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GEOLOGY AND MINERALIZATION OF THE SOUTH CENTRAL YILGARN CRATON WESTERN AUSTRALIA — A FIELD GUIDE KALGOORLIE '97

compiled by W. K. Witt

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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W. K. Witt

Contributions by

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— a field guide

Kalgoorlie '97

Introduction

This excursion guide examines the geological setting of mineralization in the south central Yilgarn Craton (Fig. 1) including the Ravensthorpe, Forrestania, and Lake Johnston greenstone belts. In addition to their common location, these greenstone belts are all relatively small or narrow and have all been metamorphosed at or close to amphibolite facies, suggesting that the present erosion level may expose the roots of greenstone belts at these localities.

Recent developments in the Forrestania greenstone belt include the commencement of gold mining at Bounty (Forrestania Gold NL) and definition of another gold deposit (3.5 t Au) at Mount Holland (Camelot Resources NL). Nickel sulphide deposits discovered by Amax Exploration (Australia) in the early 1970s at Digger Rocks, Cosmic Boy and Flying Fox have been mined in recent years by Outokumpu Mining Australia. Exploration by Forrestania Gold NL since 1991 has identified further nickel sulphide mineralization (13 Mt at 1.52% Ni and 0.05% Co) at Maggie Hays in the Lake Johnston greenstone belt. Since 1990, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has studied the nickel mineralization and their komatiitic host rocks at Forrestania and Maggie Hays. Results of this research have been published and are covered in this excursion guide. Also covered in this guide is the Bounty gold mine (45 t of gold), which is hosted by quartz veins in banded iron-formation (BIF).

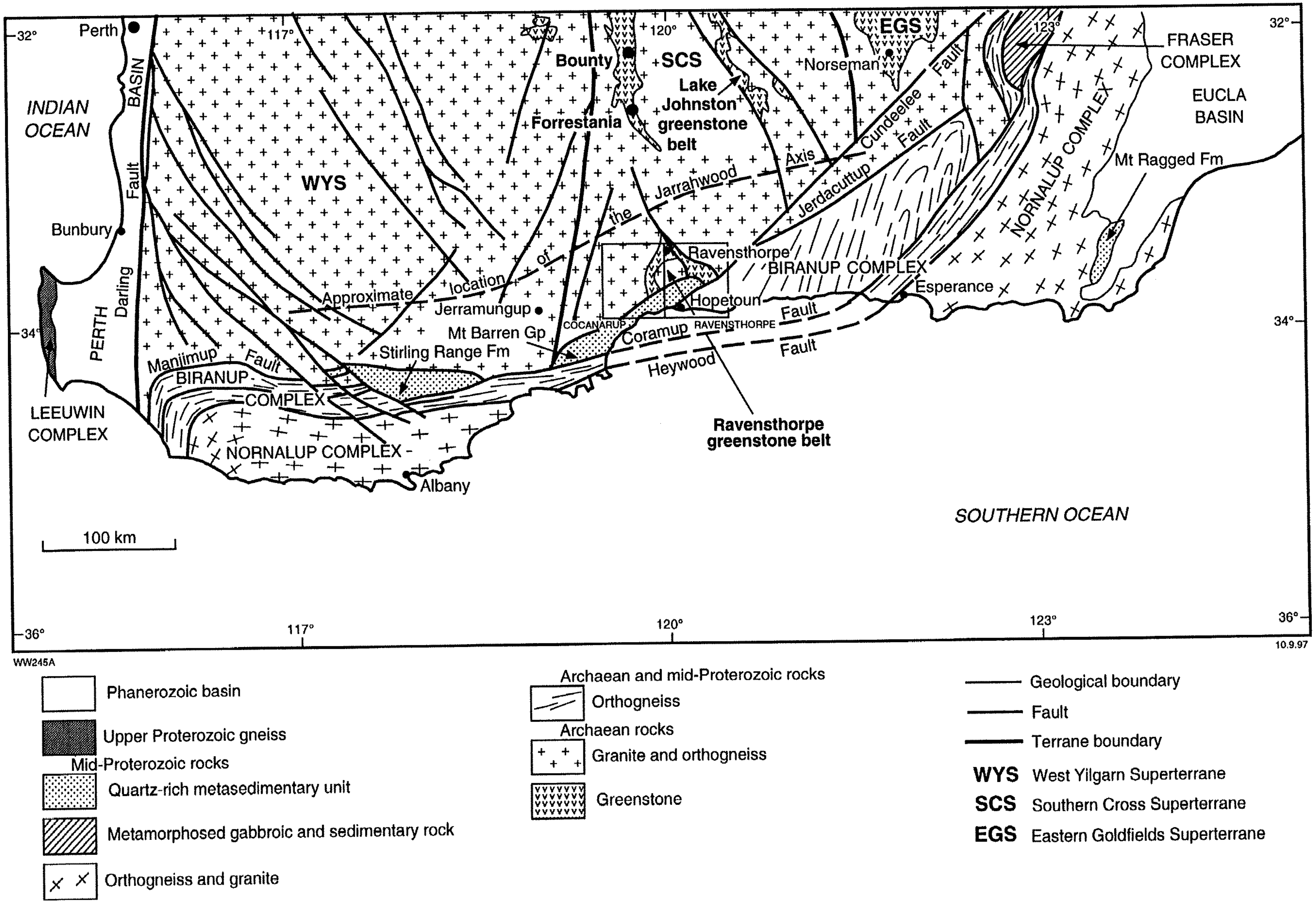

Figure 1. Regional geology of the south central Yilgarn Craton (after Myers and Hocking, 1988) showing excursion localities

I. Geology and metallogeny of the Ravensthorpe greenstone belt

by

W. K. Witt[1]

The first half of this guide examines a range of mineralization styles and their geological setting in the Ravensthorpe greenstone belt. This follows regional mapping of RAVENSTHORPE[2] and COCANARUP (1:100 000) by the Geological Survey of Western Australia (GSWA) during the period 1992–1994. A new tectonic model that envisages accretion of two distinct terranes has emerged from this mapping. Despite the diversity of mineralization styles in the Ravensthorpe greenstone belt, and a long history of copper and gold mining, there have been no significant mining developments in recent years. This situation is set to change with mining of tantalum (Greenstone Resources NL), nickel laterite (Comet Gold NL) and nickel sulphide (Tectonic Resources NL) resources likely to commence in the next few years. Copper–zinc mineralization at West River (Copper King, Last Venture) has long been regarded as one of the few known sites of stratabound volcanogenic base-metal sulphide mineralization in the Yilgarn Craton. Copper and gold have also been mined since 1899 from vein- and shear-hosted deposits at Ravensthorpe, Mount McMahon, Elverdton and Kundip. These deposits have been variously regarded as remobilized stratiform sulphide (Marston, 1979) or porphyry copper (Sofoulis, 1958; Savage, 1992) styles of mineralization. Recent investigations (Witt, in prep.) suggest that they are feeder zones to volcanogenic sulphide mineralization, similar to that at West River. The Ravensthorpe Terrane therefore emerges as an important volcanogenic base-metal district, an observation that is made all the more significant by the relative paucity of known examples of this style of mineralization in the Yilgarn Craton.

This excursion guide should be used in conjunction with the RAVENSTHORPE–COCANARUP Explanatory Notes (Witt, 1997), which describe the context for the locality descriptions that follow (Fig. 2). Although all Archaean rocks have been metamorphosed to at least upper greenschist facies, igneous rock nomenclature has been used where primary structures and textures have been preserved.

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1 Geological Survey of Western Australia, 100 Plain Street, East Perth, W.A. 6004.
Present address: Sons Of Gwalia Ltd, 16 Parliament Place, West Perth, W.A. 6005.

2 Capitalized names refer to standard map sheets

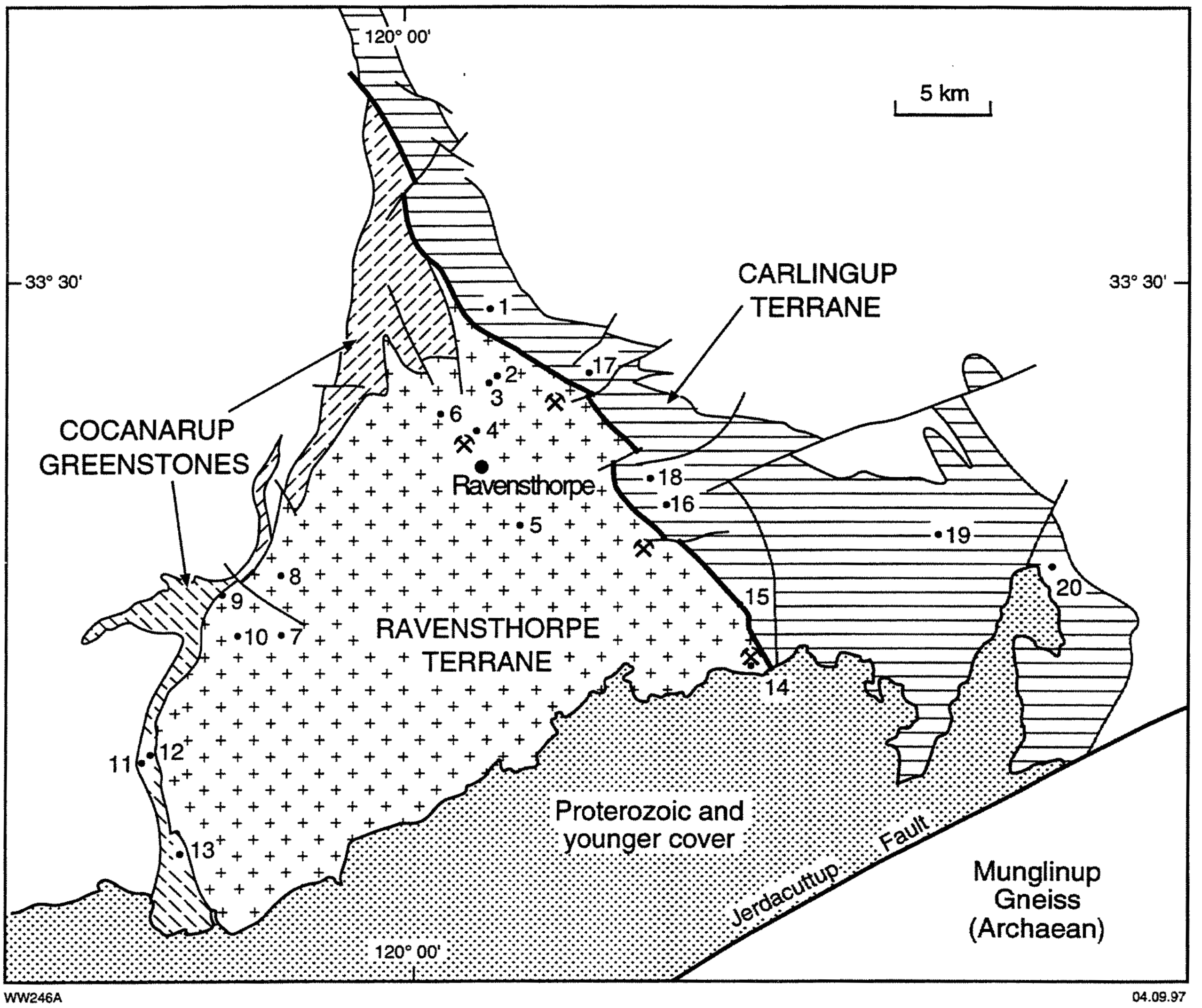


Figure 2. Ravensthorpe greenstone belt showing excursion localities

Ravensthorpe greenstone belt

The Ravensthorpe greenstone belt has been subdivided into three tectonostratigraphic units. These are the Carlingup Terrane, the Ravensthorpe Terrane and the Cocanarup greenstones (Fig. 3).

The Carlingup Terrane contains pelitic to psammitic metasedimentary rocks, BIF and metamorphosed ultrabasic to basic volcanic rocks (Fig. 4). Minor dacitic to rhyolitic rocks are also present and have yielded U–Pb in zircon (SHRIMP) geochronological data that indicate an age of 2958 ± 4 Ma for the Carlingup Terrane (Nelson, 1995). The nature of the metasedimentary rocks suggests deposition in a low-energy, shallow-water environment, comparable to the 'platform

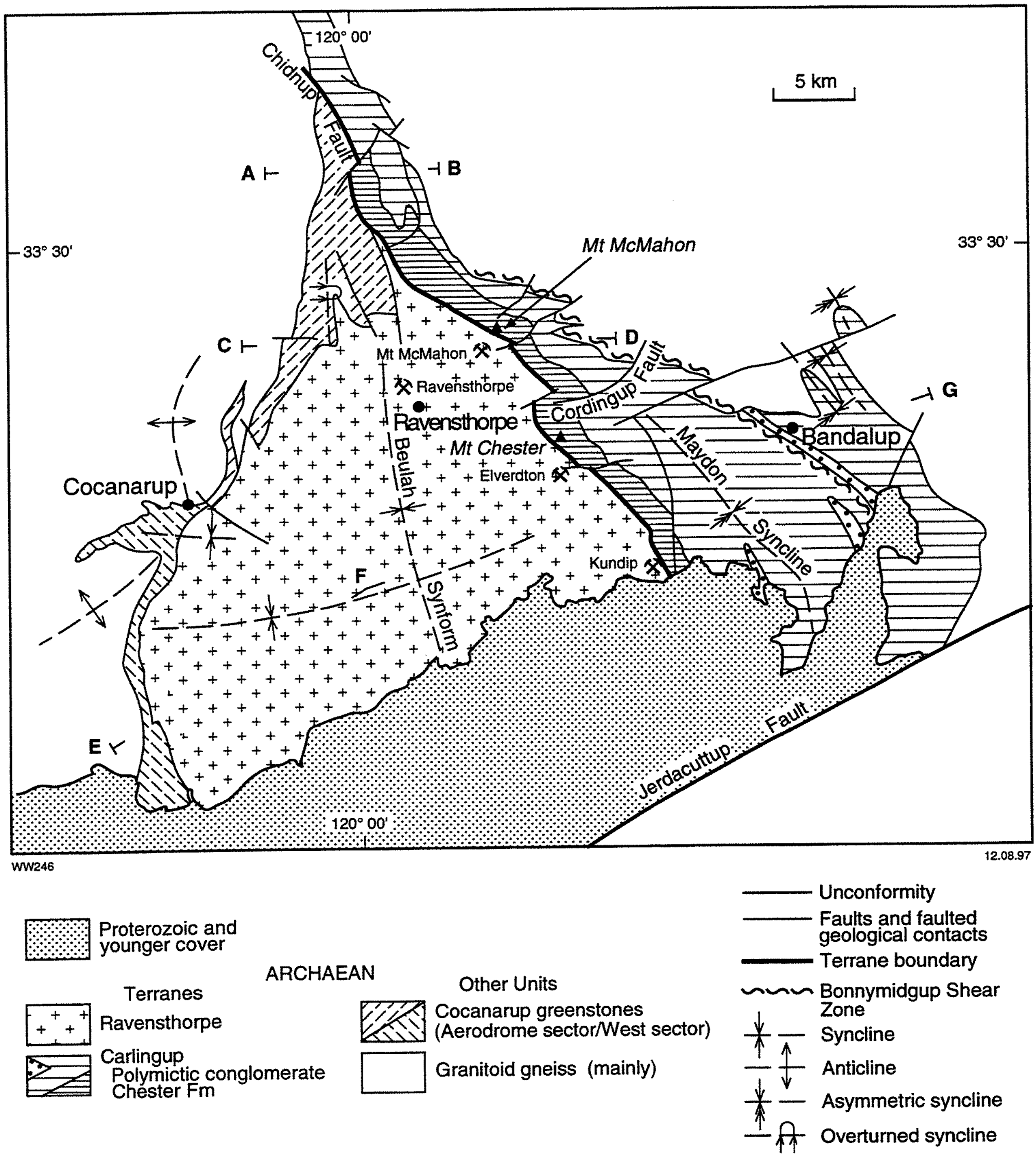


Figure 3. The main tectonostratigraphic units of the Ravensthorpe greenstone belt and adjoining areas. Also shown are some of the main structures and the four Cu–Au mining districts

greenstones' (Groves and Batt, 1984) that also characterize the Forrestania greenstone belt. Witt (in prep.) suggests a continental rift setting for the Carlingup Terrane.

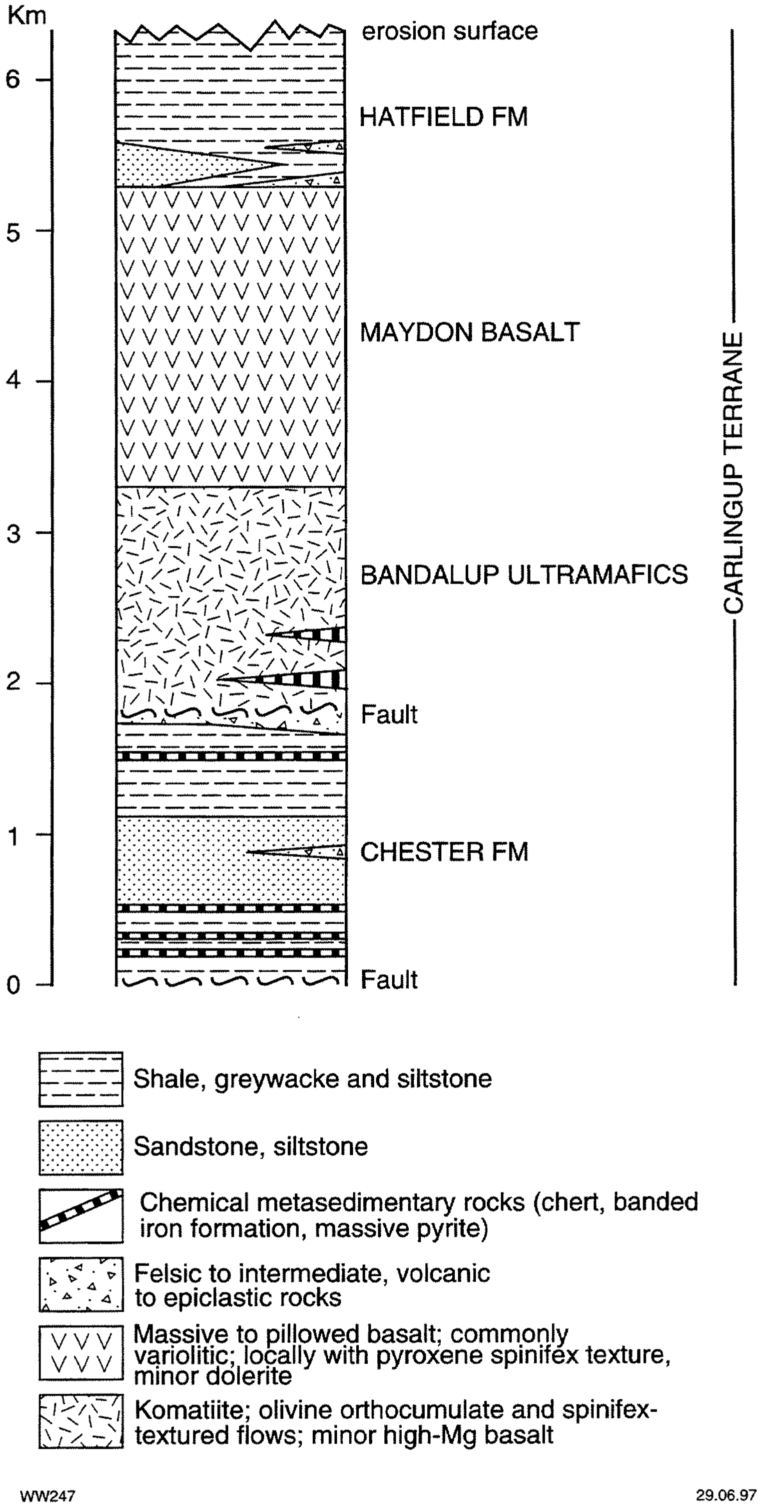


Figure 4. Stratigraphy of the Carlingup Terrane

The Ravensthorpe Terrane (Fig. 5) comprises a calc-alkaline intrusive–extrusive association (Manyutup Tonalite and Annabelle Volcanics) that has been dated at c. 2970–2980 Ma for the Ravensthorpe Terrane (Savage et al., 1995). The intimate spatial association of tonalite, tonalite porphyry dykes and calc-alkaline volcanic rocks suggests a comagmatic relationship between all

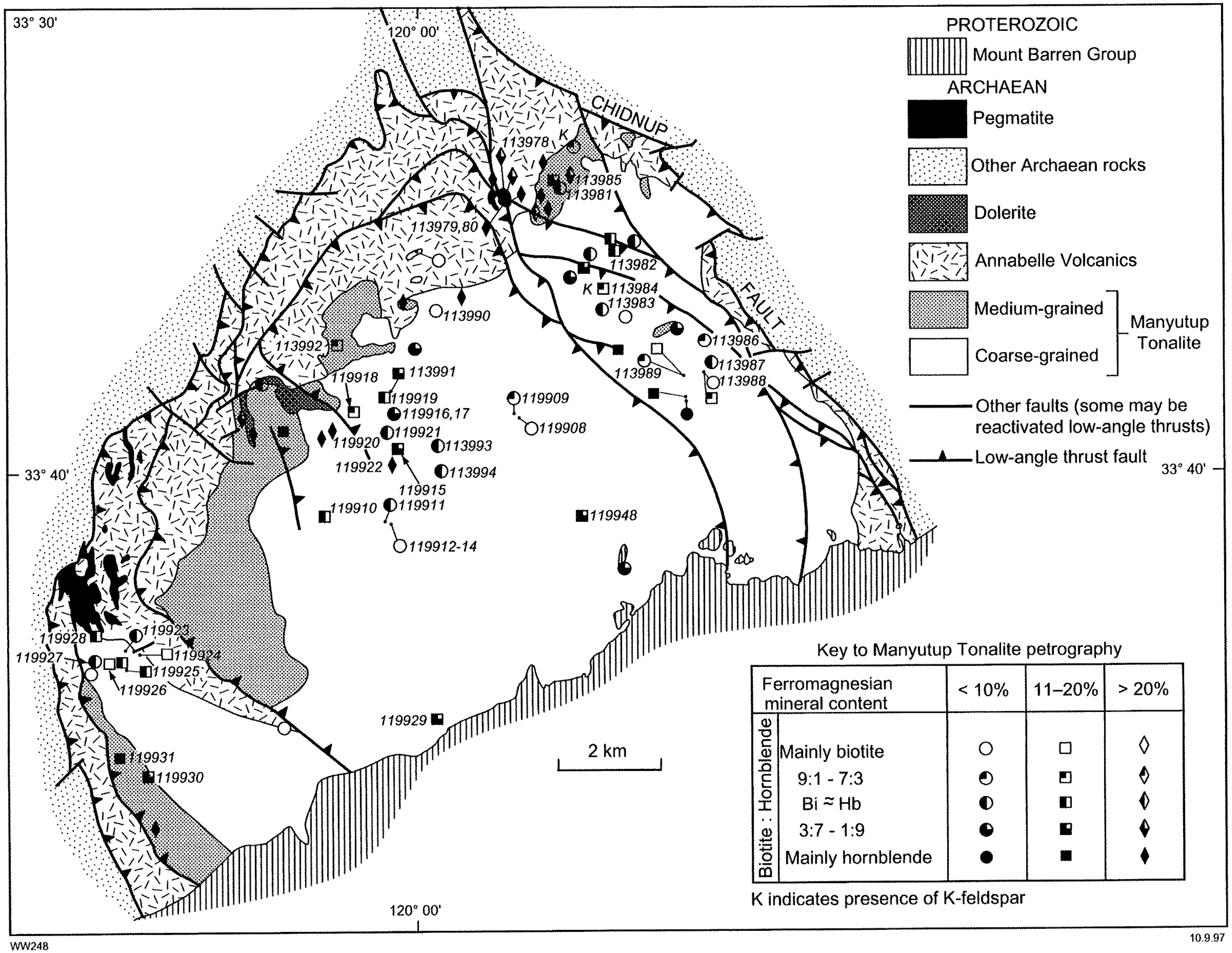


Figure 5. Geology of the Ravensthorpe Terrane showing location of whole-rock geochemical samples (see Figures 6, 7)

three and this is supported by whole-rock chemical data (Witt, in prep.). These data define two suites: a low-SiO_2 suite that extends from 49.4 to 58.1% SiO_2 and a high-SiO_2 suite that includes samples with up to 76.0% SiO_2 (not normalized to exclude volatiles). The low-SiO_2 suite produces somewhat scattered plots for many elements whereas the high-SiO_2 suite produces relatively coherent plots that define a decrease in the values of Mg#, CaO, Al_2O_3, FeO*, Ni, V, Co and Cu with increasing SiO_2 (Figs 6, 7). Both suites include tonalite, porphyry dykes and volcanic rocks.

Calc-alkaline volcanic associations are relatively uncommon in the Yilgarn Craton. Andesitic stratovolcanos, such as those that were the source for volcanogenic debris in the Annabelle Volcanics, typically occur in destructive continental margin settings as components of continental or oceanic island arcs (Fisher and Schminke, 1984; Wilson, 1989).

Interpreted cross sections through the Ravensthorpe greenstone belt are shown in Figure 8. The distribution of metamorphic isograds in the Ravensthorpe greenstone belt is shown in Figure 9. Despite the similar ages, the two terranes have distinctive lithostratigraphic associations and preserve evidence of independent tectonothermal histories prior to accretion with one another (Witt, in prep.). The two terranes were brought together during an accretionary event that saw the Ravensthorpe Terrane thrust eastward over the Carlingup Terrane (Fig. 10).

The three tectonostratigraphic units are fault-bounded. The tectonic contact between the Carlingup Terrane and the Ravensthorpe Terrane has been observed in drillcore (Witt, 1997). Additional evidence for a tectonic contact between the two terranes includes the following.

- Gross contact relationships indicate that, unlike units in the Carlingup Terrane, those in the Ravensthorpe Terrane have not been folded about the Maydon Syncline.

- The Manyutup Tonalite contains abundant xenoliths of Annabelle Volcanics but xenoliths of rocks from the Carlingup Terrane are absent despite close proximity to contacts with Manyutup Tonalite in some areas.

- There are thin slices of ultramafic schist on the tectonic contact between the two terranes.

Lenses of polymictic conglomerate within the Carlingup Terrane contain clasts derived from the Ravensthorpe Terrane but clasts of rock types that characterize the Carlingup Terrane have not been observed. These conglomerates are interpreted to have formed by erosion of uplifted tonalite and calc-alkaline volcanic rocks as the Ravensthorpe Terrane was thrust over the Carlingup Terrane.

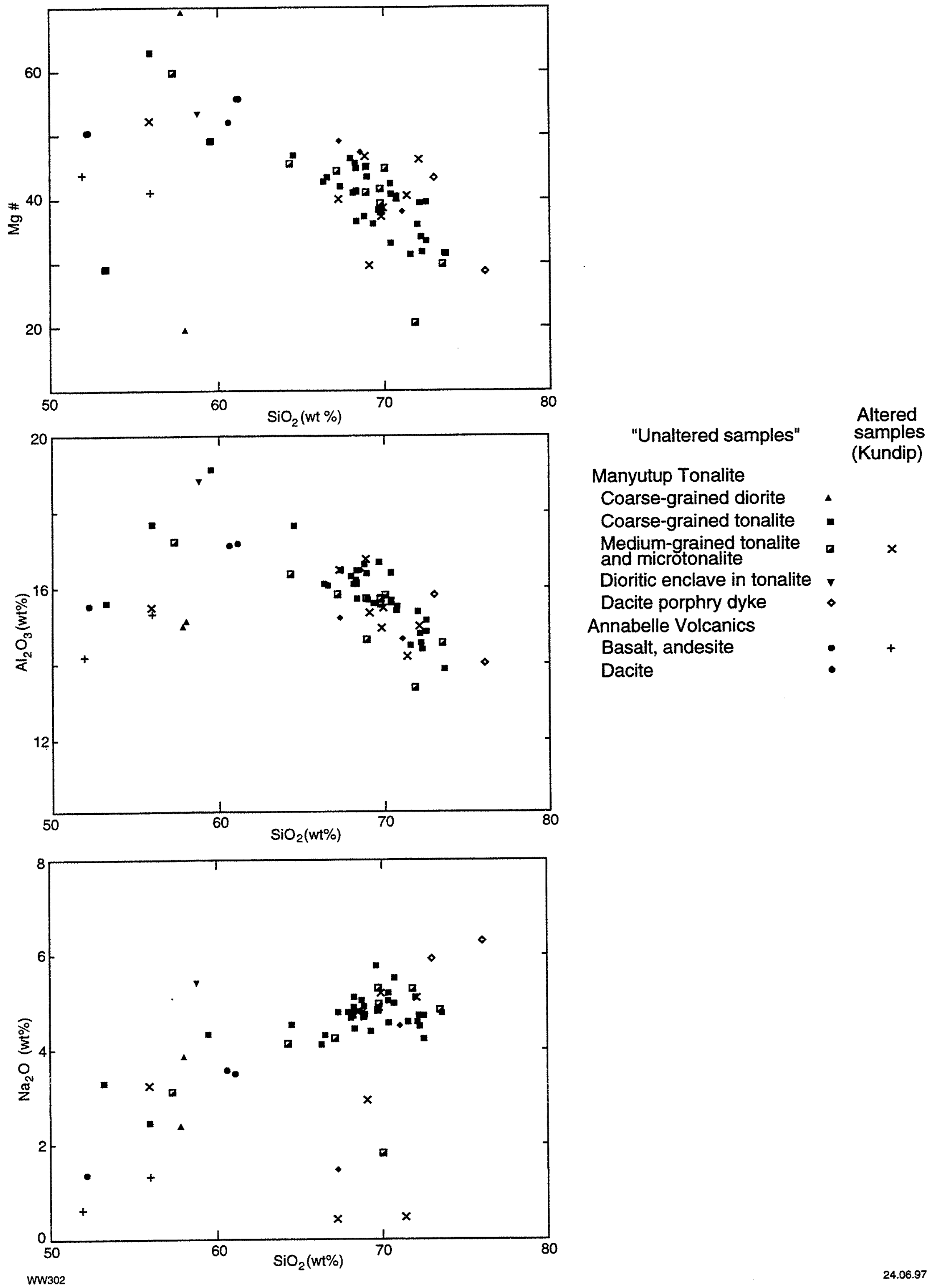


Figure 6. Harker variation diagrams showing Mg#, Al_2O_3, and Na_2O for calc-alkaline igneous rocks of the Ravensthorpe Terrane

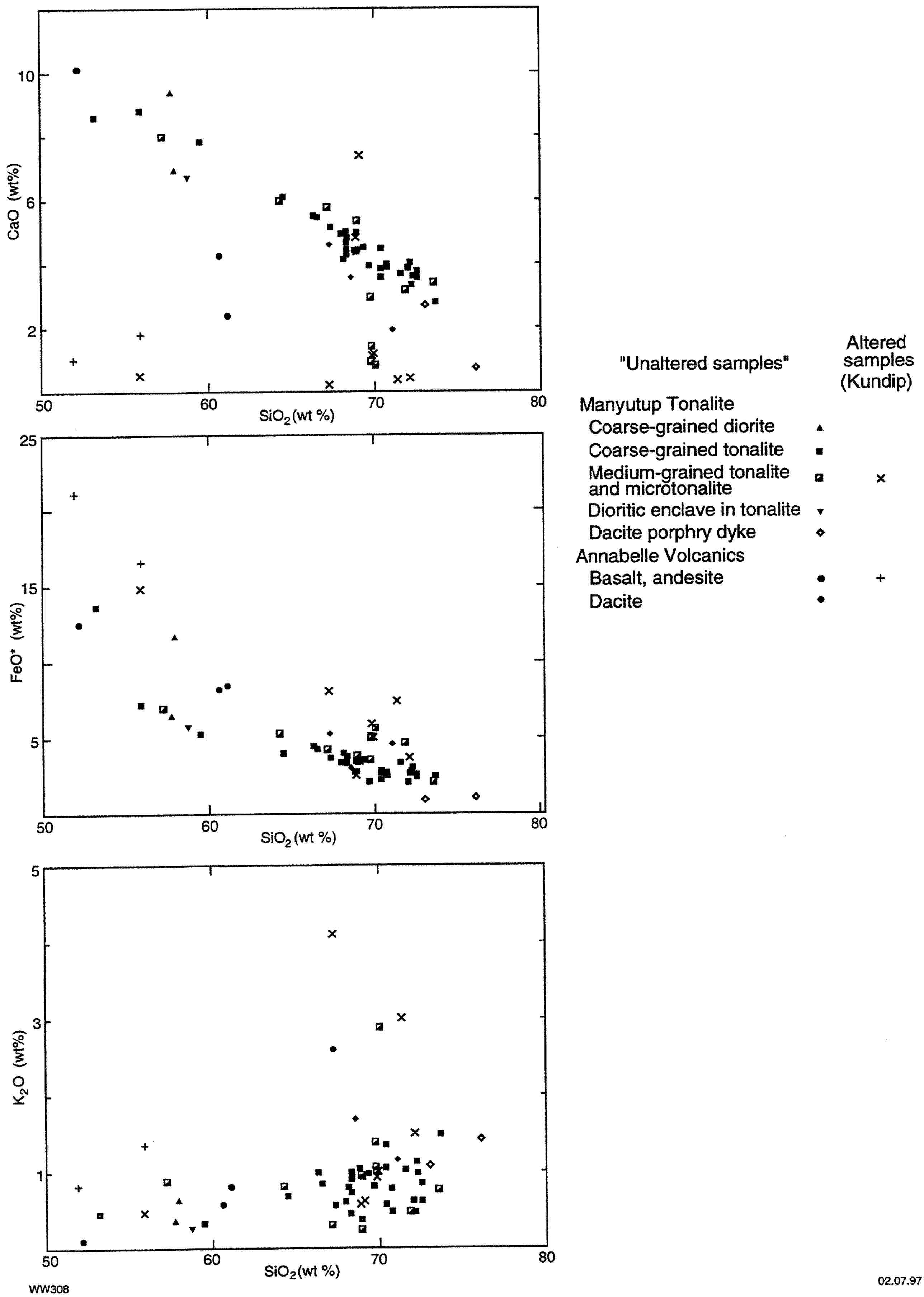


Figure 6. (continued) Harker variation diagrams showing CaO, FeO*, and K_2O for calc-alkaline igneous rocks of the Ravensthorpe Terrane

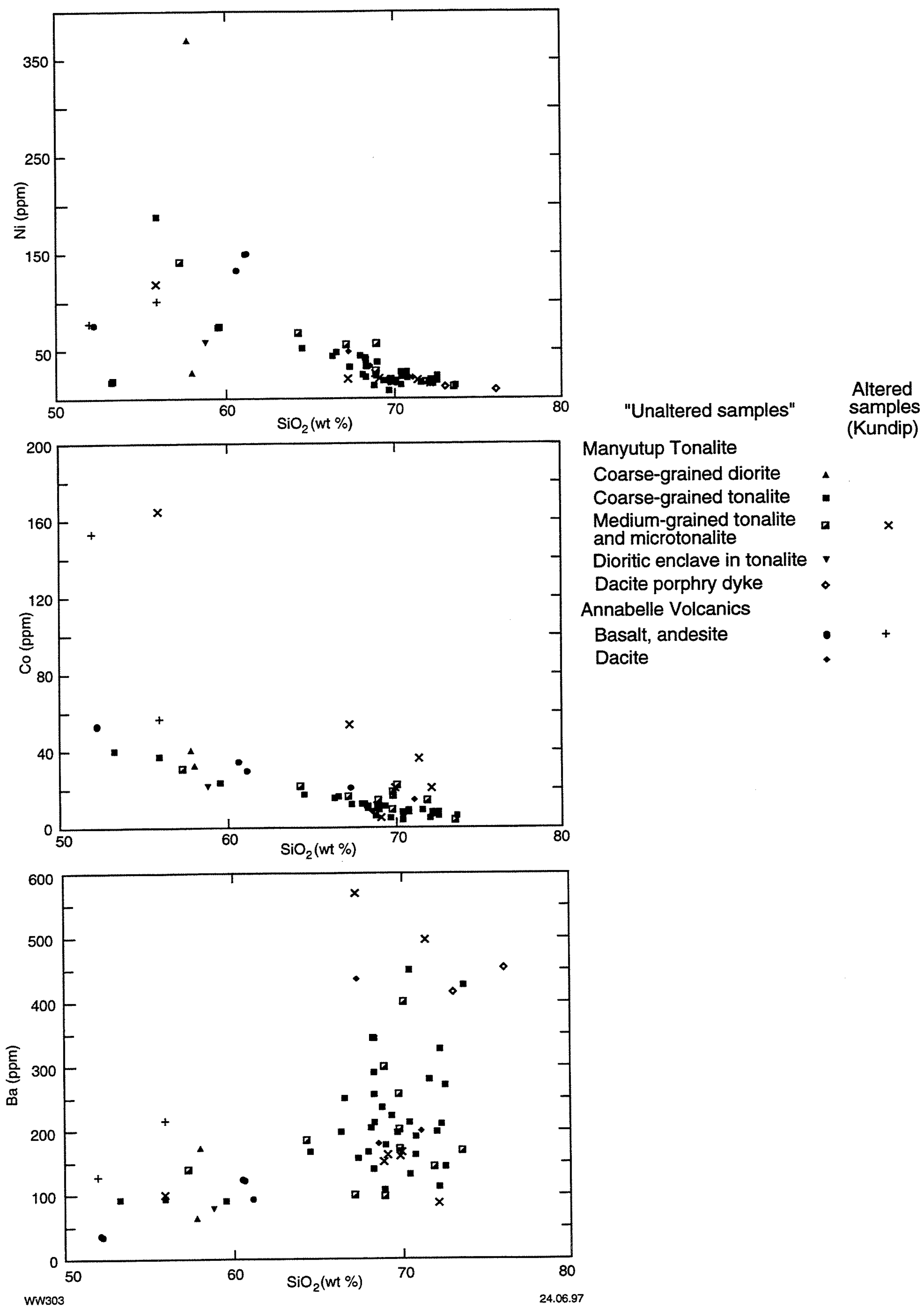


Figure 7. Harker variation diagrams showing Ni, Co, and Ba for calc-alkaline igneous rocks of the Ravensthorpe Terrane

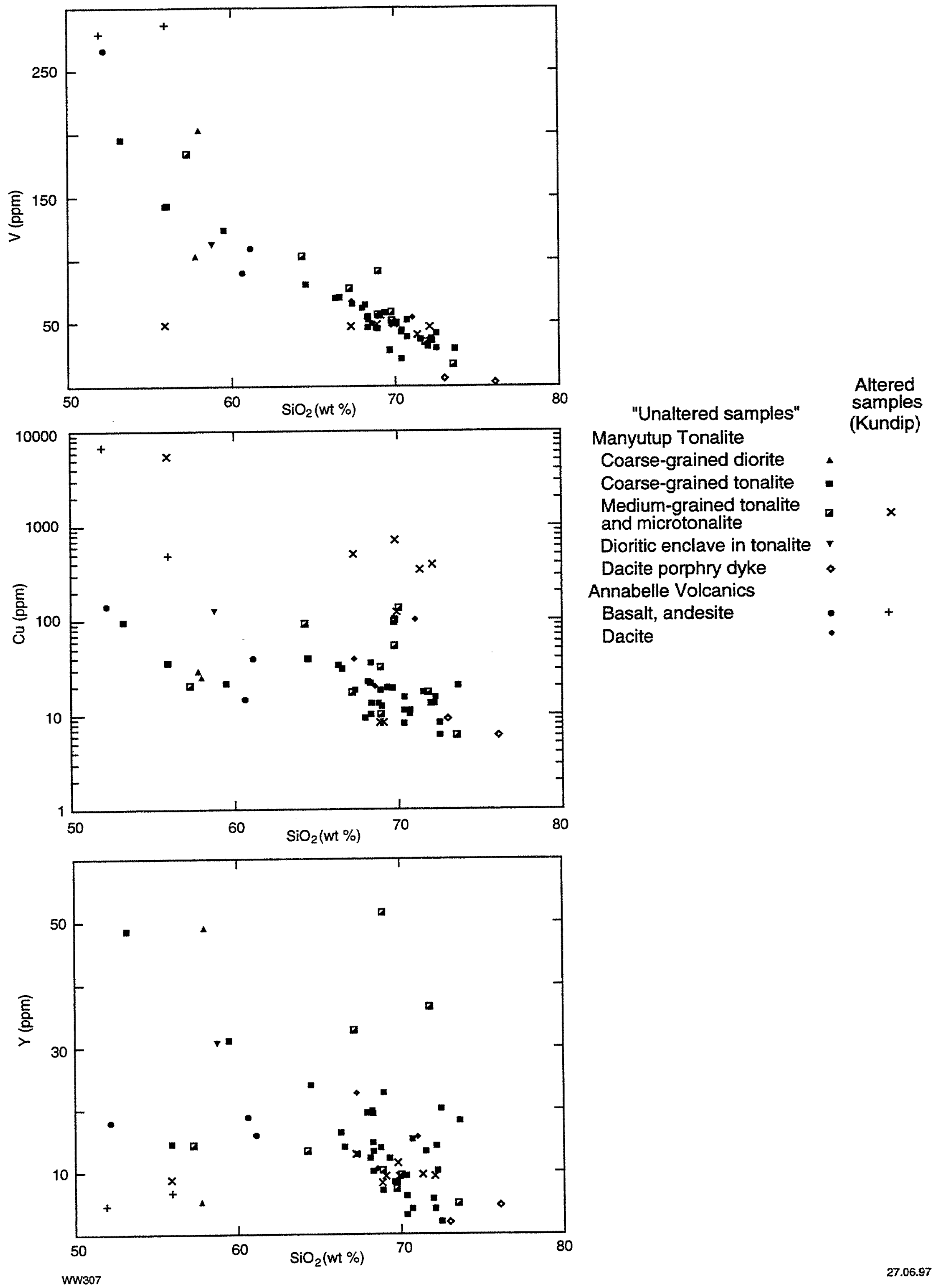


Figure 7. (continued) Harker variation diagrams showing V, Cu, and Y for calc-alkaline igneous rocks of the Ravensthorpe Terrane

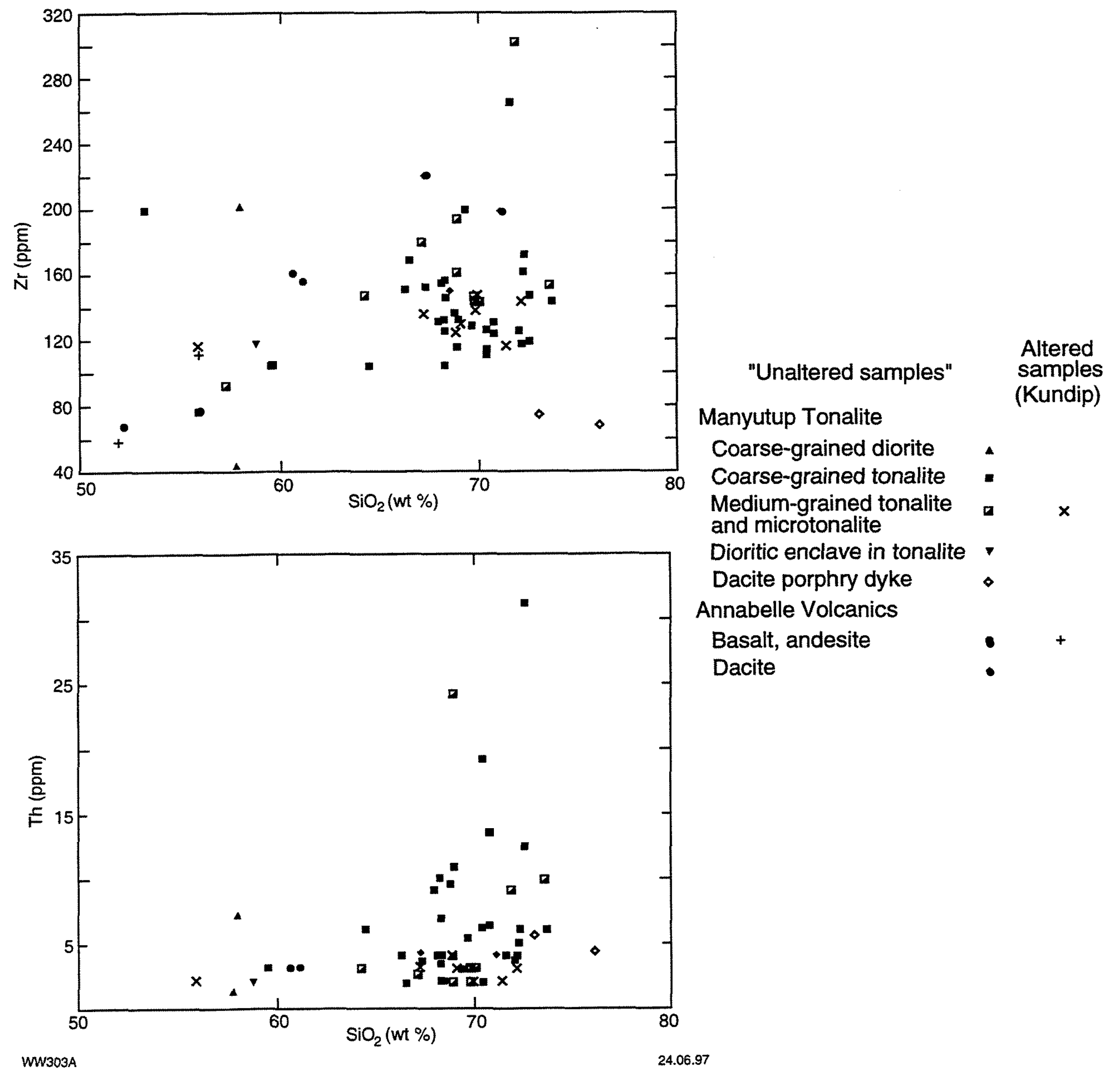


Figure 7. (continued) Harker variation diagrams showing Th and Zr for calc-alkaline igneous rocks of the Ravensthorpe Terrane

The Ravensthorpe Terrane itself appears to be a complex of thrust slices, some of which are demarcated by slices of ultramafic schist, calc-silicate rock or swarms of pegmatite dykes.

Gross geometric relationships also indicate a tectonic contact between the Ravensthorpe Terrane and the Cocanarup greenstones. Northwest of Ravensthorpe, the boundary between the two stratigraphic units cuts tight to isoclinal, macroscopic folds in the Cocanarup greenstones. The affiliation of the Cocanarup greenstones is uncertain but interpreted P–T–t paths suggest they were uplifted with the Ravensthorpe Terrane during accretion (Witt, in prep.).

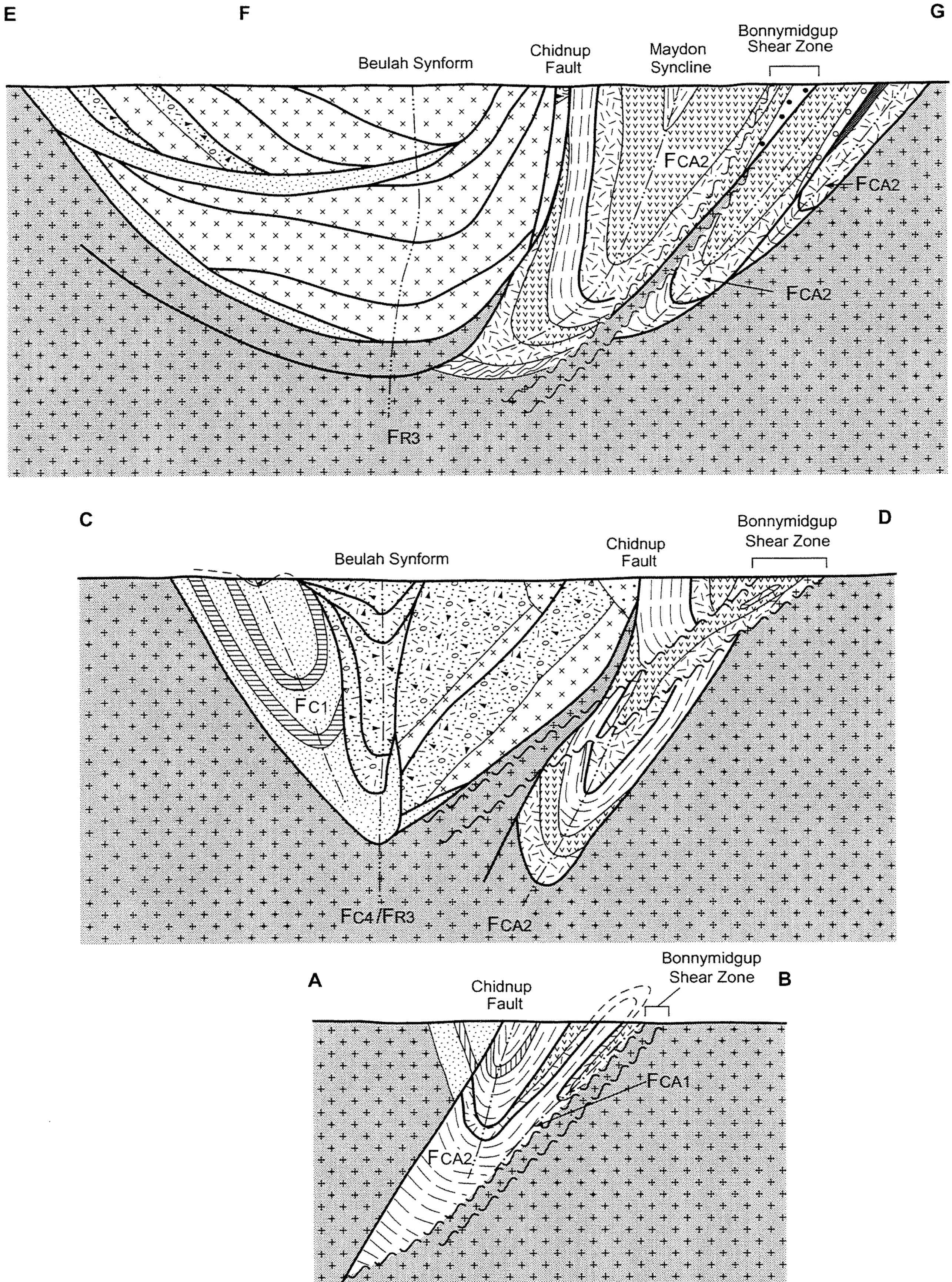
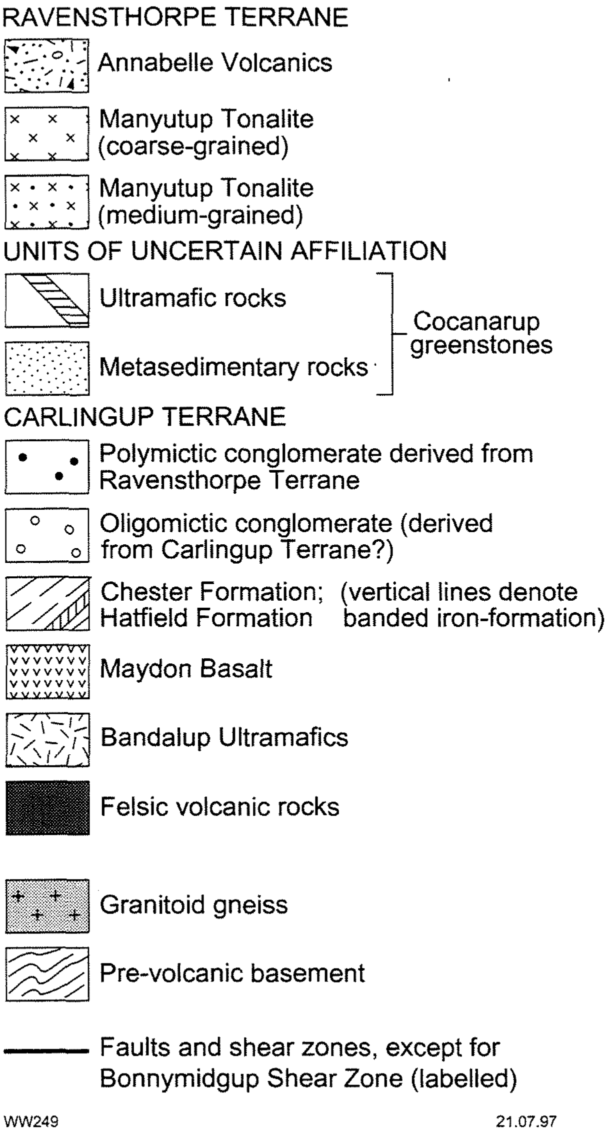


Figure 8. Interpreted cross sections through the Ravensthorpe greenstone belt. See Figure 3 for the location of sections A–B, C–D and E–F–G



There is a range of mineralization styles in the Ravensthorpe greenstone belt and they can be placed in the context of the geological history of the belt, as follows.

Mineralization

Pre-accretion mineral deposits

Ravensthorpe Terrane

Copper–zinc and copper–gold(–silver): Stratabound, volcanogenic base- and precious-metal deposits formed in the Ravensthorpe Terrane (mainly in Annabelle Volcanics) prior to deformation and metamorphism.

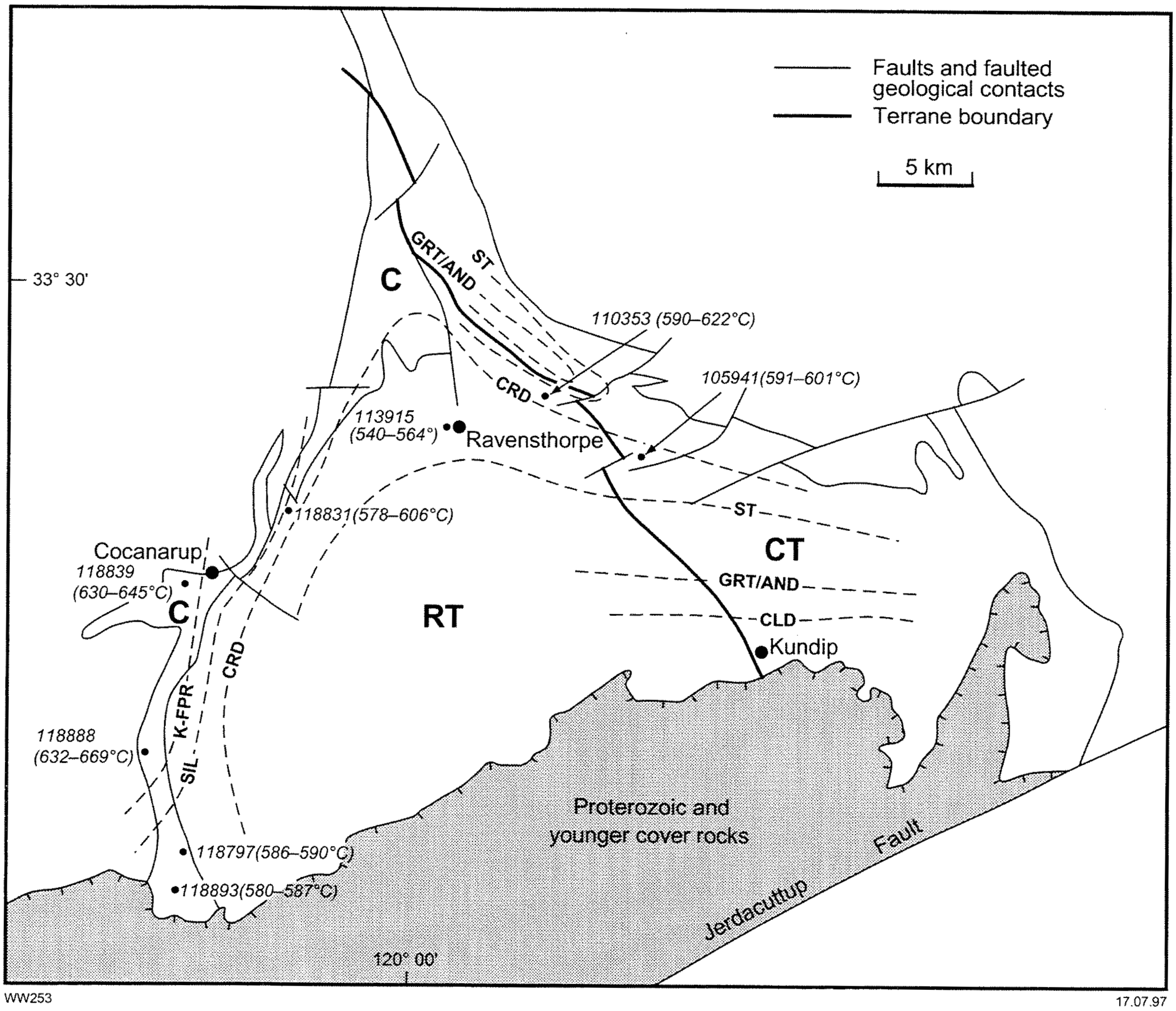


Figure 9. Distribution of metamorphic isograds in the Ravensthorpe greenstone belt, based on metamorphic mineral assemblages. Small dots represent locations of samples where peak metamorphic temperatures have been estimated from garnet–biotite geothermometry. GRT — garnet; AND — andalusite; ST — staurolite; CRD — cordierite; CLD — chloritoid; K-FPR — K-Feldspar; SIL — sillimanite; C — Cocanarup greenstones; RT — Ravensthorpe Terrane; CT — Carlingup Terrane

Carlingup Terrane

Magmatic nickel sulphides: Komatiite-hosted nickel sulphide deposits are found mainly along the northeast margin of the Carlingup Terrane.

Massive pyrite: Stratabound and stratiform, massive to bedded pyrite was deposited with fine-grained, clastic sediments in the Chester Formation of the Carlingup Terrane.

Manganese: Sedimentary manganese oxides were deposited during deposition of the Chester Formation.

?Epithermal gold: Stratabound gold in chert units of the Chester Formation (e.g. Mount Iron) may have an epithermal origin.

Syn-accretion mineral deposits

Gold associated with quartz veins: Gold-rich quartz vein deposits in the Ravensthorpe Terrane may have been remobilized from synvolcanic copper–gold mineralization during terrane accretion.

Lithium and tantalum in pegmatites: Pegmatite swarms were emplaced into syn-accretion thrust faults during accretion. Some of the more fractionated of these intrusions contain subeconomic to economic concentrations of lithium and tantalum.

Post-accretion mineral deposits

Nickel laterite: Nickel laterite at Bandalup Hill formed during Tertiary weathering of Archaean ultramafic rocks (Bandalup Ultramafics).

Magnesite: Massive to nodular magnesite formed from magnesia liberated from the Bandalup Ultramafics and redeposited at the base of the Tertiary Pallinup Siltstone, as a result of Tertiary weathering.

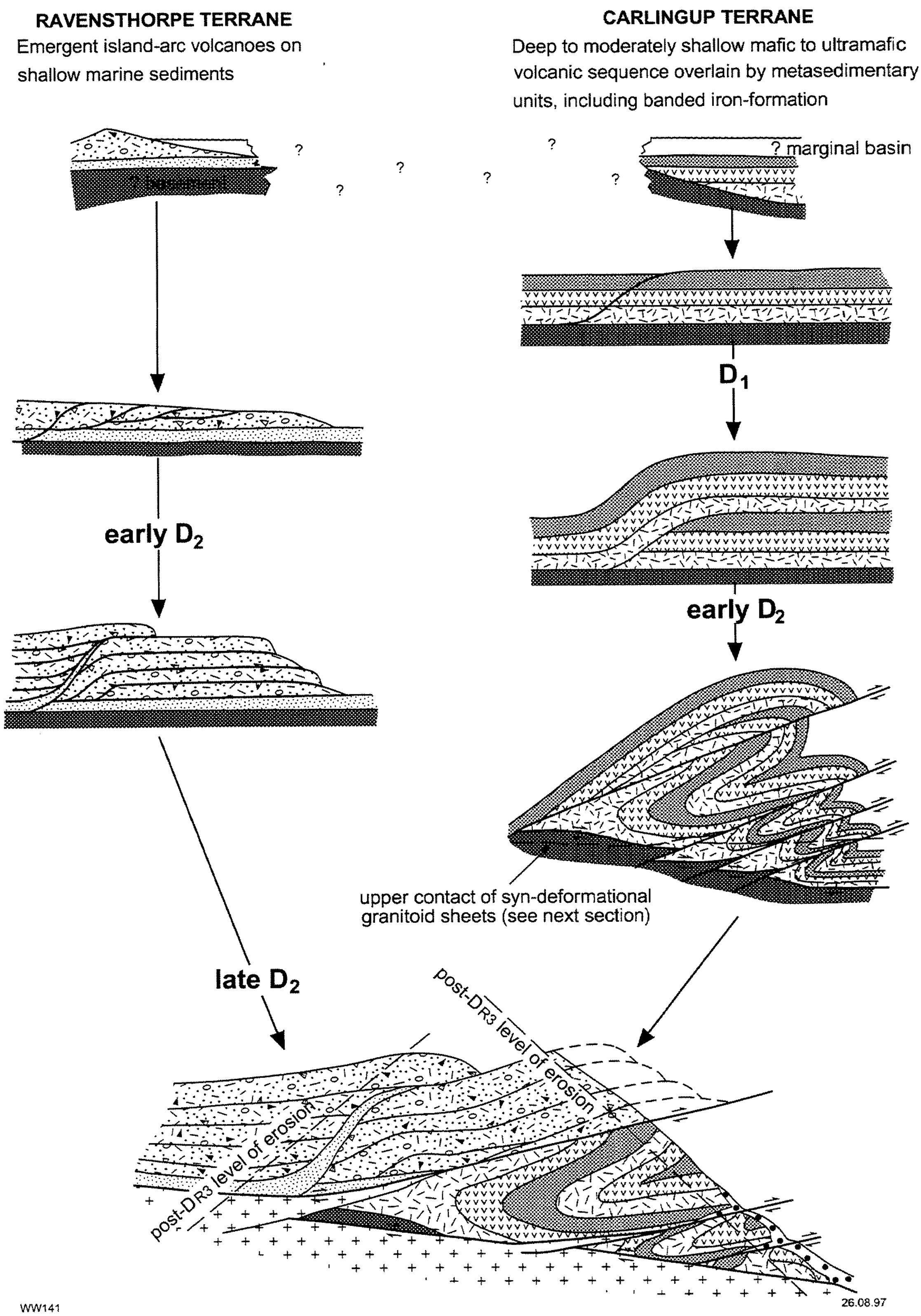
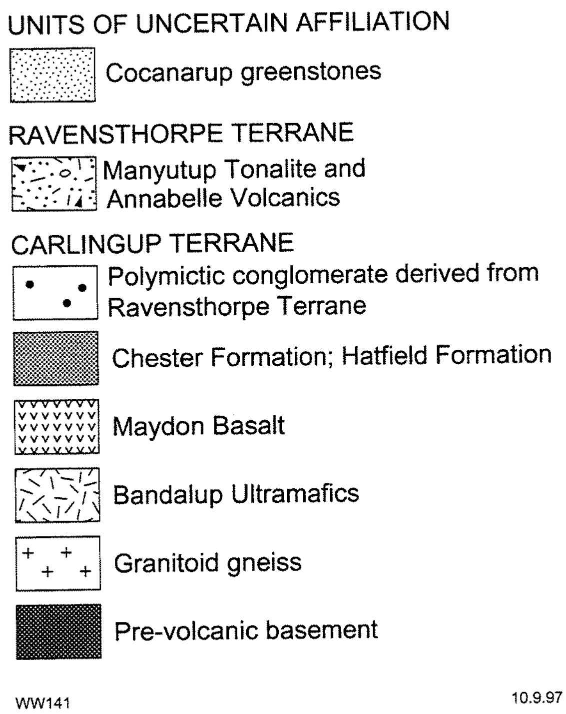


Figure 10. Schematic cross section illustrating the structural evolution of the Carlingup Terrane, Ravensthorpe Terrane and the Cocanarup greenstones, up to the time of amalgamation (prior to formation of the Beulah synform). This interpretation assumes depositional equivalence of the Chester and Hatfield Formations


UNITS OF UNCERTAIN AFFILIATION
Cocanarup greenstones
RAVENSTHORPE TERRANE
Manyutup Tonalite and Annabelle Volcanics
CARLINGUP TERRANE
Polymictic conglomerate derived from Ravensthorpe Terrane
Chester Formation; Hatfield Formation
Maydon Basalt
Bandalup Ultramafics
Granitoid gneiss
Pre-volcanic basement
WW141
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II. Ravensthorpe greenstone belt excursion localities

by

W. K. Witt

The deformation terminology used in the following descriptions refers to deformation events in the Carlingup Terrane as D_{CA}-, those in the Ravensthorpe Terrane as D_R- and those in the Cocanarup greenstones as D_{CO}-. The correlations between these events is summarized in Table 1.

Locality 1. Ravensthorpe Ranges Lookout (AMG 51 2256 62875*)

Leave Ravensthorpe along Scott Street and proceed north for 7.7 km along the Old Newdegate Road to Archer Drive and turn right. It is a further 1.8 km to the lookout.

The lookout from the Ravensthorpe Ranges provides a good overview of the district and some of its major geological features. The Ravensthorpe Ranges are formed by chert and BIF ridges that are part of the Chester Formation. Mount Chester (340 m) is visible to the southeast, and beyond that the Kundip mining centre. The contact between the Carlingup Terrane and the Ravensthorpe Terrane lies near the western foothills of the Ravensthorpe Ranges, and Kundip lies within the Ravensthorpe Terrane. The Albany–Esperance highway passes through a gap in the ranges caused by dextral offset of the Chester Formation across the Cordingup Fault.

To the south, the low ground between the lookout and the town of Ravensthorpe is underlain by the Annabelle Volcanics. Manyutup Tonalite outcrops sporadically to the south of Ravensthorpe. Together, these units constitute the greater part of the Ravensthorpe Terrane. Farther south, the prominent ridges on the skyline (East Mount Barren, Eyre Range, Whoogarup Range) are formed by Kundip Quartzite of the Mesoproterozoic Mount Barren Group.

To the southwest, Overshot Hill in the middle distance is a relict of a formerly more extensive lateritic duricrust. Behind Overshot Hill, the hills on the skyline represent the West River greenstone belt and consist of deformed equivalents of Annabelle Volcanics and the Cocanarup greenstones.

* Grid references are specified using Australian Map Grid (AMG) coordinates in which the first set of characters refers to the map zone, and the subsequent sets of four figures (eastings) and five figures (northings) uniquely define the position to within 100 m

Table 1. Correlation of deformation events in Archaean tectonostratigraphic units

	Cocanarup greenstones		*Ravensthorpe Terrane*		*Carlingup Terrane*
D_{CO1}, D_{CO2}	(north–south and northeast–southwest compression)	D_{R1}		D_{CA1}	(subhorizontal, ?south to north movement)
•	Poorly understood but indicated by subhorizontal lineations and moderately south-plunging boudins on granitoid gneiss–greenstone contact	•	Poorly understood but indicated by steep bedding attitudes in Ravensthorpe – Elstree Farm area	•	Tight to isoclinal folds, especially in metasedimentary units including BIF
				•	Irregular interleaving of units and low-angle thrust faults
•	?Tight to isoclinal folds			•	Early fabric preserved in porphyroblasts and low-strain domains in Chester Formation metasedimentary rocks
D_{CO3}	(east to west transport)	D_{R2}		D_{CA2}	(west to east transport)
•	Down-dip lineations on granitoid gneiss–greenstone contact	•	Zones of deformation on contracts with adjoining tectonic units, and contact-parallel deformation within the Ravensthorpe Terrane rocks	•	Maydon Syncline and related structures; asymmetric, overturned (to ?recumbent), vergence to east, sheared out anticlines
•	?Tight to isoclinal folds			•	Mesoscopic, reclined folds in Chester Formation
				•	Dominant northwest-trending foliation
			Amalgamation of Ravensthorpe and Carlingup Terranes		
D_{CO4}	(east-west compression)	D_{R3}	(east–west compression)	D_{CA3}	(east–west compression)
•	Beulah synform and north–south antiformal axis, near Cocanarup	•	Beulah synform	•	Rotation of all structures and gneissic granitoid–greenstone contact to form Beulah synform)
D_{CO5}	(north–south compression)	D_{R4}	(north–south compression)	D_{CA4}	(north–south compression)
•	Easterly trending folds in Cocanarup area	•	Basinal structure of Ravensthorpe Terrane; uplift of tonalite in southern part of Beulah synform	•	Reverse movement on Bonnymidgup Shear Zone
				•	Small-scale, open folds with steep easterly trending axial planes

Locality 2 is located in the uncleared eucalypt woodland to the south, between the lookout and the town of Ravensthorpe.

Locality 2. Annabelle Volcanics (AMG 51 2264 62840)

This locality is approached via a gate that leads into a paddock on the eastern side of the Old Newdegate Road, 4.9 km out of Ravensthorpe. At this point, the historic Floater gold mine and battery are located in the paddock to the west of the Old Newdegate Road. The Floater mine (350 kg Au) was one of the larger gold producers of the Ravensthorpe district. It is 1.6 km from the gate to the creek section where the Annabelle Volcanics can be examined.

Massive to coarsely bedded, dacitic to andesitic volcaniclastic rocks, including tuff, lapilli tuff and agglomerate (or related, immature epiclastic sedimentary rocks) can be examined by walking upstream several hundred metres from where the track crosses the creek. Poorly sorted, matrix-supported and clast-supported agglomeritic rocks (or ?volcaniclastic cobble conglomerate) consist of dacitic clasts in a mafic to intermediate matrix dominated by amphibole and plagioclase. Lapilli tuff consists of mafic clasts (?after chloritized dacitic glass) in a fine-grained dacitic matrix. There are also some units of dacitic tuff or volcaniclastic sandstone with crystal fragments of plagioclase and amphibole, and dolerite.

Numerous veinlets, mostly of dark green amphibole, with thin, bleached (?albitic) halos are evidence of widespread hydrothermal activity. Where the volcaniclastic rocks are foliated, these veins appear to record the same deformation, suggesting the hydrothermal activity may have been synvolcanic. Quartz and carbonate veinlets are less clearly deformed and may represent a later (?late syntectonic) period of hydrothermal activity.

This volcaniclastic association is interpreted as a rapidly deposited, proximal, subaqueous, pyroclastic to epiclastic sequence and is typical of those associated with mass wastage of emergent, calc-alkaline volcanic cones (Cas and Wright, 1987).

Locality 3. Bullfinch gold mine (AMG 51 2256 62839)

The Bullfinch gold mine is located approximately 1 km back toward the Old Newdegate Road.

The Bullfinch gold mine is one of several historic mines north of Ravensthorpe that produced minor amounts gold and little or no copper from quartz veins in the Annabelle Volcanics. The relatively low sulphide contents of the auriferous quartz veins is typical of Archaean, late-orogenic lode-gold deposits (Witt and Vanderhor, in press) and can be contrasted with sulphide-rich, shear-hosted copper(–gold) deposits typified by those at Kundip (Locality 14).

Locality 4. Cattlin Creek Pegmatite (AMG 51 2252 62818)

The Cattlin Creek pegmatite locality is located on the east side of the Old Newdegate Road, approximately 2 km north of Ravensthorpe and is accessed from town via Scott Street.

The Cattlin Creek pegmatite contains published reserves of 1.3 Mt of spodumene (Hill, 1976) and 120 000 t at 0.09% tantalum (Louthean, 1993). In addition to Ta–Nb oxide minerals, minor pink to green tourmaline, amblygonite, montebrasite and cassiterite have also been identified (Witt, 1992). A shallow pit at this locality exposes giant, green spodumene crystals up to about a metre in length. Flat-lying intrusive contacts against Manyutup Tonalite are exposed in Cattlin Creek and testify to the sheet-like form of the pegmatite intrusions. The presence of spodumene in this pegmatite can be contrasted with its absence in the Cocanarup area. Crystallization of spodumene requires pressures in excess of 2.5 kbar (London, 1990) and its presence in this area is consistent with the interpretation that this locality was buried beneath overlying thrust sheets during accretion of the Carlingup and Ravensthorpe Terranes.

Exposures of Manyutup Tonalite in Cattlin Creek display modal, grainsize and textural variation that are typically present in the margins of the pluton. Tonalite samples from this area are relatively amphibole-rich and belong to the low-SiO_2 suite. At this locality, 1–3 mm grains of hornblende may represent porphyroblasts formed by contact metamorphism adjacent to the pegmatite sheets. The tonalite also contains numerous andesitic xenoliths of the Annabelle Volcanics. Deformed, sheeted amphibole veinlets similar to those at locality 2 are also present at this locality.

Contacts between Manyutup Tonalite and Annabelle Volcanics are sharp but quite irregular. Net veining of andesite by tonalite, and the coarse grainsize of some thin tonalitic veins suggest intrusion of the tonalite magma into incompletely cooled volcanic rocks, consistent with geochemical evidence for a cogenetic relationship between Manyutup Tonalite and Annabelle Volcanics (Figs 6, 7).

Creek exposures south of the pegmatite sheets are mainly andesite of the Annabelle Volcanics. This unit is cut by a thick Proterozoic dolerite dyke about 100 m to the south.

Locality 5. Manyutup Tonalite south of Cordingup Dam (AMG 51 2303 62770)

Drive towards Hopetoun from Ravensthorpe. At 2.2 km, the road passes the old copper smelter on the left. This facility treated most of the ore from the Ravensthorpe district. Turn right into the Cordingup Dam reserve, 4.3 km out of Ravensthorpe, and then veer left along a fence line after a further 0.2 km. It is another 1.3 km to some rocky outcrops of Manyutup Tonalite.

This locality is a blast site (for a geochemical sample) within the interior of the Manyutup Tonalite. It is a massive, equigranular, coarse-grained biotite–hornblende tonalite that is fairly typical of the dominant variant of Manyutup Tonalite. Although fairly uniform at this point, the coarse-grained tonalite is cut by a few small dykes of similar but finer grained tonalite. A geochemical analysis of the tonalite from this site is shown in Table 2. This sample (GSWA 113983) is a member of the high-SiO_2 suite.

As in most samples of Manyutup Tonalite, this sample displays propylitic alteration (minor secondary epidote, chlorite and muscovite after plagioclase and ferromagnesian minerals) that is attributed to the effects of a weak but pervasive synvolcanic, sub-sea floor hydrothermal alteration.

Locality 6. Altered Annabelle Volcanics northwest of Cattlin Creek (AMG 51 2236 62830)

Proceed north on Scott Street for 2.6 km and turn left at the T-junction. The excursion examines loose boulders of metamorphosed, altered Annabelle Volcanics in the paddock next to the dam on the left, 1 km from the T-junction.

Coarsely fragmental rocks of the Annabelle Volcanics consist of angular to subangular clasts of dacite (cream coloured) in a mafic to intermediate matrix. The mineral assemblage in these rocks is diopside, K-feldspar, amphibole, epidote, titanite and radiating blades of ?vesuvianite ($\leq$ 1 cm long). This is a relatively uncommon assemblage in the Annabelle Volcanics and may be caused by metamorphism of rocks that underwent an early period of carbonation and potassium metasomatism. The relatively widespread presence of garnet and cordierite in the Annabelle Volcanics at other localities, is interpreted to reflect a different style of pre-metamorphic (?sea-floor) alteration (enrichment of Fe, Mg; leaching of Ca, Na; see also locality 14).

Table 2. Whole-rock analyses of Manyutup Tonalite

	113983	*119927*
	percent	
SiO_2	68.5	66.3
TiO_2	0.45	0.35
Al_2O_3	15.4	15.9
Fe_2O_3	1.21	1.05
FeO	2.4	2.33
MnO	bd	bd
MgO	1.11	1.59
CaO	4.46	4.82
Na_2O	4.34	4.67
K_2O	0.96	0.59
P_2O_5	0.1	0.07
S	bd	bd
LOI	0.93	1.34
Total	**99.86**	**99.01**
	parts per million	
Cr	9	28
Ni	18	43
Co	11	12
V	57	60
Cu	19	9
Pb	0	5
Zn	45	45
Rb	29	17
Ba	220	162
Sr	203	217
Ga	16	17
Li	22	41
Nb	bd	4
Zr	197	128
Y	12	19
Th	3	9

bd below detection limit

Locality 7. Deformed, coarsely bedded volcaniclastic sedimentary rocks (Annabelle Volcanics), Phillips River (AMG 50 7692 62737)

Locality 7 lies in the Cocanarup area and is approached via an unsealed road that leads south to Cocanarup from the Esperance–Albany highway, 11.4 km west of Ravensthorpe. Take the track to the left, 4.1 km from the highway and proceed a further 1.6 km to the Phillips River.

Coarsely bedded, poorly sorted, intermediate volcaniclastic sandstone and conglomerate is exposed in the bed of the Phillips River. Angular to subrounded clasts of dacite, commonly with a finer grained fragmental structure, occur in an amphibole-rich intermediate matrix. Some more coarsely fragmental beds contain melanocratic (amphibole-rich) clasts that may have been derived from andesitic rocks or chloritized dacitic glass. Epidote-rich clasts are interpreted as resedimented clasts of the Annabelle Volcanics that have undergone intense submarine hydrothermal alteration. Bedding, on a scale of tens of centimetres to metres, is overprinted by a moderate to strong foliation (S_{R2}) and a down-dip lineation (L_{R2}) that is defined by stretched clasts. Increasing strain toward the contact with granitoid gneiss, which occurs less than a kilometre upstream, is indicated within loose boulders.

Locality 8. D_{CO3} lineation defined by andalusite porphyroblasts, east of Cocanarup (AMG 50 7700 62748)

Drive back along the same access track for 1.0 km to a crossroad and turn right. After a further 0.1 km, park the vehicle and walk to the top of the hill on the left.

At the top of the hill, there is a thin slice of metasedimentary rock within the deformed Annabelle Volcanics. The focus of this stop is an andalusite-bearing horizon (quartz–feldspar–biotite–muscovite–andalusite–sillimanite–rutile schist) within the metasedimentary unit. The dominant foliation in the pelitic schist (S_{CO3}) is parallel to the contact between the greenstones and granitoid gneiss, and dips moderately to steeply to the southeast. Within this foliation, elongate andalusite porphyroblasts define a steep linear fabric (L_{CO3}). This fabric is interpreted as having formed on a subhorizontal foliation surface during eastward thrusting of the Ravensthorpe Terrane over the Carlingup Terrane (D_{CO3}). The present steep attitude of the foliation surface is attributed to tilting during formation of the Beulah Synform (D_{CO4}).

Relicts of oriented sillimanite within andalusite from these rocks imply a decrease in temperature and/or pressure during D_{CO3}. Compositional zoning in garnets in metapsammitic samples not far from this locality unequivocally indicates decreasing pressure, consistent with uplift of the Ravensthorpe Terrane during thrusting and accretion of the Ravensthorpe and Carlingup Terranes.

Locality 9. Mafic to felsic gneiss after Annabelle Volcanics (AMG 50 7682 62739)

Return along the access track from locality 7 to the unsealed road that leads from the Albany–Esperance highway to Cocanarup. Turn left and drive a further 1.5 km to Cocanarup and then turn left along the old West River baseline. It is 0.2 km to a creek crossing where locality 9 is located.

Highly strained and metamorphically recrystallized Annabelle Volcanics are exposed along the bank of this creek. Intense ductile deformation has produced a fine-grained quartz–feldspar(–hornblende–cummingtonite–biotite) gneiss. The composition varies from mafic to dacitic. The dominant foliation (S_{R2}) is parallel to the contact with granitoid gneiss, which lies about 200 m to the northwest, and dips 70° southeast. No linear fabric has been observed at this locality. There is a suggestion of deformed clasts on some parts of the outcrop, but the original volcaniclastic rock may have been much finer grained than at locality 7.

Locality 10. Pegmatite swarms in deformed Annabelle Volcanics (AMG 50 7677 62724)

Drive a further 1.9 km southwards along the old West River baseline to the crest of a steep slope where there is a view to the north and west.

The view to the north and west includes several whitish outcrops of pegmatite that intrude Annabelle Volcanics. Small exploratory pits have been sunk into one of these intrusions and drill pads are visible from this vantage point. This pegmatite contains lepidolite, zinnwaldite, amblygonite, lithiophilite and Ta–Nb oxide minerals (Witt, 1992). Tourmaline is a widespread accessory mineral and locally forms clusters of coarse crystals in vuggy 'pockets'. The black colour of the tourmaline (schorl) can be contrasted with the pink, Li-rich tourmaline (elbaite) found in the more fractionated pegmatite at Cattlin Creek (locality 4). To the south, a swarm of similar pegmatites have been intruded into a D_{R2} thrust fault within the Ravensthorpe Terrane. The pegmatites are interpreted as having been emplaced during the later stages of terrane accretion and may be genetically related to protoliths of the granite gneiss that envelops the greenstones. Unlike the Cattlin Creek pegmatite, the Cocanarup pegmatites do not contain spodumene, consistent with emplacement at lower pressures during uplift.

Pegmatite is exposed in and beside the track that forms the old baseline. Banded aplitic margins contain garnet and pass inwards into a coarse-grained quartz–feldspar–Li-mica pegmatite. The pegmatite displays much less strain than the amphibolitic to metadacitic rocks (Annabelle Volcanics) that they intrude. They were therefore emplaced after most of D_{R2} had ceased. However, locally foliated zones in some pegmatites suggest late-tectonic emplacement (see also locality 11).

Locality 11. High-grade metapelitic units in Cocanarup greenstones (AMG 50 7638 62651)

Drive a further 8 km south along the old West River baseline and turn right at the crossroads. Locality 11 lies 2.1 km from the crossroads.

Coarse-grained quartz–plagioclase–biotite–garnet(–cordierite) schist forms a thin unit along the western margin of the greenstone belt and is present here as float. The schist is associated with deformed pegmatite intrusions. Granitoid gneiss underlies the white sand plain to the west. Accessory minerals in the pelitic schist are tourmaline, rutile and opaque oxide minerals. The co-existence of garnet and cordierite in this area establishes minimum metamorphic temperatures exceeding 650°C (Fig. 11). The schistosity is interpreted as S_{CO3} and wraps around the garnet porphyroblasts. Garnet porphyroblasts contain at least two pre-D_{CO3} fabrics as inclusion trails of quartz, biotite, sillimanite, rutile and opaque minerals. D_{CO3} is correlated with D_{R2}.

Drive 0.3 km back toward the crossroads

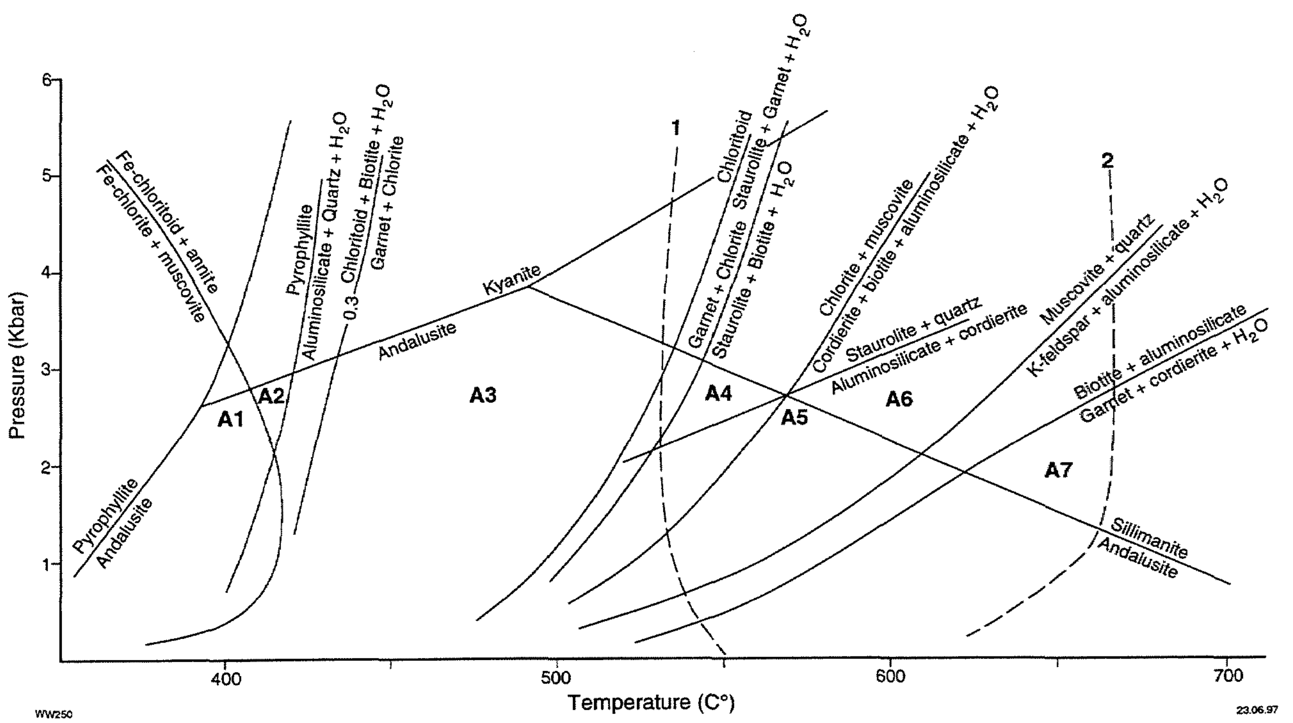

Figure 11. P–T grid for pelitic rocks (after Spear, 1993. Yardley, 1989). Further curves for ultramafic rocks (Gole et al., 1987) are 1. antigorite → talc + forsterite; 2. talc+forsterite → anthophyllite

At this locality, high-grade metapelitic rocks are quartz–K-feldspar–sillimanite and quartz–amphibole–clinopyroxene assemblages with gneissic to granoblastic fabric. Some samples display pink and white mottling, which probably reflects migmatization of the original pelite.

Locality 12. Deformed Manyutup Tonalite in allocthonous thrust slice (AMG 50 7659 62645)

Return to crossroads and proceed a further 0.4 m to the east.

Medium-grained and coarse-grained seriate tonalite is exposed at this blast site (GSWA 119927), which is located within an allocthonous thrust sheet overlying the Cocanarup greenstones and Annabelle Volcanics to the west. The tonalite varies from hornblende–biotite tonalite to biotite tonalite. Both phases of tonalite contain a foliation (S_{R2}) that is defined by oriented aggregates of biotite and also contain quartz veins that probably formed during thrusting (D_{R2}). Recrystallization of quartz and plagioclase has resulted in considerable subgrain development and, locally, a granoblastic fabric. Both hornblende and cummingtonite are present, reflecting the relatively high metamorphic grade in this area. It is likely that the medium-grained tonalite was derived from coarse-grained tonalite by grainsize reduction during deformation (accretion) and syntectonic recrystallization. Geochemically, sample 119927 is a rather primitive member of the high-SiO_2 suite (Table 2).

Locality 13. Cordierite–anthophyllite rock and Cu–Zn mineralization at the Copper King mine (AMG 50 7664 62598)

The Copper King mine site is approached by continuing east from locality 12 and then following paddock boundaries southwards until encountering a track that leads back to the west. This track intersects a north–south track that connects Copper King (turn right) and Last Venture (turn left).

Massive, coarse-grained cordierite–orthoamphibole rock is exposed near the crossroads. Coarse orthoamphible (gedrite) prisms form radiating sprays up to about 2 cm across. This rock is interpreted as the result of metamorphic recrystallization of volcanic rocks (?dacite of the Annabelle Volcanics) that have been affected by sea-floor alteration (Fe–Mg metasomatism and leaching of Ca, Na).

The Copper King mine lies near the bottom of the hill, on the west side of the track. Mine dumps contain vein quartz with azurite, malachite and chalcocite in altered dacite. The altered dacite is a quartz–plagioclase–biotite–andalusite–orthoamphibole (gedrite)(–cordierite–garnet–muscovite) rock that also contains minor gahnite (zinc spinel) and rutile. The presence of andalusite in these rocks suggests intense pre-metamorphic leaching of alkalis and perhaps enrichment of SiO_2.

Find your own way back to civilization. The best route is via Moir Road approximately 35 km out of Ravensthorpe.

Locality 14. Copper–gold mineralization at Flag mine, Kundip (AMG 51 2404 62690)

Drive 16.3 km south from Ravensthorpe on the Ravensthorpe to Hopetoun road. Turn left and take the right-hand option at the fork 1.8 km from the road. It is a further 0.3 km to a T-junction where another right turn is required. The Flag mine is another 1 km from the T-junction.

A reasonable idea of the style of mineralization in the Kundip district can be ascertained from mine dumps and two open stopes. The lodes are quartz–sulphide veins and massive sulphide in intensely chloritized andesitic agglomerate (Annabelle Volcanics). A darkening of the rock adjacent to mineralized veins and shears (in drillcore) reflects intense chloritization and the progressive destruction of amphibole and then plagioclase. The alteration assemblage is quartz–plagioclase–chlorite(–biotite–epidote–muscovite) and is interpreted as approximately equivalent to the pre-metamorphic precursor to cordierite–orthoamphibole (gedrite) alteration at locality 13. Geochemical data indicate that mineralization is associated with addition of Fe, Mg, SiO_2 and S, and loss of Ca and Na with respect to unaltered andesite (Fig. 12). The ore minerals are pyrite and chalcopyrite with minor pyrrhotite and sphalerite and, in the supergene zone, bornite, chalcocite and malachite. The chalcopyrite/pyrite ratio increases towards quartz veins. Traces of gold have been observed as fracture fillings and inclusions in pyrite. The sulphide-rich nature of this ore should be contrasted with the relatively simple, quartz-rich, sulphide-poor veins that characterize the gold deposits north of Ravensthorpe (e.g. Bullfinch, locality 3). Assemblages of garnet–biotite(–cordierite–orthoamphibole) in Cu–Au mines at Ravensthorpe and Mount McMahon mining districts are interpreted as high-temperature (metamorphosed) equivalents of mineralization at Kundip.

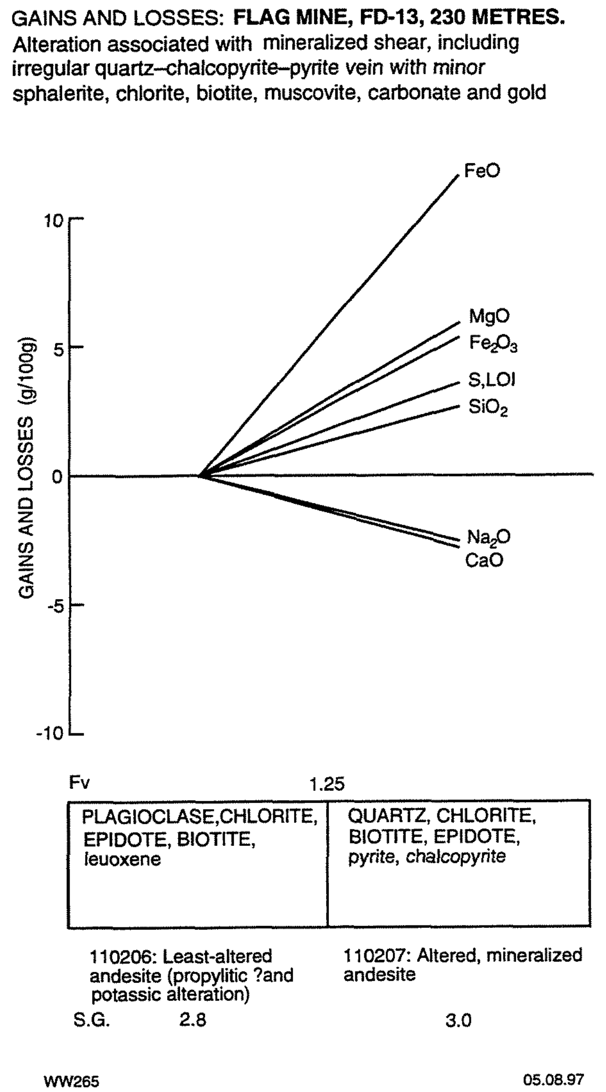

Figure 12. Diagram showing mass balance changes (after Gresens, 1967) between altered, mineralized andesite and andesite with intense propylitic alteration, Flag mine, Kundip

Locality 15. Mount Iron gold mine and tectonic slices of ultramafic schist in terrane boundary fault

Return to the fork at 1.8 km from the Ravensthorpe–Hopetoun road. Take the alternative fork uphill and past the Kundip openpit. At 0.8 km, drive straight ahead rather than taking the tracks to the left or right. From this point, it is another 2 km to the Mount Iron opencut mine.

At Mount Iron, gold has been won from a blue-grey chert that can probably be assigned to the Chester Formation of the Carlingup Terrane. The chert does not contain conspicuous disseminated sulphides and there are few quartz veins in the openpit gold mine. The nature of the gold mineralization at Mount Iron is not well understood but deserves further investigation as a possible epithermal, hot spring (sinter) precious metal deposit.

The Mount Iron openpit exposes a contact between metasedimentary rocks of the Chester Formation (Carlingup Terrane) to the west and metamorphosed mafic to intermediate volcanic rocks of the Annabelle Volcanics (Ravensthorpe Terrane) to the east. This is a zone of tectonic interleaving (the Chidnup Fault) at the boundary between the two terranes. A thin unit of talc–carbonate schist is exposed on the north face of the pit, between the sedimentary and volcanic rocks. This is interpreted as a tectonic slice (probably of Bandalup Ultramafics) that was incorporated during accretion of the two terranes. The ultramafic schist is also exposed at the surface on the western slopes of the valley, between the pit and the drainage. On the eastern side of the drainage, the Alice May copper mine is hosted by Annabelle Volcanics. Another slice of ultramafic schist occurs to the west of Mount Iron, between the Christmas Gift and Ard Patrick copper mines.

Locality 16. Manganese mine near Mount Chester (AMG 51 2349 62777)

Turn left (to the east) off the Ravensthorpe–Hopetoun road, 9 km south of Ravensthorpe. It is 1.9 km to an abandoned adit at the foot of a steep ridge. This is locality 16.

The adit exposes thinly bedded pelitic rocks of the Mount Chester Formation. Samples of a sedimentary manganese oxide ore are present on the spoil dump at the front of the adit. The ore is mainly pyrolusite with subordinate cryptomelane and reputedly contains up to 2% Co (Sofoulis, 1958). Surface exposures of the sedimentary manganese unit can be seen by following a narrow track on foot that leads behind the adit to near the top of the ridge.

Locality 17. Pelite, iron-formation and volcanic association, Chester Formation, north of Mount McMahon (AMG 51 2303 62854)

Take Carlingup Road to the left off the Albany–Esperance highway, 5 km east of Ravensthorpe. After a further 1.7 km, take the track to the left and veer right after another 0.2 km. After another 4.7 km, take a left turn instead of continuing up a steep slope.

Chester Formation float at this locality indicates an association comprising pelites, iron-formation and volcanic rock. The pelitic rocks in this area contain porphyroblasts of garnet, andalusite and chloritoid. The pelites are locally magnetite- and iron-rich and are associated with finely laminated BIF (quartz–grunerite–magnetite rock). Also present at this locality are metavolcanic or metavolcaniclastic rocks of andesitic to dacitic composition. Volcanic rocks are a minor component of the Chester Formation but are important because they signal a potential source of heat to drive large-scale submarine circulation of hydrothermal fluids. It is possible that the local abundance of porphyroblasts reflects leaching of alkalis from pelitic sedimentary rocks in a pre-metamorphic hydrothermal system. Iron-rich pelites and iron-formation are also common in many Archaean and younger sites of volcanogenic base-metal sulphide deposits (Franklin et al., 1981; Lydon, 1984; Galley, 1993).

Locality 18. Massive limonitic gossan in Chester Formation, north of Mount Chester (AMG 51 2345 62795)

Turn right off the Albany–Esperance highway, 8.7 km east of Ravensthorpe. Stop at 0.85 km and walk in a southwest direction.

This traverse crosses Chester Formation pelites en route to a prominent ridge formed by bedded to massive, gossanous limonite. The limonitic gossan probably formed by weathering of massive to bedded pyrite that has been intersected by exploration drilling at Mount Chester. Similar gossanous horizons are common elsewhere in the Chester and Hatfield Formations and grade along strike into chert and BIF.

The pelitic rocks contain coarse, randomly oriented garnet and andalusite porphyroblasts. These porphyroblasts overgrow the dominant S_{CA2} (equivalent to S_{R2} and S_{CO3}) foliation that formed during accretion of the Carlingup and Ravensthorpe Terranes. The fabric relations can be contrasted with those in the Cocanarup greenstones where garnet and andalusite growth was pre- to syn-accretion (e.g. locality 8).

Locality 19. Polymictic conglomerate exposed in Bandalup Creek (AMG 51 2514 62760)

Turn right off the Albany–Esperance highway, 25.4 km east of Ravensthorpe. The track leads along the eastern edge of Bandalup Creek, crossing over Bandalup Ultramafics and Maydon Basalt. Locality 19 is located in Bandalup Creek, about 2.5 km south of the highway.

Boulder conglomerate and greywacke sandstone are exposed in the bed of Bandalup Creek. Low-angle, planar cross-bedding is present in the sandstone. The polymict conglomerate contains rounded clasts of tonalite, dacite and andesite, similar to units that comprise a major part of the Ravensthorpe Terrane. However, rock types that are characteristic of the Carlingup Terrane (variolitic basalt, komatiite, pelites, BIF) are notably absent. This sedimentary unit is interpreted to have formed by erosion of a frontal range formed by the Ravensthorpe Terrane as it was thrust up and over the Carlingup Terrane. This unit was subsequently deformed with other units of the Carlingup Terrane. A south-plunging lineation, defined by oriented clasts, is probably related to movement on the Bonnymidgup Shear Zone (D_{CA4}). Along strike to the north, intense D_{CA4} ductile deformation of this unit has produced a quartz–feldspar–amphibole–biotite gneiss that is exposed in a road cutting adjacent to the Albany–Esperance highway.

Locality 20. Ultramafic rocks and lateritic nickel deposit, Bandalup Hill (AMG 51 2525 62747)

Take the track to the right off the Albany–Esperance highway, 33.7 km east of Ravensthorpe. It is a further 2.3 km to a crossroad. A left turn at the crossroad and a further 1 km leads to an old shaft (locality 20).

The view west from Bandalup Hill includes bright white magnesite adjacent to costeans and mining pits. Coarse, nodular magnesite (68 000 t) was mined at Bandalup between 1959 and 1984. Remaining reserves are 1.252 Mt of 18.2% $MgCO_3$. These deposits formed at the base of the Tertiary Pallinup Siltstone by hydrothermal replacement with the magnesia being derived by Cainozoic weathering of underlying Bandalup Ultramafics (Abeysinghe, 1997). Weathered Pallinup Siltstone is exposed along the southwestern margin of Bandalup Hill.

Samples from the shaft are laid out on the adjacent ground and provide a section through the weathering profile into the unweathered peridotite. A more complete description of the Bandalup Hill (Ravensthorpe) nickel laterite follows (Cooper et al., this guide).

III. Ravensthorpe lateritic nickel project

by

[1]A. Cooper, R. Jones, A. Mitchell, and B. Siggs

In October 1996 Comet Resources NL entered into an agreement to purchase an 80% interest in the Ravensthorpe Nickel Project (potentially 100%) from a group of prospectors. Comet's interest was based on results of explorers in the 1960s who located significant lateritic nickel mineralization in the Bandalup Hill area. Marston (1984) utilized the earlier exploration drilling to define an inferred resource of 15.4 Mt grading 1.4% Ni, at Bandalup Hill.

Location and access

The tenements straddle the Southern Highway, about 40 km east of Ravensthorpe (Fig. 13), at which point the port of Esperance is 135 km by road to the east. Access through the tenements is by tracks, and historical and recently cleared grid lines. Scrub, typically 1–2m high blue mallees and banksias, cover most of the project area

Previous exploration

Pickands Mather International (PMI) conducted regional stream-sediment sampling over the Ravensthorpe greenstone belt in the early 1960s. Anomalous nickel and copper values led to further exploration through the belt which subsequently located some small nickel sulphide and nickel laterite resources. Exploration by PMI included soil sampling and percussion drilling, and a winze was also sunk into the laterite nickel resource at Bandalup Hill.

Western Mining Corporation (WMC) farmed into PMI's Ravensthorpe properties in 1975. They carried out further percussion and diamond drilling that focused mainly on nickel sulphide exploration. Regional aeromagnetics and mapping were also carried out.

Since the mid 1980s, geological compilation and metallurgical test work on the tenements has focused on the potential development of nickel laterite resources.

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[1] All of Comet Resources NL, 26 Colin Street, West Perth, W.A. 6005.

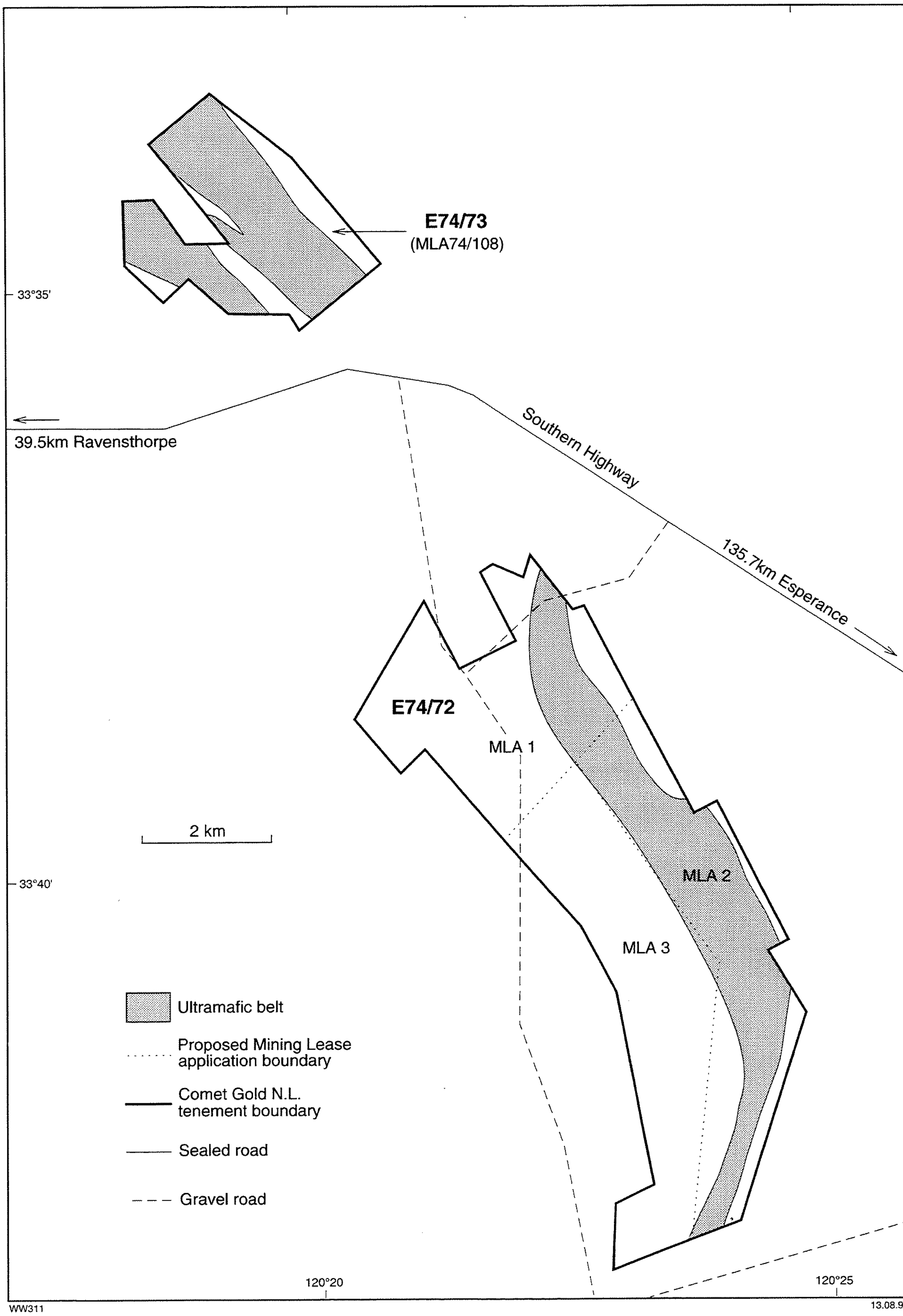

Figure 13. Location of Comet Resources NL leases, Ravensthorpe (Bandalup Hill) nickel laterite project

Geology

The project area lies on the eastern margin of Ravensthorpe Greenstone belt. There is little fresh rock outcrop within the project area. The target for lateritic nickel exploration is mainly along a laterite ridge that runs through the tenement area. This ridge is interpreted to overlie an ultramafic body that strikes approximately northwest (Fig. 13). The focus of exploration in the project area is the top of the regolith profile which, over this ridge, consists mostly of limonite, goethite and silica.

Regolith geology

Regolith geology has been determined from chip samples derived from reverse circulation (RC) drilling. Bandalup Hill regolith is dominated by iron-oxide-rich upper saprolite, which hosts the greater part of the mineralization (Fig. 14). The boundary between upper and lower saprolite, at the base of iron-oxide accumulation, is marked by a distinct change from khaki and brown in lower saprolite to orange and tan in upper saprolite.

Iron oxide-dominated weathering profiles occur over all ultramafic parent rock types including serpentine-dominated, carbonate-bearing, talc–carbonate and serpentine–carbonate rocks. These profiles (e.g. Fig. 14) comprise, from weathering front to surface:

- saprolite ('saprock') showing relic textures
- lower saprolite with variable amounts of clay minerals
- variably silicified goethite/limonite-rich upper saprolite
- a leached, siliceous upper saprolite or clay-bearing layer, overlain by
- a range of materials in transported overburden; these include pisolitic ferricretes, quartz-rich alluvial sands, magnesite-bearing and calcareous soils, and ferricretes containing fragments and blocks of the underlying uppermost residual regolith.

This profile is overprinted by secondary silica and carbonate, depending on the composition of the underlying parent material. The regolith over serpentine-bearing parent rocks is strongly overprinted by silica. Over carbonate-bearing rocks the regolith is overprinted by magnesite with lesser silica, and over talcose parent rocks the regolith is moderately overprinted by silica and

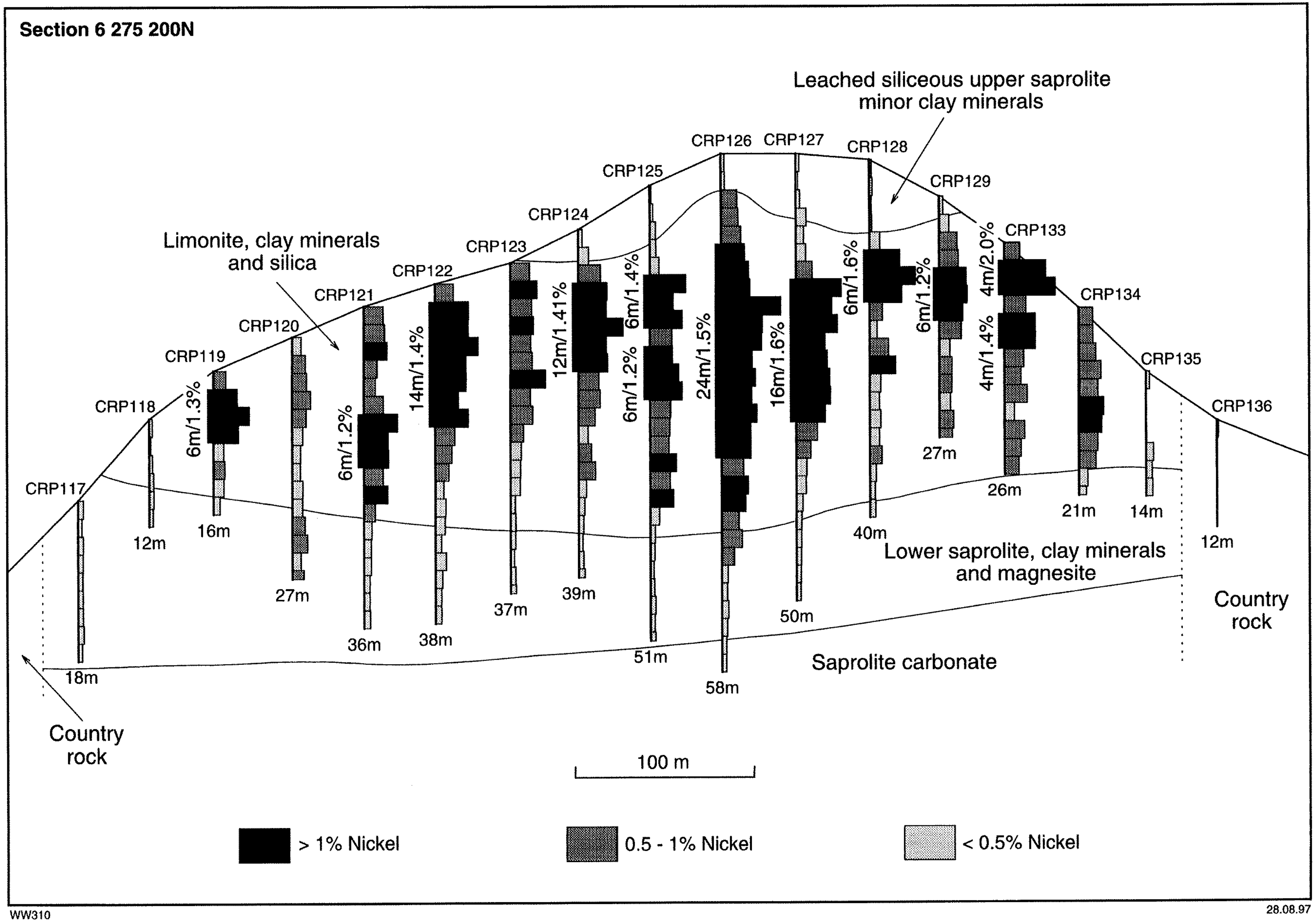

Figure 14. Cross section, 6275200mN, Bandalup lateritic nickel deposit

carbonate. Nickel is strongly enriched in horizontal layers of siliceous goethite and goethitic clays within the upper saprolite, and is also associated with serpentine minerals and Mn-oxides in the upper portion of lower saprolite.

Smectite-bearing weathering profiles are developed locally over serpentine-dominated parent material. These profiles comprise, from weathering front to surface:

- saprock
- clay-bearing lower saprolite
- upper saprolitic goethitic clays and green smectitic clays, overlain by
- transported pisolitic ferricrete overburden.

Silica overprinting marks the boundary between residual regolith and transported overburden. Nickel is enriched in smectitic clays (silicate ore) and goethitic clays (oxide ore). These profiles are not common.

Resource drilling and sampling procedures

A DINOSAUR 100 Tractor Mounted Reverse Circulation drill rig with a 350 p.s.i / 600 cfm air capacity was contracted from Budget Drilling, Welshpool, Perth. Drilling (Stage 1 of the resource evaluation program) commenced on the 3 February 1997. All holes to date have been drilled vertically, using a 120 mm face-sampling hammer. A two-metre composite sample was collected at the drill rig using an 8:1 riffle splitter. Samples, weighing in the order of 2–4 kg, were trucked to Perth and submitted to Ultra Trace Analytical Laboratories, Canning Vale and analysed for: Ni, Co, As, Cu, Zn, Cr, Fe, Mn, Al, Mg, and Ca. The splitter and cyclone are checked regularly during drilling and both are cleaned at the completion of a hole.

Logging is carried out on site using a customized log sheet and a lithologic code system. The Munsell Rock-Colour Chart is used for drill chip colour determination. A small washed sample from each metre is collected in plastic chip-trays. All plastic bags taken from the splitter are individually weighed and this value is recorded on the geological log.

Drilling conditions for the face sampling RC technique have been difficult at times due to poorly consolidated sandy clay horizons, 'rubbly' siliceous zones and damp swelling clays. The D100 tractor-mounted drill rig has proved to be well suited to the rough, uneven terrain encountered on Bandalup Hill.

Mineralization

Results from RC drillholes at the time of writing show an undulating 4–56 metre thick 'blanket' of +0.7% Ni mineralization over a 5 km strike length with a lateral extent of 200–1000 m. The main host for nickel–cobalt mineralization is the iron-rich limonite–goethite–silica horizon. However, mineralization has also been observed in the more clay-rich and siliceous horizons and to some extent in the deeply weathered ultramafic saprolite. All ore types can be benificiated with upgrades of 10–50% being recorded. The best width and grade to date is CRP 424 (58 m at 1.5% Ni).

The future

The original 'Stage 1' drilling program was mainly carried out on a 100 x 80 m pattern. This has provided confidence in lateral correlation of grades, widths and various lithological units. The infill ('Stage 2') drilling program on 40 m centres and in some cases 40 x 50 m centres commenced in June. Diamond drilling to validate RC holes and provide extra data on specific gravity and material for metallurgical work (beneficiation and processing) commenced in late May. A second RC rig has been contracted to drill out the Northern MLA 74/108. A bulk-sampling program (pit or winze or large diameter bucket drill rig) is expected to commence in August with bulk pilot-test work following.

IV. The geology and volcanological setting of komatiite-hosted nickel sulphide orebodies from Forrestania, Southern Cross greenstone belt

by

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

Regional setting

The Forrestania greenstone belt is approximately 100 km south of Southern Cross in the Archaean Yilgarn Craton of Western Australia. The belt trends northerly and has a broadly synclinal structure. The lower part of the stratigraphy is predominantly mafic, but contains at least four sequences of komatiitic rocks that are intercalated with banded iron-formation (BIF; Perring et al., 1995, 1996). The upper part of the stratigraphy consists largely of pelitic to psammitic schists (Chin et al., 1984). The regional geology of the Forrestania greenstone belt is summarized in Figure 15.

Like most greenstone sequences, the Forrestania belt has undergone polyphase deformation (Witt, 1972; Lawn, 1977; Chin et al., 1984), and peak metamorphic conditions occurred at 655 ± 30°C and 4.0 ± 1.0 kb in the southern part of the belt (Porter and McKay, 1981). The age of supracrustal sequences in this part of the Yilgarn is poorly constrained, but the volcanic and sedimentary rocks are thought to be older (~3.0 Ga: Froude et al., 1983; Fletcher et al., 1984; ~2.9 Ga: Campbell, I. H., pers. comm., 1994) than similar rocks from the Norseman–Wiluna Belt to the east (~2.7 Ga: summarized by Myers, 1993).

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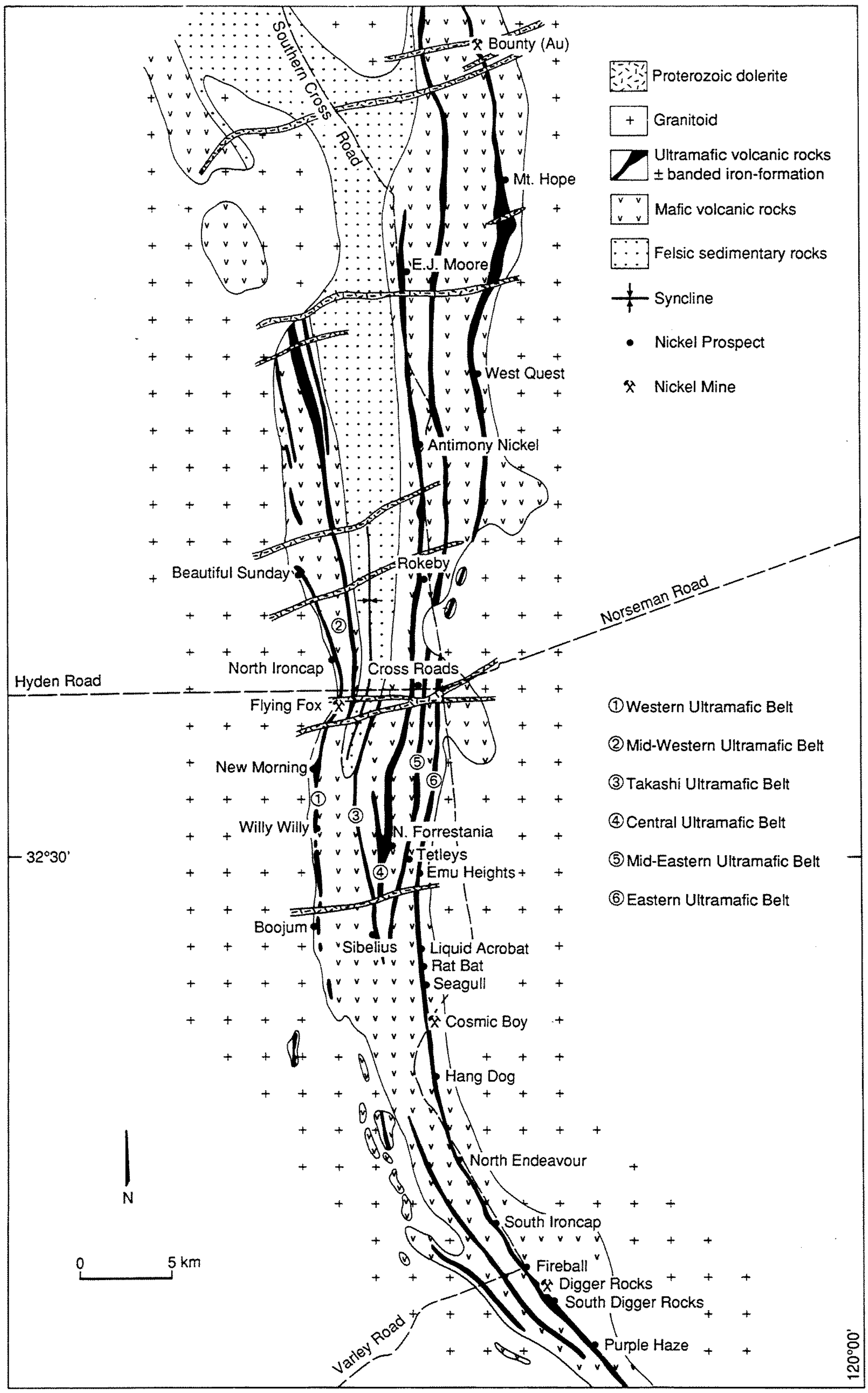

Figure 15. Regional geological map of the Forrestania area showing the major ultramafic belts and principal prospects (adapted from Woodhouse et al., 1992, and Perring et al., 1995)

Komatiitic volcanic facies

Prolonged periods of komatiite eruption give rise to extensive lava-flow complexes containing a wide variety of diverse flow units (Hill et al., 1990; 1995). The terminology used to describe the principal types of flow profile is taken from Hill et al. (1995) and is summarized below.

(i) *Thin differentiated and undifferentiated flow units.* Individual flow units are between 0.5 m and 10 m thick and tens to hundreds of metres wide. Internal textural division into an upper spinifex-textured A zone and a lower cumulate-textured B zone present in the differentiated type of flow unit reflects cooling from stagnant lava at relatively rapid cooling rates. These flow units probably formed in a complex system of lava tubes (S-J. Barnes, 1985) and reflect relatively low effusion rates and episodic emplacement of lava. Two end-member varieties of the undifferentiated type of flow unit exist. Flow units consisting entirely of spinifex-textured rock are thought to develop in distal environments as thin lava 'toes' and possibly within some levee banks. Flow units consisting solely of loosely packed olivine orthocumulates set within polyhedrally jointed quenched komatiite may represent lava tubes that have become clogged by a critical density of suspended olivine crystals.

(ii) *Thick cumulate flow units.* These flow units commonly vary in thickness with the thicker portions (<150 m thick) occurring as curvilinear bodies flanked by thinner sequences intercalated with interflow sedimentary material. The flow units are composed predominantly of olivine orthocumulates to mesocumulates and are the result of turbulent flow of lava down central distributary channels with intervening zones of slower, laminar flow (Lesher et al., 1984). Ponding and fractionation of the lava in situ within preferred pathways can lead to the formation of an upper zone of pyroxenitic and doleritic cumulates, capped by spinifex-textured material (Arndt et al., 1977; S-J. Barnes et al., 1983).

(iii) *Very thick cumulate flow units.* These are between 150 m and 1 km thick, many tens of kilometres in lateral extent, and consist almost entirely of olivine cumulates, particularly adcumulates. Like the thick cumulate flow units, they may have a fractionated zone at the top and be sheet-like or curvilinear in shape. The very thick cumulate flow units reflect cataclysmic outpourings of komatiitic lava and the different morphologies are largely due to differences in substrate composition ('erodability': Hill et al., 1989), which lead to differences in degree of lava channelization.

Metamorphism

Forrestania komatiites have been extensively reconstituted during regional metamorphism. Whole-rock geochemistry and metamorphic mineralogy have been combined with rare relict-igneous textures to determine igneous protoliths (Table 3).

Table 3. Summary of prograde silicate mineral assemblages developed in komatiites metamorphosed to amphibolite facies

Original rocktype	*Metamorphic mineralogy*	
	H_2O-rich fluid	*CO_2-rich fluid*
Spinifex-textured komatiite	chlorite, tremolite (–cummingtonite), metamorphic olivine	chlorite, tremolite ± cummingtonite, metamorphic olivine, talc, enstatite
Olivine orthocumulate	metamorphic olivine, chlorite, tremolite (–cummingtonite)	metamorphic olivine, chlorite, tremolite ± cummingtonite, talc, anthophyllite, enstatite
Olivine adcumulate	metamorphic olivine (–talc)	metamorphic olivine ± talc, anthophyllite, enstatite
Pyroxene-bearing rocks	tremolite, cummingtonite (–actinolite), chlorite	tremolite ± actinolite, cummingtonite, chlorite

There is excellent preservation of both olivine- and pyroxene- spinifex textures in some parts of the Forrestania greenstone belt, but orthocumulate textures are rarely preserved. Sequences of thin komatiite flow units typically become converted during amphibolite-facies metamorphism to olivine–tremolite–chlorite rocks(–cummingtonite, talc, anthophyllite, enstatite) with variable proportions of metamorphic olivine which reflect the original distribution of igneous olivine (Gole et al., 1987; S. J. Barnes et al., 1988).

A further tremolite-rich lithology, unrelated to spinifex-textured rocks, is also present at Forrestania. Rocks comprising tremolite–cummingtonite, with negligible amounts of actinolite, metamorphic olivine, or chlorite, commonly display relict igneous textures indicative of a medium-grained pyroxene(–olivine) assemblage.

Olivine mesocumulates and adcumulates in the thick to very thick cumulate flow units develop amphibolite-facies metamorphic assemblages, which result from dehydration following early serpentinization, and can be interpreted through reactions in the system $MgO–SiO_2–H_2O–CO_2$ (Johannes, 1969; Evans and Trommsdorff, 1974; Gole et al., 1987). These assemblages are best developed at the Digger Rocks prospect, where a core of relict olivine adcumulate is mantled by metamorphic rocks comprising the univariant and invariant assemblages metamorphic-olivine–talc–anthophyllite(–enstatite). In the core of the flow unit, which must never have been serpentinized, relict igneous olivine is identifiable by its brown colouration, which is due to minute grains of exsolved magnetite (Binns and Chapness, 1985).

Igneous terminology is used throughout the remainder of this section, for the sake of simplicity.

Geology of the Eastern Ultramafic Belt

The Eastern Ultramafic Belt has a strike-length well in excess of 80 km (Fig. 15), dips steeply (60–70°) and faces to the west. The southern portion of the belt has a northwesterly strike, which changes to north-northeasterly in the vicinity of the North Endeavour prospect. There is an abrupt change in volcanic facies between the South Ironcap and North Endeavour prospects. From South Ironcap south, the Eastern Ultramafic Belt is dominated by a thick to very thick, sheeted, cumulate flow unit, whereas from North Endeavour to the north, a series of ribbon-like cumulate flow units are set within sequences of thin komatiite flow units.

Digger Rocks

The ultramafic sequence in the Digger Rocks area is dominated by a thick to very thick, cumulate flow unit overlain by a sequence of thin komatiite flow units intercalated with komatiitic basalts (Fig. 16). The thick to very thick cumulate flow unit extends for some 11 km, pinching out to the north against a structurally thickened lens of BIF. This cumulate flow unit is commonly between 75 m and 150 m thick, swelling to 400 m in the vicinity of the Digger Rocks mine. A typical flow profile consists almost entirely of olivine mesocumulate to adcumulate with a thin spinifex-textured flowtop and an olivine orthocumulate zone of variable thickness (<10 m) at the base. To the south of Digger Rocks, an early fractionated cumulate flow unit is separated from the overlying very thick cumulate flow unit by a discontinuous, thin, sedimentary package comprising BIF and/or pelitic schist (Fig. 16). The basal contact of the ultramafic sequence is transgressive and appears to cut down through the footwall stratigraphy as it is traced from north to south. The character of the footwall changes along strike, from BIF in the north through psammitic schist to basalt in the south.

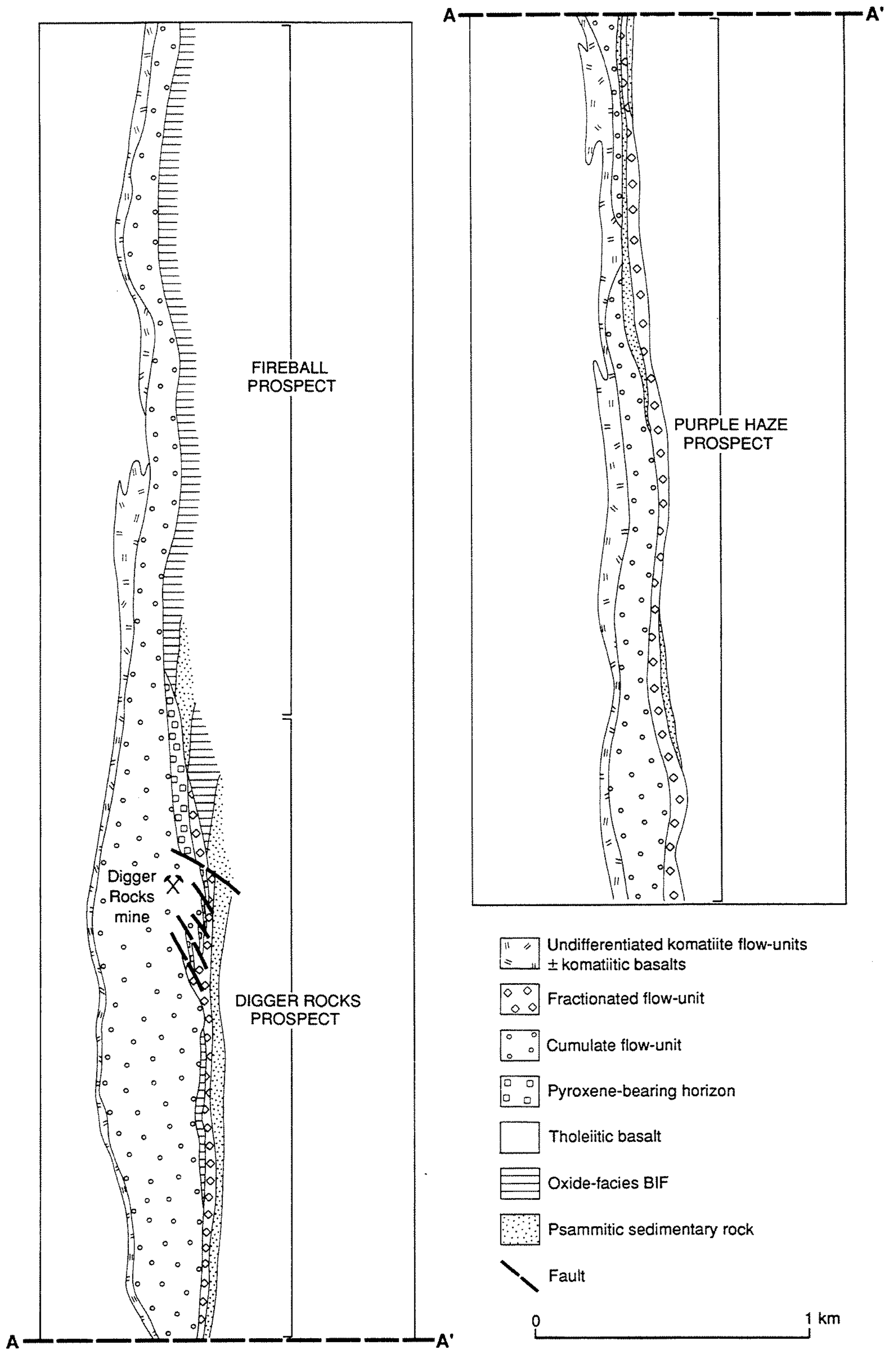

Figure 16. Schematic geological map of the southern portion of the Eastern Ultramafic Belt, from Purple Haze to Fireball (from Perring et al., 1995a). See Figure 15 for location of prospects

The Digger Rocks nickel sulphide mineralization occurs at the base of the thickest portion of the very thick, cumulate flow unit and occupies a shallow embayment (~50 m deep by 400 m wide) lined with pyroxene-bearing rocks (Figs 16–18). The interflow sedimentary horizon (comprising BIF and psammitic schist) that separates the mineralized flow unit from an earlier, fractionated, cumulate flow unit becomes discontinuous and fragmented towards the site of the mineralized lava pathway and the sedimentary rocks become altered. Within the lava pathway, blocks of BIF and psammite up to 50 m long and 5 m thick occur above, below or within the pyroxene-bearing horizon. The rare blocks of psammite have lost their banding and become granoblastic. The mineralogy of the BIF is severely modified: the chert bands gradually disappear and the magnetite bands become disaggregated, resulting in a tremolite–actinolite–rich rock with wispy laminae of magnetite. The sedimentary blocks are interpreted as substrate fragments that have been ripped up and partially assimilated during the turbulent flow of komatiite in a lava river. Pyroxene appears to have crystallized from the contaminated komatiite liquid that surrounded partially assimilated sedimentary inclusions.

The Digger Rocks orebody consists of accumulations of massive nickel sulphide (<25 m thick) which are overlain by olivine–sulphide orthocumulate, mesocumulate and adcumulate (<40 m thick and containing <20% sulphide; Figs 17, 18). Pyroxene–sulphide cumulates may occur immediately above or below the massive sulphide. Relict igneous textures are spectacularly preserved in drillcore samples and provide unequivocal evidence that sulphide accumulation and pyroxene crystallization were contemporaneous. Given the presence of sedimentary inclusions within the pyroxene-bearing unit, this intimate association with nickel sulphide mineralization strongly suggests that segregation of an immiscible sulphide liquid within the komatiitic lava was triggered by thermal erosion of sediment.

The mineralization is subhorizontal in the vicinity of the Digger Rocks openpit but plunges moderately steeply to the south, where it forms the South Digger Rocks deposit.

Cosmic Boy

Rather than being dominated by a single cumulate flow unit, this portion of the Eastern Ultramafic Belt comprises sequences of thin flow units intercalated with basaltic rocks and cherty sediments, including oxide- and sulphide-facies BIF (Figs 15, 19). Packages of flow units can be traced for considerable distances along strike. Lateral facies changes are evident and there are several locations at which multiple thin flow units merge into a single body of olivine mesocumulate.

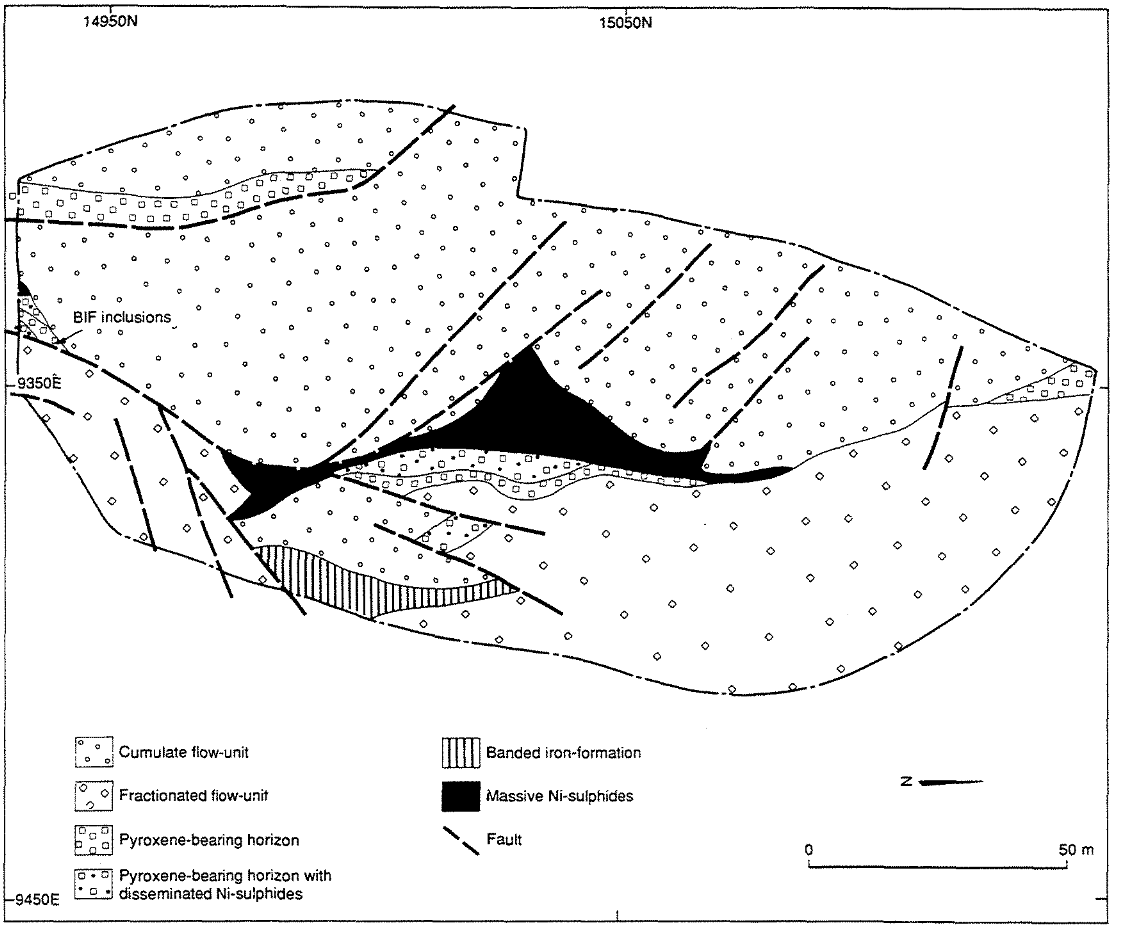

Figure 17. Bench map for the Digger Rocks pit, 35 m below the surface, showing the trough structure at the base of the thick cumulate flow unit (from Perring et al., 1995a)

A single thick cumulate flow unit can be traced over a strike length of approximately 2 km in the Cosmic Boy mine area (Fig. 19). The unit ranges in thickness from 20 to 50 m, thinning to the north and south and at one intermediate position where the basal flow unit appears to break up into at least two thinner flow units. Footwall lithology is BIF.

The basal cumulate flow unit at Cosmic Boy is composed largely of olivine mesocumulate to adcumulate. It has a marginal zone (commonly ~5 m thick) whose upper part is composed of olivine orthocumulate and whose lower part consists of pyroxene orthocumulate. In many instances this marginal zone is absent and olivine mesocumulate is in faulted contact with footwall BIF. Contact relationships between the olivine mesocumulate and the overlying stratigraphy are sharp and the absence of a flowtop in many intersections suggests that the olivine mesocumulate is commonly in faulted contact with the overlying mafic rocks or that the protolith to these mafic amphibolites was a dolerite intrusion.

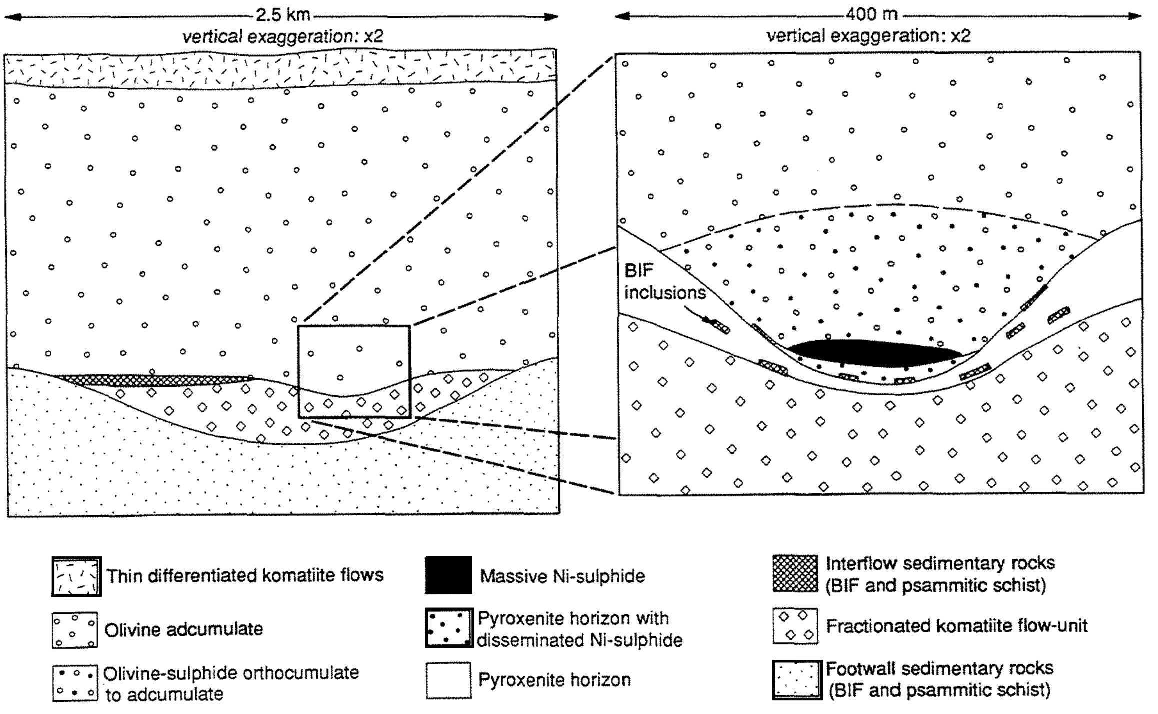

Figure 18. Schematic plan of the Digger Rocks prospect showing the relationship of the trough structure, which is lined by pyroxene-bearing rocks and hosts nickel mineralization, to the broader ultramafic stratigraphy. Copyright CSIRO Exploration and Mining

There is more than one zone of nickel sulphide mineralization at Cosmic Boy. The thickest, most sulphide-rich (<20 m thick, <30% sulphide) and most laterally persistent zone occurs at the bottom of the basal cumulate flow unit (Fig. 20). The mineralization consists mainly of olivine–sulphide mesocumulates with a basal zone comprising olivine–sulphide orthocumulates passing down into a sulphide-bearing pyroxene orthocumulate. It is difficult to ascertain whether the mineralization is confined to an embayment because of the thickness and monotonous nature of the footwall BIF: if such a feature exists, it is broad and shallow. Although the mineralization appears to be subhorizontal, this may be an artifact of the deformation.

One or more thin zones of hangingwall mineralization occur above the southern end of the basal ore zone. The olivine–sulphide mesocumulates occur within thin, differentiated komatiite flows and do not persist laterally. This lack of continuity is probably a primary volcanogenic feature, although it has undoubtedly been exacerbated by faulting.

Geology of the Mid-Eastern Ultramafic Belt

The Mid-Eastern Ultramafic Belt has a north-northeasterly strike, dips steeply (60–75°) and faces to the west. Sequences of thin komatiite flow units (both differentiated and undifferentiated) make

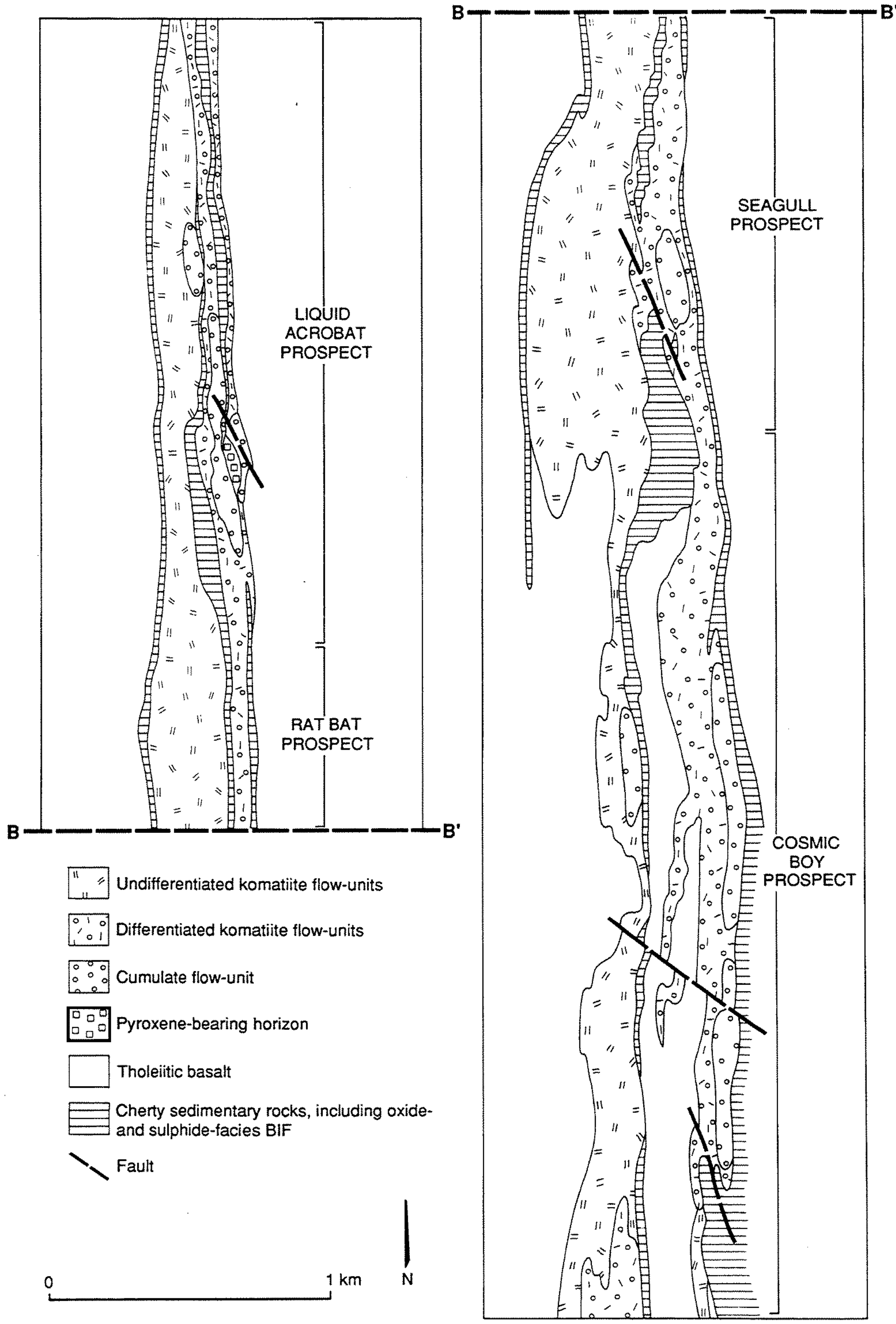

Figure 19. Schematic geological map of the northern portion (as mapped by CSIRO) of the Eastern Ultramafic Belt (from Perring et al., 1995a). Note that there are many more interflow sedimentary horizons and intercalations of basalt than can be shown at this scale. See Figure 15 for location of prospects

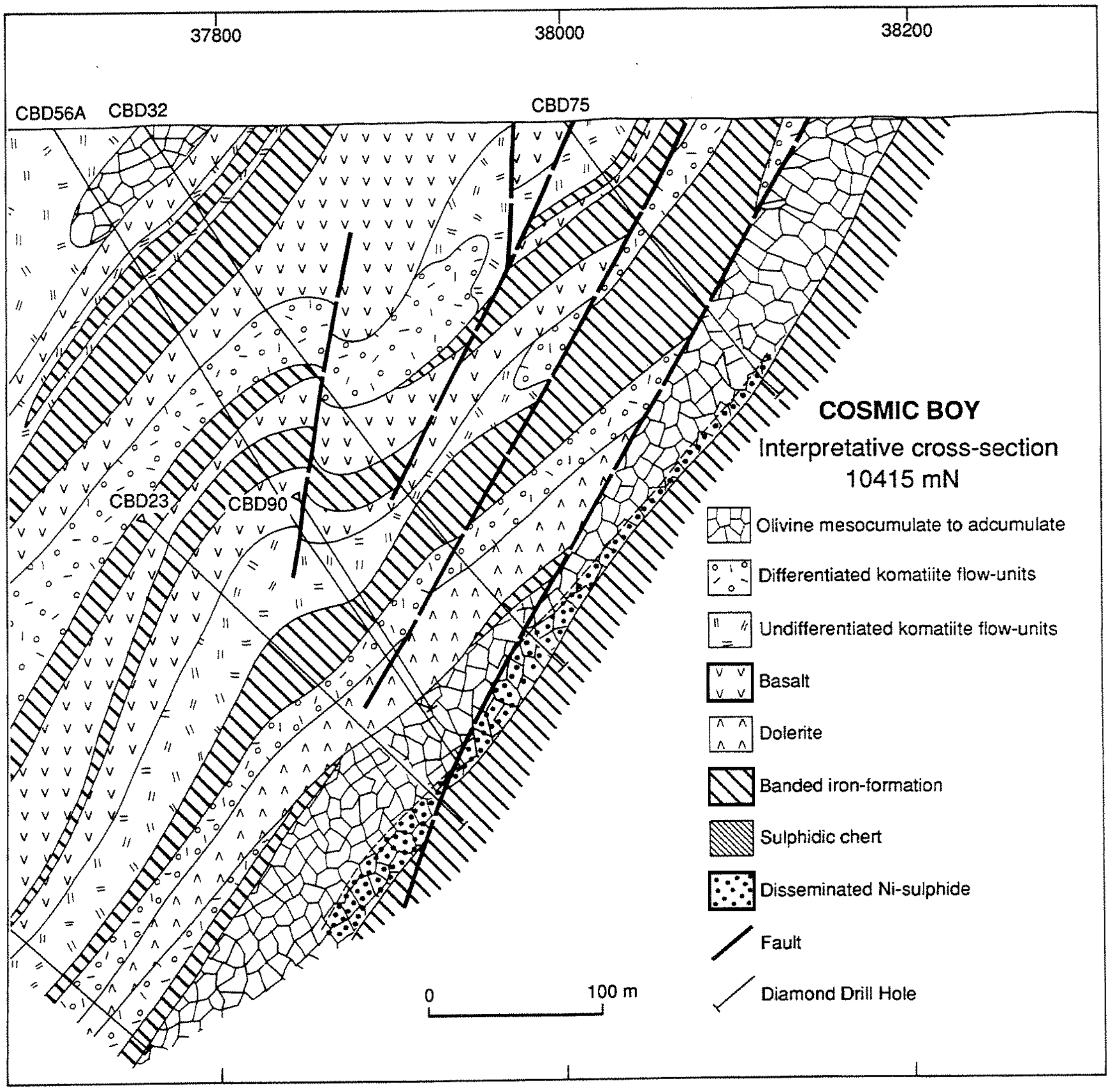

Figure 20. Interpreted geological cross section through 10415mN at the Cosmic Boy nickel sulphide deposit, Eastern Ultramafic Belt. Copyright CSIRO Exploration and Mining

up the greater part of the belt, and these are interspersed with lenticular cumulate flow units (Fig. 21). Interflow BIF and chert horizons are common and the belt is both underlain and overlain by low-Mg basalt.

Geology of the Central Ultramafic Belt

The Central Ultramafic Belt has great lateral continuity and extends approximately 40 km to the north of the Hyden–Norseman road, at least as far north as Mount Hope. To the south, the belt appears to terminate at 17435mN, as indicated by both the RAB drilling and the aeromagnetic data. The belt, which has a north-northeasterly strike and faces west, varies in dip from steep (60–70°)

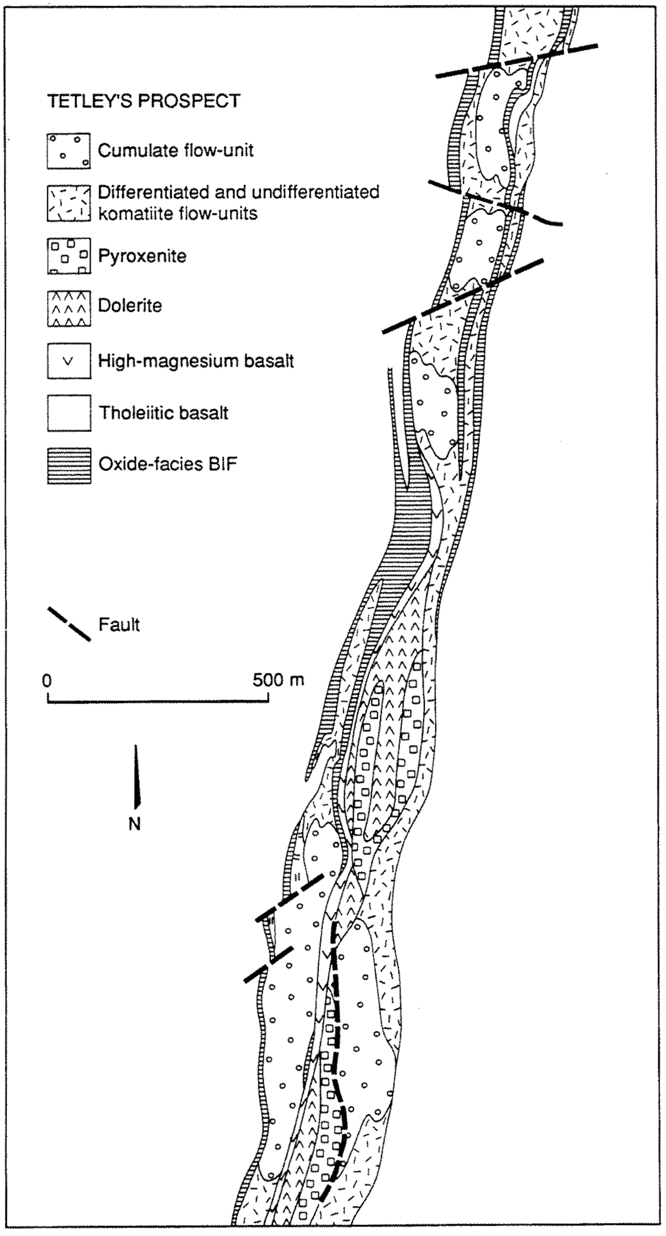

Figure 21. Interpreted geological map of Tetley's prospect in the Mid-Eastern Ultramafic Belt. Copyright CSIRO Exploration and Mining

westerly at its southern end, through subvertical to steep easterly at its northern extremity. The lower part of the Central Ultramafic Belt is dominated by a thick to very thick, sheeted, cumulate flow unit, which passes upwards into thin differentiated and undifferentiated komatiite flow units and high-Mg basalts (Fig. 22). There are breaks in the sheeted cumulate flow unit between the North Forrestania and Crossroads prospects and between the Crossroads and Rokeby prospects. In these areas, the cumulate flow unit passes laterally into multiple thin komatiite flow units. Up to four interflow BIF horizons lie within the ultramafic stratigraphy and a thin BIF horizon commonly occurs its base, separating it from the underlying low-Mg basalts. Low-Mg basalts also overlie the ultramafic rocks.

Geology of the Takashi Ultramafic Belt

The Takashi Ultramafic Belt has a north-northwesterly strike and dips and faces to the west. Up to four ultramafic units are present and these are dominated by thin differentiated and undifferentiated flow units with interflow BIF and chert horizons. Lenticular bodies of olivine mesocumulate and adcumulate are present in the lower ultramafic units. The belt is overlain by mafic tuffs and quartzofeldspathic rocks.

Geology of the Western Ultramafic Belt

Unlike the other ultramafic belts discussed, although the Western Ultramafic Belt has a northerly strike, it dips 50–80° to the east and faces east. A part of the ultramafic stratigraphy in the southern portion of the belt (from New Morning south) is stratigraphically below the basal ultramafic sequence in the northern part of the belt (from Flying Fox north; Fig. 23).

The geology of the Western Ultramafic Belt is dominated by a series of fractionated and non-fractionated cumulate flow units (<180 m thick at New Morning), with lenticular cross sections, which pass laterally into sequences of thin differentiated and undifferentiated flow units. In the upper part of the ultramafic stratigraphy there is a general upward transition from thin differentiated to thin undifferentiated flow units and these are intercalated with basalt, chert and quartz–mica schist.

The footwall to the ultramafic stratigraphy consists largely of quartz–mica schists, with oxide-facies BIF locally present in the Beautiful Sunday prospect. The footwall quartz–mica schist thins and pinches out towards the southern end of the belt (Boojum prospect), and here the ultramafic stratigraphy rests on basalt. The southern end of the belt is substantially disrupted by granitoid intrusions.

Flying Fox prospect

The ultramafic stratigraphy in the Flying Fox mine area comprises a series of up to six ultramafic sequences intercalated with low-Mg basalts and minor pelitic, shaly and cherty sedimentary horizons (Figs 24, 25). The lowermost ultramafic sequence consists of a thick fractionated cumulate flow unit that passes upwards and laterally into multiple, thin, differentiated komatiite flow units. The fractionated flow unit has a tabular shape and plunges to the southeast. Within this

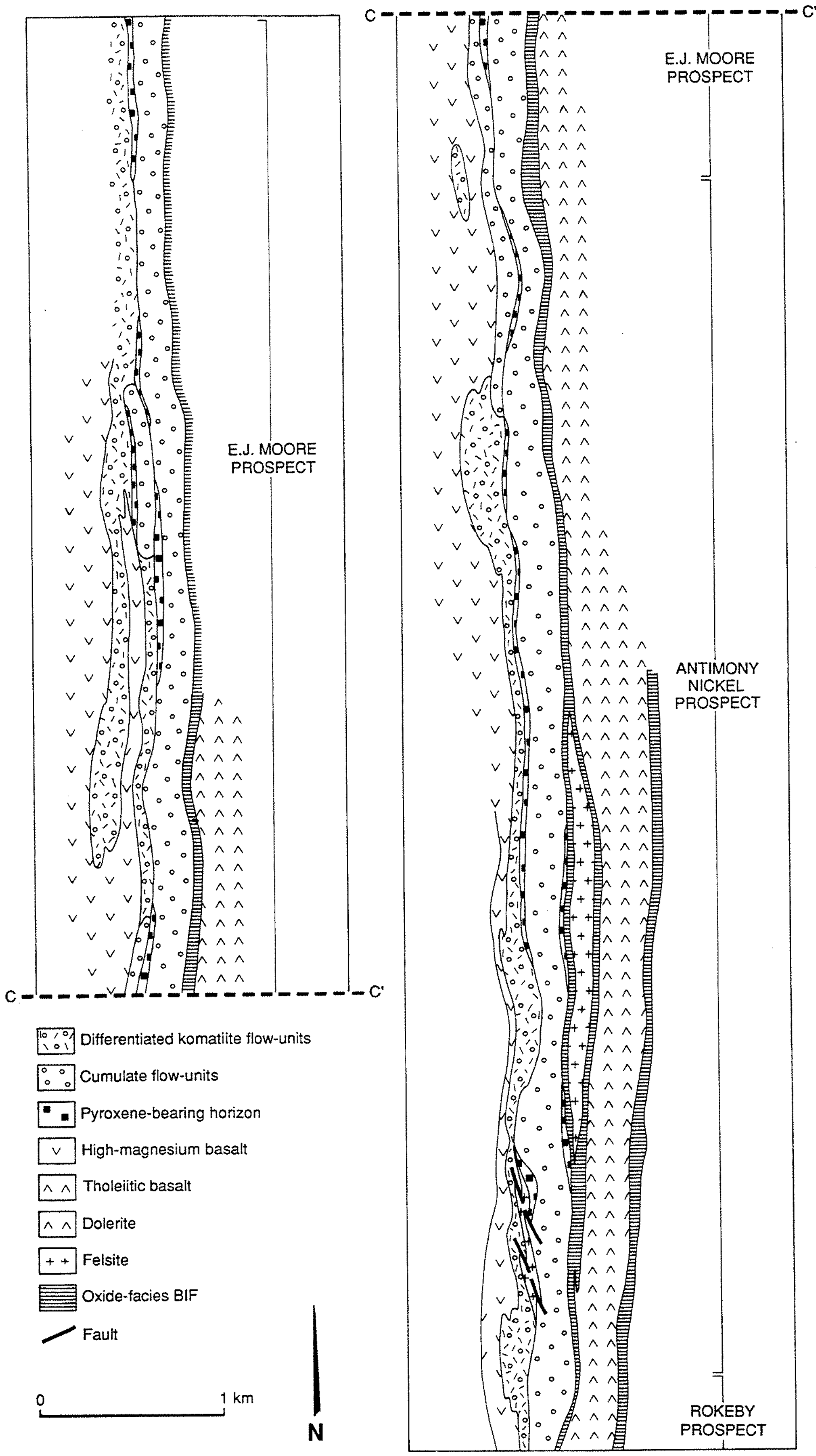

Figure 22. Schematic geological map of the northern part of the Central Ultramafic Belt, from the Rokeby to E. J. Moore prospects. Copyright CSIRO Exploration and Mining

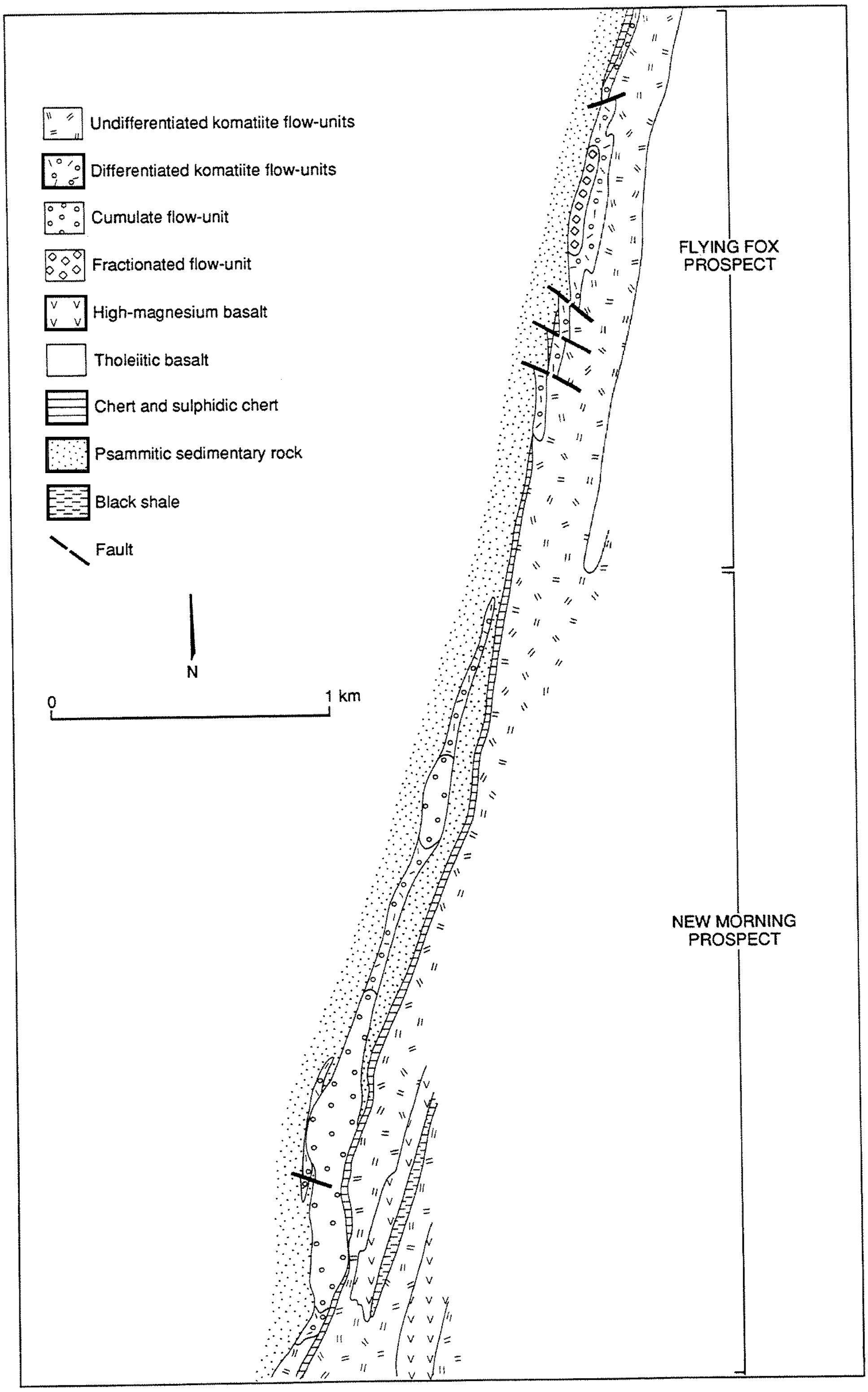

Figure 23. Schematic geological map of the central portion of the Western Ultramafic Belt (from Perring et al., 1995). Note that there are many more interflow sedimentary horizons and intercalations of basalt than can be shown at this scale

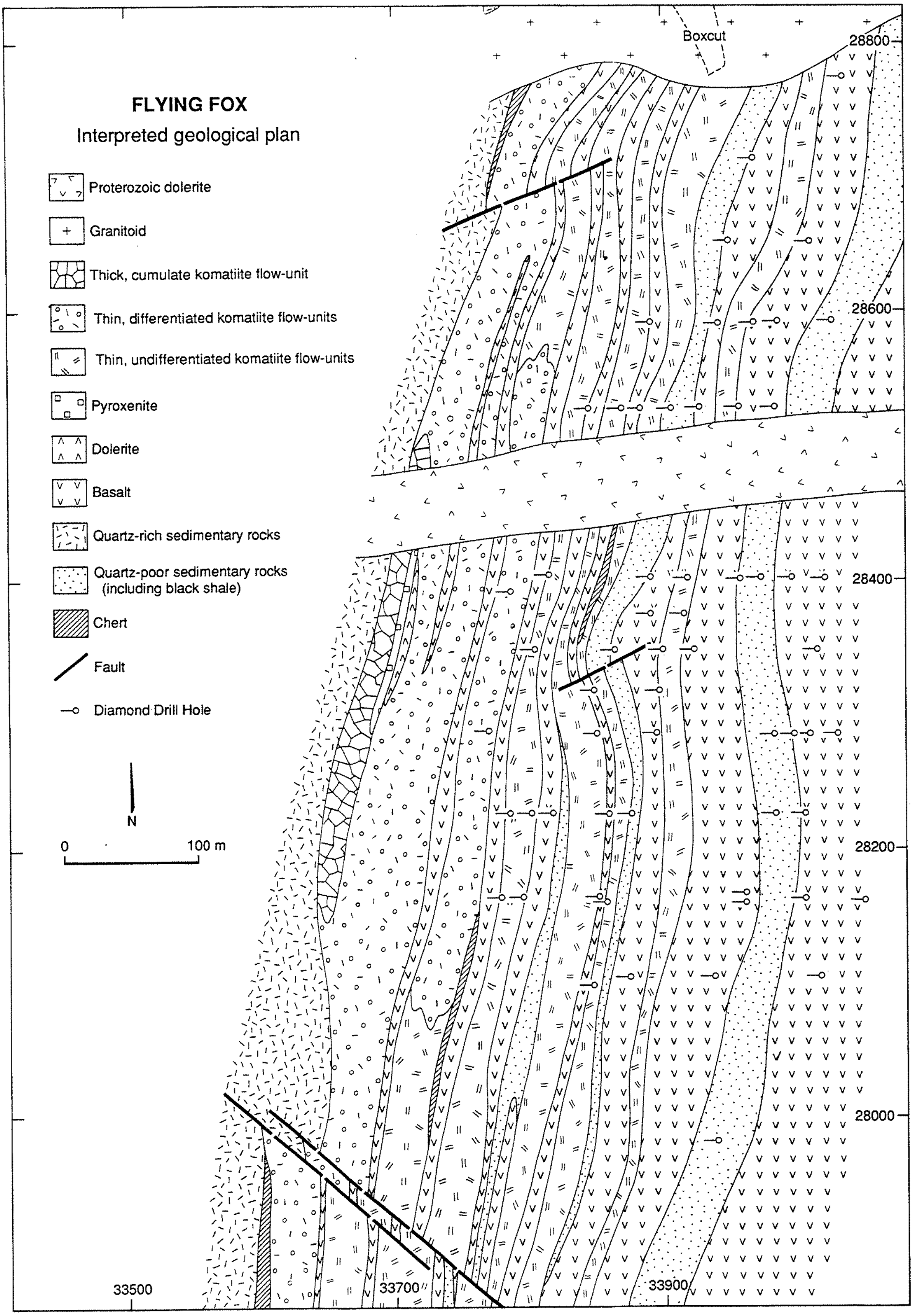

Figure 24. Interpreted geological map of the Flying Fox prospect in the Western Ultramafic Belt. Note the absence of the footwall chert beneath the lenticular cumulate flow unit at the base of the ultramafic stratigraphy. Copyright CSIRO Exploration and Mining

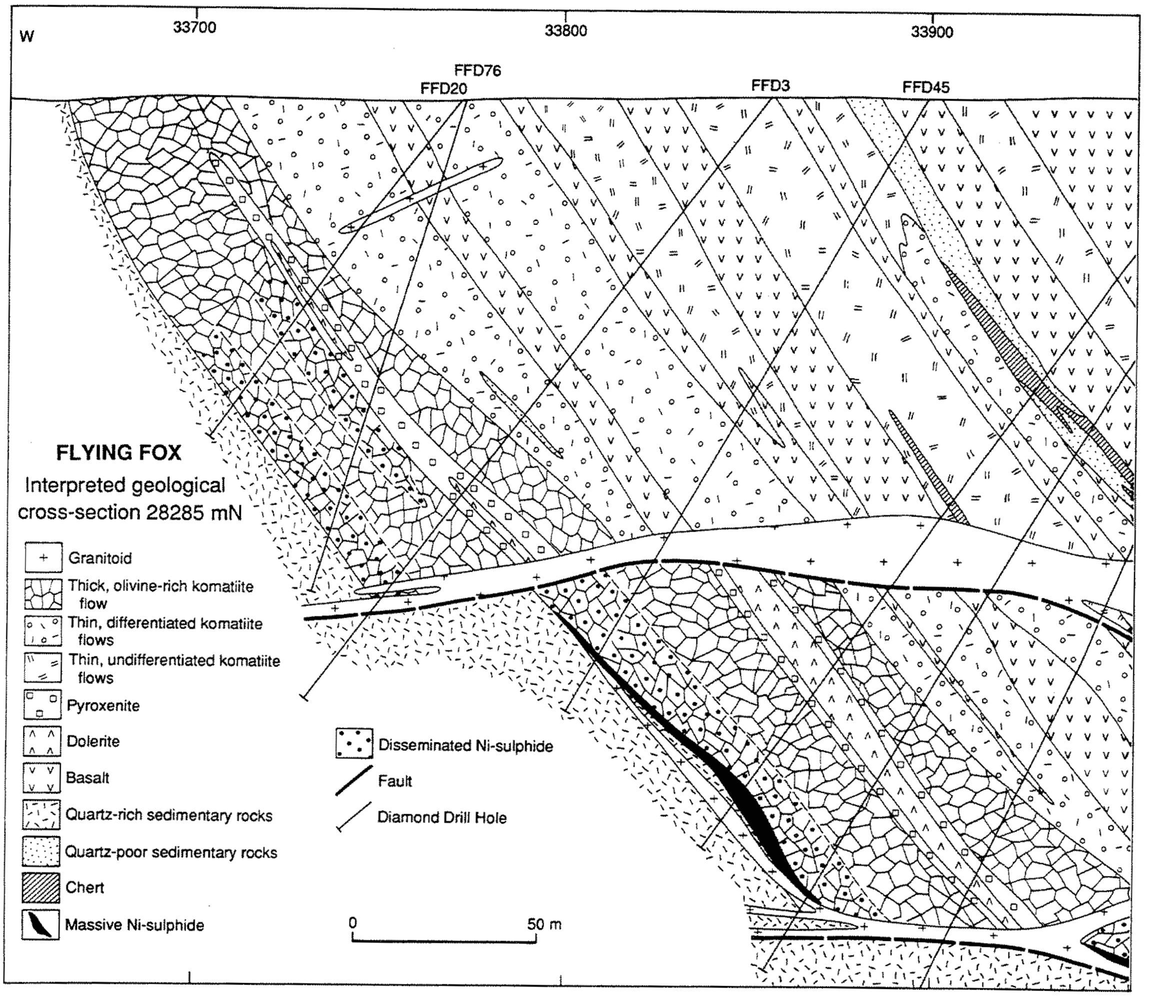

Figure 25. Interpreted geological cross section through 28285mN at the Flying Fox nickel sulphide deposit, Western Ultramafic Belt (from Perring et al., 1995a)

and subsequent ultramafic sequences, there is an upward and lateral progression from thin differentiated flow units to thin undifferentiated flow units.

Massive nickel sulphides and thin, impersistent zones of olivine–sulphide mesocumulate (<10 m thick, <10% sulphide) occur at the base of the fractionated cumulate flow unit at Flying Fox. Mineralization appears to occupy a shallow embayment in the footwall stratigraphy. To the north and south of the fractionated flow unit, there is a sulphide-bearing chert horizon between the lowermost ultramafic sequence and the psammitic footwall schists (Figs 23, 24).

The sulphide-bearing basal contact has been offset by a number of subhorizontal faults (Fig. 25). The throw on the lowermost of these is in excess of 300 m, and the continuation of this important contact at depth has been only recently intersected. The distribution of the massive sulphides has been severely disrupted during deformation and sulphide stringers occur on the fault planes and within foliation planes in the footwall sediments.

Geological summary

There are essentially three types of volcanological association developed at Forrestania: very thick sheet-like cumulate flow units, very thick curvilinear cumulate flow units, and cumulate flow units with lenticular cross sections interspersed with sequences of thin flow units.

Very thick, sheeted, cumulate flow units are common in the Eastern and Central Ultramafic Belts. They range up to 500 m in thickness and typically rest on basalt or oxide-facies BIF. The profile through a typical sheeted cumulate flow unit can be broken down into:

(a) a basal marginal zone consisting of olivine(–pyroxene) orthocumulate to mesocumulate (<10 m),

(b) a central zone comprising olivine mesocumulates to adcumulates (<500 m),

(c) an upper zone consisting of a chilled flow-top which may be underlain by spinifex-textured rocks and fractionated doleritic and pyroxenitic cumulates (<50 m).

Fractionated cumulates are especially common towards the top of sheeted, cumulate flow units in the Central Ultramafic Belt (Fig. 22). These flow units are commonly overlain by thin, differentiated and undifferentiated komatiite flow units and komatiitic basalts.

Very thick curvilinear cumulate flow units occur in the Eastern and Western Ultramafic Belts in areas where there are quartz–mica schists in the immediate footwall (at the Digger Rocks and New Morning prospects, respectively). Apart from the differences in substrate composition and morphology, these flow units are very similar to the sheet-like cumulate flow units described above.

The association of thick cumulate flow units and thin flow units is common in the Eastern, Mid-Eastern, Takashi, and Western Ultramafic Belts. Multiple sequences of thin komatiite flow units merge and pass laterally into thick, cumulate flow units with lenticular cross sections. The cumulate flow units consist largely of olivine mesocumulate with a basal zone of olivine(–pyroxene) orthocumulate. The olivine-cumulate rocks may be capped by a flow top or by a zone of fractionated cumulates. Flanking sequences of thin komatiite flow units are intercalated with cherty metasedimentary rocks (oxide- and sulphide-facies BIF, chert) and mafic amphibolites (basalts and mafic tuffs). There is commonly a vertical and lateral transition from thick, cumulate flow unit to thin, differentiated komatiite flow units and thin, undifferentiated komatiite flow units intercalated with high-magnesium basalts.

Volcanological summary

Two principal volcanic facies are now recognized for komatiites in the Eastern Goldfields and Southern Cross Provinces of the Yilgarn Block (Hill et al., 1990, 1995): these are a *flood-flow facies* and a *compound-flow facies*, and both of these can be further subdivided. The flood-flow facies is made up of areas of *unconstrained continuous sheet flow* (e.g. the southern part of the Eastern Ultramafic Belt and much of the Central Ultramafic Belt) and areas of *continuous sheet flow with erosional pathways* (e.g. New Morning, Digger Rocks). The compound flow-facies consists of *episodic sheet flows*, comprising preferred lava pathways flanked by marginal flow lobes (e.g. the northern part of the Eastern Ultramafic Belt, including Cosmic Boy, and much of the Mid-Eastern, Takashi, and Western Ultramafic Belts, including Flying Fox), and *thin compound flow lobes* without internal pathways (e.g. much of the upper part of the ultramafic stratigraphy within individual belts).

Note that thermal erosion is likely to take place at the base of preferred pathways (be these open channels or enclosed tubes) and that blockage of a preferred pathway, physical obstruction of an advancing flow or a sudden decrease in the rate of lava supply can lead to ponding (Swanson, 1973; Walker, 1991; Wilson and Parfitt, 1993; Hon et al., 1994; Pinkerton and Wilson, 1994) and fractionation of lava in situ at any scale.

Summary of principal orebodies

S. J. Barnes et al. (1994) present an amended classification scheme that takes as its principal variable the differing sulphide segregation processes (Table 4). Type 1 deposits contain basal accumulations of massive and matrix sulphides and Type 2 deposits consist of central accumulations of disseminated sulphide. The other variable, size and olivine content of the preferred lava pathway, varies continuously. The nickel sulphide orebodies at Forrestania are exclusively Type 1.

Table 4. Classification matrix for komatiite-associated nickel sulphide ores

	TYPE 1 *Basal accumulation of massive and matrix sulphide ore*	*TYPE 2* *Central accumulation of disseminated sulphide ore*
Size and olivine content	Kambalda	(not economic)
of preferred lava pathway	Flying Fox	
increases from top to	Cosmic Boy	
bottom	Digger Rocks	Yakabindie
	?Perseverance	Mount Keith

The principal sulphide accumulations at Forrestania display a number of features in common. They tend to occur at the base of flow units in positions that are interpreted as preferred lava pathways (i.e. channels or tubes marked by bodies of olivine cumulate of lenticular cross section or thickened parts of more laterally extensive sheeted cumulate bodies). In many instances there is evidence that thermal erosion occurred at the base of preferred pathways that host mineralization, as indicated by the absence of parts of the immediate footwall stratigraphy and the presence of pyroxene-bearing cumulates containing footwall xenoliths. This is significant in terms of current models for the genesis of Type 1 (massive to matrix) mineralization, in which thermal erosion of sulphidic substrate is a critical ingredient in orebody formation.

Digger Rocks

Resource (pre-mining): 1.8 Mt at 1591% Ni

Mineralization: basal massive sulphide (<25 m thick, 3–8% Ni) overlain by matrix to disseminated sulphide (<20% sulphide, Ni grades <3%, <40 m thick); orebody has a subhorizontal plunge.

Host sequence: massive sulphides, pyroxene–sulphide cumulates and olivine–sulphide mesocumulates to adcumulates occupy a broad embayment (~50 deep by ~400 m wide) at the base of the thickest part of a very thick, sheeted, cumulate flow unit (<400 m thick); pyroxene-bearing rocks containing xenoliths of BIF and quartz–mica schist line and are restricted to the embayment.

Footwall: the interflow sedimentary horizon (BIF and quartz–mica schist), which separates the mineralized flow unit from an earlier cumulate flow unit to the south, is absent in the vicinity of

Digger Rocks mine and the early cumulate flow unit forms the immediate footwall to the mineralization.

Cosmic Boy

Resource: 4.1 Mt at 2.4% Ni

Mineralization: basal matrix to disseminated sulphide (<30% sulphide, Ni grades <4%, <20 m thick); plunge appears to be subhorizontal.

Hosting sequence: olivine–sulphide orthocumulates and mesocumulates overlie weakly mineralized pyroxene orthocumulates; mineralization occurs at the base of a thick, tabular cumulate flow unit (<80 m thick).

Footwall: few drillholes pass through the thick BIF horizon that immediately underlies the mineralization; the presence of a footwall embayment is difficult to ascertain.

Flying Fox

Resource: 0.3 Mt at 6.1% Ni

Mineralization: basal massive sulphide (<5 m thick) overlain by thin, impersistent zones of disseminated sulphide (<10% sulphide, <5 m thick); the orebody plunges steeply to the southeast.

Hosting sequence: massive sulphide is typically overlain by a thin layer of olivine–sulphide mesocumulates; mineralization occurs at the base of a thick, fractionated, tabular, cumulate flow unit (<50 m thick), which occupies a broad, shallow embayment (~15 m deep by ~800 m wide).

Footwall: consists of quartz–mica(–sillimanite) schists; the embayment at the base of the komatiite sequence is marked by the absence of a sulphide-bearing chert horizon.

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V. Forrestania greenstone belt excursion localities

by

[1]K. Frost

The localities to be visited at Forrestania, South Tetley's prospect and the Digger Rocks mine show a wide range of komatiite volcanic sequences that typify the geology of the Mid-Eastern and Eastern Ultramafic Belts of the Forrestania greenstone belt. These locations are shown on the regional geology plan presented as Figure 15 (note that South Tetley's prospect is next to Tetley's prospect).

The bus will travel north from the mine office along a track parallel to the Eastern Ultramafic Belt that passes prominent hills of structurally thickened banded iron-formation (BIF) at Middle Ironcap and Mount Mason. Note that the dissected regolith in this area has exposed isolated laterite caps at ridge tops, and lower sections of the ridge slopes comprise weakly weathered basalt, BIF and spinifex-textured komatiites. Deeper weathering of the less resistant olivine-rich cumulate komatiites has generally resulted in a siliceous caprock that commonly preserves igneous and metamorphic olivine textures despite the almost total replacement by silica.

Locality 1. South Tetley's prospect

The Mid-Eastern Ultramafic Belt at this location is only 1 km west of the Eastern Ultramafic Belt, and comprises olivine mesocumulate bodies that are linked by thin differentiated komatiite flows, intercalated with BIF and chert, between two predominantly basaltic sequences that dip steeply west (Fig. 26). This belt will be traversed up the stratigraphic sequence along an east–west section through two of the lowermost komatiite flow units. The tour will also view core from drillhole MED-11, to assist with the identification of poorly exposed rocktypes in this area.

The footwall chert and basalt are obscured by saline lake clays, and mapping has relied on close-spaced RAB drill cuttings to compile the geology. The upper part of the basal and overlying cumulate flow units outcrop as resistant talc–magnesite rocks. It should be noted that the talc–magnesite assemblage indicates either a lower metamorphic grade for the Mid-Eastern Ultramafic Belt compared with the amphibolite facies metamorphism of the Forrestania belt, or a retrograde alteration event restricted to this belt. The talc–carbonate rocks are separated by a small hill of

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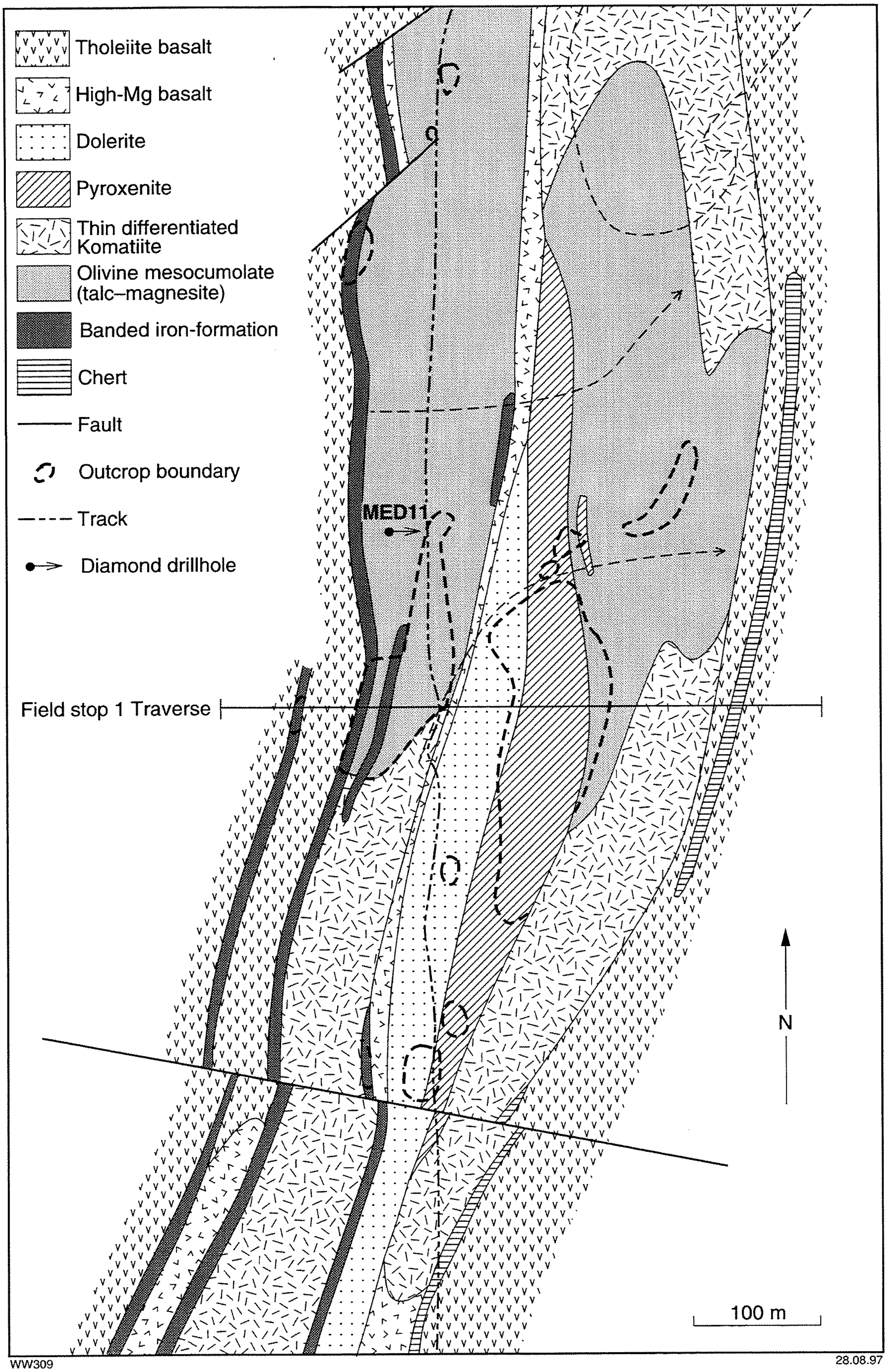

Figure 26. Interpreted geology, South Tetley's nickel prospect, Forrestania

pyroxenite and dolerite. The pyroxene in these rock-types is replaced by tremolite–actinolite (pyroxenite) and actinolite–hornblende (dolerite) and feldspar is typically preserved in the dolerite unit. Thin BIF and high-Mg basalt, situated farther along strike on the basal contact of the overlying talc–magnesite komatiite, demonstrates a marked hiatus in the komatiite volcanism between the two cumulate flow units. Thin BIFs are intercalated with komatiite rock types close to the upper contact with tholeiitic basalt.

Diamond drillhole MED-11, drilled on an easterly azimuth about 120 m north of the traverse, intersected a package of rock types similar to that described above, although a more complete section of the basal flow unit can be observed in drillcore. In addition, whole-rock geochemistry for selected rock-types (recalculated to a volatile-free basis) highlights the wide range of compositions found in komatiitic flow units.

Locality 2. Digger Rocks mine

The Digger Rocks openpit provided the first ore for the Forrestania Nickel Project in January 1993, and has since contributed over 1.1 Mt of ore grading 1.7% Ni. The depth extension of this mineralization, the Digger Deeps deposit, is currently being assessed for underground mining in 1998.

The Digger Rocks deposit is outlined in the geology section of this guide and many of the features of the local geological setting shown in Figure 17 can be observed from a lookout on the edge of the openpit. The eastern wall of the pit exposes the footwall ultramafic flows and overlying BIF (folding is evident) and quartz–mica schist, which marks the base of the nickel sulphide mineralized flow rocks. The very thick olivine adcumulate rocks in the western pit wall are weathered to an average depth of only about 30 m, although the base of oxidation is highly irregular with blocks of less-weathered serpentinite enveloped by siliceous cap rock. The physiographic setting of the deposit in an incised valley has undoubtedly contributed to the shallow weathering and improved the economics of the mine. The nickel sulphide mineralization, best viewed from underground exposures, is located in the basal zone of the very thick (≤500 m thick) olivine adcumulate and comprises a thick (≤60 m wide) low-grade halo of 1–5 vol.% disseminated sulphides, a higher grade disseminated sulphide zone (5–20 vol.% sulphides; ≤90 m thick), massive sulphide lenses (≤16 m thick), BIF containing massive sulphide stringers (well exposed in underground openings) and pyroxenite with disseminated sulphides (drillcore intersections to be viewed at core farm). The light-green pyroxenite seen on the northern and southern pit walls is located along the basal contact of the mineralized flow unit. The deposit is complicated by a set of northwesterly trending faults, one of which, towards the southern pit margin, has about 35 m of strike slip movement across the ore zone.

Underground development of the Digger Deeps orebody via a hangingwall decline provides an ideal opportunity to traverse the basal section of the very thick olivine adcumulate, and to observe the characteristic mineral assemblages formed at upper amphibolite facies metamorphism. At this location, the olivine adcumulate is completely retextured through a well developed zonation of prograde metamorphic minerals that formed under variable f_{CO2} and f_{H2O} conditions of alteration.

The mostly barren metamorphic olivine–talc rocks above the ore zone grade into metamorphic olivine–anthophyllite rocks (anthophyllite has a coarse, bladed habit) that host the economic disseminated nickel sulphide ore. The prograde metamorphic minerals, olivine and anthophyllite, are commonly retrogressed to serpentine and talc, respectively. BIF-hosted ore at this location is strongly mineralized with massive sulphide lenses.

Locality 3. Core farm

A selection of diamond drillcore shows examples of primary igneous and secondary metamorphic textures in komatiites and other rock types from Forrestania. There will be an opportunity to discuss the origin of fascinating rock types, such as mineralized basal pyroxenite and modified sedimentary units, that are cited as supporting evidence of thermal erosion by komatiite lavas flowing along preferred lava pathways.

VI. The Bounty gold mine

by

[1]R. Mason

The Bounty gold mine is located within the Forrestania greenstone belt of the Southern Cross Province (Fig. 27). The mine is situated at latitude 32° 06' S, longitude 119° 47' E (AMG 50 $_{7}$619, $_{64}$451) approximately 360 km east of Perth and 120 km south-southeast of Southern Cross on HYDEN (1:250 000). The gold mineralization is essentially stratabound hosted by a banded iron-formation (BIF) horizon.

The operation is 100% owned and operated by Forrestania Gold NL. From 1989 to June 1997 the Bounty orebody has produced a total of 4.14 MT at 6.00 g/t gold from underground and opencut mining operations for 800 000 oz gold. With reserves in situ (excluding resources) of over 260 000 oz, the Bounty orebody has a pre-mining reserve of greater than 1 000 000 oz gold.

This document is adapted from the paper 'Bounty gold mine : An Overview' written by P. Weedon and M. Stallman (unpublished, formerly employed by Normandy at the Bounty gold mine).

Exploration history

The first exploration of the Forrestania region for gold mineralization was by prospectors during the early part of the 20th century. Minor deposits were found but production of gold was minimal. The first modern exploration of the region occurred during the nickel boom of the late 1960s to early 1970s. Intensive exploration for Ni–Cu–Fe sulphide mineralization hosted by olivine peridotite metakomatiites was conducted by Amax Exploration (Australia), in joint venture with Amoco Minerals (Australia). A number of nickel resources were discovered. Extensive gridding, aeromagnetic and ground magnetic surveys, RAB bedrock geochemical drilling, percussion and diamond drilling were conducted.

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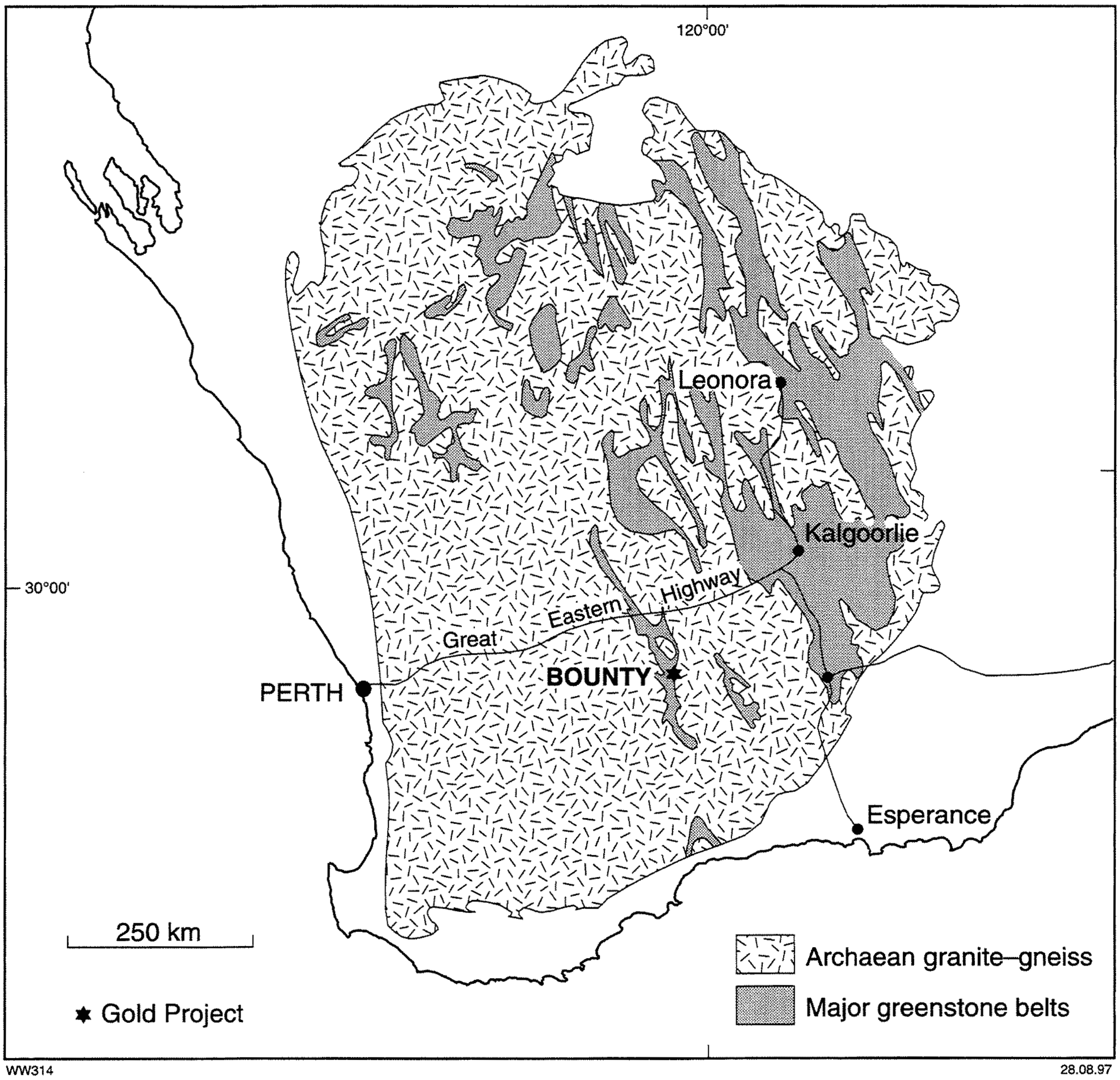

Figure 27. Map of Yilgarn Craton showing location of Bounty Gold Mine

The potential of the region to host gold mineralization was first recognized when an Amax diamond drill hole, MHD20, intersected a thin, high-grade gold zone. This hole was drilled at the Mount Hope Nickel prospect, approximately 4 km south-southeast of the Bounty gold mine. The hole intersected a 1 m zone of coarse, spotty gold on the margin of a quartz stockwork in metaporphyry. Four different assays over the interval returned values ranging from 2.3 to 190 ppm Au.

Harmark acquired tenements in the vicinity of the Bounty gold prospect in November 1980. These tenements covered a rubellite (lithium tourmaline) occurrence, and areas prospective for gold and strategic minerals (Ta, Sn, Cr and Li). Harmark then entered into a joint venture with

Minerals Estate who undertook a limited gold exploration programme during 1984. Aztec Mining entered into a joint venture with Harmark (later vended into Forrestania Gold NL) and Mineral Estates in October 1984, and became the operator of the joint venture. During 1985, Aztec conducted an exploration programme, which included auger soil sampling of all of the tenements. This sampling highlighted a number of discrete zones with values ranging from 0.10 to 1.02 ppm Au within a broad anomalous trend 10 km long and up to 1 km wide. The most significant anomalism occurred on lines 35000N, 35400N, 35600N and 35800N. The Bounty opencut is centred at approximately 34900N. These zones were tested with an initial RAB drilling program. Drilling difficulties were encountered due to the hard ground conditions and many holes did not reach bedrock. Low-order results, up to a maximum of 1.02 ppm Au were returned from RAB drilling over the Bounty deposit. Further RAB drilling during late 1985 and 1986, with follow-up RC drilling, intersected the main body of mineralization, which was eventually drilled out on 20 x 12 m centres. Diamond drilling demonstrated the depth potential of the deposit and openpit mining commenced in October 1988, excavating two pits 73 m deep with a combined strike coverage of 1000 m.

The Bounty gold mine was officially opened in June 1989. During 1992 an underground expansion begun, which included the sinking of a shaft to approximately 840 m below the surface (which was commissioned in late 1996). Posgold purchased Aztec's 62% equity in the project during March 1994, becoming the Bounty Project Joint Venture managers. Forrestania Gold NL assumed 100% ownership and operational management of the Bounty Project during February 1997 via the purchase of Normandy's 62% equity in the project.

Mine geology

The Bounty gold deposit is essentially stratabound, hosted by the 10 to 30 m thick Bounty Horizon Banded Iron Formation , the westernmost and youngest horizon of an ultramafic sequence of metakomatiitic and peridotitic or high-Mg meta-basalts, known locally as the 'Footwall Basalts', and associated metasediments known as the Bounty Sequence. Overlying the host BIF is a metadolerite sill or dyke, known locally as the 'Hangingwall Dolerite', with the contact between these two units frequently defined by a mylonitized chloritic shear. The metamorphic grade of the Archaean host sequence is amphibolite facies. Late-stage pegmatites and an easterly trending, 280 m wide, Proterozoic dolerite dyke (the Binneringie Dyke of the Widgiemooltha Suite) cut the mine sequence. The Proterozoic and Archaean stratigraphy is blanketed by a thin (<1 to 10 m) veneer of recent transported and residual overburden. Refer to Figures 28 and 29 for schematic geological summaries (in cross section and longitudinal projection) of the Bounty orebody.

The Bounty gold deposit occurs as two discrete orebodies, Bounty and North Bounty, which are essentially the same mineralized horizon separated by the younger Binneringie Dyke. Table 5 describes the dimensions and geometries of these two orebodies. The geological summary, which follows, is applicable to both Bounty and North Bounty.

Table 5. Bounty gold deposit vital statistics

	Bounty	*North Bounty*
Strike length (m)		
At surface	500	200
At depth (limit indicated)	>300 (660 m below surface)	300 (270 m below surface)
Plunge length	>1000 (unconstrained)	400
Average true ore width		
(including hangingwall shear zone)	2.5 m	2.5 m
BIF dip	75° west	75–85° west
BIF strike	350°	350°
Oz Au/v.m range	2,600 (2 L) 400 (29 L)	730 (1L) 400 (17L)
1996/97 reserve	1 168 700 t at 5.70 g/t Au	278 020 t at 5.07 g/t Au
1996/97 total reserve	1 446 600 t at 5.58 g/t Au	
1996/97 total resource	2 459 200 t at 7.17 g/t Au	
Binneringie Dyke width range	280 to 350 m	

Footwall basalts

The footwall sequence consists of banded high-Mg metabasalt, spinifex-textured metakomatiite, and metaperidotite and minor metadunite, as well as chert and other interflow metasedimentary units.

A persistent 75–85° west-dipping foliation is present throughout the footwall sequence; however, well developed spinifex blades up to 30 mm are preserved locally throughout the sequence.

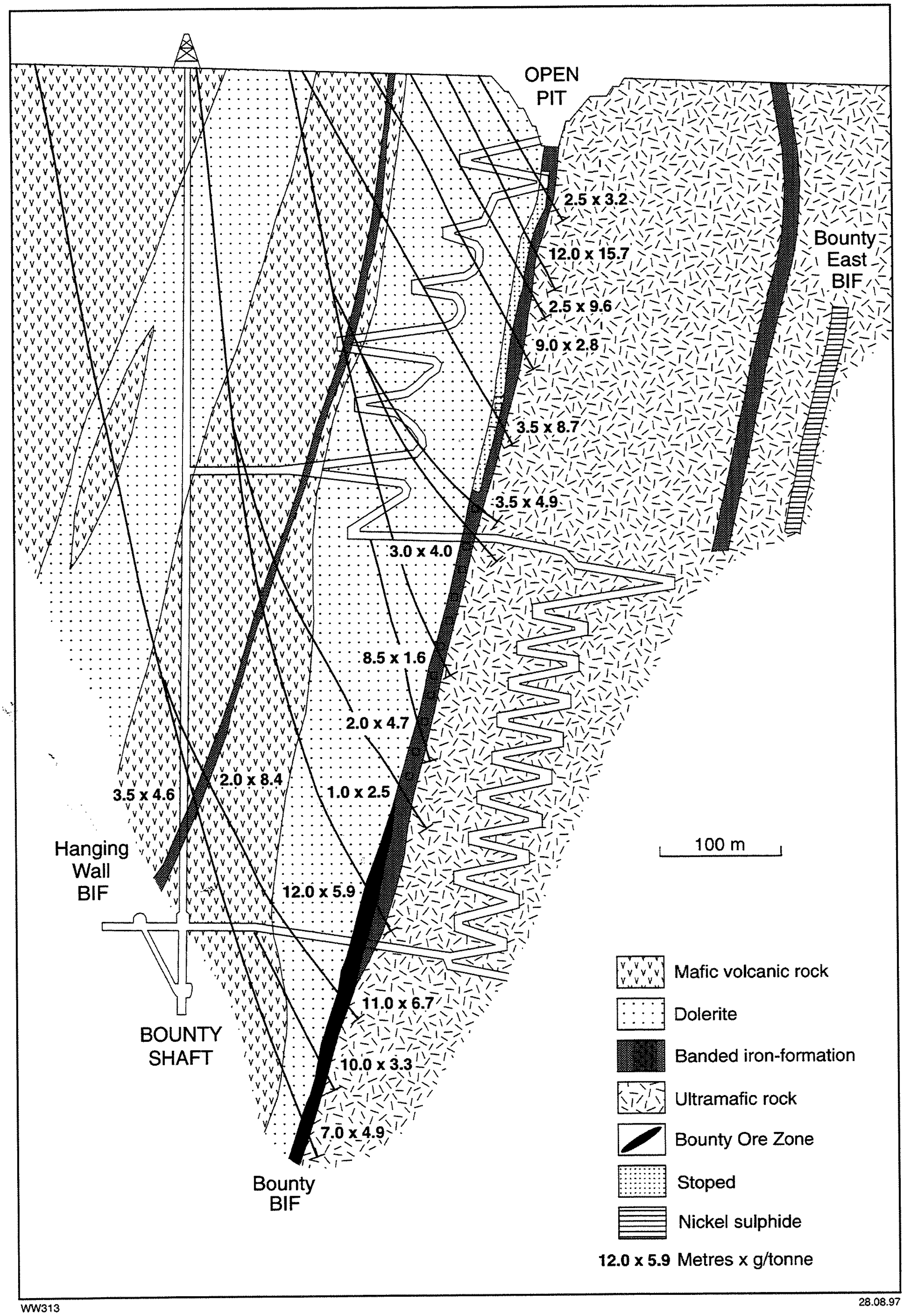

Figure 28. Cross section through Bounty gold deposit

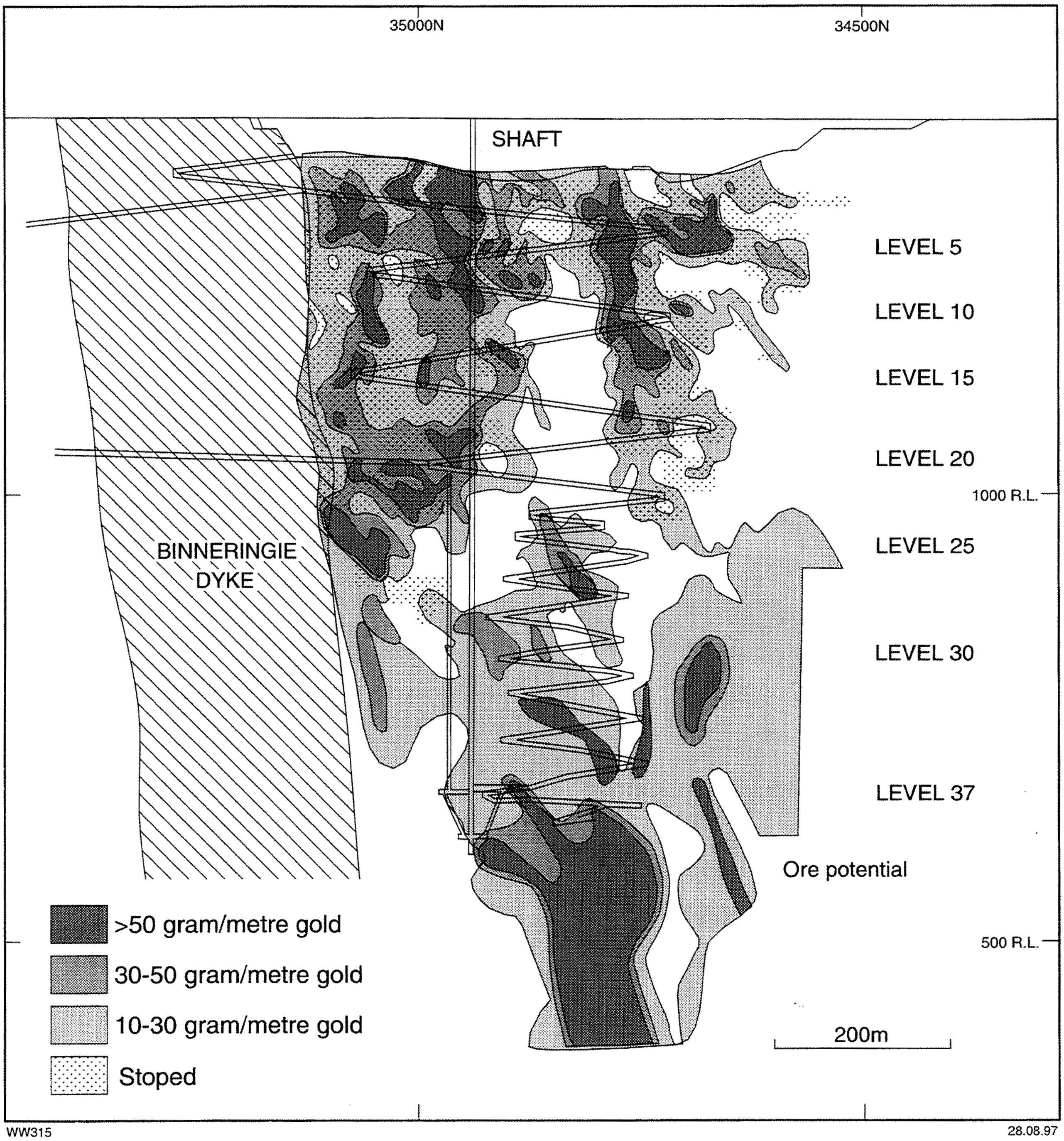

Figure 29. Schematic longitudinal projection showing gold gram/metre contours, Bounty gold deposit

Bounty Horizon Banded Iron-Formation

The Bounty Horizon Banded Iron-Formation is a variably deformed, 12 to 20 m thick iron-formation and chert unit, that strikes northerly and dips 75 to 85° west. The iron-rich bands consist of grunerite(–actinolite–magnetite–quartz–hedenbergite) assemblages and magnetite(–biotite) assemblages (Rutherford, 1991). Silica-rich beds/bands contain granoblastic quartz(–magnetite–

amphibole). Thin pelitic beds (<100 mm) comprising biotite(–garnet–amphibole) assemblages may also be present. Individual beds may be up to 150 mm thick but 10–30 mm is normal.

Peak metamorphic temperatures of 560° ± 50° have been recorded from geothermometry of biotite–garnet assemblages within the pelitic beds of the Bounty Horizon (Caswell, 1989).

Deformation within the Bounty Horizon BIF can be subdivided into three zones:

Hangingwall shear zone: The hangingwall shear zone, with strong shearing to mylonitic deformation, extends 4–6m from the hangingwall contact into the Bounty Horizon. Deformation intensity decreases rapidly away from the contact with mylonitic and brecciated zones giving way to well-preserved upright to steeply plunging asymmetric folds. This zone hosts most of the economic mineralization.

Footwall shear zone: The footwall shear zone extends up to 5 m into the Bounty Horizon BIF as well as up to 15 m into the Footwall Basalts. This zone is characterized by moderate to locally strong shearing with poorly preserved folds within the Footwall Basalts and better-preserved folds within the Bounty Horizon BIF. Mineralization in the sheared Footwall Basalt is generally gold-poor. Mineralization within the BIF proximal to the footwall contact is variable in gold content, but economic levels occur within 1–4 m of the footwall contact, particularly in the lower southern sector of the Bounty orebody.

Central low-strain zone: The central low-strain zone contains well-preserved primary bedding with minor broad open to tight folding of variable plunge. This zone is generally poorly mineralized. However, in the lower southern sector of the Bounty orebody a semi-persistent zone of moderate to high strain is developed and is consistently mineralized with gold ranging from subeconomic to economic. This zone is 2–5 m from the footwall contact and footwall proper mineralization.

Hangingwall Dolerite

The Hangingwall Dolerite, approximately 150 m thick, is fine to medium grained, with a granular, massive to weakly foliated texture of subhedral hornblende after pyroxene (40–60%), plagioclase (40–60%), actinolite and biotite. A chilled (basaltic) margin, 2–4 m wide, is present at the basal contact with the BIF, and a gradual reduction in grain size occurs 20–30 m from the BIF contact. The upper contact with the overlying metabasalt is gradational. Deformation and alteration styles are consistent with an Archaean, not Proterozoic, age for the Hangingwall Dolerite.

Mineralization

Footwall mineralization

Mineralization present within the Footwall Basalts can be subdivided into three types:

Footwall contact shear gold: Underlying the Bounty Horizon BIF contact and extending approximately 15 m from the contact, weak to moderate shearing is present within tremolitic metabasalt. Well-developed discrete elongate pods or augen of pyrite and/or pyrrhotite occur within the sheared metabasalt. This unit returns weakly anomalous gold values.

Chert and interflow sediment-hosted gold: Weak to massive pyrite and pyrrhotite mineralization is present within chert and metasedimentary horizons 180–230 m east of the metabasalt–BIF contact. This unit hosts significant gold mineralization, particularly above the base of semi-oxidation. Locally this horizon is known as the East Bounty BIF.

Nickeliferous sulphidic peridotite/dunite flows: Metaperidotite/dunite flows contain disseminated, blebby and massive pyrrhotite–pentlandite–pyrite mineralization. Approximately 280 m east of the Bounty Horizon BIF footwall contact, an inferred resource of approximately 500 000 t at 1.3–1.5% nickel is hosted by a sulphidic metaperidotite/dunite.

Mineralization in the Bounty Horizon Banded Iron-Formation

Economic mineralization within the Bounty Horizon BIF is dominated by pyrrhotite with minor pyrite, marcasite and trace chalcopyrite. Petrographic work by Rutherford (1991) and Townend (1994, unpublished data) revealed trace chalcopyrite, sphalerite, galena, arsenopyrite and molybdenite associated with gold mineralization. Visible gold is generally rare and is commonly found as fine aggregates on the margins of clear to pale-blue quartz veins or as isolated flakes within amphibole masses. In the lower northern sector of the Bounty deposit, high to bonanza grades reflect the presence of a siliceous ore facies commonly containing visible gold within epithermal-like calcite–quartz crackle veinlets which 'brecciate' the greyish quartz-rich mass.

Figures 28 and 29 summarize the distribution of gold within the Bounty orebody. Mineralization and gold distribution within the Bounty Horizon BIF can be subdivided into five categories: quartz–sulphide veins, pyrrhotite–matrix breccia, replacement ore, massive amphibolite ore and calc-silicate ore.

Quartz-sulphide veins

White quartz–pyrrhotite(–pyrite–chalcopyrite) veins: Quartz–sulphide veining may be present as large (up to 1.5 m wide) milky white veins with pyrrhotite–(pyrite–chalcopyrite) present along fracture planes and vein margins. Polished thin-section observations by Townend (1994, unpublished data) demonstrated a close association between gold, pyrrhotite and pyribole with fine gold (<5–50 micron) present as clouds within pyribole adjacent to pyrrhotite or at the margins between pyribole and pyrrhotite.

Clear to bluish-grey quartz–pyrrhotite veins: Clear to blue quartz–pyrrhotite veins occur generally as swarms of fine (<5 cm thick) veins with the pyrrhotite forming a fine intricate mesh (crackle/fracture breccia) in close association with pyribole. Fine gold (10–25 microns) is present, commonly within pyrrhotite or quartz. Rare coarse visible gold is also hosted within the quartz, mostly as clouds up to 1 cm in diameter. Rare arsenopyrite occurs with the pyrrhotite (Townend, 1994, unpublished data).

Pyrrhotite-matrix breccia

The second major mineralization style within the Bounty orebody is the pyrrhotite breccia, which can in turn be further subdivided into gold-rich (5–25 g/t) and gold-poor (<1 g/t). The gold-rich breccia may be visually distinguished from gold-poor breccia by a subtle colour change from pinkish-bronze (high-grade ore) to yellow bronze (waste), with a corresponding decrease in grain size. Rutherford (1991) noted that gold-rich breccia contains clasts of hedenbergite, calcite, plagioclase, quartz, and actinolite/hornblende while the gold-poor breccia contains clasts of quartz and actinolite with some biotite and clinozoisite. Rutherford (1991) also noted that deformed iron-formation clasts appear to be more common within the gold-poor breccia.

Both forms of the iron-formation breccia consist of a pyrrhotite-dominant matrix (≤70% pyrrhotite). The breccia zones are up to 3.5 m wide and have a maximum observed strike extent of 130 m.

Within the gold-rich breccia, gold distribution is broadly divided into clouds of very fine gold (<5 micron) associated with pyribole in the breccia matrix and relatively coarser gold (≤30 micron) associated with quartzite/chert clasts.

Replacement ore

Magnetite after pyrrhotite: Replacement of pyrrhotite by magnetite constitutes the third mineralization style within the Bounty Horizon BIF. Within 40–50 m of the Binneringie Dyke, high heat flow and/or fluids activity have resulted in the desulphidation of pyrrhotite to form magnetite, generally preserving gross texture and structure. Closely associated with the magnetite are discontinuous layers of coarse, generally euhedral pyrite (< 1.2 cm thick) parallel to the original bedding. Observed gold distribution within the magnetite facies is erratic with fine to very fine gold generally on the margins of magnetite and relic pyribole crystals.

Marcasite–pyrite after pyrrhotite (transitional ore): Oxidation of pyrrhotite in the near-surface environment has lead to the formation of marcasite–pyrite agglomerations ranging from pea-size nodules to those tens of metres across. Concentric marcasite nodules are loosely intergrown within these agglomerations. Marcasite replacement has predominantly followed the pyrrhotite breccia units. Gold distribution within the marcasite is unclear; however gold grade is quite high (15–25 g/t), generally reflecting grades in the underlying pyrrhotite-rich breccia matrix.

Massive amphibolite ore

The fourth mineralization style is associated with massive to weakly bedded units of pyribole within the strongly deformed zone of the Bounty Horizon. Fine to very fine gold (< 10 microns) occurs as clouds within pyribole or clinopyroxene. Pyrrhotite is rarely associated but, if present, forms a fine halo. Rare specks (< 0.5 mm) of visible gold have been sighted in diamond drillcore.

Calc-silicate ore

A fifth style of gold mineralization is associated with pale green or grey to pale brown or tan 'skarn-like', calcium-rich alteration assemblages consisting of texturally destructive diopside–epidote–quartz(–feldspar–calcium garnets–calcite–amphibole–chlorite–pyrrhotite–pyrite). This alteration style has become relatively abundant in the lower sector of the Bounty orebody, tending to occur along the margins of the more typical mineralization/alteration types. It is particularly abundant in a narrow (0.3–3 m wide) corridor between hangingwall splay shears to the main hangingwall BIF mylonitic shear. In these sites this calcic-alteration commonly extends into the Hangingwall Dolerite rendering recognition of the protolith difficult. Gold grades associated with this alteration style appear to be erratic (1–15 g/t). No visible gold has been recorded with this association, and sulphide does not appear to be associated with the gold at a mesoscopic scale.

Geochemistry

Lithogeochemical studies by Rutherford (1991) have indicated some chemical associations that may be used to discriminate between proximal and distal ore environments. Proximal alteration or ore appears to be enriched in Au, $FeO+Fe_2O_3$, CaO and S. The barren distal alteration halo is enriched in K_2O, Ba, Rb, As and CO_2.

Mining

Openpit

Mining of the Bounty orebody commenced in October 1988, initially excavating the Bounty, North Bounty and West Bounty pits for a total of 640 000 t at 5.55 g/t or 114 000 oz gold.

In the opencut mining phase, scraper/dozer combinations were used for overburden removal while the grade control was carried out with earth saws and ditch witches. With decreasingly rippable material, drill and blast operations took over with ore and waste fired separately and mined on 2.5 m flitches. Waste was mined to clear the hangingwall contact, whereupon the ore was fired and mined. Blast hole drilling for grade control was initially 3 x 3 m but was extended to 4 x 3 m with deeper mining. Grade-control drilling determined the footwall cutoff while the hangingwall contact was a clear lithological change. Ore mining was carried out under geological supervision. Dimensions of the pits were:

Bounty	750 m NS x 200 m EW x 72.5 m deep
North Bounty	320 m NS x 150 m EW x 55.0 m deep
West Bounty	80 m NS x 60 m EW x 30.0 m deep

Opencut mining of the Bounty orebodies finished during September 1990.

Underground

Underground mining of the Bounty orebody commenced in November 1989 via a 6 x 6 m decline with the portal located at the northern end of the Bounty openpit. The decline is situated within the hangingwall to the 23 Level, where it switches to the footwall for geotechnical reasons. At the 37 Level, the decline crosses to the hangingwall again to access the shaft and 'grizzlies'. The decline is currently at the 38 Level, within the footwall. The decline also facilitates access to the North Bounty orebody. At 30 June 1997, a total of 3 498 087 t at 6.08 g/t or 684 056 oz gold had been recovered from the underground operation.

Current development is down to the 38 Level, 830 m below the surface in Bounty (in progress), and the 17 Level, 440 m below the surface in North Bounty, where mining of the orebody is completed. As part of an upgrade and expansion program, a 6 m diameter concrete-lined shaft has been sunk to a total depth of 840 m. The shaft and associated decline access was completed and operational by November 1996. Most of the ore is hoisted to the surface via the shaft, while the waste is retained underground for use as stope backfill.

Ore development is carried out using twin- and single-boom jumbos with ore drives nominally 4.2 m wide x 4.8 m high. Current Levels are 24.5 m apart (previously 18 m) with the subsequent stope blocks between approximately 15 and 20 m high. Alimak stoping was tried at North Bounty (Levels 11 to 17) with alimak rises at 25 m centres and a 100 m stope height.

A variety of stoping methods are and have been used at Bounty with each dependent upon the stress conditions of the area to be stoped. These are

- modified Avoca,
- uphole benching,
- alimak, and
- sublevel cave.

Stope drilling is carried out using an Atlas Copco Simba drill rig while bogging and trucking utilizes three loaders (remotes as necessary), which load three trucks. The diesel fleet is summarized by Table 6. Manpower is also summarized by Table 6, but essentially the direct underground mine production team consists of three 'mining' crews of 20 people each (including fitters, electricians and sampler). These crews operate on a rotating 14 days on (12 hour shift), 7 days off fly-in fly-out roster and provide a continuous 24 hour operation. Underground production supervision is provided by two 'crews' of 12 staff members who operate on a rotating 9 days on, 5 days off roster.

Grade-control face sampling takes place after each ore drive cut is bogged and meshed with rock chip samples taken at 1.5 m above the drive floor and sample limits determined by geological boundaries. During the sampling process, a mine geologist maps ore-drive faces and the location of the hangingwall contact is marked up as a guide for the jumbo operators. If, due to logistical reasons, an ore-drive face can not be mapped and sampled, the 'dirt' from the subsequent cut is grab sampled prior to bogging. All grade-control samples are assayed on site using aqua-regia analysis. Probe sludge drillholes are completed for all ore drives on 6 to 10 m centres (approximately 25 m footwall and 3 m hangingwall hole depths) using the Simba drill rig. These probe holes, in conjunction with short (30–40 m) diamond drillholes drilled internally from the ore drives, are utilized to determine the significance of gold mineralization through the remainder of the BIF profile (i.e. 'footwall' mineralization) prior to stoping.

Table 6. Diesel fleet and work-force summary (Bounty underground)

Diesel fleet:

- 1 x Atlas Copco Single-Boom Jumbo
- 2 x Atlas Copco Twin-Boom Jumbos
- 1 x Atlas Copco Simba Longhole Rig
- 1 x Elphinstone 1500 loader
- 2 x Elphinstone 1700 loaders
- 1 x Elphinstone AD40 truck
- 2 x Wagner MT431B articulated trucks
- 2 x ITs
- 1 x Grader
- 1 x Nipper truck
- 8 light vehicles (lease fleet with maintenance contracted)

Work force:

- 14 U/G miners + 3 fitters + 2 electrician + 1 sampler per shift (x 3 crews rotating '14 On 7 Off' Roster)
- ± 2 contract rise miners (as required)
- 12 staff supervisors (x 2 crews rotating "9 on 5 off' Roster)

Geotechnical

Ground-control problems encountered at Bounty are due to elevated lateral stress. Borehole slotter and CSIRO HI cell measurements carried out by Heslop (1991, 1993 unpublished data) determined high stress magnitudes in situ from 13.2 to 96 MPa. This is compared with a calculated overburden load of 8.0 to 8.5 Mpa. Areas of local high stress are recognized by intervals of discing in diamond drillcores, spalling and slabbing of backs and shoulders in underground openings, evidence of rock bursts, cataclastic deformation, floor heave and seismic events. High localized ground stress resulted in the diversion of the hangingwall decline from crystalline metadolerite into the banded footwall ultramafic sequence where the rock types are more amenable to development.

At Bounty a range of ground support methods are used. Within the ore drives, the backs are meshed with 100 x 100 mm mesh, pinned with 2.4 m galvanized split sets after each cut. In the sill pillars, cone bolts, straps, and 6 to 18 m-long cable bolts (fully grouted) are utilized as necessary, with the emphasis being on burst-prone areas. The decline is meshed with 100 x 100 mm galvanized mesh, which is secured with 3 m galvanized split sets.

Reserves, resources and production

The published mineral resource as of 30 June 1996, summarized by Table 5, stands at 2 459 200 t at 7.17 g/t gold. This includes a proved plus probable reserve of 1 446 600 t at 5.58 g/t. In calculating this reserve, a two-tier topcut was used; all assays greater than 50 g/t were cut to 50 g/t, while grades between 30 and 50 g/t were cut to 30 g/t. Estimation techniques for the developed areas were weighted linear averages of face samples within 10 m blocks along strike, which were averaged to obtain the ore-block grade between levels. Below the developed areas classical polygonal estimation techniques were used. Future ore resources/reserves will be calculated using 3D block models via SURPAC2000 and a single topcut value of 45 g/t.

Currently the deepest drilling intersection at Bounty is 1000 m below the surface, with the orebody remaining open at depth and along strike to the south.

Bounty underground production budget for the 1996/97 fiscal year was 326 000 t at 5.94 g/t gold for 62 300 oz.

VII. The geology and regional setting of the Maggie Hays komatiite-hosted nickel sulphide deposit, Lake Johnston greenstone belt

by

[1]W. M. Hunter, C. S. Perring, R. E. T. Hill and S. J. Barnes

The Maggie Hays nickel deposit is located 440 km east of Perth and 200 km south-southeast of Kalgoorlie in the southern portion of the Archaean Yilgarn Craton. The deposit lies within the isolated Lake Johnston greenstone belt at the southeastern extremity of the Southern Cross Province (Fig. 30). Although this region was visited by early explorers such as Roe (in 1848), Hann (in 1901) and Hewby and May (in 1910), as well as a succession of anonymous prospectors, no significant mineral discoveries were made and the area has remained undisturbed until recently. Honman (1914a,b) made the first geological descriptions in the region when he outlined the extent of the greenstone belt and commented on its mineral potential. It was not until the 1960s that systematic airborne geophysical surveys by the Australian Bureau of Mineral Resources (Wells, 1962; Australian Bureau of Mineral Resources, 1965) were carried out here, and nickel exploration reached a peak, particularly in areas of ultramafic rocks. The first systematic geological survey of LAKE JOHNSTON (1:250 000), was completed by Gower and Bunting (1976), thus establishing a basis for regional understanding of the greenstone-belt distribution, stratigraphy, metamorphism, and structure. After 22 years of intermittent nickel exploration by a variety of resource companies, significant deposits of nickel sulphide were discovered in the early 1990s by Forrestania Gold NL at Maggie Hays. Subsequent collaborative research work between the company and CSIRO has established a detailed understanding of the geological setting of the Maggie Hays nickel deposit and the nature of the sulphide mineralogy itself.

Regional geology

The Maggie Hays nickel deposit lies within the northwest-trending Lake Johnston greenstone belt, which is isolated in a linear corridor by extensive, but largely concealed, granitoids and granitoid gneisses. The greenstone belt has, in detail, a skeletal regional pattern resulting from the interplay of a complex structural history and the intrusion of later granodiorite to monzogranite plutons

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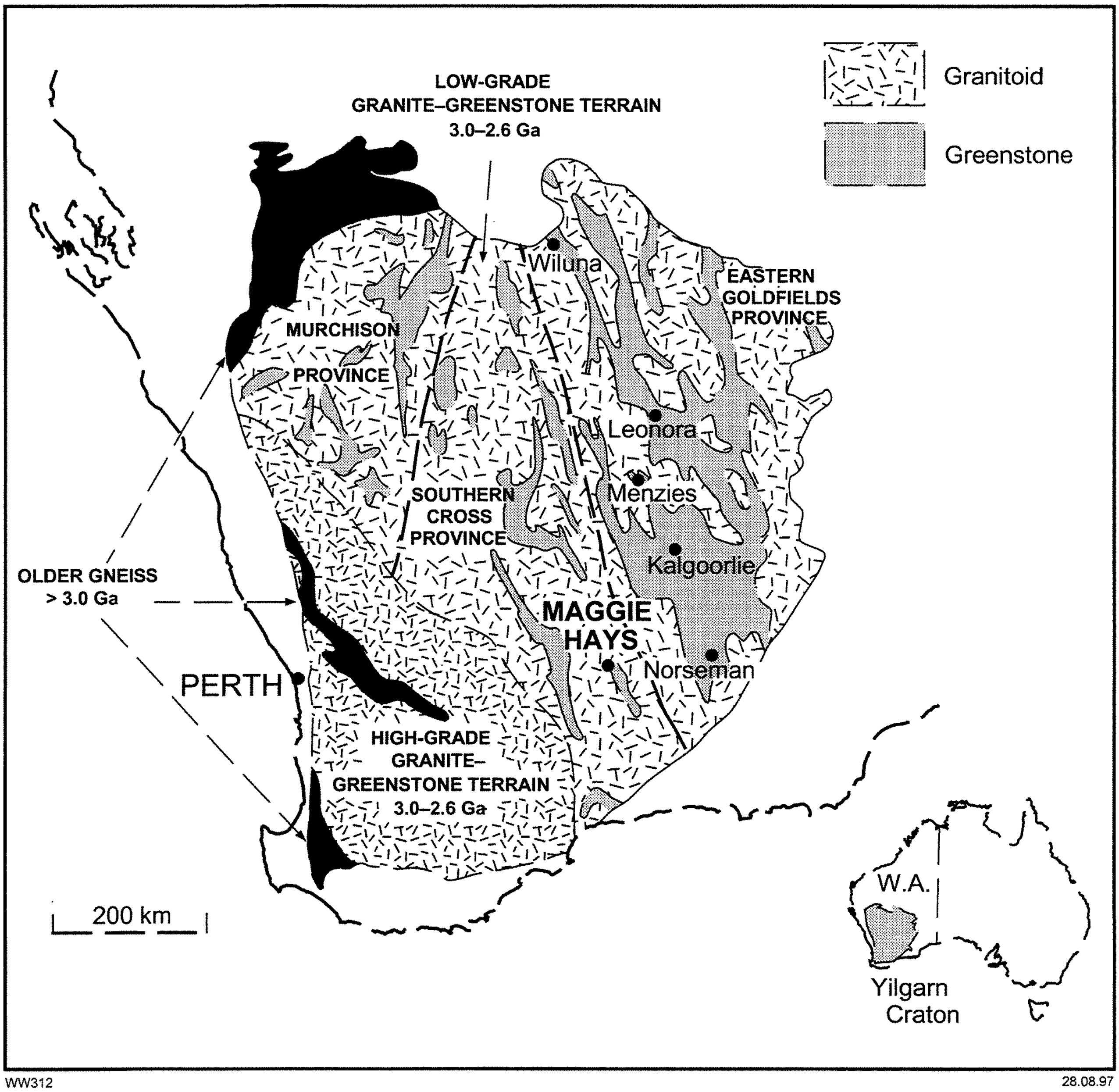

Figure 30. Principal geological elements of the Yilgarn Craton compiled from Myers (1990) and Gee et al. (1981). The location of the Maggie Hays deposit is included in the southern part of the Southern Cross Province

(Fig. 31). One study of U–Pb zircon geochronology (Wang et al., 1996) on conformable felsic volcaniclastic rocks, has constrained the age of komatiite volcanism at Maggie Hays to the period between 2903 and 2921 Ma. Just north of the centre of the belt, the Jimberlana layered gabbro dyke of Proterozoic age cuts the greenstones with an easterly trend.

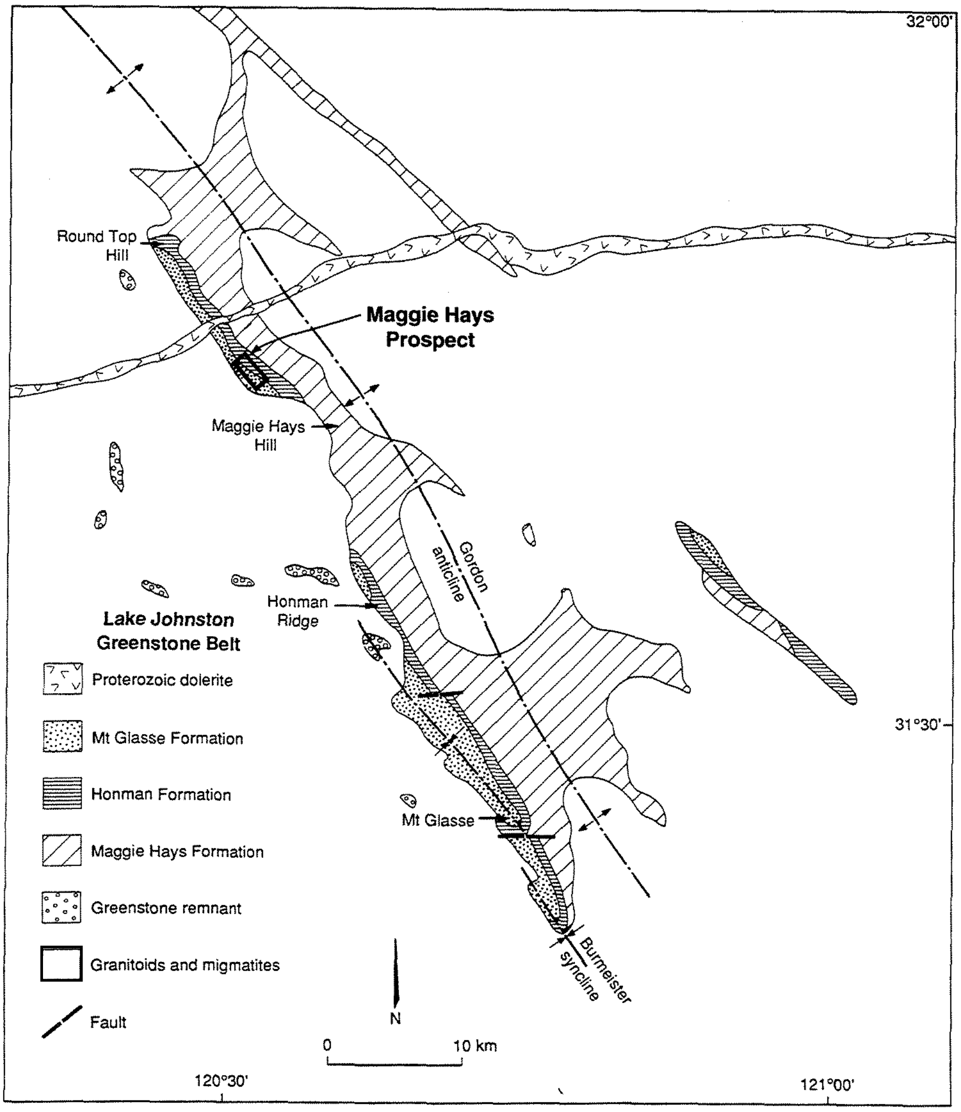

Figure 31. Geological map of the Lake Johnston greenstone belt depicting formations and positions of field areas to be visited. Copyright CSIRO Exploration and Mining

Stratigraphy

Gower and Bunting (1976) subdivided the Lake Johnston greenstone belt into three principal formations. The *Maggie Hays Formation*, which consists largely of basaltic rocks, is conformably overlain by the *Honman Formation*, comprising felsic volcanic and volcaniclastic rocks and banded iron-formation (BIF), and the *Glasse Formation* consisting largely of basalt. The ultramafic rocks in each of these formations were at that time regarded as intrusive.

More recent studies of the Lake Johnston – Maggie Hays area (Hunter, 1995a,b; Perring et al., 1994; Perring, 1995a) have refined the regional stratigraphy of the upper Honman and lower Glasse Formations and placed emphasis on an understanding of the ultramafic rocks contained in

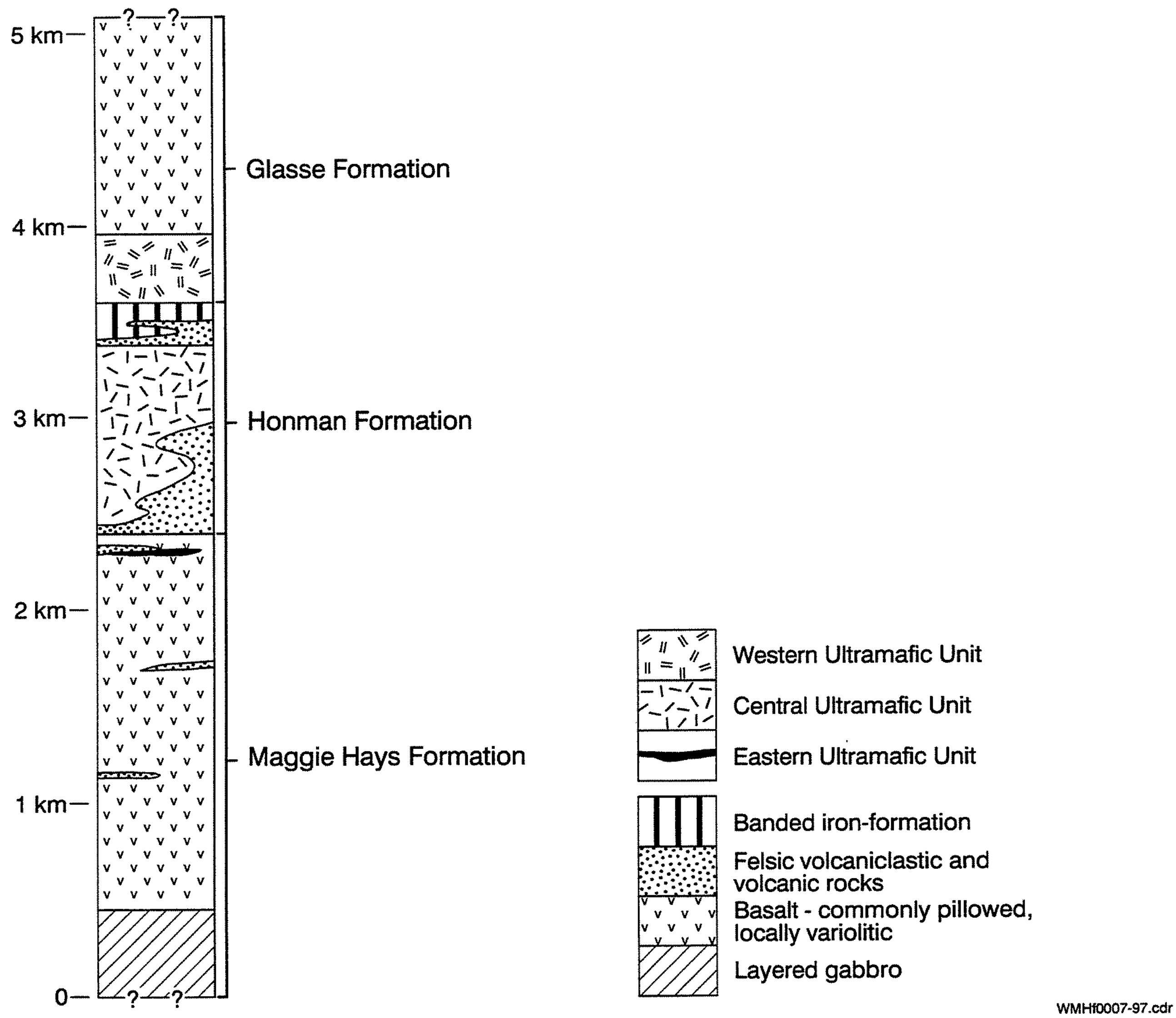

Figure 32. Stratigraphic column in the Lake Johnston greenstone belt illustrating major rock types within formations and the positions of the principal ultramafic units. Copyright CSIRO Exploration and Mining

them (Fig. 32). The ultramafic rocks are found in three distinctive, compound units, which have been mapped along strike for over 14 km, and they are now regarded as representing large-scale komatiite extrusive complexes. The *Eastern* and *Central Ultramafic Units* are separated by felsic volcanic and volcaniclastic rocks of the Honman Formation, whereas the *Western Ultramafic Unit* forms the lowermost unit of the Glasse Formation and overlies the regionally persistent BIF unit at the top of the Honman Formation.

The lowermost ultramafic unit, the Eastern Ultramafic Unit (EUU), is not well exposed and has not been extensively explored greatly, but it appears to consist of thin differentiated komatiite flow units. The thick (500–1000 m) Central Ultramafic Unit (CUU) is dominated by thick to very thick cumulate flow units with locally fractionated upper zones. The upper portion of the CUU consists of thin differentiated flow units partly interleaved with BIF and felsic rocks. The Western Ultramafic Unit (WUU) consists mainly of thin, differentiated komatiite flow units but there are scattered undifferentiated flow units and thin cumulate flow units.

Metamorphism

On a regional basis, Gower and Bunting (1976) describe the metamorphic grade as lower greenschist with localized amphibolite facies rocks; however, more recent studies (Perring et al., 1994; Hunter, 1995a,b) have revealed widespread attainment of mid-amphibolite facies in the northern part of the belt, which contains the Maggie Hays deposit.

Ultramafic rocks at Maggie Hays display a rich variety of metamorphic assemblages, which reflect the original komatiite volcanic facies type. Olivine cumulate rocks contain metamorphic olivine and various combinations of anthophyllite–talc–cummingtonite, tremolite–chlorite and chromite, depending on the nature of the protolith. Retrograde serpentine and talc are variably developed, and in some portions of the adcumulate, primary igneous olivine has survived. Largely, however, primary textures are obliterated by metamorphic recrystallization. Spinifex-textured flow rocks consist of the assemblage tremolite–chlorite–magnetite(–metamorphic olivine), talc, and primary textures vary from well-preserved pseudomorphs to those largely obliterated by olivine porphyroblasts and/or matted tremolite–chlorite.

Structure

Gower and Bunting (1976) described the Lake Johnston greenstone belt as occupying a discrete, central structural zone bounded by two regionally significant lineaments that have north to northwesterly trends. The nature of those lineaments is as yet untested but they are clearly seen on aerial photography and aeromagnetic surveys. Structural measurements on rocks close to the lineaments indicate that the western feature dips steeply to the east and that the eastern feature has a near-vertical dip.

The Gordon Anticline (Fig. 31) has an axial trend subparallel to the regional structural zone, is mildly asymmetric, and slightly overturned to the west. There is ample evidence for younging directions from pillowed lavas, sedimentary structures and fractionation trends in all three Formations. The Burmeister Syncline is partly occluded by granitoids to the west but, where it survives, displays tight folding and an undulating hinge zone.

Hunter (1995a,b) noted that BIF units in this region exhibit complex structural features that may be used to understand the structural history at regional scale. There are isoclinal minor folds with steep axial planes verging southwestward and subhorizontal undulating axial traces. In mafic and felsic rocks there is a pervasive layer-parallel foliation dipping steeply to the northeast, and within ultramafic rocks there are spaced zones of talc schist parallel to layering in otherwise undeformed units. On a semi-regional scale, the trends of BIF units show abrupt terminations in bulbous hook-folds, and distinct low-angle breaks and repetitions. Taken together, all these features indicate an early phase of thrust stacking with movement possibly concentrated in the plane of BIF. A suite of later cross faults transects the region in a north to northeasterly direction and these have produced small apparent offsets, which are most clearly seen in the trends of BIF. Some faults and fractures in a west to southwest direction became conduits for dolerite dykes in the Proterozoic.

Geology of the Maggie Hays deposit

In the vicinity of the Maggie Hays nickel deposit, there is only sparse outcrop of the upper Honman and lower Glasse Formations, but extensive drilling has detailed a comprehensive picture of the local stratigraphy and structure. The succession here has a north-northwesterly strike and, according to younging indicators in the ultramafic sequences, is steeply overturned to the west. In plan, the succession shows a significant S-form flexure, accompanied by a complex fan of faulted blocks that may represent a failed thrust ramp (see Fig. 33). In addition to the structural complexity in this area, there is a pervasive network of dykes and sills ranging in composition from mafic to felsic, including granite–pegmatite.

Stratigraphy

The portion of the Honman Formation that constitutes the footwall consists of a monotonous sequence of quartzofeldspathic rocks that are typically massive and porphyritic but which may display fragmental textures. Perring et al. (1994) and Perring (1995a) have described the dominant footwall rocks as porphyritic felsic lavas, although the primary textures are largely obscured by metamorphic recrystallization. These rocks contain 5–15% plagioclase phenocrysts set in a fine-grained groundmass containing quartz, feldspar, muscovite and biotite with accessory apatite. Also present are biotite-rich clots and schlieren, possibly after amphibole phenocrysts or lithic fragments, and localized occurrences of pink garnet (≤2%). Fragmental rocks are also feldspar-

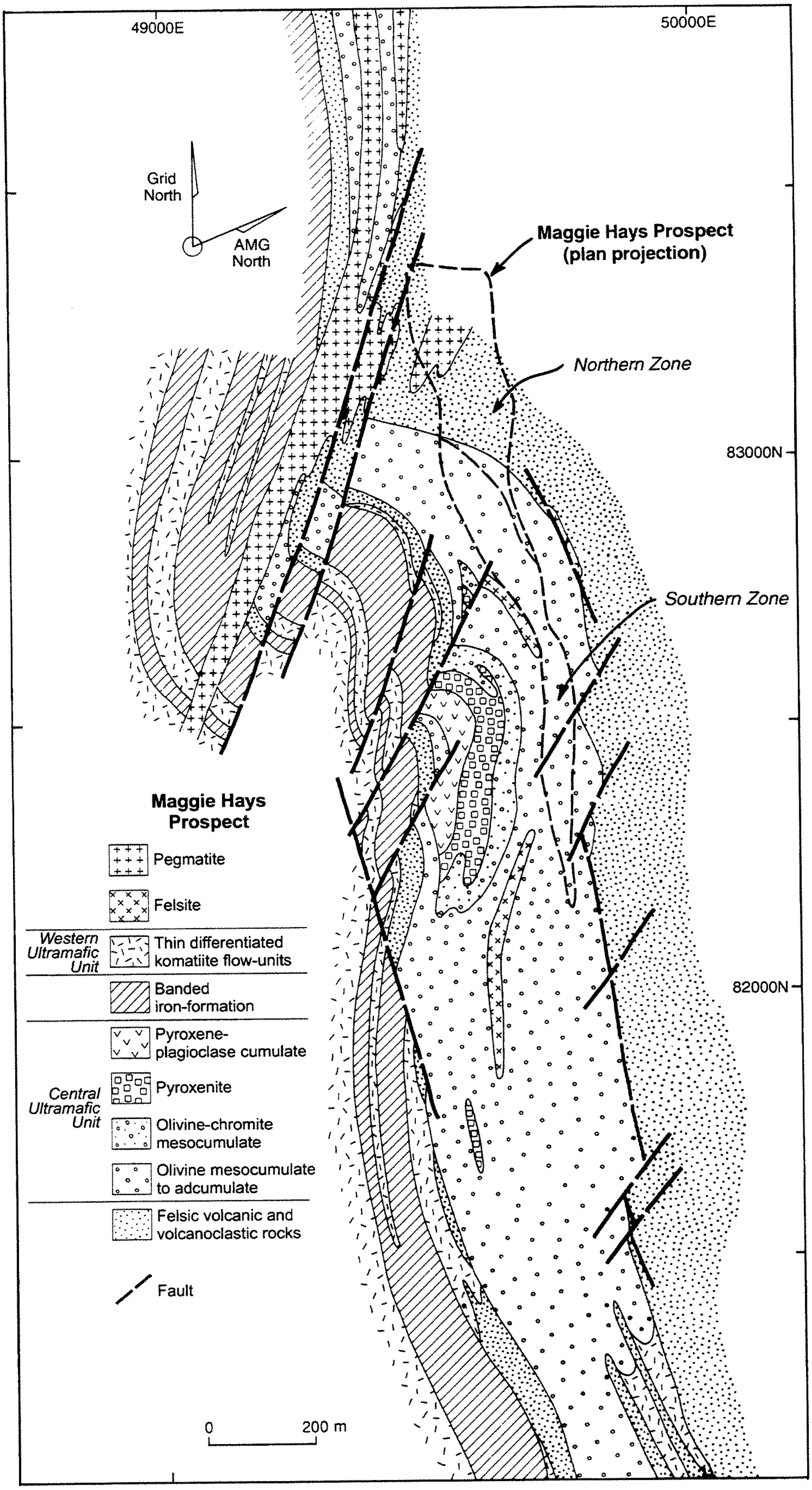

Figure 33. Geological plan in the vicinity of the Maggie Hays nickel deposit. Copyright CSIRO Exploration and Mining

phyric, and comprise subangular fragments up to 10 cm set in a fine-grained matrix of quartz, microcline and biotite, with local evidence of graded bedding.

The upper part of the Honman Formation is dominated by the Central Ultramafic Unit, which ranges from less than 100 m at its peripheries, where it is interleaved with felsic rocks, to a maximum of about 400 m at its core. The base of the unit consists of a 20–50 m thick sequence of intermittent chilled ultramafic material grading into pyroxene-bearing orthocumulate. This is overlain by a thick sequence of olivine adcumulate and lesser mesocumulate containing up to 2% chromite. Towards the top of the ultramafic unit there is a distinctive fractionation sequence ranging from olivine-chromite (10–15% chromite) through pyroxene cumulate to pyroxene–plagioclase cumulate, and finally, a thin flow top.

The Central Ultramafic Unit is overlain by 20–50 m of fine-grained quartzofeldspathic rocks and a BIF package up to 120 m thick that contains intercalations of fine-grained felsic rocks and thin, spinifex-textured komatiite flows. The BIF consists of thinly bedded alternations of quartz and magnetite that locally contain minor sulphides, but in some places grunerite or pyroxene–pyrrhotite dominate

The Western Ultramafic Unit does not outcrop significantly in the area around the Maggie Hays deposit but it has been partially investigated through costeans and extended drilling. The unit consists mainly of thin, spinifex-textured komatiite flows but these appear to lie on a base of olivine mesocumulate, which has a thin orthocumulate basal selvage. The proportion of cumulate (B-zone) olivine in the fractionated flows shows a systematic decrease up stratigraphy.

Geochemistry

Perring et al. (1994) and Perring (1995b) have investigated the whole-rock geochemistry, including selected rare-earth elements (REE) and platinum-group elements (PGE), for a large suite of samples from the Maggie Hays area. Table 7 below presents a summary of the average compositions of the various lithologies.

Table 7. Average compositions of selected lithologies from Maggie Hays (from Perring et al., 1994)

	Ukm	*Uoc*	*Umc*	*Uac*	*Upx*	*Fpf*	*Fv*
			percent				
SiO_2	49.45	46.26	45.16	41.98	48.77	73.70	63.65
TiO_2	0.38	0.31	0.08	0.03	0.40	0.40	0.81
Al_2O_3	4.79	4.22	1.23	0.59	4.90	14.26	19.36
FeO	11.05	10.15	8.58	8.17	9.84	2.36	1.10
MnO	0.20	0.20	0.14	0.16	0.20	0.06	0.04
MgO	27.56	33.48	43.83	48.75	27.73	0.96	2.45
CaO	6.12	4.80	0.66	0.08	7.71	2.29	3.24
Na_2O	0.05	0.04	0.05	0.05	0.05	3.88	1.37
K_2O	0.01	0.07	0.04	<dl	0.01	1.97	7.84
P_2O_5	0.03	0.02	0.01	0.01	0.03	0.11	0.13
			parts per million				
Cr	2 523	2 925	1 603	1 189	2 456	9	1
Co	86	92	135	125	85	45	1.1
Cu	23	31	28	10	19	<dl	<dl
Ni	1 582	1 921	3 926	3 686	1 432	1.1	31
V	132	101	32	17	129	60	56
Y	9	9	5	3	12	17	15
Zn	83	75	69	52	80	33	36
Zr	25	20	5	2	28	100	168
n	5	11	9	13	9	4	2

Ukm = chilled komatiite flow top or base; Uoc = olivine orthocumulate; Umc = olivine mesocumulate; Uac = olivine adcumulate; Upx = pyroxene-bearing komatiite; Fpf = porphyritic felsic volcanic rock; Fv = felsic volcaniclastic rock; <dl = below detection

The geochemical variation within the Maggie Hays suite indicates systematic control by olivine fractionation, combined with subtle change of composition in the komatiite lava with time. For example, the MgO and Ni contents decrease from olivine adcumulates through olivine mesocumulates and orthocumulates to chilled marginal rocks, thus reflecting the decreasing proportion of cumulus olivine in the rocks. In contrast, the incompatible elements (Al_2O_3, CaO, TiO_2, V, Y and Zr) show strong negative correlation with MgO content. Furthermore, the ratios of incompatible element abundances are relatively uniform for this suite, indicating that the rocks are cogenetic.

The Maggie Hays suite is depleted in Al_2O_3 and V with respect to chondritic values. This distinction is also found in the komatiites from Forrestania to the west and also at Ravensthorpe (Sun and Nesbitt, 1978) but it is contrasted with komatiites from the Norseman–Wiluna greenstone belt to the east that are Al-undepleted. Nesbitt et al. (1979) have suggested that komatiites depleted in Al and V were probably generated at greater depths in the Earth's mantle, where garnet is more stable and likely to be retained in the source region during partial melting.

Footwall felsic rocks are strongly enriched in light REE relative to chondritic values, so elevation of these REE in ultramafic rocks is a potential indicator of contamination through thermal erosion and assimilation. Samples from the base of the Central Ultramafic Unit show consistent but slight enrichment compared with the chilled flow top to this unit. However, no correlation has been established yet between these elevated values and proximity to interpreted erosional features.

Nickel sulphide mineralization

The nickel sulphide mineralization at Maggie Hays is in a zone of significant structural and stratigraphic complexity, and an intensive drilling program has allowed the discrimination of several distinct ore environments. Mineralization occurs over about 1400 m of strike and is found as shallow as 100 m (Buck, 1996), although the current limits of the ore body have not been fully closed off by drilling. The main zone of mineralization lies to the geographic north of the significant structural flexure depicted in Figures 33 and 34, and this zone contains two distinct styles of mineralization.

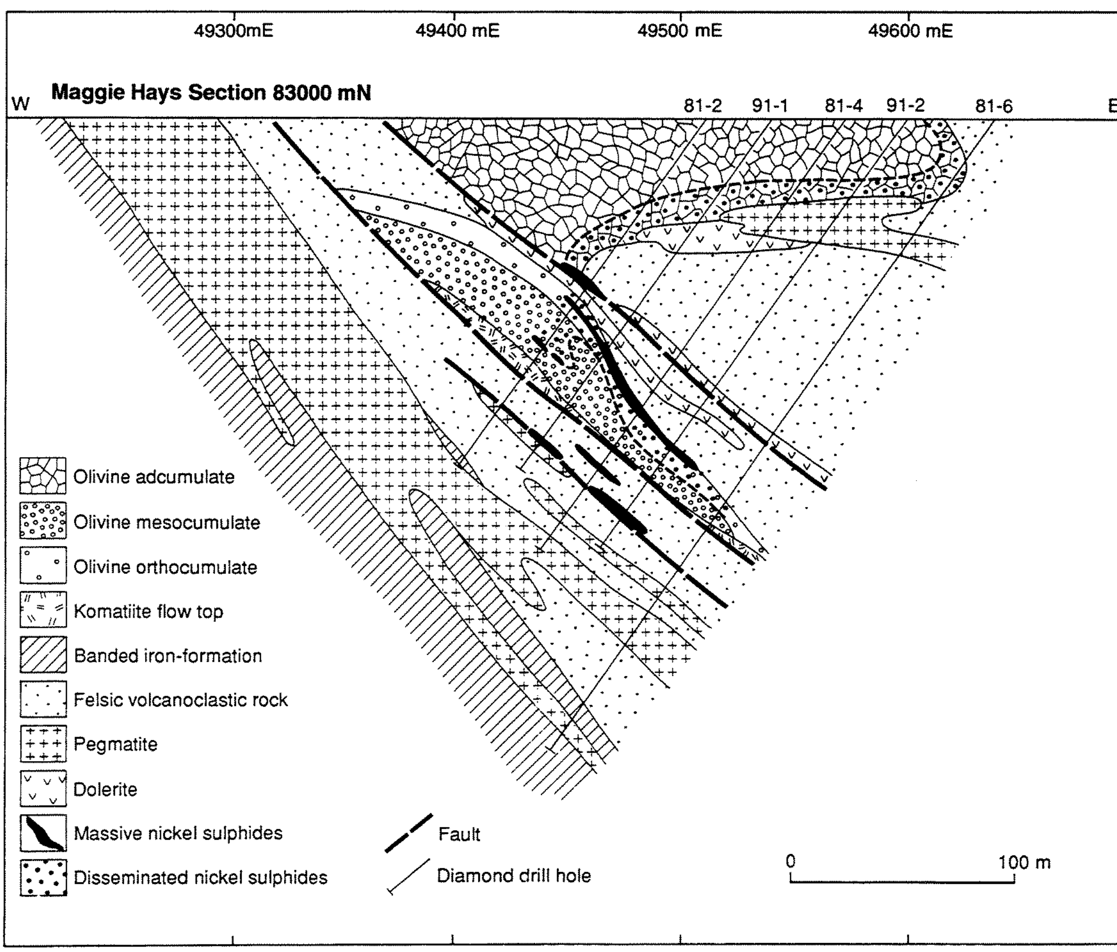

Figure 34. Geological section at 83000mN of the Maggie Hays nickel deposit illustrating the distribution of massive and disseminated sulphides, as well as the structural disruption of the succession. Copyright CSIRO Exploration and Mining

Southern Zone, Central Ultramafic Unit

The southern zone of mineralization has a strike extent of 850 m and down-dip extent of 350 m but is truncated at depth, and to the north, by fault planes of an east-dipping reverse fault system. This mineralization appears to occupy a trough-shaped depression at the base of the thickest portion of the Central Ultramafic Unit. There are up to 7 m of massive sulphide overlain by up to 40 m of disseminated (<40%) sulphides, which vary in character according to the type of ultramafic cumulate present (see Table 8).

Massive sulphide mineralization occurs as a sinuous southerly plunging shoot flanked by orthocumulates. Disseminated mineralization occurs largely as a continuous body, particularly in the lower portion, but becomes locally lenticular higher up the sequence.

Table 8. Generalized stratigraphic profile of the Southern Zone mineralization (from Buck, 1996)

	Stratigraphic section	*Content of sulphides*	*Thickness*
Top	Barren adcumulate	-	
	Olivine–sulphide adcumulate	Decreases with increasing stratigraphic height: 15–35% towards the base 5–10% towards the top	≤40 m
	Olivine–sulphide mesocumulate	15–40%	
	Olivine–sulphide orthocumulate	15–40%	<10 m
	Massive sulphide	80–100%	<5 m
Base	Chill zone pyroxenite	<10%	<1 m

Northern Zone, Central Ultramafic Unit

The Northern Zone of mineralization abuts the Southern Zone, sharing in part the same fault plane as its southern termination, but plunging beneath the disseminated ore zone. It is hosted entirely by felsic volcanic rocks akin to those forming the footwall to the Central Ultramafic Unit. Buck (1996) describes the zone as ranging from 3–9.5 m in thickness and comprising massive sulphide layers up to 3 m thick and broader zones of massive sulphide stringers, all in stacked zones of uncertain lateral continuity. It is inferred that this zone of mineralization was emplaced structurally when early deformation caused a decoupling of the orebody from its original ultramafic host.

Western Ultramafic Unit

There is massive and disseminated mineralization at the base of the Western Ultramafic Unit but its extent is as yet untested.

Sulphide mineralogy

Preliminary studies of the sulphide mineralogy and sulphide chemistry have been reported by CSIRO (Perring and Hill, 1995; Perring, 1995b; Barnes et al., 1995) and further studies are in progress. The mineralogy of the Maggie Hays deposit is dominated by pyrrhotite. In the massive ore, ratios of pyrrhotite to pentlandite range from 2:1 to 8:1 whereas in disseminated ore the range is 2:1 to 3:1. Pyrite, chalcopyrite and chromite are present in minor amounts in both massive and disseminated ore, and traces of millerite have been seen in olivine–sulphide adcumulate samples. The sulphide phases in disseminated ore commonly occur as discrete crystals or as blebby or 'triangular' aggregates interstitial to silicate phases such as metamorphic olivine blades.

Metamorphic oxidation of pyrrhotite produces a pyrite–magnetite assemblage and results in nickel enrichment of the remaining sulphides. Magnetite, which develops along cleavage planes in pentlandite and also occurs as coarse veins in sulphide blebs, has been correlated with retrograde serpentinization of metamorphic olivine.

Supergene alteration occurs to a depth of over 400 m, and shows the following sequence: pentlandite → violarite, pyrrhotite → violarite (comb-textured), pyrrhotite → pyrite.

Sulphide chemistry

In a study of the nickel sulphide chemistry, Perring (1995b) and Barnes et al. (1995) found that the composition of the ores and the contrast between massive and matrix ores on mantle-normalized PGE profiles are typical of komatiite-associated ores from elsewhere in the Yilgarn Craton. There is no systematic variation in sulphide chemistry with stratigraphic height or with rock type for the disseminated to matrix ores. In contrast, however, the massive ores tend to have lower Ni tenor, unfractionated mantle-normalized PGE profiles, and moderate to strong negative Pt anomalies.

Barnes et al. (1995) determined that most of the nickel (98%) and cobalt (97%) is contained in the sulphide minerals of the Maggie Hays ore body, and that pentlandite accounts for most of those elements (94% and 97% respectively). In general, the Ni and Co compositions of pentlandite and pyrrhotite are fairly constant and, apart from lower Ni content in some serpentinized samples, most variance is due to supergene alteration.

Typical nickel and cobalt compositions of primary sulphides are as follows:

	Ni (wt%)	*Co (wt%)*
pentlandite	35–36	0.6–1.0
pyrrhotite	<1.0	<.02
pyrite	0.1	2.0–3.0

Acknowledgements

The authors acknowledge the generous sponsorship of Forrestania Gold NL and Maggie Hays Nickel NL and would like to thank geological staff of those groups for their support; in particular, Mr S. Vallance, Mr J. Kilroe, and Mr P. Buck.

VIII. Lake Johnston greenstone belt localities

by

W. M. Hunter

The field locations (Fig. 35) described below have been chosen to illustrate the regional stratigraphic setting of the Maggie Hays nickel deposit, the diversity of high-grade metamorphic textures in the host rocks, and the styles of nickel mineralization present.

Locality 1. Maggie Hays core yard

Adjacent to accommodation village

Examples of principal rock types from stratigraphy in core. Examples of mineralization types.

The core yard is adjacent to the Exploration Camp at Windy Hill. Trays of drillcore representing examples of metamorphosed rock types that typify this region will be laid out, and there will also be examples of the nickel mineralization. Details of the rocks on display will be provided in a handout at the time of the excursion.

Locality 2. Maggie Hays Hill

Drive south along the track which follows a series of connected baselines, past areas of historic costeans, through hilly country, and past the northeastern edge of Lake Hope. After 7.5 km, the track curves around a range of steep hills containing shafts and other small gold workings at Maggie Hays Hill. Turn off the track to the left and proceed as far as possible towards the highest hilltop.

Mafic rocks of the Maggie Hays Formation

Mafic rocks of the Maggie Hays Formation occur in outcrop around Maggie Hays Hill, at small abandoned gold workings, near the hill, and in lakeside outcrops within a few kilometres of the hill. On a regional scale, the rocks have been deformed and metamorphosed to amphibolite facies,

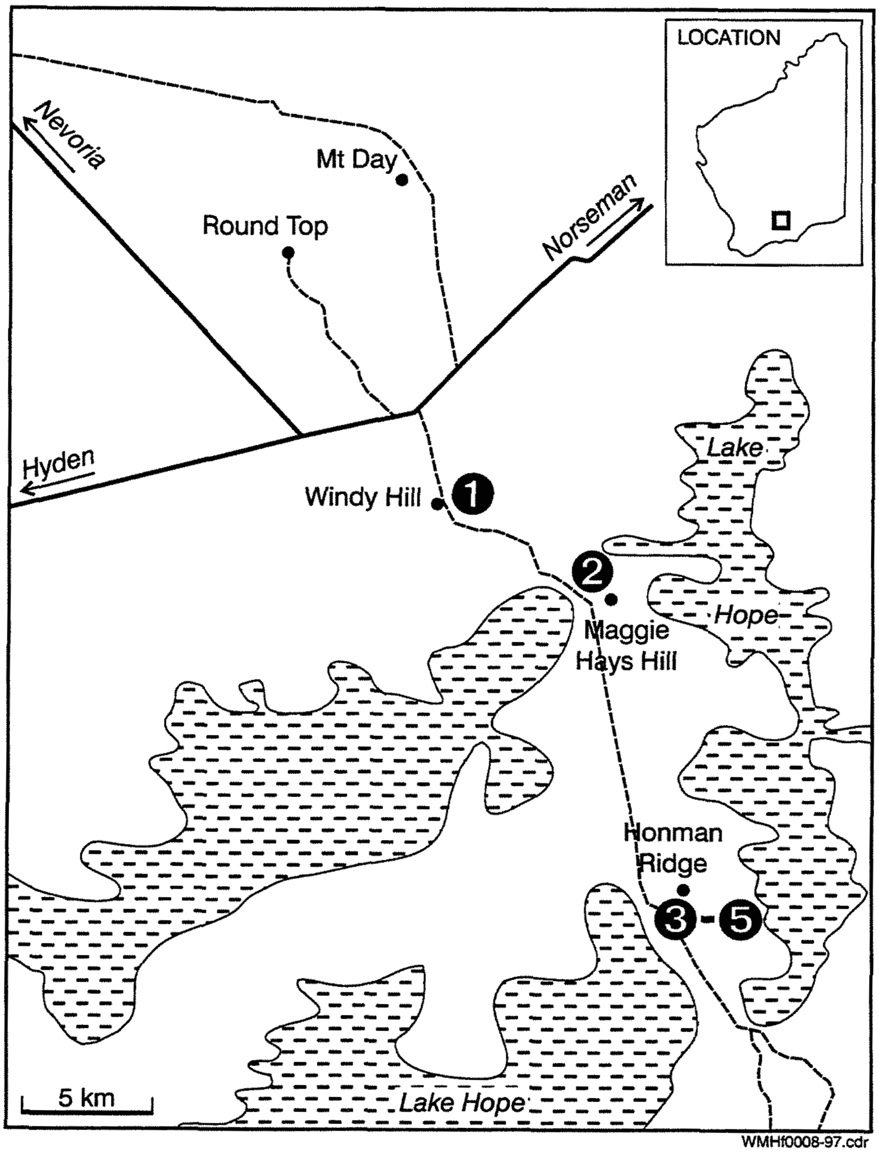

Figure 35. Locality map to indicate positions of principal excursion localities. Copyright CSIRO Exploration and Mining

but relict pillow forms that appear to be widespread (but not on top of Maggie Hays Hill — see below) in this formation can still be discerned. The mafic rocks are tholeiitic in composition and are now composed of hornblende–plagioclase–quartz.

Interbedded with these basalts are discontinuous layers of sedimentary rocks including BIF and felsic volcaniclastic rocks (Gower and Bunting, 1976). A thin (10–30 m thick) unit of porphyritic basalt forms a regionally significant marker horizon within the main volcanic pile. The latter has mineralogy similar to that of the surrounding basalt except for large (2–5 cm) relict glomerocrysts of plagioclase, which have recrystallized to mosaics of quartz and feldspar. Also common within the basalt sequence are coarse-grained mafic rocks, which range in thickness from a few metres to several tens of metres. Some of these layers show apparent chilled margins and are interpreted as metamorphosed doleritic intrusions, whereas others show gradational boundaries with finer basalt and may be cores of thick flows.

At the top of Maggie Hays Hill, there is good outcrop of fine-grained basalt, which is fresh and only mildly deformed. The basalt is homogeneous and shows no sign of pillow forms, vesicle/amygdale structures or hyaloclastite. There is a coarse-grained, metadolerite textured unit immediately to the east and similar units occur on the flanks of the hill to the southwest, particularly near the track.

At the lakeside outcrop the pillows are elongate parallel to the regional layering trend and have an aspect ratio at least half that of the original. Layers of granitoid which interfinger with the basalt have been subsequently deformed and there is a layered amphibolite–felsic schist complex developed here, close to the hinge zone of a regional anticlinal structure.

Locality 3. Honman Ridge East

Return to the track and continue south for 14 km through dense juvenile forest on sandplain overlying granitic rocks, and dunes marginal to Lake Hope. At a well-marked turnoff, leave the main track and take the track to the left, rising through a gap in the prominent strike ridge. The gap is the result of preferential erosion of a Proterozoic dolerite dyke that cuts the more resistant BIF ridge here. Continue through an old drillers' camp to the baseline at 500 m. Cross the baseline and take the small track which joins an exploration gridline, and continue for a further 800 m (see note following) to the eastern baseline.

*(**Beware** of a serious driving hazard at about 600 m, where the track deviates north from the grid line to negotiate a prominent laterite ridge. This ridge must be crossed by one vehicle at a time, so please wait well back from the base of the west flank. At the top of the west flank, there is an immediate 90 degree right-hand turn to follow the ridge. In the morning sun there is significant risk of missing this turn due to glare.)*

This locality involves a walk of about 1.5 km over generally flat terrain, examining rocks in costeans and some outcrop. The costeans are old and shallow so the best material is in the spoil to the sides.

Stratigraphy of the Honman Formation in costeans

Locality 3A

The easternmost costeans lying 100 m north of the intersection 55200mN 11000mE expose the contact between felsic rocks and the Central Ultramafic Unit components of the Honman Formation (Figs 36, 37). The low rise to the east contains sparse outcrop of lateritized felsic rocks overlain by Cainozoic sandstone, conglomerate and ferricrete.

Felsic volcaniclastic rocks are the substrate to the ultramafic sequence in this area and the boundary between the two lithologies occurs in the vicinity of the 11300 m baseline. The felsic unit ranges from 150 to 250 m and overlies a thick succession of basalt and gabbro/dolerite to the east (Maggie Hays Formation). The western (upper) boundary is moderately well constrained by costean and drill data, and aeromagnetic data. It is clear that there are significant offsets and embayments in its regional trend.

The felsic rocks are fine- to medium-grained, heterogeneous, leucocratic schists comprising quartz, feldspar and biotite. Small (2–4 mm), rounded, relict phenocrysts of feldspar are locally abundant and the proportion of biotite varies from sparse to moderately abundant. Garnet and amphibole are also developed locally. Through correlation elsewhere in this greenstone belt (Perring, 1995a; Hunter, 1995a) these rocks are inferred to be derived from felsic volcanic and volcaniclastic rocks.

Felsic rocks exposed in the costean are in the saprolite ('saprock') zone of the lateritic weathering profile and are now composed largely of kaolin and quartz; however, textures of the protolith are well preserved here. The variations in phenocryst grain size and abundance, together with variations in the relict textures of the groundmass, indicate that these rocks were originally fragmental.

This costean also reveals the contact zone with the overlying ultramafic rocks. A rusty brown layer a few metres thick contains fine- to medium-grained random olivine-spinifex texture well preserved in 'saprock'. This basal chilled zone grades abruptly into olivine orthocumulate that ranges in thickness from 20 to 250 m. At various intervals along strike, the lowermost ultramafic layer is a distinctive pyroxene cumulate, which is indicative of contamination by the siliceous substrate.

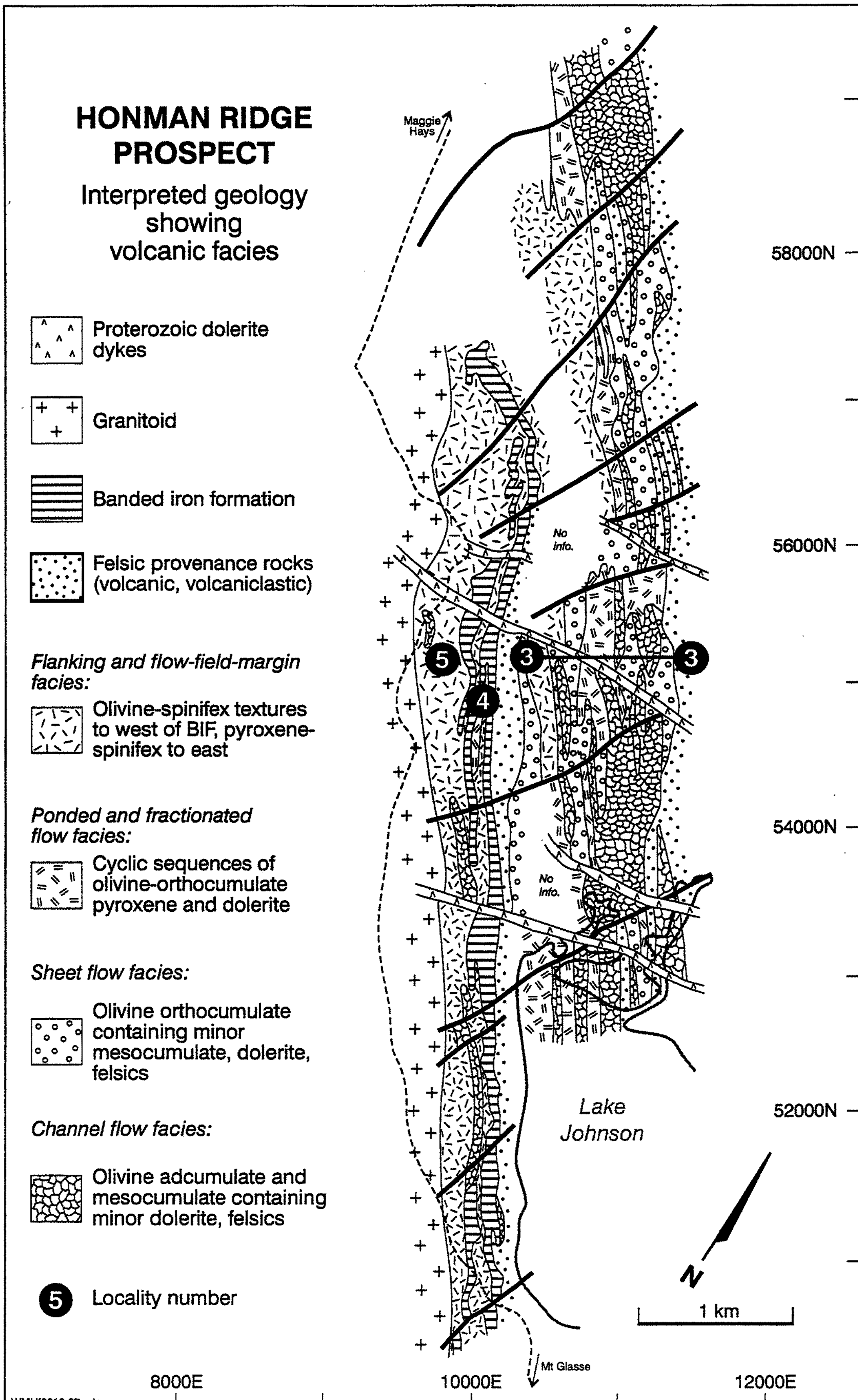

Figure 36. Geological summary map of Honman Ridge depicting volcanic facies of ultramafic rocks. Excursion localities that are detailed in the text are marked by numbers. Copyright CSIRO Exploration and Mining

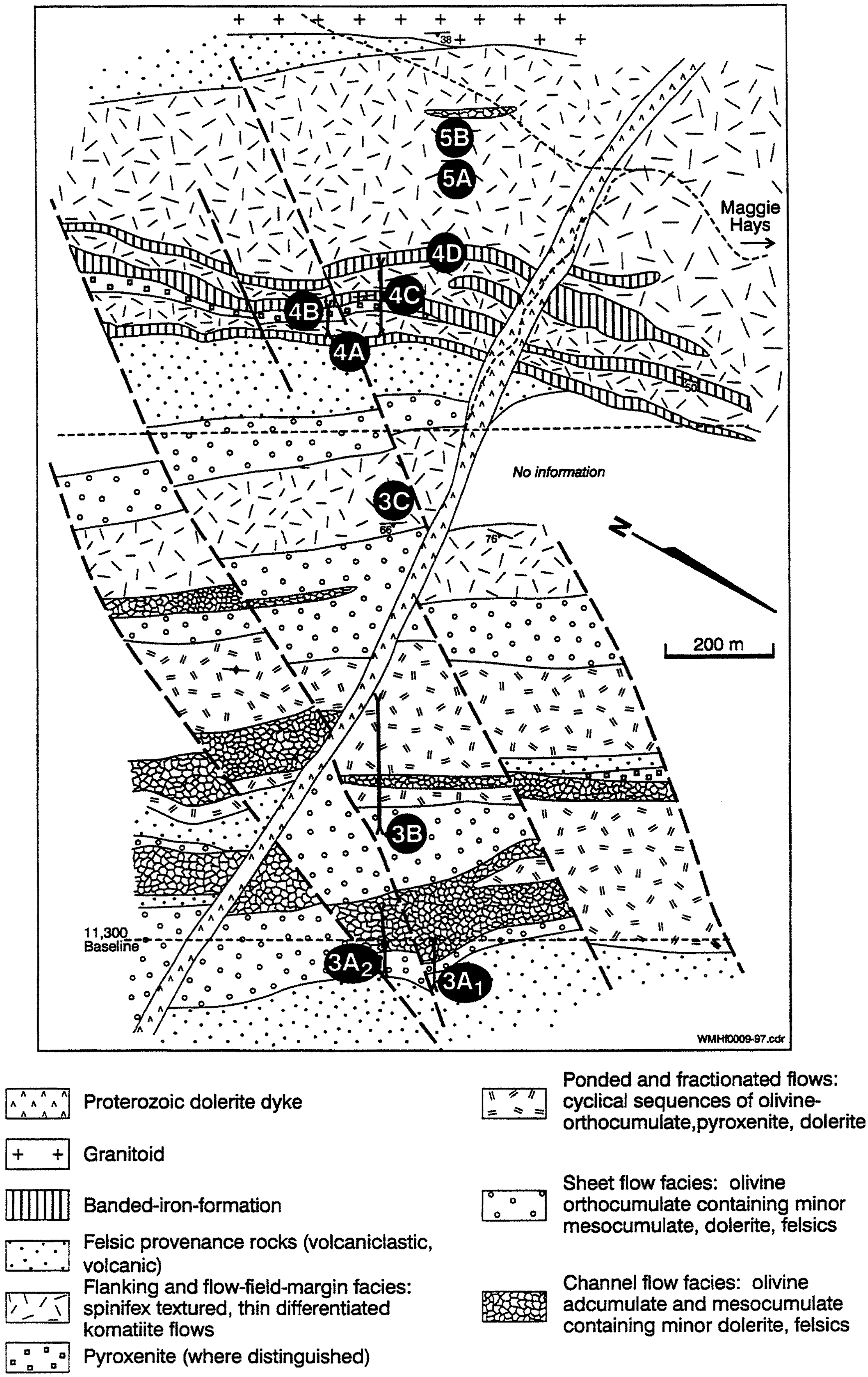

Figure 37. Geological detail map at Honman Ridge over region covered by stratigraphic traverse. Excursion localities that are detailed in the text are marked by numbers. Copyright CSIRO Exploration and Mining

There is a gradual change, over 5–10 m to more olivine-rich, mesocumulate rocks and this can be seen clearly in the costean 100 m to the south. Here, the deeply weathered olivine orthocumulate is brown with scattered, subrounded, dark-brown mottles. The brown matrix indicates a high proportion of chlorite/tremolite relative to talc which reflects a relatively high portion of residual liquid in the cumulate protolith. The mottles are the weathered remains of metamorphic olivine porphyroblasts. In the transition from ortho- to mesocumulate, there is an increase in abundance of metamorphic olivine porphyroblasts and the matrix becomes pale brown to straw or even pale green, and takes on a soapy feel as the proportion of talc increases.

To the west of the baseline, mesocumulate rocks with some adcumulate lenses are covered by distinctive silica caprock, which preserves some primary igneous textures. Towards the western end of the costean, olivine mesocumulate is cut by a medium-grained mafic intrusive rock.

From the west end of the costean, continue to walk westward to traverse the laterite ridge and to pick up the next costean after 150 m at Locality 3B.

As you cross the ridge, notice the preservation of metamorphic textures in the lateritized rocks, the variations in size and abundance of metamorphic-olivine porphyroblasts, and the variations in colour and talc content of the matrix. These features indicate that the olivine cumulates were composed of broad lenses or layers of olivine orthocumulate within olivine mesocumulate suggesting a dynamic depositional environment with fluctuating flow rates in a broad channel/tube or confined sheet.

Locality 3B

The costean here (250 m long) exposes an excellent example of a waning flow regime in which episodic hot flows become ponded and fractionate through pyroxene cumulates to pyroxene–plagioclase cumulates (Fig. 37).

The first 50 m of the costean display interleaved orthocumulate and mesocumulate ultramafic rocks. Again, these end members can be distinguished through variations in the chlorite:talc ratio of the matrix and the abundance and size of the metamorphic olivine porphyroblasts. Furthermore, in some fresher samples there appears to be finely granular metamorphic olivine preserved in the matrix.

Olivine-rich cumulate rocks are overlain by a 20 m-thick layer of pyroxene cumulate that has generally sharp upper and sharply gradational lower contacts. The rock is deep green in colour and has a mottled to bladed texture that grades from medium to coarse grained at the base to fine grained at the top. Pyroxene has been replaced by tremolite–actinolite, and there is minor serpentine and accessory chromite.

This pyroxenite represents fractionation of the komatiite lava after stagnation or ponding of the feeder flow, and rapid cooling is indicated by the presence of a chilled flow top to the west.

Over the next 50 m, there is a similar ponded flow sequence ranging from olivine mesocumulate to pyroxene cumulate. However, in this case, the lava continued to fractionate through to a pyroxene–plagioclase cumulate, possibly with influx of several pulses of more-evolved magma. The feeder flow is particularly olivine-rich and is covered by silica caprock. The lava forms a fine- to medium-grained granular, talc-rich rock containing fine-grained acicular crystals of anthophylite and sparse olivine porphyroblasts. This is succeeded by a characteristically bladed, coarse pyroxenite, which grades sharply into gabbro. Gabbro is dark green in colour and shows significant variation in grain size and texture. At least four units have been identified that range from coarse-grained, pyroxene-rich bases, through medium-grained homogeneous equant cores, to very coarse-grained harrisitic tops. Each unit is separated by thin units (a few metres thick) of plagioclase-phyric, glassy, felsic rocks. It is not clear if these are intrusions that exploited the flow bases or interflow volcanic rocks.

The last 65 m of this costean reveal a further rejuvenation of komatiite lava flow. An olivine orthocumulate 40 m thick became stagnant and then fractionated through pyroxene cumulate (10 m) to pyroxene–plagioclase cumulate (15 m).

Traverse 25 m to the north through the Melaleuca grove to pick up the east–west grid line and proceed westward for 300 m where a low rise is crossed by the cleared line at Locality 3C.

Locality 3C

The uppermost member of the Central Ultramafic Unit in this area is a basaltic komatiite consisting of a series of pyroxene-spinifex textured flows that represents the 'last gasp' of the cataclysmic komatiite eruptive event (Fig. 34). The more evolved character of these rocks may be attributed to fractionation processes at the source of the eruption as the supply of magma waned, or to contamination of the later magma batches by crustal material.

The ridge contains good outcrop and rubble of thin fractionated flows containing excellent examples of cumulate 'B-zones', and both random and sheaf forms of pyroxene-spinifex textured

'A-zones'. Unfortunately, at this locality, no single outcrop displays sufficient continuity to confidently determine a younging direction. However, in conjunction with nearby but less accessible outcrops, a westward younging may be gleaned from the distribution of rubble and outcrop.

The grey-green rocks range in grain size from fine to very coarse. Cumulate 'B-zones' tend to be paler in colour, finer grained and commonly softer rocks. They tend to be granular and contain bimodal grainsize olivine (now largely talc) intergrown with pyroxene (now tremolite–actinolite). The larger, less abundant olivine population may reach 2–3 mm and have intricate skeletal forms. Spinifex textured 'A-zones' show fine- to coarse-grained random spinifex and coarse sheaf texture (stringy-beef) up to 20 cm long.

Narrow zones of strong foliation consisting of fine-grained talc–tremolite–chlorite schist are oriented subparallel to layering and separated by 10–15 m. These zones appear to have developed in the region of the flow top and base of succeeding flow and may therefore be used as a rough guide to flow thickness here.

Locality 4. Honman Ridge

Return to the vehicles at the junction of the gridline and diversion track to the north, and drive back to the central baseline (250 m). Turn left to follow the baseline south for 200 m and then leave the baseline at gridline 55100mN to park 50 m off to the right in a small clearing.

Beware: *The next section of the stratigraphic traverse involves a 700 m walk of a prominent strike ridge formed by differential erosion of banded iron-formation. There is a steep gradient and short rock scramble to gain the crest of the ridge and a similar descent on the west side of the ridge.* ***Firstly****, this section may be physically challenging for some, so please, do not hesitate to contact the leader to arrange alternative access. Secondly, when negotiating the BIF outcrops, exercise extreme caution as the blocks are loose and may by dislodged easily and potentially cause injury.*

From the clearing, follow the approximate line of the survey pegs to gain access to the ridge to the west. Examine the BIF outcrop at the crest (Locality 4A) and look eastwards for a panoramic view of the valley containing the Lower Honman Formation, the ranges of hills beyond, which are composed of the Maggie Hays Formation, and the enclosing Lake Johnston playa.

Stratigraphy of the Upper Honman and Lower Glasse Formations in outcrop

The upper portion of the Honman Formation consists of BIF interleaved with ultramafic rocks and impersistent felsic and mafic units. The lowermost member of the Glasse Formation is called the Western Ultramafic Unit. All these rock types are beautifully exposed in the ridges, saddles and western flanks of Honman Ridge (Fig. 37).

Locality 4A

At the top of the eastern flank of Honman Ridge, a series of good outcrops reveals the characteristic layering and laminations of BIF.

The whole interlayered BIF package is 50–250 m thick and follows a broadly linear regional trend with only small perturbations and offsets attributed to late cross-faulting. It is steeply overturned to the west (Hunter, 1995a; Perring, 1995a). Banded iron-formation layers vary in thickness from 10 to 30 m: they commonly bifurcate, and contain parasitic and intrafolial folds (best seen in rock faces perpendicular to the ridge trend).

Banded iron-formation comprises alternating laminae of magnetite and quartz ranging in thickness from a few millimetres to a few centimetres, but there does not appear to be any systematic variation in the ratio of quartz to magnetite across the unit.

Traverse westward towards a short costean (Locality 4B), noting features in the first BIF layer and change from BIF layer to interleaved ultramafic rocks.

Locality 4B

Costeans and scattered outcrop reveal that the eastern two principal BIF layers are separated by pyroxenite and olivine-spinifex textured rocks in this area. A moderately thick (20–50 m) unit of coarse-grained pyroxenite occurs to the west of (?above) spinifex textured rocks and this can be seen here in the costean. Pyroxenite is a khaki to straw-coloured, coarse-grained rock composed of intermeshed blades of pyroxene (now amphibole). It is not clear at this stage how these lithologies came to lie within the BIF package. They may be primary interleaved units representing episodic volcanicity and hiatuses or, more likely, tectonically interleaved (in-folded or faulted) adjacent units.

Follow the second BIF layer to the north until we reach another costean that has now been backfilled and appears as a rough track. Turn left to follow the line of the costean westwards, to Locality 4C.

Locality 4C

At this locality, subvertical transverse faces of BIF are well exposed. These reveal complex intrafolial folding patterns that are not generally seen in flat-lying pavement outcrops. Development of a good axial-planar cleavage (33° E) here precludes these folds from being 'soft-sediment slumping' artefacts.

Continue along the costean/track towards the west and the third significant BIF layer. Enjoy a panoramic view of Lake Hope to the west before turning right and following the BIF layer to the north for 120 m. At the survey peg for gridline 55300mN drop down through the BIF outcrop at Locality 4D.

Locality 4D

Descending through the BIF outcrop to the top of the west flank of Honman Ridge allows further examination of cross sections through a BIF layer and the complex internal folding. ***Please be careful*** *as many of these blocks are loose and precariously balanced.*

Locality 5. Honman Ridge West

Follow the surveyed line (55300mN) directly down the western flank of Honman Ridge to a RAB-drillhole at 9900mE and Locality 5A.

Thin differentiated komatiite flows of the Glasse Formation

The predominant rock type on the western flanks of the ridge is olivine-spinifex textured komatiite (Western Ultramafic Unit) forming the lower member of the Glasse Formation. The unit has an apparent thickness of 250–300 m, appears to conformably overlie BIF, and is truncated to the west by a foliated granitoid with a mildly sinuous contact (Fig. 36). Komatiite is interleaved with several thin (10–15 m), conformable mafic units, which may be seen in discontinuous outcrop and

RAB hole intervals as fine- to medium-grained dolerite. Minor lenses of olivine mesocumulate are scattered throughout the Western Ultramafic Unit.

Banded iron-formation marks a significant hiatus in the volcanism that produced the ultramafic rocks of the Honman Formation. When volcanism resumed in this area, thin fractionated flows were episodically emplaced marginal to the komatiite flow field either as overbank flanking flows or as distal compound flow lobes. At several stages in the evolution of this komatiite complex, moderate sized channels or tubes were also established.

Komatiites have been metamorphosed to amphibolite facies but are apparently undeformed and so some primary igneous textures are commonly preserved. In the A-zone portions of flows, bladed olivine-spinifex textures are common and are composed of mainly tremolite and chlorite with various amounts of talc and carbonate. Where talc is more abundant, the spinifex textures remain faintly delineated by trains of microgranular exsolved magnetite. In the B-zone portions of flows, the textures are commonly destroyed by the matted growth of talc with carbonate, tremolite and chlorite. Most RAB holes contain some identifiable A-zone material so the flows are probably thin (10–20 m), but no unequivocal younging directions were determined.

Locality 5A

The piles of drill spoil at this locality contain massive, fine-grained tremolite–chlorite–talc rocks after olivine-spinifex textured komatiite (Fig. 37). Cumulate 'B-zones' tend to be more talc-rich, granular, homogeneous and paler in colour. In contrast, the 'A-zone' material is green-grey, heterogeneous and very fine grained. Careful examination of the latter may reveal relict bladed-spinifex texture, commonly resulting from the exsolution of microgranular magnetite from olivine blades during metamorphism.

Continue westward along the gridline to a natural clearing at about 9775mE, and leave the line to the north (right) for the short distance to Locality 5B.

Locality 5B

Here, thin differentiated komatiite flows are exposed in outcrop and good examples of olivine-spinifex textures can be seen in situ. However, ***please do not hammer the outcrop*** as it is a rarity in this area. If you need to collect samples, take only from the float here.

Return to the gridline and continue westward for about 100 m to rejoin the vehicles at the track that will take us back to Windy Hill Camp.

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