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The nature and dimensions of regional and local gold-related hydrothermal alteration in tholeiitic metabasalts in the Norseman goldfields: the missing link in a crustal continuum of gold deposits?

T.C. McCuaig[1], **R. Kerrich**[1], **D.I. Groves**[2], **and N. Archer**[3]

[1] Department of Geological Sciences, The University of Saskatchewan, Saskatoon, Canada, S7N 0W0
[2] Key Centre for Strategic Mineral Deposits, The University of Western Australia, Nedlands, Australia 6009
[3] Central Norseman Gold Corporation Ltd., P.O. Box 56, Norseman, Australia, 6443

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Abstract. The Archaean lode-gold deposits at Norseman, Western Australia, consist of auriferous quartz veins in dextral-reverse ductile-brittle shear zones within tholeiitic metabasalts of upper-greenschist to amphibolite facies metamorphic grade. Three types of deposits (Northern, Central, Southern) are delineated on the basis of their spatial distribution, veining style, alteration mineralogy and metamorphic grade of host rocks. Northern deposits, hosted in upper-greenschist to lower-amphibolite facies rocks, comprise massive to laminated quartz veins with selvedges of quartz-chlorite-calcite-biotite-plagioclase assemblages. Central deposits, hosted in lower-amphibolite facies rocks, consist of laminated to massive quartz veins with selvedges of quartz-actinolite-biotite-plagioclase-calcite assemblages. Southern deposits, hosted in middle-amphibolite facies metabasalts, consist of banded quartz-diopside-calcite-microcline-zoisite veins. All deposits exhibit variable ductile deformation of veins and contiguous alteration haloes, consistent with a syn-deformational genesis at high temperatures. From Northern to Southern deposits, the alteration assemblages are indicative of higher temperatures of formation, and there are progressively greater degrees of dynamically recovered textures in alteration and gangue minerals. These observations imply that a thermal variation of gold-related hydrothermal alteration exists within the Norseman Terrane over a distance of 40 km, with $T_{Northern} < T_{Central} < T_{Southern}$. This thermal zonation is corroborated by T–X_{CO_2} phase relations between vein selvedge assemblages, which signify formation temperatures of approximately 420°–475°C, 470°–495°C and > 500°C for Northern, Central and Southern deposits, respectively. The sum of structural, petrographic and mineral chemistry data indicates that the alteration assemblages formed in high-temperature, open hydrothermal systems and have not been subsequently metamorphosed. The thermal differences between the deposit groups may reflect (1) a temperature gradient, at relatively constant P, corresponding to the proximity of the deposits to regional granitoid complexes, or (2) formation of the deposits at progressively deeper crustal levels from north to south. In either case the deposits represent a continuum of gold deposition from upper-greenschist to amphibolite facies, now exposed in an oblique section through the Archaean crust at Norseman.

The genesis of Archaean "mesothermal" lode-gold deposits has been the subject of extensive research and debate, particularly within the past decade. Detailed studies of the large deposits hosted in low- to upper-greenschist facies terranes, such as those at Kalgoorlie (Golding 1982), Kambalda (Phillips and Groves 1984, Clark et al. 1989), Hollinger-McIntyre (Spooner et al. 1987) and Kerr-Addison (Kishida and Kerrich 1987), have characterised these systems in terms of alteration systematics in various lithologies, ore mineralogy, fluid chemistry, metal budgets, and P–T–X_{CO_2} conditions of alteration and mineralisation. These results have led to the formulation of several genetic models, the most current of which involve: (1) devolatilisation of host greenstones or subcreted/subducted material during regional dynamothermal metamorphism, with mineralisation after the metamorphic peak during subsequent uplift of the terranes (Groves and Phillips 1987, Wyman and Kerrich 1988), (2) magmatic fluids expelled during the ascent or crystallisation of regional granitoid batholiths (Burrows and Spooner 1989), (3) some combination of these models (Colvine et al. 1988 and references therein), and (4) deep convection of meteoric waters (Nesbitt et al. 1986).

Significant deposits exist in higher-grade metamorphic terranes such as the Kolar Schist Belt, India (Hamilton and Hodgson 1986) and Red Lake, Ontario, Canada (Andrews et al. 1986), but until recently these have been understudied. The past few years has witnessed a resurgence of interest in these deposits, and detailed documentation of high-temperature deposits has been undertaken in numerous Archaean terranes including the Murchison Province (Phillips 1985) and Southern Cross Province (Barnicoat et al. 1991, Mueller 1991), Western Australia, and the Kolar Schist Belt (Hamilton and Hodgson 1986): see Table 1 for a summary. Models proposed for the genesis of deposits in higher metamorphic-grade terranes

Table 1. Characteristics of some high-temperature lode gold deposits hosted by amphibolite facies rocks, with comparisons to giant greenschist facies counterparts in Western Australia and Ontario, Canada

High-temperature lode gold deposits (amphibolite-granulite facies)

Deposit/location	Host rocks	Metamorphism (P, T)	Hydrothermal alteration [a), b), ... denote host rock]	Hydrothermal alteration P, T	Hydrothermal alteration XCO_2	Timing	Sources
Western Australia							
Norseman Terrane						Mineralisation spans g-schist/amphibolite transition	
Northern deposits	a) Tholeiitic basalts b) High-Mg tholeiites	2–4 kb, 475–500 C	a) q, cc, chl, bi, pl(An31–43), sch, tourm	3 kb, 420–475 C	> 0.09 (projected)	Post-peak metamorphism, syn to late-deformation	Golding, 1982; this study
Central deposits	a) Tholeiitic basalts b) High-Mg tholeiites	2–4 kb, 450–575 C	a) q, cc, act, bi, pl(An40–65), sch, tourm	3 kb, 470–500 C	> 0.09 (projected)	Syn- to post-peak metamorphism, syn- to late-deformation	Mueller, 1992; this study
Southern deposits	a) Tholeiitic basalts	2–4 kb, 560–670 C	a) q, cc, di, zo, ksp, act, sch, ga (inner) bi, hb, pl(An50) (outer)	3–5 kb, > 500 C	> 0.08 (projected)	Syn-peak metamorphism, syn-deformation Ore cut by pegmatites	This study
Southern Cross Province Marvel Loch	a) Komatities b) Gabbro	3 kb, 550–630 C	a) ol, cc, q, di, amph, phl, sch (inner) b) q, di, ga, Ca-amph, pl(> An20), cc, sch	3–5 kb, 500–640 C		Post-peak metamorphism, syn-deformation Ore cut by pegmatites	Ho et al. (1990) Mueller (1988, 1991)
Fraser's	a) Mafic rocks b) Ultramafic rocks	3 kb, 520–670 C	a) q, di, cc, Ca-amph (inner) bi, crd, cumm, pl(outer)	3–5 kb, 520–590 C	0.06–0.47	Syn-peak metamorphism, sun-deformation. Ore cut by pegmatites	Ho et al. (1990) Barnicoat et al. (1991)
Nevoria	a) BIF b) Amphibolite	3 kb, 570–610 C	a) q, di, ga, cc, act, sch b) q, di, ga, cc. act-hb, pl, sch	3–5 kb, 550–580 C	0.06–0.47	Post-peak metamorphism, sun-deformation Ore cut by pegmatites	Ho et al. (1990) Mueller (1988)
Griffins Find	a) Paragneiss b) Mafic orthogneiss	5–7 kb, 700–750 C	a) q, di, ga b) ksp, cpx, tit, q	6 kb, 700 C	> 0.08	Syn-peak metamorphism, late?-deformation	Ho et al. (1990) Barnicoat et al. (1991)
Canada							
Superior Province							
Red Lake, Uchi Belt	a) Mafic rocks b) Intermediate stocks	low P, low-moderate T	a) q, Fe-dol, ser, chl, cc, tourm (greenschist) a) q, bi, ga (greenschist-amphibolite) a) q, bi, mu, ga, and, sta, crd, chltd, anth, tourm, cc (amphibolite)			Metamorphism, batholiths, shear zones all coeval with mineralisation. Mineralisation spans g-schist/amphibolite transition	Andrews et al. (1986)
Musselwhite, Sachiago Subprovince	a) Oxide facies BIF b) Basalts c) Pelite	low P, moderate T	veins = q, ab, ga, grun, cc, tourm a) q, mt, grun, bi, hb, ga	3 kb, 530–550 C		Syn-peak metamorphism. Felsic and lamprophyre dykes cut ore.	Hall and Rigg (1986)
Detour, Abitibi Belt	a) Mafic rocks b) Ultramafic rocks c) Felsic porphyries	low P, low-moderate T	veins = q, ksp, pl, cb, act a) q, pl, ksp, bi-phl, ep, ser, chl, (wallrock)			Post-peak metamorphism	Marmont (1986)
Slave Province							
Lupin, Yellowknife, Subprovince	a) BIF b) Turbidites	low P, low-moderate T	a) q, hb (greenschist-amphibolite) a) q, hb, ap, hed, sch, ep, ga, tit (amphibolite)				Lhotka and Nesbitt (1988)
Brazil							
Crixas, Sao Fransisco Craton	a) Amphibolite b) Pelite	low P–T	a) Fe-dol, bi, mu, q, chl, ilm, rut, pl(An15–40) b) q, chl, ser, ga, ep, chltd	3 kb, 440–480 C	0.15–0.26	Post-peak metamorphism	Thompson (1986, 1991)
India							
Kolar Schist Belt, Dhawar Craton	a) Tholeiites b) Komatiites c) IF d) Quartzites	low P, 470–540 C	a) qi, di, cc, sch, tourm (inner) hb, bi, q (outer)	435 C (veins) 470–540 C (sulphide lodes)		Pre-peak metamorphism; syn-deformation. Ore cut by pegmatites	Hamilton and Hodgson (1986) S-Siddaiah and Rajamani (1989)

South Dakota, USA							
Homestake, Black Hills Uplift	carbonate facies BIF	3.5–4.9 kb, 370–630 C	chl, sid, q, ank, mu, ab (greenschist) chl, grun, q, bi (greenschist-amphibolite) grun, q, chl, bi, ga (amphibolite)			Post-peak metamorphism, syn-deformation Mineralisation spans g-schist/amphibolite transition	Caddey et al. (1991)
Giant low-temperature lode gold deposits (greenschist facies)							
Yilgarn Block, Western Australia							
Golden Mile, Kalgoorlie	a) Mafic rocks b) Black shale	low P, 350–400 C	mu, q, sid (ank/dol), ab (inner) chl, cc, ank, ab, q, (outer)	250–230 C	0.2	Post-peak metamorphism, syn-deformaton	Ho et al. (1990)
Victory-Definance, Kambalda	a) Tholeiitic basalts b) High-Mg tholeiites c) Ultramafic rocks d) pelites	low P, 450–570 C	a, b) ab, dol, ank, ser (inner) bi, chl, dol, ank, q, ab, cc, ilm, rut (outer) d) ab, bi, act, dol, ank, mu, chl	1.7–2 kb, 340–430 C	0.1–0.2	Post-peak metamorphism, late?-deformation	Clark et al. (1986, 1989)
Superior Province, Ontario							
Kerr-Addison, Kirkland Lake	a) Ultramafic rocks b) Mafic rocks	low P–T	ank, Fe-dol, ab. mu (inner) chl, ank/dol, ab, talc (outer)	270–300 C		Post-peak metamorphism, syn-deformation	Kishida and Kerrich (1987)

Abbreviations used: q = quartz; cc = calcite; ank = ankerite; dol = dolomite; sid = siderite; pl = plag; An = anorthite; ab = albite; ksp = microcline; bi = biotite; phl = phlogopite; amph = amphibole; act = actinolite; act-hb = actinolitic hornblende; hb = hornblende; cumm = cummingtonite; anth = anthophyllite; grun = grunerite; cpx = clinopyroxene; di = diopside; hed = hedenbergite; zo = zoisite; ep = epidote; mu = muscovite; ser = sericite; sta = staurolite; chltd = chloritoid; crd = cordierite; ol = olivine; ga = garnet; chl = chlorite; sch = scheelite; tourm = tourmaline; mt = magnetite; ilm = ilmenite; rut = rutile; tit = titanite

variously include: (1) prograde metamorphism of typical greenschist-facies-hosted deposits (Phillips 1985, Hamilton and Hodgson 1986), (2) synmetamorphic mineralisation at similar P–T conditions to those suggested by the alteration mineral assemblages, i.e. amphibolite or granulite facies (Andrews et al. 1986, Barnicoat et al. 1991), or (3) formation as skarns from metasomatic fluids, possibly expelled during the crystallisation of regional ganitoids (Mueller 1991, Mueller et al. 1991).

Recently, data from these studies of high-temperature deposits have been considered in conjunction with observations from deposits hosted in lower-grade terranes. Groves (1993 this volume) points out that the P–T–t and radiogenic isotope data from the higher metamorphic-grade Archaean deposits in Western Australia are incommensurate with genetic models that involve devolatilisation of host greenstones alone (e.g. Groves and Phillips 1987). Furthermore, Groves (1993 this volume) argues that petrogenetic studies, thermodynamic modelling and timing relationships from these deposits point to a genetic continuum of gold mineralisation, with deposits forming at conditions that range broadly from sub-greenschist to granulite facies, potentially representing a crustal depth range from < 5 km to about 20 km, or a "crustal continuum" of gold deposition.

The deposits of the Norseman region, Western Australia, are hosted in a sequence of metabasalts that range in metamorphic grade from upper-greenschist to mid-amphibolite facies. It follows that this goldfield is well-suited to test the crustal continuum model. The aims of this paper are to: (1) document the dimensions and nature of gold mineralisation and related hydrothermal alteration in the Norseman deposits, (2) establish the pre-, syn- or post-peak metamorphic timing of alteration and mineralisation, and (3) draw comparisons to other deposits hosted in upper-greenschist to amphibolite facies terranes, in order to evaluate the crustal continuum model for gold deposition. Previous studies of the Norseman deposits have assumed a pre-peak metamorphism timing for quartz vein deposition (Golding 1982, Golding et al. 1990). This question of relative timing is vital: if the deposits have been metamorphosed, a crustal continuum model is unconstrained, whereas syn- to post-peak metamorphic mineralisation would support such a model.

Geology of the Norseman Terrane

The Norseman Terrane comprises the southernmost portion of the Archaean Norseman-Wiluna greenstone belt in the Yilgarn Block of Western Australia (Fig. 1, Groves 1993 this volume Fig. 1). The terrane is bounded by the Buldania Granitoid Complex (hornblende granodiorite) to the southeast and the Western Granitoid Complex (biotite monzogranite) to the southwest, and by major regional shear zones to the northwest (Mission Shear Zone) and northeast (Zuleika Shear Zone). The Mission and Zuleika Shear Zones separate the Norseman Terrane from the Kalgoorlie Terrane (Swager et al. 1990).

All Archaean rock types in the Norseman Terrane have been variably metamorphosed to greenschist through amphibolite facies; therefore, the prefix meta is implicit in all descriptions below. The strata, as established by Doepel (1973), consist of two distinct greenstone sequences. The Penneshaw Formation, on the eastern edge of the greenstone belt, comprises a sequence of intensely tectonised and metamorphosed basalts, with subordinate sedimentary and felsic

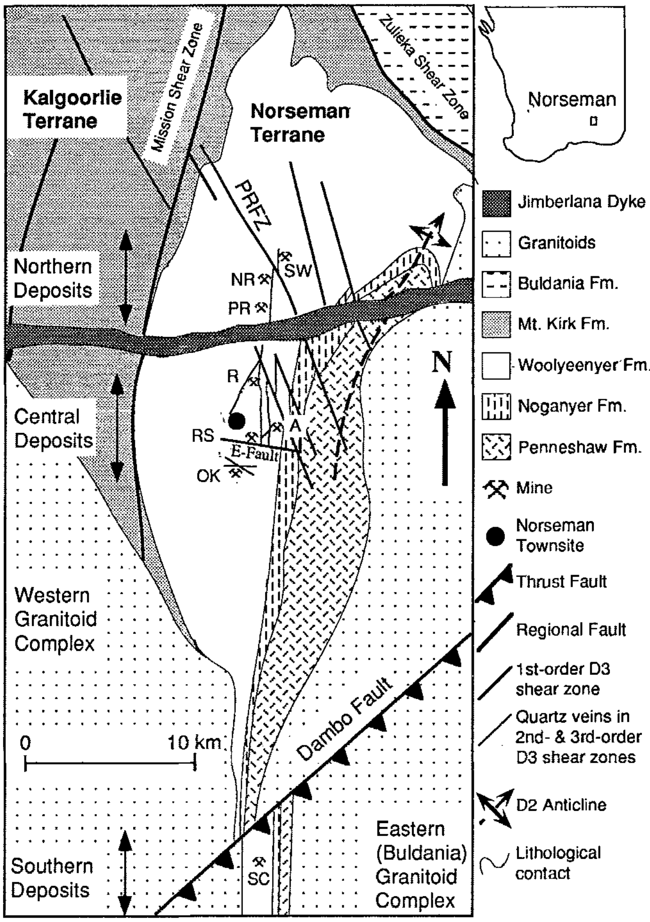


Fig. 1. Geology of the Norseman Terrane, Western Australia. Adapted from Johnson (1988) and Swager et al. (1990). 1st order structures = NNW-striking faults; 2nd order structures = N-striking quartz veins and host shear zones; third-order structures = NE-striking veins. *PRFZ* = Princess Royal Fault Zone. Deposits: *SW* = Surface Winze; *NR* = North Royal; *PR* = Princess Royal; *R* = Regent; *A* = Ajax; *RS* = Royal Standard; *OK* = Okay; *SC* = Scotia

volcanic rocks. A felsic unit in an upper member of the formation has been dated at 2938 ± 10 Ma ($U–Pb_{Zircon}$, Hill et al. 1992). To the west, the Penneshaw Formation is overlain by a stratigraphic sequence comprising the Noganyer and Woolyeenyer Formations. The Noganyer Formation directly overlies the Penneshaw, and consists of sedimentary rocks with distinct interbedded silicate-facies iron formations that serve as regional stratigraphic markers. The Noganyer Formation is in turn conformably overlain by the Woolyeenyer Formation, an 8000 m thick sequence of tholeiitic basalts that has been intruded by gabbroic dykes and sills, one of which has been dated at 2714 ± 5 Ma ($U–Pb_{baddeleyite}$, Hill et al. 1992), and a suite of high-MgO tholeiitic dykes. The Mt Kirk Formation, on the westernmost flank of the greenstone belt, is considered part of the Coolgardie Domain of the Kalgoorlie Terrane (Swager et al. 1990), and comprises a sequence of felsic volcanic, volcaniclastic and sedimentary rocks, intruded by two large layered mafic sills. An $U–Pb_{Zircon}$ date from a volcaniclastic unit near the base of this formation yields an age of 2688 ± 8 Ma (Hill et al. 1992).

Felsic intrusive rocks in the region comprise (1) the large granitoid complexes that bound the greenstones to the southeast and southwest, (2) small granitoid bodies that intrude the greenstone sequence, and (3) three suites of fine-grained intermediate to felsic dykes that intrude the Woolyeenyer Formation (Perring 1990). The Eastern and Western Granitoid Complexes have been dated at 2689 ± 22 Ma and 2691 ± 8 Ma, respectively, whereas some small internal granitoid bodies are dated at 2665 ± 4 Ma ($U–Pb_{Zircon}$, Hill et al. 1992). No radiogenic ages for the felsic dykes have been obtained. The youngest lithologies recognised in the area are those of the Jimberlana Dyke Suite, dated at 2411 ± 38 Ma ($Sm–Nd_{mineral\ isochron}$, Fletcher et al. 1987).

Regional structure

The structural architecture of the Norseman Terrane, according to Keele (1984), evolved in a sequence of six principal stages. D1 structures comprise: (1) isoclinal folds in the Noganyer Formation, and (2) WNW-striking faults, which offset W-dipping stratigraphy, but are cut by later mafic and felsic dykes, that are interpreted as block faults formed during deposition of the volcanic stratigraphy. D2 deformation involved approximately E–W compression, with the formation of shallowly N-plunging folds and a N-striking, subvertical axial planar cleavage. The Penneshaw, Noganyer and Woolyeenyer Formations are folded about the gently N-plunging D2 Penneshaw anticline, imparting a N- to NE-strike and moderate westerly dip (55–65°) to the exposed greenstones (Fig. 1). The D3 event involved overprinting of the N–S striking D2 cleavage by a NNW-striking, steeply E-dipping cleavage (70–90°) in the vicinity of dextral-reverse shear zones of the same orientation (e.g. Princess Royal Fault Zone, Fig. 1). D4 structures comprise a WNW-striking fracture cleavage that crosscuts the auriferous veins and contains retrograde mineral assemblages. Emplacement of the Jimberlana Dyke Suite along E-striking fractures is the D5 event. The latest (D6) structures identified in the terrane consist of ENE- to NE-structure Proterozoic brittle faults, probably related to the accretion of the Fraser Mobile Belt to the southeast. Some of these faults may be reactivated D1–D5 structures.

Deposit subdivisions and structural characteristics

Gold mineralisation is present in all greenstone lithologies at Norseman, although the large economic deposits are restricted to the lower members of the Woolyeenyer Formation. All orebodies are subdivided into three groups on the basis of their (1) spatial relationships over 40 km, (2) structural characteristics, and (3) associated hydrothermal alteration. These groups consists of the Northern (Surface Winze, North Royal, Princess Royal), Central (Regent, Ajax, Royal Standard, Okay), and Southern (Scotia) deposits (Fig. 1).

Northern and Central orebodies

Northern and Central deposits are hosted in D2–D3 structures, the heirarchy of which is illustrated in Fig. 1. NNW-striking, steeply E-dipping, first-order ductile shear zones transect the stratigraphy and exhibit dextral-reverse displacement, as indicated by the offset of stratigraphy and a mineral lineation (amphibole) plunging shallowly (20°) to the NNW (Keele 1984). These structures are predominantly barren of gold mineralisation and quartz veins.

The first-order D2–D3 ductile shear zones have associated second- and third-order structures (Fig. 1). Second-order structures are N-striking, moderately E-dipping (50–60°) shear zones at a high angle to the stratigraphy. These structures contain laterally continuous, variably deformed veins of laminated to massive quartz, exemplified by the 4 km strike-length Mararoa vein (Figs 1, 2, 3A–E). The N-striking shear zones commonly follow E-dipping gabbroic dykes, suggesting that the rheological contrast between the W-dipping stratigraphy and E-dipping dykes, particularly high-MgO tholeiitic dykes, controlled shear zone nucleation and quartz vein emplacement (Fig. 2, Hall and Bekker 1965, Keele 1984). Fabrics in the altered wallrocks, such as aligned amphibole (35°→010°) and

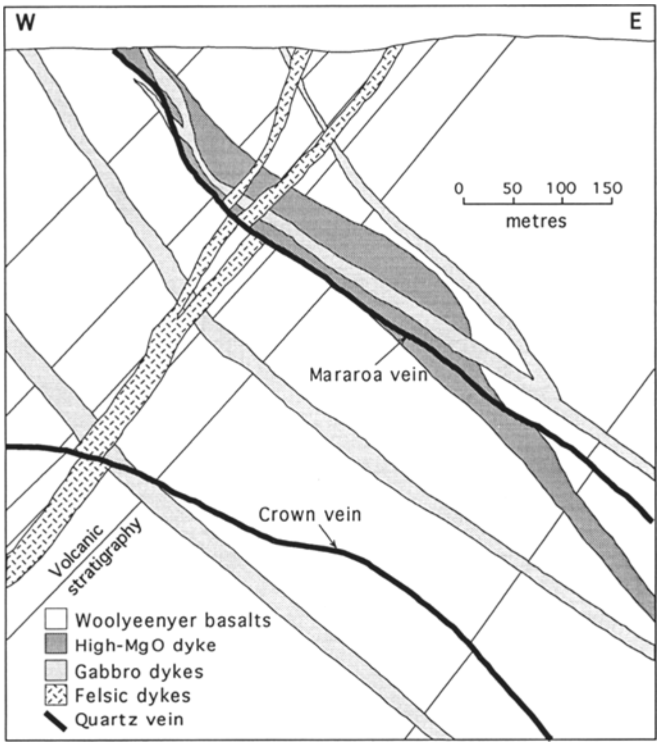


Fig. 2. Vertical cross-section through the Crown and Mararoa veins in the vicinity of the Regent shaft. Quartz veins are hosted in N-striking, 2nd-order shear zones. Modified from Thomas (1990)

foliation/quartz vein intersections (70°→150°, Keele 1984), along with features such as tensional veins, variably folded veins and wallrock inclusion alignment, indicate that wallrock shear and quartz vein emplacement occurred during ductile dextral-reverse movement along these structures (c.f. Ramsay 1980, Sibson 1990). Brittle post-vein fabrics are sporadically present, and contain retrograde mineral assemblages.

Third-order structures comprise NE-striking, shallowing SE-dipping (20–30°) tensional zones. Limited width of wallrock alteration haloes (5–50 cm), the lack of intense fabric development in the altered wallrock, and the absence of mesoscopic deformation of the quartz veins (absence of boudinage or folding, except where other structures are intersected) support the interpretation that these were dominantly tensional structures. The relationship of these structures to first- and second-order dextral-reverse shear zones is consistent with a tensional origin.

West- and WNW-striking subvertical structures are common in the mine area, and locally host quartz veins and gold mineralisation (e.g. OK Mine, Fig. 1). Where unmineralised, these structures displace the west-dipping stratigraphy, but are crosscut by NNW-striking gabbroic dykes and NNE-striking felsic porphyry dykes, and are interpreted to be syn-to early post-depositional (D1) block faults (Keele 1984). Where mineralised, these structures are ductile in nature and crosscut the gabbro and porphyry dykes, consistent with reactivation during ductile deformation and mineralisation (D2–D3). Some of the WNW-striking structures crosscut and offset the second- and third-order shear zones (e.g. E-fault, Fig. 1). and are brittle in nature, containing fault gouge and associated retrograde mineral assemblages. Although quartz veins in Northern and Central deposits are grossly similar, Northern deposits are characterised by thicker quartz veins (up to 10 m) and a greater abundance of massive quartz that contains abundant inclusions of wallrock and lacks significant laminations, whereas Central deposits consist of thinner quartz veins (generally < 1 or 2 m) that contain more laminations and proportionately less massive quartz. Gold orebodies are restricted to dilational jogs on the (D2–D3) second- and third-order, and reactivated (D1) structures, and plunge moderately to the southeast (Campbell 1990).

Southern orebodies

The Southern orebodies at Scotia are distinctive both in terms of their higher metamorphic-grade host rocks and their higher-temperature alteration mineral assemblages. Structural controls on primary gold mineralisation are difficult to constrain, as closely spaced brittle faults of varying orientation disrupt and displace the orebodies. Gold mineralisation occurs in a NNW to N-striking, east-dipping, (D2–D3) ductile shear zone that transects the stratigraphy and, in the mine workings, follows a N-striking, E-dipping (50°) gabbroic dyke (Fig. 4). Within the shear zone, weak mineral lineations (biotite and amphibole grains) plunge approximately 50° SW and parallel the foliation/vein intersections. This structure is interpreted as a reverse-dextral ductile shear zone based on the movement sense indicated by the vergence of folded quartz + clinopyroxene + calcite veinlets and the foliation/vein intersections.

Most of the ore is hosted in multiple quartz + diopside + calcite veins (D2–D3) within the shear zone. Due to offset by late brittle faults, the ore zones are limited in strike and dip extent (150 × 120 m maximum). Within the ore zones, repeated veining events have produced composite banded veins, up to 6 m in total width (average < 1 m), comprising alternating bands of quartz, clinopyroxene, calcite, amphibole, biotite and microcline. The veins vary in width from a few millmetres to 0.5 metres, are discontinuous, and variably deformed (Fig. 3f). Vein density decreases rapidly into the host shear zone where veins are thin and widely spaced. Ore shoots are difficult to define due to the disrupted nature of the orebody, but those identified to date plunge to the northeast at 20° (R. Waugh pers. comm. 1990). Quartz + plagioclase + muscovite + biotite pegmatites crosscut the orebodies (Fig. 4).

Two orientations of brittle faults (D4–D6) have been identified in the mine. These faults are recognised by their abrupt offsets of orezones and the abundance of chloritic fault gouge within them. E-striking, subvertical dextral faults average 3–10 cm in width and offset the orebodies by as much as a few metres. NNE-striking, E-dipping (60°) reverse faults, averaging only a few cm in width, also crosscut the orebodies, and smaller scale WNW faults are also present in the mine workings. The NE- to ENE-striking Dambo fault appears to have undergone the latest and largest movement, and offsets stratigraphy, in an apparent sinistral sense, approximately 5 km from the rest of Norseman Terrane (Fig. 1).

Petrography of regional metamorphic assemblages

Least-altered assemblages from tholeiitic gabbros that host the Northern deposits dominantly comprise actinolite-hornblende and plagioclase (An_{40-45}), in varying proportions, with minor quartz, epidote, ilmenite and accessory apatite, titanite, leucoxene and biotite (Fig. 5A). A distinct paragenesis is evident in all samples. Metamorphic amphiboles (actinolite to actinolitic-hornblende) pseudomorph primary pyroxenes, with relict pyroxene cores rarely preserved. Finer-grained actinolitic-hornblende to Mg-hornblende forms fibrous rims around the pseudomorphous amphiboles and along plagioclase cleavage planes and grain boundaries. Plagioclase (An_{40-45}) comprises well-preserved laths and glomeroporphyritic to (rarely) megaphenocryst patches, lightly dusted by sausseritic alteration and exhibiting relict Carlsbad and albite twinning. Minor quartz, ilmenite and accessory apatite are ubiquitous; ilmenite as skeletal grains up to 200 μm in diameter, and apatite as finer-grained inclusions in plagioclase. This amphibole + plagioclase + ilmenite + apatite metamorphic assemblage is commonly retrogressed to quartz + albite ($< An_{10}$) + epidote + chlorite + calcite along plagioclase and amphibole grain boundaries. Ilmenite grains are variably altered to leucoxene ± titanite. The latest assemblage is prehnite + albite (An_1) developed along grain boundaries and in veinlets that crosscut all of the above assemblages.

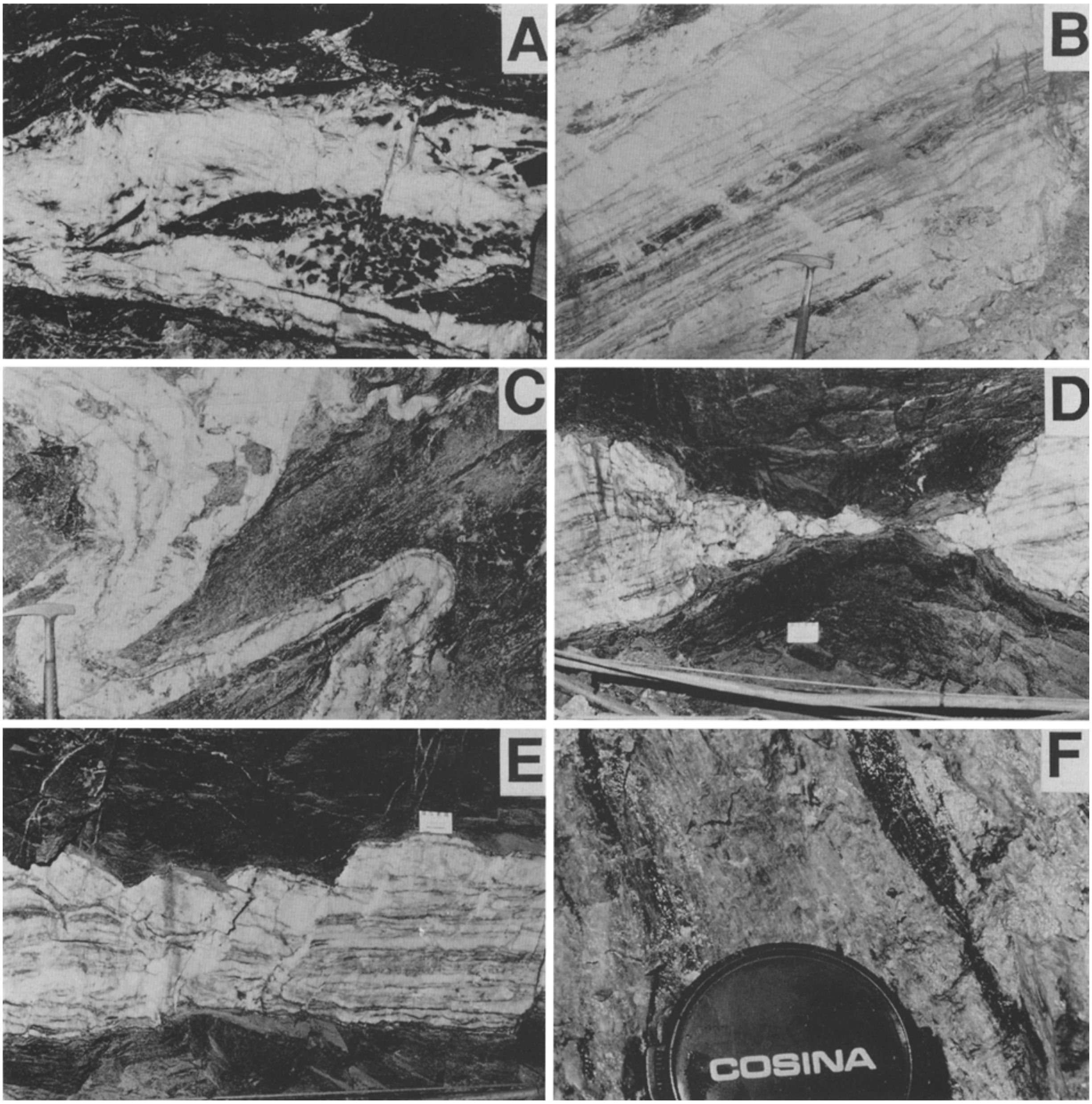


Fig. 3A–F. Photographs of selected syn- and post-depositional mesoscopic features observed within quartz veins in the Norseman gold deposits. **A** Massive quartz vein containing brecciated wallrock fragments, North Royal Mine. **B** Laminated quartz vein, Crown vein, Regent Mine. **C** Folded quartz vein hosted in N-striking second-order shear zone is folded where it intersects a 1st-order NNW-striking shear zone. Mararoa vein, Regent Mine. **D** Boudinaged quartz vein, Mararoa vein, Regent Mine. **E** Brittle faulting of quartz vein. Mararoa vein, Regent Mine. **F** Finely banded quartz-clinopyroxene-calcite-microcline vein in the Scotia orebody

Tholeiitic basalts and gabbros hosting the Central deposits are mineralogically similar to those in the northern area (amphibole + plagioclase + ilmenite + quartz ± epidote ± apatite ± biotite, Fig. 5A). As above, actinolite or actinolitic-hornblende (after primary pyroxene), rimmed by Mg-hornblende, and plagioclase are present. However, the plagioclase cores are more Ca-rich (An_{40-65}), and clear rims coexisting with Mg-hornblende, epidote and chlorite are very Ca-rich (An_{70-90}). Both of these assemblages are retrogressed to quartz + chlorite + zoisite + epidote + calcite assemblages, developed along amphibole and plagioclase grain boundaries and transgranular veinlets.

Volcanic rocks in the Scotia area consist of variable proportions of amphibole and plagioclase, with minor quartz, Mg-chlorite, ilmenite and accessory apatite and titanite. Actinolitic-hornblendes to Mg-hornblendes pseudomorph pyroxene, whereas plagioclase crystals (An_{48-52}) show preserved Carlsbad ± albite twinning and are weakly sausseritised. These amphibole-plagioclase assemblages are crosscut by zoisite + actinolite + calcite veinlets, and replaced along amphibole-plagioclase grain boundaries by fine-grained zoisite + actinolite + albite (An_1). Late prehnite + albite (An_1) ± sphalerite veinlets crosscut all of the above assemblages.

Petrography of hydrothermal alteration assemblages

The width of alteration haloes adjacent to quartz veins in the Norseman Terrane varies from a few centimetres to several metres

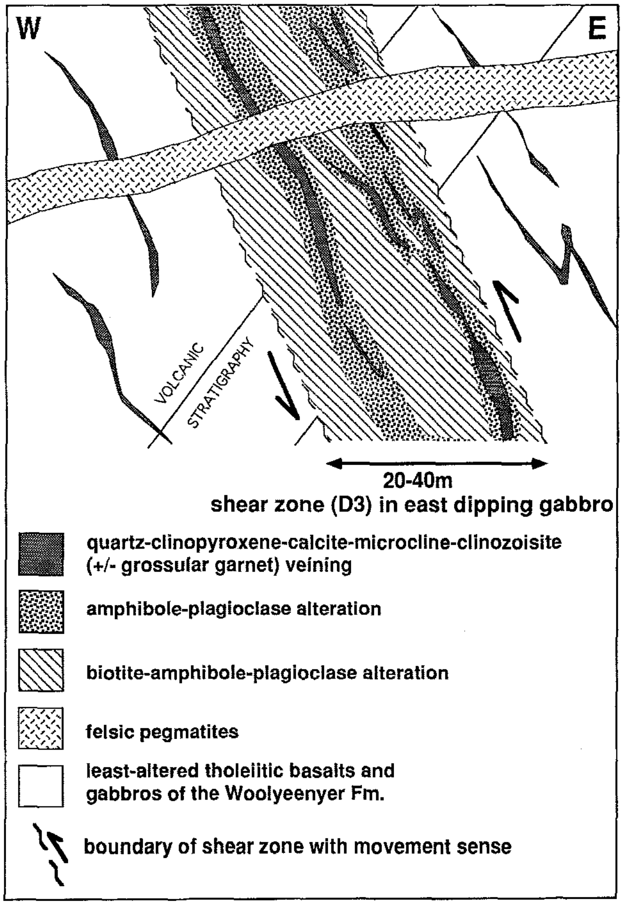


Fig. 4. Schematic sketch of orebody geometry and alteration zonation in the Scotia deposit. Later brittle faults are omitted for clarity

and correlates with the width, strain intensity, and abundance of quartz veins within the host shear zones. There is no direct correlation, however, between alteration intensity and the width of individual quartz veins. Alteration mineralogy in the wallrocks surrounding all deposits is zoned laterally toward the fluid conduits, from least-altered (metamorphic) assemblages, through outer alteration zones to inner alteration zones. This lateral zonation for the three deposit types is illustrated in Figs 6A–C. Note that the term vein selvedge in the following discussion is used to denote the mineral assemblages in the veins at the immediate contact between the quartz veins and wallrock. This zone is generally a few millimetres to a few centimetres in width. The temporal evolution of these alteration assemblages with respect to gold mineralisation and the evolution of the Norseman Terrane is schematically illustrated in Figs 7A–C.

Northern deposits

In the Northern deposits, the least-altered assemblages are amphibole-bearing, and are progressively altered to outer chlorite- and then to inner chlorite + biotite-bearing assemblages with increasing proximity to the quartz veins. Concomitantly, there is complete destruction of metamorphic amphibole, plagioclase and any primary textures, and an increase in the abundance of calcite and sulphide minerals (Fig. 6A). This mineralogical zonation is consistent with wholerock geochemical variations across the alteration zones, which reflect the progressive addition of H_2O, CO_2 and K_2O into the wallrock from the hydrothermal fluid (McCuaig and Kerrich 1990). In the biotite + chlorite zone, biotite and chlorite possess mutually overprinting relationships. Note that plagioclase proximal to the vein is slightly less Ca-rich (An_{31-43}) than its metamorphic precursor (An_{40-45}). Vein selvedges are commonly monomineralic, and consist of coarse carbonate aggregates or rosettes of chlorite or biotite, but sporadically are intergrown with quartz, scheelite, tourmaline or sulphides. Deformation fabrics are variably developed in these alteration assemblages, with vein selvedges of chlorite or biotite occurring as aligned plates, subradial rosettes and microscopic aggregates intergrown with quartz.

Pyrrhotite is the dominant sulphide in the outer and inner alteration zones. Pyrite and arsenopyrite are locally abundant adjacent to the veins. Where sulphides are abundant, ilmenite is progressively altered to leucoxene, titanite and Fe-sulphides. However, ilmenite is commonly a stable phase at the vein margins in sulphide-poor areas.

Earliest mineral assemblages in the veins consist of fine-grained actinolite and locally abundant tourmaline fibres intimately intergrown with quartz, euhedral arsenopyrite or pyrite crystals, and granular aggregates of scheelite and carbonate adjacent to vein selvedges and wallrock inclusions. Aggregates of scheelite and carbonate, and trials of euhedral arsenopyrite or pyrite crystals are also isolated, or on early fractures in quartz. Later galena, sphalerite, Ag–Pb–Au tellurides (altaite, hessite, petzite) and native gold rim and fill fractures in the earlier pyrite/arsenopyrite, or are sited along quartz grain boundaries (Fig. 5E). As these minerals occur also as rare isolated inclusions in arsenopyrite and pyrite, and never crosscut quartz grain boundaries, it is interpreted that they were introduced during or shortly after the main phase of quartz deposition (Fig. 7A). Gold occurs as free grains within the quartz veins ($>98\%$), but also is present in a sporadic dispersion halo (>10 ppb) up to a few metres from the vein margins (McCuaig and Kerrich 1990).

These hydrothermal alteration assemblages associated with quartz vein emplacement and gold mineralisation in ductile-brittle shear zones are locally retrogressed to calcite, sericite, chlorite and albite ($An_{<10}$) along vein margins and along narrow brittle structures that crosscut all other assemblages and structures. Sericite and chlorite are commonly along stylolites and brittle fractures in the quartz veins. Calcite + quartz + chlorite veinlets crosscut the veins and wallrock fabrics at high angles, and may be weakly deformed. The latest retrograde assemblage comprises gypsum precipitated along brittle fractures by modern groundwaters.

Central deposits

Hydrothermal alteration envelopes surrounding quartz veins in the Central deposits consist of three gradational zones (Fig. 6B). With increasing proximity to the veins, there are: (1) actinolite + plagioclase + epidote (least-altered zone, Fig. 5A), and (2) hornblende + actinolite + biotite + plagioclase (outer zone, Fig. 5C), and (3) biotite + quartz + actinolite + plagioclase + calcite (inner zone, Fig. 5D). Plagioclase recrystallised throughout this sequence, yet maintained a relatively uniform composition (An_{40-65}). Inner alteration zones are dominated by biotite, with subordinate actinolite and plagioclase or calcite (Fig. 5D). Plagioclase tends to be the stable Ca-phase in quartz-rich inner zones, whereas calcite is stable in quartz-poor inner zones. A sharp transition marks the selvedges to the veins, where the inner alteration zone assemblages are bounded by actinolite + quartz + calcite ± biotite ± plagioclase vein selvedges (Fig. 5D). Actinolite is present as fibrous rosettes in the quartz vein, which often exhibit progressive grain-coarsening towards the centre of fibrous aggregates, whereas calcite or plagioclase are present as medium to coarse-grained granular aggregates. Any of these minerals may form monomineralic vein selvedges.

Sulphides are locally abundant in the wallrock adjacent to the veins, but are generally less abundant than in the Northern deposits. Pyrrhotite is the dominant sulphide in the inner and outer alteration zones, whereas pyrite dominates the quartz veins and vein selvedges.

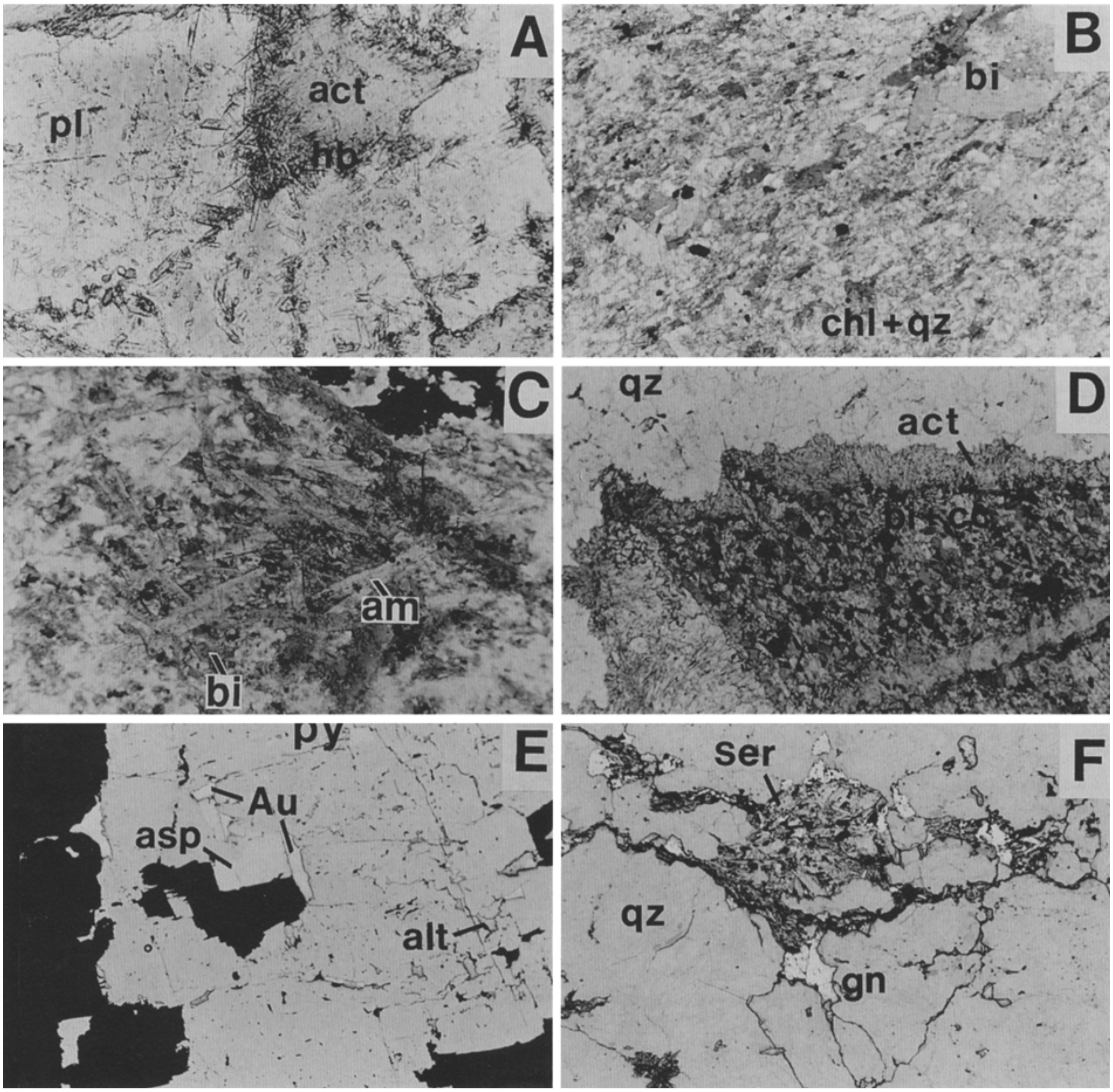
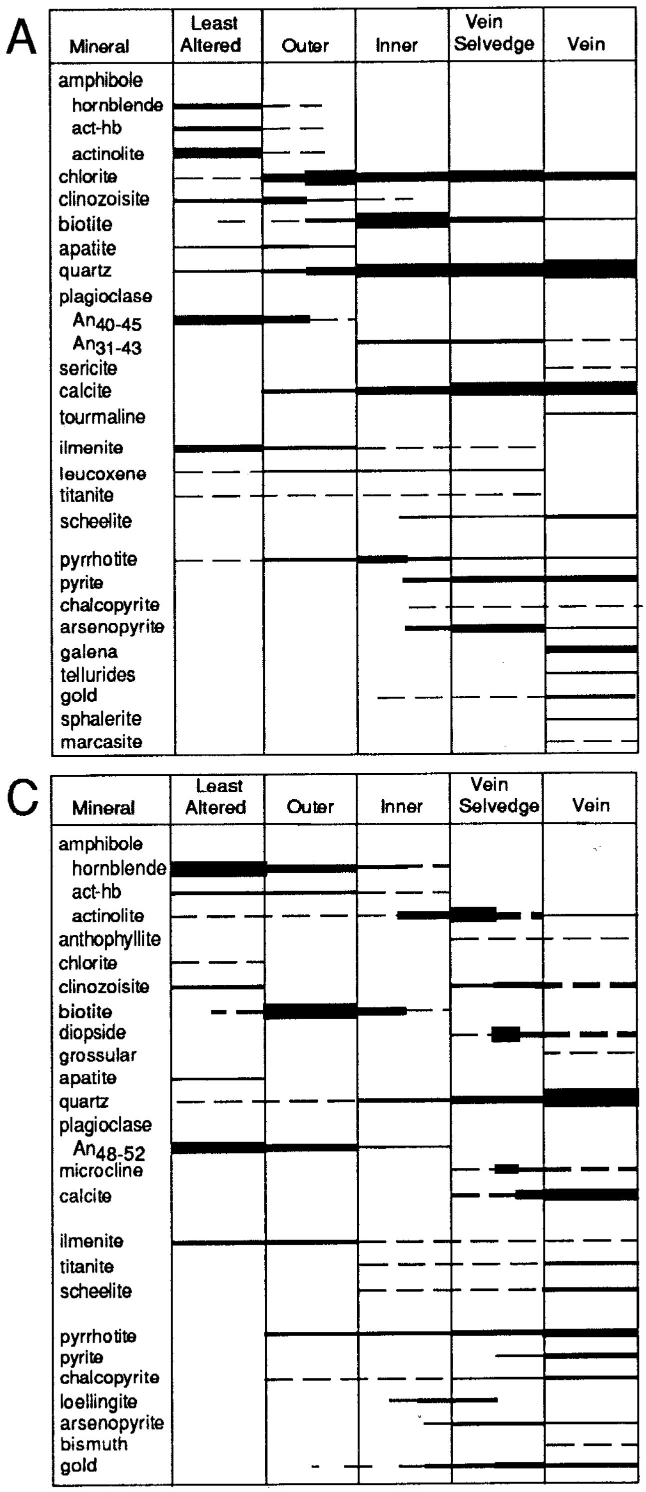


Fig. 5A–F. Photographs of alteration associated with Northern and Central orebodies. **A** Least-altered tholeiitic gabbro, sample S1113-A, Regent Mine, field of view (FOV) = 1.4 mm. **B** Biotite overprinting chlorite in the chlorite zone, sample PRS-25, North Royal Mine, FOV = 3.5 mm. **C** Amphibole overprinting biotite in the biotite zone, sample S657-2, OK mine, FOV = 3.5 mm. **D** Fibrous actinolite selvedge to quartz vein, sample CN275940, 32 level, Crown Reef, FOV = 3.5 mm. **E** Fractured pyrite crystal in quartz containing inclusions of arsenopyrite, gold and altaite. Sample NR-35, 5/150 stope, North Royal Mine, FOV = 0.3 mm. **F** Sericite, Sphalerite, galena, tellurides and gold deposited on stylolitic surfaces in quartz veins. Sample AJ-4, 7/1530 stope adjacent to E-Fault, Norseman Reef, FOV = 1.4 mm. *Abbreviations*: *pl* = plagioclase; *act* = actinolite; *hb* = hornblende; *bi* = biotite; *chl* = chlorite; *qz* = quartz; *am* = amphibole; *cc* = calcite; *alt* = altaite; *py* = pyrite; *asp* = arsenopyrite; *ser* = sericite; *gn* = galena

As in the Northern deposits, metamorphic ilmenite is generally altered to titanite and leucoxene, but may be a stable phase at the vein margins and, rarely, within the quartz veins.

Veins within the shear zones comprise over 90% quartz, intimately intergrown with subordinate calcite, scheelite, actinolite, pyrite and tourmaline. Euhedral pyrite grains within the quartz are fractured and infilled by galena, tellurides (hessite, altaite, petzite and sylvanite) and native gold. Galena, sphalerite and gold also are localised along quartz grain boundaries, away from later brittle fractures and stylolites. Where stylolites preferentially nucleate along wallrock ribbons or sulphide trials, ore minerals are located adjacent to, but not on, the stylolite surfaces. An exception is at the southern end of the Mararoa and Norseman reefs where the brittle E-fault offsets the veins (Fig. 2). In stopes adjacent to this structure, galena, sphalerite, sericite, chalcopyrite, tellurides and gold are intimately intergrown along stylolitic fractures in the veins (Fig. 5F). Significantly, galenas from this assemblage yield Proterozoic Pb–Pb ages, and suggest that Proterozoic remobilisation of Pb, Zn and gold has occurred locally in the Norseman deposits (Perring and McNaughton 1990).

Retrograde assemblages, formed from the above hydrothermal assemblages, occur in three stages: (1) chlorite + sericite + carbonate



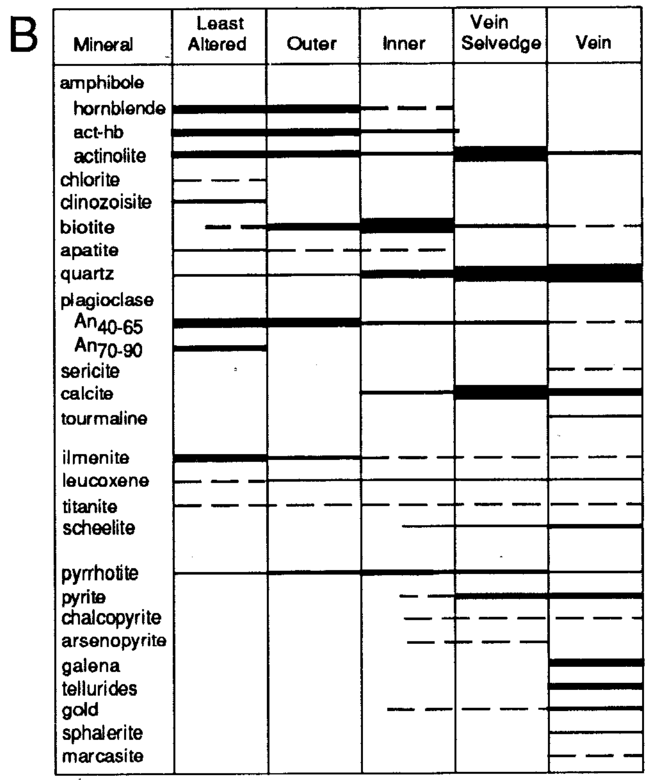


Fig. 6A–C. Zonation of alteration mineralogy surrounding the Northern, Central and Southern deposits in the Norseman Terrane. Least-altered metamorphic assemblages are at left of diagrams, quartz vein assemblages at the right. Thickness of bars correspond to the relative abundances of the minerals. **A** Northern deposits; **B** Central deposits; **C** Southern deposits

along stylolitic laminations and fractures in the quartz veins and wallrocks, (2) quartz + carbonate veinlets that crosscut the veins and wallrock assemblages, and (3) late prehnite + albite veinlets ($An_{<1}$) that crosscut alteration zones in the wallrock. As in the Northern deposits, the youngest alteration mineral is gypsum precipitated along brittle fractures by recent groundwaters. The paragenetic sequence of alteration in the Central deposits is summarized in Fig. 7b.

Southern deposits

In the Scotia orebodies, the banded nature of the ore zones produces complex overlapping alteration envelopes. However, a consistent sequence of alteration zones can be observed around isolated veinlets (Figs 6C, 8A). Throughout a large section of the host shear zone, the metamorphic assemblage of hornblende + plagioclase (An_{48-52}) + epidote + ilmenite is altered to an outer zone of

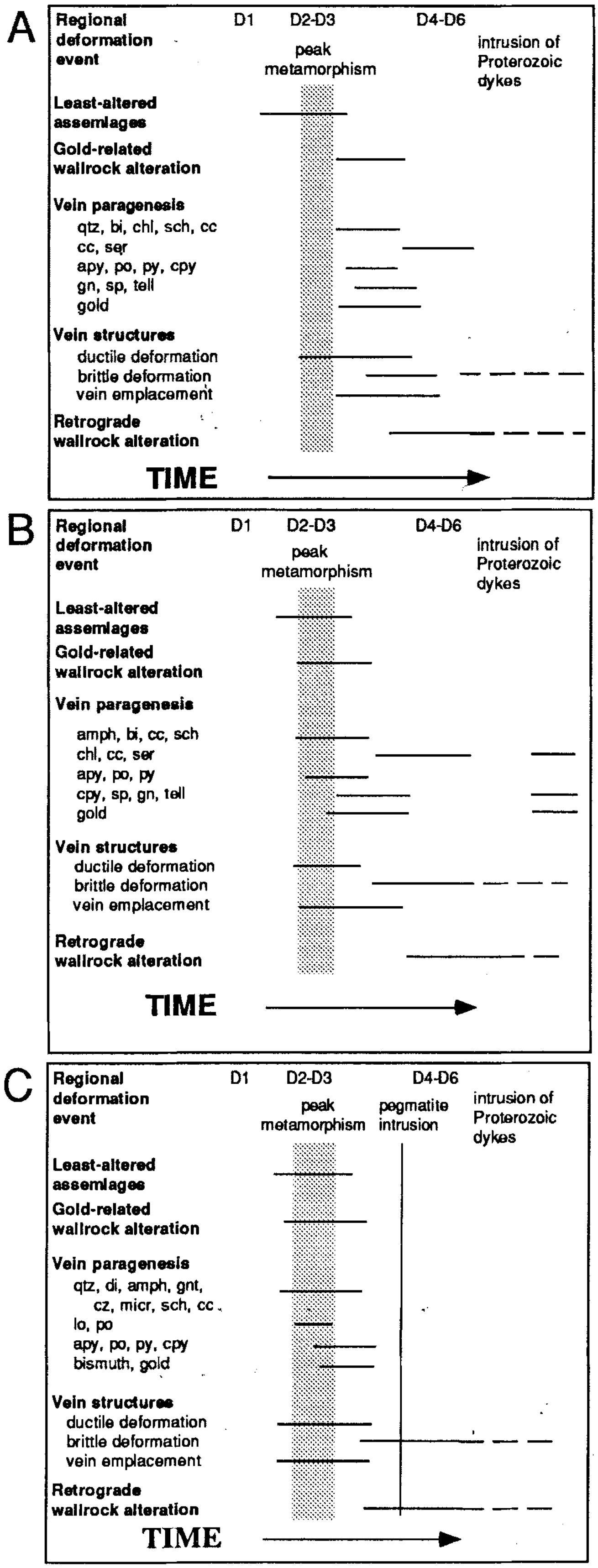


Fig. 7A–C. Paragenetic evolution of gold deposits within the Norseman Terrane. **A** Northern Deposits; **B** Central Deposits; **C** Southern Deposits

biotite + hornblende + plagioclase (Fig. 4, 8B). With increasing proximity to the veins, the biotite + hornblende + plagioclase assemblage is progressively replaced by actinolite, then clinopyroxene (diopside) + calcite + microcline + zoisite over a few millimetres to centimeters (Fig. 6C, 8A). the actinolite, clinopyroxene or calcite may form distinct, monomineralic bands in the veins (Fig. 8C). Garnet is rare in the ore zones but, where present, is associated with calcite + quartz (R. Waugh, personal communication 1990).

Ilmenite is partially altered to titanite and pyrrhotite throughout the shear zone. Near the margins of the veins, in the biotite + amphibole + plagioclase and amphibole inner zones, löellingite ($FeAs_2$) is progressively rimmed by gold and then arsenopyrite (Fig. 8D). Pyrrohotite is the dominant sulphide in the veins, and is closely associated with chalcopyrite. Fractures within clinopyroxene and quartz are infilled by actinolite + pyrrhotite + chalcopyrite. Gold and bismuth are disseminated throughout the quartz as isolated inclusions $< 10\ \mu m$ in diameter.

Clinopyroxene + microcline + zoisite + actinolite retrogress to sericite + albite ($An_{<1}$) + chlorite + calcite along cleavage planes and grain boundaries of the former minerals. Brittle fractures cross-cutting the vein are also filled with chlorite + quartz + sericite + albite, and the youngest fractures are filled with prehnite + albite + sphalerite. The sequence of alteration and mineralisation in the Southern orebodies is shown in Fig. 7C.

Discussion and summary

Metamorphism

The bulk of the Norseman Terrane has undergone low-strain metamorphism, with excellent preservation of primary textures in the basalts of the Woolyeenyer Formation (Hallberg 1970, Spray 1985, Thomas 1990). The (D2–D3) NNW-striking ductile shear zones and their subsidiary N- and NE-striking structures are localised domains characterised by pervasive foliation and an absence of primary textures. The metamorphic grade of the greenstones increases from upper-greenschist facies in the middle of the terrane to upper-amphibolite facies at the margins (Binns et al. 1976 Fig. 1). The greatest metamorphic gradient occurs in the vicinity of the Eastern Granitoid Complex, where upper-greenschist facies assemblages in the lower Woolyeenyer Formation grade to upper-amphibolite assemblages at the highly tectonised contact with the granitoids and gneisses (Keele 1984, Spray 1985). In contrast, only a few metres of hornfels are developed in basalts bordering the Western Granitoid Complex, which are interpreted to have been emplaced while the greenstones were at elevated temperature (Keele 1984).

Of more direct importance to the scope of this paper is the range in metamorphic grade along strike within the Woolyeenyer Formation, specifically between the Northern and Southern deposits. The observations of metamorphic assemblages reported above are consistent with those of Hallberg (1970) and Binns et al. (1976), and suggest that the lithologies hosting the Northern deposits straddle the greenschist-amphibolite transition, those hosting the Central deposits are within the lower-amphibolite facies, and the lithologies hosting the Southern deposits have been metamorphosed to mid-amphibolite facies. However, the reporting of prehnite-pumpellyite and greenschist facies assemblages in the vicinity of the Southern deposits (Spray, 1985) is not supported by the current study. The dominant assemblage preserved is

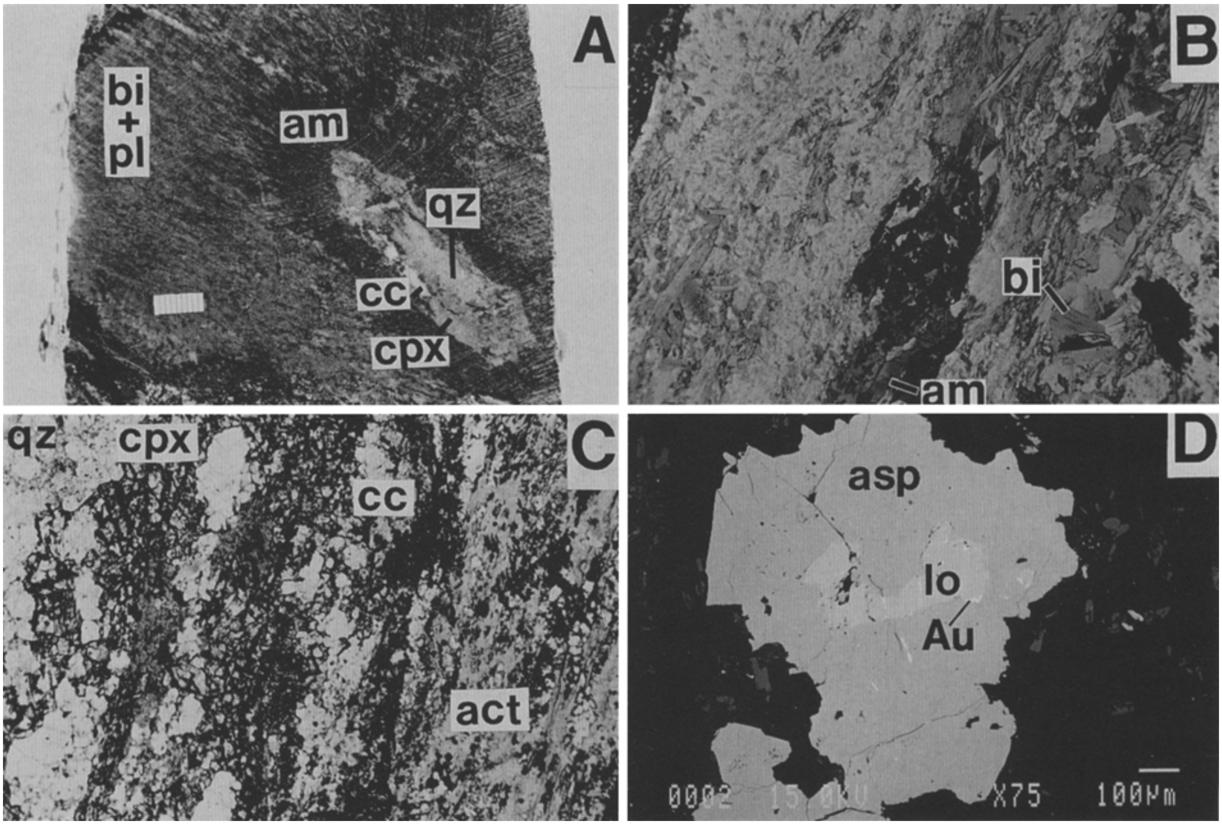


Fig. 8A–D. Photographs of alteration associated with Southern orebodies. **A** Alteration zonation around clinopyroxene-quartz veinlets within the Scotia orebody, 7/440 stope. Scale is in millimetres. **B** Biotite-amphibole-plagioclase alteration zone, Scotia Mine, field of view (FOV) = 1.4 mm. **C** Typical quartz-clinopyroxene-carbonateamphibole relationships in veins from the Scotia Mine. Sample CN389171-E, FOV = 14 mm. **D** Löellingite-arsenopyrite-gold relationships in amphibole-plagioclase alteration zone immediately adjacent to quartz-clinopyroxene-clinozoisite-vein. Löellingite is always rimmed by arsenopyrite, with gold occurring at the contact between these two phases. FOV = 0.3 mm. *Abbreviations* as for Fig. 5, with *cpx* = clinopyroxene and *lo* = löellingite

hornblende/actinolitic-hornblende and calcic plagioclase of the amphibolite facies, and the low-grade assemblages denoted by prehnite + albite veins are paragenetically very late.

Precise metamorphic conditions experienced by the mafic rocks of Woolyeenyer Formation are difficult to constrain due to the lack of interlayered rocks of appropriate composition, such as pelites. Nevertheless, a comparison of relative metamorphic grade within the Woolyeenyer Formation from the Northern to Southern deposits can be made by comparing variations in mineral assemblages and mineral chemistry between deposits in petrogenetic grids constructed from studies of metamorphosed mafic rocks. This approach yields estimated peak metamorphic temperatures of 475°–500°C in the vicinity of the Northern deposits at an estimated pressure of 2–4 kb, based on assemblages of oligoclase/andesine + hornblende ± chlorite in mafic lithologies, and 500 ± 50°C in the Central deposit area, based on assemblages of hornblende + actinolite + plagioclase in mafic lithologies, and tremolite + chlorite ± calcite ± quartz assemblages in high-MgO lithologies (Golding 1982). Amphibole-plagioclase geothermometry indicates temperatures of 500–575°C for rocks hosting the Central deposits (Mueller 1992), and 530–700°C for those hosting the Southern deposits.

The pressure of metamorphism is largely unconstrained at Norseman. Stratigraphic reconstructions of Mueller (1992) estimate that metamorphism may have taken place at 3 kb. Sedimentary rocks of the lower Noganyer Formation contain andalusite in the vicinity of both the Central and Southern deposits, (Keele 1984, Spray 1985), indicating that peak metamorphism in the Norseman Terrane occurred under low pressure conditions.

The textural preservation of plagioclase phenocrysts, concomitant with the complete recrystallisation of primary pyroxenes to amphibole (actinolite/actinolitic hornblende) and lack of significant chlorite, corresponds to the medium-grade metamorphism (lower- to mid-amphibolite facies) style recognised by Binns et al. (1976). These assemblages indicate that the early retrogression of the Norseman greenstones, presumably in sea-floor hydrothermal cells, occurred under conditions of very high heat flow and rapid burial, so as to preserve relict plagioclase yet hydrate and recrystallise primary pyroxene to amphibole (cf. Binns et al. 1976, Barley et al. 1990). The presence of actinolite cores and lack of chlorite indicate that this retrogression did not extend below upper-greenschist facies conditions. Subsequent prograde metamorphism to low-amphibolite facies in signified by Mg-hornblende rims on actinolite cores in the Northern and Central deposits. The more extensive development of Mg-hornblende rims, and more calcic plagioclase, in the Central deposits are consistent with slightly higher metamorphic temperatures in the Central versus Northern regions. In the lithologies hosting the Southern deposits, amphibole cores consisting predominantly of Mg-hornblende/actinolitic hornblende, the paucity of actinolite and chlorite, and the presence of calcic plagioclase collectively suggest that these lithologies were metamorphosed to higher metamorphic grades than the lithologies in the Central and Northern areas. Fifty kilometres east of Norseman, the Dambo Fault (Fig. 1) juxtaposes granulite facies rocks in its hangingwall against amphibolite facies rocks in its footwall (M. E. Clark pers. comm. 1992). This suggestion of south-over-north thrusting along the Dambo Fault implies that the greenstones south of the Dambo Fault, in the vicinity of Southern deposit, have seen deeper crustal levels relative to the Central and Northern areas.

Retrograde mineral assemblages in veinlets, vug fillings (Hallberg 1970) and along grain boundaries presumably represent passage of the Norseman Terrane through the greenschist and prehnite-pumpellyite metamorphic facies during uplift and cooling.

Hydrothermal alteration

Summary of observations. Hydrothermal alteration assemblages surrounding quartz-veined shear zones (fluid conduits) reflect the interaction of fluids and wallrocks as they approach chemical and thermal equilibrium (cf. Korzhinskii, 1970). The paragenetic sequence of assemblages and structures identified in both the least-altered assemblages and quartz-veined shear zones indicate that the Norseman Terrane and associated gold deposits have evolved through a number of pressure-temperature regimes. Therefore, it is imperative that the hydrothermal wallrock alteration envelopes associated with the quartz veins be examined in both a spatial (lateral zonation away from veins, and differences in alteration assemblages between mines) and temporal framework (change in alteration mineralogy and deformation styles with time). The spatial and temporal relationships of alteration to deformation, quartz emplacement and mineralisation are schematically illustrated in Figs 6 and 7, respectively. The alteration zones depicted in Fig. 6 may have sharp boundaries between zones over millimetres to centimetres, or be gradational over a few metres, with zone boundaries commonly correlating with zones of variable fabric development and, therefore, heterogeneous fluid infiltration. Sharp contacts occur between inner alteration zones in the wallrock immediately adjacent to the vein, and vein selvedges deposited directly from the hydrothermal fluid at the margins of the quartz veins (Fig. 5D).

Fluid compositions and temperatures of alteration. The alteration assemblages associated with gold deposits can reveal information about the P–T–X_{CO_2} conditions of the fluid that formed them. Using isobaric T–X_{CO_2} phase diagrams, Clark et al. (1989) deduced that alteration surrounding the greenschist-amphibolite facies Victory deposit reflects a progressive decrease of X_{CO_2} away from the vein under approximately isothermal conditions. Witt (1991) proposed that the alteration assemblages associated with amphibolite-hosted deposits can also be explained by a progressive decrease in X_{CO_2} away from the veins. Inspection of T–X_{CO_2} plots and correlation with amphibolite-grade alteration assemblages demonstrates that this X_{CO_2} gradient alone cannot explain alteration zonation to high-T deposits (Fig. 9). To explain the zonation, either a large decrease in X_{CO_2} *towards* the veins, or an unreasonably

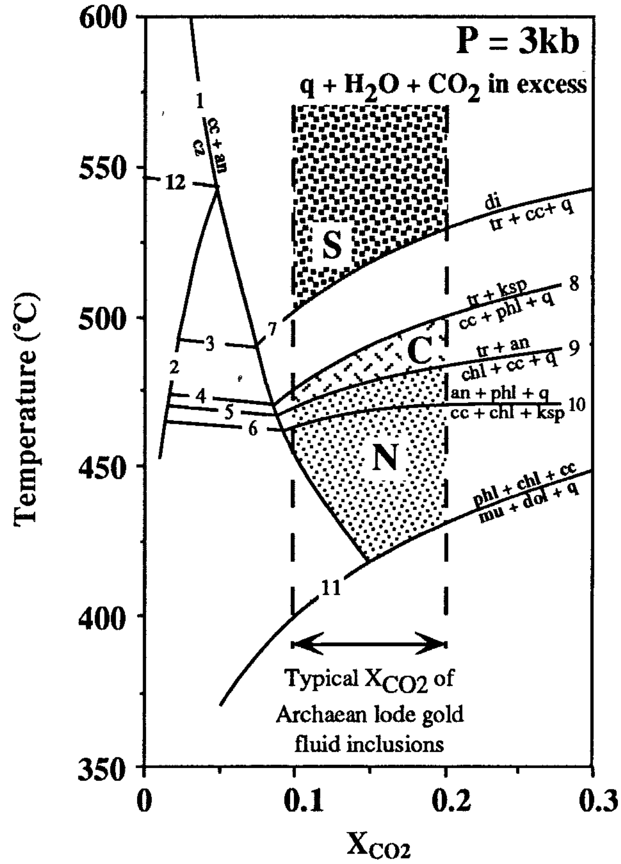


Fig. 9. T–X_{CO_2} plot of mineral reactions constraining the stability of vein selvedges in the Northern (*N*), Central (*C*), and Southern (*S*) deposits in the system KCMASH at $P_{Total} = P_{Fluid} = 3$ kbars. Quartz, H_2O and CO_2 are assumed to be in excess in all assemblages. *di* = diopside; *tr* = tremolite (actinolite); *cc* = calcite; *q* = quartz; *gr* = grossular garnet; *cz* = clinozoisite; *phl* = phlogopite (biotite); *ksp* = microcline; *an* = anorthite (plagioclase); *mu* = muscovite; *dol* = dolomite. Unit activities are assumed for all phases so that absolute T − X_{CO_2} conditions of the hydrothermal fluids cannot be constrained, however, relative differences between the hydrothermal fluids responsible for alteration in each locality can be inferred. Conditions of fluids responsible for alteration are constrained by vein selvedges of di + q + cc + tr, q + cc + tr ± bi, and q + cc + chl + bi from south to north, respectively. X_{CO_2} conditions of northern and central vein selvedge stability are unconstrained towards higher X_{CO_2} values, however an X_{CO_2} of typical greenschist-facies gold deposits is assumed (Ho et al. 1990). Prograde hydrothermal alteration associated with gold deposits appears to have formed at progressively higher temperatures from north to south within the Norseman Terrane. Diagram was constructed using the Thermocalc database of Holland and Powell (1990). Reactions not labelled on diagram *2* cc + cz + q = gr; *3* tr + cz + q = di + an; *4* cz + chl + ksp = an + phl + q; *5* chl + cz + q = tr + an; *6* phl + cz + q = ksp + tr + an

steep temperature gradient over a few millimetres is required. The narrow nature of the vein selvedges at Scotia, abundance of calcite in the veins, and the presumed isothermal conditions of the alteration process precludes these possibilities. It is more plausible that this alteration zonation reflects steep chemical gradients away from the veins, with alteration mineralogy predominantly controlled by the activites of Ca, K, SiO_2, as well as X_{CO_2} and fluid/rock ratio (cf. Ridley 1990).

Assuming the presence of steep chemical gradients away from the vein, only vein and vein selvedge assemblages, which are minerals deposited directly from the hydrothermal fluid, yield information about the initial P–T–X_{CO_2} conditions of the fluid (Ridley 1990). These critical assemblages are represented for each of the Norseman deposit groups on Fig. 9, from which the relative temperatures and fluid compositions that formed each of the deposits can be deduced. Southern deposits formed from higher-T fluids (> 500°C), whereas Northern deposits involved lower-T fluids (about 420°–475°C). The thermal difference between deposits is corroborated by variation in structural style and mineral textures. The Southern deposits are dominated by ductile deformation, with only thin discontinuous veins present, and mineral textures exhibiting a large degree of dynamic recovery. Northern deposits show much more evidence of brittle-ductile deformation, with ductile shear zones hosting thick, massive quartz veins containing abundant wallrock inclusions, and mineral textures lacking any significant degree of dynamic recovery. These observations imply higher temperatures of deformation and alteration in the Southern deposits.

X_{CO_2} conditions of the hydrothermal fluids are difficult to constrain from Fig. 9. The breakdown of metamorphic epidote/clinozoisite in distal alteration zones, where $X_{CO_2(fluid)}$ is initially very low (< 0.08), indicates that reaction 1 is traversed in all deposits. However, the flat, non-intersecting trajectories of the plotted reactions precludes precise determinations of X_{CO_2} conditions to the right of reaction 1. $X_{CO_2(fluid)}$ values of 0.1–0.2 are commonly quoted for Archaean "mesothermal" gold deposits (Ho et al. 1990), and given the similarities in structural style and mineralogy to other high-T Archean lode gold deposits (Table 1, Ho et al. 1990) this range is assumed for Fig. 9. The presence of clinozoisite or garnet in the Southern deposits, coupled with the Ca metasomatism indicated by the mineral assemblages, suggests that the vein selvedge mineralogy in these deposits is controlled by the activity of Ca in the fluid at or near the projected X_{CO_2} values (garnet = highest a_{Ca}, clinozoisite = lower a_{Ca}, cf. Fig. 2D of Ridley 1990). Resolution of fluid compositions is attendant upon the results of ongoing stable isotope and fluid inclusion studies.

Relative timing of alteration. Variably deformed veins and alteration assemblages indicate that all deposits formed during deformation. However, the deposits differ in their relative timing with respect to metamorphism. Northern deposits possess alteration assemblages with less calcic plagioclase, chlorite rather than actinolite stable, a lack of dynamically recovered gangue minerals and common monomineralic vein selvedges, which collectively reflect formation at temperatures below the thermal metamorphic peak. However, Central deposits have alteration assemblages that exhibit textures consistent with formation close to the peak of metamorphism. Amphiboles and plagioclase are stable both at the vein selvedges and in the metamorphic assemblages. Amphiboles exhibit progressive grain-coarsening towards the centre of fibrous aggregates. Locally, coarse-grained amphiboles overgrow the fabric in biotite zones, yet are commonly deformed or partially altered back to biotite (Fig. 5C). Plagioclase in the metamorphic assemblage has the same composition as plagioclase at the vein selvedges, consistent with similar thermal conditions for metamorphism and hydrothermal alteration. Quartz in the veins shows variable degrees of deformation and dynamic recovery, yet monomineralic vein selvedges with fibrous textures are common. These textural and compositional relationships imply growth during deformation and alteration at elevated temperatures near the thermal peak. The Central deposits are, therefore, interpreted as having formed syn- to possibly post-peak metamorphism. In high-temperature alteration assemblages in the Southern deposits, amphibole has commonly overgrown the fabric, and quartz and clinopyroxene in the veins shows pronounced dynamic recovery. Rosettes of fibrous amphibole on some vein selvedges, intense fabric development in the altered wallrocks, and the presence of löellengite rimmed by arsenopyrite, however, eliminates the possibility that these deposits were formed prior to the peak of metamorphism. If the deposits has been metamorphosed, greater amounts of annealing and no fibrous amphibole aggregates would be expected, monomineralic vein selvedges would be rare, and arsenopyrite would be rimmed by löellengite due to desulphidation reactions that occur during prograde metamorphism (cf. Barnicoat et al. 1991). The Southern deposits are, therefore, interpreted as having formed broadly coeval with the peak of metamorphism. Thus, a regional zonation of hydrothermal alteration exists between the deposit areas at Norseman, ranging from post-peak metamorphism, upper-greenschist facies in the north to syn-metamorphic, mid-amphibolite facies in the south.

Mineralisation. Gold is dominantly sited within the quartz veins in all deposits, typically in paragenetically late sites. However, gold is also observed as isolated inclusions in quartz and sulphides (Fig. 8D) and minor gold haloes extend into the wallrock (McCuaig and Kerrich 1990). Golding (1982) obtained a temperature of 430°C for arsenopyrite mineralisation in the North Royal deposit, consistent with temperature estimated during this study for the hydrothermal wallrock alteration assemblages. In conjunction with the location of orebodies in dilational sites on the dextral-reverse ductile-brittle shear systems (Campbell 1990), and timing constraints listed above, these observations collectively imply that quartz and gold was deposited at high temperature in structurally favourable sites in the ductile-brittle regime. Substantial remobilisation of gold may have occurred in the vicinity of Proterozoic faults, as indicated by Proterozoic Pb–Pb dates on some galenas associated with native gold, (Perring and McNaughton 1990).

A crustal continuum of gold deposits in the Norseman Terrane?

The genesis of Archaean lode gold deposits with high-temperature alteration assemblages (Table 1), and their timing relationships with respect to regional metamorphism, has been the subject of extensive debate, but until recently there were few data to constrain the processes involved. Models proposed for the genesis of these deposits include prograde metamorphism of typical greenschist-facies deposits (Phillips 1985, Hamilton and Hodgson 1986), syn-metamorphic mineralisation at the P–T conditions indicated by the alteration mineral assemblages (amphibolite facies and granulite facies, Barnicoat et al. 1991), or formation as skarns (Mueller 1991, 1992).

The prograde metamorphism model, specifically suggested for Norseman by Golding et al. (1990) is discounted on textural grounds. Fibrous rosettes of minerals such as amphibole, chlorite and biotite, variable degrees of dynamically recovered alteration and gangue minerals, and common monomineralic vein selvedges (high thermodynamic variance) collectively are consistent with alteration assemblages formed in an open hydrothermal system with little, if any, subsequent modification (e.g. prograde metamorphism).

The classification of high-temperature gold deposits as skarns is based largely upon the presence of calc-silicate hydrothermal alteration assemblages (Mueller 1991, 1992). However, it has been established that typical "mesothermal" gold-bearing fluids would be expected to produce calc-silicate alteration in these amphibolite-hosted deposits due to the higher temperature of their formation (Fig. 9) and concomitant variations in the activities of major fluid components (specifically an increase in Ca activity, cf. Ridley and Barnicoat 1990, Ridley 1990). The Northern and Central lode gold deposits of the Norseman Terrane are best classified as higher-temperature counterparts of typical greenschist facies "mesothermal" lode-gold deposits, based on their similarity to documented greenschist facies deposits with respect to structure, vein morphology, and alteration chemistry (McCuaig and Kerrich 1990, cf. Kambalda area; Clark et al. 1986, 1989). The Southern deposits, with their differences in alteration as compared to Central and Northern deposits, bear a striking resemblance to gold-silver skarns in the Southern Cross Province described by Mueller (1991). However, these deposits collectively possess similar host rocks and structural controls on mineralisation, and differences between them can be explained by their formation from a similar fluid over a range of temperatures.

The correlation of alteration mineralogy with metamorphic grade of the host rocks has been recognised for some time (Colvine et al. 1988, and references therein). Single deposits generally show no vertical zonation of alteration mineralogy, even over extensive down-dip extents (Colvine 1989); therefore, alteration in any one deposit in interpreted as having formed under isothermal conditions: a reasonable conclusion in light of their likely depth of formation (1–5 kb, or 5–25 km, Groves 1993 this volume), and uniform $\delta^{18}O_{quartz}$ values, assuming a constant $\delta^{18}O_{fluid}$ (Kerrich 1989). Colvine et al. (1988) proposed that deposits in greenschist and lower amphibolite facies both formed syn- to post-peak metamorphism and are, therefore, characterised by different alteration assemblages due to the different, P, T of their formation. Groves (1993) extends this concept, stating that "mesothermal" gold deposits in terranes of varying metamorphic grade may have formed from a common process and fluid composition, and speculates on a crustal continuum of gold deposits that were emplaced under P–T conditions ranging from prehnite-pumpellyite to granulite facies. Significantly, Groves also notes that a continuum of deposits has yet to be demonstrated in any one crustal profile.

Basalts of the Woolyeenyer Formation range from upper-greenschist (Northern deposits) to mid-amphibolite metamorphic grade (Southern deposits), and hydrothermal alteration associated with the gold deposits reflects the metamorphic grade of their hosts (Northern deposits = upper-greenschist grade alteration, Southern deposits = amphibolite grade alteration). In light of the N-plunging Penneshaw anticline (Fig. 1), the relative position of the deposit groups to regional granitoid complexes (Fig. 1), and possible thrust movement along the Dambo Fault, it is possible that this regional zonation of alteration mineralogy and metamorphic grade reflects (1) a temperature zonation directly related to proximity to regional granitoid complexes (Southern = closest, Northern = furthest), or (2) an oblique section through the Archaean crust, with deeper levels exposed in the vicinity of the Southern deposits. Consequently, Norseman is a well-suited gold district in which to test the crustal continuum model.

Although quantitative P–T–t data for the Norseman Terrane are limited, an analogy can be drawn to the Red Lake district of the Archaean Uchi Greenstone Belt in the Superior Province, Canada. In the Red Lake region, timing relationships between regional metamorphism, deformation, batholith emplacement, hydrothermal alteration and mineralisation are quantitatively and texturally constrained to a limited time interval, and all events are coeval (Table 1, Andrews et al. 1986). Metamorphic grade ranges from greenschist to amphibolite facies, alteration mineralogy in any one deposit reflects the metamorphic grade of its host rocks, and the transition from lower to higher metamorphic grade deposits is continuous.

Structural, textural, and mineralogical observations of gold deposits in the Norseman Terrane are similar to those of the amphibolite facies gold deposits at Red Lake, and elsewhere (Table 1). In the crustal continuum model for Norseman, ore-fluids responsible for the high temperature deposits are not necessarily envisaged as moving up through the crust in a single vertical 'pipe' to generate progressively lower T deposits at progressively higher crustal levels. Rather, fluids are considered to have been generated in a large, laterally extensive deep source, and to have advected up transcrustal structures, maintaining approximate thermal equilibrium with the crust. Gold mineralisation occurs where the fluids advect into structurally favourable locations. Thus, gold deposition may have occurred under upper amphibolite facies conditions at a specific point, and laterally, in the third dimension, at higher crustal levels under greenschist facies conditions. Gold deposits of the Norseman Terrane may thus provide the missing link between greenschist and amphibolite-facies in a crustal continuum of Archaean "mesothermal" lode-gold deposits in the Yilgarn Block of Western Australia.

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