

GEOCHEMICAL AND STABLE ISOTOPIC STUDIES OF THE CROWN AND MARAROA REEFS, NORSEMAN, WESTERN AUSTRALIA

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ABSTRACT The quartz reefs of Archean age at Norseman, Western Australia are restricted to the flatter-dipping sections of reverse faults and the gold mineralization is mainly stratabound. Structural and petrographic data indicate that the reefs were emplaced prior to the peak of metamorphism, but gold distribution and wallrock mineralogy were modified by metamorphism and subsequent deformation events. "Bucky" quartz crosscuts laminated quartz and was deposited during an episode of hydraulic fracturing. Gold and sulfides are concentrated on fractures in the laminated quartz reefs.

Wallrock assemblages of the Crown and Mararoa reefs require two temporally distinct phases of alteration synchronous with the emplacement of laminated and "bucky" quartz reef. The first involved the deposition of hydrothermal actinolite and biotite, whereas chloritic overprinting of these assemblages characterizes the second phase of alteration. Both potassic and chloritic assemblages were modified by the crystallization of metamorphic actinolite and tremolite. In general, single stage alteration is characterized by the addition of volatiles, K_2O and CaO , and the loss of Na_2O . Changes in whole-rock geochemistry during chloritic overprinting of the potassic assemblages include losses of CaO , Al_2O_3 , Na_2O and K_2O , and a gain of MgO .

The $\delta^{18}O$ values of the Norseman wallrocks range from 5.8 to 9.1 ‰ with a mean value of 7.2 ± 0.9 ‰ (16 samples). Reef quartzes also exhibit a narrow range of $\delta^{18}O$ values (11.7 ± 0.4 ‰, 26 samples). The wallrock assemblages are compatible with a mineralization temperature ≥ 400 °C. The calculated $\delta^{18}O$ value of the water in equilibrium with the quartzes at these temperatures is 7 ‰. Waters involved in the subsequent metamorphism have identical $\delta^{18}O$ values which suggest they have a common source, connate fluids and hydrous minerals in the greenstone pile. The observed timing relations and isotope systematics suggest that the ore fluids were connate brines which were mobilized during tectonic dewatering of the volcano-sedimentary pile and channelled up early faults.

INTRODUCTION Norseman is located in the Dundas Goldfield which has been the second largest gold producer in Western Australia. It was discovered in 1892, one year earlier than the famous Golden Mile deposits at Kalgoorlie. More than 100,000 kg of gold have been produced from several quartz reefs, the most important of which are the Mararoa, Crown and Princess Royal. Total production from the Mararoa-Crown reefs to June 1978 was 5,434,775 tonnes of ore at an average grade of 12.1 g/ton (Woodall, 1979).

The literature on the gold deposits of Western Australia is voluminous, but much of it is old. Campbell (1904) mapped the Norseman district and distinguished the volcanic and sedimentary units. McKinstry (1933) and Conolly (1936) demonstrated that ore zones within the main north-south shears are restricted to flatter-dipping sections of the shears, and that individual orebodies also display a preferred orientation. Furthermore, although the gold mineralization is clearly epigenetic, it is mainly confined to one portion of the stratigraphy (King, 1941; O'Driscoll, 1953; Bekker, 1962). More recently, Cameron (1968) and Larking (1969) have documented wallrock alteration bordering the reef channels and intrusive porphyries, respectively. The former study was primarily petrological, whereas the latter author reported limited major and trace element data for the acidic rocks and their contact aureoles.

This paper comprises a geochemical and stable isotopic study of the Crown and Mararoa reefs and is part of a comprehensive study of gold mineralization in the Kal-

goorlie-Norseman area of Western Australia (Golding, 1982). The impetus for this study came largely from a number of international review papers (Taylor, 1974; Rye and Ohmoto, 1974; White, 1974) which demonstrated the importance of stable isotopic techniques in determining the history and origin of the water in hydrothermal ore deposits. It was apparent that there was a bulk of isotopic data available for epithermal gold deposits, but only limited information for more deep-seated deposits which may be of diverse origins (see Golding and Wilson, 1981).

GEOLOGICAL SETTING Norseman lies within the Yilgarn Block which is one of two large Archean cratons within the Western Australian Shield (Gee, 1975, 1979; Fig. 1). The Yilgarn Block consists largely of greenstone belts within extensive granitoids, but higher-grade gneiss terranes are also present. Three major provinces are recognized and Norseman falls within the Kalgoorlie subprovince of the Eastern Goldfields Province (Williams, 1974). The Kalgoorlie subprovince comprises the Norseman-Wiluna greenstone belt which has a predominantly mafic-ultramafic association almost totally lacking in banded-iron formation (BIF). Corridors of granitic rocks separate the Norseman-Wiluna greenstone belt from the Laverton and Southern Cross subprovinces which contain abundant BIF. Williams (1975) concluded that the Kalgoorlie subprovince developed as a rift or graben structure within a stable crustal platform represented by these subprovinces.

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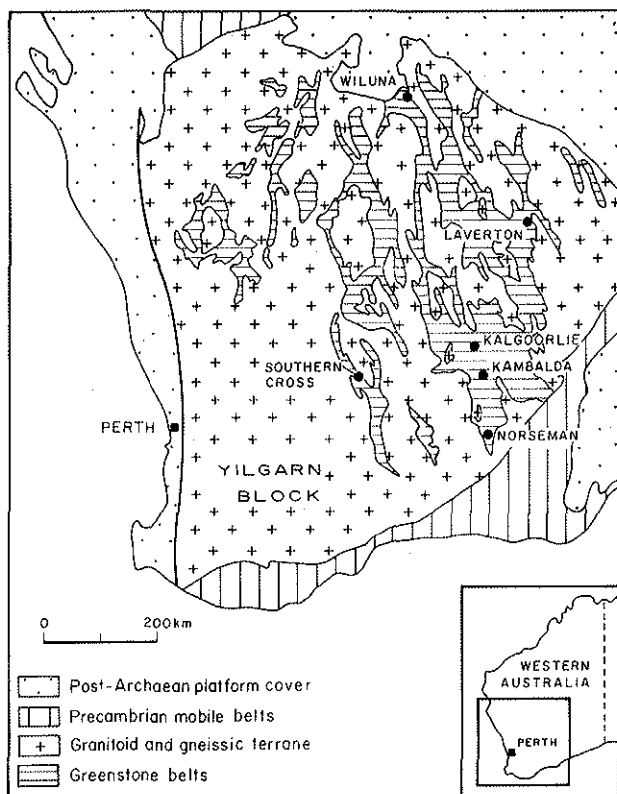


Figure 1 – Regional geology (modified from Gee, 1975)

Stratigraphic correlations within the Norseman-Wiluna belt have been hampered by poor outcrop and tectonic lineaments which have disrupted the supracrustal rocks. Several volcanic cycles of mafic-ultramafic to felsicclastic sequences have been identified (Gemuts and Theron, 1975; Williams, 1975). Rock units of the Norseman succession are equivalent to sequences 1 to 4 of Gemuts and Theron (1975) and include the oldest rocks in the greenstone belt (Table 1). Binns *et al.* (1976) placed Norseman within a

medium-grade domain, where low amphibolite facies metamorphism was accompanied by excellent textural preservation of primary structures.

Stratiform quartz-sulphide lodes in the BIF of the Noganer Group have accounted for a minor part of the gold produced at Norseman. Most production, however, has come from the quartz reefs which occur as tabular bodies along the planes of the reverse faults. This style of gold mineralization is restricted to that portion of the stratigraphy bounded by the Venture Slate and the Bluebird Gabbro. Detailed description of the rock units has been restricted accordingly.

Mararoa Pillow Lava The fine-grained lavas are low-K tholeiites with a limited range of MgO values (Table 2). The basalts may be massive or pillowed and are composed of plagioclase microlites set in a matrix of pale blue-green metamorphic amphibole with disseminated ilmenite. Analyses of the Mararoa Pillow Lava closely approximate the MORB trend on an Al_2O_3/TiO_2 vs. TiO_2 diagram (Fig. 2) and have a chondritic value for the Ti/Zr ratio of about 110 (Table 3). They also fall in the komatiite plus primitive tholeiite field on an Al_2O_3 vs. $FeO^*/(FeO^* + MgO)$ diagram (Fig. 3). High-Mg basalts have not been identified among the pillow lavas and all samples plot within the tholeiite field on a $CaO-MgO-Al_2O_3$ diagram (Fig. 4).

The basalts are silica-saturated and frequently quartz normative. Very extensive thicknesses of this type of tholeiite, with near chondritic trace ratios and limited major element dispersion, occur in the Kalgoorlie-Norseman region (Hallberg, 1972; Hallberg and Williams, 1972; Nesbitt and Sun, 1976; Bavinton, 1979).

Crown-Bluebird sequence A conformable sequence of medium to coarse-grained amphibolites which are petrologically divisible into the Bluebird Gabbro, Royal Amphibolite and Crown Basalt overlie the Mararoa Pillow Lava (Bekker, 1962). The contact is frequently marked by a slaty, graphitic sedimentary horizon, the Gee Cee Slate. The Crown-Bluebird Sequence is chemically and texturally diverse (Tables 2 and 3). Bekker (1962) proposed that the Crown-Bluebird Sequence was a composite sill, primarily because of the coarse-grained "igneous" character of the rock types.

Table 1 – Norseman stratigraphic succession

Rock unit	Approximate thickness (m)	Dominant lithology
Mt. Thirsty Beds	7,600	Slates, greywackes, cherts, jaspilites with minor basalts
Abbotshall Beds	240-1,400	Cherts, jaspilites with interbedded basalts
Woolyeeny Group	9,000	Tholeiitic pillow lavas, basic intrusives, minor high-Mg basalt with intercalated shale horizons
Desireable Pillow Lava	7,000	
Crown Basalt	200	
Nulsen Slate	1-2	
Royal Amphibolite	100-200	
Bluebird Gabbro	60-110	
Gee Cee Slate	0.2-2	
Mararoa Pillow Lava	1,300	
Venture Slate	1-3	
Kingswood Basalt	400	
Noganer Group	1,400	Jaspilites, greywacke, shale, conglomerate and sandstone
Penneshaw Beds	3,000	Tholeiitic basalts, greywackes and acid tuffs

(After Hall and Bekker, 1965).

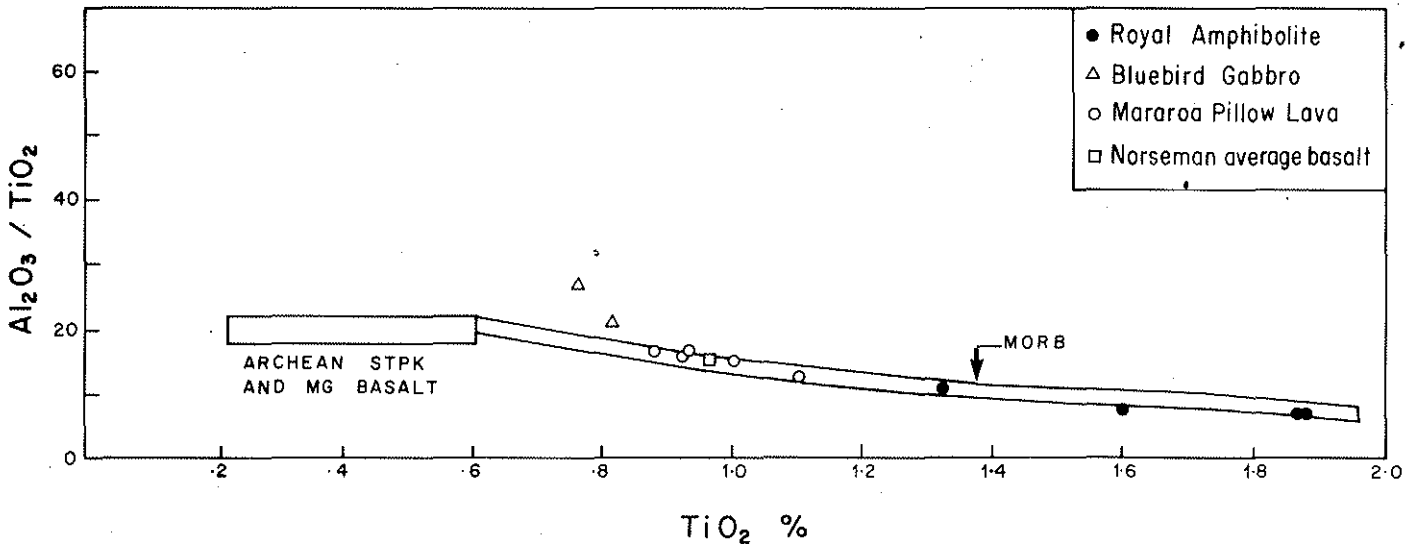


Figure 2 - Al_2O_3/TiO_2 vs. TiO_2 , fields for MORB and Archean STPK from Nesbitt et al. (1979)

The Bluebird Gabbro is characterized by a distinctive, porphyritic basal zone. Relict feldspar phenocrysts from 2 to 20 cm across are set in a medium to coarse-grained groundmass of blue-green metamorphic amphibole plates and plagioclase laths with minor interstitial quartz and ilmenite. Above this zone, the gabbro is medium-grained and has a subophitic texture. One sample of the gabbro has a chondritic Al_2O_3/TiO_2 ratio of about 20 and approximates the MORB trend on an Al_2O_3/TiO_2 vs. TiO_2 diagram (Fig. 2). The other sample which is from the lower

porphyritic zone has an Al_2O_3/TiO_2 ratio of 27 and plots above the MORB trend (Fig. 2). Both samples plot to the left of the discriminant line on an Al_2O_3 vs. $FeO^*/(FeO^* + MgO)$ diagram (Fig. 3), but fall within the Al-rich basalt field, as defined by Naldrett and Goodwin (1977). This is consistent with a plagioclase accumulation origin for the Bluebird Gabbro from a magma similar in composition to the primitive tholeiites. The trace ratios Ti/Zr and Ti/Y are near chondritic, but absolute abundances of Ti, Y and Zr are lower than in the pillow lavas.

Table 2 - Chemical data on the Norseman succession

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	49.34	47.77	49.66	50.86	46.43	47.85	52.50	48.98	49.05	52.13	49.24	51.2	50.8
TiO ₂	1.88	1.60	1.87	1.32	0.81	0.76	0.93	0.92	0.88	1.00	1.10	0.96	1.16
Al ₂ O ₃	13.33	13.33	12.86	15.09	16.92	20.46	15.54	15.29	14.79	15.67	14.10	15.2	14.5
Fe ₂ O ₃	18.99	19.14	19.29	13.30	14.10	10.20	10.77	12.31	13.31	11.93	13.16	11.9	13.1
MnO	0.27	0.22	0.30	0.32	0.17	0.14	0.23	0.28	0.22	0.28	0.22	0.22	0.21
MgO	4.55	5.26	5.16	4.01	8.47	4.00	4.59	7.04	7.72	5.36	7.40	6.4	6.9
CaO	7.89	8.72	7.29	10.09	8.26	11.66	11.23	8.95	11.10	9.93	10.76	10.7	9.9
Na ₂ O	2.79	2.48	2.69	2.01	2.29	1.98	2.71	3.30	2.01	3.01	2.01	2.8	2.7
K ₂ O	0.30	0.45	0.35	0.61	0.62	0.30	0.50	0.26	0.17	0.16	0.24	0.20	0.25
P ₂ O ₅	0.20	0.17	0.17	0.18	0.07	0.11	0.12	0.14	0.16	0.12	0.05	0.14	0.17
S	0.04	0.21	0.60	0.45	0.06	0.12	0.15	0.02	0.06	0.19	0.17		
LOI	1.15	1.29	0.82	2.73	2.55	1.82	1.56	1.53	1.08	0.90	2.36	1.1	1.1
Fe ²⁺ /ΣFe	0.83	0.81	0.81	0.80	0.87	0.85	0.82	0.85	0.74	0.84	0.84	0.88	0.88
FeO*	0.79	0.77	0.77	0.75	0.60	0.70	0.68	0.62	0.61	0.67	0.62	0.63	0.63
FeO* + MgO													
Al ₂ O ₃	7.09	8.33	6.88	11.43	20.89	26.92	16.71	16.62	16.81	15.67	12.82	15.83	12.50
TiO ₂													

- | | | |
|--------------------------------|------------------------------------|----------------------------------------------------------------------------------------|
| 1. Royal Amphibolite (314/C94) | 6. Bluebird Gabbro (1034/C94) | 11. Mararoa Pillow Lava (1989/C94) |
| 2. Royal Amphibolite (512/C94) | 7. Mararoa Pillow Lava (1216/C94) | 12. Average of 83 basalts, Norseman (Hallberg, 1972) |
| 3. Royal Amphibolite (668/C94) | 8. Mararoa Pillow Lava (1505/C94) | 13. Average of 84 premetamorphic intrusives, Kalgoorlie-Norseman area (Hallberg, 1972) |
| 4. Royal Amphibolite (740/C94) | 9. Mararoa Pillow Lava (1677/C94) | |
| 5. Bluebird Gabbro (957/C94) | 10. Mararoa Pillow Lava (1788/C94) | |

Table 3 – Trace element data (ppm) on the Norseman succession

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Rb	5	5	3	23	16	13	2	4	7	5	24	10	9
Sr	110	155	58	128	142	165	115	102	96	100	104	102	91
Y	44	36	47	37	20	17	25	25	25	27	25	22	22
Nb	7	5	6	4	4	3	4	6	3	4	5	—	—
Zr	116	98	128	90	44	44	54	54	50	58	67	57	54
Ba	64	21	38	143	187	68	51	69	38	75	71	—	—
Ni	20	30	20	60	100	30	90	70	40	80	60	166	145
Cu	65	140	185	175	65	45	45	5	135	75	80	111	111
Co	45	45	55	45	45	15	50	45	25	40	40	60	57
Zn	110	100	100	90	160	70	60	70	50	50	50	115	107
As	6	4	2	8	8	2	70	34	4	20	26	—	—
V	430	410	430	360	250	210	320	320	310	300	310	323	307
Ti	11,300	9,600	11,200	7,900	4,900	4,600	5,600	5,500	5,300	6,000	6,600	5,800	7,000
Ti/Zr	97	98	88	88	110	104	103	102	106	103	114	101	129
Ti/Y	256	266	239	214	243	268	223	221	211	222	244	262	316

- 1. Royal Amphibolite (314/C94)
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- 9. Mararao Pillow Lava (1677/C94)
- 10. Mararao Pillow Lava (1788/C94)
- 11. Mararao Pillow Lava (1989/C94)
- 12. Average of 83 basalts, Norseman (Hallberg, 1972)
- 13. Average of 84 premetamorphic mafic intrusives, Kalgoorlie-Norseman area (Hallberg, 1972)

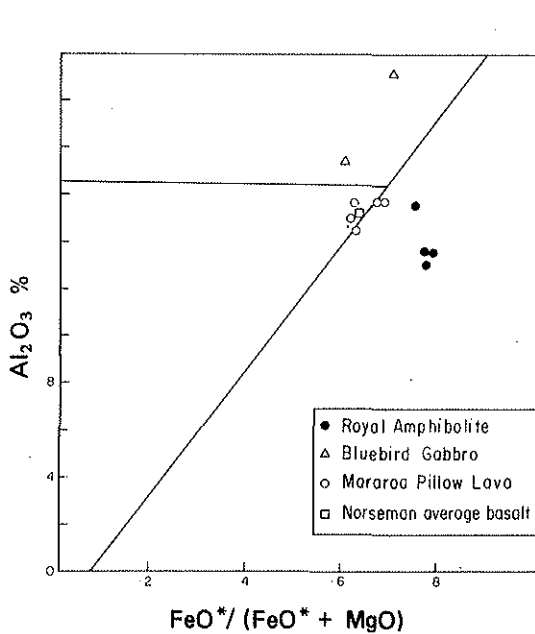


Figure 3 – Al_2O_3 vs. $FeO^*/(FeO^* + MgO)$. All analyses recalculated to 100%.

All analyses of the Royal Amphibolite are enriched in Fe and Ti relative to the pillow lavas and the Bluebird Gabbro. They plot along the MORB trend (Fig. 2) and fall within the Fe-rich tholeiite field on the Al_2O_3 vs. $FeO^*/(FeO^* + MgO)$ diagram (Fig. 3). Fractionated Fe-rich tholeiites are not common in the Eastern Goldfields sub-province but have been described by Naldrett and Turner (1977), Sun and Nesbitt (1978) and Nesbitt *et al.* (1979). Similar Fe-rich basalts occur as layered sills and thick flows

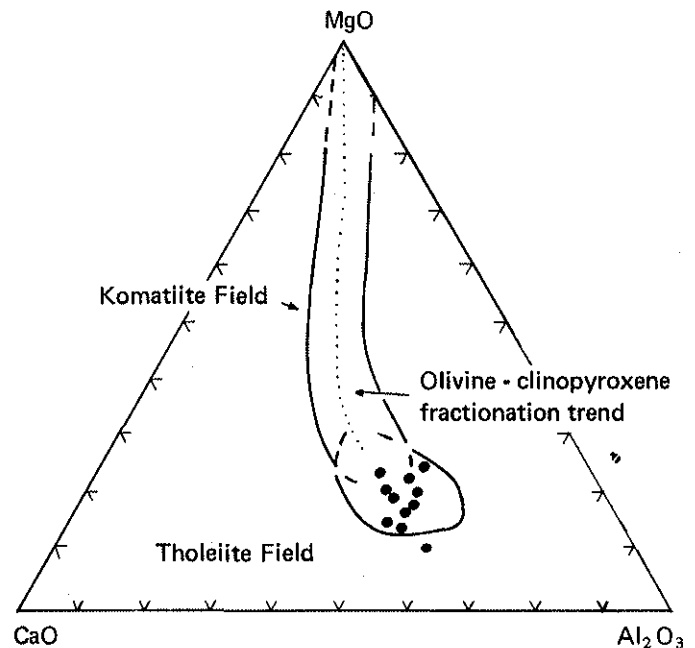


Figure 4 – $MgO-CaO-Al_2O_3$ plot of compositions of Woolyeenyer Group. Various fields from Groves and Gee (1980)

in the Abitibi greenstone belt, Canada (MacRae, 1969; Pearce and Birkett, 1974; Arndt *et al.*, 1977; Naldrett and Goodwin, 1977). Some of these authors suggest that these basalts represent primary liquids, whereas others consider they represent differentiates from tholeiites following the iron enrichment trend.

The Royal Amphibolite is extremely variable in grain size with no obvious primary structure, whereas the Crown Basalt comprises a number of clearly defined units. Discordant

intrusives petrologically similar to the Bluebird Gabbro and Crown Basalt are common in the Mararoa Pillow Lava and rarely extend into the Crown-Bluebird sequence (Hall and Bekker, 1965).

Intrusives Rhyolite porphyry dykes intrude all units of the Norseman succession and are abundant in the mining area. Glomeroporphyritic textures predominate, although non-porphyritic types are also present. The phenocrysts which comprise up to 20% of the rhyolite include embayed quartz, euhedral to subhedral albite or oligoclase, and less commonly microcline-perthite. Larking (1969) recognized sodic and potassic varieties, the latter containing microcline microphenocrysts in addition to the ubiquitous albite phenocrysts. The sodic porphyries occur as sheared lenses within the reef channels, whereas the age of the potassic varieties which occur throughout the district is not well established.

The youngest intrusive rocks are a series of east-west trending noritic and doleritic dykes which have Rb-Sr ages of about 2.4 Ga (Turek, 1966). The Jimberlana Dyke is the most important intrusive of this type as it extends for about 180 km and is up to 2.5 km wide. It is considered to be an analogue of the Great Dyke in Zimbabwe (Campbell *et al.*, 1970). Numerous fine-grained basic dykes transect the greenstones and the quartz reefs in the mining area and are probably related to the Jimberlana Dyke.

Structure The Mararoa and Crown Reefs which are current producers via the Regent Shaft lie on the western limb of a major regional anticline (Fig. 5). Archibald *et al.* (1978) have studied the structural evolution of the Widgiemooltha-Norseman area and identified four phases of folding. A more detailed structural analysis of the mining area is in progress (Keele, in prep.). The earliest phase of deformation (D_1) produced localized recumbent folds in the metasediments. A second phase of deformation (D_2) has folded the greenstones and clastic sequences about north-south axes producing a weak slaty cleavage. The peak of metamorphism was coincident with and continued beyond a third phase of coaxial folding (D_3). The strong metamorphic foliation related to this deformation is locally folded by a late deformation event (D_4).

Mesoscopic reef structures suggest that the veins formed prior to the D_3 event and the peak of metamorphism. A series of NNW-trending fault zones with strike separations of up to 2 km transect the fold structures and the reef channels. West-dipping normal faults have been recognized in the underground workings (Hall and Bekker, 1965). The youngest structures in the area are E-W trending tensional faults, frequently occupied by the Proterozoic dykes (Archibald *et al.*, 1978).

CROWN AND MARAROA REEFS The reefs occur as tabular bodies along the planes of east-dipping meridional reverse faults of D_2 age. Within a zone bounded by the Venture Slate and the Bluebird Gabbro, the faults are characterized by an alternation of steeper-dipping barren "shears" joined by flatter-dipping auriferous "links" (O'Driscoll, 1953). Above and below this zone, the dip of the faults is steeper and quartz veins are absent or only poorly developed.

There are two types of quartz which may occur together or occupy the entire reef channel. Laminated quartz is characterized by a planar structure which is parallel to the walls of the shear. Bands of white to grey quartz alternate with wallrock inclusions and fractures coated with biotite or sericite. The "bucky" quartz is massive and commonly transects the laminated quartz. Angular wallrock inclusions in the "bucky" quartz are consistent with its formation during an episode of hydraulic fracture. Gold and sulfides which include pyrrhotite, pyrite, arsenopyrite and galena are concentrated on fractures in the quartz, particularly the laminated type.

At certain localities, scheelite and calcite become major components of the reefs. Deposition of these minerals apparently accompanied carbonatization of an earlier tremolite-plagioclase-quartz assemblage. The tremolite is partially altered to calcite and clinocllore, whereas the plagioclase (An_{25}) is replaced by scheelite and sericite. Biotite flakes are isofacial with the chlorite and scheelite. This paragenesis reflects the introduction of CO_2 , K and W during a late stage hydrothermal event. Sericitic alteration is rarely seen overprinting metamorphic tremolite in the altered wallrocks. This suggests that the late hydrothermal event identified in the reef channel occurred during D_4 and may have had a significant effect upon gold distribution.

Wallrock alteration The quartz reefs are best developed in medium-grained gabbroic rocks, but also occur in fine-grained basalts. The various rock types have undergone a series of hydrothermal and metamorphic events which have

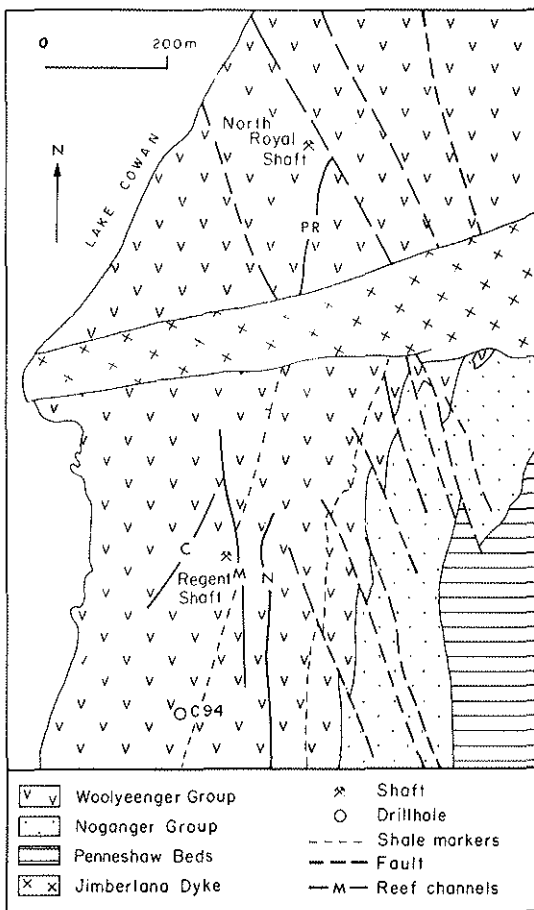


Figure 5 - Geology of the Norseman area (modified from Hall and Bekker, 1965) showing major quartz reefs; C = Crown, M = Mararoa, N = Norseman, PR = Princess Royal

modified the primary mineralogy to give distinctive wallrock assemblages. Fine and medium-grained mafic rocks remote from mineralization have a similar mineralogy, but they differ in texture as well as grain size. They consist of plagioclase (andesine or labradorite), blue-green amphibole, quartz and minor opaques. Pillow structures and amygdules are preserved in the lavas and some of the medium-grained units have chilled contacts. The typical lava contains elongate feldspar laths (0.1 to 1 mm) in a matrix of decussate amphibole (0.1 to 0.3 mm) with disseminated opaques. The medium-grained amphibolites have a subophitic to equigranular texture with the plagioclase laths (1-2 mm) partly enclosed by metamorphic amphibole (1-4 mm). The skeletal opaques are also distinctive.

Within the zone of wallrock alteration, the textures and mineralogy of the mafic rocks are conspicuously different and the following assemblages have been recognized.

HORNBLLENDE-ACTINOLITE ASSEMBLAGES The characteristic amphibole in the mafic units is a pale blue-green hornblende. This has a plate-like form in the medium-grained rocks and, in proximity to the reef, is partially replaced by aggregates of fibrous actinolite. The feldspar also shows patchy alteration, but retains its twinned, subidioblastic form and has an oligoclase to andesine composition (An_{30} to An_{40}). Alteration of the lavas is characterized by the development of fine actinolite needles. The plagioclase microlites are replaced by granular, interstitial, untwinned grains, but the ilmenite retains its characteristic fine, even distribution.

The absence of chlorite in these rocks suggests that the actinolite has not formed from pumpellyite-chlorite-quartz assemblages during the transition from very low to low grade metamorphism. There is empirical (Spooner and Fyfe, 1973) and experimental evidence that actinolite forms in hydrothermal systems at temperatures above 400 °C and pressures greater than 0.5 kb (Hajash, 1975; Mottl, 1976). The ubiquitous occurrence of actinolite in the altered wallrocks and its rarity in unaltered mafic units is consistent with a hydrothermal origin. The coexistence of this actinolite with metamorphic hornblende and plagioclase during the subsequent deformation (D_3) and metamorphism places an upper limit on this event of 550 °C at 2 kb or 575 °C at 5 kb P_{H_2O} (Liou *et al.*, 1974).

ACTINOLITE-BIOTITE ASSEMBLAGES With decreasing distance from the reef, the subophitic texture of the medium-grained amphibolites is modified by the development of actinolite-biotite assemblages. Biotite-rich samples are schistose, whereas the actinolitic samples have a crude foliation. Hornblende is absent and bands of blue-green subidioblastic actinolite (0.1-1 mm) are developed. The andesine laths are replaced by lenticular, granoblastic aggregates of untwinned plagioclase. Red-brown subidioblastic biotite (0.05-1 mm) is most abundant immediately above and below the reef channels. Chlorite is rarely observed with biotite in carbonate-rich specimens. The skeletal ilmenite is replaced by elongate lenses of fine, granular opaques and sphene, often intergrown with biotite.

In contrast, alteration of the fine-grained lavas is characterized by an increase in grain size and preservation of the fine, evenly distributed opaques. Subidioblastic actinolite (0.1-1 mm) porphyroblasts are set in a finer matrix of granoblastic plagioclase, quartz, biotite and opaques. The blue-green actinolite is strongly pleochroic and commonly

shows a preferred orientation, whereas red-brown biotite is evenly distributed throughout the matrix.

This style of alteration is gradational with the hornblende-actinolite assemblages previously discussed, but is mainly developed within 10 m of the reef channels. Biotite also coats laminations within the quartz reefs and is abundant in wallrock inclusions between laminated "reef splits". This suggests that biotitization of the mafic units accompanied deposition of the laminated quartz.

Some actinolite crystals apparently postdate the biotite fabric. It is probable these actinolite developed during metamorphism at the expense of phlogopite-calcite-quartz at around 500 °C for fluid pressures of 2-4 kb (Helgeson *et al.*, 1978). An upper temperature limit for the metamorphism is given by the stability of actinolite-calcite-quartz with respect to diopside. Account has not been taken of the replacement of Mg by Fe and the conditions of the relevant reaction are dependant on the mole fraction of CO_2 . Despite these limitations, the data for this reaction are in accord with the previous estimates. At 2 kb fluid pressure, they are 500 °C at $X_{CO_2} = 0.2$ or 540 °C at $X_{CO_2} = 0.5$ (Walther and Helgeson, 1980). The presence of sphene limits the mole fraction of CO_2 to ≤ 0.5 at 500 °C and 2 kb (Hunt and Kerrich, 1977).

To summarize the earlier discussion, the actinolite-biotite assemblages were formed simultaneously with the laminated quartz reef by hydrothermal alteration at PT conditions exceeding 400 °C and 0.5 kb. Minor textural and mineralogic changes during the subsequent deformation and metamorphism suggest an upper limit for this event of about 500 °C.

TREMOLITE-CHLORITE ASSEMBLAGES A second type of alteration is developed within the fault zones and is also associated with the Crown and Mararoa reefs. Biotite is absent and the rocks are composed of randomly orientated tremolite set in a matrix of aligned chlorite, with scattered quartz or calcite grains and minor opaques. The contact between the tremolite-chlorite rocks and the actinolite-biotite rocks is generally sheared and frequently biotitic.

Primary structures are not preserved in the tremolite-chlorite rocks and the texture is independent of the primary rock type. The absence of biotite in these rocks and its concentration along the sheared margins of tremolitic zones, together with the strong chlorite fabric and the predominance of sheared contacts with other rock types are taken to indicate that they formed by alteration of the actinolite-biotite assemblages. Overprinting of the chlorite fabric by decussate tremolite laths suggests that crystallization of tremolite postdates the chloritization event. The inclusion of chlorite-tremolite rocks within "bucky" but not laminated reef is consistent with chloritization of the wallrocks prior to, or simultaneously with emplacement of the "bucky" quartz reef.

Winkler (1976) noted that very low CO_2 concentrations are necessary to stabilize actinolite or tremolite relative to chlorite at low grades of metamorphism. Thus, chloritization of actinolitic wallrocks during a phase of hydrothermal fluid access could be subsequently followed by the crystallization of metamorphic tremolite. Bekker (1962) reported that chlorite-tremolite assemblages are developed in deuterically altered gabbro dykes from the Mararoa workings. This suggests that the formation of tremolite is dependant on the presence of chlorite prior to peak metamorphism. Thus, tremolitic assemblages are most commonly associated with

the reef channels, but also occur in rocks of suitable mineralogy and bulk chemistry.

The metamorphic conditions for the formation of the paragenesis tremolite \pm quartz \pm calcite have been calculated for a fluid pressure of 2 kb by Walther and Helgeson (1980). The upper limit for the coexistence of tremolite and calcite is dependant on mole fraction of CO₂ and ranges from 500 °C to 600 °C. The occurrence of chlorite with quartz and the non-occurrence of almandine garnet is pressure dependant in this temperature range. Winkler (1976) reported that almandine does not form at pressures less than 4 kb at 500 °C.

In summary, two distinct phases of wallrock alteration synchronous with deposition of laminated and the later "bucky" quartz have been identified. The first involved the formation of actinolite \pm biotite assemblages, whereas chloritic overprinting of these potassic assemblages characterizes the second phase of alteration. Both single and multistage alteration were subsequently modified by metamorphism and the consequent crystallization of actinolite or tremolite.

CHEMISTRY Larking (1969) investigated the major and trace element distribution of altered amphibolites bordering sodic porphyries in the Crown workings. However, before the present study, there were little geochemical data available for wallrock alteration associated with the auriferous reefs. Major and trace element data for the Regent Shaft suite are given in Table 4. Composition-volume diagrams (Gresens, 1967) have been constructed to illustrate the chemical changes which occurred during wallrock alteration. Volume factors have been estimated from the mean intersection of the relatively "immobile" elements, generally Al₂O₃, TiO₂

and Fe₂O₃ with the isochemical axis ($\Delta x = 0$). Selection of the parent-rock composition is important as there is considerable chemical variation among the mafic units of the Norseman succession (Table 2).

Wallrock alteration of the mafic rocks which border the Crown and Mararoa reefs involved the deposition of hydrothermal actinolite and biotite. Chloritic overprinting of these assemblages was related to an episode of hydraulic fracturing during which the "bucky" quartz was deposited. Single and multistage assemblages were subsequently modified by low grade metamorphism. It is difficult to evaluate the effects of this event on the major element distribution, but the metamorphic mineralogy is compatible with low fluid-rock ratios. The consistency of chemical changes inferred from the composition-volume diagrams suggests limited element mobility during metamorphic recrystallization of the hydrothermal assemblages.

Volume factors for the biotite-actinolite assemblages are close to unity for fine and medium-grained amphibolites. In general, this style of alteration is characterized by the addition of volatiles, K₂O and CaO; relatively constant Al₂O₃ and Fe₂O₃; and the loss of Na₂O (Fig. 6). TiO₂ is stable or augmented during potassic alteration, whereas the behaviour of MgO and SiO₂ is not consistent. These changes are compatible with the destruction of plagioclase and the formation of biotite, actinolite and calcite.

It is probable that the tremolite-chlorite assemblages were formed by chloritic overprinting of the biotite-actinolite assemblages. Composition-volume calculations for this transformation show losses of CaO, Al₂O₃ and Na₂O; relatively constant Fe₂O₃; and a gain in MgO (Fig. 7). These changes which reflect the breakdown of actinolite and plagioclase, and the deposition of chlorite are essentially the same when unaltered amphibolite is used as the parent

Table 4 - Analyses of Regent Shaft mafic suite

Sample	1/1	2	5	7	8/1	101/2	104	105	106	107/2	109/2	109/3	111/2	111/3	112/2	112/3
SiO ₂	48.01	60.05	49.54	22.95	49.76	47.98	54.13	48.50	44.58	38.89	50.63	42.84	36.76	47.75	48.68	46.94
TiO ₂	1.03	0.83	0.82	0.89	0.98	0.59	0.97	0.76	0.72	1.11	1.57	0.97	0.96	1.08	0.65	0.84
Al ₂ O ₃	14.26	11.38	14.06	14.24	15.44	11.61	14.92	14.23	12.81	15.02	12.95	6.74	16.24	14.75	16.15	15.58
Fe ₂ O ₃	13.30	6.20	12.41	13.61	11.67	12.64	10.81	13.01	12.18	13.90	16.06	16.21	12.44	13.14	10.96	12.43
MnO	0.34	0.16	0.23	0.30	0.19	0.17	0.22	0.19	0.20	0.25	0.22	0.22	0.16	0.20	0.17	0.18
MgO	5.95	2.80	7.74	8.08	7.56	14.01	4.40	7.77	7.82	7.81	5.19	17.80	8.14	7.16	7.70	8.38
CaO	10.36	15.36	12.47	20.72	11.27	7.62	9.29	10.36	12.52	12.78	8.99	10.18	12.95	10.10	10.34	9.78
Na ₂ O	2.64	0.07	1.39	1.11	2.37	0.87	4.16	2.56	0.96	1.69	1.21	0.73	1.79	1.91	2.89	1.06
K ₂ O	0.86	0.16	0.21	0.27	0.35	1.38	0.46	0.60	3.13	3.06	1.19	0.66	3.56	2.36	1.02	2.51
P ₂ O ₅	0.14	0.12	0.13	0.13	0.09	0.00	0.10	0.08	0.11	0.12	0.15	0.13	0.12	0.15	0.09	0.09
S	0.02	0.05	0.14	0.03	0.10	0.02	0.04	0.04	0.28	0.26	0.10	0.56	1.30	0.53	0.08	0.16
LOI	2.26	2.01	0.75	17.97	0.72	3.51	1.38	1.89	5.08	5.03	1.43	3.24	5.53	1.89	1.07	1.62
Total	99.17	99.19	99.89	100.30	100.50	100.40	100.88	99.99	100.39	99.92	99.69	100.28	99.95	101.02	99.80	99.48
Fe ² /ΣFe	0.87	0.48	0.82	0.92	0.84	0.78	0.83	0.83	0.81	0.83	0.83	0.77	0.75	0.96	0.85	0.88
Rb	60	0	1	8	3	45	1	2	82	99	32	1	113	69	29	81
Sr	95	93	76	106	119	25	131	118	45	134	107	37	43	75	79	72
Y	26	21	22	27	22	15	26	16	18	31	28	20	24	25	17	20
Nb	4	5	4	3	3	4	4	4	4	6	8	6	5	4	3	5
Zr	61	50	53	49	115	41	57	38	50	73	110	73	61	67	37	47
Ba	198	14	15	33	35	114	36	22	153	459	48	0	136	190	83	123
Ni	70	20	30	120	50	250	30	60	110	110	40	860	120	120	130	150
Cu	5	5	125	5	80	25	5	25	70	85	35	190	75	135	75	175
Co	45	40	35	45	30	40	25	30	45	40	65	75	40	40	65	35
Zn	90	0	30	140	40	50	20	40	60	100	70	50	50	60	40	60
As	8	26	2	8	2	2	2	2	4	6	16	20	2	8	70	2
V	350	220	300*	230	250	230	320	250	250	360	250	200	290	280	240	260

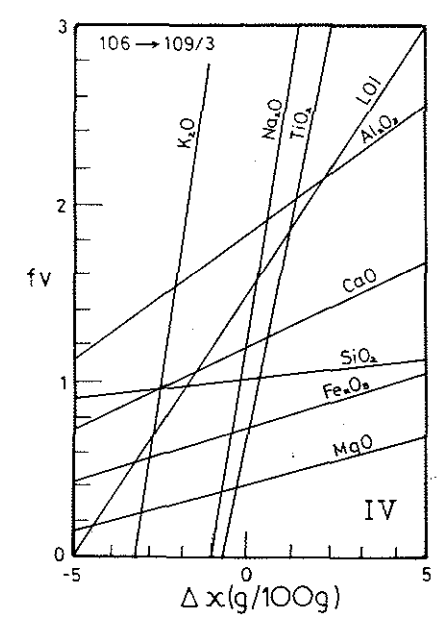
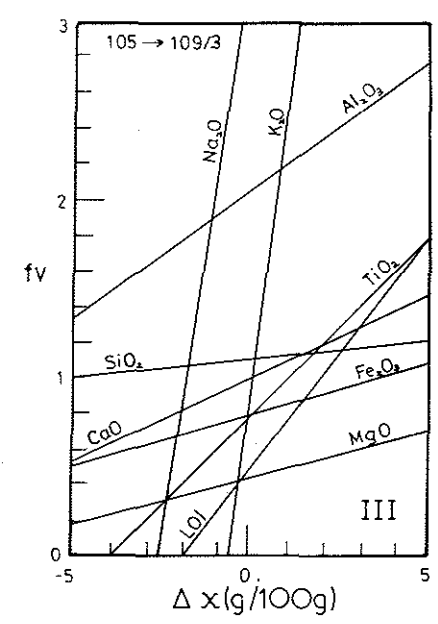
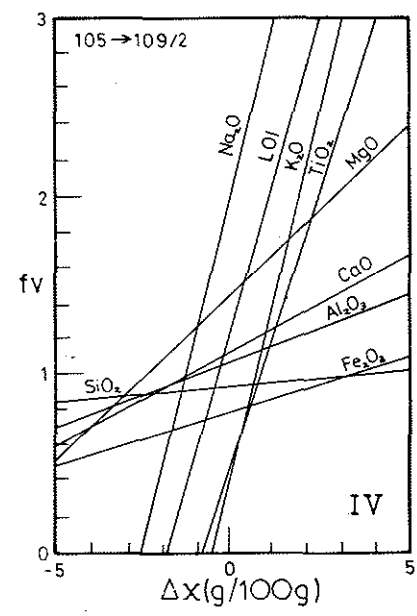
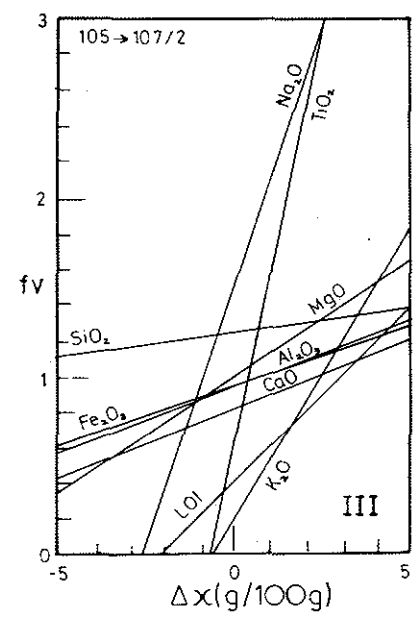
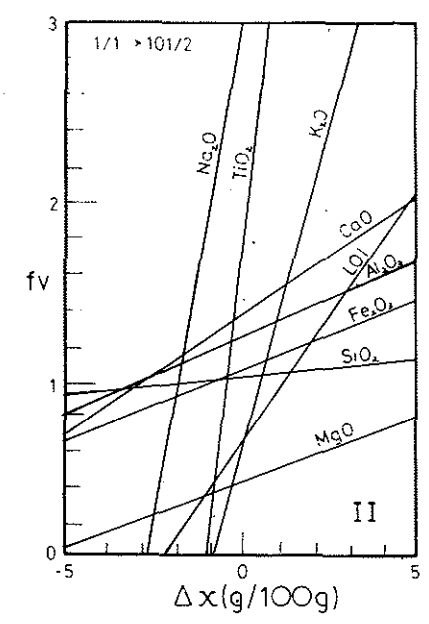
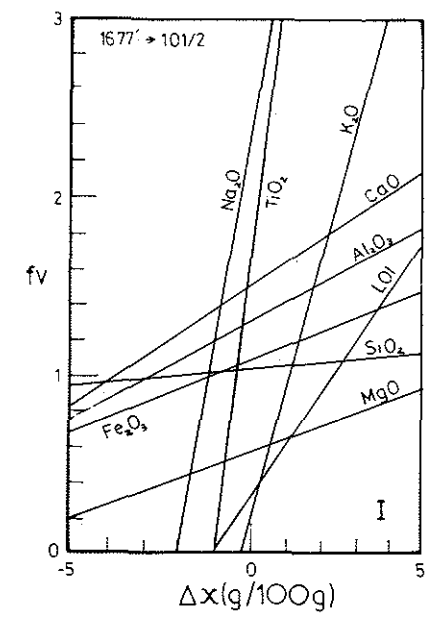
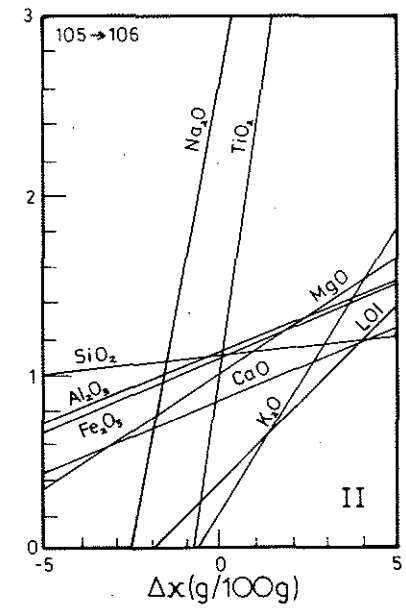
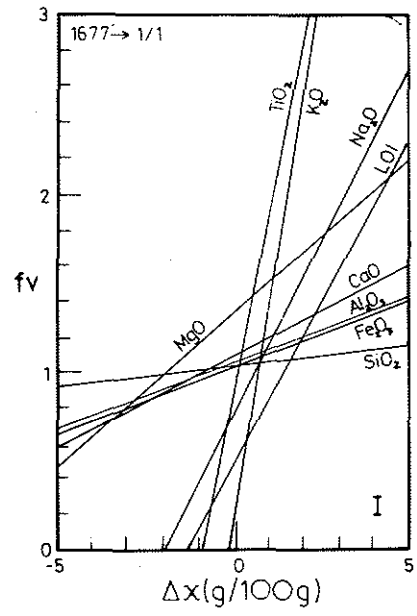


Figure 6 – Composition-volume diagrams for actinolite-biotite assemblages from the Regent Shaft showing trends: (I) fine-grained amphibolite and (II, III, IV) medium-grained amphibolite

Figure 7 – Composition-volume diagrams for tremolite-chlorite assemblages from the Regent Shaft, showing trends for unaltered and actinolite-biotite parent rock compositions, respectively; (I, II) fine-grained amphibolite and (III, IV) medium-grained amphibolite

composition (Fig. 7). However, the behaviour of K_2O , LOI , SiO_2 and TiO_2 reflect the abundance of biotite, quartz and opaques in the tremolite-chlorite assemblages and their assumed precursors. Volume changes during chloritic alteration were variable, with the fv value for Fe_2O_3 ranging from 1.07 to 0.73. This indicates the importance of hydrothermal leaching in the formation of tremolite-chlorite assemblages.

In general, trace element behaviour corresponds with the major element changes during wallrock alteration. The transition metals Ni, Cu and Co, together with S are enriched in the actinolite-biotite and tremolite-chlorite assemblages relative to the unaltered amphibolites. Composition-volume calculations indicate that Ti, Zr and Y (also V and Nb) behaved coherently during wallrock alteration (Table 5). TiO_2 was generally augmented during potassic alteration and was stable or depleted during chloritic alteration.

Ba and Rb are enriched in the potassic assemblages. Local mobility of Sr and Zn is evident and their depletion in the tremolite-chlorite assemblages reflects the destruction of plagioclase, actinolite and calcite. The behaviour of As is enigmatic, but there is little evidence for its introduction with the hydrothermal solutions.

Table 5 – Volume factors of Ti, Zr and Y calculated for the condition $\Delta x = 0$ (i. e. no compositional change) and the transformation from parent amphibolite to actinolite-biotite assemblage, then to tremolite-chlorite assemblage

Sample	Assemblage	fv(Ti)	fv(Zr)	fv(Y)
1677' → 1/1	Act-Biot	0.86	0.83	0.97
105 → 106	Act-Biot	1.06	0.76	0.89
105 → 107/2	Act-Biot	0.68	0.52	0.52
105 → 109/2	Act-Biot	0.47	0.34	0.56
1/1 → 101/2	Trem-Chlor	1.76	1.50	1.75
106 → 109/3	Trem-Chlor	0.72	0.66	0.87

STABLE ISOTOPES Stable isotopic values of whole-rocks, carbonates and vein quartzes are set out in Tables 6 and 7. Oxygen was extracted from whole-rocks and quartz separates by overnight reaction with BrF_5 at 650 °C in nickel vessels (Clayton and Mayeda, 1963). CO_2 was extracted from calcite by overnight reaction with H_3PO_4 in glass vessels at 25 °C (McCrea, 1950). Carbonate composition was confirmed by XRD and the acid fractionation factor was taken to be 1.01025 (Sharma and Clayton, 1965). $\delta^{18}O$ values are reported relative to SMOW in the usual δ notation and $\delta^{13}C$ values are relative to the PDB standard.

Oxygen Two distinct stages of quartz emplacement and wallrock alteration have been recognized for the Mararoa and Crown Reefs. Metamorphism and deformation have subsequently modified the wallrock assemblages. It is important to establish whether these events have produced reequilibration of the oxygen isotopes.

WHOLE ROCKS Mafic rocks remote from mineralization (DDH C94) have a mean $\delta^{18}O$ value of 7.0 ± 0.4 ‰ (eleven samples) which is similar to reported values for tholeiites from the Eastern Goldfields (Hoefs and Binns, 1978). Unaltered MORB has a restricted $\delta^{18}O$ range fo

Table 6 – Stable isotopic values of whole-rocks from the Regent Shaft suite

Sample	Description	$\delta^{18}O$ ‰ SMOW
1:1	Act-Biot assemblage	6.3
2	Trem assemblage	8.3
5	Hbe assemblage	6.2
7	Chlor-Act assemblage	8.7
8:1	Hbe-Act assemblage	9.1
101:2	Trem-Chlor assemblage	6.6
104	Hbe assemblage	7.2
105	Hbe-Act assemblage	6.9
106	Act-Biot assemblage	6.9
107:2	Act-biot assemblage	6.4
109:2	Act-Biot assemblage	7.6
109:3	Trem-Chlor assemblage	6.6
111:2	Act-Biot assemblage	5.8
111:3	Act-Biot assemblage	7.6
112:2	Act-Biot assemblage	7.6
112:3	Act-Biot assemblage	7.1
314/C94	Royal Amphibolite	7.4
512/C94	Royal Amphibolite	6.6
668/C94	Royal Amphibolite	6.8
740/C94	Royal Amphibolite	8.0
957/C94	Bluebird Gabbro	6.8
1034/C94	Bluebird Gabbro	6.6
1216/C94	Mararoa Pillow Lava	7.1
1505/C94	Mararoa Pillow Lava	7.0
1677/C94	Mararoa Pillow Lava	7.2
1788/C94	Mararoa Pillow Lava	6.8
1989/C94	Mararoa Pillow Lava	6.7

Table 7 – Stable isotopic values of minerals from the Regent Shaft suite

Sample	Description	$\delta^{18}O$ ‰ SMOW		$\delta^{13}C$ ‰
		QTZ	CAL	
1 2	Mararoa reef	11.7		
2	QTZ breccia	12.6		
3	QTZ veining	10.7		
4	QTZ veining	10.2	9.7	-4.9
6:1:1	B fault zone	11.3		
6:1:2	B fault zone	11.0		
6:1:3	B fault zone	12.1		
6:1:4	B fault zone	11.3		
6:1:5	B fault zone	11.1		
7	CAL veining		10.1	-6.5
9	Crown HW reef	11.6		
10:1	Crown HW reef – Omm*	11.5		
10:2	Crown HW reef – 300mm	11.6		
10:3	Crown HW reef – 500mm	11.4		
10:4	Crown HW reef – 900mm	11.2		
10:5	Crown HW reef – 1600mm	11.6		
11:1	Crown HW reef	10.4		
47:1	Crown reef – 200mm	12.2		
47:2	Crown reef – 600mm	11.7		
47:3	Crown reef – 800mm	12.4		
48:1	Crown reef – 150mm	12.0		
48:2	Crown reef – 600mm	11.8		
48:3	Crown reef – 850mm	12.4		
49:1	Crown reef – 300mm	12.4		
49:2	Crown reef – 600mm	11.5		
49:3	Crown reef – 900mm	12.2		
102:1	Mararoa reef	12.4		
102:2	Mararoa reef	11.3		
103	Mararoa reef	11.8		
108	Crown reef	10.6	10.5	-6.2
109:1	Crown reef	11.2		
110	Crown reef	11.3		
111:1	Crown HW reef	11.7		
112:1	Crown FW reef	11.3		
113:1	Crown FW reef	11.1		
113:2	Crown FW reef	11.1		
114:1	North Crown reef	11.5		
114:2	North Crown reef	10.8		

*Omm is vertical distance of sample from upper contact of reef

5.7 ± 0.2 ‰, whereas weathered submarine basalts are enriched in ^{18}O (Muehlenbachs and Clayton, 1972 and 1976; Pineau *et al.*, 1976; Spooner *et al.*, 1977; Muehlenbachs, 1977). In general, the water content of basalts altered by reaction with seawater at low temperatures is proportional to the degree of ^{18}O enrichment (Muehlenbachs and Clayton, 1976). Average deep sea basalts contain $0.30\% \text{H}_2\text{O}^*$ (Moore and Schilling, 1973), whereas the volatile content of the Norseman greenstone ranges from 0.82 to 2.73%. The excellent preservation of chemical and textural diversity in the mafic rocks of the Norseman area suggests that metamorphism has been largely isochemical (Hallberg, 1972; Binns *et al.*, 1976). It is probable, therefore, that the ^{18}O enrichment of the greenstones with respect to their igneous precursors is due to seafloor alteration.

The oxygen isotopic values of the Regent mafic suite range from 5.8 to 9.1 ‰ with a mean value of 7.2 ± 0.9 ‰ (sixteen samples). The three samples with high values are atypical; one is interpillow material and the others were collected in the vicinity of an east-west calcite vein of dubious affinity. If they are excluded, the mean $\delta^{18}\text{O}$ value is 6.8 ± 0.6 ‰ (thirteen samples). In either case, the mean value is not significantly different to the mean of mafic rocks remote from mineralization.

The stability of hydrothermal actinolite is consistent with a mineralization temperature ≥ 400 °C, whereas the silicate assemblages imply a peak metamorphic temperature around 500 °C. The alteration mineralogy is dominated by amphibole, biotite, chlorite and quartz. Accurate fractionation factors for amphibole and chlorite are not available, but these minerals are depleted in ^{18}O relative to water in the temperature range 400 °C-500 °C (Taylor, 1968; Wenner and Taylor, 1971; Bottinga and Javoy, 1973). Biotite is also depleted in ^{18}O with respect to water at 400 °C (-3.07 ‰; Hoernes, 1980), whereas quartz is enriched in ^{18}O (4.56 ‰; Clayton *et al.*, 1972). Therefore, the constant oxygen isotopic values of the altered wallrocks can be explained if:

- 1) The hydrothermal fluid had a $\delta^{18}\text{O}$ value similar to the unaltered mafic rocks (~ 7 ‰).
- 2) The low $\delta^{18}\text{O}$ of the ferromagnesium minerals was balanced by the high $\delta^{18}\text{O}$ of quartz, plagioclase and calcite.

The observation that the highest $\delta^{18}\text{O}$ whole-rock values are for samples with abundant quartz or carbonate is in accord with this model.

It is possible that the isotopic similarities between the altered wallrocks and the mafic country rocks are the product of isotopic homogenization during the subsequent metamorphism. However, several studies suggest that quartz and biotite but not amphibole are resistant to isotopic exchange at moderate grades of metamorphism (Hoernes and Friedrichsen, 1978; Hoernes and Hoffer, 1979; Ripley and Ohmoto, 1979). Therefore, the whole-rock data cannot be interpreted unambiguously, although the mineral data are in good agreement with the proposed model.

VEIN MINERALS $\delta^{18}\text{O}$ values of vein quartzes from the Mararoa and Crown reefs are similar with mean values of 11.8 ± 0.5 ‰ (four samples) and 11.5 ± 0.5 ‰ (25 samples), respectively. Three scheelite-bearing quartzes included in the latter average have distinctive light oxygen values (10.6 ± 0.2 ‰). The B fault zone is an enigmatic

structure of comparable age to the auriferous reefs. Quartzes from this zone are isotopically indistinguishable from the reef quartzes and have a mean value of 11.3 ± 0.4 ‰ (5 samples).

Two generations of quartz are commonly present in the Mararoa and Crown reefs; a central "bucky" type and marginal laminated type. There are small but consistent differences in the $\delta^{18}\text{O}$ values of the quartzes sampled in detail on the 16 level. Five samples of the central portion of the Crown reef have a mean $\delta^{18}\text{O}$ value of 11.5 ± 0.2 ‰, whereas nine samples of the footwall and hangingwall zones have a mean $\delta^{18}\text{O}$ value of 12.0 ± 0.4 ‰. Thus, there is a progressive decrease in the oxygen isotopic values of quartzes from the laminated reef, "bucky" reef, B fault zone and scheelite-bearing reef, respectively. This sequence is in accord with the observed timing relations and may be caused by a change in the isotopic character of the fluid phase. However, a slightly higher temperature of emplacement for the "bucky" and B fault zone quartzes would be sufficient to account for their ^{18}O depletion with respect to the laminated quartz.

The petrography of the scheelite-rich reefs shows that the introduction of a W-bearing phase occurred after the peak of metamorphism. The extent of oxygen isotopic exchange between this hydrothermal fluid and the host quartz is not clear. Kerrich and Fryer (1979) reported that scheelite-quartz veins in the Dome Mine, Canada had lighter $\delta^{18}\text{O}$ quartz values than the main auriferous veins. They concluded that these veins were formed at a higher temperature than the main veins from a reservoir with a similar oxygen isotopic value.

The Crown and Mararoa reefs exhibit a narrow range of $\delta^{18}\text{O}$ values if the scheelite-bearing quartzes are excluded (11.7 ± 0.4 ‰, 26 samples). The temperature of quartz emplacement is not well established, but the wallrock assemblages are compatible with temperatures ≥ 400 °C. The $\delta^{18}\text{O}$ value of water in equilibrium with the reef quartz is 7 to 8 ‰ at these temperatures (Clayton *et al.*, 1972). This calculated $\delta^{18}\text{O}$ value is consistent with fluids of magmatic, metamorphic or connate origin (Taylor, 1979). Only epithermal gold-base metal deposits and volcanogenic massive sulphide deposits which were formed from circulating meteoric water and seawater, respectively, are isotopically distinct.

Three calcite samples of diverse origin have $\delta^{18}\text{O}$ values from 9.7 to 10.5 ‰ which suggests they have exchanged oxygen isotopes with the metamorphic fluid reservoir. The calculated $\delta^{18}\text{O}$ value of the fluid in equilibrium with the calcites at 400 °C-500 °C is 8 ± 2 ‰ (O'Neil *et al.*, 1969). Thus, waters involved in ore deposition and the subsequent metamorphism have identical $\delta^{18}\text{O}$ values which imply they have a common source, connate fluids and OH-bearing minerals in the volcanic rocks. Isotopic data for the Princess Royal reef support this proposal (Golding, 1982).

Carbon Calcites from the Regent Shaft suite have light $\delta^{18}\text{C}$ values from -4.9 to -6.5 ‰. Addy (1973) demonstrated that calcites in the ore zone of the Ducktown copper-zinc deposits had identical $\delta^{13}\text{C}$ values to the country rocks. He proposed that there had been carbon isotopic reequilibration during regional metamorphism of the syngenetic ores. However, the mineralogy of metabasalts remote from mineralization at Norseman is not compatible with significant CO_2 dilution of the metamorphic fluid. It is possible, therefore, that the calcites have retained their primary

$\delta^{13}\text{C}$ values although there is some evidence for reequilibration of their oxygen isotopes. The dubious affinities of the samples preclude further discussion. However, carbon isotopic data for the Princess Royal reef are consistent with $\delta^{13}\text{C}_{\Sigma\text{c}}$ near 0‰ which suggests that this CO_2 was derived by the dissolution of carbonates within the pile (Golding, 1982).

CONCLUSIONS The observed timing relations and isotope systematics strongly suggest that the ore fluids were connate brines mobilized during the D_2 event and channelled up through the reverse faults. Intrusion of the porphyries clearly predated deposition of the "bucky" quartz. Archibald *et al.* (1978) concluded that synkinematic emplacement of the granitoids began during D_2 and possibly initiated the change from a tensional to compressional environment. Fluids may have been released from the volcanics and sediments in the vicinity of these intrusions, and it is not possible to discount a magmatic component in the ore fluids.

The BIF which underlies the greenstone sequence throughout the mining area hosts significant stratiform gold and could have been the source of the ore components. However, Naldrett *et al.* (1978) have demonstrated that there is a positive correlation between the S and total Fe content of basalts. They also report that Archean basalts retain much of this sulfur, because of less extensive seafloor alteration than experienced by modern ocean floor basalts. Recent studies have shown that gold is incorporated in sulfides in basic rocks and is liberated readily by hydrothermal leaching (Keays and Scott, 1976; Mironov *et al.*, 1978). Thus, iron-rich basalts within the pile constitute an additional source of precious and other metals.

The inferred hydrothermal sulfide assemblages indicate fluids of low redox potential at elevated temperatures (400 °C). It has been suggested that relatively "immobile" elements such as Ti, Ni and W may be soluble in such fluids (Kerrick, 1980; Hutchinson *et al.*, 1980). The metal content of convective brines reflects the chemistry of the fluid and the source rocks, the water-rock ratio and the

PT regime (Casadevall and Ohmoto, 1977; Hutchinson *et al.*, 1980; Mottl and Seyfried, 1980). It is interesting that those elements which are anomalous in all the wallrocks, namely Ni, Cu and Co are also most abundant in mafic and ultramafic rocks (Turekian and Wedepohl, 1961).

It is difficult to evaluate the importance of the later deformation events (D_3 and D_4). The concentration of gold in laminated quartz is compatible with the early introduction of gold, but could also reflect continued fluid access during metamorphism. The morphology of the ore-shoots is apparently controlled by the intersection of F_3 axial planes with the reverse faults. It may be coincident that peak metamorphic conditions in the Regent and Princess Royal areas fall on the boundary between low and medium grade metamorphism. However, large fluid volumes are released from hydrated and carbonated mafic rocks over this PT interval (Fyfe *et al.*, 1978). Rye and Rye (1974) have shown that the Homestake gold ores are restricted to a transition zone across the garnet isograd. They suggest the orebodies were formed by the metamorphic concentration of syngenetic gold. There is considerable evidence that the Norseman reefs are epigenetic and that gold was introduced during the initial hydrothermal event. The structural and petrographic data do suggest that the metamorphism and late deformation events were responsible for local redistribution of the gold.

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