

**ECONOMIC GEOLOGY  
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**SHEAR-ZONE-HOSTED GOLD ALONG THE SOUTHERN  
MARGIN OF THE LIMPOPO BELT:  
A METAMORPHIC PERSPECTIVE ON THE  
ORIGIN OF THE MINERALISING FLUIDS**

**G. STEVENS**

**INFORMATION CIRCULAR No. 295**

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ON THE ORIGIN OF THE MINERALISING FLUIDS**

by

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## **SHEAR-ZONE-HOSTED GOLD ALONG THE SOUTHERN MARGIN OF THE LIMPOPO BELT: A METAMORPHIC PERSPECTIVE ON THE ORIGIN OF THE FLUIDS**

### **ABSTRACT**

Numerous small gold mines and prospects are localised on the Hout River Shear Zone and related structures that developed during southwards thrusting of the granulite grade Southern Marginal Zone of the Limpopo Belt over the lower grade rocks of the Kaapvaal Craton. Petrographic evidence from the mineralised sites suggests that thrusting and mineralization occurred under amphibolite-grade conditions, i.e. during the retrograde path in the granulites, and close to the peak of metamorphism in greenstones on the craton. Thus, the mineralization is an integral part of the tectonometamorphic cycle that produced, and then partially exhumed, the granulites. Fluid inclusion studies suggest that mineralization was associated with the mobilization of low  $\alpha\text{H}_2\text{O}$ ,  $\text{CO}_2$ -rich fluid along the uplift-related shear zones. However, the entire southern portion of the Southern Marginal Zone records the retrogression of former granulite-facies mineral assemblages by interaction with a fluid of similar composition. This does not represent the general infiltration of the terrane by a carbonic fluid of external origin. Rather, the fluids are of internal origin and resulted from the oxidation of biogenic graphite through interaction with  $\text{H}_2\text{O}$ -rich fluids derived from crystallizing, *in situ* anatetic leucosomes. In this study it is proposed that the evacuation of this internally derived retrograde fluid along active shear zones resulted in the associations observed at the sites of mineralization.

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# SHEAR-ZONE-HOSTED GOLD ALONG THE SOUTHERN MARGIN OF THE LIMPOPO BELT: A METAMORPHIC PERSPECTIVE ON THE ORIGIN OF THE FLUIDS

## INTRODUCTION

The sensitivity of melting equilibria to the activities of volatile components, and the affinity of granitoid magmas for H<sub>2</sub>O determines that the involvement of fluids and melts are inextricably linked in the evolution of crustal rocks metamorphosed to grades appropriate for anatexis. Despite this fact and the abundant development of anatetic migmatites, partial melting has generally not been considered in past studies of fluid:rock interaction in the granulites of the Southern Marginal Zone of the Archaean Limpopo Belt. These studies have either dealt with the fluid-induced regional retrogression of former granulites (Van Reenen, 1986; Van Reenen and Hollister, 1988; Van Schalkwyk and Van Reenen, 1992; Baker *et al.*, 1992), or concentrated on the fluids associated with gold mineralization in shear zones along which the granulites were uplifted and juxtaposed against the lower grade rocks of the Craton (Fig. 1) (Pretorius *et al.*, 1988; Van Reenen *et al.*, 1994; Gan and Van Reenen, 1995). Despite this substantial volume of research, none of these works has been able to identify the source, or sources, of these fluids. Several recent studies have focused on the anatexis of the metapelitic units in the Southern Marginal Zone (Stevens and Van Reenen, 1992a; Stevens, 1995) and emphasised the important constraints that melting equilibria place on the presence or absence, compositions and abundances of fluid phases in the evolution of high-grade, quartz-saturated rocks. This study builds on these works in an attempt to further the general understanding of the interaction between fluids and melts during the retrograde evolution of the Southern Marginal Zone, with particular emphasis on the implications for associated gold mineralization.

This paper reviews data on the geology of some of the better documented sites of mineralization, and briefly examines past work on the regional retrogression of the granulites. New petrographic and bulk rock compositional data is then presented on the regional hydration of the migmatitic granulites. These data highlight the important role of crystallizing anatetic melts in controlling retrograde fluid production and illustrate the potentially complex interactions between melt escape, H<sub>2</sub>O liberation during crystallization and subsequent fluid modification by redox equilibria. Finally, a model is proposed that allows for the internal (to the terrane) production of a retrogressing fluid and subsequent mineralization in the shear zones along which the fluid escaped upwards. This model appears to be consistent with all the current published data on mineralization and retrogression in the Southern Marginal Zone.

## METAMORPHISM AND TECTONICS OF THE SOUTHERN MARGINAL ZONE

The granulites and former granulites of the Southern Marginal Zone occur as a discrete terrane bounded by crustal-scale shear zones (Fig. 1). The Palala Shear Zone separates the Southern Marginal Zone from the Central Zone of the Limpopo Belt in the north and the Hout River Shear Zone separates the Southern Marginal Zone from the lower grade rocks of the Kaapvaal Craton in the south. Geophysical data (De Beer and Stettler, 1992), interpreted by Roering *et al.* (1992), suggest that both these shear zones extend to the base of the crust and dip steeply to the north

(Fig. 2). The southwards-verging Hout River Shear Zone post-dates the peak of metamorphism in the granulites and accommodated uplift of these rocks relative to the Kaapvaal Craton. In the geophysical interpretation, this structure truncates older, northwards-verging thrust stacks in the greenschist-to-amphibolite facies rocks of the northern Kaapvaal Craton (Fig. 2), which are interpreted as resulting from an original ~ 2.7 Ga collision between the Kaapvaal and Zimbabwe Cratons. This event produced granulite grade metamorphism in former surface sedimentary sequences at the deep crustal levels exposed in the Southern Marginal Zone (Roering *et al.*, 1992).

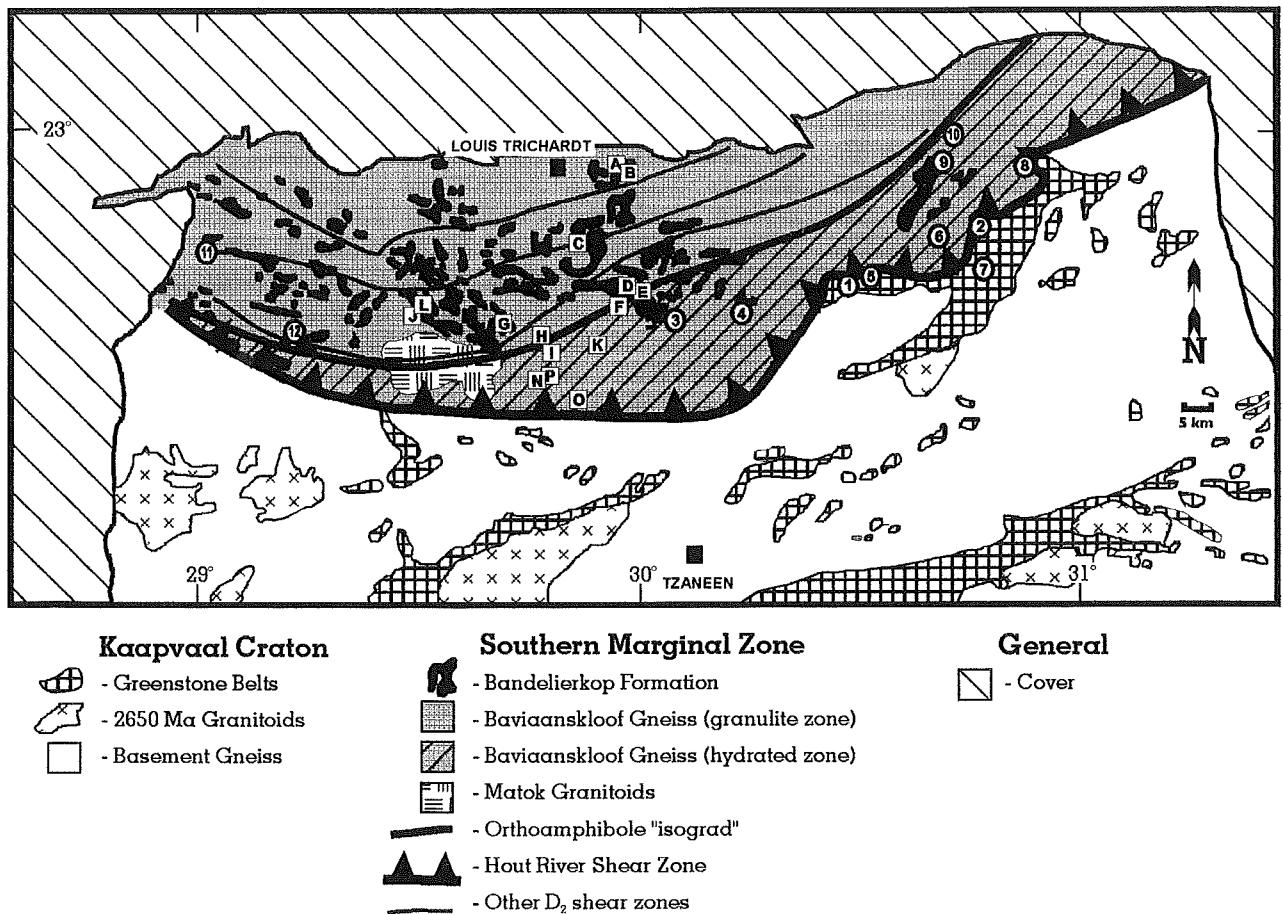


Figure 1: The geology of the Southern Marginal Zone of the Limpopo Belt modified after Van Reenen *et al.* (1990) and Gan and Van Reenen (1995). Note the tectonic contact between the low-grade rocks of the Kaapvaal Craton and rocks formerly at granulite-grade, and the broad band of hydration between the proposed retrograde orthoamphibole isograd and the Hout River Shear Zone. The sample localities of the present study are indicated on the map as squares. Decompression of the terrane was achieved through uplift on the D<sub>2</sub> shear zones that dip steeply to the north. Gold mineralization is largely localized on these structures and the specific sites of mineralization are indicated by circles; (1) Klein Kemp, (2) Overscot, (3) Doornhoek, (4) Bontfontein, (5) Klein Letaba and Franke, (6) Louis Moore, (7) Birthday, (8) Fumani, (9) Osprey, (10) White Reefs, (11) Buchum and (12) Harlequin.

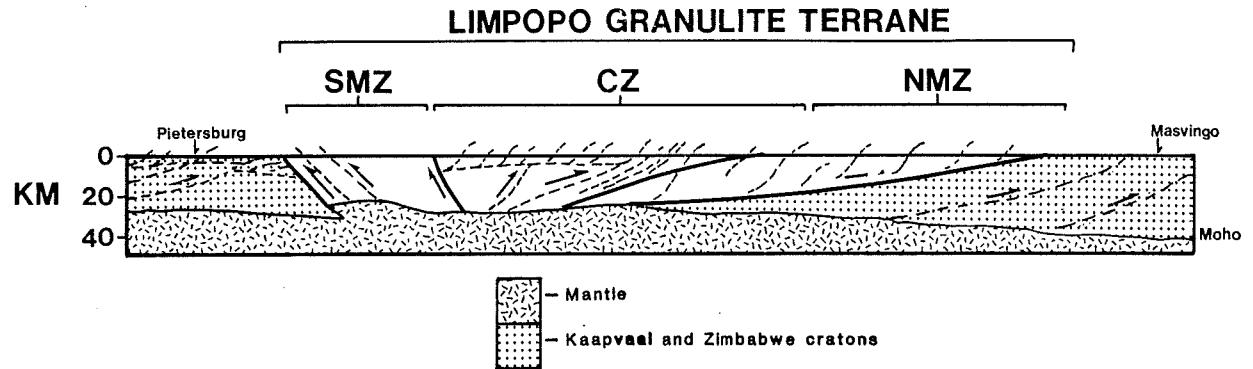


Figure 2: A crustal profile across the Limpopo Belt after Roering *et al.* (1992).

The rocks of the Southern Marginal Zone consist primarily of the deformed, attenuated and ultra-metamorphosed equivalents of the granite-greenstone successions of the bounding Kaapvaal Craton (Du Toit *et al.*, 1983; Van Reenen *et al.*, 1990). The tonalitic-to-trondhjemite grey gneiss of the craton is represented by the migmatized Bavianskloof Gneiss, and the greenstones of the craton have been transformed into the granulite-grade pelitic, mafic and ultramafic units of the Bandelierkop Formation. Thus, these rocks represent underthrusted cratonic components. Previous studies on metamorphism in the Bandelierkop metapelites have described a clockwise *P-T* loop (Fig. 3) that is based on the identification of relic reaction textures used as "fossil geothermobarometers" (e.g. Frost and Chacko, 1989). The key elements in these data are: 1) new generations of anhydrous phases associated with several generations of anatexic leucosome, identified and described by Stevens and Van Reenen (1992a), which allow the identification of a period of prograde heating ( $M_1$ ) in the sillimanite stability field (Stevens and Van Reenen, 1992b); 2) the overprinting of assemblages developed during  $M_1$ , by lower pressure mineral associations - garnet and sillimanite are replaced by cordierite and, in less aluminous rocks, by cordierite-orthopyroxene symplectites. These textures indicate a period of decompression at high grade ( $M_2$ ) (Van Reenen, 1983; Stevens and Van Reenen, 1992b); and 3) hydration textures indicating reactions that consumed cordierite and orthopyroxene in the granulite facies assemblages ( $M_3$ ). These reactions produced kyanite in rocks in which biotite-garnet thermometry indicates retrograde temperatures of approximately 600 °C (Van Reenen, 1986).

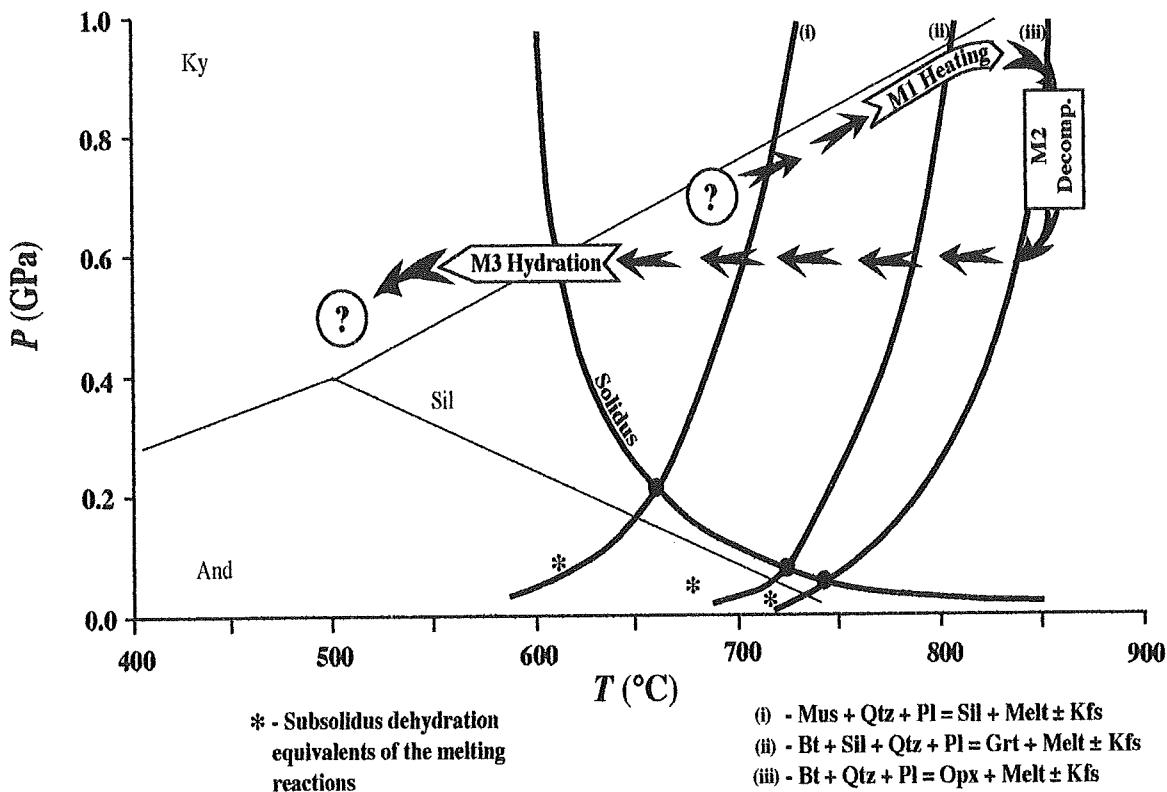


Figure 3: The  $P$ - $T$  loop for the Southern Marginal Zone proposed by Stevens and Van Reenen (1992b). The loop is characterised by an  $M_1$  period of prograde heating during which partial anatexis occurred through biotite fluid-absent melting reactions in the sillimanite stability field; a period of decompression close to the peak of metamorphism ( $M_2$ ); and, a period of cooling ( $M_3$ ) that culminated with retrograde hydration reactions in the kyanite stability field at a temperature of approximately 600  $^{\circ}$ C.

## CHARACTERISTICS OF THE GOLD MINERALIZATION

Gold deposits related to the Limpopo tectonometamorphic event occur on the Kaapvaal Craton, predominantly in the Sutherland greenstone belt, as well as in the zone of regional rehydration of former granulites (Fig. 1). The characteristics of some of the better documented occurrences are summarised below to emphasise the timing of the mineralizing event relative to the evolution of the Limpopo Belt.

### Fumani

The Fumani Gold Mine is located at the northeastern end of the Sutherland greenstone belt in an extension of the Hout River Shear Zone (Fig. 1). The geology at this locality has been investigated in detail by Pretorius *et al.* (1988) and the following is a summary of their findings. The mineralization is characterised by quartz-sulphide vein development in sheared and metamorphosed BIF. The dominant sulphide mineral is pyrrhotite with subordinate arsenopyrite. The mineralization is strongly controlled by both structure and host rock chemistry, with the main

mineralized zone located in a zone of intensely sheared BIF close to the contact with a micaceous quartzitic layer.

The peak metamorphic assemblage includes ferrohypersthene, salite, poikilitic garnet and minor magnetite. The two-pyroxene geothermometer of Wood and Banno (1973) indicates a temperature of  $620 \pm 70$  °C for this assemblage. Mineralization postdates the peak of metamorphism and is associated with retrogression and ductile shearing in the lower amphibolite facies. New, inclusion-free garnet growth is produced on the poikilitic high-grade cores and sulphide crystallization has been documented from pressure shadows in the shear fabric around the resultant zoned garnet. Pyroxene crystals show reaction to amphiboles and the resultant retrograde assemblage is garnet<sub>2</sub>, grunerite, hornblende, biotite and sulphides. Gold occurs as inclusions in amphiboles, biotite, quartz and arsenopyrite, and zones of mineralization are orientated parallel to the mineral elongation lineation in the Hout River Shear Zone.

Fluid inclusions in quartz from the mineralized zones are predominantly CO<sub>2</sub>-rich (Van Reenen *et al.*, 1994). Data on bulk rock compositions from the deposit at Fumani also suggest a carbonic mineralizing fluid and wt% CO<sub>2</sub> in the bulk rock correlates strongly with S, As and Au abundances (Fig. 4). The minimum age of the mineralization is indicated by a Rb-Sr age of  $2632 \pm 53$  Ma from muscovite extracted from a pegmatite that intrudes the ore zone.

### Franke

Franke Mine is located at the northwestern tip of the Sutherland greenstone belt very close to the Hout River Shear Zone (Fig. 1). The geology of this deposit has been investigated in detail by Gan and Van Reenen (1995) and the following is largely a summary of their findings. Mineralization is predominantly hosted in sheared BIF and consists of quartz-sulphide veins, although rocks of mafic-to-ultramafic affinity also occur. Pyrrhotite is the most common sulphide mineral with subordinate chalcopyrite and arsenopyrite. The mineralized veins occur as syntectonic features along the C surface of S-C mylonites in early shear zones. Fracturing during later shearing under a more brittle regime has resulted in the crystallization of sulphides as veins in anastomosing networks that crosscut brecciated mylonites. This is probably a remobilization feature. Gold occurs as inclusions in syntectonic quartz and sulphides.

The peak metamorphic conditions at Franke were middle-to-upper amphibolite facies. Common assemblages in the mineralized Fe-rich metasediments are: biotite, anthophyllite, hornblende, quartz and plagioclase ± garnet ± magnetite; biotite, plagioclase, quartz, and magnetite; and, garnet, anthophyllite, quartz and magnetite. Mineralization appears to have occurred close to the peak of metamorphism due to fluid movement along the Hout River Shear Zone. The mineralized zones are characterised by increases in the bulk rock Au, S and SiO<sub>2</sub> content (Fig. 5). Fluid inclusion compositions have been determined from similar ore zones at the spatially related Klein Letaba Mine (Fig. 1) and are CO<sub>2</sub>-dominated. A ca. 2660 Ma muscovite Rb-Sr age from a pegmatite that intrudes the ore zone at this locality (Barton and Van Reenen, 1992) is probably also a reasonable minimum age for the mineralization at Franke.

### Louis Moore

The Louis Moore deposit occurs in the zone of regional retrogression of former granulites. Mineralization is restricted to a shear zone within ultramafic granulites. The ore bodies occur in carbonate- and biotite-rich zones within partially rehydrated ultramafic granulite (Van Reenen *et al.*, 1994). Petrographic analysis has revealed that gold occurs as inclusions in bands of serpentine

truncating olivine, on cleavage planes in orthopyroxene and as inclusions in calcite (Van Reenen *et al.*, 1994). Gold mineralization is not associated with sulphide minerals at this deposit. The dominant fluid inclusion population at Louis Moore is CO<sub>2</sub>-rich (Van Reenen *et al.*, 1994). The inclusions studied were in quartz that occurred as syntectonic boudins and veins within the ore zone. Thus, the mineralizing fluids are believed to have been carbonic.

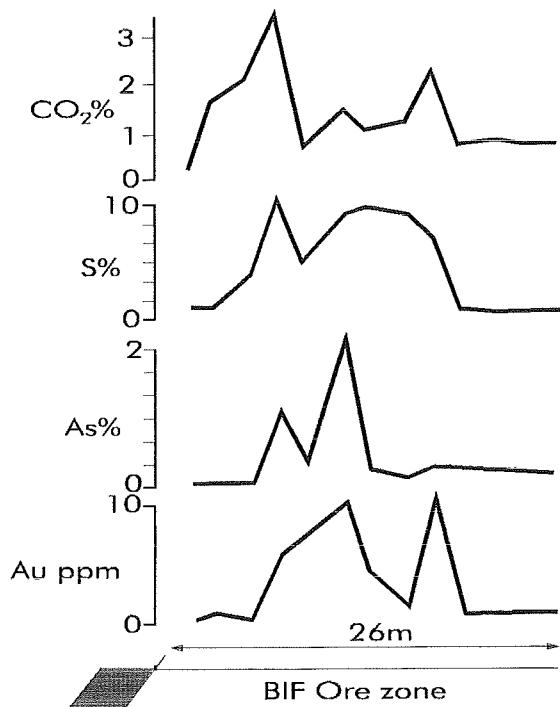


Figure 4: Abundances of bulk rock CO<sub>2</sub>, S, As and Au across the ore zone at Fumani Mine (after Pretorius *et al.*, 1988).

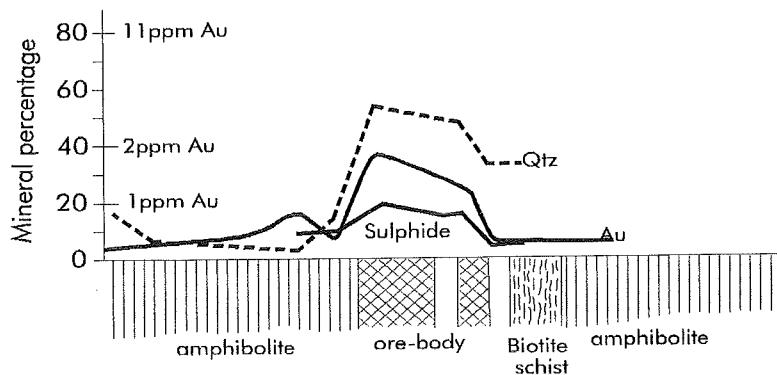


Figure 5: Abundances of bulk rock S, SiO<sub>2</sub> and Au across the ore zone at Franke Mine (after Gan and Van Reenen, 1995).

### Osprey

Two shear-zone hosted deposits some 800m apart occur at Osprey in the Southern Marginal Zone. In the western shear zone, gold is associated with syntectonic quartz veins developed in a garnetiferous amphibolite of mafic affinity. In the eastern shear zone, gold mineralization is developed in sheared BIF with associated metapelite (Van Reenen *et al.*, 1994). Relic assemblages indicate that peak metamorphic conditions in both deposits were in the granulite facies. However, the metapelites associated with the ore zone are characterised by retrograde assemblages of garnet, orthoamphibole, biotite, quartz and plagioclase, indicating that mineralization occurred in the amphibolite facies during retrogression of the granulites. Gold occurs as inclusions in the amphibolite-grade silicate assemblages, and as inclusions in arsenopyrite associated with pyrrhotite. Both the shear zones at Osprey are splays off the Hout River Shear Zone.

### Summary

The Hout River Shear Zone appears to have been a major locus of fluid movement during the retrograde history of the Southern Marginal Zone. Gold mineralization resulted from the migration of carbonic fluids along this structure during active shearing. Thrusting of the hot granulites southwards along the shear zone produced a concentrated metamorphic gradient in the Sutherland greenstone belt. Here, in the highest grade rocks at the contact with the former granulites along the Hout River Shear Zone, mineralization occurred close to the peak of metamorphism while at the same time it coincided with retrogression in the granulites. The largest and richest deposits appear to be located at sites where the mineralising fluids encountered bulk compositions with Fe<sup>3+</sup> reservoirs, facilitating the precipitation of sulphide minerals. However, such compositions are rare in both terranes and deposits also occur in metapelitic, ultramafic, mafic and granitoid hosts.

## RETROGRADE FLUIDS IN THE SOUTHERN MARGINAL ZONE

The widespread hydration of former granulites in the southern portion of the Southern Marginal Zone was first described by Van Reenen (1986). The identification of a well-defined transition zone separating granulite-grade rocks in the north from a hydrated zone in the southern portion of the Southern Marginal Zone, where orthopyroxene is not preserved, resulted in Van Reenen's proposal of a retrograde orthoamphibole isograd (Fig. 1). CO<sub>2</sub>-rich fluid inclusion compositions (Van Reenen and Hollister, 1988) and the apparent displacement of the reaction Opx + Fl + Qtz = Anth, to temperatures of approximately 600 °C in the kyanite stability field (Fig. 6), led Van Reenen and Hollister to suggest the pervasive flushing of this portion of the deep Archaean crust with a CO<sub>2</sub>-dominated retrograde fluid. The presence of an H<sub>2</sub>O-undersaturated fluid during the retrograde history of the Southern Marginal Zone has been confirmed by a study of the retrogression in the associated ultramafic unit of the Bandelierkop Formation (Van Schalkwyk and Van Reenen, 1992), and has also been suggested by a phase-equilibrium study by Baker *et al.* (1992). The timing of regional retrogression is compatible with that of inferred fluid movement and mineralization in the sheared former granulites associated with the Hout River Shear Zone. The composition of the retrogressing and mineralizing fluids are also similar. Thus, it appears likely that the regional retrogression of the granulites and the mineralization along the Hout River Shear Zone was accomplished by the same fluid.

All previous studies have proposed an external fluid source for the regional retrogression of the granulites. This is largely due to the carbonic nature of the proposed fluid compositions, coupled

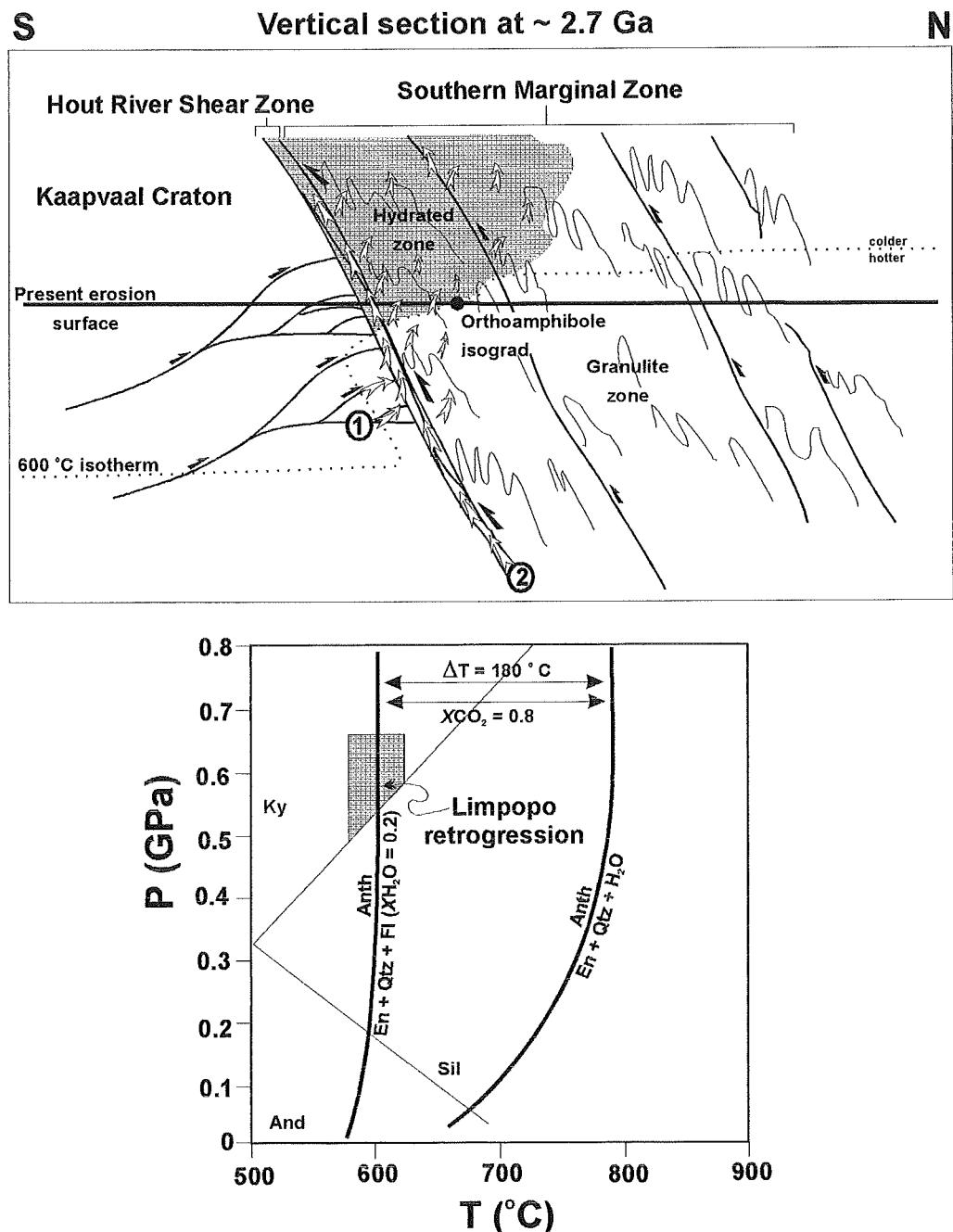


Figure 6: An illustration of the potential fluid sources proposed by previous studies in the Southern Marginal Zone. The open arrows indicate fluid migration and the filled arrows indicate tectonic transport. (1) Devolatilization of cratonic greenstones. (2) Carbonic fluids from a mantle or unconstrained deep crustal source. In both cases the fluids are required to comprehensively infiltrate the retrogressed granulites after gaining ingress along the Hout River Shear Zone. In the  $P$ - $T$  diagram the curve of the reaction  $\text{Opx} + \text{Qtz} + \text{H}_2\text{O} = \text{Anth}$  is almost vertical. Thus, the orthoamphibole isograd proposed by Van Reenen (1986) would represent an intersection of the current erosion level with the approximate  $600\text{ }^{\circ}\text{C}$  isotherm.

to the apparent lack of a suitable source of such fluids in this terrane. Two potential sources have been proposed. The first of these involves devolatilization reactions in the underthrust greenstones of the Kaapvaal Craton during southwards thrusting of the granulites (Van Reenen and Hollister, 1988). Such reactions in mafic greenstone lithologies have been proposed as a general source of mineralizing fluids in Archaean lode gold deposits (Phillips, 1993). However, calculation of the fluid compositions produced at the upper greenschist - lower amphibolite facies transition in mafic to ultramafic greenstones suggests that such a fluid would be far more hydrous ( $X_{CO_2} = 0.25$ ) (Powell et al., 1991) than the proposed composition of the mineralizing and retrogressing fluid in the Southern Marginal Zone ( $X_{CO_2} = 0.8$ ). The second proposed source involves a fluid from an unspecified "deep seated origin" has been proposed (Gan and Van Reenen, 1995) with inferences to a mantle origin (Van Schalkwyk and Van Reenen, 1992). This is inequitable with two other lines of evidence. Firstly, in a study of the stable isotope geochemistry of rocks from both the granulite zone and the hydrated zone, Venneman and Smith (1992) observed that  $\delta^{13}C$  values in the graphitic metasediments varied by 5 to 6 ‰ on a layer scale (metres). Also, original  $^{18}O/^{16}O$  ratios were generally preserved between different rock types. Thus, the stable isotope systematics appear to rule out the equilibration of the rocks with a pervasive, externally-derived fluid of any composition. This finding is supported by  $\delta^{18}O$  data from a subsequent study of Hoernes and Van Reenen (1992), which also suggested that the bulk of the hydrated rocks have not equilibrated with a voluminous, externally-derived fluid. Secondly, an increasing body of experimental evidence on the physical interactions at mineral-fluid interfaces suggests that it is not possible for  $CO_2$ -dominated fluids to pervasively infiltrate the high-grade silicate crust (Brennan and Watson, 1987; Watson and Brennan, 1987; Holness and Graham, 1991), and that the ingress of such fluids should be deformation-controlled and strongly channelized (Fein et al., 1994). Thus, a carbonic fluid from a "deep seated source" could have mobilized up the Hout River Shear Zone, but it could not pervasively infiltrate the crust and accomplish regional retrogression. A petrographic and chemical investigation of hydrated former metapelitic granulites in this study has provided a solution to this dilemma by establishing the possibility of an internally derived fluid source.

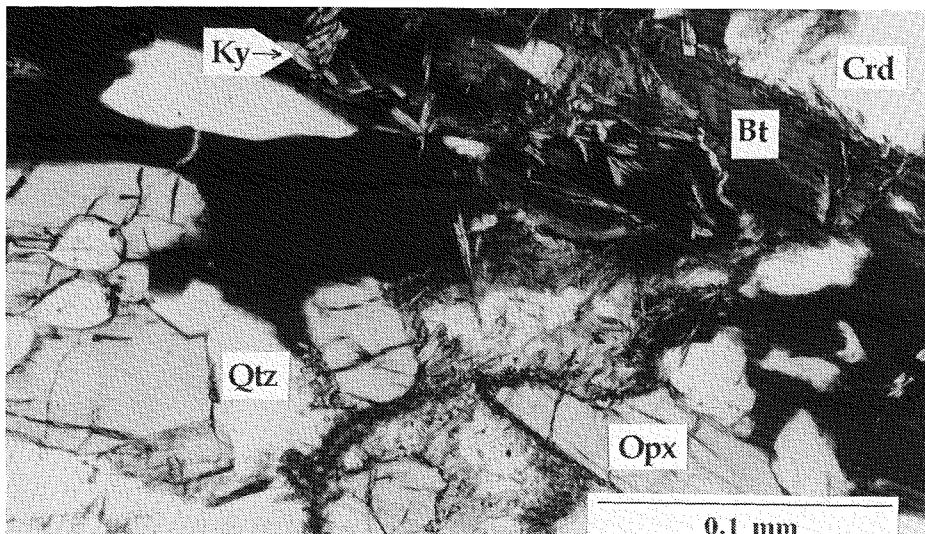
## THE REGIONALLY REHYDRATED METAPELITIC GRANULITES

In the migmatitic metapelites the regional retrogression appears to be intimately linked to the evolution of the *in situ* anatetic melts identified by Stevens and Van Reenen (1992a). During fluid-absent partial melting events, reactions that can be modelled as  $A(OH) + B + C = X + Melt(H_2O)$  result in the consumption of a hydrous silicate phase and produce a more anhydrous restitic assemblage (granulite) in equilibrium with a  $H_2O$ -undersaturated granitoid melt (Brown and Fyfe, 1970; Fyfe, 1973; Clemens, 1990). In the case of fluid-absent anatexis in metapelites, the hydrous silicate most likely to be partially consumed by melting in the granulite facies is biotite and the resultant melt will be truly granitic. If the melt mobilizes out of the high grade crust, crustal differentiation will have been accomplished (Vielzeuf et al., 1990), but if the melt remains in the sites of anatexis migmatitic granulites result and there is potential for retrograde interaction between the hydrous magma and the anhydrous, restitic, granulite-grade assemblage (Ashworth, 1985; Ashworth and McLellan, 1985; Stevens and Clemens, 1993).

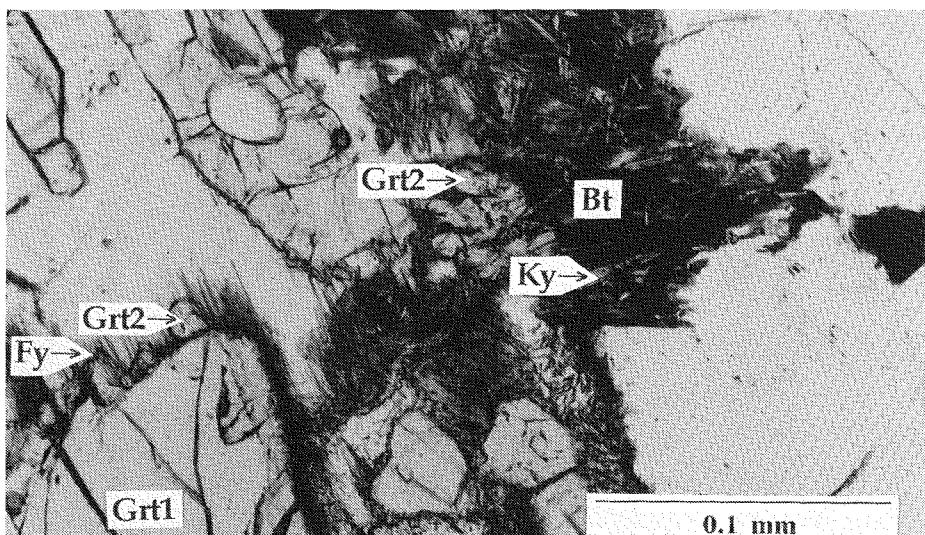
In the Southern Marginal Zone, rehydration appears to have been initiated by such  $H_2O$ -conserving crystallization-hydration reactions, i.e.  $Crd + Melt = Bt + Ky + Qtz$  and  $Opx + Melt = Bt + Qtz$  (Fig. 7a) (mineral abbreviations after Kretz, 1983). The development of these reaction

textures is restricted to the proximity of anatetic leucosomes and cannot be ascribed to a general, terrane-wide increase in  $\alpha\text{H}_2\text{O}$ . These reactions were followed by further breakdown of cordierite in the granulite zone, and cordierite and orthopyroxene in the hydrated zone, as the system became fluid-present, probably due to the leucosome melts becoming  $\text{H}_2\text{O}$ -saturated during the latter stages of crystallization, i.e.  $\text{Crd} + \text{Fl} = \text{Oamph} + \text{Ky}$  and  $\text{Opx} + \text{Fl} = \text{Oamph}$  (Fig. 7b and c). These initial fluid-present reactions are not restricted to the proximity of leucosomes and produced orthoamphibole in rocks that appear to be too potassic and aluminous to contain orthoamphibole as an equilibrium phase with biotite, garnet and kyanite (Fig. 8). The final equilibrium recorded by the retrograde assemblages results from the reaction:  $\text{Ky} + \text{Oamph} + \text{Qtz} + \text{Fl}(\text{K}_2\text{O}) = \text{Grt} + \text{Bt}$  (Fig 7d and e). In both zones the retrograde assemblages are characterised by incomplete reactions. The products and reactants of the numerous sequential hydration reactions are generally present in all samples (Fig. 9). This argues for restricted fluid availability as the controlling factor in determining the degree of hydration and the preservation of disequilibrium features. An analysis of the leucosome compositions in the two zones provides a possible reason for the differences in fluid abundance.

(a)

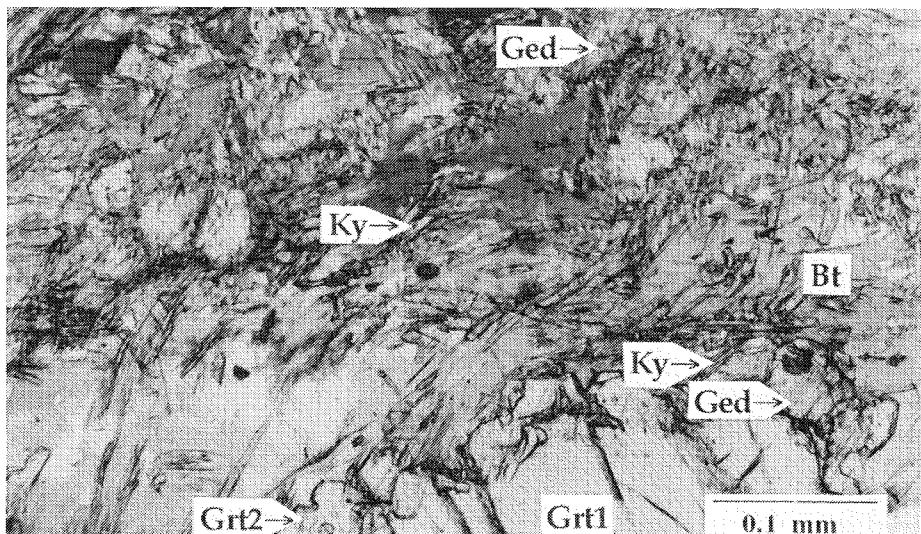


(b)

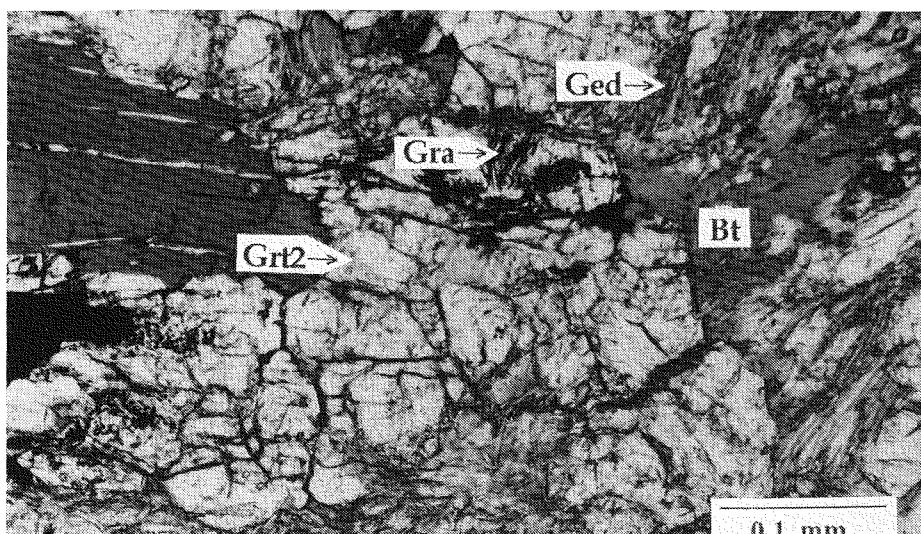


Caption on page 12.

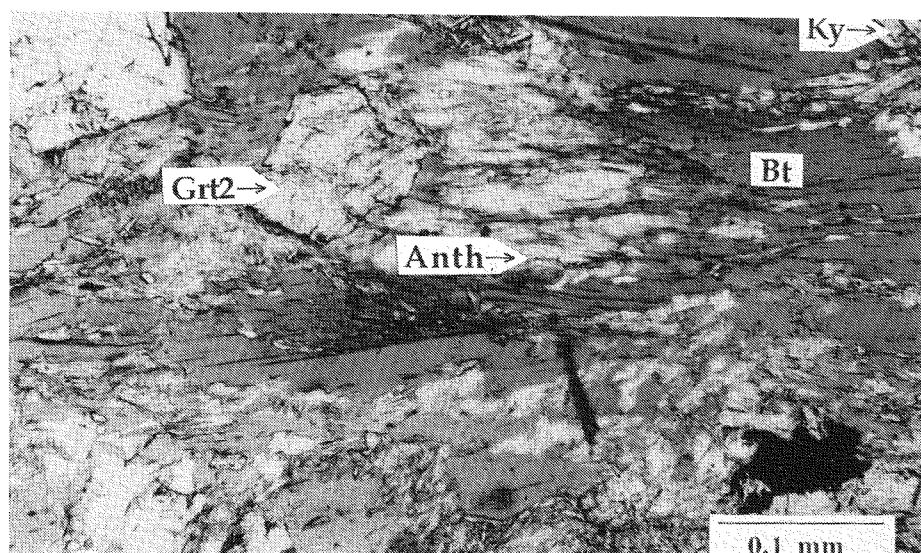
(c)



(d)



(e)



Caption overleaf.

Figure 7: Details of the hydration textures in the Southen Marginal Zone.

- (a) Photomicrograph illustrating the texture produced by the reaction  $\text{Crd} + \text{Melt} = \text{Bt} + \text{Ky} + \text{Qtz}$  in the rocks that retain a granulite facies mineralogy.
- (b) The later replacement of cordierite by a fine-grained, fibrous intergrowth of kyanite and orthoamphibole in the same rocks. This texture appears to indicate the presence of a grain boundary fluid film and is confined to cordierite crystal margins. Note the late generation of small euhedral garnet (Grt 2) crystals that overprint the fibrous intergrowth and represent the last reaction recorded in these rocks.
- (c) The textures produced by the same reactions in samples from the locality of the proposed orthoamphibole isograd. The mineral relationships are similar, but the degree of reaction and the grain size of the products is greater. Note the abundant late garnet growth, largely nucleated on the granulite-grade cores, that clearly overprints the orthoamphibole-kyanite assemblage.
- (d) A photomicrograph of the retrograde textures in sample I7 from the hydrated zone. In these rocks new garnet growth is extensive and garnet contains inclusions of kyanite, orthoamphibole and graphite. Graphite is remobilized during hydration and is intimately associated with the hydration assemblages.
- (e) In the same samples, where degrees of retrogression are highest, there is clear textural evidence for the replacement of orthoamphibole by biotite. Thus, the final hydration assemblage is garnet + biotite + quartz + plagioclase  $\pm$  kyanite.

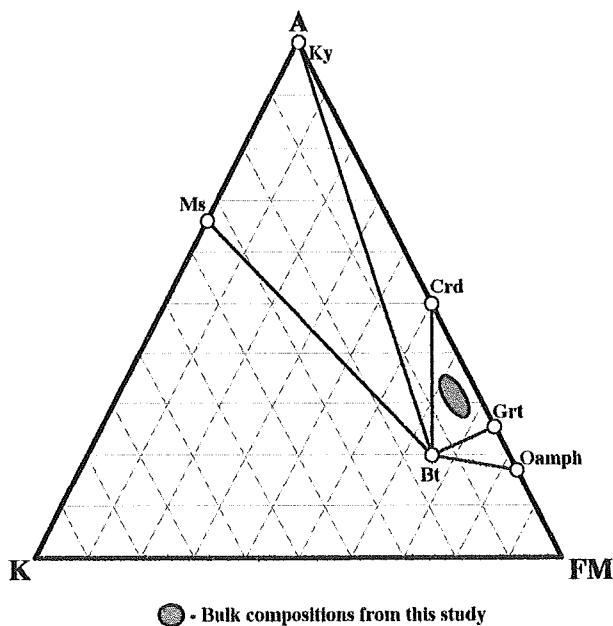


Figure 8: Representative hydrated zone bulk-rock and mineral compositions plotted on an A-K-FM projection adapted from Arnold and Sandiford (1990). Apices are A:  $\text{Al}_2\text{O}_3$ , K:  $\text{K}_2\text{O}$ , FM:  $\text{FeO} + \text{MgO}$ . The projection is from plagioclase, quartz and fluid. The bulk compositions analysed in this study plot in the field Ky-Bt-Grt, consistent with the suggested production of orthoamphibole by a metastable, overstepped reaction, and the subsequent overprinting of orthoamphibole by the biotite-garnet assemblage.

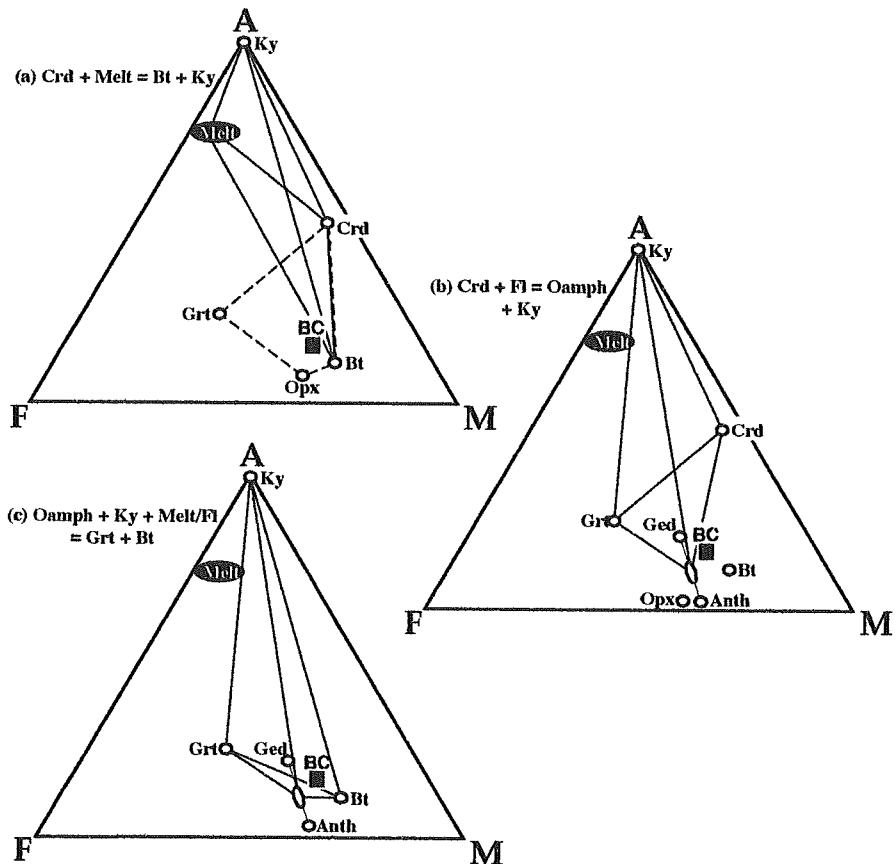


Figure 9: AFM plots for some of the retrograde equilibria proposed in this study. (a)  $\text{Crd} + \text{Melt} = \text{Ky} + \text{Bt}$ . Note that the granulite-grade association  $\text{Grt} + \text{Opx}$  persists, introducing the disequilibrium assemblage (at  $600\text{ }^{\circ}\text{C}$  and  $0.6\text{ GPa}$ )  $\text{Opx} + \text{Qtz} + \text{Ky}$ . (b)  $\text{Crd} + \text{Fl} = \text{Oamph} + \text{Ky} + \text{Qtz}$ . This reaction occurred through an overstepped equilibrium as the system became fluid-present in rocks that contained melt. (c) The final retrograde assemblage overprint in both zones resulted from the reaction  $\text{Oamph} + \text{Ky} + \text{Melt/Fl} = \text{Bt} + \text{Grt}$ . Representative mineral compositions are listed in Table 1.

**Table 1:** Representative mineral compositions from the Southern Marginal Zone. Analytical techniques are detailed in Stevens *et al.* (1995). Where Fe<sup>3+</sup> contents are given they were calculated using the methods proposed by Droop (1987). The sample localities are given in Figure 1. (a) Retrograde biotite compositions, (b) orthoamphibole compositions, (c) garnet compositions; these are rim compositions in the case of granulite zone samples, in the case of the hydrated zone samples they represent the composition of the retrograde garnet overgrowths, and (d) cordierite and orthopyroxene compositions

(a) Retrograde biotite (22 oxygen)								
	Granulite zone			At the "isograd"			Hydrated zone	
	C3a	C8d	H6	DV3	F19	D22	I7	K7b
<b>Si</b>	5.35	5.47	5.49	5.36	5.45	5.43	5.43	5.44
<b>Al<sup>4</sup></b>	2.65	2.53	2.51	2.64	2.55	2.57	2.57	2.56
<b>Al<sup>6</sup></b>	0.40	0.40	0.40	0.30	2.36	0.54	0.44	0.36
<b>Ti</b>	0.44	0.52	0.40	0.40	0.33	0.28	0.29	0.33
<b>Cr</b>	0.00	0.00	0.00	0.09	0.03	0.00	0.04	0.07
<b>Fe</b>	1.25	1.29	1.41	1.39	1.83	1.72	1.34	1.31
<b>Mg</b>	3.63	3.40	3.48	3.63	3.25	3.29	3.69	3.71
<b>Na</b>	0.07	0.02	0.00	0.08	0.23	0.12	0.16	0.19
<b>K</b>	1.93	1.83	1.78	1.80	1.63	1.58	1.73	1.73
<b>Total</b>	15.72	15.47	15.47	15.69	15.66	15.53	15.69	15.70

(b) Orthoamphibole (23 oxygen)						
	Gedrite			Anthophyllite		
	DV3	I7	Kb	DV3	I7	K7b
<b>Si</b>	6.09	5.70	5.79	7.67	7.30	7.22
<b>Ti</b>	0.01	0.00	0.02	0.00	0.00	0.00
<b>Al</b>	3.49	2.66	2.68	0.42	0.51	0.20
<b>Cr</b>	0.00	0.00	0.00	0.02	0.03	0.03
<b>Fe<sup>3+</sup></b>	0.00	1.31	1.25	0.18	0.75	1.31
<b>Fe<sup>2+</sup></b>	1.98	2.32	2.12	1.97	1.75	2.37
<b>Mn</b>	0.01	0.04	0.03	0.02	0.00	0.04
<b>Mg</b>	3.25	2.92	3.08	4.70	4.66	3.81
<b>Ca</b>	0.04	0.04	0.03	0.02	0.00	0.02
<b>Na</b>	0.63	0.45	0.47	0.05	0.00	0.00
<b>Total</b>	15.50	15.44	15.47	15.05	15.00	15.00

**Table 1 contd.**

<b>(c) Garnet (24 oxygen)</b>								
	Granulite zone (rims)			At the isograd			Hydrated zone	
	C8d	C3a	H6	DV3	F19	D22	I7	K7b
<b>Si</b>	6.02	6.02	5.97	6.11	5.95	5.92	5.94	5.99
<b>Al</b>	4.08	4.10	3.95	4.01	3.95	3.98	3.97	3.94
<b>Cr</b>	0.02	0.01	0.00	0.02	0.00	0.03	0.00	0.00
<b>Fe</b>	3.25	3.10	3.53	3.80	4.13	4.09	3.95	3.95
<b>Mn</b>	0.10	0.09	0.07	0.07	0.10	0.04	0.07	0.06
<b>Mg</b>	2.21	2.27	2.39	1.66	1.72	1.79	1.80	1.78
<b>Ca</b>	0.24	0.31	0.10	0.21	0.19	0.17	0.27	0.23
<b>Total</b>	15.92	15.90	16.01	15.88	16.04	16.02	16.00	15.95

<b>(d) Cordierite and orthopyroxene</b>						
	Cord (18 - O)		Opx (6 - O)			
wt %	C3a	DV3	C8d	C3a	DV3	I7
<b>Si</b>	5.03	5.02	1.88	1.87	1.91	1.93
<b>Al</b>	3.95	3.98	0.24	0.27	0.13	0.13
<b>Cr</b>	0.00	0.00	0.01	0.01	0.01	0.00
<b>Fe</b>	0.22	0.33	0.62	0.63	0.74	0.71
<b>Mn</b>	0.00	0.00	0.00	0.00	0.01	0.00
<b>Mg</b>	1.79	1.65	1.23	1.19	1.20	1.20
<b>Ca</b>	0.00	0.00	0.01	0.00	0.00	0.00
<b>Na</b>	0.01	0.02	0.00	0.00	0.00	0.00
<b>Total</b>	11.00	11.00	3.99	3.97	4.00	3.97

## SOUTHERN MARGINAL ZONE LEUCOSOME COMPOSITIONS

In this section, leucosome compositions from both zones are compared to those of glasses produced in a series of fluid-absent biotite melting experiments investigating the influence of bulk rock chemical characteristics on the anatexis of metasedimentary protoliths (Stevens, 1995). These glass compositions are useful as they probably very closely replicate the initial melt compositions produced by biotite fluid-absent melting in the Southern Marginal Zone. In this terrane, biotite was never exhausted, and the natural melts coexisted with garnet and sillimanite, garnet and orthopyroxene, or orthopyroxene and cordierite (Stevens and Van Reenen, 1992a), as they did in the run products from experiments on comparable bulk compositions (Stevens, 1995). Representative leucosome compositions from both the hydrated and granulite zones, and the experimentally produced glass compositions are listed in Table 2 (details of the starting compositions, experimental procedures, results, and analytical techniques are given in Stevens *et al.*, 1995).

The Southern Marginal Zone leucosome compositions clearly differ from the proposed compositions of the initial melts (experimental glasses). There are also distinct differences between the granulite and hydrated zone leucosomes. All of the natural leucosomes have substantially lower K<sub>2</sub>O contents than the glasses. This is reflected by the ratio of normative orthoclase relative to total normative feldspar content (Or') in Table 2. The leucosomes in the granulite zone are generally poorer in K<sub>2</sub>O than those in the hydrated zone. Normative plagioclase compositions (Ab') are significantly more calcic in the granulite-zone leucosomes than in either the hydrated-zone leucosomes or the glasses. The hydrated-zone leucosomes have normative plagioclase compositions that are similar to, but slightly more albitic than, those of the glasses. The leucosomes generally have lower total FeO + MgO than the glasses. Mg#s (Mg<sup>+</sup>/(Mg+Fe)) in the hydrated-zone leucosomes are generally similar to, or lower than those in the glasses. Leucosome Mg#s in the granulite zone are generally higher than those in the glasses.

**Table 2: (a) Representative leucosome compositions from the granulite zone of the Southern Marginal Zone. (b) Representative leucosome compositions from the hydrated-zone of the Southern Marginal Zone, as well as some experimental glass compositions. M1 - 875 °C, 0.5 GPa; M2 - 850 °C, 1 GPa. A1 - leucosomes coexisting with garnet and sillimanite, A2 - leucosomes coexisting with garnet and orthopyroxene, A3 - leucosomes coexisting with cordierite and orthopyroxene. The wt% totals have been normalized to 100%. Ab' = (100.Ab/Ab + An), Or' = (100.Or/Or + Ab + An)**

(a)	A1					A2		A3
wt%	C5	A13	G5	C10	B6	C12	B9	C25
<b>SiO<sub>2</sub></b>	72.49	75.38	75.02	75.30	76.94	76.25	79.93	75.47
<b>TiO<sub>2</sub></b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08
<b>Al<sub>2</sub>O<sub>3</sub></b>	17.57	16.49	15.98	15.92	14.37	14.79	13.27	15.44
<b>Fe<sub>2</sub>O<sub>3</sub></b>	0.00	0.13	0.05	0.33	0.06	0.00	0.09	0.00
<b>FeO</b>	0.43	0.15	0.15	0.59	0.19	0.66	0.18	1.01
<b>MnO</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>MgO</b>	0.36	0.09	0.09	0.16	0.14	0.61	0.31	1.94
<b>CaO</b>	3.52	2.48	3.28	1.26	2.33	3.36	2.48	2.48
<b>Na<sub>2</sub>O</b>	4.32	4.07	3.82	4.04	4.20	3.77	3.00	2.73
<b>K<sub>2</sub>O</b>	1.31	1.21	1.61	2.40	1.77	0.57	0.84	0.85
<b>Mg#</b>	60	56	47	33	53	62	75	77
<b>Ab'</b>	67.67	73.68	65.51	70.68	75.46	65.67	65.25	65.25
<b>Or'</b>	12.53	13.26	16.36	11.44	18.17	6.48	12.42	12.42

**Table 2 contd.**

(b)	A1				A2		Glasses	
	K9	N12	O5a	P8	E11	K13	M1	M2
<b>SiO<sub>2</sub></b>	74.35	75.84	73.75	74.44	74.69	74.87	73.57	73.47
<b>TiO<sub>2</sub></b>	0.04	bd	0.03	0.06	0.14	0.09	0.24	0.29
<b>Al<sub>2</sub>O<sub>3</sub></b>	15.68	15.18	16.10	15.81	15.64	15.74	14.44	14.58
<b>Fe<sub>2</sub>O<sub>3</sub></b>	na	na						
<b>FeO</b>	0.97	1.06	0.61	0.75	0.64	0.77	1.74	1.69
<b>MnO</b>	0.07	0.08	0.09	0.03	0.08	0.05	0.00	0.00
<b>MgO</b>	0.12	0.14	0.18	0.28	0.05	0.19	0.45	0.51
<b>CaO</b>	1.47	1.54	1.12	1.00	1.58	1.73	0.99	0.96
<b>Na<sub>2</sub>O</b>	4.21	4.82	4.94	3.87	4.70	4.25	3.67	3.83
<b>K<sub>2</sub>O</b>	3.09	1.28	3.29	3.76	2.39	2.31	4.90	4.67
<b>Mg#</b>	14	19	45	34	12	26	32	32
<b>Ab'</b>	83.01	84.20	88.26	86.84	83.53	80.73	81.63	81.36
<b>Or'</b>	29.85	13.50	29.10	37.08	22.87	23.46	51.99	56.13

The above comparison suggests that granulite-zone leucosomes represent crystal cumulates of quartz and plagioclase (Fig. 10) and that this portion of the Southern Marginal Zone has lost an appreciable quantity of melt. Even the most potassic, lowest Mg# leucosomes in the granulite zone have normative plagioclase compositions that are significantly more calcic than those of the glasses. This cannot be the result of a substantially higher degree of melting in the natural rocks than in the experimental charges, since neither biotite, quartz nor plagioclase was exhausted by the melting reactions in the Southern Marginal Zone. Melt fractions and melt compositions thus remained buffered by the same biotite-quartz-plagioclase consuming equilibria as in the experiments.

In the case of the hydrated-zone leucosomes, normative plagioclase compositions are slightly more albitic than those in the glass. This might be a function of slightly lower degrees of melting than represented by the glass compositions. Alternatively, the starting plagioclase composition in the natural rocks might have been more sodic than that used in the experiments. However, this difference could not have been large as the plagioclase used in the reported experiments was more albitic than that in the granulite-zone metapelites. Based on the normative plagioclase compositions, and the normative Q:Ab ratios (Fig. 10), it appears that the hydrated-zone leucosomes have lost a substantially smaller quantity of melt than those of the granulite zone. The K<sub>2</sub>O contents of these leucosomes are generally slightly lower than those of the glasses. However,

in both zones, orthopyroxene and cordierite crystals of the leucosomes and in the associated metapelites, have been consumed by reactions producing biotite where melt is inferred as a reactant. These ferromagnesian phases are rare in the leucosomes, but are abundant in the host metapelites. It is proposed that  $K_2O$  transfer from the leucosomes to the host rocks was the major mechanism of  $K_2O$  depletion in the leucosomes of the hydrated zone. In the case of the granulite zone leucosomes, which are also more calcic and have higher Mg#s, melt mobilization out of the granulite-grade source is seen as the major process that shaped the leucosome compositions.

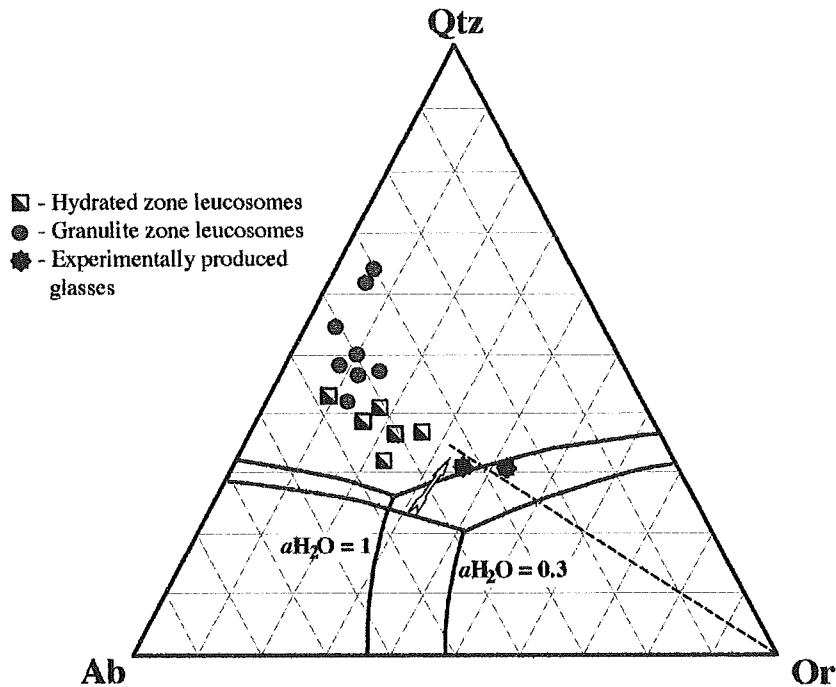


Figure 10: A plot of normative Q, Ab and Or in the Southern Marginal Zone leucosomes and the glass compositions listed in Table 2 on the haplogranite phase diagram at 1 GPa of Ebadi and Johannes (1991). The granulite zone leucosomes have the composition of cumulates of quartz and plagioclase. Those of the hydrated zone are also  $K_2O$ -poor, but extrapolate along a line of K-feldspar enrichment close to the glass compositions. The arrow indicates the direction of the evolution of the eutectic with decreasing pressure.

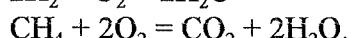
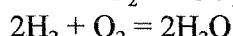
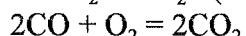
#### P-T-XFI CONDITIONS OF HYDRATION

The garnet-biotite thermometry published by Van Reenen (1986) suggested that in the retrogressed zone the final equilibration temperature was 600 °C. The presence of kyanite in these rocks suggests a minimum pressure of 0.6 GPa at this time (Fig. 3). Temperatures calculated in this study using the garnet-biotite geothermometer of Ferry and Spear (1978), and the mineral compositions in Table 1, indicate temperatures of between 580 and 600 °C for the final garnet-biotite assemblage illustrated in Figure 7e. These P-T conditions represent the final conditions of equilibration for the regional hydration event and are consistent with the inferred involvement of a crystallizing granitic melt in the early stages of the retrogression.

The mineral textures produced in the reactions that are inferred to have involved a fluid all have an association with graphite that appears to have precipitated as the reaction occurred, indicating that CO<sub>2</sub> was a component of the fluid. This could not have been exsolved from the melts, as the solubility of CO<sub>2</sub> in granitic melt at 0.6 GPa is negligibly small (Holloway, 1976). The metasediments in both zones, however, contain a graphite component, interpreted to represent original biogenic graphite (Venneman and Smith, 1992). It is useful, at this point, to consider the interaction between melt-derived, almost pure, H<sub>2</sub>O and this graphite.

### Graphite Oxidation

To derive fluid compositions at the time of melt H<sub>2</sub>O saturation in graphitic host rocks it is necessary to consider possible reactions in the simple system C-O-H, i.e.:



Equilibrium fluid compositions were calculated using the modified Redlich-Kwong equation of state plus the equations for log K of Ohmoto and Kerrick (1977). The calculations assume ideal mixing of fluid species, graphite saturation and fO<sub>2</sub> buffered at (a) the quartz-fayalite-magnetite buffer(QFM), (b) one log unit below QFM, (c) and two log units below QFM. Calculated fluid compositions in equilibrium with graphite at 0.6 GPa and between 600 to 700 °C are listed in Table 3 and illustrated in Figure 11.

**Table 3: Calculated fluid compositions in equilibrium with graphite at 0.6 GPa**

		600 °C	650 °C	700 °C
<b>Q</b>	XCO <sub>2</sub>	0.265	0.946	0.962
	XH <sub>2</sub> O	0.727	0.051	0.034
	XCH <sub>4</sub>	0.000	0.000	0.000
	XCO	0.000	0.003	0.004
	XH <sub>2</sub>	0.008	0.001	0.001
<b>F</b>	XCO <sub>2</sub>	0.100	0.844	0.885
	XH <sub>2</sub> O	0.871	0.142	0.098
	XCH <sub>4</sub>	0.000	0.000	0.000
	XCO	0.001	0.008	0.012
	XH <sub>2</sub>	0.028	0.006	0.005
<b>M</b>	XCO <sub>2</sub>	0.032	0.611	0.687
	XH <sub>2</sub> O	0.878	0.326	0.241
	XCH <sub>4</sub>	0.001	0.001	0.001
	XCO	0.001	0.018	0.029
	XH <sub>2</sub>	0.088	0.044	0.042
<b>-1</b>	XCO <sub>2</sub>	0.100	0.844	0.885
	XH <sub>2</sub> O	0.871	0.142	0.098
	XCH <sub>4</sub>	0.000	0.000	0.000
	XCO	0.001	0.008	0.012
	XH <sub>2</sub>	0.028	0.006	0.005
<b>-2</b>	XCO <sub>2</sub>	0.032	0.611	0.687
	XH <sub>2</sub> O	0.878	0.326	0.241
	XCH <sub>4</sub>	0.001	0.001	0.001
	XCO	0.001	0.018	0.029
	XH <sub>2</sub>	0.088	0.044	0.042

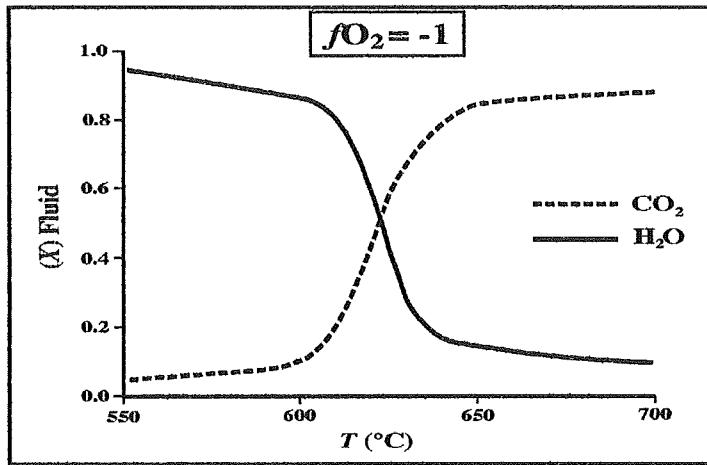


Figure 11: Calculated fluid compositions expressed as a function of  $XH_2O$ ,  $XCO_2$  and  $T$ .  $P = 0.6$  GPa and  $fO_2$  was assumed to be buffered one log unit below QFM. See text for the method of calculation.

Irrespective of the chosen  $fO_2$  conditions, there is a sharp change in calculated fluid composition between 650 and 600 °C, with fluids at lower temperature becoming progressively more  $H_2O$ -rich (Fig. 11).  $H_2O$  and  $CO_2$  are the only significant volatile species in the fluid. Assuming  $fO_2$  to be buffered at QFM -1, the composition of the fluid would change from  $XH_2O = 0.14$  at 650 °C, to  $XH_2O = 0.87$  at 600 °C.

In the natural rocks, fluid-present conditions would have been attained at the moment that the melts became  $H_2O$ -saturated. The relatively oxidizing  $H_2O$ -rich fluid would have reacted with graphite, evolving towards an equilibrium fluid composition. The final fluid composition, and the fluid volume, would have depended on the equilibrium fluid composition, the relative amounts of  $H_2O$  and graphite in the system and the ability of the system to buffer  $fO_2$ . If insufficient graphite were available to attain the graphite buffered equilibrium composition, a less voluminous, more  $H_2O$ -rich fluid, not coexisting with graphite, would result. If the amount of  $H_2O$  in the rock, the equilibrium fluid composition, and the molar volumes of the equilibrium fluids at  $P$  and  $T$  are known, then the amount of graphite that would be required, and the resultant fluid:rock ratio, can be calculated. To do this it is necessary to deal with a representative volume of migmatite and treat it as a homogeneous unit. Field observations suggest that 25% partial melt is a realistic estimate for the Southern Marginal Zone metapelites at peak  $P$ - $T$  conditions (Stevens, 1992). Biotite-melt coexistence during fluid-absent biotite melting buffers the melt  $H_2O$  content to values very close to 3 wt% for all pressures between 0.5 and 1 GPa (Vielzeuf and Montel, 1994). Molar volumes of the mixed fluids at 0.6 GPa and between 500 and 700 °C were calculated by means of MRKZ, a program written by J.D. Clemens to calculate molar volumes of fluid species and mixtures using the modified Redlich Kwong equation of state as given by Holloway (1981). Thus, it can be calculated that, at 650 °C and 0.6 GPa, if all the  $H_2O$  formerly residing in the melt were available for reaction, the fluid:rock ratio would be > 30 vol%, if an equilibrium fluid composition were produced (Fig. 12). This substantial fluid volume is a function of both the  $CO_2$ -dominated nature of the fluid (a little  $H_2O$  produces a lot of  $CO_2$ -dominated fluid) and the relatively high

molar volume of such a CO<sub>2</sub>-rich fluid. It would, however, require that the rocks have at least 3.3 wt% graphite prior to crystallization (Fig 12). In the Southern Marginal Zone the solidus was probably intersected close to 620 °C. This would have resulted in less voluminous, less CO<sub>2</sub>-rich fluids that would have required less graphite to produce. However, from Figure 12 it can be seen that fluid:rock ratios as high as 1:5 by volume are likely for Southern Marginal Zone rocks where graphite was sufficiently abundant.

Falling temperature, and the retrograde hydration reactions documented in the previous section, would have resulted in graphite precipitation. This is confirmed by the textures. As original carbon isotopic heterogeneities are preserved in the Southern Marginal Zone, either a substantial amount of graphite remained unreacted, or graphite oxidation, subsequent hydration reactions, and resultant graphite precipitation all occurred essentially *in situ*, with little or no fluid mixing.

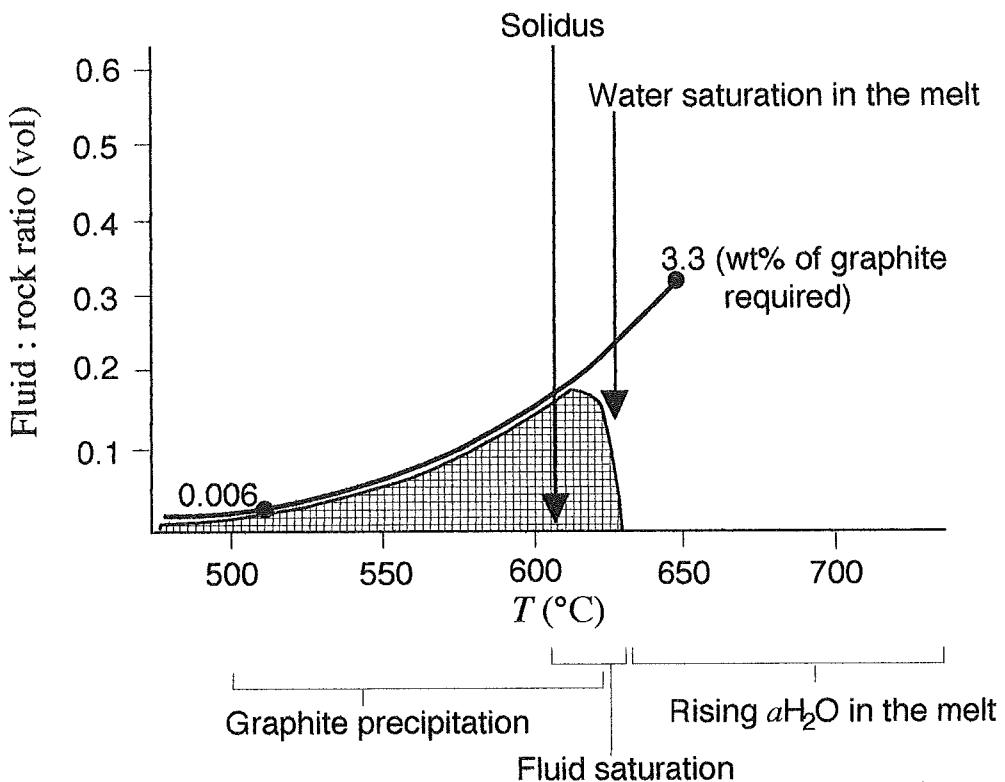


Figure 12: Calculated fluid:rock ratios (heavy curve) generated if the equilibrium fluid composition was attained. The calculations assume a 25 vol% partially melted source with 3 wt% H<sub>2</sub>O in the melt and graphite saturation. Fluid compositions used are those in Figure 12. Mixed fluid molar volumes were calculated by means of MRKZ, a program written by J.D. Clemens. The points on the heavy line indicate the quantity of graphite required in the precursor to ensure graphite saturation at 520 and 650 °C. The hatched area represents the conditions proposed for the hydrated zone of the Southern Marginal Zone.

## CONCLUSIONS

The findings of this study appear to resolve a long-standing inconsistency between the stable isotopic and mineralogical characteristics of the Southern Marginal Zone hydrated rocks. The rocks *did* interact with an extensive, pervasive, H<sub>2</sub>O-undersaturated fluid, but it was internally derived and thus, the isotope systematics carry no record of fluid infiltration. The petrographic investigation of the hydration reactions illustrates the degree to which fluid availability has controlled the retrogression. In many of the rocks, disequilibrium assemblages are preserved simply because there was insufficient fluid with which to react. Melt migration out of the granulite zone, probably at conditions approaching the peak of metamorphism, was more effective than in the hydrated zone. Consequently, in the hydrated zone, much of the H<sub>2</sub>O, which partitioned into the leucosomes during prograde melting, was released back into the rocks during cooling. This occurred through reactions between melt and high-grade phases and through reactions between fluid and high-grade phases in the presence of a melt. In the hydrated zone, H<sub>2</sub>O was effectively recycled between fluid-absent melting equilibria on the prograde path and crystallization-hydration equilibria on the retrograde path.

The orthoamphibole used to delineate the retrograde isograd appears to be a transitory reaction product that is overprinted by the same biotite-garnet-producing reaction in both the granulite zone and the hydrated zone. It can therefore have no grade-related relevance for the end of the retrogression period. The consumption of orthoamphibole by the final garnet and biotite producing reaction appears to be driven by an increase in the size of the equilibration volume in the rocks as the fluid phase became abundant, and possibly also by an increase in  $\alpha K_2O$  in the fluid as XCO<sub>2</sub> declined through falling  $T$ . It is concluded that the previously proposed orthoamphibole retrograde "isograd" does not represent a reaction front resulting from a change in grade ( $P-T$ ); rather it seems most likely to be a fault boundary between two high-grade Southern Marginal Zone blocks with different H<sub>2</sub>O contents, due to different degrees of melt loss (Fig. 13).

It appears that the fluid-present hydration reactions occurred in the narrow temperature interval of melt-fluid coexistence and that the pervasive nature of the hydration resulted from the large fluid phase volume increases brought about by the production of CO<sub>2</sub> through graphite oxidation. Regional retrogression in the granulites coincided with mineralization in the Hout River Shear Zone. Thus, the steeply dipping shear zones that formed during uplift of the granulites provided a convenient plumbing system for the evacuation of the retrogressing fluid from the high-grade source. In many of the mineralized sites, the restrictions on fluid-availability that allow for the identification of sequential hydration reactions through the various stages of partial retrogression do not appear to have applied. Fluid:rock ratios in this zone (and possibly within other less well defined zones in the former granulites) appear to have been substantially higher. In these areas fluid volumes seem to have been sufficient to override the bulk-rock domination of fluid chemistry. This was not observed in the bulk of the terrane where the fluid composition remained buffered by graphite and the hydration equilibria. Background gold concentrations were possibly scavenged from the high-grade terrane during this fluid genesis event and the carbonic fluid had sufficient capacity to transport this gold, or remobilize existing gold, and produce significant ore deposits in favourable sites along the Hout River Shear Zone.

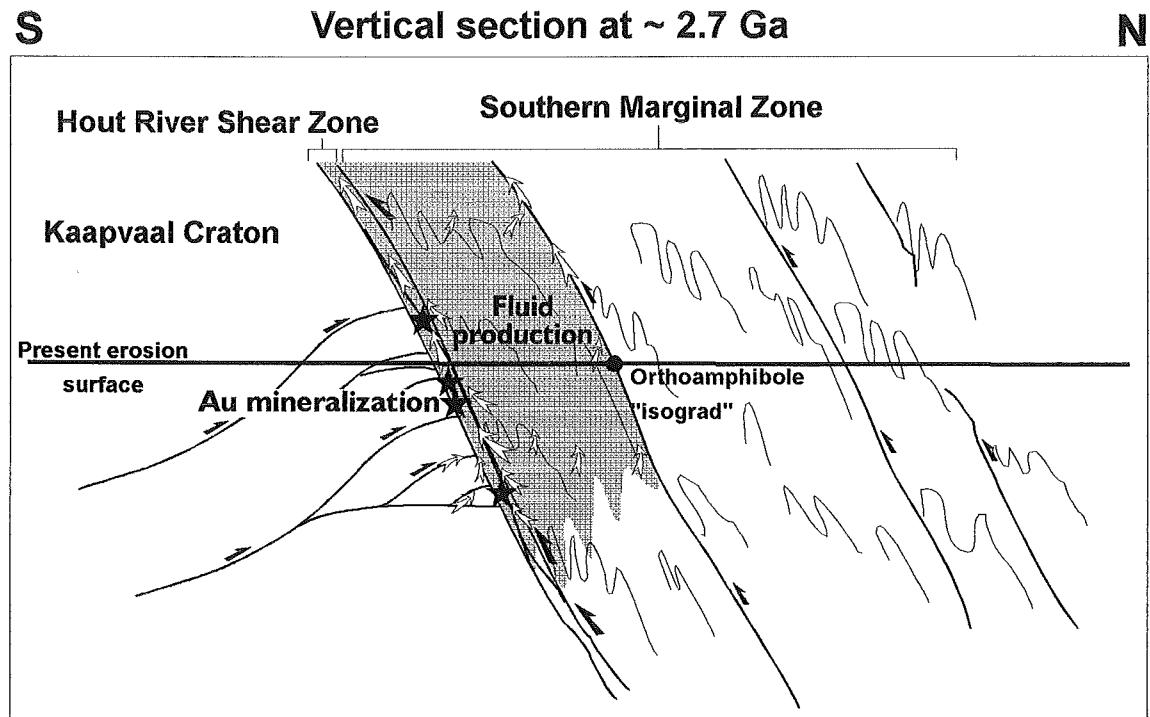


Figure 13: An interpretation of the relationship between the Kaapvaal Craton and the two zones of the Southern Marginal Zone, as suggested by the data presented in this study. The open arrows indicate fluid migration and the filled arrows indicate tectonic transport. The orthoamphibole isograd is a fault boundary separating high grade crustal blocks with different H<sub>2</sub>O contents due to different degrees of melt loss, it is not grade related. Fluid production through leucosome crystallization and graphite oxidation was internal to the terrane and fluid flowed out of the former granulites. This can be contrasted with the infiltration required by other models (Fig. 6). Syn-retrogression mineralization during thrusting of the granulites over the craton suggests that the escape of this fluid along the Hout River Shear Zone was responsible for the observed mineralization.

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