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ARCHAEOAN GOLD DEPOSITS OF AUSTRALIA

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INFORMATION CIRCULAR NO.175

UNIVERSITY OF THE WITWATERSRAND
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by

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ABSTRACT

Archaean greenstone belts have been the source of 50 per cent of world gold production (includes Witwatersrand contribution). Thirty per cent of Australia's gold production (2000 t Au, out of 6000 t Au total) has come from greenstone belt gold deposits of Western Australia, of which Kalgoorlie (1200 t Au) is by far the largest deposit.

Gold distribution is heterogeneous within Australian greenstone belts and favours the younger (2.8 Ga) rift-phase successions of the Eastern Goldfields Province. The largest deposits are in mafic rocks (metadolerites and metabasalts) of greenschist facies grade, in areas of considerable structural complexity. Shear zones, thick quartz veins and vein stockworks all form important sites for mineralization, and each is itself controlled by host-rock type. Wallrock alteration is ubiquitous around the mafic-hosted deposits and includes narrow auriferous pyritic zones, K-metasomatic zones and broad zones of carbonation. Variations in alteration style mainly reflect fluid access and host rock composition.

Banded iron-formations are important host rocks in the platform-phase greenstone belts, but are at least an order of magnitude smaller than the largest mafic-hosted deposits. Sulphide mineralization and gold are spatially and genetically associated with quartz veins and later structural features, and there is no critical evidence of syngenetic concentrations of gold. The Water Tank Hill deposit show clear epigenetic evidence on the regional, mine, stope, hand-specimen and microscopic scales. Only some of this evidence is preserved at other deposits in banded iron-formation.

All the larger gold deposits, both those in mafic rocks and banded iron formations, illustrate two essential features of gold localization : adequate fluid access to large volumes of host rock, and fluid-wallrock interaction that leads to gold precipitation. Iron-rich host rocks are typical of all the larger gold deposits.

Metamorphosed gold deposits are less-well understood, but Big Bell represents a major gold resource and a very attractive modern exploration target. Amphibolite facies metamorphism has overprinted gold-related alteration and produced mica schists in and around mineralization.

The metamorphic replacement model is the only model that can adequately explain features of all the large gold deposits. It invokes metamorphic fluids, derived by devolatilization deeper in the greenstone sequence, that rise along major shear zones until they reach depositional sites. Reaction between Fe in host rocks and gold-sulphur complexes in solution, leads to Fe-sulphide formation and gold precipitation.

Exploration for greenstone gold is likely to remain concentrated around known goldfields, but with a greater emphasis on alternative host rocks and/or different structural settings, from those already dominating production. Major new discoveries are likely to involve the application of regional metallogenic, and more local gold genetic, models, coupled with geophysical techniques in covered areas. Means of differentiating major deposits from the numerous smaller ones, will play an important role in prospect evaluation.

ARCHAEOAN GOLD DEPOSITS OF AUSTRALIA

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ARCHAEOAN GOLD DEPOSITS OF AUSTRALIA

I. INTRODUCTION

Archaean terranes account for over half the World gold production (Fig. 1). Of this 30000 t have come from the Witwatersrand Basin of South Africa, presumably derived from a neighbouring Archaean craton (Pretorius, 1981). A further 20000 t have been produced from Archaean greenstone belts, mainly in Canada (6000 t), Australia (2100 t) and Zimbabwe (2000 t). Within Australia, production from Archaean terranes is comparable to that from the Palaeozoic geosyncline of Victoria or from the rest of Australia (Table 1).

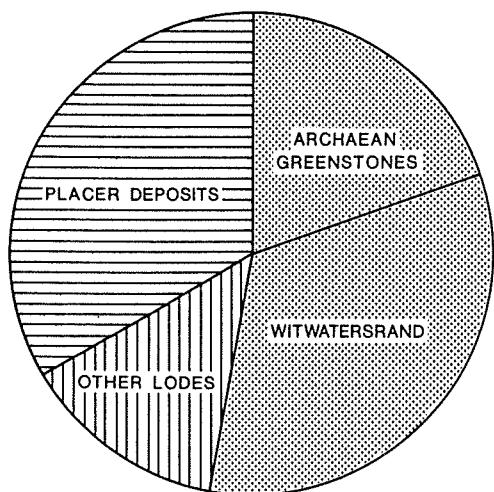


Figure 1 : Breakdown of all-time gold production (total 100000 t) into major associations.

TABLE I
Major World Gold Associations, and their Importance Within Australia

Gold Association	World (%)	Australia (10^3 t)
<u>Witwatersrand</u> (pebble conglomerate)	30	-
<u>Archaean greenstone belts</u>	20	
volcanic		1,8
sediment		0,2
<u>Palaeozoic turbidite sequences</u>	20	
Victoria		2
rest of Australia		2
<u>Tertiary volcanics</u>	15	-
<u>Placers</u>	30	added to primary source
Archaean		minor
Palaeozoic		major
	10^5 t	6×10^3 t

The first significant gold discovery in Western Australia was in 1885 in the far north at Halls Creek. Soon after, the major goldfields of the Yilgarn Block were discovered - Southern Cross (1888), Coolgardie (1892), Kalgoorlie (1893) - and State production peaked at 75 t of gold in 1903 at a time when Australia was the world's leading gold producer. At the same time the major South African goldfields had been discovered (1886), and Victoria production was waning after the initial rush of 1851. By 1920, most of the significant Western Australian gold deposits had been discovered from outcrop, and despite small revivals, production had since decreased (Fig. 2).

The long and intense weathering history of the Archaean Yilgarn Block of Western Australia, including widespread lateritization, has led to considerable supergene gold enrichment and nugget formation. Neither supergene enrichment nor placer formation (minor in the Yilgarn Block) are discussed below, and the interested reader is referred to Mann (1984) and Webster and Mann (1984).

This paper outlines different Western Australian gold deposits and describes some larger vein-type deposits in mafic rocks, disseminated deposits in banded iron-formation, and some other important gold deposits.

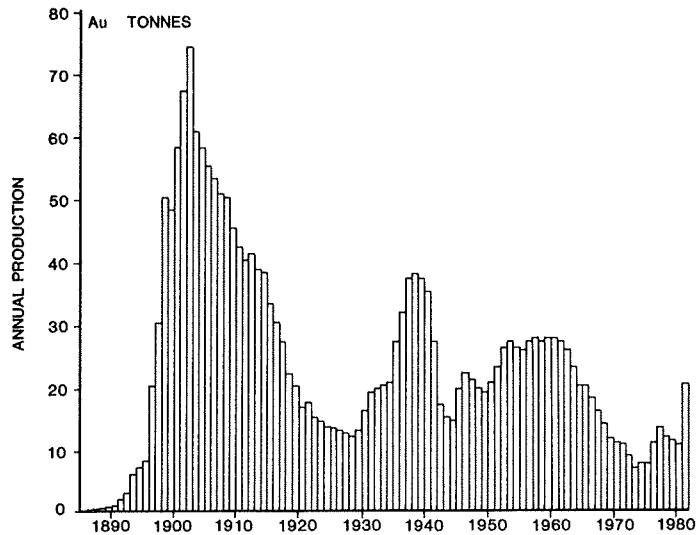


Figure 2 : Annual gold production from Western Australia (from Mines Department, Western Australia)

The term "vein-type deposits" is used to cover mineralization that, in detail, transgresses layering and may be classic vein-filling with replacement, shear-related lodes or stockworks. In contrast, "disseminated deposits" include near-stratiform sediment-hosted deposits and other broadly stratiform mineralization. The description of deposits is emphasized as it forms the basis for both genetic and exploration models. Finally, an overall genetic model is discussed that allows predictions about prospective greenstone belts and the identification of large deposits.

Most Archaean gold deposits are stratabound in the sense of showing strong host-rock control. In some deposits, gold is directly related to veining which is developed only in one specific lithology (Fig. 3); whereas in other deposits, a more subtle stratigraphic control is apparent. Yet other gold deposits, commonly in specific well-layered host rocks, are disseminated and near-stratiform.

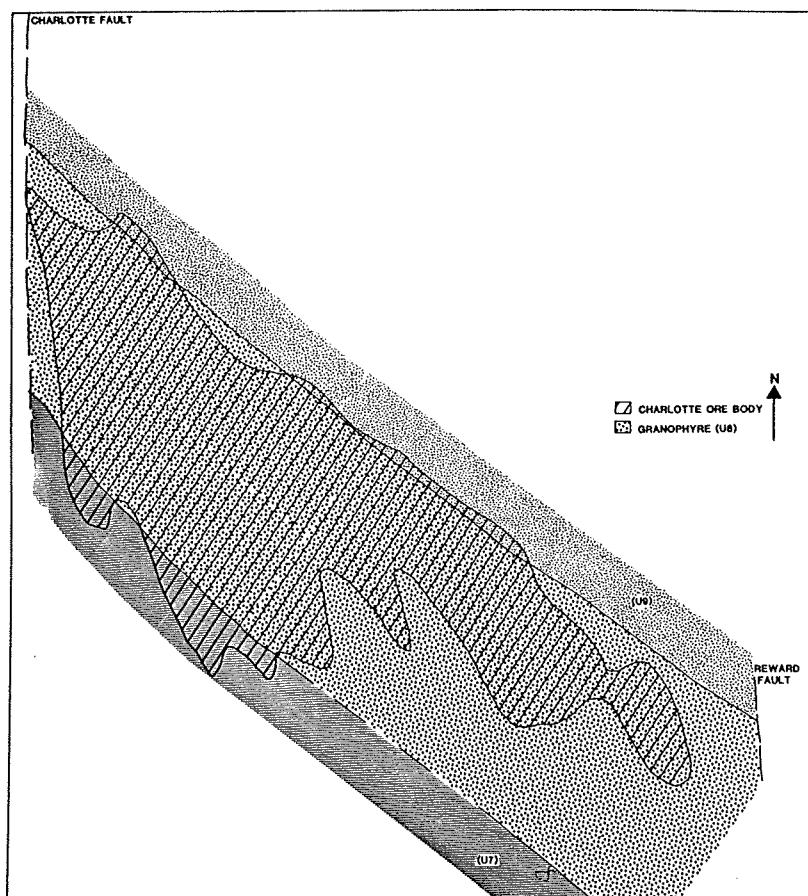


Figure 3 : Plan of the Mt Charlotte Mine illustrating strata-bound nature of stockwork mineralization. Although the gold is vein-related, veining is restricted to one specific unit (i.e. granophyre) of the Golden Mine Dolerite. Units 7 and 9 (both ophitic) have only minor veining, alteration and gold mineralization.

II. AN OVERVIEW OF WESTERN AUSTRALIAN ARCHAEN TERRANES

In Australia, the two major areas of Archaean rocks are the Pilbara and Yilgarn blocks of Western Australia. Both blocks comprise granitoid-greenstone terranes, but a number of important differences between them are summarized below.

The Pilbara Block appears to be characterized by stellate greenstone belts as old as 3500 Ma and some shallow water environments in the east, with younger, more linear belts of fluvial to trough sediments. The Yilgarn Block contains several deeper water sequences, greenstone belt ages from 3000 to 2800 Ma, and mineralization is much more intense (Fig. 4).



Figure 4 : Map showing the Yilgarn and Pilbara cratons. The largest gold producers are shown and account for over 75 per cent of gold produced from the Australian Archaean.

Studies of the east Pilbara Block (Barley *et al.*, 1979; Bettenay *et al.*, 1981; Hickman, 1981) are facilitated by particularly good outcrop. The area is characterized by few ultramafic rocks, laterally continuous sediments, and extensive carbonate and siliceous alteration that, in some areas, leaves little trace of original whole rock composition. The main mineralization in the east Pilbara appears to be tin, molybdenite and barite, with little nickel or gold (Groves, 1982). Small nickel-copper and copper-zinc deposits occur in the west Pilbara.

The Yilgarn Block can be conveniently subdivided into four provinces (Gee, 1979). Along the western margin, the Western Gneiss Terrane (Fig. 5) contains small sedimentary sequences infolded with granitic gneisses. The regional metamorphic grade in this terrane is mostly amphibolite to granulite facies, and ages from the north-west sector of the Yilgarn Block are as old as 4200 to 4000 Ma years (De Laeter *et al.*, 1981; Compston *et al.*, written comm., 1982). The Western Gneiss Terrane lacks significant gold or nickel deposits.

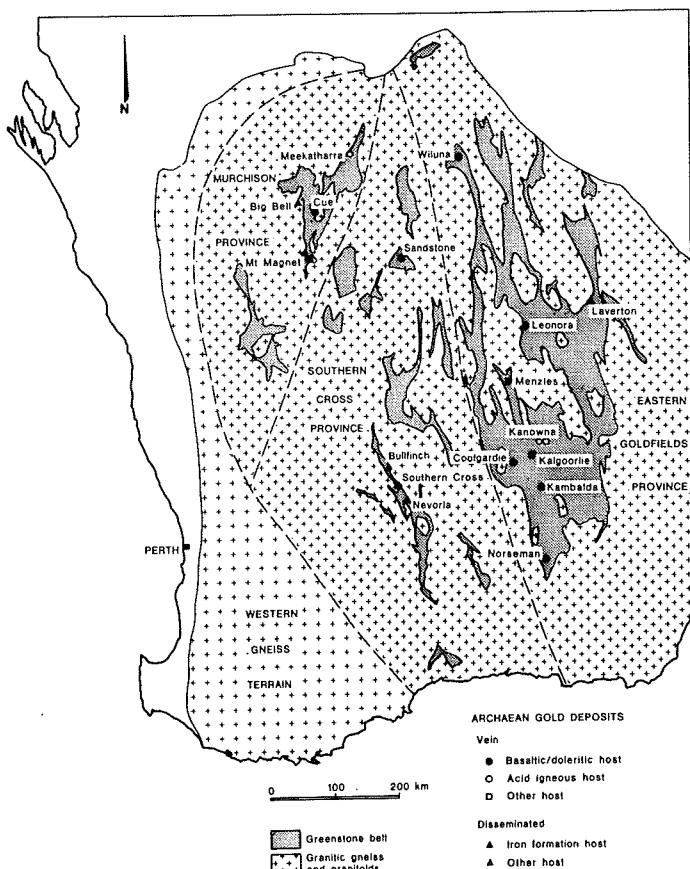


Figure 5 : Map of the Yilgarn Block showing main tectonic provinces and a selection of gold deposits.

The rest of the Yilgarn Block comprises three provinces of granitoid-greenstone belts (Fig. 5). The Murchison and Southern Cross provinces are, in many ways, intermediate between the Pilbara Block and Eastern Goldfields Province (Groves and Batt, 1984). These two provinces contain significant, but narrow, greenstone belts of around 3000 Ma (Fletcher and Rosman, 1981), commonly with banded iron-formations, but only minor komatiites. Little is known about depositional environments or metamorphic grade on a regional scale, although greenschist facies areas are widespread, and higher grades occur on greenstone belt margins. Gold deposits of moderate size are found in banded iron-formation and mafic rocks, but nickel mineralization is minor. Golden Grove in the Murchison Province (Frater, 1978) is the most significant copper-zinc massive sulphide deposit in the Western Australian Shield.

The Eastern Goldfields Province includes the youngest greenstone belts (ca 2800 Ma; McCulloch *et al.*, 1983) and is rich in gold and nickel deposits. It contains wide linear greenstone belts, and the greenstone sequences are characterized by a high proportion of komatiites. The Norseman-Wiluna belt, in particular, exemplifies these characteristics, and is virtually devoid of banded iron-formations. This belt has widespread deeper water sediments and fewer laterally continuous sequences, contrasting it with the Pilbara Block (Gee, 1979; Groves, 1982). Carbonate alteration, although very common, does not usually remove the geochemical signature of the original rock types. Large parts of the Eastern Goldfields Province that are poorly auriferous, appear to correspond to shallower water sequences (Phillips and Groves, 1984).

The progression from the Pilbara through the Southern Cross/Murchison to the Eastern Goldfields provinces corresponds to greater gold, nickel, komatiites, and deeper water sediments. It has been suggested that this progression represents increased crustal extension rates with time (Groves, 1982).

Similar variations appear to affect the greenstone belts of the Canadian, Zimbabwean, and South African Archaean cratons (e.g. Groves and Batt, 1984). Gold is most common in younger (3.0-2.8 Ga) greenstones (e.g. Abitibi belt) and in deeper water, widely-carbonated sequences that contain ultramafic rocks.

TABLE II
Australian Archaean Gold Producers

Location	Deposit/Type	Tonnes	Host Rock	Mineralization
<u>EASTERN GOLDFIELDS PROVINCE</u>				
Kalgoorlie	Golden Mile	1000	dolerite	vein (shear zone related)
	Oroya	200	basalt/sediments	breccia vein near contact
	Mt Charlotte	50	granophyre	quartz vein
Leonora	Sons of Gwalia	90	amphibolite	quartz vein
Norseman	Mararoa-Crown	69	basalt	quartz vein
	Princess Royal	46	basalt	quartz vein
Wiluna	Wiluna	46	basalt	quartz vein
Laverton	Lancefield	18	banded iron-formation	disseminated
Kanowna	White Feather	7	conglomerate	quartz vein (Kanowna Main Reef)
	Red Hill	1	felsic	quartz vein
Kambalda	Hunt	1	basalt	quartz vein
	Victory	1	basalt/sediments	quartz vein
<u>SOUTHERN CROSS PROVINCE</u>				
Bullfinch	Copperhead	21	banded iron-formation	disseminated
Marvel Loch	Marvel Loch	1	basalt	quartz vein
	Nevoria	2	banded iron-formation	disseminated, quartz veins
Southern Cross	Fasers	9	basalt	quartz vein
<u>MURCHISON PROVINCE</u>				
Big Bell	Big Bell*	110	schist	disseminated in altered mafic
Cue	Great Fingall	39	dolerite	quartz vein
	Golden Crown	1	dolerite	quartz vein
Mt Magnet	Hill 50	42	banded iron-formation	disseminated
	Hill 60	2	banded iron-formation	disseminated, quartz veins
	St George	4	banded iron-formation	disseminated
	Water Tank Hill	1	banded iron-formation	disseminated, quartz veins
	Morning Star	3	basalt	quartz vein
Meekatharra	Paddys Flat	28	? schist	quartz vein, porphyry
<u>PILBARA BLOCK</u>				
Marble Bar	Comet	4	ultramafic	vein

* includes published reserves

III. OUTLINE OF WESTERN AUSTRALIAN GOLD DEPOSITS

There are over 2 000 gold deposits in the Archaean greenstone belts of Western Australia (Maitland, 1979), but a small fraction of these accounts for most of the production (Fig. 6). The ten largest deposits, all in the Yilgarn Block, account for 75 per cent of total Archaean production (Table II). Even allowing for its smaller area than the Yilgarn Block, the Pilbara Block has produced little gold (Fig. 4). Production from the high metamorphic grade Western Gneiss Terrane is negligible, and within the granitoid-greenstone belt terranes, all deposits are in the greenstone belts or within a kilometre of their margins. Within the Yilgarn Block, gold distribution is heterogeneous, and is dominated by the Eastern Goldfields Province and in particular Kalgoorlie (Figs. 6 and 7; Table III), the only giant goldfield.

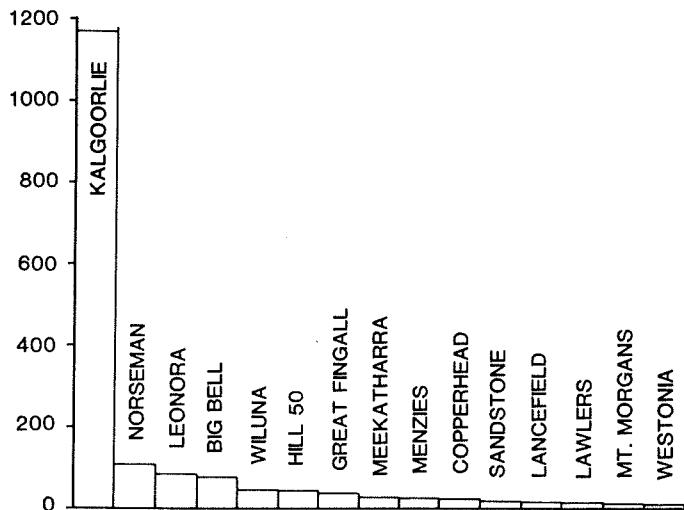


Figure 6 : Histogram of total production and established reserves at 1980 from the larger Western Australian gold mines (in tonnes Au).

TABLE III
Subdivision of Archaean Gold Deposits

Relationship to Layering	Host Rock
VEIN-RELATED	mafic felsic ultramafic granitic other
DISSEMINATED	banded iron-formation other metasediment other
Size	Class
over 1000 t Au	giant
100 - 1000 t	very large
10 - 100 t	large
1 - 10 t	medium
less than 1 t	small

Although small deposits are widespread throughout the Archaean greenstone belts, they are concentrated near the few larger deposits, partly because of more intense exploration there. For example, Hill 50 Mine in the Murchison Province is surrounded by numerous smaller deposits, some in banded iron-formation like Hill 50, but others in metabasalt, felsic metavolcanics and metasediments (Fig. 8). These concentrations of smaller deposits with a few larger ones, define fields (e.g. Mt Magnet Goldfield), and most goldfields are characterized by several different gold deposit styles, even though one style may account for most production. At Cue, for example, most gold has come from quartz veins in a quartz dolerite of the Great Fingall deposit (39 t), but small mines are common in neighbouring metasediments (e.g. Mountain View, see Fig. 24), less siliceous parts of the same dolerite, felsic metavolcanics, and granitoid margins.

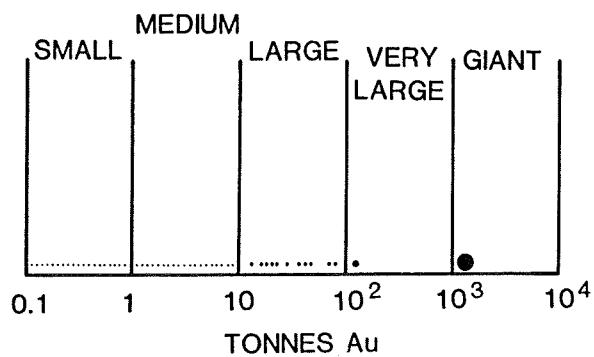


Figure 7 : Classification of Australian Archaean gold deposits by size, based on a logarithmic scale. Kalgoorlie and Timmins (Canada : not shown) are the only giant greenstone gold deposits in the Archaean, but Canada has a number of very large deposits.

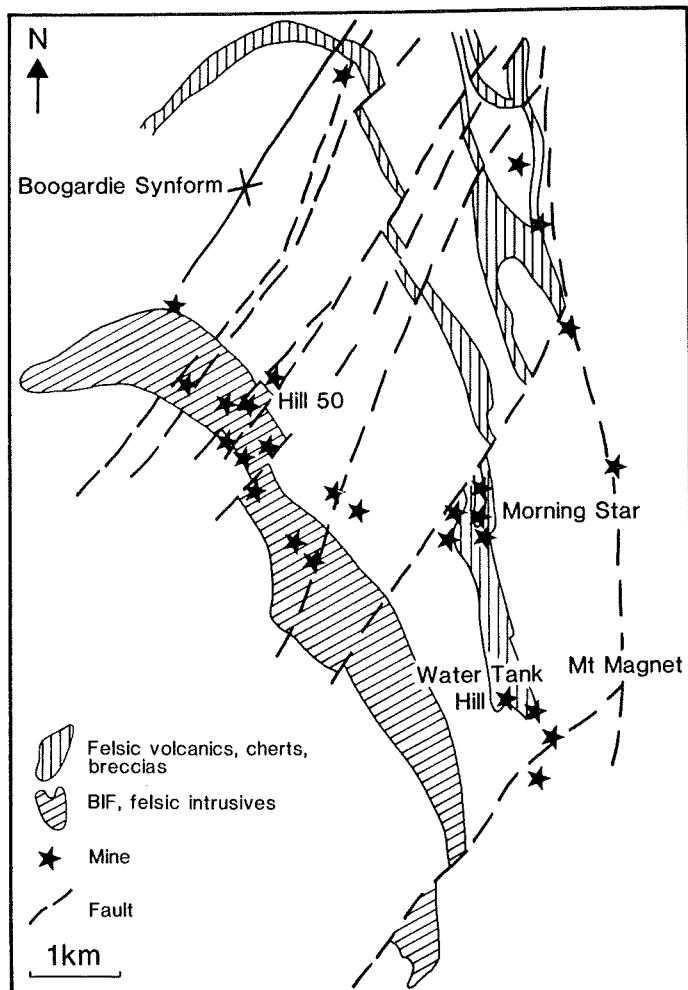


Figure 8 : Gold deposits of the Mt Magnet area showing a diversity of host rock settings (from Archibald, 1982). Unshaded areas are mostly basaltic, felsic, and ultramafic rocks, with some banded iron-formation.

Several schemes have been devised to classify Archaean gold deposits (e.g. Boyle, 1979), but none are completely satisfactory. One of the major problems is that several different styles of mineralization, and even different host rocks, may exist in a single gold mine, and although the styles are too intimately related (spatially and temporally) not to bear a genetic relationship, they commonly fall into quite different classifications. On a broader scale, the range of deposits in a single goldfield also presents problems to any scheme, as several categories of deposit may exist side by side. In essence, deposits can be categorized in many ways, but the value of certain schemes is dubious.

The classification approach taken here aims to identify the main associations (Table I) and then, within the greenstone association, to distinguish the host rocks and the relationship of mineralization to primary layering (e.g. vein, disseminated), and the deposit size. Host rocks to the Archaean deposits include mafic, felsic, and ultramafic metavolcanics and intrusives, granitoids, banded iron-formations and clastic metasediments. Mineralization may be grossly discordant (though still stratabound), as in vein-type deposits, or may be near-stratiform and disseminated (Table III). Any further classification runs into problems because, when studied closely, every deposit is morphologically quite distinct. It is not until the genesis of the Western Australian deposits is considered (below), that unifying concepts can be used to relate large numbers of seemingly dissimilar deposits.

Most of the gold produced in Western Australia has come from vein-type deposits in mafic rocks (over 70%), with significant production from disseminated deposits in banded iron-formation (15%). In general, deposits in felsic extrusives and intrusives, clastic sediments, and ultramafic rock, are small and contribute less than 10 per cent to the total production. This breakdown of deposit types is similar to that for the younger (3,0-2,8 Ga). Archaean terranes of Zimbabwe which are also dominated by vein-type deposits in mafic rocks (Foster *et al.*, 1985). Older (3,5-3,0 Ga) Zimbabwean greenstone belts have more deposits in banded iron-formation. The smaller Barberton greenstone belt of South Africa has significantly more deposits in clastic and chemical metasediments than Western Australia (Fig. 9); and the Canadian Shield has a larger production from felsic intrusives and meta-sediments (Boyle, 1979), though mafic host rocks still dominate.

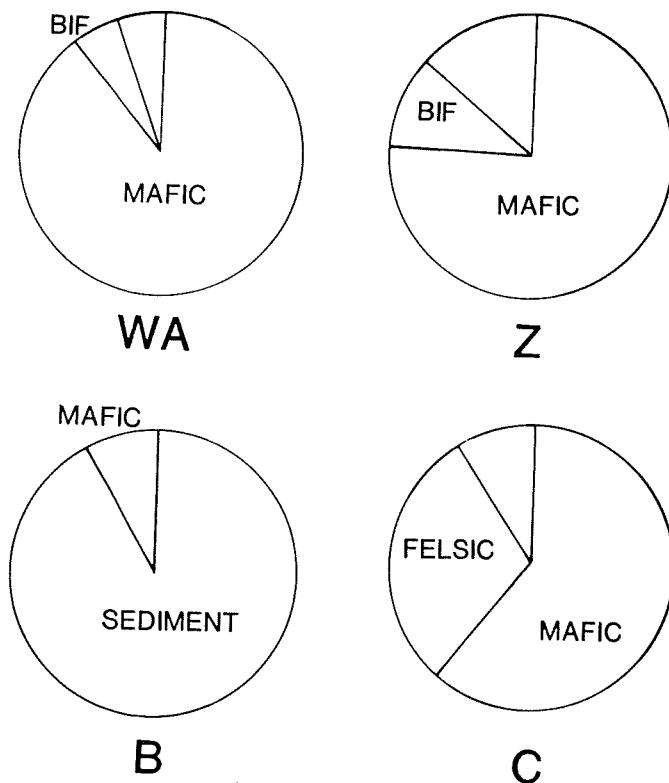


Figure 9 : Proportions of gold production from varying host rocks in the Western Australian (WA), Zimbabwean (Z), Barberton (B) and Canadian (C) Archaean cratons. Unlabelled segments include gold from a variety of less important rock types.

IV. MAFIC-HOSTED VEIN DEPOSITS

Vein-type deposits in mafic rocks are by far the most important gold source in Western Australia, accounting for over 70 per cent of total production. Both metadolerite and metabasalt represent favourable host rocks, and the mineralization can be related to simple or folded quartz veins, shear zones, and fractures without quartz veins, stockworks, or to breccia zones thought to have been formed by hydraulic fracture (Phillips and Groves, 1984).

Within the Yilgarn Block, mafic-hosted vein deposits tend to be more abundant and larger in the younger Eastern Goldfields Province. The older Murchison and Southern Cross provinces have diverse gold deposit types, whereas deposits of the Norseman-Wiluna belt are mainly veins in mafic rocks.

Some mafic host rocks of the Yilgarn Block contain abundant relic igneous textures, whereas others are metamorphically recrystallized amphibolites. Flow-top breccias and pillows are reported, suggesting that many flows were erupted into submarine environments, especially within the Norseman-Wiluna belt. Metadolerites show well-developed magmatic differentiation in sills that are up to several hundred metres thick (Travis *et al.*, 1971). The mafic rocks are typically tholeiitic and Fe-rich, although at some deposits (e.g. Norseman), Fe-enrichment of host tholeites relative to nearby unmineralized sequences, is subtle. Along with Fe-enrichment, more intermediate compositions are host to many gold deposits (i.e. quartz tholeiite granophyres).

The veining or fracturing that defines mineralization can extend to 1-2 km below the present surface, and gold may be confined to quartz veins, to surrounding wallrock alteration, or to shear zones and veinlets that are barren of quartz. The distribution of veins varies with host-rock type. Perhaps the best example is Mt Charlotte, Kalgoorlie (Phillips, 1982), where only the granophyre is veined intensely enough to make an economic deposit (Fig. 3), though adjacent metadolerite contains subeconomic auriferous veins (see below). In many deposits, the veins lie in early deformational features (e.g. shear zones), but are subsequently deformed. The relationship of mineralization to metamorphism varies and syn- and post-peak metamorphic deposits are common in the Yilgarn Block.

The following description of some Western Australian deposits includes a medium sized occurrence (Hunt Mine) that clearly shows the structural and chemical controls on mineralization. Some of the largest mines have been closed for several decades, leaving few records, whereas others such as Kalgoorlie have been the topic of detailed but spasmodic research for a long time. The following descriptions draw partly on published literature from several deposits, but also rely on data of the Archaean Gold Group at the University of Western Australia.

A. Hunt Mine, Kambalda

The Hunt Mine has been studied in detail and provides an example of host-rock control on fluid access and gold precipitation (Phillips and Groves, 1984). Discovered in 1979, the Hunt Mine is a small, low-grade gold deposit (4 ppm) made economic by a pre-existing nickel mining operation.

The regional setting of the Hunt Mine is described by Gresham and Loftus-Hills (1981). Gold mineralization is adjacent to quartz veins that are confined to a biotite schist zone (shear zone) in footwall metabasalt. The overlying massive Fe-Ni-Cu sulphide ore and talc-magnesite ultramafic rock are virtually barren of gold-bearing quartz veins (Fig. 10). The regional metamorphic grade around Kambalda is lower amphibolite facies (hornblende-andesine in tholeiitic metabasalt) and the confining schist zone is inferred to be D_2 in age (Gresham and Loftus-Hills, 1981). Across the schist zone, the 1-2m thick massive Fe-Ni-Cu sulphide ore is offset and attenuated

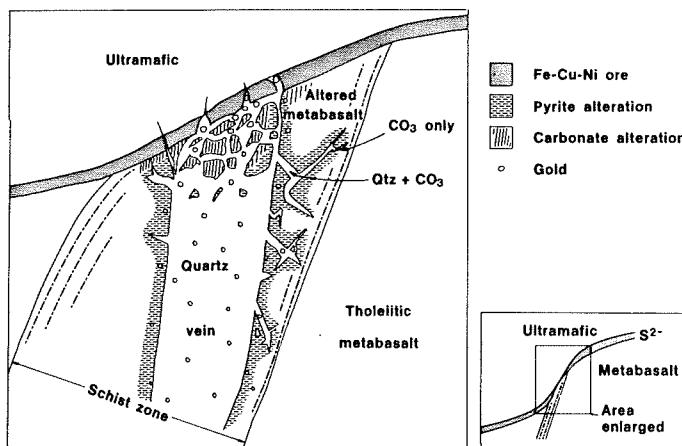


Figure 10 : Schematic cross section of the Hunt gold deposit, showing a veined and mineralized shear zone confined to footwall metabasalts. The shear zone is poorly expressed in the overlying more ductile, ultramafic rocks and the fabric flattens just below this contact (Phillips and Groves, 1984). Only the most intense carbonate alteration is shown (see Fig. 11 for more detail).

1. **Fluid Access:** The geometry of the auriferous quartz veins gives insight into the controls on fluid access in the Hunt Mine gold system (Phillips and Groves, 1984, Fig. 5). More than 10m below the Fe-Ni-Cu sulphide contact,

the quartz veins are 1-2m thick and arranged *en échelon* along the schist zone of the metabasalt. The vein minerals are mainly quartz except at the vein margins and in small, folded offshoots of schist that contain ankerite, calcite, pyrite, and albite. Quartz fabrics include abundant sub-grain development, kink bands and zones of incipient recrystallization, indicating deformation after vein emplacement.

Five to ten metres below the metabasalt-ultramafic contact, the veins are only 2-20 cm thick and form complex conjugate vein-sets, in contrast to the underlying thicker, discrete veins. Closer to the contact, the veining is more intense and results in a breccia of host rock fragments in a quartz matrix. As brecciation intensifies upwards, the rock fragments are smaller and the proportion of vein quartz to country rock is greater.

At the upper contact of the schistose metabasalt, two situations are possible, depending on whether Fe-Ni-Cu sulphides are present or absent at the base of the ultramafic sequence. Where massive sulphides are present, multiple generations of quartz veins terminate at the lower contact of the sulphides. In areas where Fe-Ni-Cu sulphides are absent, the veins terminate within one metre of the lower ultramafic contact as thin chlorite-talc lined fractures.

A further variation is provided by thin acid porphyry sills intruded 1-2m below the Fe-Ni-Cu sulphide contact. Quartz vein thin upon entering the porphyry and either terminate there, or thicken upon re-entering the overlying schistose metabasalt.

TABLE IV
Veining in Different Host Rocks, Hunt Mine

	Mafic Schist	Porphyry	Ultramafic Rock	Sulphide Ore
Veining	several, continuous, 2-100cm thick	many, discontinuous, 1-4cm	rare, 1 cm	none
Mineralogy of Vein	quartz, pyrite, albite, calcite, ankerite	quartz, carbonate	talc, chlorite	-
Alteration	strong, 10's m, pyrite, carbonate	weak, 1-5cm carbonate	poor, 1cm chlorite	poor, perhaps pyrite
Gold Potential	good	fair, limited extent	poor	negligible extent

This contrast in the nature of quartz veining in four different host rocks (Table IV) is evidence that fluid access was controlled by rock type. Quartz veins and the most intense wallrock alteration are restricted to the schist zone, suggesting that this zone has been the channelway bringing hydrothermal fluids into the Hunt Mine environment from depth. Upon meeting any barrier to fluid flow, such as ductile, relatively impermeable ultramafic rocks or massive Fe-Ni-Cu sulphide ore, pore-fluid pressure built up and resulted in the hydraulic fracture and brecciation of more competent rock types. At Hunt Mine, the lower tensile strength of the acid porphyry and mafic schist led to their preferential fracture. The net result was a far greater surface area of schist being exposed to the fluids where veining occurred.

The broader control on hydraulic fracture is uncertain, but may be related to late-stage regional uplift leading to reduced confining pressures (Groves *et al.*, 1984) or to waning deformation, again leading to a relative increase in pore fluid pressure. The first possibility appears unlikely at any reasonable permeability and uplift rate (Etheridge, M.A., pers. comm., 1982).

2. *Fluid-wallrock Interaction:* Enveloping the Hunt Mine quartz veins are several zones of wallrock alteration over a width of \approx 10m. The strong correlation between gold and 1m thick pyritic wallrock alteration zones, and the inefficiency of hydraulic fracture as a precipitating mechanism, suggest that the alteration is the single most important process in precipitating gold from solution. For this reason, the alteration is described in some detail.

The most intense form of alteration is the bleaching of metabasalt in the highly brecciated upper portion of the vein system (Table IV). A wider zone of pyrite-biotite- ankerite-chlorite schist envelopes the veins for 1-2m and marks the outer limit of economic gold (>1ppm). The remainder of the schist zone comprises chlorite- ankerite-biotite schist, which grades outward into non-schistose chlorite-calcite metabasalt and eventually hornblende-plagioclase metabasalt. The disposition of the zones varies along the veins, but an idealized distribution can be compiled from several veins (Fig. 11).

The rather large number of coexisting minerals and the relatively low variance (i.e. degrees of freedom) of many of the alteration assemblages (e.g. biotite-chlorite-plagioclase-pyrite-pyrrhotite-ankerite-calcite-ilmenite-quartz; Phillips and Groves, 1984, Table V), suggest that only a few components have been significantly mobile during wallrock alteration. A whole-rock geochemical profile across a carefully documented vein sequence shows

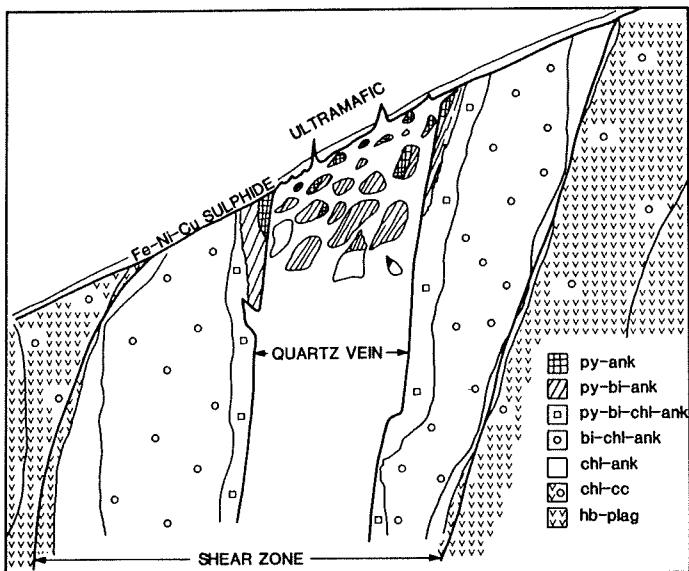


Figure 11 : Schematic distribution of alteration zones around Hunt Mine quartz veins, based mainly on mineral assemblages in Phillips and Groves (1984). Abbreviations used: ank - ankerite, bi - biotite, cc - calcite, chl - chlorite, hb - hornblende, plag - plagioclase, py - pyrite.

systematically coherent behaviour between a large number of elements (Fig. 12). The relative proportions of Fe, Ti, V, P, Al, Zr, Y, Nb, and Mg remain fairly constant indicating that real differences in the absolute amount of any one of these components is due to "dilution-effects" caused by the addition or removal of a mobile component(s), and that these nine components have been virtually immobile.

TABLE V
Alteration Assemblages in Tholeiitic Metabasalt Around Auriferous
Quartz Veins, Hunt Mine (from Metabasalt Towards Vein)

<u>Metabasalt:</u>	hornblende-chlorite-epidote-plagioclase-ilmenite-magnetite-quartz hornblende-chlorite-calcite-plagioclase-ilmenite-magnetite-quartz chlorite-calcite-plagioclase-ilmenite-magnetite-quartz chlorite-ankerite-calcite-plagioclase-ilmenite-quartz biotite-chlorite-ankerite-calcite-plagioclase-pyrrhotite-ilmenite-quartz pyrite-biotite-chlorite-ankerite-calcite-albite-ilmenite-quartz pyrite-biotite-ankerite-calcite-albite-ilmenite-quartz
<u>Vein:</u>	pyrite-ankerite-calcite-albite-quartz
<u>Also:</u>	widespread minor chalcopyrite, sporadic tourmaline, and pentlandite. Some biotite, pyrrhotite, and pyrite outside zones mentioned.

A group of elements, however, were mobile under the prevailing alteration conditions and have, in general, been considerably enriched in the wallrocks (Fig. 13). The wide zone of K-enrichment is paralleled by Ba and Rb enrichment, coinciding with the stabilization of biotite. Narrower zones of S and Au-enrichment coincide with pyritic zones. The extent of carbonate alteration is considerably greater than that of other mobile components and, except for its consistent relationship to auriferous zones, is on a scale (tens of metres) that makes it difficult to directly relate to the gold mineralizing episode. The alternative possibility would be that the carbonate alteration is an earlier event, but timing data do not substantiate this view (Phillips and Groves, 1984).

The composition of individual minerals changes in the space of a metre, with progressive distance from the veins (Phillips and Groves, 1984; Neall and Phillips, 1984). Biotite and chlorite are more Mg-rich nearer the veins, reflecting the formation of pyrite and the concomitant reduction in the amount of Fe available to silicate phases. Ankerite compositions are less systematic and are in the range $Mg/(Mg + Fe) = 0,65$ to $0,8$. Pyrrhotite occurs in small amounts on the outer edges of pyritic zones and in the upper 10m of the vein system below the pre-existing, massive pyrrhotite-rich Fe-Ni-Cu sulphide ore.

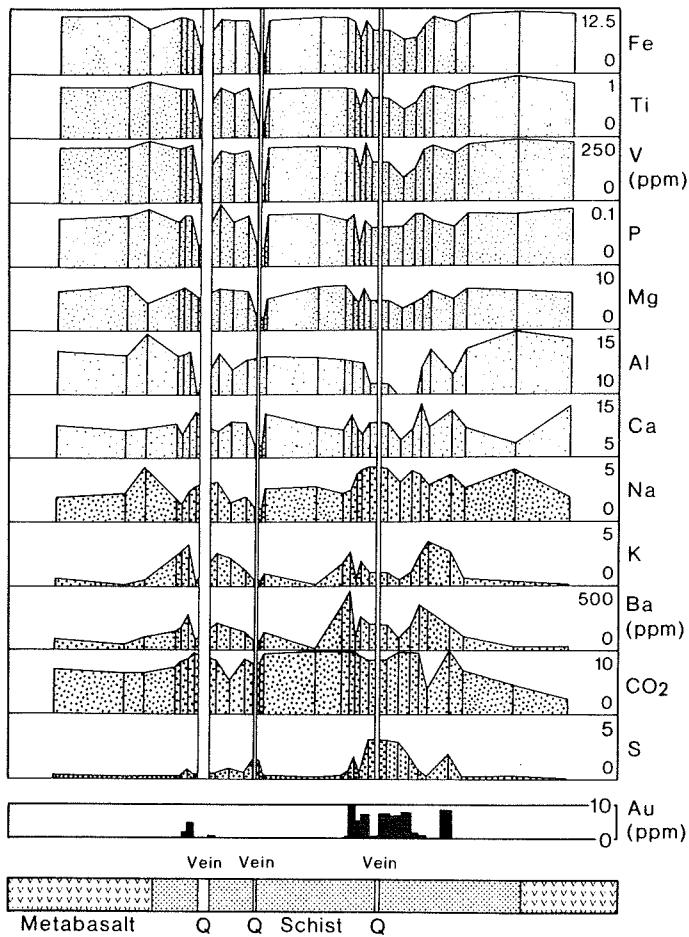
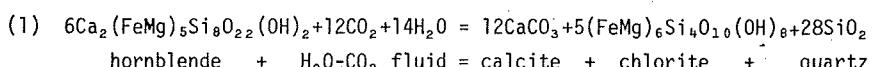
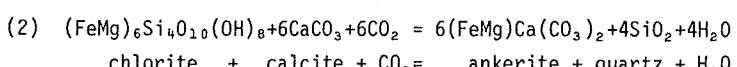


Figure 12 : Immobile (Fe, Ti, Zr, Y) and mobile ($K, Ba, Rb, Sr, CO_2, S, Au$) element profile across Hunt Mine quartz veins showing coherence among the first four components. This coherence is the strongest evidence for immobility. Enrichment of the other components is apparent around veins. Full scale values are in per cent unless indicated (Phillips and Groves, 1984).

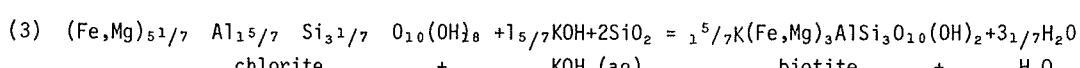
Although the precise wallrock alteration reaction pathway is impossible to specify at present, equations can be deduced that link the various alteration zones and highlight the controlling chemical parameters. On a broad scale, the alteration of the regional metamorphic hornblende-bearing assemblage to chlorite-calcite can be represented by a simplified carbonation equation, using idealized end-member components.



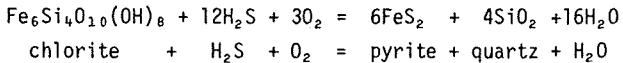
Further carbonation of chlorite-calcite assemblages can incorporate Fe-Mg into carbonate phases, but the coexistence of chlorite-ankerite over several zones indicates that this is at least a divariant (sliding) reaction.



Addition of K^+ to the carbonated metabasalt assemblage is required to stabilize biotite.



The formation of pyrite, whether at the expense of chlorite or biotite leads to a reduction in the activity of Fe-silicate end-member components, and produces more Mg-rich, silicate phases. This trend would tend to stabilize chlorite slightly, relative to the less-Mg biotite, all other parameters being unchanged. The higher $a(S_2)$ required for pyrite stabilization reflects the composition of the hydrothermal fluid (Phillips and Groves, 1984)



This last equation is important because it illustrates the major redox reaction in the alteration system (i.e. the formation of pyrite from Fe-bearing phases). None of the previous equations involved oxidation or reduction of reactants; but as the formation of pyrite requires the oxidation of S^{2-} to S^{2-} , a complementary reduction of the fluid (and its contained metal cations, including gold) results.

The effect of pyrite formation on gold solubility will depend on the form of gold transport. Although gold-sulphur complexing better explains the natural observations at many mines (Phillips and Groves, 1984) any realistic transport will be as Au^{1+} complexes (Seward, 1979), and precipitation will occur in response to fluid reduction.

Equation (4) is controlled not only by fluid composition ($\alpha\text{H}_2\text{S}$, αO_2 , $\alpha\text{H}_2\text{O}$), but also by the composition of the reacting Fe-bearing phases. At Hunt Mine, as Fe-Mg-silicates become more Mg-rich they will retard further reaction to pyrite as the activity of their Fe-end member decrease. No such retardation occurs in reactions involving only Fe-oxides, as Fe-Mg solid solution is negligible in these phases (e.g. magnetite).

These equations (1-4) summarize the gross changes in hornblende metabasalt during wallrock alteration. They require an $\text{H}_2\text{O}-\text{CO}_2$ -bearing fluid phase carrying H_2S and Au, and Fe-rich host rocks. The abundance of $\text{H}_2\text{O}-\text{CO}_2$ is substantiated by fluid inclusion studies (i.e. 75 mole% H_2O , 25% CO_2 ; Ho *et al.*, in press). Freezing experiments on the inclusions suggest low salinities (<3 wt% NaCl equivalent), and homogenization temperatures of 250–300°C are pressure corrected to trapping temperatures of 285–340°C, inferred to be mineralizing temperatures also (Groves *et al.*, 1984).

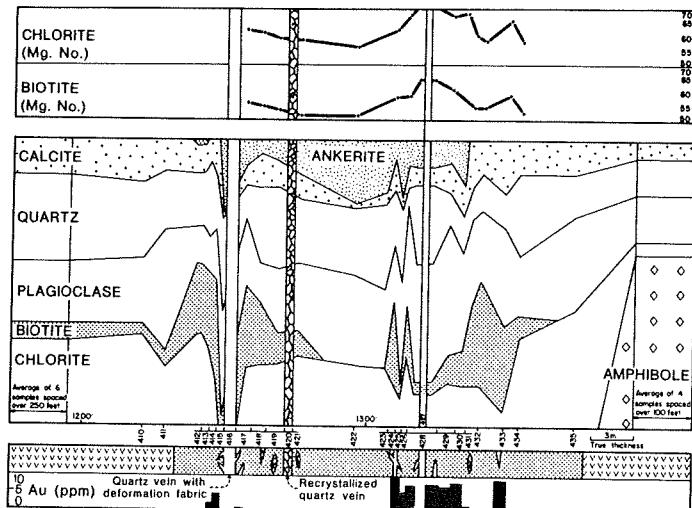


Figure 13 : Mineralogical profile across the Hunt Mine quartz veins showing changes in modal composition and phase chemistry that occur in response to bulk chemical changes (see Fig. 12). Silicate phases become more Mg-rich in the pyrite alteration zone (Phillips and Groves, 1984).

3. Gold Occurrence: Gold is restricted to pyritic alteration within the shear zone, and is considerably richer towards the top of the metabasalt. At depth, values in the range 1–4 ppm characterize the pyrite-biotite alteration zone with negligible gold in the quartz vein. Gold at depth is associated with both pyrite and biotite, commonly occurring along cleavage flakes of the latter. Nearer the contact of the schist zone with Fe-Ni-Cu sulphide ore and/or ultramafic rocks, gold values of > 10 ppm are typical of the pyrite-ankerite zone. The quartz veins in this area contain free gold, numerous tellurides of Au, Ag, Cu, Ni, Pb, and both chalcopyrite and pentlandite, the latter two presumably remobilized from the massive sulphide ore.

4. Interim Summary: Hunt Mine comprises *en echelon* quartz veins in a shear zone within tholeiitic metabasalt. The shear zone is unrecognized in overlying ultramafic rocks, and the contact of ultramafic and metabasalt marks the upper termination of quartz veining and gold distribution. This shear zone is inferred to be a major fluid channelway, and preferential hydraulic fracture of the metabasalt by high pore-fluid pressures has extensively veined this unit and exposed it to widespread fluid-wallrock interaction.

Several zones of alteration are recognized around the quartz veins : from a narrower pyrite zone to wider biotite and even wider carbonate zones. Nearly all the gold is in the pyrite alteration zones. The alteration pattern formed from the reaction of a low salinity, $\text{H}_2\text{O}-\text{CO}_2$ rich fluid with the metabasalt, during which the formation of pyrite from Fe-bearing silicates provided the redox mechanism to deposit gold.

Hunt Mine provides the opportunity to study the effects of host rock and structural control on fluid access and fluid-wallrock interaction on a relatively small scale. It is important because the entire alteration system can be viewed in a limited area. Many of the conclusions derived from the Hunt deposit can be transferred and/or adapted to suit other larger gold deposits.

B. Kalgoorlie

Over 1100 t of gold have been produced from the Golden Mile of Kalgoorlie, reputably making this the richest square mile of land anywhere (Casey and Mayman, 1964). Kalgoorlie has attracted much scientific interest since its discovery in 1894 and the literature covers structural, mineralogical and geochemical aspects of the field (Woodall, 1965; Travis *et al.*, 1971).

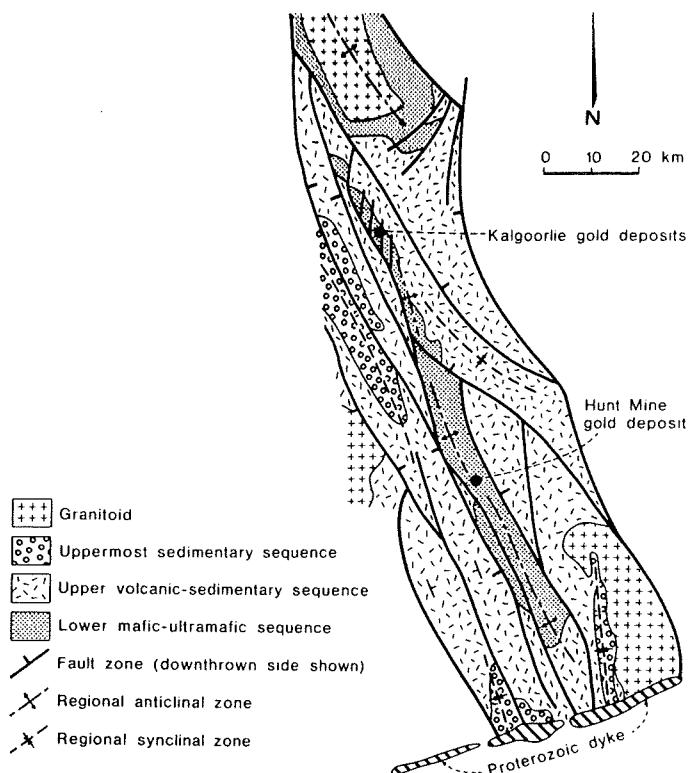


Figure 14 : Map of Kalgoorlie and surrounding Eastern Goldfields Province. The auriferous zone at Kalgoorlie represents a deeper part of the sequence relative to surrounding younger metasediments (based on mapping of the Geological Survey Western Australia).

Kalgoorlie is situated within an area of complex faulting and greenschist facies metamorphism in the widest greenstone belt in the Yilgarn Block (Fig. 5). The sequence of auriferous rocks at Kalgoorlie is truncated to the west by the Boulder Fault, and is flanked on the east and west by stratigraphically higher Archaean metasediments with intermediate to felsic metavolcanics (Fig. 14). Shearing within this north-south horst block has had a major influence on the distribution of rock units (Fig. 15). NNW-trending folds plunge south in the Golden Mile, but further to the north plunge north, placing Kalgoorlie near the culmination of a broad fold arch (Woodall, 1965). Major folds include the relatively open Kalgoorlie anticline (to the east) and Brownhill syncline, and the very tight Kalgoorlie syncline which is marked by shearing, porphyritic dykes and a narrow infold of Black Flag Beds (Fig. 15). A complex deformation history is recorded in the Golden Mile on a mesoscopic and microscopic scale, by isoclinal folding of metasediments and local high strain zones in all rock types.

The Kalgoorlie sequence has been described in detail by Travis *et al.* (1971) and consists mainly of an ultramafic to mafic sequence overlain by volcano-sedimentary rocks of the Black Flag Beds (Fig. 16). Of great economic significance is a thick tholeiitic sill, the Golden Mile Dolerite. Mining operations are typically confined to this dolerite, the Paringa Basalt and Black Flag Beds (Fig. 16), and only rarely are the other formations exposed underground. Over three-quarters of the gold produced has come from the Golden Mile Dolerite and the rest from the Paringa Basalt and contacts. Although commonly pyritic, gold production from the overlying Black Flag Beds has been minimal.

The Paringa Basalt is a sequence of basaltic flows that are brecciated and pillowled in the upper part. The contact of the Paringa Basalt and enclosed metasediments is the site of extensive shearing, though in most areas it is obscured by intrusion of the Golden Mile Dolerite. Clastic metasediments are common in the upper part of the Paringa Basalt and are essentially indistinguishable from those of the overlying Black Flag Beds. These interflow sediments are mainly carbonaceous shale, greywacke, and mudstone retaining fine-scale bedding, cross- and graded-bedding and ripple marks. The metasediments exhibit at least two fabrics: an earlier pervasive fabric and a regional spaced fabric (Ion, 1982). The whole-rock composition of the basalt varies from komatiitic at the base to Fe-tholeiitic at the top (L.Y. Golding, 1978), though much of the metabasalt has now been extensively carbonated.

The Golden Mile Dolerite intruded the Kalgoorlie sequence prior to the period of folding responsible for the Kalgoorlie syncline, and before metamorphism. The dolerite contact with the Paringa Basalt is roughly parallel to other lithological contacts, though sharp re-entrants on the scale of tens of metres, lead to small-

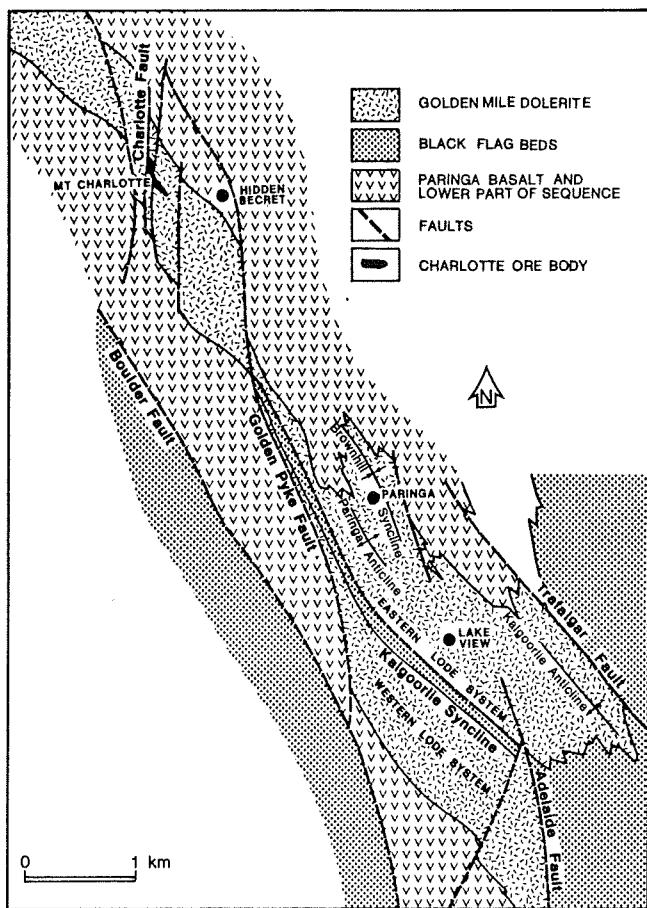


Figure 15 : Map of Kalgoorlie goldfield showing some major faults/shear zones and their influence on rock distribution. The Golden Mile is made up of an Eastern and Western Lode System separated by the Kalgoorlie syncline. Two active mines are shown: Perseverance (NW) and Lake View (SE). Mineralization of the Eastern Lode System extends into the Paringa Basalt.

scale repetition of these lithologies near the boundary. In places, these re-entrants are demonstrably controlled by shear zones (Fig. 17), whereas other re-entrants may be local dykes of Golden Mile Dolerite intruded into the Paringa Basalt though this has not been clearly demonstrated. The sporadic occurrence of black shales near the contact is more likely to reflect slight discordancy of the dolerite, rather than rapid lateral variation in sediment accumulation.

The contact of the Black Flag Beds and Golden Mile Dolerite is usually the site of considerable deformation in the Golden Mile. However, a small, but informative, exposure of the contact at Mt Charlotte has been described by Clark (1980). Here, fine-grained marginal dolerite is nearly concordant with fine-grained sediments of the Black Flag Beds, suggesting an intrusive and not an erosive contact.

The Golden Mile Dolerite is differentiated from a near-ultramafic base to a granophyric section. Four main textural variants exist: fine-grained, feldspar-phyric (ophitic), granophyric, and pyroxene-phyric. Travis *et al.* (1971) subdivided the dolerite into 10 distinct units on the basis of oxide components. Their subdivision is particularly useful in the less-deformed Mt Charlotte area, but presents local problems and variants in the much foliated and altered Golden Mile rocks. Regardless of these minor problems, the subdivision of the dolerite (Travis *et al.*, 1971) provides a stratigraphic tool useful over the length of the Kalgoorlie goldfields. The textural changes that form the basis of the subdivision are analogous to trends in other tholeiitic sills, providing evidence that the Golden Mile Dolerite formed from *in situ* differentiation of a single magma (Phillips, 1982). To support this model, Clark (1980) has shown from available analyses (Travis *et al.*, 1971; L.Y. Golding, 1978) that the weighted average composition of the 10 units is virtually identical to the composition of the chilled marginal dolerite supporting the "single magma" model.

In the past, other models have been proposed to account for the internal layering in the Golden Mile Dolerite. From a smaller analytical data base than is now available, Travis *et al.* (1971) recognized the sill-like nature, but suggested multiple intrusions were required to produce the present sequence. Tomich (1974, 1976) described possible "pyroclastic" features, but always in altered dolerite. Shapes resembling embayed quartz phenocrysts are relatively abundant in carbonated samples, but are absent when traced only a matter of metres outside the zone of carbonation. L.Y. Golding (1978), in a careful study of the mineralogy of part of the Golden Mile, mentioned volcanic-like breccias and zenoliths on the upper contact of the dolerite. As this

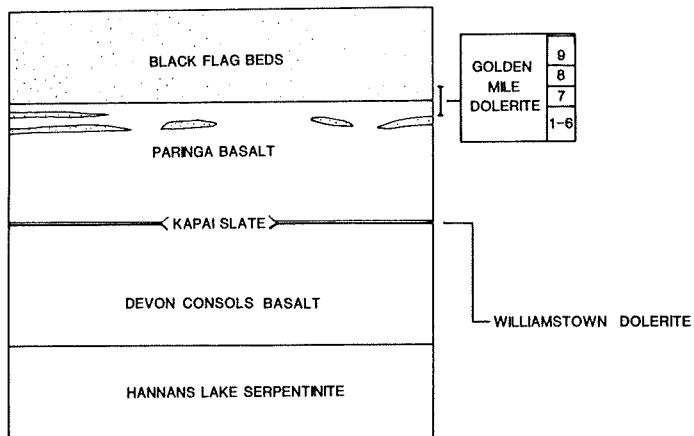


Figure 16 : Stratigraphic sequence for the Kalgoorlie area showing position of early sills. The Golden Mile Dolerite sill is near the contact of underlying mafic rocks and overlying metasediments.

study was based on drill core only, her findings are difficult to confidently interpret in the light of the considerable tectonic brecciation and deformation evident underground. The occurrence of metasediments reported in diamond drill hole sections of Golden Mile Dolerite (Travis *et al.*, 1971; L.Y. Golding, 1978) is easily explained by in-faulting, as observed underground. There is no evidence from underground workings to suggest there were sediments within the Golden Mile Dolerite at the time of cooling.

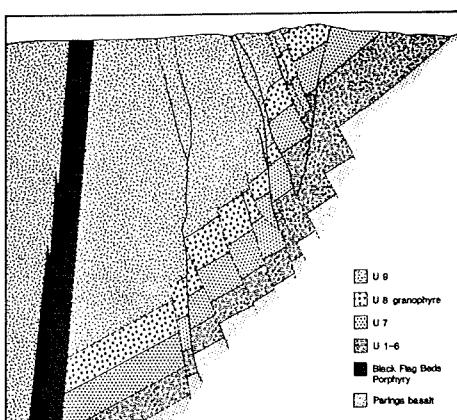


Figure 17 : Cross section of the Eastern Lode System of the Golden Mile near Perseverance and Lake View mines. Lithological contacts are disrupted by reverse movement on east-dipping shear zones. The Kalgoorlie syncline has a core of black shales that are intensely intruded by porphyritic dykes.

The entire area around Kalgoorlie is auriferous and, typical of other gold districts in the Yilgarn Block, there are numerous styles of mineralization. On the basis of host rocks and structural setting, three main styles are identified here (Table VI). This subdivision into Golden Mile, Oroya, and Charlotte styles is not totally satisfactory as the styles are spatially, and probably genetically, inter-related; but it is retained as a classification on which to base descriptions.

1. Golden Mile-style Mineralization: Golden Mile mineralization comprises classic, steeply-dipping shear zones that are concentrated around the Kalgoorlie syncline. The Western Lode System is characterized by strong lode structures that dominantly parallel the syncline trend, dip steeply west or steeply east, and persist for over 1 km depth. The Eastern Lode System has a large number of smaller lode structures of various orientations.

Four orientations of lode structures account for nearly all gold production from the Eastern and Western Lode Systems. These are "main" lodes ($320/85^\circ$ west), "caunter" lodes ($300/70^\circ$ west), "cross" lodes ($230/65^\circ$ south) and "easterly" lodes ($160/80^\circ$ east). Shear movement is documented on each of these structures except for the cross lodes which may be purely tensional features. In the Eastern Lode System, stratigraphic offset of many tens of metres suggests an "east block up and/or south" movement on the easterly lode structures (Fig. 17). The geometry of these four major lode structures is broadly compatible with that expected from E-W compression perpendicular to the "main" lode direction (Boulter, C.A., pers. comm., 1982; Fotios, 1983), and such compression would explain the movement on the easterly lode structures and the inferred tensional nature of the cross lode structures. Other less important lode directions appear to be anastomosing branches of larger shear systems and account for lesser production.

The Eastern Lode System is being mined (reopened 1979) and is used as a basis for the following description of ore mineralization. The Western Lode System has many similarities, but in detail may prove to have local differences. As the lode structures in the Eastern Lode System dip more steeply than the rock unit boundaries (Fig. 17), the lodes tend to transect units of the Golden Mile Dolerite. A smaller number of lode structures continue into the underlying Paringa Basalt.

TABLE VI

Main Mineralization Styles of the Kalgoorlie Goldfield

Style	Gold	Host Rock	Structural Setting	Mineralogy/Alteration
Golden Mile	1000t	Golden Mile Dolerite, occasionally Paringa Basalt and porphyry dykes	a) Steeply dipping veins that follow shear zone system. With or without quartz b) Commonly near sediments	a) Pyrite, rare arsenopyrite, tourmaline, free gold very rare. 0.1 to 10+m zones of carbonate alteration. Gold mostly in alteration zone b) Rich; tellurides, free gold, base metal sulphides
Oroya	200-300t	Paringa Basalt, rarely interflow sediments	1. Shallow plunging ore pipes near top of Basalt and shear zones (e.g. Oroya Shoot) 2. Breccia zones in Basalt near interflow sediments (e.g. Lewis Lode). 3. Immediate footwall of interflow sediments and sediments themselves (e.g. OHW Shoot)	Complex, very rich. Pyrite, numerous tellurides, vanadium mica, free gold, tourmaline, galena, sphalerite, and chalcopyrite
Charlotte	50t	Golden Mile Dolerite, nearly all in granophyre	Two quartz vein sets localized between steep oblique shear zones, within the granophyre	Quartz veins with ankerite/siderite, scheelite and albite: pyrite (nearer surface) or pyrrhotite (deeper). Muscovite, carbonate, pyrite alteration with pyrrhotite at depth. Rare tellurides. Gold in alteration zone
Other	minor	Black Flag Beds, other rock types	Stratabound, but near shear zones	Pyrite, pyrrhotite, arsenopyrite

Host rocks largely control the mineralization, deformation, and alteration. Firstly, "main" lode orientations appear to dominate in and near the granophytic (Unit 8, Fig. 17) and upper ophitic sections (Unit 9) of the Golden Mile Dolerite. Second, carbonate alteration (bleaching) is intense in the granophytic section and weaker in the rest of the Golden Mile Dolerite. From reconnaissance data these two relations probably hold for the Western Lode System. Third, "counter" and "cross" lode orientations are more common in the lower parts of the Golden Mile Dolerite (Units 1-6) and in the Paringa Basalt. Fourth, alteration is closely localized around mineralization in the lower part of the Golden Mile Dolerite (Units 1-6), but is pervasive in parts of the Paringa Basalt and Golden Mile Dolerite (Units 7,8).

In describing mineralization within the lode structures, it is useful to identify two components that have quite different origins: altered/replaced country rock and vein filling (Fig. 18). Both these components may be auriferous, and have been lumped together as "lode" in earlier literature. The present subdivision recognizes the "precipitation" origin of the vein-filling and stresses the presence of quartz-bearing veinlets in most Golden Mile lodes.

Vein-filling varies from quartz-rich breccia veins over 1m thick to thin 1-3cm quartz-carbonate veinlets. All veins lens along a mineralized zone, and may be surrounded by altered country rock or be faulted against unaltered country rock. The vein fillings carry minor tourmaline, some pyrite and modest gold, and are commonly referred to as "cherty" lode because of the fine-grained quartz. A geochemical profile across altered country rock and vein filling, shows that elements such as Zr, Y, Fe, and Ti are slightly diluted in the altered country rock, but they are virtually absent in the vein filling, confirming quite different precursors to the two components of mineralization.

Altered country rock varies from 1cm to tens of metres thickness around vein-filling cores. Several zones of alteration surround veins, but the mineralogy of these zones and their relative widths vary considerably. The simplest form is a narrow pyrite-ankerite-muscovite zone surrounded by a carbonate zone (ankerite ± siderite) without pyrite, and then chlorite-calcite country rock. The unaltered metamorphic, actinolite-plagioclase form of Golden Mile Dolerite is rarely, if ever, encountered near mineralization. A less common zoning scheme is from pyrite-carbonate-chlorite to chlorite-calcite with little bleaching (i.e. only minor carbonation of chlorite) around mineralization. Economic concentrations of gold only occur in the pyritic zones and this provides a visual cut-off to mineralization.

Telluride minerals are found in the richer parts of the Golden Mile mineralization, and include gold, silver, lead, mercury, nickel, and mixed tellurides. The usual modes of occurrence are as cross-cutting veinlets; these are an important source of gold accounting for 10-20 per cent of the Kalgoorlie production. Although most of the rich telluride ores were in the upper levels and exploited early in the life of the mines, important occurrences extend to 1,5km depth (L.Y. Golding, 1978). There are several detailed accounts of telluride mineralogy (e.g. Stillwell, 1931) but, unfortunately, the abundant evidence for remobilization and related compositional readjustment makes the tellurides of limited use in deducing physio-chemical characteristics of initial gold mineralization.

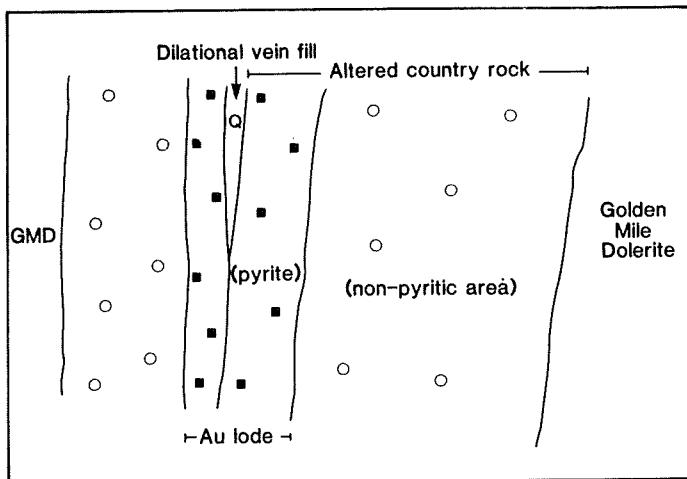


Figure 18 : Idealized sketch of vein-filling and pyritic altered country rock that together constitute a typical Golden Mile "lode". The current terminology refers to the broadly planar confining feature as a "lode structure" and the mineralization as "veinlets" and "altered wallrock".

2. Oroya-style Mineralization: Oroya mineralization has also referred to as "flat" or "contact" ore from its association with the Paringa Basalt-Golden Mile Dolerite contact. The term is used for those ore shoots that are related to lithologic contacts including interflow sediment horizons, as opposed to major steeply-dipping shear zones. Shearing is nevertheless important in the localization of Oroya mineralization. The best-known example is the Oroya shoot itself which was mined from the surface for 1.5km along plunge, producing 60 t of gold (Tomich, 1959). Other examples include the Blatchford ore shoot and the Oroya Hanging Wall (OHW) shoot, also of high grade, but lesser tonnage (Figs. 19,20). Most of the Oroya mineralization was discovered early this century and was quickly mined out. Remaining areas give an impression of the overall shape of these bodies and provide small amounts of ore samples (Scantlebury, 1983). From the limited areas of Oroya mineralization and the reported production of the Oroya Shoot (Tomich, 1959), Oroya-type ore is estimated to account for 20 per cent of Kalgoorlie production, or 200-300 t of gold.

The Oroya shoot lies on the east limb of the Brownhill syncline, and plunges 30° to the south as it parallels the upper contact of the Paringa Basalt. It follows a faulted-offset or minor fold of the contact for part of its length, and lies in the immediate footwall of the steep east-dipping Australia East shear zone (Fig. 20). The OHW Shoot is within the Paringa Basalt immediately below a metasediment unit and joins the Oroya shoot up dip (Scantlebury, 1983).

The mineralogy of the Oroya shoot is more diverse than most other Kalgoorlie ores (Table VI), and besides pyrite, common phases include tellurides, free gold, base metal sulphides and arsenopyrite. The whole area for several metres around the Oroya shoot appears to carry gold, either in small quartz veins, in altered basalt or associated with metasediments or Golden Mile Dolerite. Distinctive green ore ("green leader") accompanies high gold values and takes its colour from a vanadium-bearing mica ($\leq 8\text{wt\% V}_2\text{O}_5$; Nickel, 1977).

3. Charlotte-style Mineralization: Charlotte mineralization comprises quartz stockworks in specific parts of the Golden Mile Dolerite (Fig. 3). Exploitation of this type of ore occurred after many of the Golden Mile-type lodes had been mined out, and the lower grade (5 ppm Au average) of Charlotte ore has been offset by large-scale mining methods over the last 30 years. The Mt Charlotte Mine extracts 750,000 t of ore per annum from a number of stockworks (mainly Charlotte and Reward ore bodies), accounting for about half of recent Kalgoorlie gold production (1978-1982). The Mt Charlotte Mine provides ready access to currently mined areas (i.e. approximately at 800m depth), and the ore bodies are classic examples of host rock control on gold mineralization. Recent studies of mineralogy (L.Y. Golding, 1973), oxygen isotopes (S.D. Golding, 1982), and fluid inclusions (Clark, 1980), complement a detailed knowledge of the geology (Table VI; Phillips *et al.*, 1983; Groves *et al.*, 1984) to give a coherent model for the gold mineralization of this deposit.

Distribution of known quartz stockworks is heavily biased towards the northern end of the Kalgoorlie field, within the granophytic section of the Golden Mile Dolerite (unit 8) and near steep-dipping oblique shear zones (Fig. 15). The Charlotte ore body is virtually continuous between adjacent oblique shear zones and, allowing for faulting, is known to persist to over 1km depth (Fig. 21). Smaller stockworks occur around Mt. Charlotte in similar structural/lithological settings, and less-commonly within the Golden Mile. The Golden Pyke orebody on the north-west flank of the Golden Mile is the largest stockwork in the south of the field, and lies in the granophyre (unit 8) adjacent to the Kalgoorlie syncline and Golden Pyke Fault (Fig. 15). The Charlotte ore body is the largest stockwork, and as its geology is best understood it is described in detail based on recent studies (Clark, 1980; Phillips, 1982, Phillips *et al.*, 1983).

The structural setting of the Charlotte ore body is important on both regional and local scales. Rock units trend north-west and dip 70-80° west. Oblique shear zones strike north, dip steeply west, and offset the Golden Mile Dolerite into a series of blocks. Individual ore bodies plunge steeply, parallel to the intersection of layering and the oblique shear zones. Flatter, strike-parallel shear zones (340°/40°W) disrupt the vertical continuity of ore bodies with apparent displacements of 50-100m.

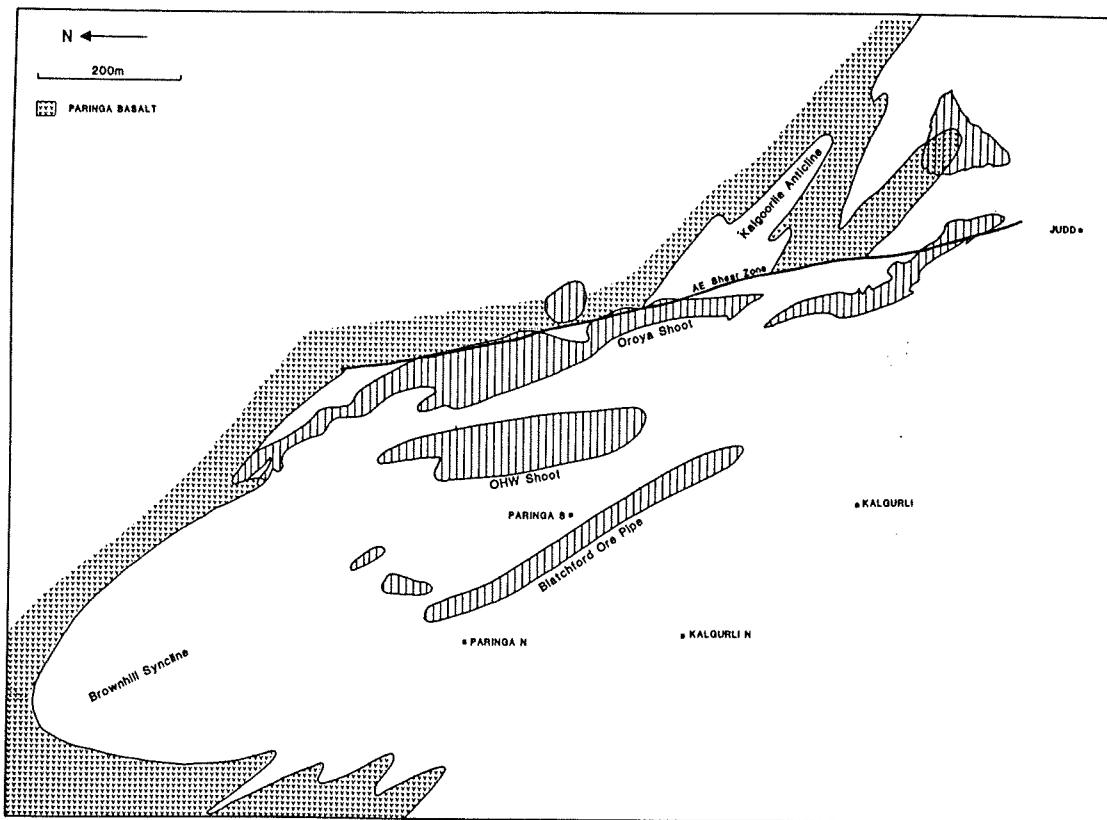


Figure 19 : Surface map of Brownhill syncline with projected position of Oroya-style mineralization (vertical shading). Golden Mile Dolerite makes up the core of the syncline. Abbreviations : AE = Australia East, OHW = Oroya hanging wall.

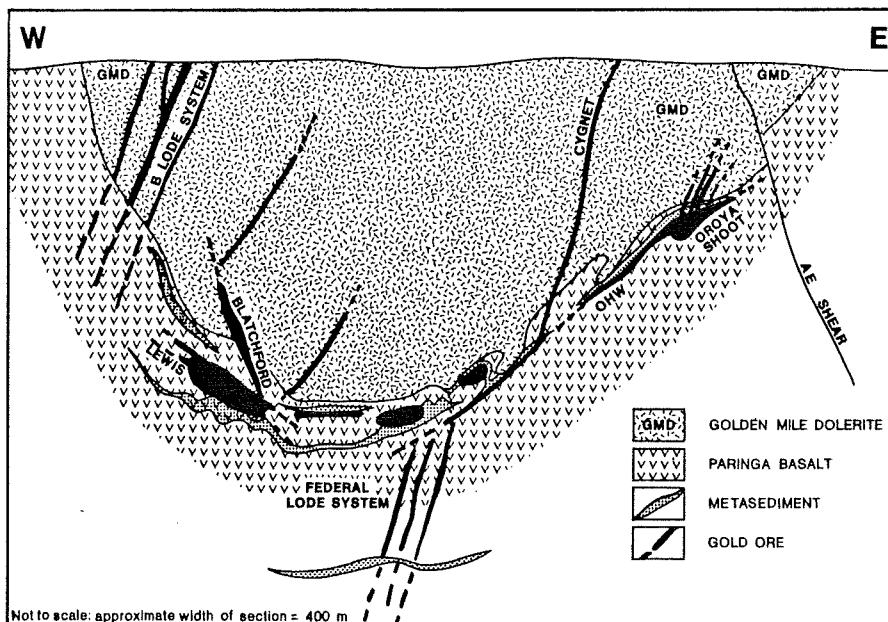


Figure 20 : Diagrammatic cross section of Brownhill syncline showing Oroya shoot and other Oroya-type mineralization related to the Paringa Basalt and its upper contact with the Golden Mile Dolerite. Golden Mile mineralization (e.g. B Lode system) is also shown (Scantlebury, 1983).

Two main quartz-vein sets and their thick alteration haloes constitute stockwork one. The veins are up to 30cm thick and may be continuous for tens of metres. Vein density reflects ore grade, and veining is virtually restricted to the granophytic zone of the Golden Mile Dolerite (unit 8). Mineralization in adjacent ophitic host rocks is marginal to sub-economic because of the paucity of veins and their thin alteration haloes. The poor development within the granophyre of one vein set near strike-parallel shear zones may account for lower bulk grades of ore in that area (Clark, 1980).

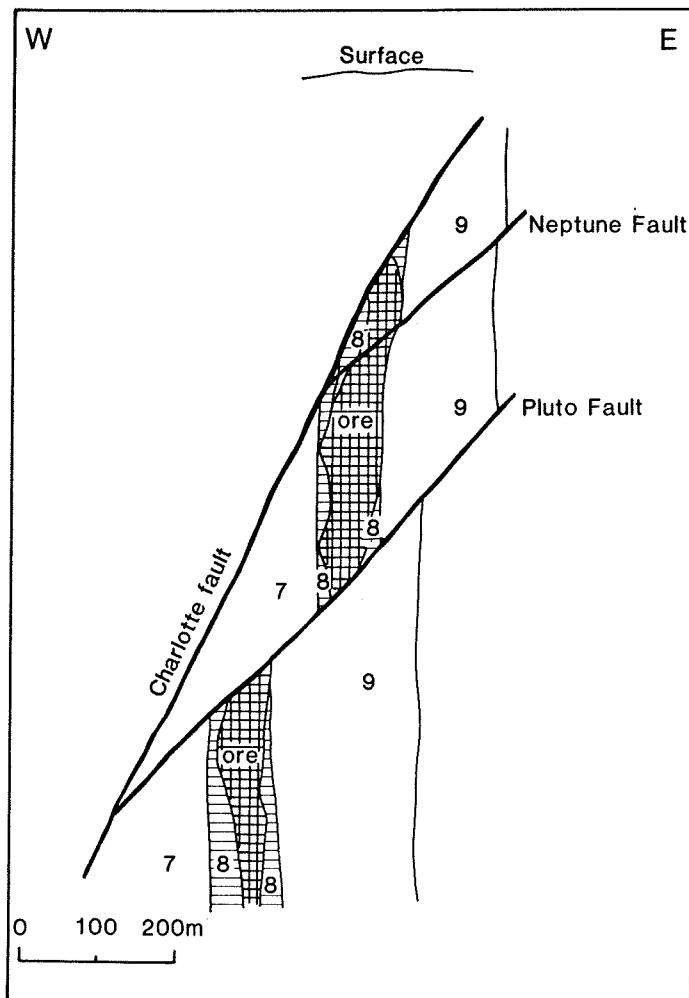


Figure 21 : Cross section of the Charlotte ore body (cross hatched), Mt Charlotte Mine, showing restriction to granophyre (U8, horizontal hatched) and relationship to zones of intense deformation.

The terminations of veins reflect their host rock, and provide important insight into the control on vein localization and, in turn, fluid access and economic gold mineralization. In the granophyre, veins end by simple tapering, whereas branching and forking of veins are more common in adjacent ophitic hosts (Clark, 1980). Most veins end within a few metres of the granophyre contact. This bias of veins to one rock type (i.e. granophyre) and the nature of the terminations have been used as evidence for vein formation by hydraulic fracture, with stable crack development only in the more competent granophyre (Phillips *et al.*, 1983). Vein centres have rare vuggy quartz and some late anhydrite (Clark, 1980).

Wallrock alteration varies in intensity between different host rocks, even along a single vein. In the granophyre, alteration may be metres wide and overlap with the alteration around adjacent veins to form an extensively altered, chlorite-free ore zone within the Golden Mile Dolerite. In contrast, alteration haloes in ophitic (units 7,9) and pyroxene-phyric (unit 4) hosts are generally only 1-5 cm thick.

Wallrock alteration assemblages change with depth, but essentially represent carbonation and sulphidation of the host dolerite (Fig. 22). A zone of bleaching surrounds all veins and represents the alteration of chlorite to Fe,Mg,Ca carbonate and some muscovite. Sulphides persist beyond this zone into the less-carbonated calcite-chlorite rocks. Where pyrrhotite and pyrite occur, pyrite is typically closer to the veins, and even at 1,200m depth some pyrite is present, though pyrrhotite dominates.

The striking visual difference between Charlotte and Golden Mile mineralization mainly reflects the tensional nature of Charlotte veins (cf. shear zones of the Golden Mile), and hence the preservation of host rock fabrics after intense alteration. Minor shear-related mineralization in the Mt Charlotte Mine carries rare tellurides and, in gross appearance, is very like Golden Mile mineralization.

Gold is rare in the quartz veins and confined to minor visible specks. The carbonated wallrocks have fine gold as discrete grains and on fractures in pyrite, but values are considerably lower where pyrrhotite is the dominant sulphide phase. The contribution of telluride-bound gold is negligible.

In erecting a genetic model for Charlotte mineralization, a basic premise is that gold introduction was by hydrothermal fluids that also caused extensive wallrock alteration. The position and shape of the Charlotte-type ore bodies, together with oxygen isotope contours (S.D. Golding, 1982) and the alteration and minor mineralization on shear zones, suggest that oblique (e.g. Charlotte Fault) and strike-parallel shears (e.g. Neptune and Pluto faults) were fluid channelways during gold mineralization. The confinement of extensive veining to the granophyre (unit 8), and the vein terminations suggest that the relative tensile strengths of rocks controlled hydraulic fracture near major shear zones. Extensive fluid access to the granophyre followed from its preferential fracture on all scales.

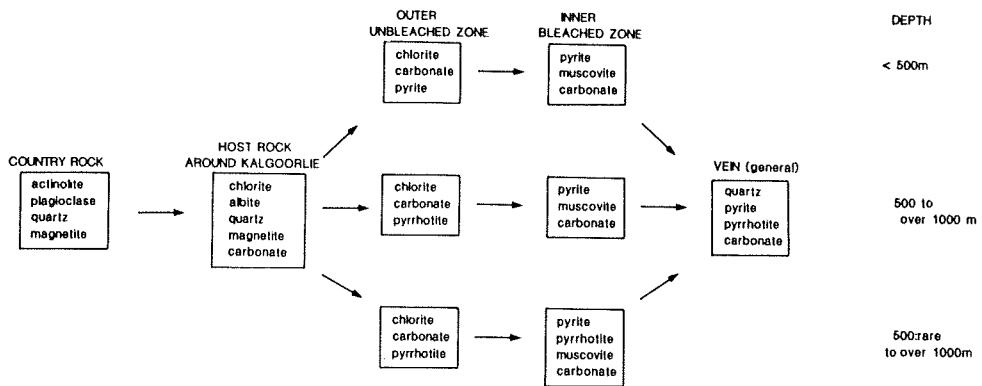


Figure 22 : Alteration zones around quartz veins in granophyre at different depths in the Charlotte ore body. Gold grades decrease slightly as pyrrhotite becomes the dominant sulphide at depth (after Clark, 1980).

Gold deposition from solution was a result of fluid-wallrock interaction that induced changes in fluid composition. Temperature gradients based on fluid inclusions from varying depths appear to be minimal, though temperatures may have waned slightly during progressive inward vein growth (Clark, 1980). Homogenization temperatures around 320°C are pressure corrected to near 400°C (Groves et al., 1984). Phase separation (H_2O , CO_2) took place late in the mineralization event, but there was no boiling. A depth of 3-6 km at the time of gold deposition is suggested by the fluid inclusion data.

Like other Archaean gold deposits (Phillips and Groves, 1983), the fluids responsible for Charlotte mineralization were H_2O - CO_2 -rich fluids of low salinity with gold carried as reduced-sulphur complexes (see discussion on Gold Transport). Interpreted stable isotope values (S.D. Golding, 1982) for this fluid ($\delta^{18}O = +8\text{‰}$, $\delta^{13}C = -5\text{‰}$) accord with, but do not prove, a metamorphic origin for the auriferous fluid.

Compared to Charlotte style mineralization, Oroya and Golden Mile mineralization formed in quite different structural environments but, although no detailed model of their genesis is available, they appear to involve fluids of basically similar H_2O - CO_2 -rich composition. Host rock control at these latter areas is evident, but less specific than at Mt Charlotte, whereas ore mineralogy is more diverse.

Interim summary: Kalgoorlie has produced over 1 per cent of world gold and by any standard this giant deposit represents an extreme concentration of gold. Kalgoorlie and Timmins (Canada) are by far the largest Archaean greenstone gold deposits.

Kalgoorlie is situated in a highly deformed part of the Norseman-Wiluna belt and mineralization surrounds the tight Kalgoorlie syncline. The main host rocks are the tholeiitic Golden Mile Dolerite and Paringa Basalt, though rich shoots are common near metasediments. Three mineralization styles are recognized. Golden Mile mineralization comprises pyrite-altered dolerite in steeply dipping shear zones, Oroya mineralization comprises altered basalt and sediments just below the base of the dolerite, and Charlotte mineralization comprises altered granophytic dolerite within a quartz-vein stockwork.

The size of the Kalgoorlie field means that genetically diagnostic features are rarely seen at any one locality, so the genetic model for this deposit results from detailed local studies (e.g. Mt Charlotte), parallels to Hunt Mine (see above), and many isolated underground observations. Fluid access has been facilitated by intense local deformation, lithologic contacts and hydraulic fracture, while fluid-wallrock interaction has involved the sulphidation of Fe-rich tholeiites (dolerite and basalt) to form pyrite and gold. Rich ore shoots containing tellurides have formed during later stages of fluid evolution, but the main ore-forming event at Kalgoorlie is qualitatively similar to that postulated at other Archaean gold deposits.

C. Norseman

Norseman is the major goldfield in Western Australia outside Kalgoorlie (Figs. 5,6), and has produced 120 t Au, nearly all from veins in tholeiitic metabasalts and intrusive rocks. The goldfield is situated at the southern end of the Norseman-Wiluna belt and consists of upper greenschist facies tholeiites, lesser high-Mg lavas and minor metasediments (Hall and Becker, 1965).

The large-scale gold-localizing feature of the Norseman area is a tholeiitic sequence between meta-sedimentary units, which contain numerous deposit types and all the main producers (Fig. 23). Adjacent sequences are superficially similar, with the exception of higher average FeO in the auriferous sequence (15 wt % cf. 12-13 wt %; J. Pagel, pers. comm., 1981).

The Princess Royal mineralization is confined to biotite alteration haloes around shear zones, in which quartz veins are not an essential part of the mineralization. Wallrock alteration assemblages are mainly biotite-actinolite (S.D. Golding, 1982). In contrast, the Crown and Mararoa ore bodies are thick (1-10 m), folded, laminated quartz veins carrying free gold, pyrite, galena, minor sulphides, and tellurides. Ore bodies form plunging ore shoots within the quartz veins, and are surrounded by biotite-carbonate and chlorite-carbonate wallrock alteration.

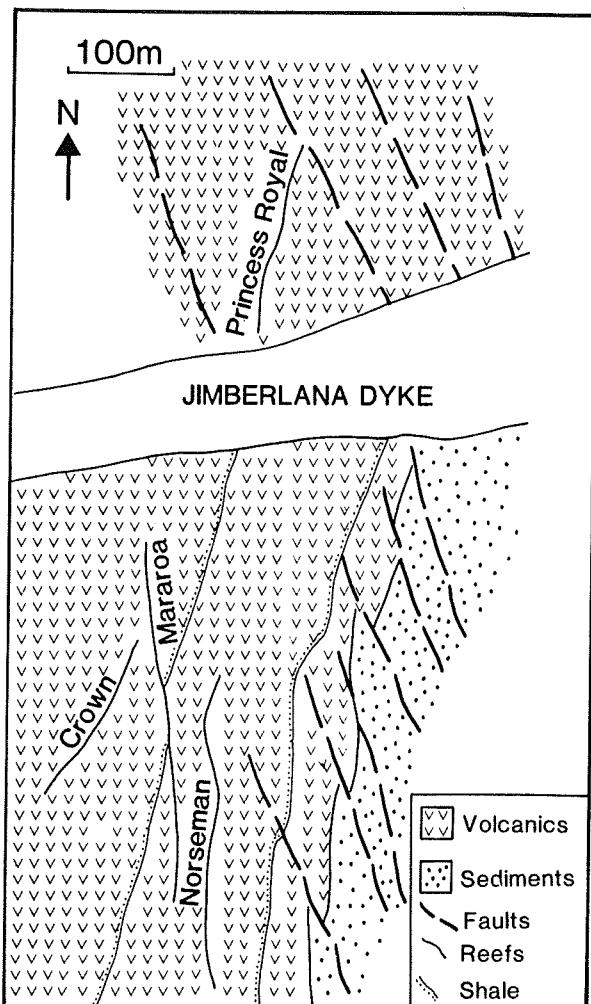


Figure 28 : Map of the Norseman goldfield with major rock units and the four largest quartz gold reefs.

The Norseman wallrock alteration is here inferred to have been metamorphosed, and has a strong planar fabric post-dating mineralization. An alternative interpretation is that the present alteration assemblages are essentially those formed during gold mineralization, and thus can be used along with stable isotope data to directly constrain gold genesis (S.D. Golding, 1982). The interpretation preferred here is that the Norseman deposits have been deformed and metamorphosed subsequent to mineralization, though there were earlier important deformational events.

The detailed stratigraphic relations for Norseman are yet to be fully understood, so genetic models are in an early stage. The gold-bearing fluid has a similar interpreted stable isotopic (S.D. Golding, 1982) and overall H₂O-CO₂ composition as for several other deposits (Phillips and Groves, 1983), and reaction with Fe-rich country rocks has been important. However, the control on vein distribution is unresolved, and appears to differ from the shear zones and hydraulic fracture zones in deposits described so far.

D. Great Fingall

The Day Dawn area near Cue (Fig. 5) is characterized by numerous small gold deposits in a variety of settings. Metasediments, tholeiitic metabasalt, a quartz tholeiitic sill and a mafic intrusive all host deposits, but by far the greatest production has come from the Great Fingall Mine (39 t). Discovered in 1891, this 1-10m-thick quartz vein was mined to 800m by the 1920's and abandoned. Free gold was present in the quartz vein, and the overall grade (25 ppm) was rather high.

The Great Fingall deposit lies on a prominent fracture that transects the stratigraphy and has smaller deposits along its length (Fig. 24). The best development of auriferous quartz reef is in the granophytic section of the Great Fingall Dolerite. Previously, this granophyre had been mapped separately from adjacent more mafic dolerites ("Mt Fingall Dolerite and arborescent dolerite" of Australian Consolidated Minerals, unpublished reports); but considered together, these rock types suggest a single differentiated tholeiitic sill with a pyroxene-phyric base (now tremolite-plagioclase with interstitial quartz), ophitic centre (rich in plagioclase laths with quartz and actinolite), granophyre (quartz, feldspar-rich, minor actinolite), upper ophitic zone (very coarse actinolite and feldspar), and a fine upper ophitic margin. From such an interpretation, the better development of gold and quartz in the most competent unit and the parallelism of ore shoots to dolerite layering is consistent with relations at Mt Charlotte, Kalgoorlie. By analogy with other goldfields, there is a strong possibility of further deposit types at Day Dawn (including quartz stockworks) in this poorly outcropping sill.

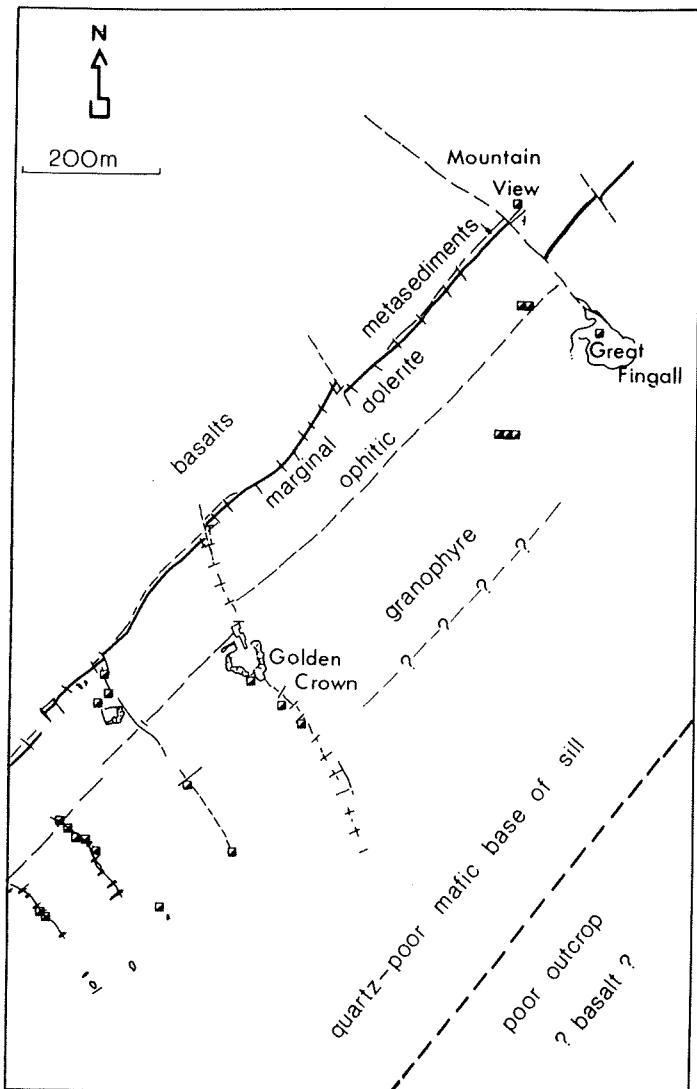


Figure 24 : Schematic map of Great Fingall Mine area near Cue, showing approximate distribution of the various lithologies that comprise the differentiated Great Fingall Dolerite. The top of the dolerite sill is to the south-west. Numerous small mines are aligned along cross fractures.

Virtually no records are available of the mine geology at Great Fingall, but the neighbouring small Golden Crown Mine provides some data. At Golden Crown, small auriferous quartz veins are surrounded by pyrite-carbonate alteration haloes with anomalous gold, and these grade into less-carbonated chloritic granophyre away from veins. Igneous (granophyric, ophitic) textures are preserved in the bleached alteration zones. The quartz veins are tens of centimetres thick at Golden Crown (cf. several metres at Great Fingall) and gold is in the alteration envelope rather than the quartz itself. The alteration at Great Fingall appears to be limited to only a few hundred metres as uncarbonated epidote-actinolite dolerite is relatively common in the mine vicinity.

The Day Dawn setting has much in common with Kalgoorlie (differentiated dolerite sill, strong quartz veining in granophyre, muscovite-carbonate-pyrite/chlorite-biotite alteration) and this analogy suggests the potential for deposit types in various Fe-rich host rocks. The same broad alteration pattern (actinolite, chlorite, carbonate, pyrite) exists at both deposits, but is on an order of magnitude smaller scale at Day Dawn.

E. Other Mafic-hosted Vein-type Deposits

Vein gold deposits are known in mafic host rocks from all greenstone belts of the Yilgarn Block, but the majority are very small. There is a marked concentration of such deposits in the Norseman-Wiluna belt of the Eastern Goldfields Province and in parts of the Southern Cross Province.

The Sons of Gwalia Mine near Leonora has produced 90 t of gold and, at the turn of the century, was one of the deepest mines in the world. Host rocks to the gold are mafic schists and the overprinting of igneous textures by a metamorphic fabric has obscured their original nature. Based on the limited access to upper levels, gold appears closely related to thin (0.5-2cm) folded quartz veins. These veins post-date the earliest recognizable fabric, but pre-date a further schistosity that is axial planar to the small folds. On a broader scale, the ore forms steeply plunging shoots (Finucane, 1965), possibly confined to one lithological unit, that continued to 1900m depth. The limited data suggest this deposit is vein-type, and not stratiform in the sense implied by Woodall (1979).

Numerous mafic-hosted deposits occur in a very narrow (10km wide) belt from Menzies (15 t Au) to south of Kambalda. Portions of this belt are uplifted relative to flanking sequences, and it has the favourable host

rocks and metamorphic grades to make it highly prospective (Groves *et al.*, 1984). Subsequent finds, including Paddington, north of Kalgoorlie, and Victory and Defiance near Kambalda, substantiate this view. The Victory deposit is within carbonaceous metasediment and metabasalt that overlie the Kambalda ultramafic sequence (cf. Hunt Mine underlies these ultramafic rocks) in an area intruded by porphyry dykes. Defiance is a tholeiitic dolerite-hosted deposit 200m west of Victory.

The Southern Cross Province has a number of vein deposits in mafic rocks of higher metamorphic grade. Many of these mafic rocks are cummingtonite-biotite-hornblende-plagioclase-quartz-ilmenite amphibolites, with pyrrhotite, minor, if any, calcite, and sporadic almandine garnet. With the exception of lower volatiles (H_2O, CO_2), these host rocks compositionally resemble the carbonate-chlorite mafic rocks that host gold deposits in the Eastern Goldfields Province. No detailed study of the metamorphic history of the Southern Cross Province has been made, but it appears that several of the gold deposits have undergone amphibolite facies metamorphism and concomitant readjustment of the wallrock alteration assemblages.

F. Other Vein-type Deposits

Further vein-type gold deposits occur in clastic metasediments, felsic metavolcanics, ultramafic rocks, and granitoids. These rock types contain a number of the small deposits (Fig. 7) but very few large-or medium-size deposits. Those in granitoids are at, or very near to, contacts with greenstone belts, a feature also found in the Rhodesian craton (Mann, 1984) and indicative of a fundamental relationship to the greenstones rather than the granitoids.

The very strong host-rock control exhibited by the large to giant gold deposits is not evident within the smaller deposits and, in terms of absolute number of deposits, mafic rocks would not constitute a preferred host rock. The smaller vein deposits are great in number, but appear to show fewer localizing features of gold mineralization than large deposits. Late shear zones and quartz veins are, however, characteristic.

In order to identify the basis of the host rock control noted for the large vein deposits, a goldfield is described that has deposits in a wide range of host rock settings. The Kanowna area, 20km north-east of Kalgoorlie, contains some of the better studied vein deposits not in mafic rocks (Grigson, 1981; Ho, 1984), and allows a comparison between spatially related deposits in contrasting host rocks. Kanowna is in an area of metasediments, felsic, mafic and ultramafic metavolcanics, an ultramafic/mafic/felsic polymict conglomerate, and felsic intrusions. The main deposits are Kanowna Main Reef (7 t Au) in conglomerate, and Red Hill (1 t Au) in a felsic intrusive (Fig. 25). Kanowna has also produced 7 t of gold from deep leads making it a major Yilgarn alluvial field.

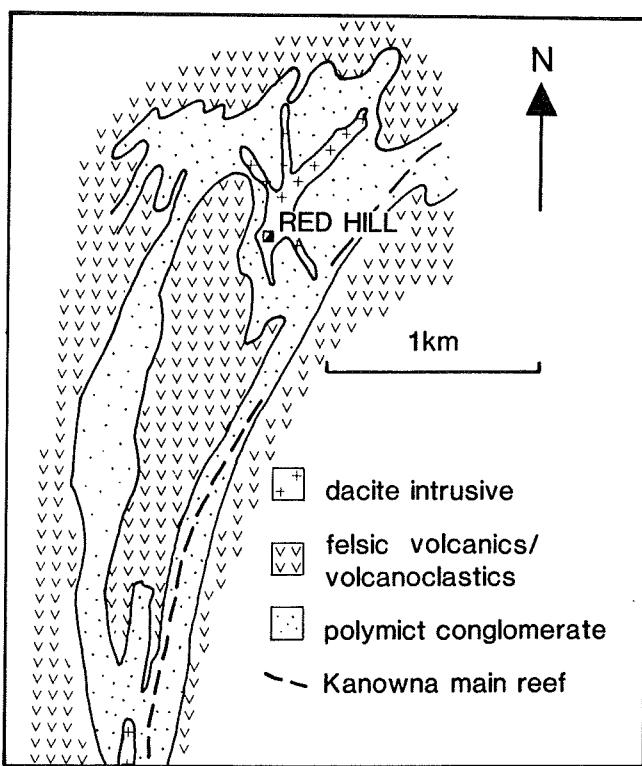


Figure 25 : Map of Kanowna goldfield showing Kanowna Main Reef and Red Hill deposits in different host rocks (Grigson, 1981).

The Kanowna Main Reef is a 1-3m thick quartz vein system, continuous for 3km in a thick conglomerate unit. Conglomerate clasts 1 to 80cm in length include felsic extrusive and intrusive rocks, differentiated dolerite and spinifex-textured ultramafics. The unit is interpreted to be debris flow deposits within a thicker turbidite sequence (Grigson, 1981). The quartz reef trends north-south, dips 60° east and bifurcates along its length. It is confined to the conglomerate although adjacent felsic porphyry dykes may form bounding walls. Some of these dykes contain flat auriferous quartz veins similar to those at Red Hill (see below; Blatchford and Jutson, 1912). The reef is surrounded by a zone of intense carbonation (ankerite, siderite), with local pyrite and chrome-mica, but most of the gold is hosted by the quartz vein itself. Pyrite is preferentially developed in the dolerite clasts and matrix, and is rare in the felsic components.

The Red Hill Mine is in a dacitic porphyry stock within the conglomerate, 300m from the Kanowna Main Reef. Mineralization is in subhorizontal, 5-30cm-thick quartz veins with pyrite-ankerite/siderite-muscovite-albite alteration haloes.

Fluid inclusion evidence from both Kanowna Main Reef and Red Hill suggests H_2O-CO_2 -rich fluids indistinguishable from those found in the mafic-hosted vein deposits (Grigson, 1981; Ho *et al.*, 1985). Freezing data indicate very low salinities, and filling temperatures of 320-400°C are derived from homogenization data (Groves *et al.*, 1984). Phase separation (H_2O -rich and CO_2 -rich fluids) was significant during later precipitation of the Kanowna Main Reef and as a late event at Red Hill.

The careful documentation of Red Hill and Kanowna Main Reef has provided an opportunity to compare vein gold deposits in felsic, mafic, and ultramafic rock types. It appears that the ore fluids for these deposits were H_2O-CO_2 -rich with low NaCl, regardless of host rock mineralogy, and that the wallrock alteration was predominantly carbonation and sulphidation. In the conglomerate, pyritization of mafic fragments occurred in preference to those of ultramafic or felsic composition, whereas the felsic clasts are only carbonated. The composition of the host rock (or fragment) determines which cations are available during alteration, and hence whether Cr-mica, siderite, dolomite, and/or ankerite form. The Fe-rich nature of the mafic rocks have made them favourable hosts for pyritization.

VII. BANDED IRON-FORMATION (BIF) HOSTED DEPOSITS

Banded iron-formations (BIF) host gold deposits in the Murchison, Southern Cross, and Eastern Goldfields Provinces (Fig. 26) and contribute about 10 per cent of the overall Australian Archaean gold production. However, the Norseman-Wiluna belt is virtually devoid of such deposits. The three major deposits, Hill 50 (42 t Au), Bullfinch (21 t Au) and Lancefield (16 t Au) each consist of gold in sulphide-bearing iron-formation with strong structural control and quartz veining (Finucane, 1953; Forman, 1960; Lewis, 1965; Williamson and Barr, 1965). Two of the smaller BIF gold deposits, Water Tank Hill (~1 t Au) and Nevoria (2 t Au) exhibit these same features and are better understood geologically (Phillips *et al.*, 1984).

Initial inspection of the BIF-hosted gold deposits in Australia (and overseas) reveals very systematic, fine-scale bedding, and a syngenetic gold origin has usually been assumed from this evidence (Crocket and Lavigne, 1982; Hutchinson and Burlington, 1982; Hallager, 1982). However, all these studies have failed to demonstrate the timing of gold emplacement. Studies that do attempt to determine timing of ore components are rare and have so far suggested an epigenetic introduction of gold.

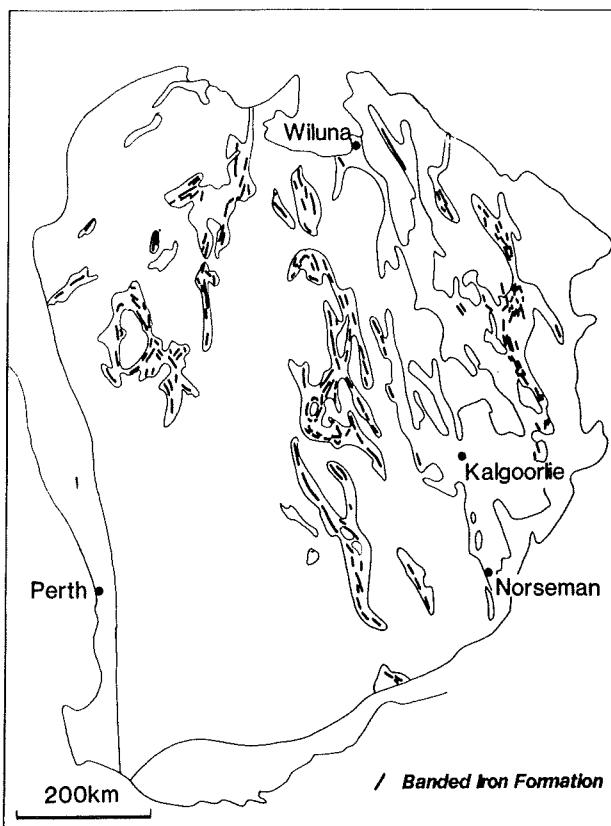


Figure 26 : Map of major banded iron-formations (BIF) in the Yilgarn Block from Gole (1981).

Water Tank Hill is a small BIF gold deposit in a district of many BIF deposits (including Hill 50) and small to medium felsic- and mafic-hosted deposits (Fig. 8). The Water Tank Hill sequence is a well-layered quartz-magnetite BIF within felsic and mafic metavolcanics. This BIF has alternating 2mm magnetite-rich and quartz-rich layers with minor siderite, and some hematite in the quartz layers. Several episodes of folding are recognized (Archibald, 1982) and many deposits, including Water Tank Hill, are related to late north-east-trending fractures.

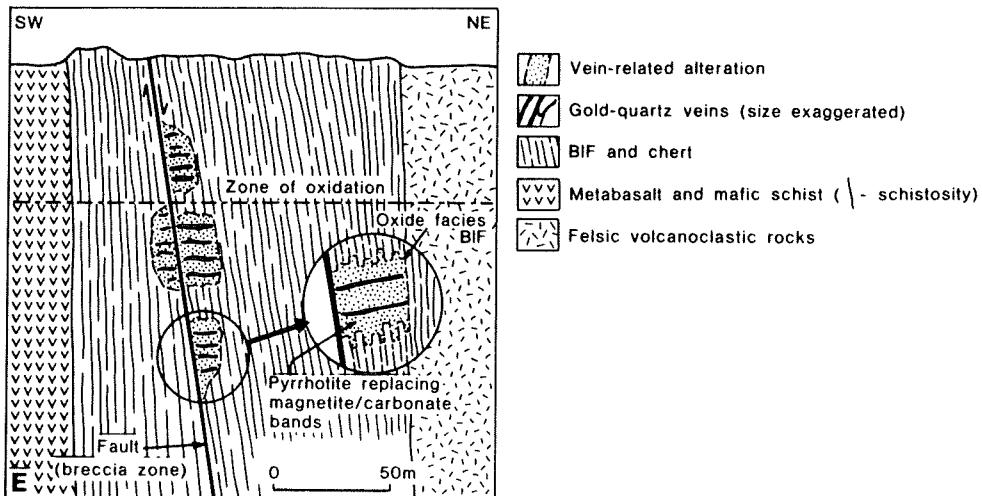


Figure 27 : Section through Water Tank Hill Mine showing arrangement of auriferous pyrrhotite BIF along faults within more regional oxide BIF (Groves et al., 1984; Phillips et al., 1984).

At Water Tank Hill, several ore pods occur along faults (Fig. 27) in areas with abundant, shallow-dipping quartz veins (Groves et al., 1984). The 1-5cm thick quartz and pyrrhotite veins are preferentially localized in the BIF. The ore pods are invariably well-layered quartz-pyrrhotite BIF, in contrast to the gold-poor, more widespread quartz-magnetite BIF. The strong correlation between sulphide BIF and gold suggests a similar origin for these two components in this, and many other, deposits.

Although the macroscopic structural control on Au and S distribution (ore bodies arranged along late fractures) suggests epigenetic mineralization (Fig. 8), the textural details are even more convincing evidence of epigenesis. In several areas of vertically dipping BIF and horizontal quartz veins, the transition from magnetite- to pyrrhotite-rich BIF is very sharp (1 mm in single Fe-rich layers). If transitions in all adjacent layers are joined, they form an envelope around quartz veins with pyrrhotite nearer the vein fracture (Fig. 28). This "fish spine" arrangement is clear evidence of sulphide (and Au) introduction related to the quartz veins, and these veins post-date at least two regional deformations (Archibald, 1982).

On a microscopic scale, there is a zone of less than 1cm width at the oxide-sulphide transition where pyrrhotite partially replaces magnetite, but retains the shape of the original idioblasts (Woad, 1981). Closer to fractures, pyrrhotite no longer retains this shape, possibly because of grain adjustments with siderite. In neighbouring silica-rich layers, hematite and magnetite are unaltered and appear to have been shielded by quartz from sulphidation.

The genetic model for Water Tank Hill is important because it has implications for other more deformed BIF deposits. Although the fine layering of the auriferous BIF and the chemical nature of the host metasediments have been used to suggest syngenesis for BIF gold deposits, the evidence from Water Tank Hill favours epigenetic replacement (Groves et al., in press). The main arguments supporting this are:

- (1) there is a strong regional and local structural control on mineralization;
- (2) Au occurs with sulphide BIF, which has formed by post-metamorphic replacement of the original oxide BIF that has, itself, undergone metamorphism;
- (3) veining correlates with sulphide BIF and Au, and post-dates early deformation; and
- (4) the high gold to base metal ratio is typical of mafic-hosted gold deposits and quite unlike the ratios found in sulphide-rich sediments.

Phillips et al. (1984) argued from the viewpoint that because Fe-rich mafic rocks fracture easily and are good host rocks for vein deposits, the competent, Fe-rich BIFs should also be ideal sites for replacement gold deposits as they provide ready fluid access in fractured zones and Fe-rich host rocks to facilitate gold deposition. Such a replacement model predicts a well-layered sulphide-gold ore and, by analogy with Water Tank Hill, replacement microstructures may be extremely rare.

Nevoria, in the Southern Cross Province, is a small gold deposit in strongly deformed BIF. Quartz-Fe-silicate-magnetite assemblages occur away from mineralization, whereas pyrrhotite accompanies gold. Veining is typical in the sulphide BIF and transitions between sulphide and oxide are sharp and vein-related (J.E. Martyn, pers. comm., 1982). Subsequent metamorphism has produced a cummingtonite-quartz-diopside assemblage in unmineralized BIF away from the veins, and made the sulphide-oxide transitions less clear than at Water Tank Hill. The many similarities between the two deposits suggest the processes forming Water Tank Hill may be rather general to BIF gold deposits, but this deposit (WTH) preserves key genetic evidence in a relatively unstrained form. Further observations in Barberton, South Africa (Agnes Mine), and Zimbabwe (Vubachikwe Mine) indicate that the Water Tank Hill replacement features are widespread, but difficult to identify.

Further documentation of BIF gold is required before a universal model can be applied to this deposit type, but from structural setting, textures, and metal ratios similar to mafic-hosted deposits, many other BIF deposits are difficult to reconcile with their supposed syngenetic origin.

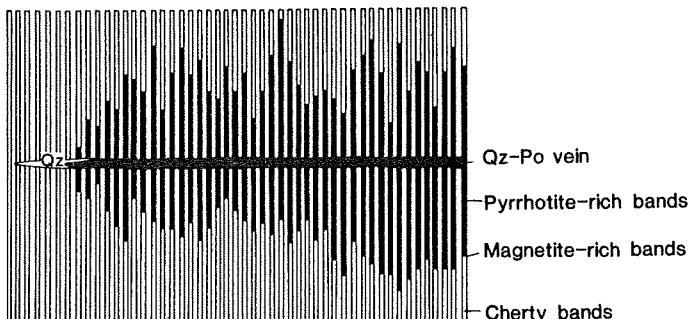


Figure 28 : "Fish-spine" arrangement of sulphide BIF as an envelope around a quartz vein, all within oxide BIF, Water Tank Hill Mine.

The replacement model has important exploration consequences. Undiscovered deposits might be expected in structurally complex zones (fold axes, faults) where fluid access is facilitated, and are more likely to be rod-like and steeply plunging. In contrast, a syngenetic model would suggest that the sedimentary facies distribution controls gold mineralization, and in particular the occurrence of sulphide BIF. The only facies control that may, in fact, be necessary is to have sufficiently Fe-rich oxide layers in the BIF so that quartz does not shield the oxides from fluid-wallrock interaction. There is no evidence yet that "oxide facies" to "sulphide facies" or "carbonate facies" changes during sedimentation play a significant role in gold localization. Commonly these changes can be shown to be alteration zones. The Water Tank Hill model has prompted reinterpretation of a number of Canadian gold deposits in BIF that have been quoted as examples of syngenetic mineralization. Replacement features analogous to Water Tank Hill are now known (e.g. Fyon *et al.*, 1983; MacDonald, 1983).

VIII. METAMORPHOSED DEPOSITS - BIG BELL

Big Bell is one of the most striking (and largest) exceptions to the generalization that large gold deposits occur in BIF or as veins in greenschist facies mafic rocks of the Yilgarn Block. The deposit represents an accumulation of 175 t of gold, counting production and reserves. It is in a narrow, highly strained, upper amphibolite facies greenstone belt, and is devoid of major veining, carbonation, or obvious fluid channelways (Chown *et al.*, 1984; Phillips, 1985).

Big Bell is 30km west of Great Fingall in a 1km wide greenstone belt between granitoids of the Murchison Province (Fig. 5). Total production to date is 23 t of gold to 300m depth, but drilling to 1500m accounts for the much larger total resource. Five stratigraphic units have been recognized in the greenstone belt (Chown *et al.*, 1984) :

I: (inferred earliest though younging evidence is lacking) quartzo-feldspathic gneiss and banded iron-formation,

II: mafic and ultramafic amphibolite,

III: felsic gneiss and amphibolite,

IV: Big Bell lode schist, biotite schist, and felsic gneiss, and

V: amphibolite.

A graphite-bearing mylonite, up to 1m wide, separates units IV and V and provides a useful marker over the extent of mineralization. The belt has undergone high strain making the recognition of precursors more difficult than usual for Archaean gold deposits. Schistose and gneissic fabrics are common in appropriate lithologies.

Gold mineralization is in a steeply plunging lens of 10-20m-thick pyritic muscovite-K-feldspar-quartz schist. Associated phases include rutile, cordierite, tourmaline, andalusite, and spinel with minor sphalerite, chalcopyrite, molybdenite, and several arsenic and antimony phases. Gold is disseminated throughout the schist and, based on drill core logging, bears no apparent relationship to major quartz veining. However, close inspection of the pyritic lode schist and surrounding biotite schist reveals a large number of quartz and quartz-rich lenses (0.2-1cm thick) that are surrounded by higher concentrations of sulphides. The possibility that these represent deformed and recrystallized gold-mineralizing veins cannot be ignored.

Enclosing the lode schist on three sides is a biotite schist that carries minor gold mineralization. This unit has a mineralogy that is inconsistent with its direct derivation from a metasediment or a metavolcanic precursor. Phases include cordierite, garnet, andalusite/sillimanite, dumortierite, pyrrhotite, K-feldspar, magnetite, ilmenite, rutile, and tourmaline. Assemblages such as K-feldspar-sillimanite-cordierite attest to the low pressure, high temperature nature of the prograde metamorphism, and imply a pre-peak metamorphic origin for the unusual nature of the lode and biotite schists (and the gold).

One of the major problems in exploration and genetic modelling at Big Bell is the origin of the lode rocks and hosting sequence. In a study designed to determine the nature of the Big Bell host rocks, Chown *et al.* (1984) used extensive whole-rock major and minor element geochemistry to support field observations. They inferred from whole-rock compositions and the homogeneous, massive character that the felsic gneisses underlying the lode and biotite schists were acid meta-igneous rocks, and that the amphibolites overlying and underlying the same schists were originally rocks of basaltic composition. Unusual compositions within the felsic gneiss and amphibolite sequences were linked to early alteration of the volcanic rocks.

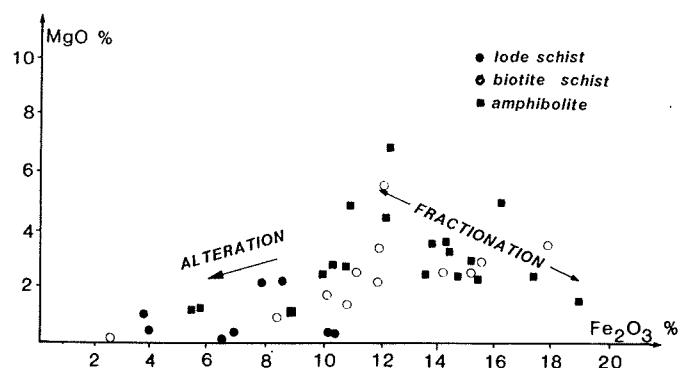
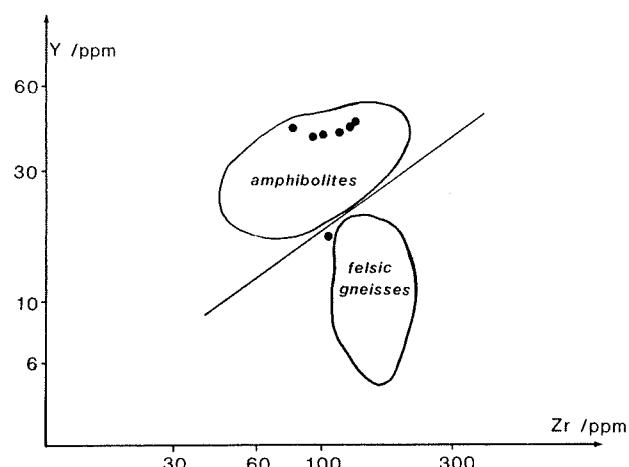
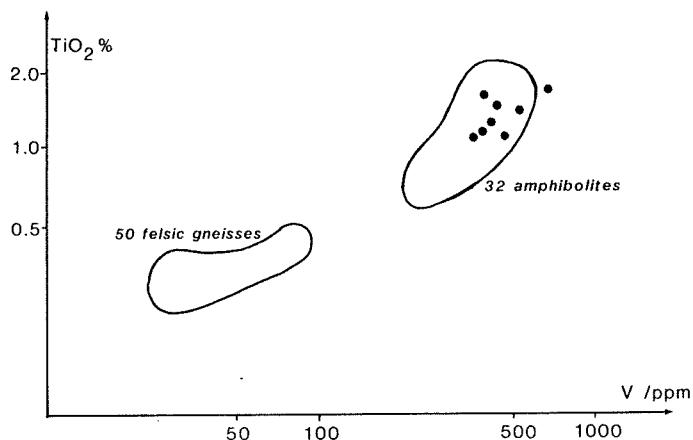


Figure 29 : Element plots for felsic gneisses, amphibolites, biotite schists, and lode (pyritic) schists from the Big Bell Mine. Immobile element plots (Ti , V , Y , Zr) are used to suggest a mafic precursor for the biotite and lode schists, and the $\text{Fe}-\text{Mg}$ plot documents extensive alteration.

The precursor of both the lode schist and surrounding biotite schist is thought to be basaltic in composition (Chown *et al.*, 1984) on the basis of immobile minor element geochemistry (Fig. 29). Two-element plots involving Ti, V, Y, and Zr show the schists have similar minor element composition to the amphibolites and not the felsic gneisses. The schists were generated by pre-metamorphic alteration of a basaltic starting material involving addition of K, S, B, Ba, Au, Ag, As, and Sb, with depletion of Mg and Ca, followed by metamorphism of this alteration. Limited data from the lode schist suggest slightly higher V/Ti, Zr, and Nb than may be expected in an ordinary tholeiitic basaltic composition, raising the possibility that the lode schist precursor was a more differentiated part of the tholeiite sequence, maybe from a differentiated sill (Fig. 30). By comparison with well-studied, differentiated tholeiites, the Big Bell Lode schist approximates the doleritic (ophitic)part of a sill and not the cumulate section or granophyre.

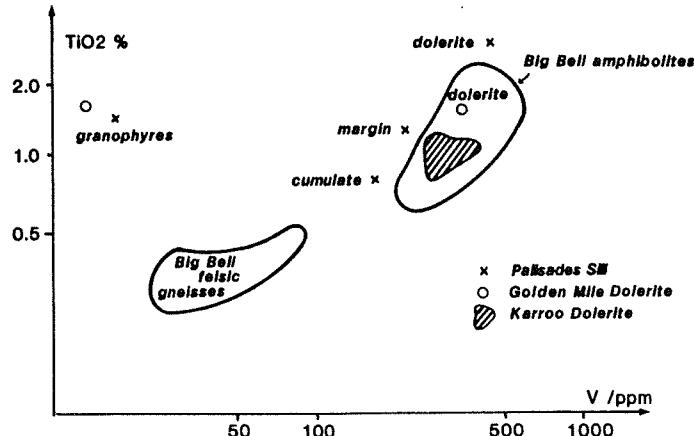


Figure 30: Element plots comparing Big Bell host rocks to possible precursors. Similarities exist between the Big Bell host rocks and differentiated tholeiitic sills (but not the granophytic sections). The Big Bell biotite schists and lode schists plot with the amphibolites.

Most criteria that could be used to support particular genetic models have been overprinted (fluid inclusions, wallrock alteration assemblages), and although Chown *et al.* (1984) discussed the relative merits of a volcanogenic exhalative model and an epigenetic replacement model, they came to no definite conclusion. The syngenetic model involving exhalation of ore components onto the seafloor is supported by evidence of an undiagnostic nature (a dominantly volcanic sequence, inferred asymmetric footwall alteration). The arguments for epigenetic replacement include the Fe-rich nature of the host rocks, shape and orientation of the ore body, and base metal ratios more similar to the epigenetic vein gold deposits and not to classic volcanogenic massive sulphides (Phillips, 1985).

It would appear that with the present level of geological knowledge of Big Bell, a definite genetic model cannot be sustained. However, it is useful to compare the metamorphosed Big Bell to late-metamorphic mafic-hosted deposits such as the Hunt Mine. Perhaps the major difference between Big Bell and the vein-type mafic-hosted deposits is the absence of carbonates around the Big Bell lode. If, as seems most likely, any original carbonate at Big Bell was siderite (and/or ankerite), devolatilization at upper amphibolite facies ($T > 550^{\circ}\text{C}$) would be expected (Frost, 1979). Similarly, pyrite may devolatilize to form pyrrhotite, particularly on the fringes of the ore where sulphur activities would be lower (e.g. in the biotite schists). A further contrast is the lack of large-scale veining at Big Bell, and although thick quartz veins are common in mafic-hosted gold deposits (e.g. Crown-Mararoa at Norseman, Hunt, Mt Charlotte, Day Dawn) they are not universal (e.g. Golden Mile at Kalgoorlie, Sons of Gwalia at Leonora). Massive auriferous veins are lacking at these last two examples, but it is significant that veinlets of quartz + carbonate (0.5-2cm thick) are found in each deposit, and are commonly surrounded by sulphides and gold (e.g. Golden Mile). The quartz veinlets in Big Bell drill core may represent recrystallized equivalents of the veinlets found in mafic-hosted deposits: any mobility of silica during metamorphism at Big Bell would further complicate the interpretation of the lack of thick veins there.

The inferred alteration of the Big Bell sequence does not exactly resemble that found near mafic-hosted vein gold deposits (Fig. 29, Table VII). The strong Na, Ca, and Mg depletion at Big Bell is not that expected from the metamorphism of wallrock alteration at the Hunt Mine or at Mt Charlotte, for example; and Fe-mobility (Fig. 29) is more common in volcanogenic massive sulphide deposits. This latter model, however, does not account for some of the Big Bell minor element features (Phillips, 1985; Table VII).

The lack of obvious fluid channelways at Big Bell is not unexpected. If carbonate-bearing shear zones were present in the sequence prior to peak metamorphism, they would be extremely difficult to recognize after recrystallization and flattening. The graphitic mylonite between units IV and V may, however, be such a channelway.

Documentation of Big Bell is useful even without a definite genetic conclusion. The deposit illustrates many of the difficulties in rock identification, alteration studies, and genesis, that exist at metamorphosed deposits in high strain environments. Obvious problems arise using a near-stratiform character to be indicative of syngensis (see also BIF gold) and there is a need to collect diagnostic data. Big Bell-type deposits are very unlikely to outcrop in the Yilgarn Block, and therefore make challenging, but very rewarding, large low-to-medium grade targets.

TABLE VII

Comparison of Element Metasomatism at Various Archaean Gold Deposits,
and in Volcanogenic Massive Sulphide Deposits

	Zr	Y	V	Ti	Fe	Mg	Al	P	Mn	Sc	Ce	Co	Na	Ca	K	Ba	Rb	Sr	Li	Mo	Sn	CO ₂	S	Te	B	Cu	Pb	Zn	Nb	Cr	Ni	W
Golden Mile	0	0	0	0	0	0	0	0	0	0	*	+	0	*	-	0	*	*	*	+	*	0	0	+	+	*						
Hunt	0	0	0	0	0	0	0	0	0	0	0	*	*	*	*	*	-	*	*	+	*	0	+	+								
Kanowna ¹	0	0	0	0	0	0	0	0	0	0	0	*	+	0	0	*	*	*	0	0	0	*	+	*								
Big Bell	0	0	0	0	-	-	0	0	-	-	*	*	0	0	*	*	0	*	0	*	0	+	+	-	*							
Vubachikwe ²	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	*	*	*	0	+	+	+										
Water Tank Hill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+								
Con ³	0	0	0	0	?	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+							
Dickensen ⁴	0	0	0	0	0	0	0	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+	*	+	*					
Campbell ⁴	0																	0	0	*												
VMS ⁵	?	-	+	?	+	+	?	+	+	-	0	+	-	?	?	?	?	?	?	?	?	*	*	*	+	+	+	-	+	+		

¹ Red Hill (Grigson, 1981)

VMS : volcanogenic massive sulphides

* major gain

² Fripp (1976)

Note : Ag, Au, Sb, As always added.

+ minor gain

³ Yellowknife, Canada

: Local major V and Te gains in

0 little change

⁴ Red Lake, Canada

Golden Mile

- loss

⁵ Kerrich (1979)

? variable

Finlow-Bates and Stumpf (1981),
Franklin *et al.* (1981)

IX. GENESIS OF AUSTRALIAN ARCHAEOAN GOLD DEPOSITS

A. Introduction

A metamorphic replacement model is adequate to account for most of the Archaean gold deposits in Western Australia (> 90% of the Au), and gives considerable predictive success. Alternative models are discussed where the available data do not rule out their viability. However, when looked upon as a whole, the worldwide occurrence of gold-bearing Archaean greenstone belts suggests some coherence of gold formative processes. The metamorphic replacement model (Phillips and Groves, 1983) evolved from application to small deposits. It relates to the main gold-forming event and not to later modifications.

The metamorphic replacement model has three essential stages, and a preliminary overview of these (source, transport, and deposition) is given below. Source processes must account for all fluid components, including gold, and most importantly fit in with the timing inferred for metamorphic and deformational events. Fluid is generated by the devolatilization of deeper parts of the greenstone sequence during amphibolite/granulite facies metamorphism. Such fluids scavenge gold from large rock volumes and are active during peak and/or waning metamorphism.

The transport stage requires fluids hot enough and of suitable composition to transport gold. Available data suggest low salinity, H₂O-CO₂ fluids (Ho *et al.*, 1985) with gold carried as a reduced-sulphur complex (Phillips and Groves, 1983). In addition, deep channelways are required so that enough fluid can be focussed to form a gold deposit. Deep shear zones and extensive fracturing play an important role in the transport and deposition stages.

The deposition stage is the most complex, but has by far the most important implications for exploration. Prior to actual deposition, access of fluids to mechanically suitable host rocks must occur. High pore-fluid pressures and competent host rocks favour extensive hydraulic fracture and, in turn, fluid access to large surface areas of rock. Gold deposition is a consequence of fluid-wallrock interaction, and in this, Fe-rich rocks play a major role in destabilizing gold reduced-sulphur complexes (see below).

Alternative hypotheses for Archaean gold genesis either apply to individual deposits (e.g. Spargoville; Fehlberg and Giles, 1984) and/or are not supported by diagnostic evidence from Western Australian gold deposits. Replacement characteristics of Archaean gold deposits have long been noted (e.g. Finucane, 1953; Williamson and Barr, 1965), and the postulation of metamorphically-derived gold-bearing fluids is not new (Boyle, 1969; Kerrich and Fyfe, 1981; Kerrich and Fryer, 1981). Incorporation of stratiform and vein-type deposits into one unified model of H₂O-CO₂ fluids and Fe-rich host rocks (Fig. 31) represents a recent extension of these ideas (Phillips and Groves, 1983).

B. Source of Fluid

Part of the Yilgarn greenstone sequence underwent low grade hydration and carbonation prior to peak metamorphism (Binns *et al.*, 1976). Later regional metamorphism involved expulsion of these volatile components. Mafic assemblages in rocks of low metamorphic grade areas suggest that H₂O, CO₂, and S were important volatile components., as chlorite, calcite, and minor sulphides are widespread. Assuming some of the deeper mafic and ultramafic units also contained these components before metamorphism, they would be ready sources of H₂O-CO₂-H₂S

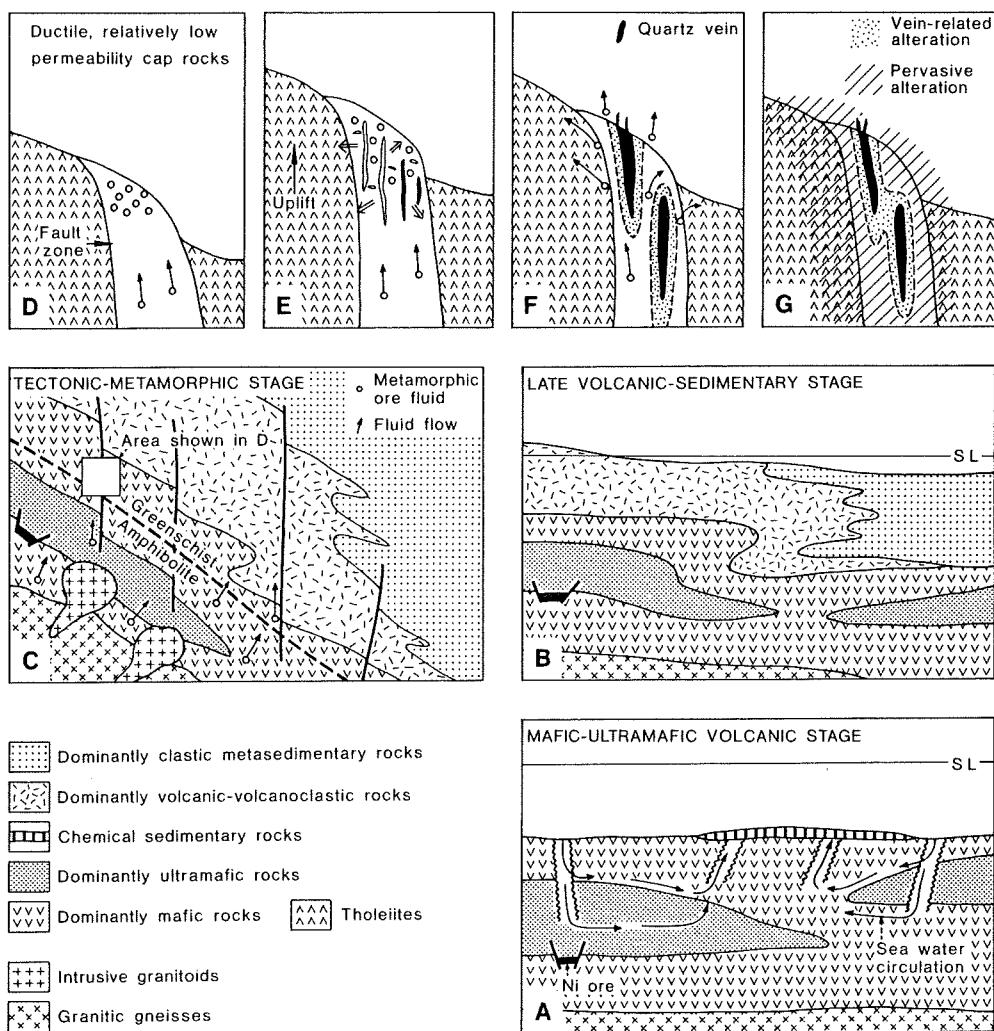


Figure 31 : Metamorphic replacement model for the genesis of Archaean gold deposits. Early seawater alteration of a volcanic-rich pile adds H_2O , CO_2 , and S (A) as sediments and felsic volcanics are emplaced (B). During burial and deformation/metamorphism, devolatilization releases an H_2O - CO_2 rich, auriferous fluid that rises via major channelways (C). Deposition of gold (D-G, based on Hunt Mine) is in response to fluid-wallrock interaction, where fractures have facilitated fluid access (from Groves et al., 1984).

fluids at high metamorphic grade. Comparison of typical greenschist facies assemblages from much of the Eastern Goldfields Province with middle amphibolite to granulite facies assemblages from greenstone belt margins and the Southern Cross Province (based on general observations), suggest that significant devolatilization (loss of H_2O , CO_2 , H_2S) occurred in mafic and/or ultramafic rocks somewhere above the greenschist/amphibolite facies transition (i.e. 550–650°C range). Hence it is likely that H_2O - CO_2 - H_2S fluids were a widespread product of greenstone belt metamorphism.

Oxygen isotope compositions of fluids can be used to suggest fluid source, and inferred values from Yilgarn gold deposits are compatible with a metamorphic fluid. Values of $\delta^{18}O = +6$ to $+8\text{‰}$ (S.D. Golding, 1982) are those expected from both magmatic and metamorphic fluids, but not deep circulating seawater or meteoric water (commonly negative values).

The style of early alteration (post-magmatic, pre-metamorphic) in greenstone belts may influence their later ability to yield auriferous fluids. Volcanic sequences that have little H_2O , CO_2 , or S before metamorphism are unlikely to produce large gold deposits, as they can generate very little suitable fluid during metamorphism.

Quantitative data to specify the precise metamorphic conditions under which H_2O - CO_2 - H_2S fluids are released, are unavailable. Nor is the influence of changing carbonate, sulphide, or mica phase compositions known accurately. However, the almost total lack of chlorine-bearing phases in hypogene greenstone sequences means any NaCl that was present will be expelled very early during burial, and all subsequent metamorphic fluids will be of low salinity.

C. Source of Gold

Differences of opinion as to the importance of gold-enriched source rocks are unlikely to be resolved without accurate knowledge of gold values in source rocks before metamorphism. Data from Western Australia are lacking, so those from other Archaean greenstone sequences are used. Widespread alteration and the mobility of gold hinder collection of the required data, and measured gold values from Archaean greenstones (Kwong and Crocket,

1978; Saager *et al.*, 1982) need bear no relationship to original gold values or the potential of a sequence as a gold source. There is some agreement, however, that the mafic-ultramafic rocks are likely to be the major source of gold (Kerrick and Fryer, 1979; Keays, 1984). One interesting attempt to extrapolate to original Archaean gold contents is that of Keays (1984), who used Tertiary high Mg-lavas from Disco Island, Greenland, as analogues for Archaean komatiites. Based on precious metal ratios (Pt, Pd, Ir, Au), Keays suggested that higher gold values occurred in certain source rocks and these may be necessary for gold deposits. However, the analogy between Tertiary and Archaean lavas remains unsubstantiated.

Average background gold values for Archaean volcanic rocks are in the range 1-10 ppb, and to produce a > 10 ppm Au deposit requires a 1000-10,000 times enrichment over source rock values. Because of this very high enrichment factor, Phillips and Groves (1983) argued that later hydrothermal processes are critical, and that source rock gold values are of secondary significance. For example, highly gold-enriched Archaean volcanic rocks with, say, 5-50 ppb gold, only reduce the volume of source rock required, and do not alter the need for a very effective hydrothermal process. The inefficiency of magmatic processes to concentrate gold (Vincent and Crocket, 1960) suggests that even values of 50 ppb Au are very unlikely in komatiitic or tholeiitic magmas.

Keays and Scott (1976) have pointed out the importance of the mineralogical siting of gold and its availability to various fluids. Gold sited in sulphides represents readily available gold. This led Groves (1982) to suggest that the degree and style of pre-metamorphic alteration may be critical, and may bear some relationship to water depths of depositional basins. Early silicification, carbonation, hydration, and sulphidation are all represented in greenstone sequences. Regional studies to understand fully the implications of early alteration are lacking, but preliminary results point to less intensely silicified volcanics from deeper water environments (e.g. Norseman-Wiluna belt) being more auriferous than highly silicified volcanics from shallower water basins (marginal parts of Eastern Goldfields Province; Pilbara Block).

Order-of-magnitude calculations show that there are enough mafic-ultramafic rocks in greenstone belts to more than account for all the produced gold, even if they only have initial concentrations of 1-5 ppb gold; such values appear reasonable from published analyses. Whether fluids can tap the necessary huge volumes of rock is often doubted, but recent studies (Ferry, 1981; Etheridge *et al.*, 1984) show large-scale fluid movements during metamorphism are realistic.

D. Fluid Channelways

The requirement to focus large volumes of fluid from depth, and the presence of both regional and local shear zones around most gold deposits, suggest these shear zones play an important role in the movement of fluid from source areas to depositional sites. In the Eastern Goldfields Province, NNW-trending (D_2) shear zones (Gee, 1979) are closely associated with mineralization (e.g. Hunt Mine), and according to the tectonic model of Archibald *et al.* (1978), the initiation of such shear zones immediately pre-dated the time inferred here for gold introduction.

A number of gold deposits have undergone deformation, and the ore-confining shear zones are either folded or have been the locus of later movement. Shear zones such as the Golden Pyke Fault, Kalgoorlie (Fig. 15), are folded (Travis *et al.*, 1971), but one of the best examples is the highly mineralized Sheba Fault, Barberton, South Africa (Anhaeusser, 1976). This shear zone, which can be traced for many kilometres, is folded around the Eureka syncline and is the site of many small, and some larger, gold deposits. However, recognition of similarly folded shear zones in the poorly outcropping Yilgarn Block of Western Australia may be very difficult without better stratigraphic control. The shear zones of the Golden Mile have been the site of repeated movement (Fotios, 1983).

Although the larger shear zones are closely related to gold mineralization, internally they are typically sub-economic. Charlotte Fault, Kalgoorlie (Fig. 21), has muscovite-carbonate-pyrite altered areas, but gold is minimal. Similarly, the major shear zones in the Golden Mile are only weakly mineralized (e.g. Boulder, Golden Mile, Adelaide faults). Instead, mineralization is most abundant adjacent to large shear zones (Mt Charlotte deposit; Sheba Mine, Barberton) and/or in secondary shear zones (Golden Mile deposits). A notable exception is the Hunt Mine where auriferous veins are confined to the main recognized shear zone, but here a lithological contact appears to be the dominant ore-localizing influence.

In general, the major shear zones are interpreted as pathways to focus metamorphic fluid at depth, and allow it to migrate upwards to suitable depositional sites where larger surface areas of host are available for interaction and alteration. The role of these shear zones as depositional sites is subordinate.

E. Gold Transport

Gold solubility is highly dependent on temperature and fluid composition (Henley, 1973; Seward, 1973, 1979, 1984). Gold solubility increases greatly above 400°C, and is significant in both acidic chloride solutions and slightly alkaline sulphide solutions (Helgeson and Garrels, 1968; Weissberg, 1970). The most direct method of establishing compositional constraints for the Archaean fluids is by studying fluid inclusions.

Fluid inclusion data from several Archaean gold deposits (Groves *et al.*, 1984) including Hunt, Mt. Charlotte, and Kanowna, indicate H_2O-CO_2 fluids of low salinity (< 3 wt % NaCl equivalent). Constraints on solution pH are poor, but alteration assemblages suggest slightly alkaline conditions. For example, at Red Hill, Kanowna, Na^+/K^+ data and alteration assemblages suggest near-neutral to slightly alkaline conditions at 300-350°C. Wallrock alteration assemblages also suggest a mildly reducing fluid (reduced sulphur, oxidized carbon, and ferrous minerals are stable during alteration).

The most likely form of gold transport can be inferred from experimental solubilities and the solution and alteration characteristics. Unless gold is complexed with a ligand, solubilities are negligible; and Au^{1+} is much more soluble than Au^{3+} under ore-forming conditions (Seward, 1979). Carbon-, sulphur- and chlorine-bearing ligands are likely to be the most abundant in gold-bearing fluids, and their relative importance is discussed by Phillips and Groves (1983). Gold Au^{1+} is a large, weakly charged cation and, as such, preferentially complexes with softer bases (Pearson, 1963). Bonding through S atoms is more favourable than through O or Cl atoms, and this suggests gold-sulphur complexing will dominate. The enrichment of Au relative to base metals in Archaean gold deposits is further evidence against chloride transport, as deposits formed from chloride-rich solutions show little, if any, gold to base metal enrichment (e.g. volcanogenic massive sulphides). Thus, this ratio is a very

powerful reconnaissance tool in assessing likely ore solution types. Further evidence against chloride transport of gold (cf. Helgeson and Garrels, 1968; Kerrich and Fryer, 1981) is the low concentration of chloride in solution, low gold solubility as a chloride complex in alkaline solutions, and the spatial association of gold and sulphide alteration in so many Archaean gold deposits (Phillips and Groves, 1983). This last observation and the softer nature of sulphur complexing argues against gold-carbonate complexing even though CO_2 is a major component of the fluid. It is difficult to evaluate the role of carbonyl (CO) complexing in the absence of experimental data, but it may require unreasonably reducing conditions. The present evidence favours sulphur complexing, and at temperatures over 300°C an associated species {i.e. $\text{HAu}(\text{HS})_2$ } is probable.

The recognition of reduced-sulphur complexing with gold $\{\text{HAu}(\text{HS})_2\}$ is important because the presence of high host-rock Fe will stabilize Fe-sulphides in the wallrocks and readily precipitate gold.

F. Chronological Constraints

Specific studies to date all the events during the formation of a gold deposit have not been attempted, so that the current discussion is limited to relative timing. On a broad scale, gold occurs in greenstones ranging in age from 3.5 to 2.8 Ga, but the period between 3.0 and 2.7 Ga accounts for most Archaean gold introduction in Western Australia, Canada, Zimbabwe, and South Africa. On a more local scale, there is a temporal relationship between gold and metamorphism/deformation, but it is varied in detail.

Adopting a regional structural history of early recumbent folding, tight upright folding and later more open folding, similar to that suggested by Archibald *et al.* (1978) for the southern Norseman-Wiluna belt, many gold deposits are syn-deformational. Many, such as the Hunt Mine, are confined by D_2 shear zones, but have veins that have undergone late folding. A similar situation exists at Norseman and Sons of Gwalia (Leonora). Golden Mile-type mineralization is also localized in early structures (shear zones), and is overprinted by later fabrics (Fotios, 1983). Although not universal, several larger gold deposits appear to be localized by D_2 features and folded during D_3 deformation. Despite searching, no diagnostic evidence has been found to suggest that any gold deposit pre-dated D_1 deformation.

Although much of the deformation occurred under regional metamorphic conditions, the peak metamorphic assemblages now preserved are commonly synchronous with D_3 deformation (Binns *et al.*, 1976; Archibald *et al.*, 1978). Hence many gold deposits formed close to peak metamorphic conditions. Phillips and Groves (1984) suggested that the Hunt gold mineralization post-dated peak metamorphism on the basis of 500–550°C regional metamorphic temperatures and 350°C fluid inclusion filling temperatures, and alteration assemblage stabilities. Several major deposits are inferred to significantly predate peak metamorphism on the basis of their metamorphosed wallrock assemblages. Such deposits include Big Bell, some of the Norseman deposits and many of the deposits in the Southern Cross greenstone belt. Most are close to granitoids that form the greenstone belt margins, and intrusion of the latter is likely to be related to the heat source for the metamorphism.

Felsic, intermediate, and mafic porphyry intrusions are an important feature at many deposits, and this spatial association has given rise to suggestions of a genetic association. However, where porphyries and ore are closely related, the porphyries are altered by the ore-forming fluids (Golden Mile) and intruded by gold-quartz veins (Hunt). This suggests that the porphyries provided, or were intruded along, pre-existing changes in rock competency, and thus viable solution channelways.

The cumulative evidence suggests that there was no unique interval in the metamorphic and structural history when all greenstone gold deposits formed, but most are synchronous with regional metamorphism (pre- to post-peak metamorphism), and many are post- D_2 , pre- D_3 deformation. One of the major hindrances in further resolution is the lack of a detailed structural history for most gold deposits. Problems to be encountered in erecting such histories include the heterogeneous nature of deformation and lack of good overprinting textures in competent host rocks.

G. Fluid-rock Access

The metamorphic conditions inferred for many vein gold deposits are such that host rocks would have low porosities; but the extensive wallrock alteration suggests considerable fluid access to these rocks. The extent of alteration depends on several factors, including chemical disequilibrium and time available for alteration, but the surface area of host rock exposed to fluid is of major importance. This is well demonstrated at the Hunt Mine, where alteration becomes more intense upwards as the size of host rock fragments decreases, and at the Mt Charlotte Mine in which alteration is more widespread where veining is most dense: both are examples of greater alteration where there was greater surface area for fluid-wallrock alteration.

Hydraulic fracture (W.J. Phillips, 1972) is generally thought to play a major role in the generation of gold-quartz veins (Kerrich and Allison, 1978). Fracturing occurs when the pore fluid pressure exceeds the confining pressure (specifically the minimum principal stress) plus the tensile strength of the rock. The process of fracturing is temporarily self-retarding, in that the opening of a crack increases pore volume, decreases pore-fluid pressure and stops fracturing – until pore pressure builds up again. The net result is a large number of short-lived, small fracturing events, giving rise to a major fracture zone. In a heterogeneous sequence of rock types, fracture will preferentially occur in lithologies of lowest tensile strength. In other rock types, ductile failure may be favoured, and shear zones developed.

Clark (1980) drew attention to the importance of hydraulic fracture at Mt Charlotte, where Travis *et al.* (1971) had recognized that the mechanical properties of the granophyre were controlling ore localization. Fluid access to the granophyre was facilitated by more extensive fracture compared to the less siliceous parts of the Golden Mile Dolerite. Hunt Mine provides a further example of preferential fracture of a more competent unit, but here the sharp lithological contact may also be acting as a fluid barrier and leading to increased pore fluid pressures (Fig. 10). Other competent rock types (e.g. felsic intrusive: Red Hill, Kanowna; banded iron-formation: Water Tank Hill) are also sites of more intense fracturing and better fluid access than surrounding lithologies.

Although high pore fluid pressure is the prime factor in initiating hydraulic fracture, the over-riding control on fluid pressure itself is less certain. From the equation of hydraulic fracture (W.J. Phillips, p. 28, 1972), two possibilities are suggested (Groves *et al.*, 1984). Regional uplift (and hence lower minimum principal stress) can explain why almost all the gold of the Eastern Goldfields Province (> 98%) comes from blocks uplifted relative to neighbouring areas (C.A. Henderson, written comm., 1982). An alternative explanation is that the waning

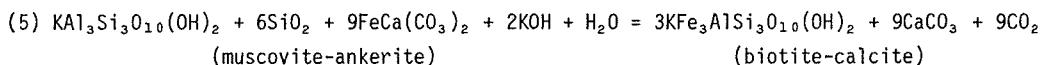
stage of deformation accompanies reduced stresses that in turn facilitate hydraulic fracture. At Red Hill, Kanowna, sub-horizontal extension veins are related to upright folding (Ho, 1984). No meaningful experiments have been carried out on the specific host rocks to gold deposits to test these aspects of hydraulic fracture, yet the relevance of such experiments is obvious from deposits such as Mt Charlotte and Hunt.

H. Fluid-wallrock Alteration

The few deposits from which fluid inclusion data are available (Groves *et al.*, 1984; Ho *et al.*, 1985) suggest that gold deposition occurred at 300-400°C and 1-2 kb, or 3-5 km depth. Fluids were H₂O-CO₂-H₂S rich and, in reacting with Fe-rich host rocks, deposited Fe-bearing carbonates, pyrite (or pyrrhotite) and gold. In mafic-hosted gold deposits, a number of elements were added to the ore environment during alteration (i.e. were carried by solution), but a further significant group of elements appear to have been relatively immobile (Table VII). Deposits within banded iron-formation vary in that some elements that are added to mafic vein systems (K, Ba, Rb, Sr, B) are negligible in BIF deposits. This non-enrichment, especially of K, is almost certainly related to the low Al₂O₃ in BIF and hence inability to stabilize micas; that is, the lack of K-rich phases does not imply low potassium concentrations in the fluid.

As some major elements are relatively immobile (Fe, Mg, Al, Ca, Ti, Na), and as significant differences in gold fluid compositions are not noted between deposits, the different wallrock alteration assemblages that are produced by fluid/rock interaction are primarily a function of the host rock composition and any subsequent metamorphism. The biotite-ankerite and actinolite assemblages from Norseman, for example, could represent subsequent metamorphic modification of a lower grade alteration assemblage, as could the cummingtonite-biotite mafic rocks of the Southern Cross Province, and the Big Bell wallrocks. The siderite-rich alteration in BIF reflects the precursor rock composition (i.e. low Ca, Mg).

Changes in fluid physio-chemical parameters (P , T , α_{CO_2}) play a lesser role in generating different alteration assemblages, but may account for the biotite assemblages at Hunt Mine contrasting with the muscovite assemblages at Kalgoorlie, as both are in Fe-rich tholeites. Assuming mobility of CO_2 , K, Si, and H_2O in the fluid phase, the ankerite-muscovite-bearing assemblages of the Golden Mile can be related to the calcite-biotite-bearing assemblages of the Hunt Mine (using Fe-end members of a Fe-Mg series):



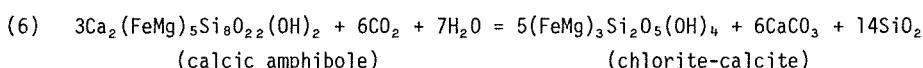
This equation is a simplification of the reaction linking the assemblages and does not account for other carbonates or feldspar. However, it does show the controls on either assemblage. An expression for the equilibrium constant for equation (5), omitting solid phases, is:

$$K_5 = \{(a\text{KOH})^2 * (a\text{H}_2\text{O})\} \quad (\text{fluid components only})$$

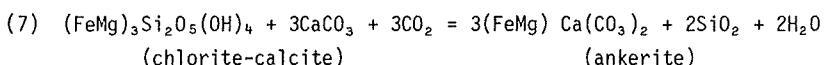
and $X(\text{CO}_2) \approx 1.0 - X(\text{H}_2\text{O})$ in typical $\text{H}_2\text{O}-\text{CO}_2$ -rich auriferous fluids. This suggests that increased potassium activity or especially decreased CO_2 would favour biotite stabilization. Lower P or higher T would probably have a similar effect. Data are currently unavailable to quantitatively determine the specific controlling factor in this example. A further process that may influence gold deposition is a change in the physical state of the hydrothermal fluid. There is no evidence (and it is unlikely at the inferred pressure) that boiling occurred (i.e. formation of coexisting liquid and vapour phases). However, the separation of two immiscible fluid phases (CO_2 -rich, H_2O -rich) has been widespread (Groves *et al.*, 1984). Several deposits show evidence for late phase separation in the form of adjacent CO_2 -rich and H_2O -rich fluid inclusions (Mt Charlotte, Hunt, Morning Star, Red Hill), and for Kanowna Main Reef, a heterogeneous fluid was present throughout most of the ore deposition (Grigson, 1981; Ho, 1984). The separation of an $\text{H}_2\text{O}-\text{CO}_2$ fluid into two immiscible phases is predicted from experimental data (Roedder and Bodnar, 1980, for summary of method) from either lower P or T, increased NaCl, or from decreased $a(\text{CO}_2)$. If fluid/rock ratios were low, the continual precipitation of carbonate phases could be sufficient to change either of these last two parameters and bring about immiscibility (Fig. 32).

Alteration studies of Archaean gold deposits are rare, but a consistent pattern is emerging from the better known areas. Carbonate alteration is usually the most extensive, with narrower zones of mica and sulphide alteration closer to the vein systems.

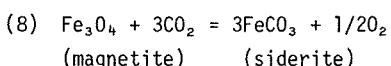
1. Carbonation: Volumetrically, the most important wallrock reaction in many gold deposits within mafic host rocks is the carbonation, firstly to calcite and ultimately to Fe-bearing carbonate. An outer zone of calcite-chlorite commonly represents the breakdown of amphibole in mafic-hosted deposits (somewhat simplified):



Further carbonation yields a zone of ankerite closer to the vein:



In banded iron-formation and some magnetite-bearing mafic rocks, high Fe/Mg leads to the formation of siderite instead of ankerite :



This reaction leads to oxidation of the ore fluid. This overall scheme of carbonate formation is a generalization for Archaean gold deposits and forms a basis that can be modified for a specific deposit.

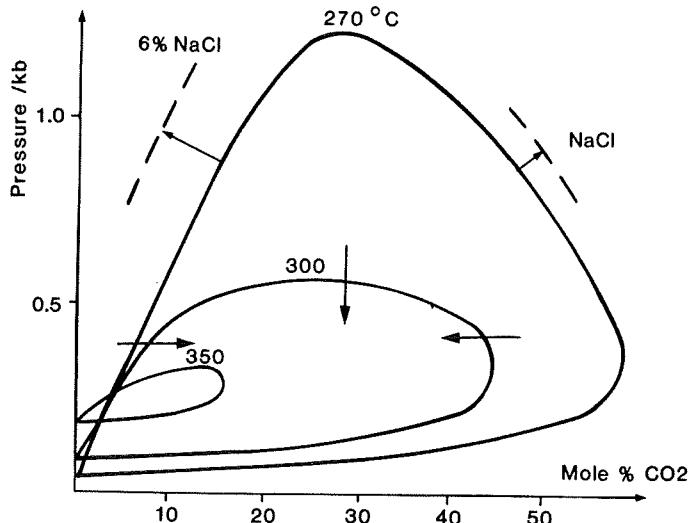
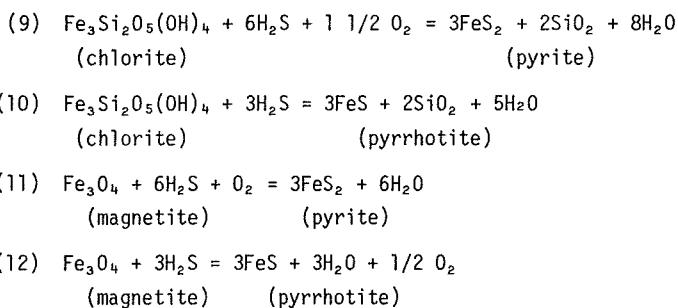


Figure 32 : P-T stability diagram of one and two phase H_2O-CO_2 fluids with variable $NaCl$ content. Immiscibility can result from either lower pressure (arrow), lower temperature, higher ($NaCl$) or higher CO_2/H_2O (arrow).

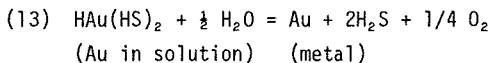
2. Sulphidation: The wallrock reactions that produce iron sulphides are closely related to gold formation. These are usually redox reactions, but differ depending on the initial Fe phase and the particular sulphide formed.



From these equations, it is evident that the formation of pyrite always involves fluid reduction. However, pyrrhotite formation may involve no redox change (10) or fluid oxidation (12).

3. Muscovite/biotite Alteration: The addition of K to mafic and felsic host rocks leads to the stabilization of mica phases. Whether muscovite or biotite is formed depends on several factors (see equation 5) that include the possible later metamorphism of inferred muscovite to form biotite. Mica generally forms by complex reactions involving carbonation of plagioclase and the release of Al to form silicates. However, as chlorite, carbonates, feldspars, and micas are all involved it is difficult to give a simple, useful equation. The general immobility of Al in auriferous solutions means that micas will not be stabilized in low Al-rock (e.g. BIF) regardless of αK^+ in solution.

4. Gold Zone: Arguments are presented elsewhere (Phillips and Groves, 1983) that gold transport is by associated reduced sulphur complexes $\{HAu(HS)_2\}$. Gold precipitation follows from destabilization of these complexes and can result from fluid reduction or lowering of $\alpha(H_2S)$, that is, lowering sulphur in solution:



All reactions that produce iron sulphide (equations 9-12) will lower sulphur in solution, but only the pyrite-forming reactions will supplement this effect by also reducing the oxidation state of the fluid. This may partly explain the worldwide occurrence of gold in pyrite-bearing rocks. Interestingly, the redox influence of equation (8) would hinder gold precipitation, and could explain the typical sharp gold grade cut-off in the carbonate zone outside the iron-sulphide zone (e.g. Golden Mile).

The formation of pyrrhotite reflects physio-chemical conditions different from those in which pyrite forms (it may also be a later metamorphic effect - see below). In a simple Fe-O-S system, the pyrrhotite field is favoured by moderate sulphur and low oxygen activities, and in BIF, which approximates this system, pyrrhotite is the common sulphide. However, the mafic rocks have significant Mg/Fe and Ca/Fe, which stabilize further Fe-bearing phases such as silicates and carbonates. The effect of Mg is to stabilize Fe-Mg silicates relative to magnetite or pyrrhotite, and reduce the stability field of these latter phases (Fig. 33). The net result is a paucity of pyrrhotite assemblages, in mafic-hosted deposits, and where they do form (Hunt, Charlotte), they represent lower $\alpha(S_2)$ than pyrite alteration. Interestingly, the pyrrhotite alteration around Charlotte veins is low in gold compared to pyrite alteration, and as might be predicted, the more extensive pyrrhotite alteration

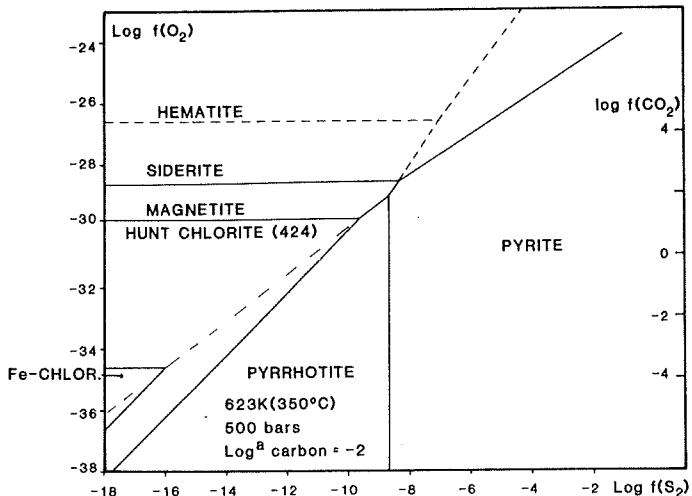


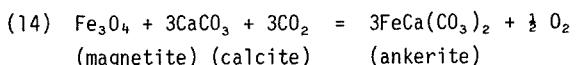
Figure 33: fO_2 - fS_2 stability of Fe-bearing phases in the alteration of a mafic host rock. In mafic rocks, Fe-Mg silicates limit the stability range of magnetite and pyrrhotite. The Hunt Mine chlorite field is based on calculations by F:B: Neall.

at depth in this mine accompanies lower bulk gold grades. A further influence favouring pyrrhotite is higher temperature, but this does not appear to be a major factor at any deposit so far studied. The difference in iron-sulphide phases between adjacent deposits (e.g. Water Tank Hill, pyrrhotite, BIF; Morning Star, pyrite, mafic) is more likely to reflect differing host rocks than physical conditions.

I. Fluid Modification: Sulphur

In nearly all the Archaean gold deposits, small size and restricted fluid flux within the deposit combine to limit any evolution of fluid chemistry that could potentially be recorded in the wallrocks. However, in the largest deposits, wallrock alteration may progressively change fluid composition and this may be recorded during the temporal evolution of the deposit. Redox changes can lead to new species being stabilized in solution and concomitant stable isotope fractionation.

The most widespread reaction is generally that of carbonation, and where magnetite is present in the host rock, solution oxidation may be a response to ore-related alteration involving the stabilization of iron-rich carbonates (written for Fe end member):



Any reduced sulphur in solution could be oxidized by the formation of widespread ankerite, giving coexisting sulphur species of different $^{32}\text{S}/^{34}\text{S}$ ratio (Ohmoto and Rye, 1979). Pyrite precipitating from solution will reflect the changes in isotopic composition of S^{2-} in solution, if there is continuous fluid evolution.

Sulphur isotopic compositions of many Archaean ore environments are close to magmatic values ($\delta^{34}\text{S} = 0$ to $+2\text{‰}$). These data include volcanic massive sulphides, komatiite-hosted nickel deposits (Secombe *et al.*, 1981) and sulphidic metasediments (Donnelly *et al.*, 1981) and sulphidic metasediments (Donnelly *et al.*, 1977). These data are interpreted to mean an absence of oxidized sulphur in most hydrothermal and sedimentary systems in the Archaean, and thus virtually no isotopic fractionation.

Sulphur isotope results from 30 Archaean gold deposits from Australia and Zimbabwe show a small scatter around $\delta^{34}\text{S} = +2\text{‰} \pm 4$. These values are inferred to mean no significant development of oxidized sulphur species during gold evolution, as the source of sulphur in any genetic model is likely to have $\delta^{34}\text{S} \approx 0$ to $+2\text{‰}$.

The giant Golden Mile deposit at Kalgoorlie, next to the whole Timmins camp in Canada, is the largest Archaean gold deposit. As it represents a substantial hydrothermal system with evidence of alteration and ore to over 1.5 km depth, there has been considerable scope for fluid modification during ore genesis. Furthermore, ankerite/siderite alteration forms broad zones in rocks that formerly had magnetite as a major phase, and hence there was the potential for large scale fluid oxidation. The sulphur isotope compositions of pyrite (Lambert *et al.*, 1983) from the Golden Mile are distinctive and statistically different to sulphides analysed from other Archaean gold deposits (Fig. 34). Potentially this provides a means to identify large hydrothermal gold systems using stable isotope values, and opens the way for investigating other geochemical methods to serve the same purpose.

J. Later Modification

Later metamorphism is one of the most important events in determining the gross appearance of a deposit. It has led to many of the observed differences between deposits, and has obscured the formation processes inferred to be common to many.

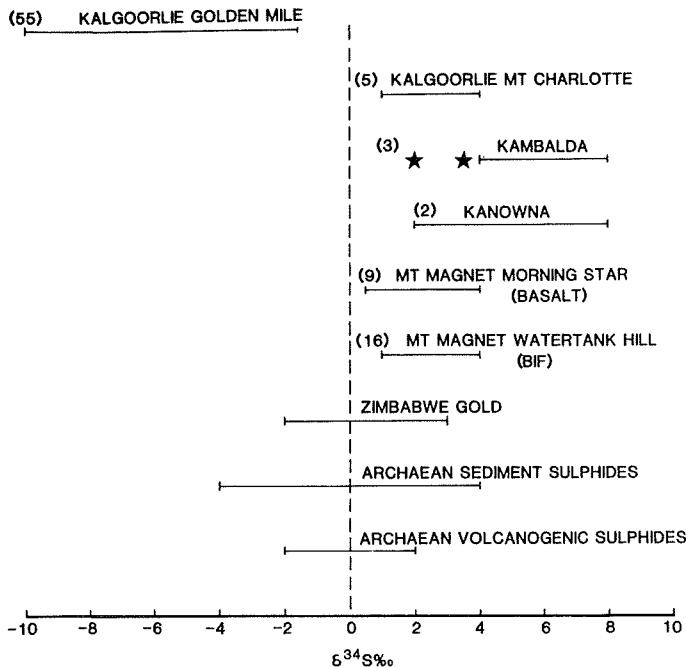


Figure 34 : Summary of sulphur isotopic compositions of Fe-sulphides from Archaean gold deposits, showing the distinctive character of the Golden Mile pyrites. Kambalda "stars" are averages for nickel ore (left) and sediments. The Kanowna data represent both porphyry host rocks (+2‰) and polymict conglomerate (+8‰).

Gold deposits near greenstone belt margins are those most likely to be metamorphosed, especially adjacent to syn- and post-kinematic granitoid intrusions (Archibald *et al.*, 1981). These granitoid intrusions are syn- to post-D₃, and may account for the less-carbonated, pyrrhotite-bearing assemblages in adjacent gold deposits. Given temperatures of 550°C or more, decarbonation of ankerite/siderite, desulphidation of pyrite, and dehydration of micas and amphiboles are predictable processes in the appropriate host rocks (e.g. Frost, 1979). This mechanism rationalizes the low carbonate, pyrrhotite-bearing deposits (e.g. in the Southern Cross Province) in terms of the nature of gold deposits from lower metamorphic grade environments. As yet, no experimental data allow quantitative testing of these ideas. Theoretically, such devolatilization could lead to small vein deposits higher in the pile synchronous with granitoid intrusion: this may be the origin of some of the small vein gold deposits that show no particular host rock control, but are clustered around granitoid contacts.

Remobilization of pre-existing, moderate-grade gold deposits can lead to particularly rich ore shoots, such as the telluride ores of Kalgoorlie. This is the topic of continuing research.

X. FUTURE DEVELOPMENTS

A. Exploration

It is unlikely that the broad exploration targets will change dramatically as a result of recent research. Favourable targets will still be areas surrounding known goldfields where sulphide mineralization is recorded, and close to major structures. Proximity to outcrop will also remain a magnet to exploration activity. These premises, however, are much the ones that guided the thorough prospectors 80 years ago, and it must be significant that a majority of Western Australia's gold was found in the ten years immediately following the first finds. A number of new finds (Victory-Defiance, Hunt, Harbour Lights, Paddington) followed the resurgence of research in the late 1970's. Within this framework, there is a notable shift in emphasis from the narrow vein deposits, to large tonnage disseminated deposits such as Big Bell, and low grade surface occurrences.

Conceptual models will play a larger part in guiding exploration, both in the justification of established methods and in the prediction of new ones. In the latter class, new structural sites and host-rock settings around old deposits hold interest, and competent Fe-rich lithologies should be a prime target. On a regional scale, parameters such as favourable metamorphic grade, host rock sequence and age can guide the choice of areas, sometimes under deep cover. Further understanding is required about large hydrothermal gold systems: both their identification from small samples (even if metamorphosed), and their distinction from smaller hydrothermal systems. On the mine scale, unresolved questions include the exact control on payable ore shoot location, the nature of ore shoot terminations and the reason for especially rich patches of ore; these are three aspects that have received little research attention in the past but are part of ongoing studies.

B. Research

Research, particularly of an applied nature, must play a greater role now that most easily-located Archaean gold deposits have been found. Basic documentation of existing mines is required before a representative and statistical data base of these disappearing exposures is established. Documentation of many older mines is limited to assay information, with no recording of rock types, structural fabrics, alteration, or veining. As collecting

this information requires considerable time over a protracted mine-operating period, a greater commitment to basic geological recording must be made. Once this documentation is well established, it will benefit both the individual mine by leading to a clearer geological understanding of that deposit, and regional exploration by giving confidence to well-established practices as well as suggesting new ones.

Mine documentation will also benefit broader gold genetic modelling, which in turn will lead to better conceptual models for exploration. Genetic modelling generally requires detailed scientific input, but understanding the gold-depositing reactions and the controls on fluid plumbing systems, for example, have instant application. More esoteric studies on a regional scale are ultimately going to also play a major role. Such studies might include the importance of greenstone belt age, tectonic chronology, initial sedimentary/volcanic environment, early seawater alteration, gold source rocks, and fluids in metamorphism (Groves *et al.*, 1984). However, such studies have few short term economic rewards, and are difficult to initiate.

XI. SUMMARY

Archaean greenstone belts have been a major source of gold, especially in South Africa, Canada, Zimbabwe, and Australia. The Yilgarn Block of Australia has produced over 2000 t of gold, mostly from younger greenstone belts (3,0-2,8 Ga).

Over 75 per cent of Western Australian gold has come from a small number of vein deposits in mafic host rocks, and, in fact, 50 per cent comes from Kalgoorlie alone. The larger deposits are characterized by strong carbonate and sulphide wallrock alteration and are broadly synchronous with deformation and metamorphism (usually greenschist facies). Important localizing features appear to be major fluid channelways, permeable zones (breccias, hydraulic fracture zones, early shear zones), and Fe-rich host rocks that can readily react with sulphur-bearing fluids to precipitate pyrite (\pm pyrrhotite) and gold.

Banded iron-formations are only a minor part of greenstone belts, but contribute 10 per cent of Western Australian gold. The fine layering of the host rocks is preserved in the disseminated ores that are typically Fe-carbonate/sulphide rich. Many epigenetic features are present in gold deposits in BIF, including veining, replacement features, and structural control; and the same localizing features (fluid access, Fe-rich host rocks) as in the mafic-hosted vein deposits apply.

Most of the smaller Western Australian gold deposits are on local shear zones in a variety of host rocks, and their contribution to production is low. Big Bell is exceptional in that it is a very large deposit that occurs in a high metamorphic grade area and has virtually no carbonates. Geochemical data suggest that gold mineralization was confined to a mafic host at Big Bell.

A metamorphic replacement model can account for nearly all large Australian Archaean gold deposits, and provides a useful model for current and future exploration. The model envisages fluids being evolved by devolatilization during high grade regional metamorphism of the lower parts of greenstone belts. These fluids were H_2O-CO_2 rich and carried gold as reduced-sulphur complexes. Major channelways guided upward fluid flow, and large gold deposits formed where fluid access permitted fluid/wallrock interaction with large surface areas of suitable Fe-rich host rocks. Pre-existing permeable zones, such as breccias and shear zones were important, as were hydraulic fracture zones in competent host rocks.

Gold deposition was a result of the sulphidation of wallrocks to form pyrite and the consequent destabilization of gold sulphur complexes in solution. More widespread carbonate alteration led to calcite-chlorite, siderite, or ankerite zones in various host rocks. The continued evolution of fluid composition in large hydrothermal systems may alter isotopic ratios (e.g. $^{32}/^{34}S$), and provide a means to identify the rare giant gold deposits from the many smaller ones. Metamorphism/deformation after gold deposition has played a major part in determining the final alteration assemblage and shape of the ore zone, and hence plays a dominant role in the appearance of many deposits.

Research will play a more important part in prospecting for new deposits now that obvious surface ores have been located. Mine documentation is an important basis for research, but is inadequate in most mines. Conceptual gold genetic models give a framework to search for blind deposits and add confidence in the search for extensions to known ores.

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REFERENCES

- Anhaeusser, C.R. (1976). The nature and distribution of Archaean gold mineralization in southern Africa. *Min. Sci. Engng.*, 8, 46-84.
- Archibald, N.J. (1982). Structure, lithological association units and gold mineralization, Mt Magnet area. In: Baxter, J.L. (ed.) *Archaean geology of the Southern Murchison*. Geol. Soc. Aust. West. Aust. Div. Excursion Guide, 15-27.
- Archibald, N.J., Bettenay, L.F., Bickle, M.J., and Groves, D.I. (1981). Evolution of Archaean crust in the Eastern Goldfields Province of the Yilgarn Block, Western Australia. In: Glover, J.E. and Groves, D.I., Eds., *Archaean Geology*. Spec. Publ. geol. Soc. Aust., 7, 491-504.
- Archibald, N.J., Bettenay, L.F., Binns, R.A., Groves, D.I., and Gunthorpe, R.P. (1978). The evolution of Archaean greenstone terrains, Eastern Goldfields Province, Western Australia. *Precambrian Res.*, 6, 103-131.
- Barley, M.E., Dunlop, J.S.R., Glover, J.E., and Groves, D.I. (1979). Sedimentary evidence for an Archaean shallow-water volcanic-sedimentary facies, eastern Pilbara Block, Western Australia. *Earth Planet. Sci. Lett.*, 43, 74-84.
- Bettenay, L.F., Bickle, M.J., Boulter, C.A., Groves, D.I., Morant, P., Blake, T.S., and James, B.A. (1981). Evolution of the Shaw Batholith- an Archaean granitoid-gneiss dome in the eastern Pilbara, Western Australia. In: Glover, J.E., and Groves, D.I., Eds., *Archaean Geology*. Spec. Publ. geol. Soc. Aust., 7, 361-372.
- Binns, R.A., Gunthorpe, R.J., and Groves, D.I. (1976). Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia. In: Windley, J.F., Ed., *The Early History of the Earth*, Wiley, London, 303-313.
- Blatchford, T., and Jutson, J.T. (1912). The mining geology of the Kanowna Main Reef line. *Bull. geol. Surv. West. Aust.*, 47, 106 pp.
- Boyle, R.W. (1969). Hydrothermal transport and deposition of gold. *Econ. Geol.*, 64, 112-115.
- Boyle, R.W. (1979). The geochemistry of gold and its deposits. *Bull., geol. Surv. Canada*, 280, 584 pp.
- Casey, G., and Mayman, T. (1964). *The Mine that Midas Touched*. Rigby, Sydney.
- Chown, E.H., Hicks, J., Phillips, G.N., and Townsend, R. (1984). The disseminated Archaean Big Bell gold deposit, Murchison Province, Western Australia: an example of premetamorphic hydrothermal alteration. In: Foster, R.P., Ed., *Gold '82*. A.A. Balkema, Rotterdam, 305-324.
- Clark, M.E. (1980). *Localization of gold, Mt Charlotte, Kalgoorlie, Western Australia*. B.Sc. (Hons) thesis (unpubl.), Univ. Western Australia, Perth.
- Crocket, J.H., and Lavigne, M.J. (1982). Sulphur isotope study of gold ores from the Dickenson Mine, Red Lake District, Ontario. *Gold-82 Conf. Abst.*, Harare, 19.
- De Laeter, J.R., Fletcher, I.R., Rosman, K.J.R., Gee, R.D., and Libby, W.G. (1981). Early Archaean gneisses from the Yilgarn Block, Western Australia. *Nature*, 292, 322-324.
- Donnelly, T.H., Lambert, I.B., Oehler, D.Z., Hallberg, J.A., Hudson, D.R., Smith, J.W., Bavinton, O.A., and Golding, L. (1977). A reconnaissance study of stable isotope ratios in Archaean rocks from the Yilgarn Block, Western Australia. *J. geol. Soc. Aust.*, 24, 409-420.
- Etheridge, M.A., Wall, V.J., Cox, S.F., and Vernon, R.H. (1984). High fluid pressures during regional metamorphism and deformation: implications for mass transport and deformation mechanisms. *J. Geophys. Res.*, 89, 4344-4358.
- Fehlberg, B., and Giles, C.W., (1984). Archaean volcanic exhalative mineralization at Spargoville, Western Australia. In: Foster, R.P., Ed., *Gold '82*. A.A. Balkema, Rotterdam, 285-303.
- Ferry, J.M. (1981). Petrology of graphitic sulfide-rich schists from south-central Maine: an example of desulfidation during prograde regional metamorphism. *Amer. Mineral.*, 66, 908-930.
- Finlow-Bates, T., and Stumpf, E.F. (1981). The behaviour of so-called immobile elements in hydrothermally altered rocks associated with volcanogenic submarine-exhalative ore deposits. *Mineral. Deposita*, 16, 319-328.
- Finucane, K.J. (1953). Hill 50 gold mine, Boogardie. In: Edwards, A.B., Ed., *Geology of Australian Ore Deposits*. Australas. Inst. Min. Metall., Melbourne, 231-235.
- Finucane, K.J. (1965). Geology of the Sons of Gwalia gold mine. In: McAndrew, J., Ed., *Geology of Australian Ore Deposits*. 8th Comm. Min. Metall. Cong., Melbourne, 95-97.
- Fletcher, I.R., and Rosman, K.J.R. (1981). Major Sm-Nd age differences within the Yilgarn Block. *Geol. Soc. Aust., Abst. Geol. Conv.*, Perth, 3, 81.
- Forman, D.J. (1960). Stratigraphy of the Boogardie group. *J. Roy. Soc. West. Aust.*, 43, 83-96.
- Foster, R.P., Mann, A.G., Stowe, C.W., and Wilson, J.F. (1985). Archaean gold mineralization in Zimbabwe. In: *Mineral Deposits Southern Africa*. Geol. Soc. S. Afr., (in press).

- Fotios, M.G. (1983). *Structural analysis of mineralised shear zones in Lake View and Perseverance gold mines, Kalgoorlie.* B.Sc (Hons) thesis, (unpubl.), Univ. Western Australia.
- Franklin, J.M., Lydon, J.W., and Sangster, D.F. (1981). Volcanic-associated massive sulfide deposits. *Econ. Geol.*, 75th Anniv. Vol., 485-627.
- Frater, K.M. (1978). *The Golden Grove copper-zinc deposit, Western Australia : An Archaean, exhalative, volcanogenic occurrence.* Ph.D thesis, (unpubl.), Univ. Newcastle.
- Fripp, R.E.P. (1976). Stratabound gold deposits in Archean banded iron-formation, Rhodesia. *Econ. Geol.*, 71, 58-75.
- Frost, R.B. (1979). Mineral equilibria involving mixed-volatiles in a C-O-H fluid phases: The stabilities of graphite and siderite. *Amer. J. Sci.*, 279, 1033-1059.
- Fyon, J.A., Crocket, J.H., and Schwarcz, H.P. (1983). The Carshaw and Malga iron-formation-hosted gold deposits of the Timmins area. *Miscell. Paper Ontario Geol. Surv.*, 110, 98-110.
- Gee, R.D. (1979). Structure and tectonic style of the Western Australian Shield. *Tectonophysics*, 58, 327-369.
- Golding, L.Y. (1973). *Mineralogy and geochemistry of the Mt Charlotte ore environment, Kalgoorlie, W.A.* (B.Sc) (Hons) thesis, (unpubl.), Univ. Melbourne.
- Golding, L.Y. (1978). *Mineralogy, geochemistry and origin of the Kalgoorlie gold deposits, Western Australia.* Ph.D thesis, (unpubl.), Univ. Melbourne.
- Golding, S.D. (1982). *An isotopic and geochemical study of gold mineralization in the Kalgoorlie-Norseman region, Western Australia.* Ph.D thesis, (unpubl.), Univ. Queensland, Brisbane.
- Gole, M.J. (1981). Archean banded iron formations, Yilgarn Block, Western Australia. *Econ. Geol.*, 76, 1954-1974.
- Gresham, J.J., and Loftus-Hills, G.D. (1981). The geology of the Kambalda nickel field, Western Australia. *Econ. Geol.*, 76, 1373-1416.
- Grigson, S.E. (1981). Nature and genesis of gold-quartz vein-type deposits, Kanowna, Western Australia. B.Sc (Hons) thesis, (unpubl.), Univ. Western Australia, Perth.
- Groves, D.I. (1982). The Archaean and earliest Proterozoic evolution and metallogeny of Australia. *Revista Brasileira de Geociencias*, 12, 135-148.
- Groves, D.I., and Batt, W.D. (in press): Spatial and temporal variations of Archaean metallogenetic associations in terms of evolution of granitoid-greenstone terrains with particular emphasis on the Western Australian Shield, 73-98. In: Kröner, A., Ed., *Archaean Geochemistry*, Springer-Verlag, Berlin.
- Groves, D.I., Phillips, G.N., Falconer, L.J., Houstoun, S.M., Browning, P. and Dahl, N. (in press). BIF-hosted gold deposits in Archaean greenstone belts of Western Australia : evidence for an epigenetic origin. *Krystallinchum*, 20.
- Groves, D.I., Phillips, G.N., Ho, S.E., Henderson, C.A., Clark, M.E., and Woad, G.M. (1984). Controls on distribution of Archaean hydrothermal gold deposits in Western Australia. In: Foster, R.P., Ed., *Gold '82*, A.A. Balkema, Rotterdam, 689-712.
- Hall, H.I.E., and Bekker, C. (1965). Gold deposits of Norseman. In: McAndrew, J., Ed., *Geology of Australian Ore Deposits*. 8th Comm. Min. Metall. Cong., Melbourne, 101-106.
- Hallager, W.S. (1982). Geology of a stratiform Archaean gold deposit near Jardine, Montana. *Gold '82 Conf. Abst.*, Harare, p. 28.
- Helgeson, H.C., and Garrels, R.M. (1968). Hydrothermal transport and deposition of gold. *Econ. Geol.*, 63, 622-635.
- Henley, R.W. (1973). Solubility of gold in hydrothermal chloride solutions. *Chem. Geol.*, 11, 73-87.
- Hickman, A.H. (1981). Crustal evolution of the Pilbara block, Western Australia. In: Glover, J.E., and Groves, D.I., Eds., *Archaean Geology*, Spec. Publ. geol. Soc. Aust., 7, 57-69.
- Ho, S.E. (1984). Alternative host rocks for Archaean gold deposits. Nature and genesis of hydrothermal gold deposits, Western Australia. *Aust. Inst. Min. Metall.*, (in press).
- Ho, S.E., Groves, D.I., and Phillips, G.N. (1985). Fluid inclusions as indicators of the nature and source of ore fluids and ore depositional conditions for Archaean gold deposits of the Yilgarn Block, Western Australia. *Trans. geol. Soc. S. Afr.*, 88(1), (in press).
- Hutchinson, R.W., and Burlington, J.L. (1982). Some broad characteristics of greenstone belt gold lodes. *Gold-82 Conf. Abst.*, Harare, 21-22.
- Ion, J.C. (1982). *Wallrock alteration and structural evolution of steeply dipping Golden Mile Dolerite hosted lodes of the Perseverance Gold Mine, Kalgoorlie.* B.Sc (Hons) thesis, (unpubl.), Univ. Western Australia, Perth.
- Keays, R.R. (1984). Gold and its source rocks: Further evidence for the mantle connection. In: Foster, R.P., ed., *Gold '82*. A.A. Balkema, Rotterdam, 17-51.
- Keays, R.R., and Scott, R.B. (1976). Precious metals in ocean-ridge basalts: implications for basalts as source rocks for gold mineralization. *Econ. Geol.*, 71, 705-720.
- Kerrich, R., and Allison, I. (1978). Vein geometry and hydrostatics during Yellowknife mineralization. *Can. J. Earth Sci.*, 15, 1653-1660.

- Kerrich, R., and Fryer, B.J. (1979). Archaean precious metal hydrothermal systems, Dome Mine, Abitibi greenstone belt. II. REE and oxygen isotope relations. *Can. J. Earth Sci.*, 16, 440-458.
- Kerrich, R., and Fryer, B.J. (1981). The separation of rare elements from abundant base metals in Archean lode gold deposits : Implications of low water/rock source regions. *Econ. Geol.*, 76, 160-166.
- Kerrich, R., and Fyfe, W.S. (1981). The gold-carbonate association: source of CO₂ and CO₂ fixation reactions in Archean lode deposits. *Chem. Geol.*, 33, 265-294.
- Kerrich, R. (1979). Archean lode deposits: a synthesis of data on metal distribution, rare earth elements and stable isotopes, with special reference to Yellowknife. In: Morton, R.D., Ed., *Proceedings of the Gold Workshop, Univ. Alberta*, 95-173.
- Kwong, Y.T.J., and Crocket, J.H. (1978). Background and anomalous gold in rocks of an Archean greenstone assemblage, Kakagi Lake area, northwestern Ontario. *Econ. Geol.*, 73, 50-63.
- Lambert, I.B., Donnelly, T.H., Phillips, G.N., and Groves, D.I. (1983). Sulphur isotope compositions and genesis of Archean gold mineralization, Western Australia. *CSIRO Research Review 1983*, 96-97.
- Lewis, B.R. (1965). Gold deposit of Hill 50 mine. In: McAndrew, J., Ed., *Geology of Australian Ore Deposits*. 8th Comm. Min. Metall. Cong., 98-100.
- Maitland, A.G. (1979). *The Gold Deposits of Western Australia*. Hesperian Press, Western Australia, 1-92.
- Mann, A.G. (1982). Gold in granite rocks in Zimbabwe. *Gold-82 Conf. Abst.*, Harare, 30-31.
- Mann, A.W. (1984). Mobility of gold and silver in lateritic weathering profiles - some observations from Western Australia. *Econ. Geol.*, 39, 38-49.
- MacDonald, A.J. (1983). The iron formation-gold association : Evidence from Geraldton area, 75-83. In: Colvine, A.C., Ed., *The Geology of Gold in Ontario*. *Miscell. Pap. Ontario geol. Surv.*, 110, 278p.
- McCulloch, M.T., Compston, W., and Froude, D. (1983). Sm-Nd and Rb-Sr dating of Archean gneisses, eastern Yilgarn Block, Western Australia. *J. geol. Soc. Aust.*, 30, 149-154.
- Neall, F.B., and Phillips, G.N. (1984). Fluid-wallrock interaction around Archean hydrochemical gold deposits : a thermodynamic model. *Geol. Soc. Aust. Abst.*, 12, 400.
- Nickel, E.H. (1977). Mineralogy of the "green leaden" gold ore at Kalgoorlie, Western Australia. *Proc. Aust. Inst. Min. Metall.*, 263, 9-13.
- Ohmoto, H., and Rye, R.O. (1979). Isotopes of sulphur and carbon. In: Barnes, H.L., Ed., *Geochemistry of Hydrothermal Ore Deposits*, 2nd edn., Wiley, New York, 509-567.
- Pearson, R.G. (1963). Hard and soft acids and bases. *J. Amer. Chem. Soc.*, 85, 3533-3539.
- Phillips, G.N. (1982). Mt Charlotte gold mine, Kalgoorlie. In: Groves, D.I., and Lesher, C.M., Eds., *Regional Geology and Nickel Deposits of the Norseman-Wiluna Belt, Western Australia*. Univ. Western Australia Extension Service Publ. 7, C13-16.
- Phillips, G.N. (1985). Interpretation of Big Bell/Hemlo-type gold deposits : Precursors, metamorphism melting, and genetic constraints. *Trans. geol. Soc. S. Afr.*, 88(1), (in press).
- Phillips, G.N., and Groves, D.I. (1983). Fluid access and fluid-wallrock interaction in the genesis of the Archean gold-quartz vein deposit at Hunt Mine, Kambalda, Western Australia. *Proc. Gold-82 Conf.*, Harare.
- Phillips, G.N., and Groves, D.I. (1984). The nature of Archean gold-bearing fluids as deduced from gold deposits of Western Australia. *J. geol. Soc. Aust.*, 30, 25-40.
- Phillips, G.N., Groves, D.I., and Clark, M.E. (1983). The importance of host rock mineralogy in the location of Archean epigenetic gold deposits. *Spec. Publ., geol. Soc. S. Afr.*, 7, 79-86.
- Phillips, G.N., Groves, D.I., and Martyn, J.E. (1984). An epigenetic origin of Archean banded iron-formation hosted gold deposits. *Econ. Geol.*, 79, 162-171.
- Phillips, W.J. (1972). Hydraulic fracturing and mineralization. *J. geol. Soc. Lond.*, 128, 337-359.
- Pretorius, D.A. (1981). Gold and uranium in quartz-pebble conglomerates. *Econ. Geol. 75th Anniv. Vol.*, 117-138.
- Roedder, E., and Bodnar, R.J. (1980). Geologic pressure determinations from fluid inclusion studies. *Ann. Rev. Earth Planet. Sci.*, 8, 263-301.
- Saager, R., Meyer, M., and Muff, R. (1982). Gold distribution in supracrustal rocks from Archean greenstone belts of Southern Africa and from Paleozoic ultramafic complexes of the European Alps : Metallogenesis and geochemical implications. *Econ. Geol.*, 77, 1-24.
- Scantlebury, G.M. (1983). The characterization and origin of the gold lodes in and around the Brownhill syncline, Golden Mile, Kalgoorlie, Western Australia. B.Sc. (Hons) thesis, (unpubl.), Univ. Western Australia.
- Seccombe, P.K., Groves, D.I., Marston, R.J., and Barrett, F.M. (1981). Sulfide paragenesis and sulfur mobility in Fe-Ni-Cu sulfide ores at Lunnon and Juan Main Shoots, Kambalda : Textural and sulfur isotopic evidence. *Econ. Geol.*, 76, 1675-1685.

- Seward, T.M. (1973). Thio complexes of gold and the transport of gold in hydrothermal ore solutions. *Geochim. cosmochim. Acta*, 37, 379-399.
- Seward, T.M. (1979). Hydrothermal transport and deposition of gold. In: Glover, J.E., and Groves, D.I., Eds., *Gold Mineralization*, Univ. Western Australia Extension Service Publ., 3, 45-55.
- Seward, T.M. (1984). The transport and deposition of gold in hydrothermal systems. In: Foster, R.P., Ed., *Gold '82*. A.A. Balkema, Rotterdam, 165-181.
- Stillwell, F.L. (1931). The occurrence of telluride minerals at Kalgoorlie. *Proc. Aust. Inst. Min. Metall.*, 84, 115-190.
- Tomich, S.A. (1959). The Oroya Shoot and its relationship to other flatly plunging ore pipes at Kalgoorlie. *Proc. Aust. Inst. Min. Metall.*, 190, 113-124.
- Tomich, S.A. (1974). A new look at Kalgoorlie Golden Mile geology. *Proc. Australas. Inst. Min. Metall.*, 251, 27-35.
- Tomich, S.A. (1976). Further thoughts on the application of the volcanogenic theory to the Golden Mile ores at Kalgoorlie. *Proc. Australas. Inst. Min. Metall.*, 258, 19-29.
- Travis, G.A., Woodall, R., and Bartram, G.D. (1971). The geology of the Kalgoorlie goldfield. *Spec. Publ. geol. Soc. Aust.*, 3, 175-190.
- Vincent, E.A., and Crocket, J.H. (1960). Studies in geochemistry of gold. I. The distribution of gold in rocks and minerals of the Skaergaard intrusion, East Greenland. *Geochim. cosmochim. Acta*, 18, 130-142.
- Webster, J.G., and Mann, A.W. (1984). The influence of climate, geomorphology and primary geology on the supergene migration of gold and silver. *J. Geochem. Expln.*, 22, 21-42.
- Weissberg, B.G. (1970). Solubility of gold in hydrothermal alkaline sulphide solutions. *Econ. Geol.*, 65, 551-556.
- Williamson, H.C., and Barr, D.J. (1965). Gold mineralization in the Yilgarn goldfield. In: McAndrew, J., Ed., *Geology of Australian Ore Deposits*, 8th Comm. Min. Metall. Cong., Melbourne, 87-94.
- Woad, G.M. (1981). *Nature and genesis of banded iron-formation hosted gold deposits at Water Tank Hill, Mount Magnet, Western Australia*. B.Sc.(Hons) thesis, (unpubl.), Univ. Western Australia, Perth.
- Woodall, R.W. (1965). Structure of the Kalgoorlie goldfield. In: McAndrew, J., Ed., *Geology of Australian Ore Deposits*, 8th Comm. Min. Metall. Cong., Melbourne, 71-79.
- Woodall, R. (1975). Gold in the Precambrian shield of Western Australia. In: Knight, C.L., Ed., *Economic Geology of Australia and New Guinea. 1. Metals*. Australas. Inst. Min. Metall., Melbourne, 175-184.
- Woodall, R. (1979). Gold - Australia and the World. In: Glover, J.E., and Groves, D.I., Eds. *Gold Mineralization*, Univ. Western Australia Extension Service Publ., 3, 1-34.