Mineral Provinces

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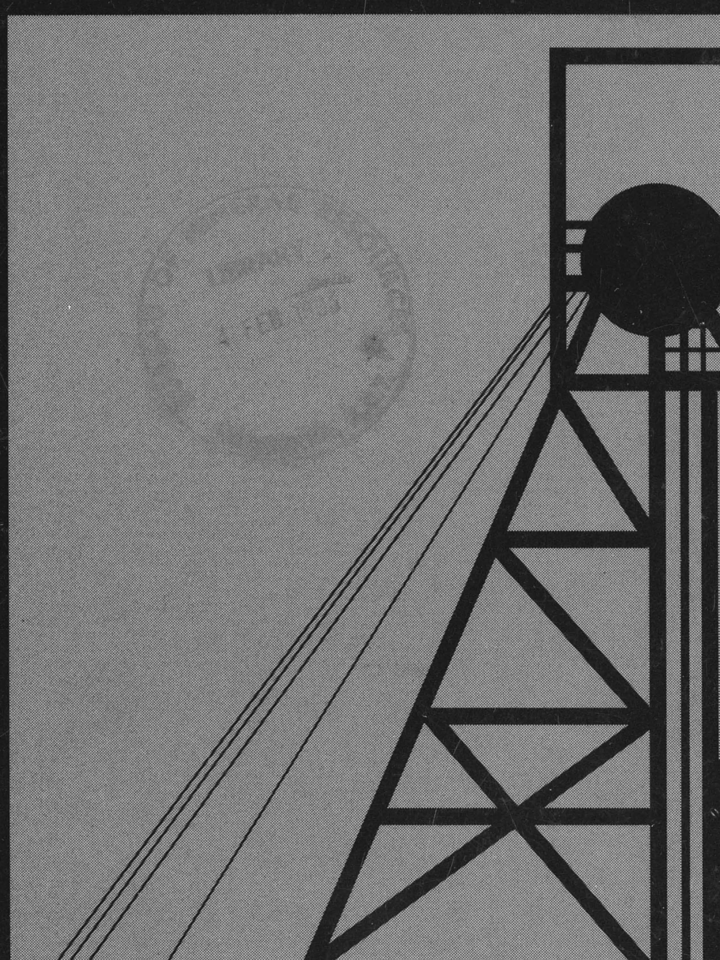
District surrounding the Armanda Sill, Halls Creek Inlier, Western Australia
Record 1992/70

AUSTRALIA



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R G Warren

MINERALS AND LAND USE PROGRAM
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

AGSO

AUSTRALIAN GEOLOGICAL
SURVEY ORGANISATION

District surrounding the Armanda Sill, Halls Creek Inlier, Western Australia Record 1992/70

R9207001

R G Warren

Minerals and Land Use Program

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Resources: The Hon. Alan Griffiths
Secretary: Geoff Miller
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION
(formerly BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS)

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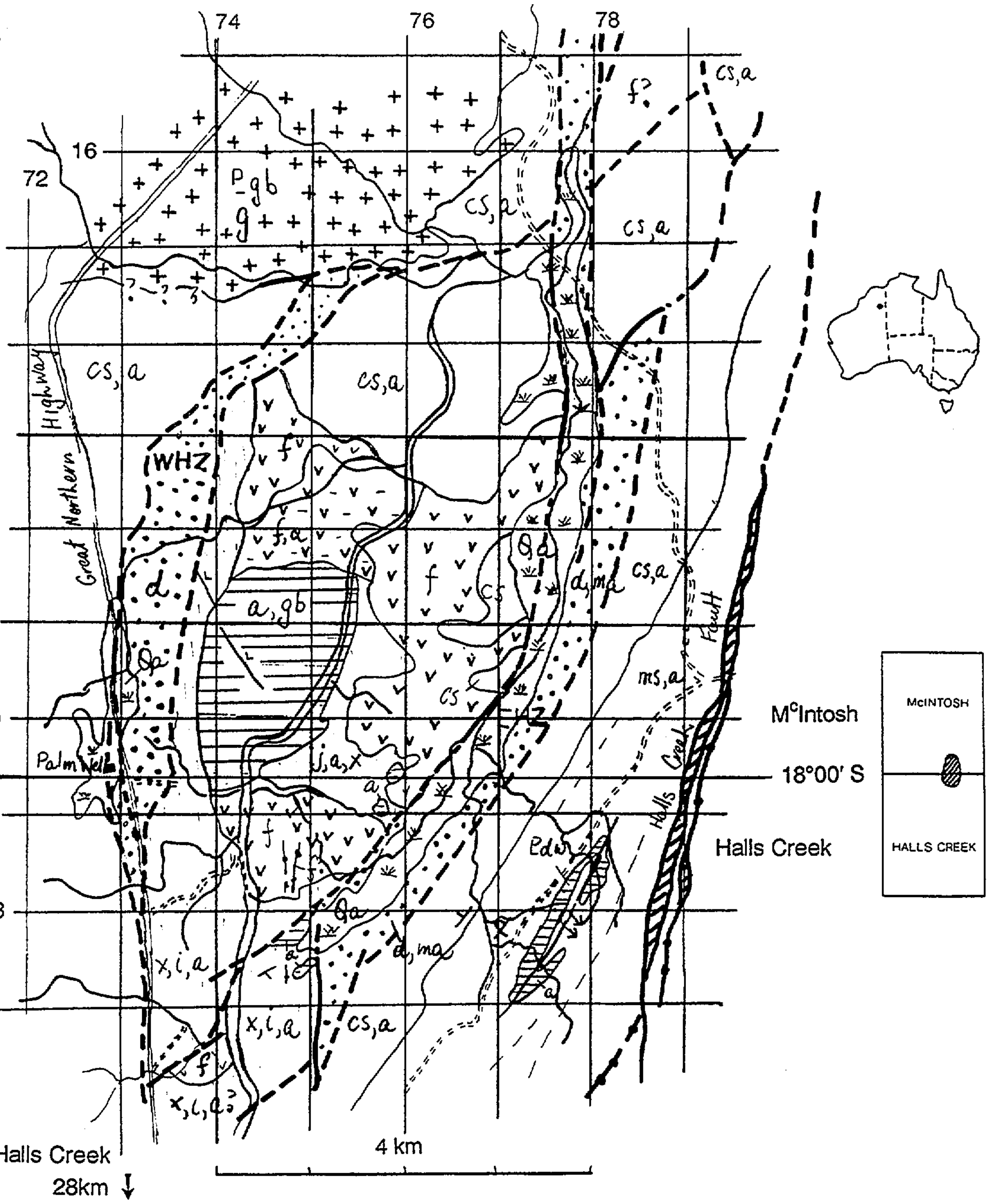
CONTENTS

ABSTRACT

The Armanda Sill is a small (circa 2 km in diameter) gabbroic intrusion in the Halls Creek Inlier about 30 km north of Halls Creek township, and east of the Great Northern Highway, extending from the north of the Halls Creek 1:100 000 Sheet area into the McIntosh 1:100 000 Sheet area.

The quartz-filled Halls Creek Fault forms the eastern edge of the area examined. Parallel to this are two wide (circa 0.5 km) high-strain zones which are situated east and west of a block containing the Armanda Sill, the rhyolite unit and associated sediments. Between the eastern high-strain zone and the Halls Creek Fault farther east, sediments and mafic extrusives of the Biscay Formation and meta-dolerite, probable Woodward Dolerite, are metamorphosed to upper greenschist facies. In the north, interlayered calcareous sediments and mafic rocks of the upper Biscay Formation are intruded and metasomatised by the Bow River Granite. The rhyolite, previously reported as intrusive into the gabbro, overlies these calc-silicate rocks, with apparent angular unconformity. It therefore appears extrusive and is pre-metamorphic. The sample analysed is more correctly a meta-dacite. It has a thin cap of alteration and is overlain by sediments of a style found associated with volcanogenic ore deposits. Cordierite alteration (metamorphosed chloritic alteration) on the southern and western margin of the rhyolite passes up into an association of cordierite rocks, calc-silicate rocks, breccia and BIF. Overlying this association are interlayered cordierite and andalusite granofels and amphibolites. These and the rhyolite have been intruded by McIntosh Gabbro (the Armanda Sill and satellite intrusions). All have been metamorphosed to low-pressure amphibolite facies. Retrogression at transitional amphibolite facies in the high-strain zone occurred at temperatures slightly lower than those at peak conditions. High Cl content in amphiboles and biotite in samples of granite and rhyolite shows fluid circulation, post regional metamorphism, did not extend beyond the high-strain zones.

Comparison of the analysis of the rhyolite with the chemical analyses of other felsic units in the area show that it is unlikely to be related to the Brockman volcanics, nor to the tonalitic suites to the north. The dacitic composition is best considered as the product of interaction between a potassic felsic magma with the characteristics of northern Australian Proterozoic and the upper Biscay Formation.



Qa	Alluvium	WHZ	Western high-strain zone
Pra	M^c^Intosh Gabbro (Armanda Sill)	d	deformed rock
a	amphibolite	EHZ	Eastern High-strain zone
gb	gabbro	d	deformed rock
Pgb	Bow River Granite	ma	marble
g	granite s.l.	/	fault (dashed where concealed or inferred)
Pdw	Woodward Dolerite	q	quartz-filled fault
a	amphibolite	f	felsic dykes
peb	Biscay Formation		
a	amphibolite		
cs	calc-silicate rock		
f	felsic rock (metarhyolite)		
j	meta-sediment		
i	cordierite-bearing rock		
x	andalusite-bearing rock		
ms	muscovite-bearing schist		

Fig. 1. Geological map of the area surrounding the Armanda Sill, Halls Creek and M^c^Intosh 1:100 000 sheet areas.

INTRODUCTION

The area surrounding the Armanda Sill, a small gabbroic intrusion in the Halls Creek Inlier, about 30 km north of Halls Creek township, was examined in August, 1990. The area lies east of the Great Northern Highway, and extends from the north of the Halls Creek 1:100 000 Sheet area into the McIntosh 1:100 000 Sheet area (Fig. 1). Gemuts (1971) described the gabbroic intrusion, which he named the Armanda Sill, as having faulted margins but a relatively undeformed central section. He also reported that the area immediately adjacent to the sill contained somewhat higher grade rocks than its surrounds, a conclusion supported by this study. However, the sequence of geological events is more complex than was recognized in earlier reports (Fig. 2). The rhyolite, previously considered intrusive into the gabbro, appears extrusive, and has a thin cap of alteration and sediments of a style seen in volcanogenic ore deposits. The single sample (AGSO registered number 90524831) collected for geochemical analysis is strictly a dacite (Fig. 3), though in this report the unit is still referred to as a rhyolite, firstly, to maintain continuity with previous studies, and secondly, so as not to pre-empt any more detailed geochemical study. All the units, including the Bow River Granite and the McIntosh Gabbro, exhibit some effects of metamorphism; the prefix *meta* is omitted to avoid tedious repetition. Sample numbers carry the prefix 9052, which is omitted from the text for simplicity.

PREVIOUS INVESTIGATIONS

The study area takes in parts of the areas covered by the Gordon Downs and Dixon Range 1:250 000 geological maps (Smith & Gemuts, 1967; Dow & Gemuts, 1969). Gemuts (1971) produced a detailed map of the Armanda Sill and its surrounds; his interpretation of the rock relationships and stratigraphy is shown as Figure 2A. At the time of these reports, the Biscay Formation was considered to be Archaean; the rhyolite, the McIntosh Gabbro and the Bow River Granite, all being less deformed, were assigned to the Proterozoic. All units are now considered Proterozoic (See Blake, 1991, for a review of time relations as presently available.)

GEOLOGICAL SETTING

The Halls Creek Fault Zone, which served as the eastern boundary of the study area, is locally a prominent topographic feature, by virtue of the quartz veins marking its trace. These record repeated growth into open spaces and are relatively undeformed. West of the Halls Creek Fault and subparallel to it there are two wide high-strain zones, situated east (EHZ) and west (WHZ) of the Armanda Sill. The EHZ is not well exposed, apart from a ridge-forming carbonate unit caught up within it; and its form was interpreted from exposures in deeply incised creeks which cut down through alluvial cover. It appears to be at least 500m wide, with poorly defined margins. An intensely deformed central region of phyllonitic and mylonitic rocks merges through less deformed rocks into undeformed rocks either side. Isoclinal folds (possibly dissected sheath folds) exposed in a pavement in the carbonate unit (McIntosh GR 774101) refold the foliation (dip of foliation 50° to the east), and severely deformed rocks in the central section are also folded. Air-photo interpretation indicates that the EHZ breaks up into a series of anastomosing faults north of the area examined. The EHZ locally marks the eastern limit of the Bow River Granite and McIntosh Gabbro. The WHZ is better exposed than the EHZ, in ridges of deformed rock and along an east-west section in the banks of the creek northeast of Palm Well. It has a width of about 500m near Palm Well, but becomes a narrower feature to the north. The Great Northern Highway follows a topographic low close to the western margin which may be relatively sharp, as outcrops close to the highway on the west are reportedly only weakly deformed. (In Figure 4 of Gemuts, 1971, much of the area west of the highway is mapped as granite-gabbro breccia, and trend lines in meta-sediments are west-northwest, almost at right-angles to the WHZ.). Severely deformed rocks east of the highway have isoclinal folds with axial planes dipping parallel to the foliation in sheared rocks (strike 20^o, dip 60^o to the WNW). Retrogression that affected the deformed rocks (see below) was accompanied by hydration, so that the WHZ is more schistose, compared with the more mylonitic EHZ. Lateral displacement along the high strain zones cannot be assessed, but they may have modest vertical displacement, since metamorphic grade increase across them westwards. The differences in character between the two appear to reflect the difference in crustal level to which they are exposed in the area examined.

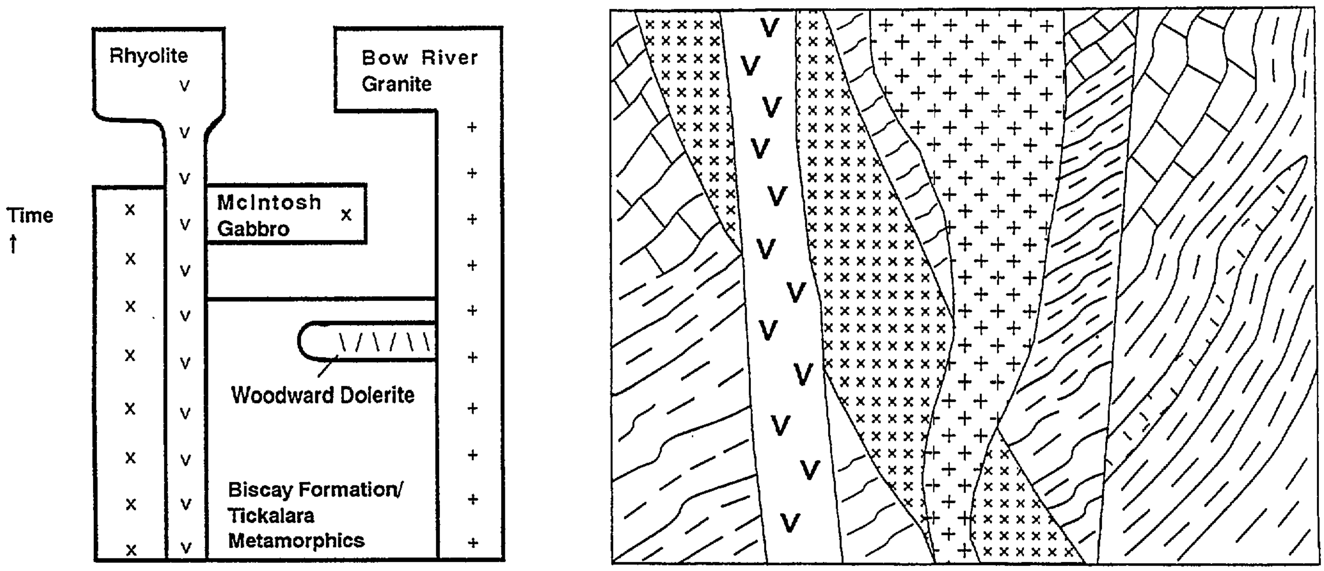
The Halls Creek Fault and the two high-strain zones subdivide the area into two elongate belts of relatively undeformed metamorphic rocks. In the eastern belt, broad open folds, similar to those in the Biscay and Olympio Formations east of the Halls Creek Fault, are apparent on air photographs. Pelites have a well-developed layer-parallel fabric crenulated by a later fabric, possibly formed in the event which produced the high-strain zones. Dolerites (probably sills) in the sequence retain an igneous appearance in outcrop, but are entirely hydrated. The western belt is dissected by cross faults, but lacks any indication of regional folds. The various rock types in the western belt retain much of their original texture, and the Armanda Sill, in part, its anhydrous primary mineralogy. Small mafic bodies, Bow River Granite and Biscay Formation are all metamorphosed and hydration is extensive. Pelites have "reversed graded bedding", due to the formation of porphyroblastic andalusite in the upper parts of beds.

GEOLOGICAL UNITS

Biscay Formation (Halls Creek Group)

The sediments in the study area were previously mapped as partly Biscay Formation and partly Tickalara Metamorphics, but with the understanding that the Tickalara Metamorphics are the higher-grade equivalents of the Biscay Formation. All these rocks are included in this report within the Biscay Formation, together with the rhyolite and overlying sediments. However, given the possibility of an angular unconformity between the rhyolite and the underlying carbonate-dominated facies of the Biscay Formation; the rhyolite and the overlying sediments may need to be assigned eventually to a separate stratigraphic unit.

The rocks in the eastern belt correlate with units 3 and 4 in the type area of the Biscay Formation as described by Dow and Gemuts (1969). Graded bedding in the pelites close to the boundary with the calc-silicate sequence show that the latter overlies the pelite-dominated unit, as in the type area. The calc-silicate rocks range from near-pure carbonate rock to well-banded variants with thin siliceous layers and siliceous-calcareous rocks. Both units contain interlayered mafic rocks, which tend to be recessive. Most mafic rocks are fine-grained, and so are probably metamorphosed extrusives. Coarser-grained meta-dolerites have been mapped as Woodward



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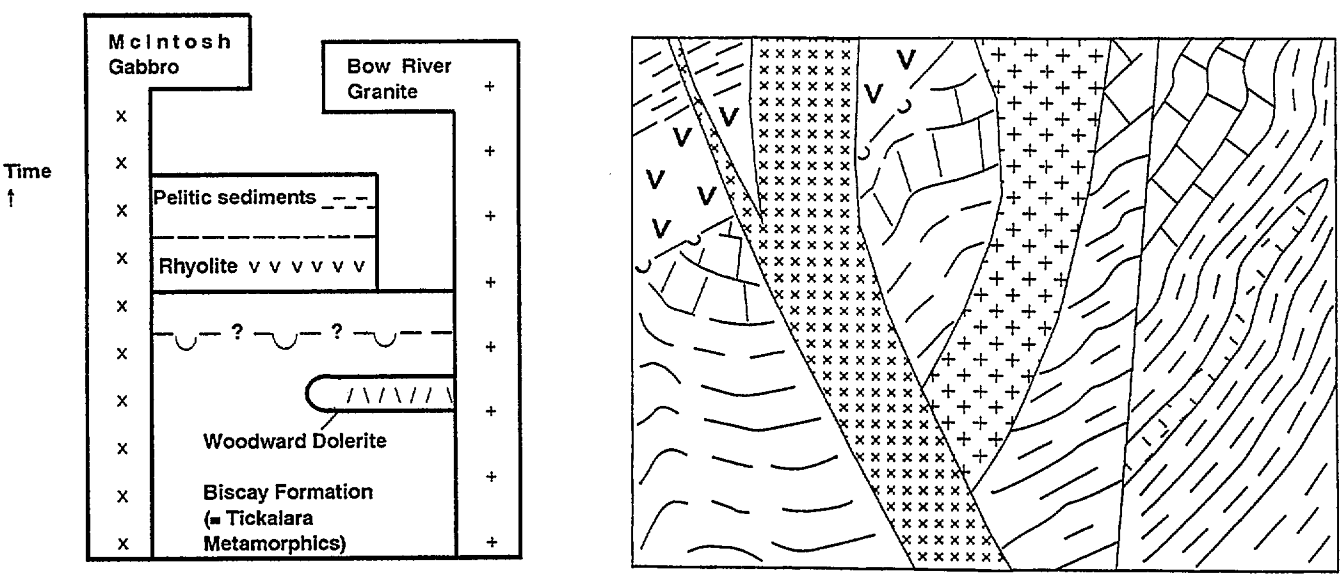

B

Figure 2. A. Stratigraphic units and rock relationship diagram as given by previous reports (after Gemuts, 1971; Dow & Gemuts, 1967). B.Stratigraphic units and rock relationship diagram from this study (N.b. The relationship between McIntosh Gabbro and Bow River Granite is not seen within the area covered by this report; Blake (1991) has interpreted net-vein relationships between the two as showing intrusion of the Bow River Granite by the McIntosh Gabbro. The Bow River Granite has a zircon age circa 1850 Ma, (Page & Hancock, 1988); the McIntosh Gabbro likewise has an age circa 1850 Ma (Sun & others, 1991; S.S. Sun, personal communication, June, 1992).

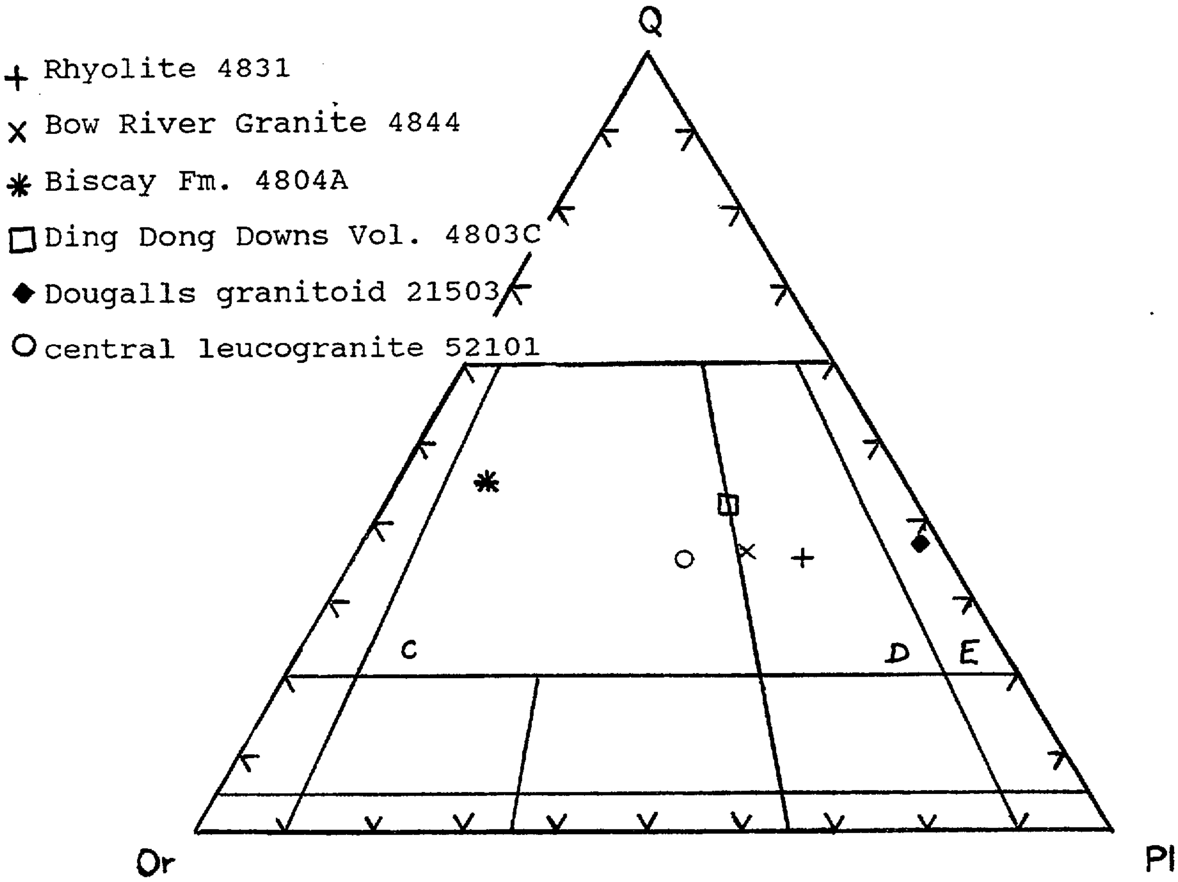

Figure 3. Plot of normative q, or and pl with subdivisions after Streckeisen (1979). C – field of granite/rhyolite, D – field of granodiorite/dacite, E – field of tonalite/dacite. Analyses of Dougalls granitoid and central leucogranite from Ogasawara (1988).

Dolerite, large outcrops of which are shown in the northern extension of the eastern belt in the Dixon Range 1:250 000 Sheet area (Dow and Gemuts, 1967).

In the western belt, north of the Armanda Sill, along the eastern and southern margin of the Bow River Granite, calc-silicate rocks, interlayered with mafic rocks, are compositionally and texturally very like those to the east and therefore are placed in unit 4 of the Biscay Formation. Metamorphic recrystallization is more pronounced, probably as a result of regional metamorphism overprinting contact metamorphism. Metasomatism adjacent to the Bow River Granite has produced dark green rocks with the field appearance of ultramafic rocks, but a sample of which consisted of actinolite, possibly anthophyllite, plagioclase, spinel and trace corundum. In places interaction between granite and calc-silicate rocks has produced near-monomineralic plagioclasite, possibly albitite (c.f. the empirical observations of Joplin, 1957, on the interaction of potash granite and calcareous rocks).

The rhyolite crops out in two larger bodies and several smaller ones, totalling several square kilometres, along the western margin of the EHZ in the north of the study area. The rhyolite is a dark grey, fine-grained rock, with poorly defined layering. Despite its fine-grained nature and the absence of penetrative deformation, it has been pervasively hydrated. Ghosts of original phenocrysts are visible in thin section. Sample 4831A, collected for geochemical analysis, contains quartz, biotite, amphibole, muscovite, epidote, and trace (e.g., several grains) tourmaline and carbonate. Many outcrops are speckled by numerous rounded pale quartzose patches forming haloes about dark cores. In specimens from the southern body, these central cores consist principally of hornblende, retrogressed to biotite, chlorite and epidote; in specimens collected from the northern outcrops the cores contain biotite, variously with chlorite, muscovite, clinozoisite, tourmaline and/or calcite. The northwards change in assemblage may record retrogression rather than a decrease in grade, as the northern outcrops were sampled relatively close to the EHZ.

The junction between the rhyolite and the calc-silicate unit is, overall, not well exposed. However at one locality (McIntosh GR 769107) where the two are in contact, the rhyolite cuts discordantly across layering in a calc-silicate lens, infilling irregularities in the calc-silicate unit in a fashion that suggests the rhyolite infilled a karst-like surface. From this contact, an extrusive origin is inferred for the rhyolite. The previous interpretation, of an intrusive plug of rhyolite, is considered improbable on the grounds that at GR769107 there are no metasomatic effects and no calc-silicate xenoliths in the rhyolite immediately adjacent to the contact nor are there rhyolite intrusions in the calc-silicate lens beyond the contact. This contact stands in complete contrast to contacts between the calc-silicate unit and Bow River Granite, where metasomatism is pronounced and numerous small bosses of granite appear within the calc-silicate rocks. Thus it seems that the rhyolite overlies Unit 4 of the Biscay Formation after an erosional break and probably with angular unconformity. The overall very fine-grained nature of the rhyolite indicates a fine-grained protolith (grainsize tends to increase with metamorphism), consistent with an extrusive parentage.

Layered sediments and small lenses of calc-silicate rock, one to several metres thick and five to twenty metres long, crop out within the rhyolite away from the contact with the Biscay Formation and are parallel to layering in the rhyolite. Andalusite-bearing metasediments occur (D Blake, pers. comm., 1990) in the belt that separates the two larger bodies of rhyolite, and finely layered rocks and a lens of calc-silicate rock occur in the east of this belt. These sediments may be products of sedimentary interludes between pulses of felsic volcanic activity, though the largest outcrop area could be a fault-repetition of the sediments along the southern margin of the rhyolite.

The upper part of the rhyolite contains rounded porphyroblasts of cordierite, or, for the most, pseudomorphs of muscovite-biotite, muscovite-chlorite, or pinnite as the result of late retrogression. These are particularly well displayed in outcrops in the Armanda River, but the most intense cordierite concentration was found in the southern margin of the rhyolite, where subhedral cordierite crysts to several centimetres long are locally abundant. The cordierite-bearing margin of the rhyolite merges up into a sequence of cordierite-bearing rocks, with minor thin layers of breccia, conglomerate, calc-silicate rock and BIF. This sequence is overlain by pelites, including both cordierite- bearing and more-aluminous types, interlayered with amphibolites. The pelites commonly have metamorphically-reversed "graded" bedding with abundant randomly orientated poikilotic andalusite porphyroblasts in the upper parts of beds.

The cordierite-bearing outer zone of the rhyolite and the immediately overlying lithological association of meta-sediments are metamorphosed compositional analogues of the hydrothermally altered, chloritized volcanic rocks and associated volcanogene sediments found in relatively unmetamorphosed submarine volcanic piles and especially in volcanogenic ore deposits (Fig. 4). No indication of sulphide minerals or gossanous material was found with these rocks.

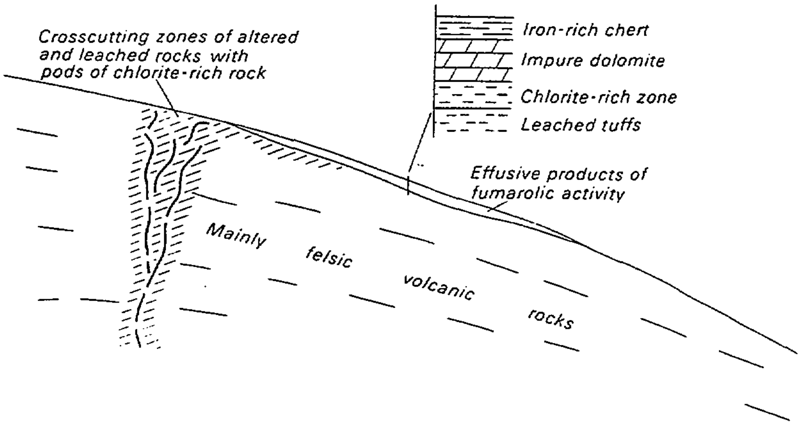

Figure 4. Schematic interpretation of the cap of cordierite-bearing rocks, thin layer of calc-silicate rocks and BIF as the alterites (leached chloritic rocks) and exhalites (leached tuffs with chlorite-rich zones, impure dolomite and iron-rich chert) over the extrusive rhyolite (modified from Warren, 1979) above the rhyolite.

Bow River Granite

Granitic rocks, assigned in previous mapping (e.g., Dow and Gemuts, 1967), to the Bow River Granite, crop out in the northern part of the western belt, intruding Unit 4 of the Biscay Formation. Two phases are present. The more leucocratic phase, represented by 4844 collected for geochemical analysis, consists of quartz, abundant microcline, minor oligoclase, hornblende and biotite. The other is a melanocratic type with abundant zoned plagioclase and hornblende, some quartz and biotite, but little or no K feldspar. Both phases contain opaques (ilmenite?) with sphene rims. The hornblende in both phases was identified optically as hastingsite; it is poikiloblastic and partly replaced by felted brown biotite. Microprobe analysis of the hornblende in 4844 confirmed this identification; as is usual with hastingsitic hornblende in the Proterozoic of northern Australia, it contains chlorine. Late epidote occurs in some plagioclase. In outcrop, the melanocratic phase has the appearance of poorly foliated Mabel Downs Granodiorite as mapped by Dow & Gemuts (1967) to the north. The published zircon age of the Bow River Granite is 1850 Ma (Page & Hancock, 1988).

McIntosh Gabbro: Armanda Sill and satellite intrusions

The Armanda Sill is a gabbroic intrusion, assigned to the McIntosh Gabbro by Dow & Gemuts (1967) about 2km across in the central part of the study area. It has small satellites to the east and southeast. The Armanda Sill itself is a satellite body to the extensive gabbro intrusions west of the Great Northern Highway. The Armanda Sill was examined only near its margins. Gemuts (1971) described the central portion as a layered olivine gabbro with leucogabbro lenses. The

	Rhyolite					
Sample number	90524831	90524844	87596001	90524809A	90524810	DR5.71.5
Stratigraphic unit	Upper Biscay	Bow River Granite	Bow River Granite	Bow River Granite	Bow River Granite	Bow River Granite
SiO2	73.11	74.29	69.58	66.43	77.69	71.90
TiO2	.13	.20	.49	.74	.10	.40
Al2O3	13.20	12.98	14.14	15.27	11.57	13.40
Fe2O3	1.45	.81	1.08	1.26	.71	.74
FeO	1.50	1.48	2.94	4.48	.50	2.29
MnO	.06	.03	.06	.05	.02	.04
MgO	.14	.36	.82	1.48	.03	.50
CaO	1.94	1.65	2.16	3.43	.55	1.82
Na2O	4.40	3.80	2.70	2.71	2.51	2.02
K2O	2.52	3.42	4.30	2.83	5.94	5.18
P2O5	.02	.04	.12	.16	.01	.13
H2O+		-	-	-	-	1.17
H2O-		-	-	-	-	.04
CO2		-	-	-	-	.11
LOI	1.20	1.04	1.47	1.08	.49	-
Rest	.22	.18	.36	.25	.11	.00
Total	99.89	100.28	100.22	100.17	100.23	99.74
O=F,S,Cl	.00	.00	.00	.01	.00	.00
Total	99.89	100.28	100.22	100.16	100.23	99.74
		Trace elements in parts per million				
Ba	786	708	749	783	110	-
Li	9	38	41	37	7	-
Rb	64	141	208	133	251	-
Sr	108	72	105	168	11	-
Pb	8	9	29	19	27	-
Th	11	18	28	18	25	-
U	3.50	3.50	6.00	2.50	4.00	-
Zr	258	137	250	258	149	-
Nb	32	11	15	15	9	-
Y	79	47	52	28	68	-
La	67	48	50	36	45	-
Ce	136	90	91	71	99	-
Nd	68	40	41	30	56	-
Pr	16	11	11	9	15	-
Sc	6	7	11	18	5	-
V	<2	11	26	58	<2	-
Cr	1	3	19	42	1	-
Mn	531	289	-	470	133	-
Co	7	8	7	17	6	-
Ni	2	3	3	16	1	-
Cu	<1	1	5	33	1	-
Zn	109	27	53	79	32	-
Sn	3	<2	8	4	<2	-
W	7	<3	-	3	6	-
Mo	<2	<2	<2	<2	<2	-
Ga	22	18	18	21	19	-
As	.50	2.00	2.00	2.00	1.00	-
S	60	70	<100	110	<10	-
F		-	1300	-	-	-
Be	4	4	3	2	2	-
Ag	2	2	-	3	2	-
Bi	<2	<2	2	<2	<2	-
Hf	6	3	7	5	3	-
Ta	4	<2	<2	<2	<2	-
Cs	<3	4	11	8	<3	-
Ge	2.00	1.50	1.50	2.00	2.00	-

Table 1. Chemical analyses of the rhyolite, Bow River Granite and Brockman volcanics.

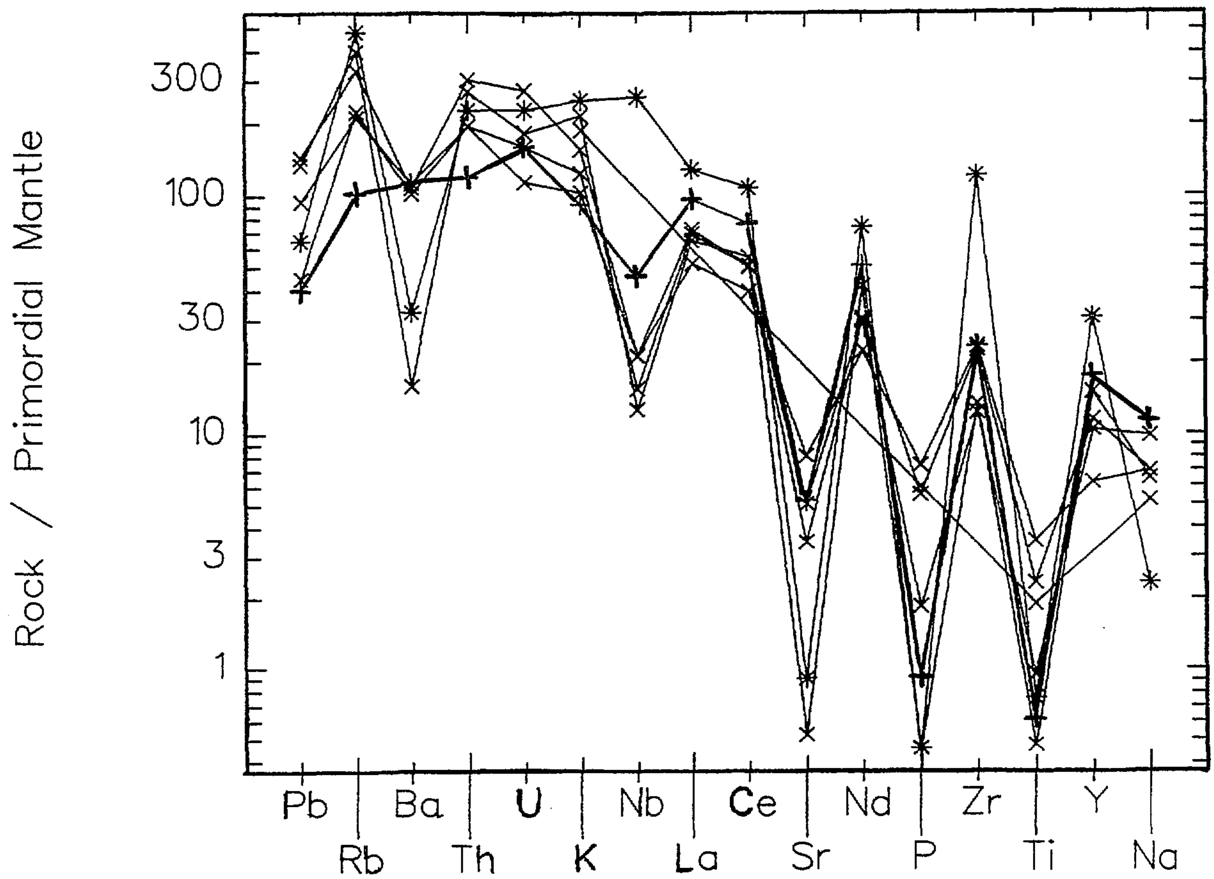

Figure 5. Mantle-normalized element-ratio plots for the rhyolite (+), the Bow River Granite (x) and sample 4804A (*) from the Brockman volcanics.

margins exposed in the Armanda River and in the creek northeast of Palm Well are converted to amphibolite, as are the satellite intrusions. Gemuts (1971, Fig. 4) showed extensive outcrops of uralitized gabbro north of the central body; at least some of these appear to be amphibolitized mafic rocks interlayered with the calc-silicate rocks within the Biscay Formation, and therefore either extrusives within the Biscay Formation or Woodward Dolerite. The poorly exposed rocks on the southwestern margin of the main body are leuco-amphibolite with a relict igneous texture.

Breccia-like outcrops of mafic and felsic rock are extensively developed in a broad contact zone between the gabbro and the rhyolite east of the Armanda River, and are also exposed in the creek northeast of Palm Well (See Figure 1, Plate 4 of Gemuts. 1971). The grainsize of the felsic rock increases towards the contact with the gabbro. Small patches with compositions intermediate between the gabbro and the siliceous rhyolite occur within this zone. Such features are indicative of a hornfelse zone in which temperatures were high enough to re-melt the rhyolite. As the rhyolite is now considered to be extrusive, one of the small satellite mafic plugs has a chilled margin against the rhyolite and another intrudes the metasediments above the rhyolite, it follows that the Armanda Sill is younger than the rhyolite and intrusive into it. The contact between the gabbro and the sediments in the gorge cut by the Armanda River was not investigated but has potential for uncommon rocks and mineral assemblages, these may provide information on the timing of the very high-T contact metamorphism and the regional metamorphism.

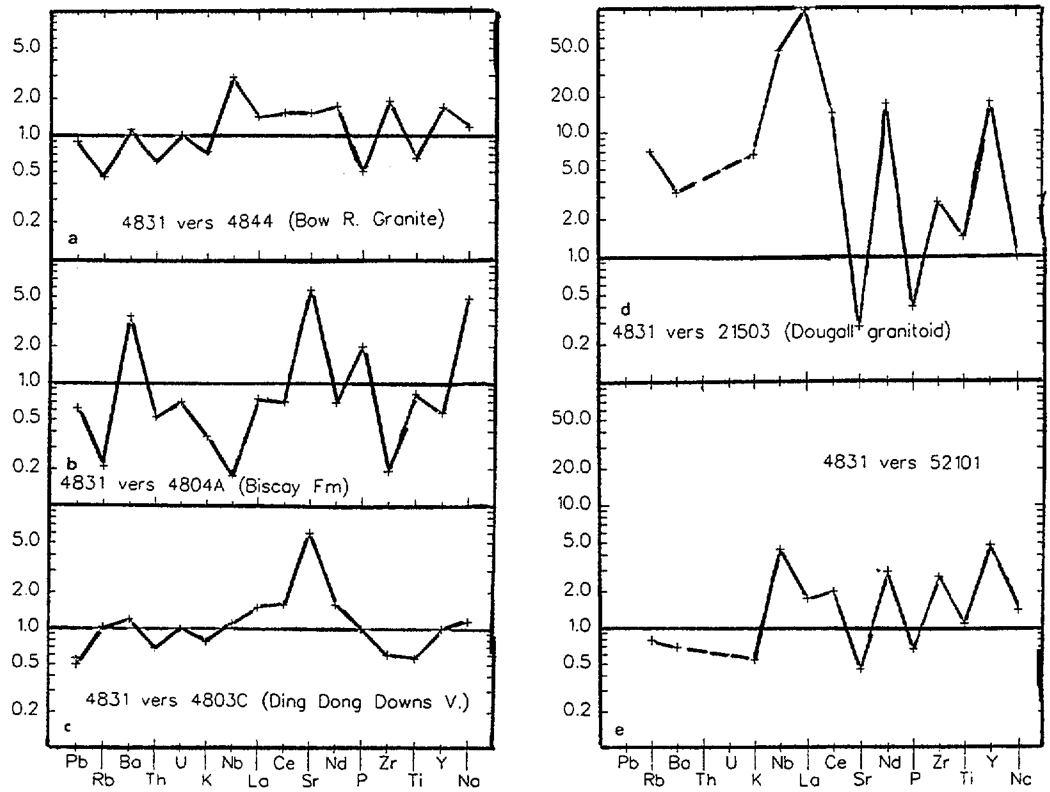

Figure 6. Element-ratio plots comparing the chemical signature of the rhyolite as analysed (using 4831), with those of other felsic rocks in the Halls Creek Inlier. Specimens 21503 (Dougall granitoid) and 52101 (central leucogranite) from Ogasawara (1988).

GEOCHEMISTRY

Samples of the rhyolite, a sample of the leucocratic phase of the Bow River Granite, an amphibolite from one of the satellite plugs east of the Armanda Sill and samples of felsic meta-volcanic rocks from the Biscay Formation and Ding Dong Downs Volcanics east of the area covered by this report were collected during the 1990 field season for analysis. (Table: Sample data and analyses are available in the AGSO ROCKCHEM database.)

The sample 4831A selected from the rhyolite strictly classifies as a dacite (e.g., Fig. 3). Since it is diopside-normative, and plots on the minimum-melt curve for 0.5 kbar of Tuttle and Bowen (1958), its chemical signature is taken to indicate that it has retained its original igneous chemistry and has not been significantly metasomatized by the alteration represented by the cordierite-bearing margins. The sample was selected in the field as typical of the rhyolite unit, but as true dacites are uncommon in the Proterozoic of northern Australia (e.g., Wyborn & others, 1988; Wyborn & others, in press), the result requires interpretation. Apart from the low K/Na, the analysis shows major and trace element concentrations that are mostly "normal" for a northern Australian Proterozoic felsic rock of 73.11 weight percent SiO_2. Its signature is Sr-depleted, Y-enriched (Fig. 5), again normal for Northern Australian Proterozoic felsic rocks, indicating a shallow source, above the eclogite transformation, probably in an extensional setting (e.g., Tarney & others, 1987), in keeping with the intra-rift setting of the Brockman volcanics in the underlying Biscay Formation (Taylor & others, in press) and continental rift environment for the mafic rocks of the McIntosh Gabbro (Sun & others, 1991).

A second sample, 4828a from the northernmost outcrops, carries numerous quartz haloes. Its analysis shares the Sr-depleted signature (Fig. 5),

The analysis of sample 4831A indicates the rhyolite is somewhat different from other felsic units in the Halls Creek Inlier (Fig. 6), but closest to the normal Proterozoic, 1880-1850 Ma potassic felsic suite as represented in the Halls Creek Inlier by the Whitewater-Bow River association.

The stratigraphic position of the rhyolite above the Biscay Formation is similar to that of the alkaline felsic Brockman volcanics in the Biscay Formation to the east. However these are distinctive, consistently containing high Zr, Y, Nb and LREE (e.g., Page and Handcock, 1988, also sample 4804A, Halls Creek GR860078); thus the rhyolite is markedly less enriched in Nb and Zr relative to 4804A (Fig. 6b) and appears not to be a correlate (See below).

Available analyses of the Whitewater Volcanics are much more siliceous (e.g., SiO_2 75.01 weight percent) with KNa; but those for the Bow River Granite span a range of silica values (Fig 7). Comparison with 4844 (SiO_2 74.29 weight percent, see Fig. 6a) shows that the rhyolite on the whole is not dissimilar to nearby Bow River Granite, with the obvious exception of K/Na and therefore high normative plagioclase for the SiO_2 level (Fig. 3). The rhyolite also resembles compositionally the normal northern Australian Proterozoic potassic felsic suite (e.g., 4803C) within the Ding Dong Downs Volcanics, which underlie the Biscay Formation, though enriched in Sr (correlating with higher normative plagioclase) and with lower K/Na (Fig. 6c). The dacitic chemistry of the rhyolite would suggest affinity with the tonalite-trondhjemite suites (Dougalls granitoid suite, Mabel Downs granitoid suite, central leucogranites and Ord River tonalite suite) recognized by Ogasawara (1988); but the analysed sample shows marked enrichment in LREE, Zr, Nb, and Y over these suites at similar silica levels (Figs 6d&e).

The probable solution to the enigma is provided by the observation of Wyborn & others (1988) on the changes to granite composition in the Williams Batholith (eastern Mount Isa Inlier) through interaction with calc-silicate country rocks, giving "noticeably higher Fe_2O_3/FeO ratios and Na_2O and lower K_2O, Rb and Ba". Figure 7 shows that 4844 (74.29 weight percent SiO_2) from the Bow River Granite intruded into calc-silicate rocks shows slight signs of such changes. This is consistent with a sample site somewhat removed from the immediate contact zone. The rhyolite, erupted through the same calc-silicate sequence, shows the effects more markedly; especially, the decrease in Rb has increased the K/Rb ratio. Thus the inference is that the dacitic composition is an artifact of interaction with calc-silicate rocks in the volcanic conduit, which modified a potassic felsic composition originally close to normal for the north Australian Proterozoic circa 1880-1850 Ma. It may represent an early episode in the emplacement of the Bow-Whitewater association or an earlier (but post-Biscay) igneous interlude.

Despite the stratigraphic position, the rhyolite appears distinct from the Brockman volcanics near the top of the Biscay Formation. The possibility that the rhyolite is part of the Brockman volcanics, modified by interaction with calc-silicate rocks cannot be entirely discounted. Arguments for considering a correlation with the Brockman volcanics are the slightly elevated Ga/Al, Nb, LREE and Zn contents of 4831A.

The rhyolite does not appear to a correlate of the syntectonic tonalitic intrusions in the central axis of the Halls Creek Inlier.

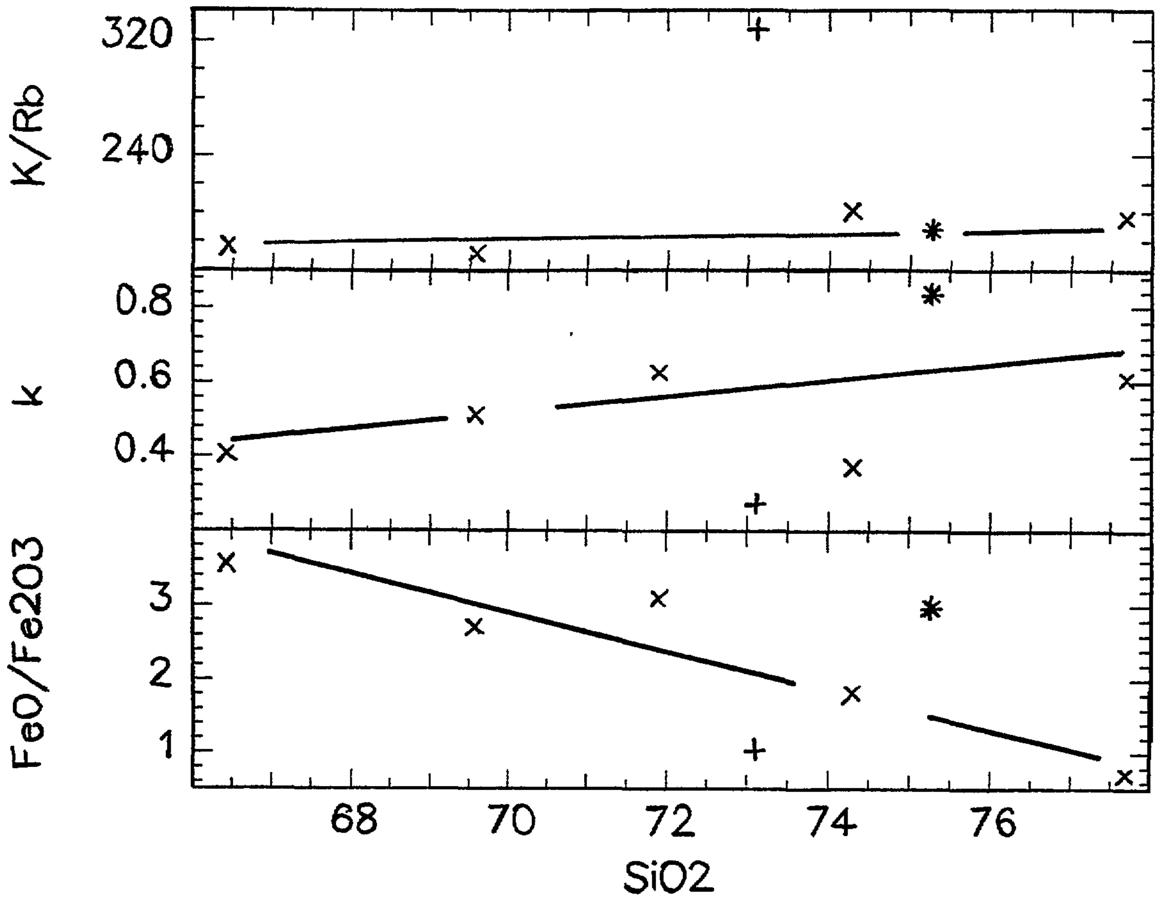

Figure 7. Harker plots for rhyolite sample 4831A (+), Bow River Granite (x) and Brockman volcanic sample 4804A (*). Sample 4831A, relative to the normal Proterozoic Bow River Granite, shows a marked increase in K/Rb, a decrease in k (= $K_2O/[K_2O + Na_2O]$), and a decrease in Fe^{2+} to Fe^{3+} iron, interpreted as indicative of interaction with calc-silicate rocks.

METAMORPHISM

The EHZ divides the area into two metamorphic zones. East of the EHZ, the rocks contain uppermost greenschist to lowermost amphibolite assemblages with muscovite-chlorite, muscovite-biotite, and actinolite-epidote.

The western belt, between the EHZ and the WHZ, is at amphibolite facies, reflecting higher temperatures than to the east, but nevertheless low pressure conditions, shown by the development of andalusite and cordierite in pelites. Relatively coarse muscovite (4838A), interpreted as a relict prograde phase, suggests conditions remained below about 600°C; certainly there are no indications of partial melting in the pelites. (Melting of the rhyolite in the hornfelsed margin of the gabbro preceded regional metamorphism, which produced amphiboles in mafic rocks where water was available.) The rhyolite contains aggregates of amphibole (hastingsite in 4831A) in quartz haloes. These are interpreted as reaction textures, generated by hydration of pyroxene phenocrysts, rather than incipient partial melts. As such they are consistent with amphibolite facies metamorphism. A small lens of calc-silicate, collected from within the sediments above the rhyolite, contains a prograde assemblage of quartz-calcite-diopside-garnet, which has been overprinted by a more hydrous tremolite-bearing assemblage. This is consistent

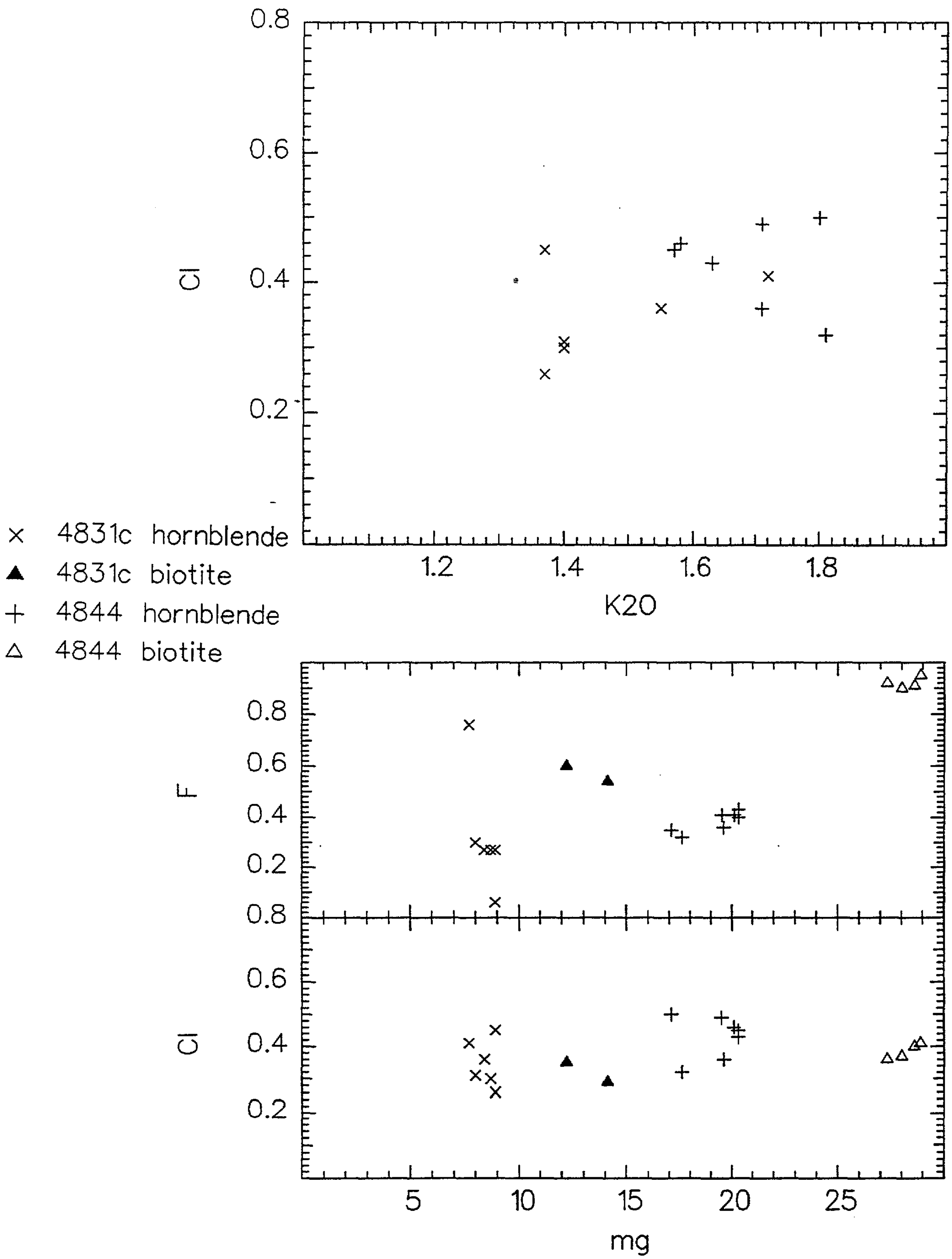

Figure 8. Preliminary assessment of the distribution of Cl and F in amphibole and biotite in 4831C (rhyolite) and 4844 (Bow River Granite); showing (a) positive correlation between Cl and K content of the amphiboles (cf Volfinger & others, 1985), but (b) a poor correlation between decreasing mg and Cl (the Mg-Cl exclusion principle), except in amphibole from 4844.

with conditions close to 600°C, initially with local high fCO_2, which subsequently decreased whilst still at near-peak temperatures.

Hastingsite, where it has been analysed in Proterozoic metamorphites from the Mount Isa Inlier (Wyborn & Page, 1983) or the Arunta Block (unpublished data) invariably contains chlorine. Microprobe analysis of the amphiboles in 4831C (rhyolite) and 4844 (Bow River Granite) confirms the optical identification of hastingsite, with Cl contents of 0.26-0.45 and 0.43-0.56 weight percent respectively (Figs 8a&b) and similar F contents. Later biotite contains appreciable Cl and F. The probable source of Cl is the calc-silicate rocks of the Biscay Formation, and it seems a likely premise that the hastingsite-like amphiboles in other rocks from the study area will likewise contain chlorine. The chlorine content of the amphiboles and biotites shows that these rocks have experienced low fluid to rock ratios during prograde metamorphism and thereafter, since chlorine preferentially partitions into the fluid phase relative to solid phases and would then have been removed by devolatization or fluid infiltration (Mora & Valley, 1989). Hydration related to the formation of the retrograde zones therefore was limited to the vicinity of the deformed zones.

Retrograde metamorphism close to the WHZ produced assemblages with anthophyllite and gedrite co-existing with relict forsterite and spinel, probably at the expense of cordierite-bearing assemblages. Chlorite was noted in the field, but material selected for thin section contains only traces. Retrogression to epidote-actinolite facies is overprinted on a prograde amphibolite-facies partial hydration in the leuco-gabbro 4840A. These observations indicate that the high-strain zones existed before cooling from peak conditions was far advanced.

GEOLOGICAL HISTORY (Figure 2)

The oldest rocks in the study area, interlayered pelites and mafic rocks, are correlated with Unit 3 of the Biscay Formation, and were intruded by the Woodward Dolerite. Deposition of the pelites gave way to carbonate-dominated sediments, also interlayered with mafic rocks, and perhaps intruded by the Woodward Dolerite. In the western belt, the carbonate-dominated sequence was overlain by rhyolite. More than one episode of rhyolite eruption, separated by sedimentation, may have occurred. By the end of rhyolite eruption the area was below sea level, so that the upper part of the rhyolite was hydrothermally altered and overlain by a thin sequence of rocks characteristic of hydrothermal interaction between hot volcanic rocks and seawater. Deposition of a predominately pelitic (both chloritic and aluminous) sequence with thin mafic layers followed.

Subsequently the rhyolite and overlying sediments were intruded by mafic rocks (McIntosh Gabbro s.l.), forming the Armanda Sill and smaller plugs, and the Biscay Formation by the Bow River Granite. No assessment of the temporal relationship between intrusion of gabbro and the Bow River Granite was possible within the study area, though available radiometric ages suggest these were penecontemporaneous.

Metamorphism of high-T, low-P type (locally peaking at ~600°C, kbar) postdates all units. Retrogression in high strain zones commenced whilst temperatures were still elevated, showing that these developed soon after peak metamorphism.

CONCLUSIONS: points for additional studies

The rhyolite appears to postdate the Biscay Formation, and may represent an early eruption of the Whitewater-Bow River association, modified by interaction with calc-silicate rocks of the Biscay Formation. It appears not to be part of the Brockman volcanics; and, if so, has been severely altered by interaction with the calc-silicate rocks. The stratigraphic position can be tested by isotope geochemistry.

The cordierite alteration can be interpreted as a submarine interaction between seawater and rhyolite. Such alteration is associated with exhalive mineralization, though no indication of such is present at this locality.

Hastingsitic hornblende and biotite containing Cl have been identified. The distribution of Cl-bearing phases is of value in the study of the pattern of fluid infiltration.

Metamorphic rocks close to the Armanda Sill may be useful in showing the timing of regional metamorphism relative to the intrusion of the McIntosh Gabbro.

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