Offset on dykes, and the fabric configuration, suggest that the main fault has 30 m of sinistral strike-slip displacement. Mineralisation in the Southern and North-South shoot is controlled by an oblique fault (dextral-reverse fault) with a displacement of 1-5 m. The major quartz vein in the Southern shoot has numerous splays with a variety of orientations. The shoot commonly has a wider alteration halo, and hence wider ore body compared to the other shoots. Mineralisation is present in the main D-fault and within R and T veins, with the highest grade ore developed where any of these intersect. Mineralisation in the North-South shoot is developed in narrow (up to 0.5 m) massive to poorly laminated quartz veins and breccia zones.

Metasomatic alteration, similar in all three shoots, shows distinct colour zonation, related to sequential wallrock alteration around the veins. Progressive hydrothermal alteration has resulted in the actinolite-chlorite assemblages of the metamorphosed wallrock being replaced by chlorite-albite-biotite-calcite assemblages within the distal chlorite-calcite zone. Intense alteration proximal to veins led to replacement of these phases by muscovite-ankerite-sulfide (pyrite-pyrrhotite-chalcopyrite-sphalerite-arsenopyrite) assemblages. The muscovite-ankerite zone can, itself, be subdivided into distal pyrrhotite and proximal pyrite subzones.

In the wallrock, gold occurs as discrete, ≤100 µm-sized (maximum dimension) particles included in gangue and sulfide minerals. In the veins, gold occurs as coarse grains (commonly 1 to 2 mm), shows evidence of late development in the vein paragenesis, and is commonly associated with zones of recrystallized quartz or deposited along with sericite, chlorite, and ankerite within late, cross-cutting fractures and 'spider' veinlets. Minor galena, sphalerite, pyrite, pyrrhotite, chalcopyrite, and scheelite also occur within gold-bearing veins.

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Excursion 5

A workshop to explore the controversial aspects of the Kalgoorlie Geology

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PMB 27
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At the centenary celebration of the discovery of the Kalgoorlie Gold Field, there are still many controversies regarding the nature and genesis of the various Kalgoorlie gold deposits. Generations of geologists, working at the mines or coming from a wide variety of research institutions, have tried to unravel the intricacies of differentiated dolerites, a variety of deformation phases and styles, alteration patterns and gold-telluride mineralogy. Credit must be given for the vast amount of internal and external publications which have been produced. Due to the historically fragmented ownership of the mine leases, and the large size of the orebodies, the research was in most cases restricted to only parts of the mineralised system. Now, for the first time in 100 years, the whole of the Kalgoorlie field is under the same ownership. This provides a unique opportunity for geoscientists to conduct a comprehensive overview of the total mineralising system at Kalgoorlie.

Reflecting the enormous size and complexity of the Kalgoorlie deposits, a range of different opinions on the nature and genesis of the mineralisation has arisen from research over the past decades. This workshop will address the critical problems in current interpretations of the geology at Kalgoorlie. Attention will be paid to the controversies highlighted in the following paper, by discussing the following specific questions:

1. Stratigraphy

The recognition of the Aberdare and Eureka dolerites as separate intrusive bodies changes the interpretation of the south plunging Kalgoorlie Anticline. What are the stratigraphic relationships of the various doleritic bodies? What are the structural implications of a revised stratigraphy?

2. Structure

What was the tectonic setting (thrust, wrench, etc.)? What was the deformation style during mineralisation: brittle, brittle-ductile or ductile? What are the relationships between major structures and mineralised zones? How do each of the specific structural elements (cleavage, faults, etc.) link into the structural evolution history of the Kalgoorlie Gold Field?

3. Alteration

What is the alteration zonation, timing and relationship to structural elements or lithology? What is the significance of the Green Leader? What is the influence of the sediments?

4. Source of fluid/deposition of gold/geological setting

What was the source of the mineralising fluid(s): metamorphic, meteoric, igneous, etc? Was gold deposition by sulphidation or phase separation? What were the P-T conditions of mineralisation? What was the overall geologic setting? What were the unique conditions that controlled the formation of these world-class gold deposits?

5. The future of geological research at Kalgoorlie

How can these critical issues be best addressed? By whom? What are the priorities? Are there additional issues? How should it be funded?

The programme of the workshop consists of short seminars and discussions, and visits to the Fimiston Open Pits, the Mount Charlotte Underground operations, and the KCGM core yard. Due to the rapid changes in the open pit and underground exposures and access, it will not be possible to finalise an exact programme until immediately before the workshop. Detailed handouts will be made available at the start of the Workshop.

Geology of the Kalgoorlie gold deposits: a summary

The Kalgoorlie gold deposits have produced a total of 1300 t (43 Moz) of gold, out of 150 Mt of ore, since their discovery in 1893. This equates to approximately 1% of the total world gold production. The majority of this production has come from the lodes of the Golden Mile, historically mined by underground methods, and currently the site of a large-scale open pit operation. Other significant production has come from the Mt Charlotte and Hannans North underground mines and the Mt Percy open pit mine. Current resources are in excess of 18 Moz.

Regional geology

The Kalgoorlie gold deposits are located within the Kalgoorlie Terrane (Swager & others, 1990) of the Norseman–Wiluna greenstone belt. This terrane consists of a series of komatiites, basalts and sediments, intruded by several mafic sills and granitoid bodies. Early thrusting, upright folding and strike-slip faulting have resulted in a strong regional north-northwest structural trend. Metamorphic grade in the Kalgoorlie area varies from lower to upper greenschist facies.

Stratigraphy

At Kalgoorlie, the stratigraphic sequence has been well established since Woodall (1965) (Fig.1). It consists of a series of komatiitic to high-magnesian to tholeiitic volcanics (Hannans Lake Serpentinite, Devon Consols Basalt and Paringa Basalt), intercalated with thin sedimentary horizons, including the sulphidic black shales and cherts of the Kapai Slate. This sequence is overlain by the volcanic-sedimentary series of the Black Flag Beds.

Several differentiated, concordant doleritic sills are found concordantly within or between the stratigraphic units. The economically most important of these is the Golden Mile Dolerite. It has been subdivided into ten units (Travis & others, 1971), showing a tholeiitic differentiation trend. Clark (1980) showed that the sequence was the result of an *in situ* differentiation in a gabbroic sill.

Recent work (Clout & others, 1990) has resulted in a re-interpretation of the Golden Mile Dolerite geology, immediately to the south and east of the Golden Mile. Dolerites, previously thought to be extensions of the Golden Mile Dolerite, were identified as being separate intrusions, the Aberdare and Eureka Dolerites (Fig.1). This interpretation has important implications for the structural geology of the Golden Mile area.

Structure

The structure at the Kalgoorlie Gold Field is dominated by tight, northwest-trending, upright folds, strike-parallel faults and late, north-trending, oblique faults (Fig.1).

The Kalgoorlie Syncline and Anticline are the earliest, D1 (Swager, 1989) structures recognized. The Kalgoorlie Syncline is an asymmetrical structure, with a very steep westerly limb, and a moderately dipping easterly limb (Fig.2). A core of Black Flag Beds is bound on the eastern side by the Golden Mile Fault. It has been interpreted as a normal fault with a west-block up movement of about 3 km (Woodall, 1965), or as a D1 thrust fault, later refolded by the regional D2 deformation (Swager, 1989).

This folded and faulted Kalgoorlie sequence has been refolded around the northerly plunging D3 Boomerang Anticline, which itself has been truncated by the regional north-northwest striking Boulder Fault.

Late (D4), north-trending, predominantly oblique dextral strike-slip faults crosscut and appear to offset all structures. The main faults are (from south to north): Adelaide, Golden Pike, Maritana, Reward, Charlotte, Mystery and Lamington Faults. Net strike-slips of up to 2 km have been observed, but are typically in the order of hundreds of metres. The relationship between the Boulder Fault and the oblique faults is unclear. Most interpretations (e.g. Keats, 1987, Mueller & others, 1988, Swager, 1989) argue that the Boulder Fault is part of the Boulder–Lefroy fault system, showing early sinistral movement, and possibly later dextral reactivations. The oblique faults horsetail off, or are cut off by, the Boulder Fault. Clout (1989), based on slip directions and cross-cutting oblique faults, suggested an early (D1) age for the Boulder Fault, similar to the Golden Mile Fault.

Structural controls on mineralisation

The Golden Mile mineralisation consists of a complex array of shear zones within the Golden Mile Dolerite and Paringa Basalt, between the oblique Golden Pike and Adelaide Faults (Figs. 2 & 3). The mineralised lodes, consisting of a high-grade lode shear zone and a low-grade alteration halo, form a subset of these shear zones. The lodes

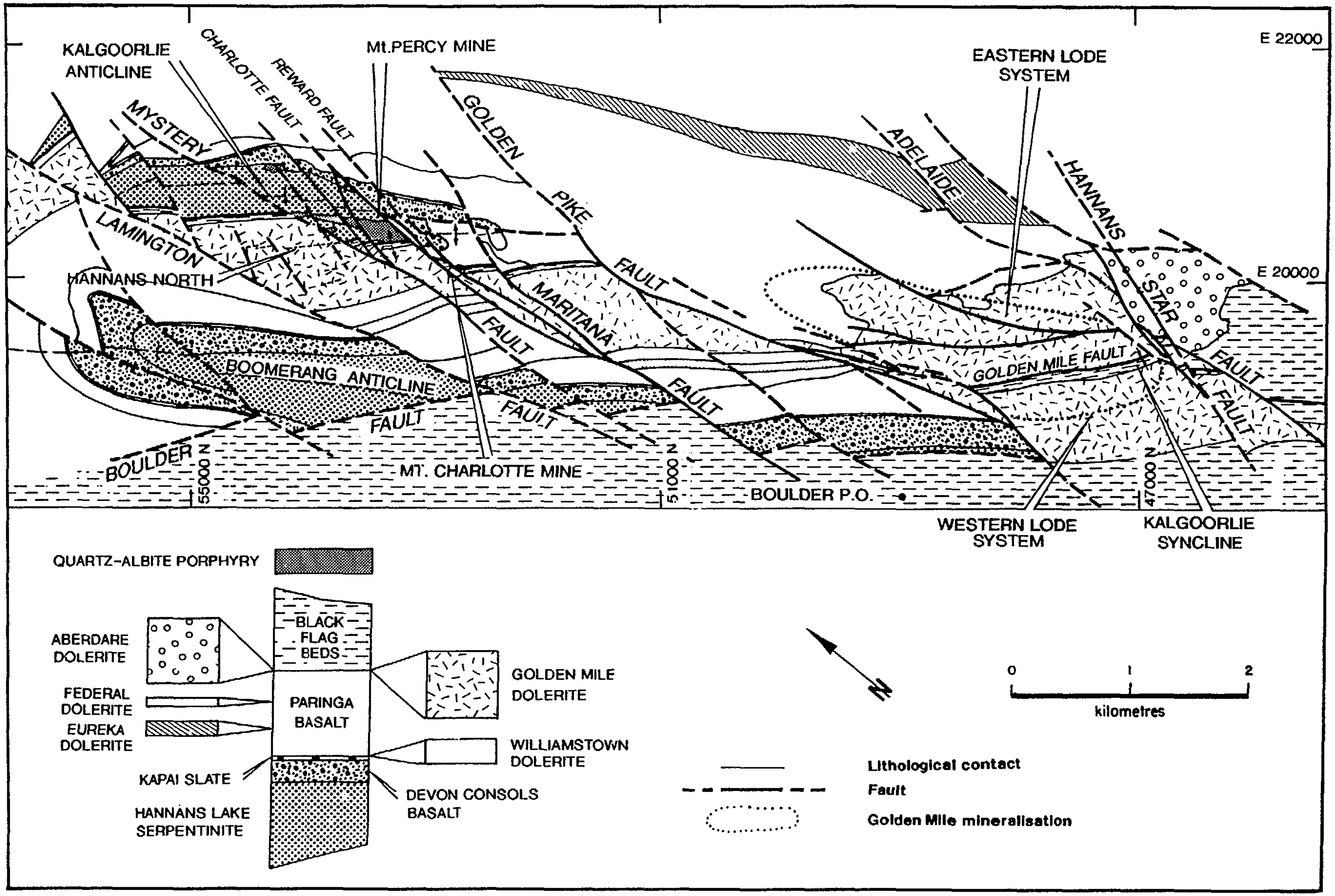

Fig. 1. Interpreted geology of the Kalgoorlie area. After Clout & others (1990).

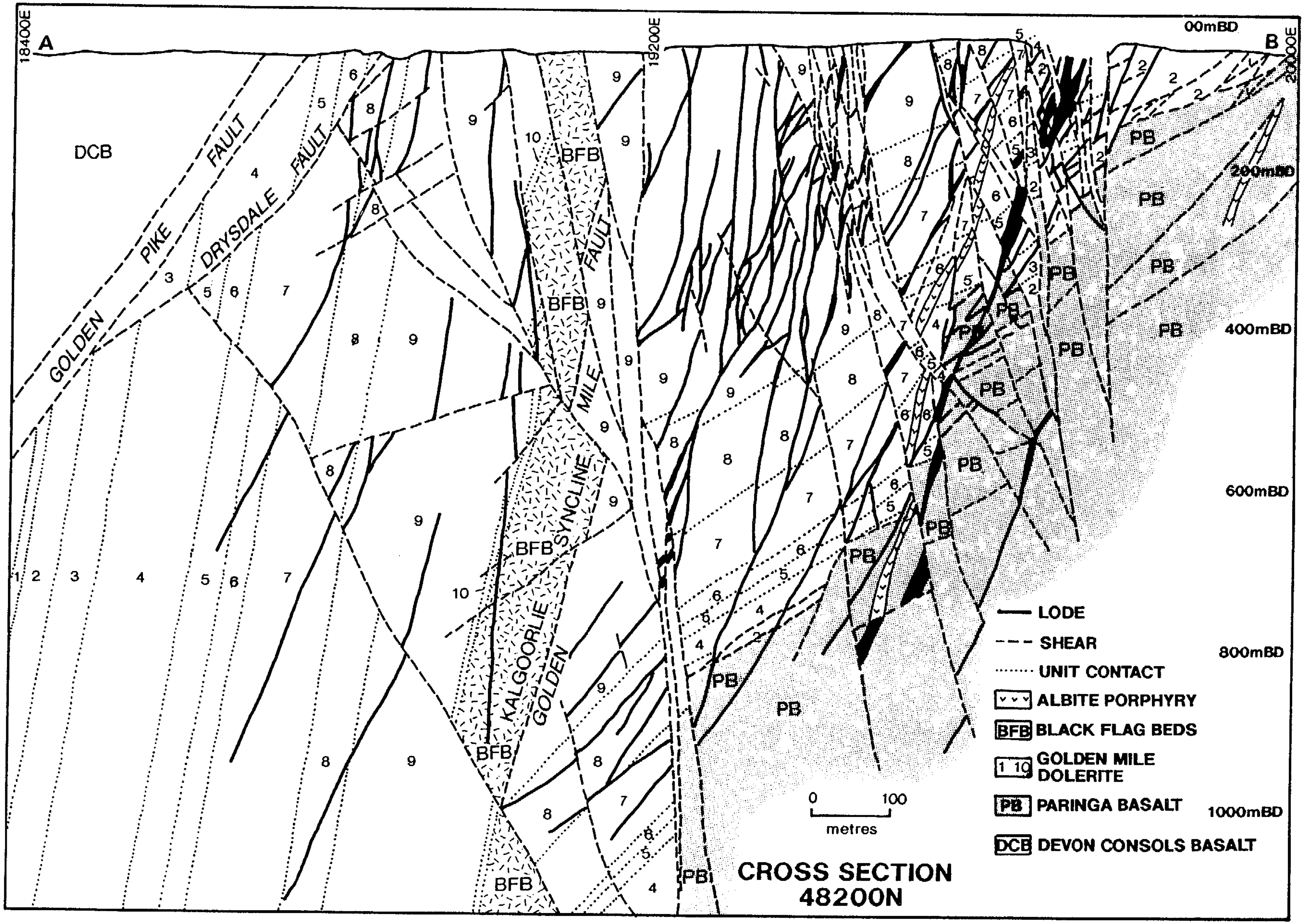

Fig. 2. Cross-section A-B (see Fig.3) through the Golden Mile. After Clout & others (1990).

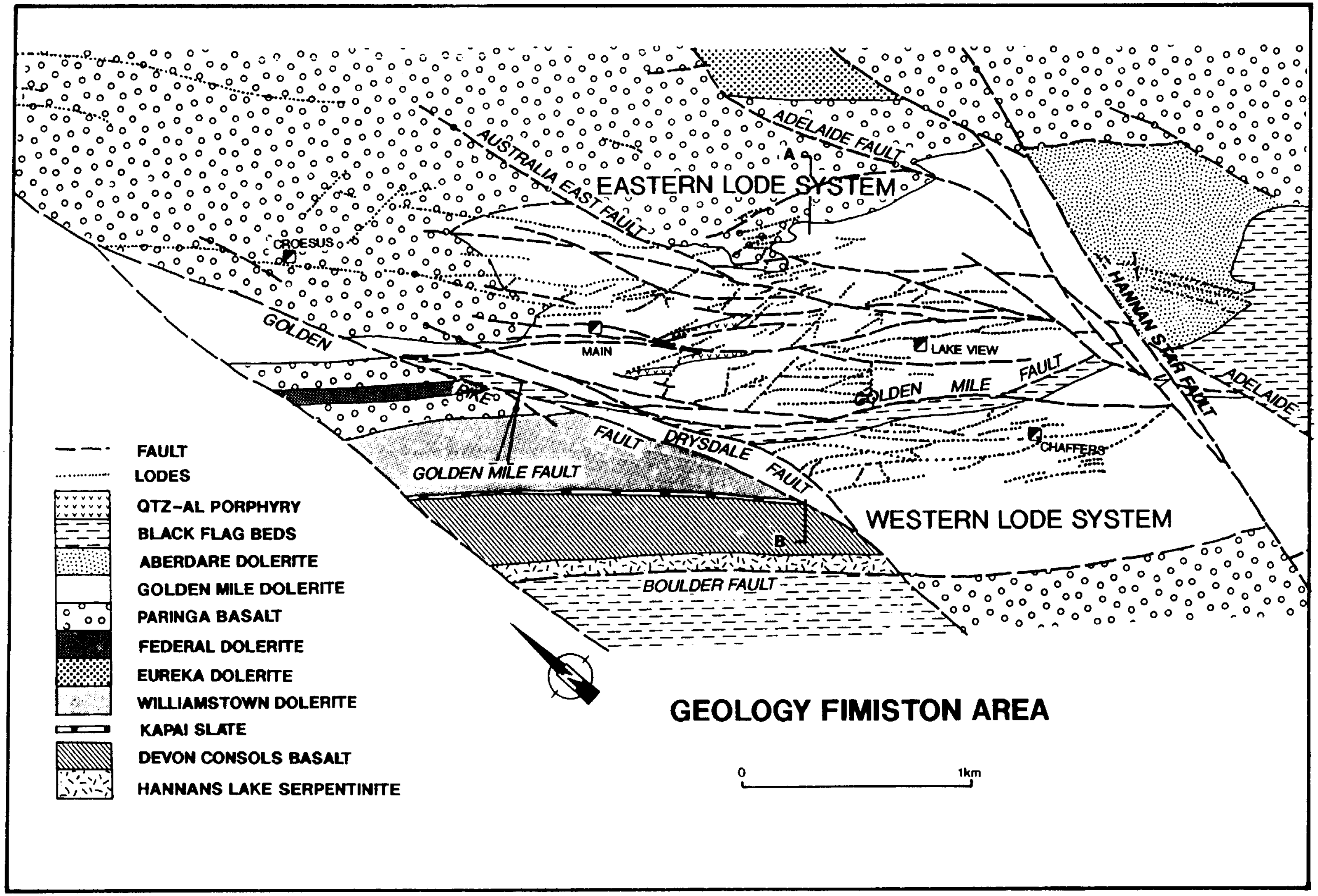

Fig. 3. Interpreted geological plan of the Golden Mile. After Clout & others (1990).

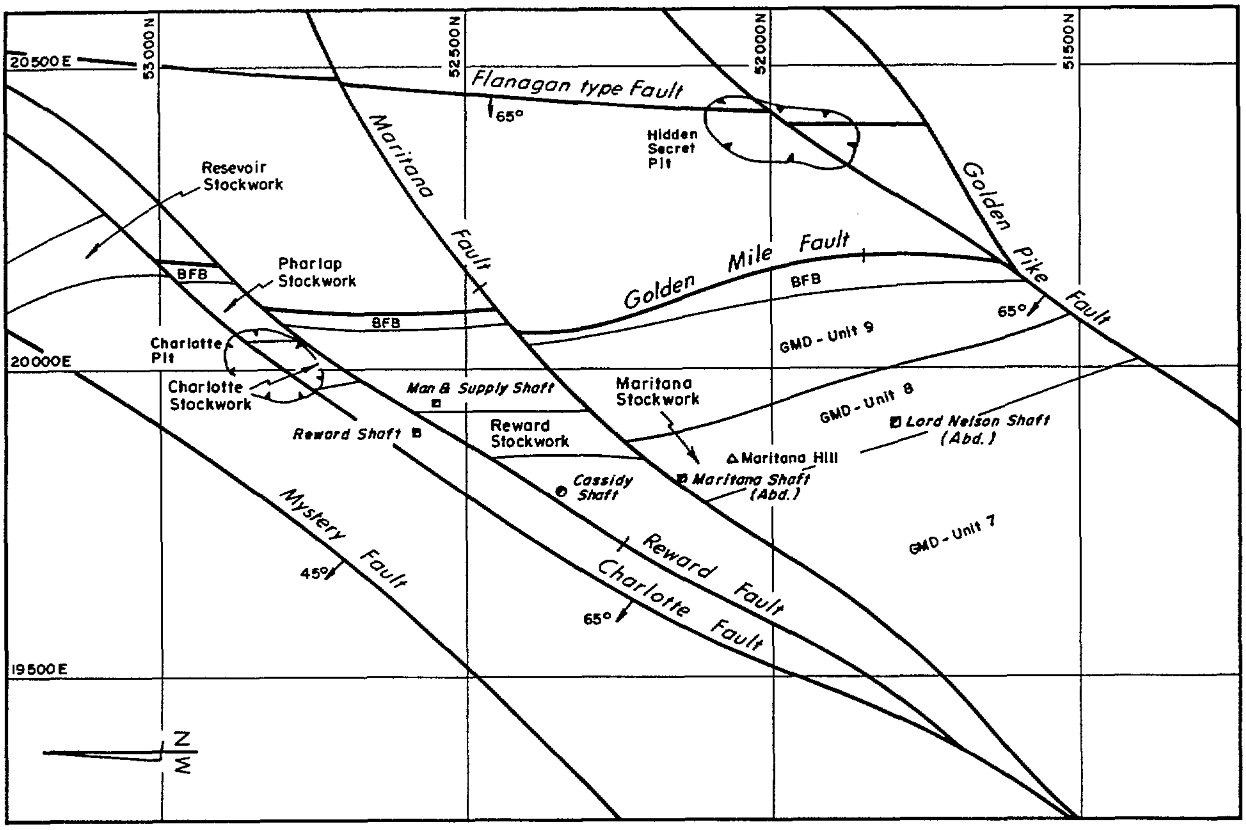

Fig. 4. Surface plan of the Mt Charlotte area, showing locations of Maritana, Reward, Charlotte, Pharlap and Reservoir Stockworks, in relation to Golden Mile Dolerite Unit 8 and oblique faults. From Bischoff & Morley, in press.

may have dimensions of up to 1800 m in length, 1200 m in depth, and several metres wide. Historically, several lode orientations have been recognised:

- steep-dipping lodes of the Main Lode-style, in several orientations (Main, Caunter, No.2, Cross lodes); and
- flat-dipping and Oroya-style, mainly at the Golden Mile Dolerite and Paringa Basalt contact.

The nature and origin of the shear zone system is still under debate. The more recent interpretations are:

- The lodes are in ductile shear zones, and have been developed during the formation of the D1 Kalgoorlie syncline (Boulter & others, 1987);
- the lodes were formed in a typical Riedel system during wrench fault tectonics, during initial sinistral movement of the Boulder and Parkeston Faults (Mueller & others, 1988, Swager, 1989), and as a result of late-D3 regional northeast-southwest shortening (Swager, 1989);
- the lodes are brittle shear zones, formed during east-northeast shortening, by cyclic behaviour of the shear zone system during earthquake rupture on the Golden Pike and Adelaide master faults (Clout, 1989).

The Mt Charlotte-style of mineralisation (Clout & others, 1990, Bischoff & Morley, in press), consists of a quartz-stockwork, mainly confined to the granophyric Unit 8 of the Golden Mile Dolerite. The best example of this mineralisation style is the Mt Charlotte orebody (Figs. 4 & 5). Mineralisation has developed as a result of brittle fracturing, bounded by a series of steep, westerly-dipping dextral faults. Veins are usually between 5 and 100 mm wide, with two preferred orientations, with steep northerly and flat northerly dips. The mineralised alteration halos are up to 1m wide.

Locally, the quartz stockwork overprints the lode-style of mineralisation. The stockworks are considered to have developed during the D4 formation of the oblique faults (Swager, 1989), or during late dextral reactivation of the same faults (Clout & others, 1990).

At Mt Percy, mineralisation has developed in stockworks and shears, in the Devon Consols Basalt, and in porphyries intruded into the Hannans Lake Serpentinite. Mineralisation appears to have been mainly controlled by the Reward, Charlotte and Mystery Faults and their splays.

At the Hannans North Mine, mineralisation is mainly concentrated in a single lode shear structure, approximately 1000m long, and mined to

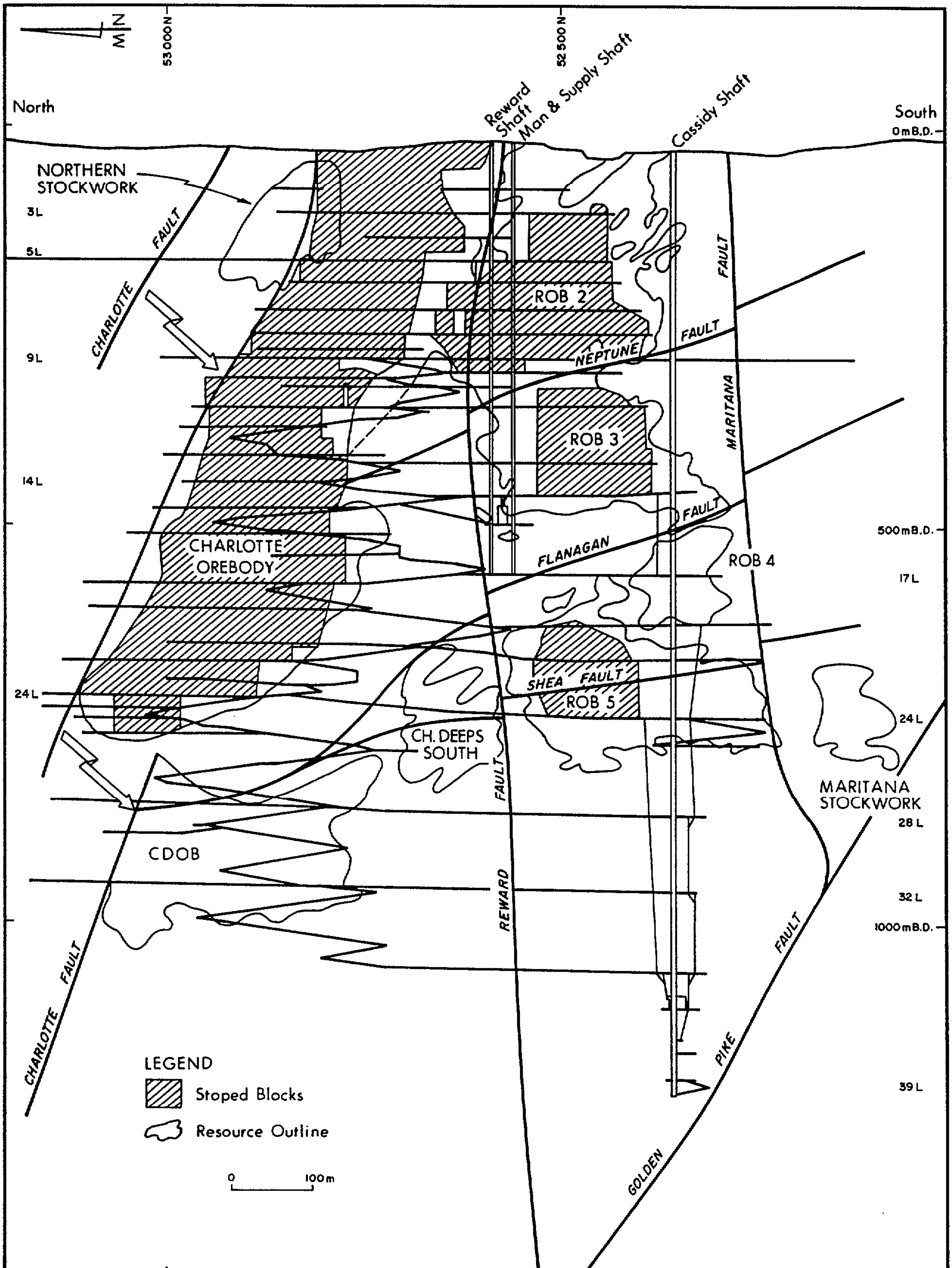

Fig. 5. Longitudinal section through Mt Charlotte mine. From Bischoff & Morley, in press.

a depth of about 500m. The structure, within Golden Mile Dolerite Units 6 and 7, is truncated by the D4 Mystery Fault.

Alteration and mineralisation

The regional metamorphic upper-greenschist assemblage of albite-epidote-actinolite-quartz-ilmenite/sphene, has been overprinted, on a Kalgoorlie-wide scale, by a chlorite-calcite alteration assemblage. At the Golden Mile, this assemblage has been locally replaced by a pale-coloured ankerite-siderite assemblage, accompanied by the replacement of ilmenite by leucoxene (Clout & others, 1990).

At the Golden Mile lode-scale, a consistent alteration zonation pattern has been documented by Clout (1989) and Clout & others (1990). Major alteration types are an outer, low grade, ankerite-dolomite zone, a sericite zone, with sericite-pyrite-telluride assemblages, probably accounting for 50% of the total gold mined, and a central dilational brecciation zone with a quartz-hematite core. Locally, anhydrite and albite zones are developed, while ephesite (brittle mica) and V-sericite zones (also known as "green leader") occur at the top of the lodes. The vanadium-bearing minerals and tellurides indicate very high gold tenors. Gold at the Golden Mile occurs as free gold or as gold and silver tellurides, often intimately associated with pyrite. The ore is refractory.

The proposed position of some of the alteration zones would indicate, for the first time, a vertical zonation for the lodes (Clout, 1989). The interpretation that green leader ores are part of the alteration zonation is in contrast with findings from other workers who argue that green leader, including the high-grade Oroya shoot, is a separate, possibly later, ore type, mainly formed close to the Golden Mile Dolerite-Paringa Basalt contact, in association with sediments (compare Phillips, 1986, Swager, 1989).

At Hannans North, only a narrow chlorite alteration zone adjoins the lode (Bartram, 1969, Roberts, 1993). Although having the appearance of a Golden Mile-style lode, the ore mineralogy is similar to the other deposits at the northern end of Kalgoorlie, consisting of free milling gold in association with pyrite.

At Mount Charlotte, the semi-regional chlorite-calcite alteration is replaced by chlorite-ankerite-(sulphide) and ankerite-sericite-sulphide in alteration haloes around the quartz veins (Clark, 1980, Clout & others 1990). Pyrite and pyrrhotite are the dominant sulphide species, pyrrhotite becoming more abundant with depth. Gold is present as 5 to 15 m grains in fractures of pyrite or as blebs at pyrite grain boundaries. Minor tellurides are present. The ore is free milling.

At Mt Percy, porphyries and basalts show a widespread sericite-carbonate-pyrite alteration. At the contacts with the mineralised porphyries, the ultramafics show a characteristic fuchsite alteration. Gold is associated with pyrite, although rare tellurides have been found (Sund & others, 1984).

Source of fluids, deposition of gold and geological setting

Light stable isotope studies on Kalgoorlie samples have generated a range of views on the possible fluid source. Early studies, such as by Golding (1982), favoured a metamorphic derivation of the ore fluids, but recent work by Clout (1989) has proposed a more mixed source. Greenschist facies metamorphism appears to be related to seafloor alteration, while the chlorite-calcite and lode alteration were invoked by varying proportions of magmatic and seawater or meteoric waters. The involvement of fluids other than that of metamorphic origin in the ore-forming processes has been supported by Sr isotope studies (Mueller & others, 1991).

Sulphur isotopes of the Golden Mile mineralisation reflect the rare, for Archaean gold deposits, oxidised nature of the ore fluids. Additional evidence for oxidised ore fluids is the presence of hematite, vanadium oxides and sulphates. The presence of oxidised fluids has been explained as the result of fluid-wall rock interaction (Phillips & others, 1986), or as a result of phase separation and/or mixing with surface fluids (Clout, 1989). The depletion in ^{34}S in the sulphides is caused by isotopic fractionation between pyrite and sulphates (Clout, 1989).

Fluid inclusions have provided some further constraints on the nature of the ore fluids, as well as on the temperature and pressures of deposition. Again, results of the various studies have been quite variable. Representative sampling in the large and complex lode system of the Golden Mile appears to be a major problem in achieving consistent results. Results reported by Ho & others (1990), mainly from late-stage Golden Mile mineralisation, display values typical for Archaean gold deposits: low to moderate salinities, 20-40 wt% CO_2, Tt of 195-355°C and Pt of 150 to 400 MPa. In contrast, Clout (1989) suggests much lower pressures, maximum 26 MPa, for the ore fluids, with gold being deposited in the 170 to 250°C range. From his work, fluid inclusions show widely varying salinities, most likely due to fluid mixing. Phase separation is proposed to explain homogenisation behaviour in lodes as well as in chlorite-calcite alteration veins. Based on fluid characteristics, Clout (1989) proposes that different fluids were involved in each of the stages of chlorite-calcite alteration, lode mineralisation and late extensions veins, although consistent K/Rb ratios for the alteration zones (Phillips, 1986) suggest that these fluids may have been generated from a single evolving source.

Sulphidation has been proposed as the major gold depositional mechanism at the Golden Mile, consistent with many Archaean gold deposits (e.g. Groves & Phillips, 1987). Fluid inclusions and the locally poor correlation between sulphide contents and gold values suggest that other mechanisms such as phase separation or fluid mixing may have played a role (Clout, 1989).

The structural, alteration, fluid inclusion and isotopic studies by Clout (1989), augmented by some zircon U-Pb age determinations, suggest a much higher level depositional environment for the Golden Mile mineralisation, in contrast to the more conventional Archaean mesothermal setting (e.g. Groves & Phillips, 1987).

Acknowledgements

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