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HOST ROCK AND FLUID CONTROL ON CARBONATE ASSEMBLAGES IN THE GOLDEN MILE DOLERITE, KALGOORLIE GOLD DEPOSIT, AUSTRALIA

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ABSTRACT

Four carbonate minerals occur in the differentiated tholeiitic Golden Mile Dolerite sill, Kalgoorlie (Australia), and all are related to carbonation and sulfidation processes that accompanied gold mineralization. Ankerite, the most widespread carbonate, occurs throughout the dolerite and in the zones of chlorite, carbonate and pyrite alteration. Calcite occurs sporadically in the chlorite zone within less-differentiated host rocks. In contrast, siderite is abundant in the carbonate zone and more differentiated sections of the dolerite. Dolomite is found in all parts of the dolerite, but is restricted to the pyrite zone, where it formed from intense sulfidation of ankerite-bearing wallrocks. All compositions from dolomite to ankerite occur in single samples from the pyrite zone, whereas the chlorite and carbonate zones contain uniform mineral compositions. Host-rock composition has a strong control on alteration-mineral assemblages, but exerts only a minor effect on carbonate-phase compositions; instead, the latter mainly reflect the temperature (300–350°C) and composition of the gold-bearing fluid with which they equilibrated. Such a conclusion can be extended to other Archean greenstone lithologies to explain the carbonate species found in ultramafic rocks, metabasalts and banded iron-formations.

Keywords: carbonation, sulfidation, siderite, calcite, dolomite, ankerite, gold mineralization, Archean, Kalgoorlie, Australia.

SOMMAIRE

Quatre carbonates se trouvent dans le filon-couche de dolérite tholéiitique différenciée, dite Golden Mile, à Kalgoorlie (Australie). Ils sont tous les quatre en relation avec les processus de carbonatation et sulfuration qui ont accompagné la minéralisation en or. L'ankérite, le carbonate le plus répandu, se présente dans toute la dolérite et dans les zones d'altération en chlorite, carbonate et pyrite. On observe la calcite sporadiquement dans la zone d'altération en chlorite, au sein de roches encaissantes peu différenciées. La sidérite, par contre, abonde dans la zone d'altération en carbonate et dans des parties plus différenciées de la dolérite. La dolomite se trouve dans n'importe quelle partie de la dolérite, mais uniquement dans la zone d'altération en pyrite, où elle s'est formée sous l'effet d'une sulfuration intense des roches de parois contenant de l'ankérite. On observe toutes les compositions, de celle de la dolomite à celle de l'ankérite, dans les échantillons isolés de la zone d'altération en pyrite, tandis que les zones d'altération en chlorite et carbonate ont chacune une composition minéralogique uniforme. La composition de la roche encaissante, qui gouverne celle des minéraux d'altération, n'a que peu d'effet sur celle des phases carbonatées. Ces dernières reflètent surtout la température (300–350°C) et la composition du fluide aurifère avec lequel elles ont atteint l'équilibre. Pareille conclusion est aussi valide pour les autres lithologies de ceintures de roches vertes archéennes et rend compte des espèces carbonatées qu'on trouve dans les roches ultramafiques, métabasaltes et formations de fer rubannées.

(Traduit par la Rédaction)

Mots-clés: carbonatation, sulfuration, sidérite, calcite, dolomite, ankérite, minéralisation en or, Archéen, Kalgoorlie (Australie).

INTRODUCTION

Carbonate alteration is an important feature of Archean greenstone belts; it is well displayed in komatiite-associated (*e.g.*, Gresham & Loftus Hills 1981) and komatiitic dunite-associated nickel deposits (Donaldson 1981), in metabasaltic sequences (Hallberg 1972) and in epigenetic gold deposits (Kerrich & Fyfe 1981, Groves *et al.* 1982, 1984, Kerrich 1983, Phillips & Groves 1983). Some major gold deposits are surrounded by a halo of carbonate alteration in excess of 1 km in diameter (Larcombe 1912, Bartram & McCall 1971, Travis *et al.* 1971, Fyon & Crocket 1982, Davies *et al.* 1982). The most common carbonate phases in greenstone belts are ankerite, siderite, calcite, dolomite and magnesite; although several carbonates may occur in individual deposits (Bartram 1969), very few investigators have attempted to explain the distribution of different carbonate minerals (*e.g.*, Kerrich & Fyfe 1981). Fluid-inclusion data, including those for Kalgoorlie (Ho *et al.* 1985), give no indication of highly variable values of the H_2O/CO_2 ratio or variations in CO_2 activity that may account for the different carbonate minerals.

The identification of four carbonate minerals within the Golden Mile dolerite sill at Kalgoorlie provides an ideal opportunity to study carbonate distribution within a limited and geologically constrained environment (Phillips 1985, 1986). This study demonstrates the importance of host-rock control within the halo of carbonate alteration and of

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sulfidation reactions within the gold lodes. Pairs of coexisting carbonates also constrain temperature during alteration. The model developed for the Golden Mile Dolerite can readily be applied to other greenstone lithologies, or to the same lithology elsewhere.

In the Golden Mile Dolerite and some other greenstone-related gold deposits, major elements such as Al, Ti, Fe, Mg, Ca and Na are relatively immobile during gold mineralization, except in the most intensely altered areas such as shear zones (Phillips 1985, 1986). The significance of this immobility was recognized by Kerrich & Fyfe (1981) and Phillips & Groves (1984), who showed that the levels of major elements were not substantially changed during alteration and, therefore, major lithological variations correspond to changes in carbonate assemblages. The present study extends their conclusions to illustrate how the proportions of Fe, Mg and Ca in the host rocks exert an important control on the type and composition of the carbonate minerals.

The Golden Mile Dolerite has been subdivided into ten mappable units, of which Units 7, 8 and 9 represent 80% of the sill. Four sections typify the major compositions within the sill (Table 1, Fig. 1), and have been used for detailed sampling of these three units.

GEOLOGICAL SETTING OF THE GOLDEN MILE DOLERITE

The Kalgoorlie district is situated within the Norseman–Wiluna belt of the Archean Yilgarn Block, Western Australia (Groves & Batt 1984), and has been a major source of gold (1200 tonnes Au recovered). The main host-rock, the Golden Mile Dolerite, is a 400- to 600-m thick, differentiated tholeiitic sill intruded between underlying mafic and ultramafic rocks (Fig. 1), and overlying metasediments and felsic metavolcanic units (Travis *et al.* 1971). South of Kalgoorlie, the dolerite has been subdivided into ten mappable units (Travis *et al.* 1971), and recently this subdivision has been extended by mapping of the underground workings in the Golden Mile, Kalgoorlie (Phillips 1986).

The marginal units of the Golden Mile Dolerite (Units 1 and 10) are fine-grained; their composition approximates that of the whole sill. The interior units of the dolerite vary from a more Mg-rich pyroxene-phyric phase at the base and top (Units 2, 3, 4 and part of 9) to more Fe-rich plagioclase-phyric sections in the middle (Units 5, 6, 7 and part of 9), and a highly differentiated granophyre just below the top (Unit 8). Whole-rock compositions reflect this textural subdivision; differentiation toward the granophyre is accompanied by an increase in SiO_2, Fe/Mg and incompatible elements, with decrease of Mg and Ca (Travis *et al.* 1971, Phillips 1986). Regional greenschist-facies metamorphism stabilized actinolite – albite – chlorite – epidote – quartz assemblages in the dolerite, but throughout the Golden Mile area the metamorphic assemblage has been overprinted by carbonate-, muscovite- and pyrite-bearing assemblages. Three alteration zones have been mapped: i) a chlorite zone representing weak carbonation of the metamorphic assemblage, ii) a carbonate zone representing more local, intense carbonation, and iii) a pyrite zone representing sulfidation and gold addition in and around zones of ductile shear (Phillips 1986). The texture of the dolerite is typically massive; it preserves relict igneous features, except for local strongly foliated zones that define 1- to 2-m thick zones of ductile shear.

Chlorite is the dominant Fe–Mg-bearing mineral in the chlorite zone, where it overgrows and pseudomorphously replaces actinolite; some calcite and ankerite are also produced during actinolite breakdown. Other phases include quartz, albite, magnetite and ilmenite. Except in the shear zones, magmatic textures are commonly preserved.

The carbonate zone appears bleached owing to the predominance of carbonates over chlorite. Ankerite and siderite are the dominant phases, although up to 10% chlorite may remain. Chlorite from the carbonate zone $[Fe_{2.8}Al_{1.7}Mg_{1.5}(Si_{2.8}Al_{1.2})O_{10}(OH)_8]$ is

TABLE 1. DESCRIPTION OF SAMPLING SECTIONS WITHIN GOLDEN MILE DOLERITE

Section	Mine Level	Dolerite Unit	Carbonates	Alteration Zone
3000 (DDH UWA 1)	4 (130 m)	9	Ankerite	Mainly chlorite zone with 2 m pyrite zone in centre.
2100 (412 EXC)	4 (130 m)	9	Siderite Calcite Ankerite	Major shear zone in centre. Predominantly chlorite zone to west. Carbonate zone to east.
2500 (DDH 8610)	13 (430 m)	9 to 8	Ankerite Siderite Calcite	Mainly chlorite zone.
1000 (DDH 8553)	3 (100 m)	9 to 8 to 7	Siderite Ankerite	Several large shear zones in the section, mainly carbonate zone.

Mine levels are approximate depths below ground level, correlating with Fig. 1.

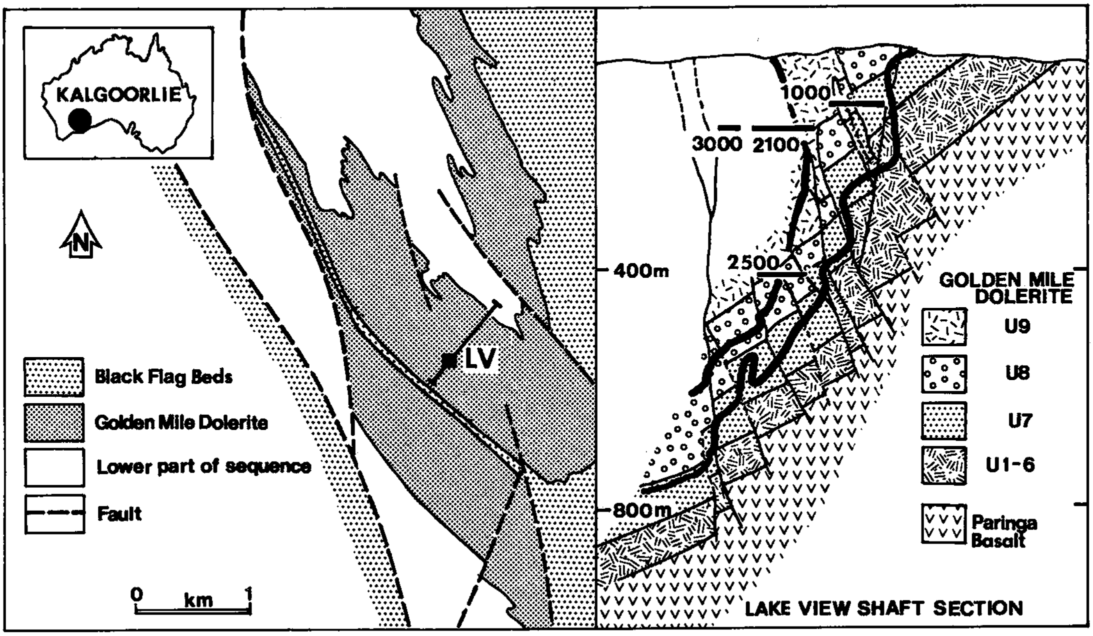

FIG. 1. Geological map of the Golden Mile area at Kalgoorlie (left) showing the position of the Lake View shaft (LV) and cross section through this shaft. The lower part of the sequence consists predominantly of the Paringa Basalt. Cross section (right) of the eastern side of the Golden Mile show the position of the four sampling sections, distribution of four mappable variants of the Golden Mile Dolerite (Units 1–6, Unit 7, Unit 8, Unit 9), and major east-dipping zones of ductile shear; smaller shear-zones are omitted, but numerous. Note that the four sampling sections are projected onto this common cross-section to maintain their actual relationship to the stratigraphy. In so doing, vertical depths are slightly distorted, but given in Table 1. The area between the two thick, steeply dipping lines outlines the zone of carbonate alteration, and approximately follows Unit 8 and upper Unit 7. The zone of chlorite alteration is the area outside these lines.

less iron-rich than that from the chlorite zone [$Fe_{3.3}Al_{1.4}Mg_{1.3}(Si_{2.5}Al_{1.5})O_{10}(OH)_8$ in unit 8 and $Fe_{3.1}Al_{1.5}Mg_{1.4}(Si_{2.6}Al_{1.4})O_{10}(OH)_8$ in unit 9]. Quartz and muscovite are more abundant, and other minor phases include tourmaline, pyrite, paragonite and chalcopyrite.

The pyrite zone is characterized by introduced cherty vein-material. A foliation defined by muscovite is better developed adjacent to, and within, the pyrite zone, and represents considerable overprinting of relict igneous textures. Modal quartz increases from the chlorite to the carbonate zones and to the quartz-rich pyrite zone. Although economic gold (pyrite zone) occurs in all units of the dolerite, the type and thickness of alteration are strongly controlled by dolerite stratigraphy (Phillips 1986). The general immobility of most major elements during gold-related alteration is partly responsible for this stratigraphic control.

Although carbonate alteration around Archean gold deposits has been tacitly assumed to be early, possibly related to sea-floor alteration (Davies *et al.* 1982, Fyon & Crocket 1982, Karvinen 1982), Bartram & McCall (1971) suggested a post-peak-of-metamorphism age for carbonate alteration at Kalgoorlie. M.G. Fotios (written comm. 1983) confirmed this timing by showing that chlorite-zone assemblages (chlorite – calcite) overprint regional metamorphic actinolite. Phillips (1986) suggested that chlorite alteration, carbonate alteration, pyrite alteration and gold mineralization were all part of one essentially synchronous event contemporaneous with progressive deformation.

In this paper, initial discussion of host-rock control is confined to the zones of chlorite and carbonate alteration, in which siderite, calcite and ankerite are stable. Sulfidation (pyrite zone) stabilizes dolomite locally and is discussed separately.

Host-Rock Control on Carbonate Assemblages in the Zones of Chlorite and Carbonate Alteration

There is a systematic distribution of carbonate minerals throughout the zones of chlorite and carbonate alteration within the Golden Mile Dolerite. Ankerite is found in all units of the dolerite in both zones. Calcite occurs sporadically in the chlorite zone

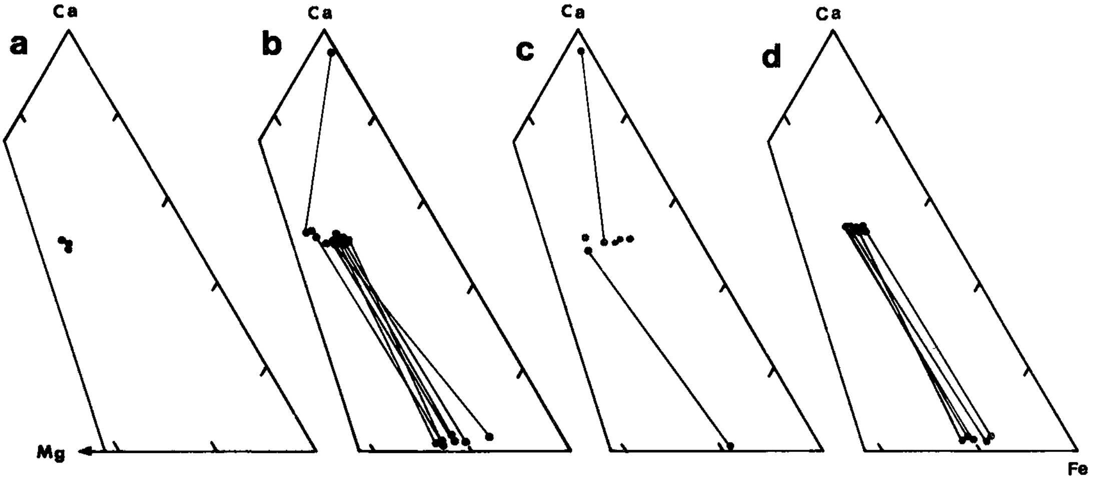

FIG. 2. Atomic proportion of Ca, Mg and Fe in carbonates from the chlorite and carbonate zones. The four plots represent the four sampling sections arranged in approximate order of increasing differentiation within the dolerite: a) 3000 section, b) 2100 section, c) 2500 section, d) 1000 section. The varying host-rock composition influences the carbonate assemblage, but has only minor affect on the phase compositions.

in Mg-rich units (Unit 9 and Units 1–6), but is unrecorded in the Fe-rich units (Unit 7 or 8) and in the zone of carbonate alteration. Siderite is widespread in the zone of carbonate alteration in the Fe-rich units (Units 7, 8 and 9), but is scarce in Units 1–6 and upper Unit 9 (*e.g.*, less differentiated part of the dolerite). This pattern of distribution reflects whole-rock compositional trends in the dolerite, in that siderite is abundant in Fe-rich units of the sill, and calcite in the more Mg-rich units. All carbonate compositions can be adequately represented by variations in Fe–Mg–Ca (Fig. 2), as $MnCO_3$ is typically less than 1.5% (molar basis). Routine identification of phases was made by X-ray diffraction, and compositions were determined by electron microprobe (see Appendix).

A total of 122 analyses of ankerite (Tables 2, 3, 4, 5) were recorded from the chlorite and carbonate zones. The most Fe-rich ankerite, which contains on average 34.5% $FeCO_3$ and 13.8% $MgCO_3$, places limits on the temperature of equilibration (Essene 1983); this is discussed below. In general, the ankerite from Unit 8 is slightly more $FeCO_3$-rich (26–32%) than that from Unit 9 (20–29%), though there is considerable overlap. Three samples from the most differentiated part of the dolerite sill (2518, 2520, 2524) are particularly Fe-rich (Table 4).

TABLE 2. COMPOSITION OF ANKERITE, LEAST DIFFERENTIATED DOLERITE

Sample No.	3002	3028	3053
Distance (m)	0.6	10.0	17.0
Unit	9	9	9
Alteration Zone	Chl	Chl	Chl
Fe	24.6	24.5	23.3
Mn	0.7	0.7	1.0
Mg	24.0	23.9	24.3
Ca	50.8	51.0	51.2
No. of analyses	2	2	4
100Fe/(Fe+Mn+Mg)	50	44-56	45-51

Expressed in atomic %. All samples from 3000 section. Distances measured from collar of DDH.

Forty-four analyses of siderite (Tables 3, 4, 5) from the chlorite and carbonate zones show that it contains between 15 and 30% $MgCO_3$ in solid solution, with minor $CaCO_3$ (0–2%) and $MnCO_3$ (up to 2%). The more Fe-rich siderite (75–83% $FeCO_3$) is from the chlorite and carbonate zones of Unit 8 and upper Unit 7 (*cf.* 70–80% $FeCO_3$ in Unit 9).

On the basis of eleven analyses (Tables 3 and 4), the calcite shows high Fe/Mg, approximately 3–4% $FeCO_3$, and $MnCO_3$ and $MgCO_3$ both less than 1.5%. The two calcite-bearing samples come from different sections in Unit 9.

Carbonate distribution within the Golden Mile Dolerite closely reflects host-rock composition, and to a lesser extent, the degree of alteration. The Mg-rich units (*e.g.*, unit 9) of the dolerite stabilize chlorite - ankerite ± calcite assemblages, even close to the shear zones, whereas Fe-rich units (*e.g.*, upper unit 7, unit 8) stabilize siderite over wide areas at the expense of chlorite and calcite (Fig. 3). This leads to a thicker zone of carbonate alteration in the more Fe-rich units (Phillips 1986), but is not directly related to either gold grade or inferred activity of carbon dioxide (*i.e.*, compared to Mg-rich units, Fe-rich compositions favor the breakdown of chlorite-bearing silicate assemblages to carbonates, given a constant composition of the fluid).

TEMPERATURE OF CARBONATE FORMATION

Two methods of estimating temperature are applicable to carbonate assemblages. Coexisting calcite–

TABLE 3. AVERAGE COMPOSITIONS OF ANKERITE, SIDERITE AND CALCITE, LESS DIFFERENTIATED DOLERITE

Sample No.	2101	2102	2104	2108	2112	2116	2119	2121	2123	2124	2126	2131	2132	2133
Distance (m)	2.5	4.0	7.8	14.5	32.6	43.8	46.8	47.7	50.4	52.6	58.5	77.9	79.8	82.3
Unit	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Alteration Zone	Chl	Chl	Chl	Chl**	Chl	Chl	Carb*	Carb*	Carb*	Carb*	Carb	Carb	Carb	Carb
							ANKERITE							
Fe	27.1	24.9	27.8	27.5	19.7	16.8	21.7	28.8	25.6	20.6	27.1	25.8	28.2	26.3
Mn	0.8	0.8	0.7	0.8	1.5	0.4	0.6	0.9	0.7	0.5	0.3	0.6	0.4	0.7
Mg	20.6	24.3	20.4	21.1	27.2	32.0	26.1	20.1	21.8	26.7	22.5	22.5	20.5	21.8
Ca	51.5	49.9	51.0	50.5	51.6	50.8	51.6	50.3	51.0	52.2	50.2	51.1	50.9	51.2
No. of analyses	3	4	3	2	5	4	3	6	3	9	6	3	3	2
100Fe/(Fe+Mn+Mg)	55-57	44-53	55-58	53-58	38-42	27-37	45	57-62	47-56	35-56	51-58	49-56	57-58	53-55
					CALCITE			SIDERITE				SIDERITE		
Fe					3.1		70.6	71.2	72.5		78.7	74.8	77.4	71.8
Mn					0.7		2.4	2.4	1.4		2.7	0.9	0.6	0.0
Mg					1.2		25.0	25.5	23.1		16.3	22.6	20.8	27.2
Ca					95.0		2.0	0.8	3.1		2.3	1.7	1.3	1.0
No. of analyses					7		6	4	3		4	2	3	2
100Fe/(Fe+Mn+Mg)					57-70		70-74	67-80	74-76		80-82	76-77	77-81	72-73

Expressed in atomic %. All samples from 2100 section.
Distances measured from Lake View lode at west end of 412 EXC, toward east.
* samples containing localized pyrite, part of major shear zone. ** close to later quartz vein.

TABLE 4. COMPOSITION OF CARBONATES, MORE DIFFERENTIATED DOLERITE

Sample No.	2501	2509	2513	2518	2520	2524
Distance (m)	15.0	29.4	35.8	45.8	49.5	55.8
Unit	9	8	8	8	8	8
Alteration Zone	Chl	Chl	Chl	Chl	Chl	Chl
		ANKERITE				
Fe	28.2	25.1	26.8	32.8	34.5	31.4
Mn	1.6	1.3	1.0	1.6	1.4	1.5
Mg	19.5	22.6	23.3	15.4	13.8	18.2
Ca	50.8	51.4	48.8	50.2	50.3	49.2
No. of analyses	1	4	2	1	3	5
100Fe/(Fe+Mn+Mg)	60	51-53	46-59	63	71	63-70
	CALCITE		SIDERITE			
Fe	3.7		78.1			
Mn	1.3		0.7			
Mg	0.8		19.8			
Ca	94.3		1.4			
No. of analyses	4		1			
100Fe/(Fe+Mn+Mg)	62-64		79			

Expressed in atomic %. All samples from 2500 section.
Distances measured from collar of DDH.

ankerite pairs can be used (Powell *et al.* 1984), and the most Fe-rich ankerite places a limit on temperature (Essene 1983). Assuming that formation of chlorite, carbonate, pyrite and gold were synchronous (Phillips 1986), a temperature estimate can be made for the main Au mineralizing event in the Golden Mile.

Coexisting calcite–ankerite pairs from two samples (2112 and 2501) suggest temperatures of 335 and 330°C (± 40°C) using the thermometer of Powell *et al.* (1984). Multiple analyses demonstrate homogeneity of compositions, and textural relationships suggest that the carbonate pairs coexisted at the time of the alteration event. Manganese is unlikely to affect this result, given the low proportions of $MnCO_3$ in all carbonates, but there are suggestions from other gold deposits in a greenstone setting that carbonate thermometry may give results slightly higher than other geothermometers (Neall & Phillips 1987). The temperature estimate from carbonates from the Golden Mile is considerably higher than that based on sulfur-isotope values in separated pyrite and anhydrite (Golding & Wilson 1983), but totally consistent with temperatures derived from primary fluid-inclusions in quartz veins from gold lodes (Ho *et al.* 1985).

The three-phase-triangle method of Essene (1983) can be used to verify the above estimates of temperature. With increasing temperature, the miscibility gap along the $FeCa[CO_3]_2$ - $MgCa[CO_3]_2$ join decreases, permitting more Fe-rich ankerite in appropriate host-rock compositions. The most Fe-rich ankerite from the Golden Mile is slightly less Fe-rich than that documented by Essene (1983) for the biotite zone (estimated 400°C), in accord with temperatures below 400°C for the Golden Mile.

SULFIDATION AND ITS CONTROL ON CARBONATE COMPOSITION IN THE PYRITE ZONE

Pyrite formation in and around 0.5- to 2-m thick zones of ductile shear within the dolerite represents sulfur addition in rather restricted loci that coincide with economic Au mineralization. Pyrite typically comprises 2–10% of the altered dolerite in the pyrite zone and is accompanied by muscovite, ankerite, quartz and albite.

Samples from the 2-m thick pyrite zone from upper Unit 9 (3000 section, see Table 1) have highly heterogeneous compositions of ankerite and a complete gradation from Fe-poor dolomite (Fig. 4). This spread of carbonate compositions (Table 6) is not found in either the carbonate zone or chlorite zone (Fig. 2), but is displayed by three samples from the pyrite zone in Unit 9 (3040, 3042, 3045) and two samples in Unit 7 (1030, 1038). A representative range in ankerite compositions within a single sample is from *ca.*52% $FeCa(CO_3)_2$ to *ca.*10% $FeCa(CO_3)_2$. These wide ranges occur within a single thin section and are closely related to areas of pyrite concentration. Dolomite is almost invariably associated with the most pyrite-rich areas, in particularly with areas of fine granular pyrite along the margins of quartz veinlets.

Siderite is uncommon in the pyrite zone. The over-

TABLE 5. COMPOSITION OF CALCITE AND SIDERITE, MORE DIFFERENTIATED DOLERITE

Sample No.	1002	1017	1020	1024	1028	1032	1045	1050	1068
Distance (m)	2.5	22.9	27.8	28.9	30.8	32.0	38.9	49.4	65.3
Unit	9	9	9	8	8	7	7	7	7
Alteration Zone	Carb/Chl	Chl	Carb	Carb	Carb	Carb	Carb	Carb	Carb
		ANKERITE							
Fe	28.3	28.0	29.8	30.1	31.8	27.4	28.2	28.6	28.9
Mn	1.0	1.1	0.8	0.8	0.7	0.9	1.0	0.6	0.6
Mg	20.6	20.2	19.0	17.4	17.4	20.6	19.9	20.1	20.0
Ca	50.2	50.7	50.4	51.6	50.1	51.1	50.9	50.7	50.4
No. of analyses	5	2	4	2	6	4	6	4	6
100Fe/(Fe+Mn+Mg)	56-58	56-58	56-64	59-66	60-64	54-60	51-64	56-60	55-62
			SIDERITE					SIDERITE	
Fe			75.1	80.1			80.5	77.2	77.4
Mn			1.8	1.6			1.9	0.8	1.4
Mg			22.2	16.2			16.7	20.5	20.1
Ca			0.9	2.0			0.8	1.5	1.1
No. of analyses			5	3			1	5	5
100Fe/(Fe+Mn+Mg)			74-80	80-83			81	77-80	75-80

Expressed in atomic %. All samples from 1000 section.
Distances measured from collar of DDH.

all spread of siderite compositions in this zone is similar to that found in the zones of chlorite and carbonate alteration (Fig. 4). However, the most Fe-rich siderite (83% $FeCO_3$) occurs in the pyrite zone of Unit 7.

The heterogeneity of the ankerite and the scarcity of siderite in the pyrite zone can be accounted for by incorporation of much of the iron into pyrite in response to sulfidation. The inferred high activity of sulfur stabilizes pyrite, leaving the remaining silicate assemblage with relatively low Fe/(Fe + Mg + Ca). There is no evidence that the distribution of ankerite *versus* dolomite is controlled by variations in whole-rock Fe:Mg:Ca proportions. The compositional variations in ankerite and dolomite across thin sections are explained in terms of small-scale variations in sulfur activity; *i.e.*,

$$\underset{\text{in ``ankerite''}}{FeCO_3} + \underset{\text{in fluid}}{2H_2S} = \underset{\text{pyrite}}{FeS_2} + \underset{\text{fluid}}{H_2CO_3 + H_2}$$

Importantly, small areas of pyrite within a thin section are positively correlated with more Mg-rich compositions of dolomite and ankerite.

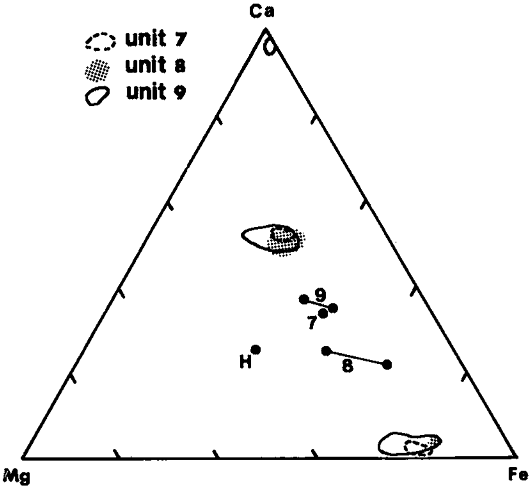

FIG. 3. Summary of carbonate compositions (in atomic proportions of Ca, Mg and Fe) from the chlorite and carbonate zones of the Golden Mile Dolerite (shown as fields), based on host rock (*i.e.*, Unit 7, 8 or 9). Whole-rock compositions are also shown (by dots) for the three units, and the Hunt mine metabasalt (H) from Kambalda, for comparison (Phillips & Groves 1984).

CARBONATES IN GREENSTONE BELTS

A marked feature of many greenstone belts is the widespread and commonly intense carbonate alteration of several rock-types. The principles governing alteration mineralogy developed for the Golden Mile Dolerite can readily be extended to include other lithologies.

The nature of fluids during the metamorphism of greenstone belts is particularly important in discussions of carbonate alteration. Direct measurements of fluid composition based on fluid inclusions are available for numerous gold deposits in Western Australia, southern Africa and Canada (Smith *et al.* 1984, Ho *et al.* 1985). The fluids associated with mineralization are typically rich in H_2O and CO_2, of low salinity, and inferred to be metamorphic in origin (Kerrich & Fryer 1979, Groves *et al.* 1982, Phillips & Groves 1983, Golding & Wilson 1983). The importance of H_2O–CO_2 fluids in determining carbonate mineralogy is twofold; clearly they are a possible source for CO_2, but also their inferred near-neutral to slightly alkaline nature (Phillips & Groves 1983, Ho *et al.* 1985) controls the mobility of major elements.

These concepts can be extended to other litholo-

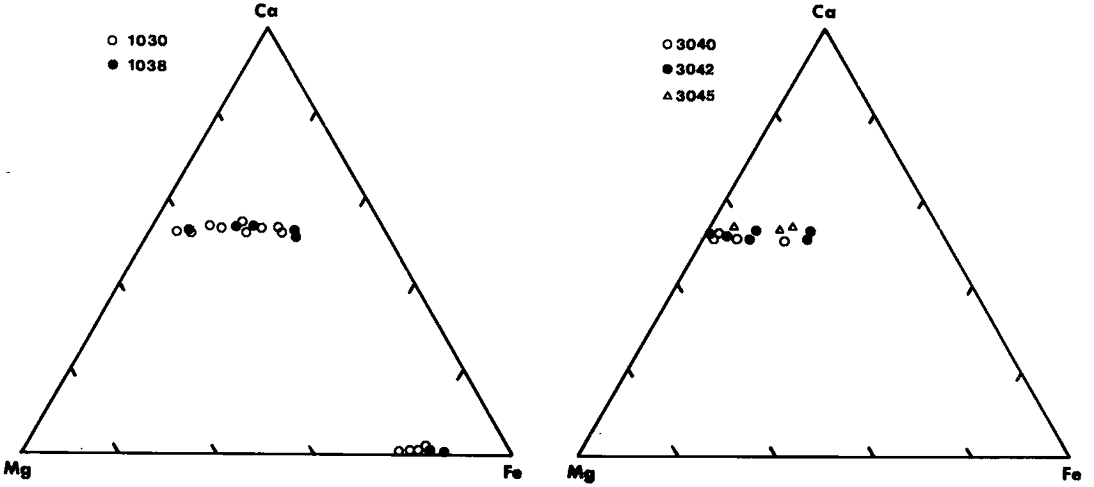

FIG. 4. Representative carbonate compositions (in atomic proportions of Ca, Mg and Fe) from the pyrite zone: 1000 section (left), 3000 section (right). Single samples show complete trends from Fe-rich ankerite to dolomite.

TABLE 6. EXTREME COMPOSITION OF CALCITE AND SIDERITE, PYRITE ALTERATION ZONE

Sample No.	1030		1038		3040		3042		3045	
Distance (m)	31.4		36.1		14.8		14.95		15.1	
Unit	7		7		9		9		9	
	ANKERITE - DOLOMITE									
Fe	26.0	5.0	29.1	16.5	16.6	1.4	21.1	1.0	16.7	3.3
Mn	0.9	2.6	0.8	2.6	0.8	0.1	0.6	1.4	1.8	1.7
Mg	22.6	42.3	19.1	29.8	32.9	46.2	26.8	46.7	29.2	43.8
Ca	50.6	50.1	51.0	51.1	49.7	51.3	51.6	51.0	52.2	51.2
No. of analyses	10		6		8		12		4	
100Fe/(Fe+Mn+Mg)	10-53		34-59		3-33		2-43		7-35	
	SIDERITE									
Fe	80.7	75.2	83.1	80.5						
Mn	1.4	1.5	1.6	1.9						
Mg	17.5	22.4	14.8	16.9						
Ca	0.4	0.9	0.5	0.8						
No. of analyses	6		2							
100Fe/(Fe+Mn+Mg)	76-81		81-84							

Expressed in atomic %. Distances measured from collar of DDH.

gies in greenstone belts, where the highly Mg-rich nature of komatiitic lavas and intrusive bodies (compositional range of pyroxenite to dunite) commonly leads to talc–magnesite plus dolomite assemblages during pervasive carbonate alteration (*e.g.*, Gresham & Loftus-Hills 1981, Donaldson 1981). High-Mg rocks, such as those hosting the Murchison antimony deposits in South Africa (Pearton 1980), have magnesite- and dolomite-bearing assemblages with talc and chlorite (Fig. 5). Diverse carbonate-bearing assemblages, which include ankerite, calcite and siderite, reflect the wide compositional range of mafic rocks in greenstone belts (Fig. 5), such as the Fe-rich units of the tholeiitic dolerite at Kalgoorlie and the more magnesian tholeiitic metabasalts at the Hunt mine, Kambalda (Fig. 3). A number of gold deposits occur in banded iron-formation, where large-scale structural and textural evidence suggests an origin by metamorphic replacement (MacDonald 1983, Phillips *et al.* 1984). The carbonate mineral in these deposits is dominantly siderite (reflecting the iron-rich host rocks); a reconnaissance study shows that the composition of siderite is locally more Mg-rich near pyrrhotite than in sulfide-poor areas (G.M. Woad, written comm. 1981).

The broad association, within greenstone belts, of nickel deposits with rocks of the komatiitic suite (*e.g.*, Marston *et al.* 1981), and of many major gold deposits with Fe-rich host rocks (generally mafic volcanic or intrusive rocks, and banded iron-formations), implies that the typical carbonate assemblages near nickel deposits and gold deposits are quite different, and reflect their respective host-rocks.

SUMMARY

The distribution of ankerite, siderite and calcite within the Golden Mile Dolerite is strongly controlled by the bulk-rock composition of the host. Siderite

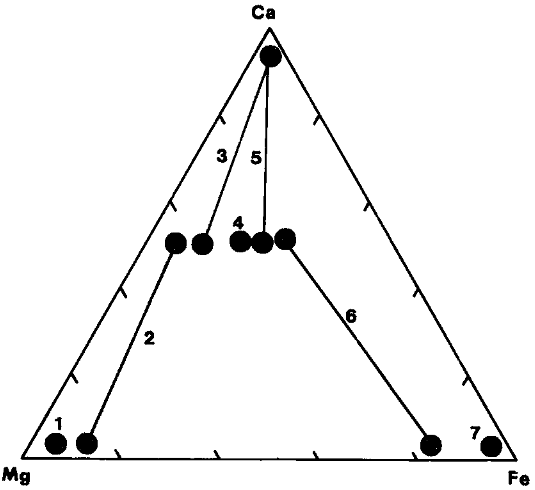

FIG. 5. Ca–Mg–Fe plot of carbonate assemblages common in Archean greenstone belts. Magnesite (1) and magnesite – dolomite assemblages (2) are typical of ultramafic sequences (*e.g.*, Pearton 1980, Donaldson 1981). Dolomite + calcite + ankerite (3, 4, 5) assemblages are common in mafic host-rocks (*e.g.*, Phillips & Groves 1984). Siderite – ankerite (6) is typical of more differentiated mafic rocks such as the Golden Mile Dolerite, and siderite (7) is common in banded iron-formation.

is abundant in Fe-rich units, calcite in more Mg-rich host rocks, and ankerite is widespread. The predictable pattern of their distribution implies that broad-scale equilibrium was achieved during stabilization of the carbonate-bearing assemblages in the zones of chlorite and carbonate alteration. In contrast, the compositional variations in ankerite and in dolomite in the pyrite zone suggest variations in physicochemical parameters (*e.g.*, sulfur activity) even on the scale of a single thin section.

Temperatures of *ca.* 300–350°C derived from coexisting calcite – ankerite pairs are in accord with fluid-inclusion data and provide a temperature for the main event of gold mineralization. The principles governing the distribution of carbonate species within the Golden Mile Dolerite have wider applicability than just at Kalgoorlie, and can be used to rationalize the mineralogy of other altered rock-types in greenstone belts.

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APPENDIX: ANALYTICAL PROCEDURE

All carbonate analyses were performed using energy dispersion on the MAC electron microprobe at CSIRO, Floreat Park, Western Australia. The generally fine grain-size and common intergrowths precluded significant widening of the 1-3 μm beam, a technique that would be more applicable to coarser-grained rocks (Essene 1983); however, count times were reduced from 100 seconds to 40 seconds. An operating voltage of 15 kV was used for all analyses. A number of replicate analyses were made initially to evaluate the degree of volatilization of the carbonates under these conditions. There was found to be very little loss of volatile components. Small mineral inclusions were readily detected during the analysis of carbonates. Nearby chlorite grains were avoided when choosing areas for analysis. Small amounts of SiO_2 were attributed to quartz and were disregarded, whereas analyses showing TiO_2 were usually rejected owing to possible contamination by ilmenite.