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Fluid-rock interaction during high-grade metamorphism: instructive examples from the Southern Marginal Zone of the Limpopo Complex, South Africa

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ABSTRACT

The Southern Marginal Zone of the Limpopo Complex documents strong evidence that CO_2-rich ($X^{\text{fluid}}_{CO_2} = 0.7\text{-}0.9$, $X^{\text{fluid}}_{H_2O} = 0.1\text{-}0.3$) and brine fluids of greatly reduced water activity interacted with cooling metapelitic granulite during the thrust-controlled emplacement at 2.69-2.62 Ga onto the granite-greenstone terrain of the northern Kaapvaal Craton. Interaction of cooling metapelitic granulite with CO_2-rich fluids at $T < 600\text{-}630$°C and $P <$ ~6 kbar is recognized by the presence of a regional retrograde Opx-out/Ath-in isograd and an associated zone of retrograde hydrated granulites that occupies ~4500 km^2 of retrogressed crust located in the hanging wall section of the shallow north-dipping Hout River Shear Zone that bounds the Southern Marginal Zone in the south. On the other hand, brine fluids are considered to have triggered the main pulse of anatexis that resulted in production of large volumes of

granodioritic-trondhjemitic melts that intruded and started to interact with metapelitic granulite in the deep crust at *T* > ~900°C, *P* > ~7.5 kbar. Interaction of hot melt with metapelitic granulite continued until final emplacement in the middle crust (*P* = ~6 kbar, *T* = ~630°C). Brine fluids also initiated shear zone-hosted metasomatism of quartzo-feldspathic gneisses at *T* between ~600 and ~900°C. and amphibolite-facies lode-gold mineralization. Available data implicate devolatilization of underthrusted greenstone material as the dominant deep crustal source for infiltrating CO_2-rich and brine fluids.

1. Introduction

Interaction of granulite-facies rocks with externally derived fluids remains a contentious issue among metamorphic petrologists (e.g., Rigby and Droop, 2011; Touret and Huizenga, 2011, 2012; Yardley, 2013). This is true because most researchers agree that, in most cases, rocks undergoing high-grade metamorphism have a very low permeability and contain only small amounts of metamorphic fluids at near-lithostatic pressures during peak metamorphism (Yardley and Valley, 1997; Yardley, 2009, 2012). When the metamorphic rocks cool, they hardly back react with fluids to form a lower temperature mineral assemblage (retrogression) because fluids produced during prograde metamorphism escape and thus are no longer available.

However, in situ geophysical and geochemical studies carried out in active (modern) regional metamorphic terrains have shown that metamorphic fluids are an integral part of the tectonic system (e.g., Koons and Craw, 1991; Wickham et al., 1993; Wannamaker et al., 1997; Koons et al., 1998). Early studies done in the Himalaya, for instance, established the importance of aqueous fluids being driven out during metamorphism of sediments under the Main Central Thrust when overridden by the hot hanging wall of the Tibetan slab (Le Fort et al., 1987). These fluids triggered anatexis in the hanging wall, which resulted in the generation of leucocratic granite, which intruded into the upper levels of the Tibetan slab (Le Fort et al., 1987).

Different workers have also provided mineralogical and isotopic evidence for the existence of high time integrated fluid fluxes and fluid flow directions in many thermal aureoles and regional metamorphic belts (Rubenach, 2013). For example, Markl and Bucher (1998) and Gleeson et al. (2003) have documented evidence for amphibolitization of lower crustal granulites through brine influx, while others (Van Reenen, 1986; Ferry and Dipple, 1991; Ferry, 1994; Hoernes et al., 1995; Putnis and Austrheim, 2010) described evidence for infiltration-driven regional metamorphism.

The reasons why researchers often doubt whether infiltration metasomatism is widespread during regional metamorphism appears to arise from concerns about the availability and source of fluids (e.g., Yardley, 2013). However, recent experimental data (e.g., Newton and Manning, 2010; Aranovich et al., 2013, under review; Safonov et al., under review) clearly show that, regardless of their origin, deep crustal fluids and specifically brines, must be important agents of metasomatism and mass transfer wherever such processes are recognized in the field or hand specimen (e.g., Harlov, 2012).

Wet versus dry middle to deep crust furthermore implicates the issue of fluid-absent (dehydration melting) versus fluid-assisted mechanisms of crustal anatexis. Proponents of the fluid-absent origin of granulite (e.g., Rigby and Droop, 2011) argue that granulite (and crustal anatexis) were formed in the mid to deep crust in the absence of a free fluid phase via high temperature metamorphism (dehydration melting/anatexis; e.g., Fyfe, 1973; Thompson, 1983; Clemens and Vielzeuf, 1987; Waters, 1988; Stevens and Clemens, 1993; Yardley and Valley, 1997). A strong argument usually used in favour of the fluid-absent model is that important features of granulite facies rocks support a dehydration melting origin, including the high-temperature nature of a number of granulite assemblages as well as the observation that many granulite-facies rocks preserve the protolith O-isotope signature, thus excluding involvement of a pervasive fluid flow in their origin (e.g., Valley, 1986; Vennemann and Smith, 1992).

On the other hand, proponents of the fluid-assisted model for granulite formation and for associated anatexis have shown that temperature estimates ($T < 850°C$) obtained by geothermobarometry from numerous “normal” granulite facies rocks are in fact lower than the values required for the onset of fluid-absent dehydration melting (Aranovich et al., 1987, under review; Newton, 1989; Johannes and Holtz, 1991; Newton et al., 1998, under review; Nair and Chacko, 2002; Safonov et al., under review). They ascribe the apparent undisturbed protolith O-isotope signatures of granulite to low fluid/rock ratios (e.g., Hoernes et al., 1995). The fluid-assisted model is also supported by the common occurrence of CO_2, brine and mixed CO_2-brine fluid inclusions (e.g., Touret, 2012; Touret and Huizenga, 2011; Aranovich et al., 2013; Newton et al., under review; Safonov et al., under review). Finally, the presences of large volumes of anatectic granitic melt in high-grade metamorphic terrains argue in favour of a mechanism of “water-fluxed melting” (e.g., Sawyer et al., 2011).

High-temperature metasomatism involving chemical and mineralogical changes are undisputable features of high-grade shear zones in granulite-facies terrains and indicates that they are sites of focused fluid flow (Skelton et al., 1995; Smit and Van Reenen, 1997; Glassley et al., 2010; Touret and Huizenga, 2012). Archaean lode-gold mineralisation at different *P*-*T* conditions in high-grade gneiss terranes is clearly linked to metasomatism of precursor rocks by infiltrating fluids (e.g., Phillips and Groves, 1983; Phillips, 1985; Smith et al., 1984; Van Reenen et al., 1994; Groves et al., 2003). Such fluids involve H_2O-CO_2±CH_4 fluids (e.g., Mikucki, 1998), with a maximum mole CO_2 mole fraction ($X_{CO_2}^{fluid}$) of ~0.25 derived from crystallizing magma at depth, metamorphic devolatilization reactions, or the mantle as is indicated by stable isotope data (Smith, 1986; Golding et al., 1987; Kerrich, 1987). These fluids will, depending on their prevailing temperatures and fluid-rock ratios, either metamorphose or metasomatose (and possibly mineralize) the rocks through which they pass (e.g., Le Fort, 1981; Vrolijk, 1987; Sisson et al., 1989; Moore et al., 1987; Hyndman, 1988; Hyndman et al., 1989).

Given the complexity of the issues involved, it is imperative that strong field evidence in support of regional and local scale fluid-rock interaction should ideally be interpreted within the context of the overall geological evolution of the rocks in which such processes occur (Yardley, 2013; Huizenga et al., 2014; Smit et al., under review). This paper contributes to specific aspects of this contentious issue by providing, for the first time, a comprehensive record compiled from published (Van Reenen, 1986; Van Reenen and Hollister, 1988; Baker et al., 1992; Hoernes and Van Reenen, 1992; Van Reenen et al., 1994; Van Schalkwyk and Van Reenen, 1992; Hoernes et al., 1995; Smit and Van Reenen, 1997; Van Reenen et al., 2011; Huizenga et al., 2014) and unpublished data (Du Toit, 1994; Mokgatlha, 1995; Stefan, 1996) regarding interaction of low H_2O-activity ($a_{H_2O}^{fluid}$) fluids and cooling granulites in the Southern Marginal Zone of the Limpopo Complex. Although this paper recognizes devolatilization of underthrusted greenstone material as the primary source for infiltrating fluids, we will also discuss alternative fluid sources (crystallizing granitic magma, upper mantle) that might have contributed to the overall fluid budget of the SMZ during the thrust-controlled exhumation.

Fluids that infiltrate cooling granulites of the Southern Marginal Zone is expressed by a variety of high-temperature fluid-rock interaction phenomena including pervasive retrogression of granulite, anatexis, and shear zone-hosted metasomatism of high-grade rocks including gold mineralization. High-temperature metamorphic and metasomatic phenomena have shown not to be mutually exclusive but are closely linked processes involving CO_2-rich ($X_{CO_2}^{fluid} = 0.7\text{-}0.9$, $X_{H_2O}^{fluid} = 0.1\text{-}0.3$) fluids and brines. Metasomatism in this context is regarded as changes in the bulk chemical composition of non-volatile components (e.g., Putnis and Austrheim, 2010; Yardley, 2013).

Finally, this paper is a general introduction to different case studies in the present issue that deal with special aspects of pervasive and channeled fluid-rock interaction in the Southern Marginal Zone (Dubinina and Aranovich, under review; Koizumi et al., under review; Tsunogae and van Reenen, under review; Safonov et al., under review). Devolatilization of underthrusted greenstone material as a specific deep crustal fluid source and a tectono-metamorphic model that controlled persistent fluid flow into overriding hot granulite during exhumation, are the focus of a separate paper (Smit et al., under review).

2. Tectonic setting of the Southern Marginal Zone and the northern Kaapvaal Craton

The high-grade Limpopo Complex in South Africa is a late Archean ENE-WSW trending zone located between the granite-greenstone terrains of the Zimbabwe and Kaapvaal Cratons (Fig. 1). The complex is subdivided into the Northern Marginal Zone, the Central Zone, and the Southern Marginal Zone (e.g., Van Reenen et al. 2011), of which the Northern and Southern Marginal Zones comprise high-grade granitoids and greenstone belt lithologies (inset in Fig. 1) (e.g., Kreissig et al., 2001; Van Reenen et al. 2011). The Northern and Southern Marginal Zone are juxtaposed against the Zimbabwe and Kaapvaal Craton, respectively, as a result of compression-related exhumation during 2.69-2.62 Ga (Van Reenen et al., 2011). The Central Zone is separated from the marginal zones by Paleoproterozoic crustal-scale strike slip shear zones (e.g., Roering et al., 1992b).

The origin and critical role that reactive fluids have played in the Southern Marginal Zone (SMZ) can only be appreciated if this process is considered within the context of the geotectonic relationship of the SMZ with the juxtaposed northern Kaapvaal Craton (NKVC)

(Fig. 1, 2). Smit et al. (under review) provide a comprehensive overview of the complex shared evolutionary histories of these two disparate juxtaposed terrains, and only pertinent aspects that impact directly on the focus of this paper will be briefly mentioned here.

A shallow north-dipping terrain bounding structure named the Hout River Shear Zone (HRSZ) (Fig. 1, 2) separates two distinct geological terrains that, prior to the onset of the Limpopo Orogeny (~2.72 Ga), formed part of the granite-greenstone terrain of the NKVC. The SMZ of the Limpopo Complex (LC) presently occupies the hanging wall section of this major crustal boundary, whereas granite-greenstone belts of the NKVC occupy the footwall section (Fig. 1, 2). These two disparate terrains are typified by different geological characteristics that evolved as a direct result of the superimposed 2.72-2.62 Ga Limpopo Orogeny (see Smit et al., under review, for a detailed discussion). The following discussion mainly focuses on the evolution of the SMZ.

The SMZ comprises foliated, banded and migmatitic enderbitic gneisses (locally known as the Baviaanskloof gneiss) that are complexly infolded with mafic-, ultramafic-, and metapelitic granulite and minor granulite facies BIF of the Bandelierkop Formation (Fig. 1). Major-, trace element-, and isotope geochemical data show that the SMZ represents 3.20-2.99 Ga old granite-greenstone material similar to that of the NKVC (Kreissig et al., 2000, 2001). This provides irrefutable evidence that the granulite facies rocks exposed in the SMZ represent the high-grade metamorphic equivalents of granite-greenstone lithologies in the adjacent NKVC (Du Toit et al., 1983; Kreissig et al., 2000, 2001).

Emplacement of the SMZ onto the NKVC during the exhumation stage of the LC was controlled by 2.68-2.69 Ga shallow SW-verging HRSZ and related system of steep SW-verging deep crustal shear zones within the SMZ (Fig. 1, 2). This is reflected by: (1) Retrograde metamorphism comprising an early decompression-cooling stage (~2.69 Ga) illustrated by the reaction (Perchuk et al., 2000a, Smit et al., 2001) (mineral abbreviations after Whitney and Evans, 2010):

$$2\ \text{Grt} + 3\ \text{Qz} \rightarrow \text{Crd} + 2\ \text{Opx} \quad (1a)$$

followed by a near-isobaric cooling stage reflected by the reaction (Perchuk et al., 2000a, Smit et al., 2001):

$$3\ \text{Crd} \rightarrow 2\ \text{Grt} + 4\ \text{Sil} + 5\ \text{Qz} \quad (1b)$$

(2) Regional retrograde hydration caused by CO_2-rich fluids (e.g., Van Reenen et al., 2011), which illustrates the final visible stage of cooling; (3) A zone of retrograde hydrated granulites, separated from the granulites by the retrograde Ath-in/Opx-out isograd (from here onwards referred to as retrograde isograd) resulted from this event; (4) Development of a dominant gneissic (D2) fabric that has developed during exhumation. Regional-scale D2 shear zones are associated with exhumation; (5) Localized D2 shear zoned-hosted metasomatism and lode gold mineralization caused by brines.

While the SMZ shows only evidence for high-grade retrograde metamorphism, the underthrusted Giyani greenstone belt in the footwall of the HRSZ (Fig. 1), on the other hand, provides evidence for prograde metamorphism at ~2.69 Ga (Van Reenen et al., 1987, 1988, 2011; De Wit et al., 1992b; McCourt and Van Reenen, 1992; Roering et al., 1992a; Miyano et al., 1992; Perchuk et al., 1996, 2000; Smit et al., under review).

3. Different sources for the retrograde fluids

Hollister (1992) discussed three possible sources to account for the retrograde fluid that infiltrated the high-grade rocks of the SMZ during thrust-controlled exhumation and established the retrograde isograd and associated hydration zone: (1) The upper mantle, or mantle derived melts that underplate the lower crust; (2) Crystallizing anatectic melts that originated within the SMZ (Vennemann and Smith, 1992; Stevens, 1997); (3) Prograde devolatilization reactions related to emplacement of hot SMZ granulite over cooler low-grade greenstone belt material of the NKVC (Van Reenen and Hollister, 1988).

Hoernes et al. (1995), following on the suggestion by Vennemann and Smith (1992) that O-isotope data failed to identify an external fluid source in the SMZ during hydration, pointed out that recognition of the ultimate fluid source based on O-isotope studies alone is complicated by the fact that the first and second fluid sources are clearly magmatic, and that magmatic rocks (greenstone belt material) also would dominate the third source. This follows from the fact that the SMZ comprises the high-grade metamorphic equivalents of typical greenstone belt material (Kreissig et al., 2001), indicating that the O-isotope signature of the fluids derived from underlying greenstone belts should be similar.

3.1. Mantle source

Speculations on the possible role of mantle fluids in metasomatism are supported by the fact that mantle fluids include brines and CO_2-rich fluids (e.g., Touret and Huizenga, 2011, 2012). Direct evidence that mantle derived mantle fluids have infiltrated the SMZ during exhumation may be provided by C-isotopic compositions of CO_2 extracted from magnesite produced by the high-temperature Ol-breakdown reaction Ol + CO_2 → Opx + Mgs. This reaction produced a second generation of porphyroblastic Opx in former unhydrated ultramafic granulite (Van Schalkwyk and Van Reenen, 1992). Four samples collected at two different localities in the zone of retrograde hydrated granulites show Mgs δ^{13} C values varying between −5.5 and −6.0‰ (Van Schalkwyk and Van Reenen, 1992). However, these values do not conclusively point to a mantle source as similar values are found in different rock types (Kerrich, 1989).

3.2. Crystallizing granitic melts

Vennemann and Smith (1992) and Stevens (1997) have suggested that water-rich fluids resulting from crystallizing granitic melts (internally buffered fluids) were responsible for the hydration of the cooling granulites under closed-system conditions to produce the zone of retrograde hydration (Fig. 1). In this model, the crystallizing fluids may become enriched in CO_2 species as a result of water-graphite interaction in an oxidized environment (Stevens, 1997), while water-rich fluids might evolve into brine fluids during hydration of the granulite (e.g., Markl and Bucher, 1998). However, direct evidence that fluids released by crystallizing granitic melt did interact with hot granulite is restricted to crystallization-hydration (back) reactions that are commonly observed features of metapelitic granulite sampled in close proximity to intrusive leucocratic veins and bodies (Van Reenen et al., 1983; Stevens and Van Reenen, 1992; Safonov et al., under review).

3.3. Devolatilization of underthrusted greenstone belts

A large published database comprising field, structural, and petrological data (Van Reenen, 1986; Van Reenen and Hollister, 1988; Van Reenen et al., 1988, 2011; De Wit et al., 1992a,b; McCourt and Van Reenen, 1992; Miyano et al., 1992; Roering et al., 1992a,b; Van Schalkwyk and Van Reenen, 1992; Perchuk et al., 1996, 2000a,b; Passeraub et al., 1999; Smit et al., 2001) supported by geochemical, isotopic (Kreissig et al., 2000, 2001) and geophysical (e.g., De Beer and Stettler, 1992 and references therein) data provide convincing evidence for a tectono-metamorphic scenario that includes the following essential elements. Firstly, the NKVC dips at shallow angles underneath the SMZ at the position of the HRSZ (Fig. 2). Second, greenstone belt material underlies the SMZ for a distance of at least 40 km north of the HRSZ (De Beer and Stettler, 1992). Third, the overriding granulite interacted thermally and dynamically with underthrusted greenstone belts at ~2.69 Ga at the position of the HRSZ (Fig. 2, 3) (e.g., Perchuk et al., 1996). Such a tectono-metamorphic scenario is expected to have resulted in the production of large volumes of fluids derived from devolatilization of underthrusted greenstone belts that infiltrated the overriding SMZ. Evidence for this process will be presented and discussed in this paper and further elaborated on in a separate paper (Smit et al., under review). The upper mantle as an additional fluid source will not be further discussed because of a lack of evidence. Safonov et al. (under review) discuss evidence for localized high-temperature fluid-rock interaction of per-aluminous metapelitic granulite with low $a_{H_2O}^{fluid}$ fluids released by crystallizing anatectic trondhjemitic melts at the Petronella locality (Fig. 1) in the SMZ.

4. Evidence for high-temperature fluid-rock interaction in the SMZ

The SMZ is subdivided into a northern granulite zone that is separated from a southern zone of retrograde hydrated granulite by the retrograde isograd (Fig. 1). Evidence that cooling granulites interacted with immiscible CO_2 and brine fluids of greatly reduced $a_{H_2O}^{fluid}$ at $T >$ 700°C within the granulite zone (without affecting Opx in metapelitic granulite) will first be discussed, followed by a discussion of pervasive retrograde metamorphism of metapelitic granulite that established the retrograde isograd at T = 600-630°C. Evidence for high-temperature melt-fluid-rock interaction will be concluded with a discussion of shear zone-hosted metasomatism including the formation of Qz vein-hosted lode gold deposits.

4.1. P-T evolution of the SMZ

The essentials of the tectono-metamorphic evolution of the SMZ that directly impact on fluid-rock interaction can be summarized with reference to relevant structural-metamorphic data (see Smit et al., under review, for a detailed discussion). *P*-*T* paths (Fig. 3) were constructed for the common Grt-Opx-Crd/Grt-Sil-Crd bearing assemblages in metapelitic rocks that outcrop throughout the granulite domain (Fig. 1) using the net-transfer reactions (1a) and (1b) and Fe-Mg cation exchange reactions (see Perchuk et al., 2000 for mineral compositions and thermodynamic data and Perchuk, 2011 for a detailed explanation of the methodology). The *P*-*T* paths show that the retrograde evolution of the SMZ can be linked to two successive stages; an early decompression-cooling (DC) stage that was uninterruptedly followed by a near-isobaric cooling (IC) stage. An important observation is that metapelitic granulite sampled in the granulite domain north of the Annaskraal shear zone (Fig. 1, DR45) only documents evidence for a two-stage DC history (Fig. 3) during which rocks that record maximum *P*-*T* conditions of ~8 kbar and ~850°C, were initially emplaced into the middle crust (P = ~6 kbar, T = ~720°C, Fig. 3). This was followed by the second DC stage that resulted in emplacement into the upper crust (Fig. 3, DR45). In contrast, similar metapelitic mineral assemblages sampled in the much larger granulite domain located south of the Annaskraal Shear Zone (Fig. 1) document evidence for a near IC stage that commenced at mid-crustal level, i.e. corresponding to the gap between successive stages of DC *P*-*T* paths (Fig. 3). Near IC *P*-*T* paths ranging from ~6 kbar and ~700°C to 5-5.5 kbar and 570-600°C (Fig. 3, DR19, DV81, DV101) were followed by decompression-cooling to upper crustal levels (Fig. 3). In this scenario, DC *P-T* paths are linked to the early exhumation stage of the SMZ that ended with emplacement into the middle crust, whereas IC *P-T* paths reflect the subsequent thrust-controlled emplacement of the SMZ onto the adjacent NKVC along a near-isobaric surface (6-5.5 kbar), i.e. the HRSZ (Fig. 2) (Smit et al., under review).

4.2. Evidence for near-peak fluid-rock interaction during granulite-facies metamorphism

Fluid inclusions and microscale metasomatic textures suggest that CO_2-rich fluids and brines interacted with hot granulite at peak and near-peak metamorphic conditions. Primary mixed brine-CO_2 fluid inclusions in Opx and in Qz inclusions in Grt, respectively in metapelitic granulite have been described by Van den Berg and Huizenga (2001) and Touret and Huizenga (2011). These inclusions indicate the coexistence of a brine fluid and pure CO_2 at the peak of metamorphism in the SMZ (Touret and Huizenga, 2011).

Further, post-peak micro-scale high-temperature fluid-rock interaction is suggested by the common presence of metasomatic perthitic Kfs micro-veins between Qz and Grt in metapelitic granulite (Touret and Huizenga, 2011). Orthopyroxene in contact with these Kfs veins does not show alteration indicating that $a_{H_2O}^{fluid}$ of the fluids responsible for these veins was low (Harlov et al., 1998; Harlov, 2012). The widely accepted interpretation is that Kfs micro-veins are due to influx of low $a_{H_2O}^{fluid}$ brines during the initial phases of post-peak metamorphic uplift (e.g., Harlov et al., 2000; Newton and Manning, 2010; Touret and Huizenga, 2012), identical to the situation described for the granulite zone of the SMZ. Thermocalc pseudosections of the Grt-Bt-Opx-Crd-Kfs-Pl-Qz in the NCKFMASH system show that $a_{H_2O}^{fluid}$ is between 0.4 and 0.5 (Koizumi et al., under review) for *P-T* conditions of 9 kbar and 900°C, respectively. This is consistent with $a_{H_2O}^{fluid}$ calculated from the Bt dehydration reaction using revised thermodynamic data (Newton et al., under review), corresponding to

$X_{H_2O}^{fluid}$ being between 0.3 and 0.4 for mixed CO_2-H_2O fluids (Aranovich and Newton, 1999). These $X_{H_2O}^{fluid}$ values relate to H_2O volume fractions between ~0.15 and ~0.25 for the highest density CO_2-rich fluid inclusions reported in the SMZ (homogenization temperature of the CO_2 phase is −30°C; Van den Berg and Huizenga, 2001). Generally, H_2O volume fractions below 0.2 are hardly visible in CO_2-rich fluid inclusions (Bakker and Diamond, 2006).

Finally, the observation that metapelitic granulite sampled south of the Annaskraal Shear Zone (Fig. 1) are characterized by near-IC *P-T* paths (Fig. 3, DR19, DV81, DV101) strongly suggests that hot rock emplaced at the middle crustal level cooled rapidly while still at a relatively high pressure. The only reasonable mechanism for rapid cooling of hot granulite at mid-crustal level and distant from the juxtaposed NKVC (Fig. 1) is the infiltration of relatively cool fluids derived from underthrusted greenstone belts that underlay much of the granulite domain south of the Annaskraal Shear Zone (Fig. 1, 2) (De Beer and Stettler, 1992; Perchuk et al., 1996, 2000a,b; Smit et al., under review). The observation that rocks north of the Annaskraal shear zone show no evidence for near-isobaric cooling *P-T* trajectories is thus in agreement with the fact that the northern granulite domain is far removed from the area that is underlain by greenstone belts (De Beer and Stettler, 1992; Smit et al., under review).

4.3. Dehydration melting versus fluid-induced melting

The most contentious issue regarding the role of fluids in the evolution of granulite facies terrains relates to fluid-present versus fluid-absent melting mechanisms that might have accompanied high-grade metamorphism (e.g., Stevens and Van Reenen, 1992; Stevens, 1997; Rigby and Droop, 2011; Touret and Huizenga, 2011; Nicoli et al., in press; Belyanin et al., in press). Evidence for anatexis in the SMZ is reflected by: (1) the presence of migmatitic gneisses comprising tonalitic Baviaanskloof gneiss as well as mafic and metapelitic granulite that characterize the entire SMZ (Du Toit et al., 1983). These migmatites are characterized by small volumes (< 10 vol.%) of leucocratic Pl-Qz (± perthite/antiperthite) bearing anatectic material that occurs as small lenticels and veins (cm scale) that enhance the high-grade gneissic fabric of the migmatitic gneisses in which they occur (Fig. 4a). (2) Concordant and discordant almost non-foliated granodioritic/trondhjemitic veins and bodies up to100 meters high and more than a kilometer wide (Fig. 4b-d). These Pl-Qz-perthite/antiperthite (±Grt±Crd±Sil±Bt±Gph) bearing bodies (Du Toit et al., 1983; Stevens and Van Reenen, 1992) intrude the Bandelierkop Formation (Fig. 4c,d) (Du Toit et al., 1983) implying that they are related to a major pulse of anatexis that post-dated the main granulite facies and deformational events.

Kreissig et al. (2001) obtained a U/Pb age (2691±7 Ma) for monazite that occurs as inclusions in plagioclase and biotite coexisting with Grt, Crd, and Opx in migmatitic granulite from the Bandelierkop locality (Fig. 4b). They interpreted this date as the age of monazite growth under granulite facies conditions reflecting the “peak” of granulite facies metamorphism in the SMZ (~2.69 Ga). The same authors also obtained a U-Pb zircon age of 2643±0.3Ma for the large (meters wide) granodioritic band exposed in the Bandelierkop locality (Fig. 4b) and interpreted this age, which is significantly younger than that of the metapelitic granulite (~2.69 Ga) which it intrudes, to indicate decompression melting during exhumation. This interpretation is supported by U-Pb data of monazite from the leucocratic part of a migmatitic granulite that occurs as a xenolith in the Matok Complex that recorded an age of 2663±4Ma (Kreissig et al., 2001). It should be noted that Stevens and van Reenen (1992) and Stevens (1997) interpreted this granodioritic band (Fig. 4b) as the product of in-situ prograde fluid-absent partial melting due to muscovite and biotite breakdown reactions (see also Nicoli et al., in press).

Evidence that Crd-bearing metapelitic granulite at Bandelierkop quarry interacted with aqueous fluids released by the crystallizing anatectic melt is plainly provided by intergrowths of fine-grained Ged and Ky (Fig. 5a) and coarser-grained Bt and Ky that replaces Crd (Van Reenen, 1983; Stevens and Van Reenen, 1992). However, Opx from the same granulite was not unaffected by this process (Fig. 5a), testifying that a low $a_{H_2O}^{fluid}$ fluid was released during crystallization (Safonov et al., under review).

Two prime examples of granodiorite/trondhjemite outcrops on Farm Kameelkuil (S23º13’36.80”; E29º49’19.34”) next to the Bandelierkop quarry and on Farm Petronella located about 25 km west-southwest of the Bandelierkop quarry (S23°20’42.43”; E29°36’42.72”) (Fig. 1). The trondhjemite (Fig. 4d) intruded into high-grade migmatitic metapelitic granulite cutting the D2 fabric. The trondhjemite on Farm Petronella contains small and large remnants of partially assimilated migmatitic metapelitic granulite (Fig. 4d) (Safonov et al., under review). Partially assimilated metapelitic material is also preserved as trails of ferro-magnesium minerals such as Bt, Grt, and Crd that mimic the foliation of the enclosing country rock (Fig. 4d). Garnet porphyroblasts within such trails are often rimmed by symplectic Crd and Opx reflecting evidence for decompression reaction (1a). This reaction was used to determine the retrograde *P-T* path (sample DR45, Fig. 3) (Perchuk et al., 2000a; Smit et al., 2001) during which the main D2 fabric developed (Smit et al., under review). Features related to the interaction of the metapelitic granulite with fluids expelled by crystallizing trondhjemitic magma are identical to those described at the Bandelierkop quarry and is the focus of a separated paper in the present volume (Safonov et al., under review). The trondhjemitic body at the Petronella locality (Fig. 4d) has recently been dated at ~2.67 Ga (Belyanin et al., under review). This age is in agreement with the emplacement of this magmatic body postdating the main ~2.69 Ga D2 fabric-forming event (Kreissig et al., 2001).

The composition (granodioritic to trondhjemitic), intrusive relationships, large volumes, and timing of the main pulse of anatexis (2.67-2.64 Ga) relative to the timing of the main D2 fabric-forming (~2.69 Ga) event at the Bandelierkop quarry and Petronella locality clearly require a mechanism of fluid-fluxed decompression melting. Safonov et al. (under review) show that the tonalitic melt at Petronella locality already intruded the host metapelitc granulite (Fig. 4d) at P > 7.5 kbar, T > 900°C and continued to interact with the host rock until final emplacement into the middle crust (P = ~6 kbar, T = ~630°C). This scenario strongly argues against the hypothesis that these large bodies might represent the products of in-situ fluid-absent partial melting of muscovite and biotite during the prograde stage of metamorphism (Stevens and Van Reenen, 1992; Stevens, 1997; Nicoli et al., in press). A more plausible scenario based on data presented here and also published as separate papers (Aranovich et al., under review; Newton et al., under review; Safonov et al., under review), is that brine-fluxed decompression melting (Sawyer et al., 2011) resulted in emplacement of granodioritic-trondjhemitic magma into rocks of the Bandelierkop Formation during exhumation. Aranovich et al. (under review) in particular argue that the dehydration-melting model of granite genesis has numerous issues: (1) Heat sources for melting large amounts of the lower crust are often inadequate; (2) H_2O available in mica and amphibole for lower crust dehydration melting is restricted; (3) Depletion of large-ion lithophile elements in granulites cannot be explaned by dehydration melting. Furthermore, recently obtained O-isotope fractionation data show that the leucocratic band and host granulite exposed at the Bandelierkop locality (Fig. 4b) are not isotopically related to each other and, therefore, excludes the host metapelitic granulite as a source for these veins (Dubinina et al., under review).

Three important issues related to the above scenario should be highlighted. Firstly, fluids expelled by crystallizing melts at both the Bandelierkop and Petronella localities reacted with Crd (Fig. 5a) to form Ged and Ky. Orthopyroxene was not affected, which implies that a low $a_{H_2O}^{fluid}$ fluid was involved. Secondly, Ky and not Sil (Van Reenen, 1983; 1986; Safonov et al., under review; Koizumi et al., under review) was produced by Crd hydration (Fig. 5a). This indicates that anatexis and the associated crystallization-hydration of Crd could not be related to fluid-absent dehydration melting at peak metamorphic conditions as suggested by several authors (Stevens and Van Reenen, 1992; Stevens, 1997; Nicoli et al., in press). In that case one would expect a relatively high temperature and, therefore, Sil to be formed rather than Ky. Finally, Crd hydration at Bandelierkop and Petronella localities (Fig. 5a) (Safonov et al., under review) are identical to the observed hydration reactions involving Crd north and on the retrograde isograd (Fig. 5b), and occurred at similar *P-T* conditions (~6 kbar, 600-630°C, see next section). This suggests that distinct hydration phenomena linked to the establishment of the retrograde isograd (next section) and the crystallizing granitic melts in the granulite zone were triggered by similar low $a_{H_2O}^{fluid}$ fluids. Moreover, this also explains the observation that O-isotope fractionation data often fail to identify the presence of an externally derived fluid that interacted with the granulites (Vennemann and Smith, 1992; Hoernes and Van Reenen, 1992; Hoernes et al., 1995), because this fluid was produced as a result of devolatilization of underthrusted greenstone material, which is identical to the precursor material of the granulite facies rocks in the SMZ (Kreissig et al., 2000; Van den Berg and Huizenga, 2001).

4.4. Pervasive fluid-flow: the regional retrograde isograd

4.4.1. The retrograde isograd

An unusual but significant feature of the SMZ is that clear evidence for regional fluid flow is primarily based on retrograde reactions that occurred at relatively high temperatures and affected all rock types of the Bandelierkop formation as well as the Baviaanskloof enderbitic gneiss (e.g., Van Reenen et al., 1983, 2011; Van Reenen, 1986). The infiltrating fluid rehydrated large areas of the SMZ (> 4500 km^2), leaving a sharp demarcation between unhydrated Opx-Crd-bearing metapelitic granulite in the north (Fig. 6a,b) and hydrated (Opx-Crd-absent, Ath±Ged±Ky/Sil-bearing gneisses) in the south (Fig. 6c,d) (Fig. 1). This demarcation is defined by the retrograde isograd that cuts major folds and lithologies in the central part of the SMZ (Fig. 1) (Van Reenen, 1986), implying that granulite-facies metamorphism was overprinted by amphibolite-facies metamorphism.

Petrographic evidence for regional (pervasive) hydration during cooling is reflected in metapelitic granulite by two major retrograde hydration reactions involving Opx-Crd-bearing granulite (Fig. 6c,d) (Van Reenen, 1986; Huizenga et al., 2014):

$$5\ Crd + 2\ H_2O \rightarrow 2\ Ged + 6\ Al_2SiO_5 + 7\ Qz \qquad (2)$$

$$3.5\ Opx + Qz + H_2O \rightarrow Ath \qquad (3)$$

Reaction (2) is not an accurate reflection of the hydration of Crd since Ged does contain up to 2 wt.% Na_2O. This suggests that either a Na-bearing aqueous fluid (Huizenga et al., 2014) or plagioclase was involved in the reaction. Crd hydration goes hand-in-hand with production of fine-grained euhedral Grt associated with Ky and Bt. Formation of this assemblage is probably related to the following reaction (Huizenga et al., 2014):

$$3\ Ged + 2\ K_2O\ \text{(in fluid phase)} + H_2O \rightarrow Grt + 4\ Bt + 3\ Al_2SiO_5 \qquad (4)$$

Reaction (3) defines the retrograde isograd, which can be uninterruptedly mapped from west to east across the entire SMZ (Fig. 1). This reaction resulted in the coexistence of Opx and Ath (Fig. 6c) over a narrow (hundreds of meters) interval in the field (Van Reenen, 1986; Van Reenen et al., 2011) that follows the trend of the HRSZ (Fig. 1). This implies a direct link of pervasive fluid flux with the thrust-controlled exhumation of the SMZ (Fig. 2) (Van Reenen and Hollister, 1988; Van Reenen et al., 2011; Smit et al., under review). Finally, it is important to note that graphite is commonly associated with the products of the reactions (2), (3), and (4) (Van Reenen, 1986; Stevens, 1997).

4.4.2. Regional metamorphic control on fluid influx

The retrograde isograd has been interpreted to reflect evidence for relatively high-temperature interaction of cooling granulite with an externally derived mobile low $a_{H_2O}^{fluid}$ fluid that infiltrated the overriding high-grade rocks during the thrust controlled exhumation of the SMZ (Fig. 2). Evidence in support of this is outlined below.

Orthopyroxene and Ath coexist in metapelitic gneiss along a restricted metamorphic interval (Fig. 1) that separates a granulite zone in the north showing no evidence for Opx hydration (Fig. 6a,b), from a zone of retrograde hydrated granulite in the south where Opx and Crd have been completely replaced by Ath, and Ged and Ky, respectively, as a result of hydration reactions (2) and (3) (Fig. 6c,d) (Van Reenen et al., 1977, 1983, 1986). This observation suggests that hydration reaction (3) should be univariant in the subsystem (Mg,Fe)O_2-SiO_2-H_2O, which is confirmed by the fact that coexisting Opx and Ath have a similar Mg/(Mg+Fe) mole ratio between 0.6-0.7 (Van Reenen, 1986). Moreover, the univariant nature of hydration reaction (3) requires the presence of a free fluid phase that was externally buffered (Van Reenen, 1986). In contrast, the Crd hydration reaction (3) is divariant in the sub-system MgO-FeO-SiO_2-Al_2O_3-H_2O as is shown by contrasting Mg/(Mg+Fe) mole ratios of Crd and Ged (Van Reenen, 1986). Consequently, coexisting reactants and products of reaction (2) straddle the retrograde isograd over a larger surface area in the field. The fact that the retrograde isograd was established as the result of the emplacement of hot granulite over cool greenschist and is superimposed onto major fold structures in the area (Fig. 1) implies a scenario in which regional hydration was controlled by infiltration of a mobile H_2O-bearing fluid (Van Reenen, 1986). If this were not the case, reaction (3) would have been divariant; a scenario that would have resulted in the irregular dispersal of retrograde hydrated granulite closely associated with unhydrated rocks. Systematic variations in the composition of coexisting Grt (Fig. 7a) and Bt (Fig. 7b) in metapelitic granulite compared with their hydrated equivalents indicates that hydration occurred at (near) equilibrium conditions.

Mafic and ultramafic gneisses in the hydration zone sometimes still contain partially hydrated high-grade minerals (Van Schalkwyk and Van Reenen, 1992), expressed by relict Cpx and/or Opx, which are being replaced by Hbl and/or Mgs, respectively. The peak assemblage of Fo, Opx, Spl and pargasitic Hbl in ultramafic granulite is replaced by hydrous (Hbl, Chl and Tlc) and carbonate (Mgs, Dol) minerals. This provides conclusive evidence that ultramafic rocks interacted with externally derived CO_2-rich fluid (Van Schalkwyk and Van Reenen, 1992). Moreover, the occurrence of Opx and Cpx relicts in partially hydrated mafic and ultramafic granulite in the hydrated zone of the SMZ (Van Reenen, 1986; De Wit et al., 1992c; Van Reenen et al., 2011) attests to the fact that the granulite occupied the entire SMZ before retrograde hydration occurred (Fig. 1). The general cooling trend is reflected in the Ca-amphibole compositions of the ultramafic rocks (Fig. 7c) (Van Schalkwyk and Van Reenen, 1992).

4.4.3. P-T constraints and fluid composition

Garnet-biotite thermometry, using the calibration by Kaneko and Miyano (2004, 2006), of samples on the retrograde isograd (using mineral analyses from Van Reenen, 1986) gave a temperature range of 600-630°C (*P* = ~6 kbar) for the breakdown of Opx to Ath (Huizenga et al., 2014). Chemically similar rocks in the zone of hydration (using mineral analyses from Van Reenen, 1986) show slightly lower Grt-Bt temperatures that remain relatively constant at 600-550°C (Huizenga et al., 2014). Pressure conditions on the retrograde isograd are constrained to ~6 kbar as Crd hydration on the isograd produced Ky rather than Sil (Van Reenen, 1986; Koizumi et al., under review). However, Sil has been identified as a stable phase in some rocks in the hydrated zone (Van Reenen, 1986). These *P-T* conditions have been established by numerous other studies (Van Reenen, 1986; Baker et al., 1992; Hoernes et al., 1992; Huizenga et al., 2014; Koizumi et al., under review; Dubinina et al., under review). This suggests that Opx hydration occurred at temperatures more than 200°C lower than the temperature (*T* = ~830°C at *P* = ~6 kbar, Fig. 8a) at which En and Ath coexist in presence of a pure H_2O fluid phase (e.g., Newton, 1994; Van Reenen, 1986). A lowering of this equilibrium temperature to 600-630°C is only possible if the hydrating fluid has a $a_{H_2O}^{fluid}$ of 0.2 (Van Reenen, 1986; Van Reenen and Hollister, 1988; Huizenga et al., 2014; Koizumi et al., under review). However, it should be noted that the $a_{H_2O}^{fluid}$ value of 0.2 represents a minimum value as Opx and Ath have Mg/(Mg+Fe) mole ratio’s between 0.6 and 0.7 (Huizenga et al., 2014). Based on the association of graphite with the hydration reactions (2), (3), and (4) (e.g., Huizenga et al., 2014) and other evidence presented below, it can concluded that the low $a_{H_2O}^{fluid}$ fluid phase relates to a CO_2-rich fluid, of which $X_{H_2O}^{fluid}$ ranges between 0.1 and 0.3.

Support for a low $a_{H_2O}^{fluid}$ CO_2-rich fluid is, in addition to the presence of graphite, also provided by the partial hydration/ carbonation of ultramafic granulites where the Ol-Ca-Hbl-Opx-Spl peak assemblage has been replaced by a retrograde Ol-Hbl-Opx-Spl-Mgs-Dol-Chl-Tlc assemblage (Fig. 8b) (Van Schalkwyk and Van Reenen, 1992). Of special significance is the replacement of Ol (Van Schalkwyk and Van Reenen, 1992) by Mgs according to the reaction Ol + CO_2 → Opx + Mgs, providing evidence that granulite interacted with an externally derived CO_2-rich fluid (Van Schalkwyk and Van Reenen, 1992). The hydrated/carbonated ultramafic assemblage shows that the granoblastic ultramafic rocks were infiltrated at T = 610-640°C at P = 4-5 kbar by an externally derived CO_2-rich fluid of which $X_{H_2O}^{fluid}$ = ~0.3 (Fig. 8b). Note that the pressure should be lower than 6 kbar considering that Sil (produced by Crd hydration) does occur south of the isograd (Van Reenen, 1986).

Further evidence for a CO_2-rich fluid is given by fluid inclusion data. Hydrated granulites show dominantly trail bound inclusions composed of (nearly) pure CO_2 (Van Reenen and Hollister, 1988; Touret and Huizenga, 2011; Huizenga et al., 2014). Although H_2O is not visible in the CO_2 inclusions, it has in a few cases been detected by clathrate melting (Van Reenen and Hollister, 1988). This implies that inclusions can contain up to 20 vol. % H_2O (corresponding to a maximum $X_{H_2O}^{fluid}$ of 0.3), which is optically undetectable in the inclusions (e.g., Bakker and Diamond, 2006). Considering the P-T conditions of retrograde hydration, CO_2-rich fluid inclusions should have homogenization temperatures (Th) between −20 and −10°C (Huizenga et al., 2014). However, the lowest Th that has been found for these inclusions is +10°C. The absence of high-density CO_2-rich fluid inclusions could be explained by re-equilibration during decompression-cooling. However, in that case one would expect a small fraction of the inclusions to maintain their original density (Vityk and Bodnar, 1995; Van den Kerkhof et al., 2014), which is not the case here. Therefore, it is plausible that trapping of the fluid occurred at a pressure between the lithostatic and hydrostatic pressure (Huizenga et al., 2014). Fluid pressures below lithostatic pressures are likely to occur in strike slip shear zones that are present in the hydrated portion of the SMZ (Fig. 1) (Roering et al., 1995). In addition, volume changes associated with hydration reactions (2), (3) and (4) may cause an increase of the rock permeability and, therefore, result in a fluid pressure lower than the lithostatic pressure (Huizenga et al., 2014).

Summarizing, retrograde hydration of granulites occurred at $P \leq 6$ kbar and $T \leq 600$-630°C by means of an infiltrating fluid CO_2-rich fluid ($0.1 < X_{H_2O}^{fluid} < 0.3$). This is based on (1) volatilization reactions in metapelitic and ultramafic granulites; (2) the presence of graphite in hydrated metapelitic granulites, and (3) the presence of CO_2-rich fluid inclusions.

4.4.4. Open versus closed system behavior during pervasive hydration

Whole-rock/mineral O-isotope fractionation patterns (Vennemann and Smith, 1992; Hoernes and Van Reenen, 1992; Hoernes et al., 1995) showed that whereas closed system conditions prevailed in some cases (Fig. 9a), many metapelitic and mafic granulite provided clear evidence for influx of an external fluid and thus open system behavior during pervasive hydration (Fig. 9b,c) (Hoernes et al., 1995). This is demonstrated by whole-rock mineral fractionation patterns for Opx-bearing metapelitic and mafic granulite that show evidence for influx of an externally derived fluid at T = ~635-670°C (Fig. 9a,b). The temperature of 1230°C calculated from whole-rock/Opx O-isotope fractionation (Fig. 9b) for the same sample is obviously too high, indicating that closed system behavior is not realistic. The absence of Ath, Ged and Ky from this Opx-Crd-bearing metapelitic granulite implies that hydration started at T < 670°C, i.e. Crd and Opx hydration only occurred when the temperature was low enough (Van Reenen, 1986). Moreover, the temperature of 635°C derived from whole-rock/Ath/Qz O-isotope fractionation (Fig. 9b) is in good agreement with temperature conditions of hydration on the retrograde isograd based on Grt-Bt geothermometry (Van Reenen, 1986; Huizenga et al., 2014).

Hoernes and Van Reenen (1992) showed, on the basis of whole-rock/mineral O-isotope data, that the amount of infiltrating fluid necessary to hydrate dry granulite is very small. However, it should be kept in mind that the greenstone belt material in the footwall of the HRSZ is chemically identical to their high-grade equivalents in the SMZ (Kreissig et al., 2001). Fluids derived from the devolitilization of footwall greenstone belts may, therefore, not significantly change the granulite whole-rock/mineral O-isotope system upon infiltration. On the other hand, shear zone-hosted metasomatism in the zone of retrograde hydrated granulite demonstrates isotopic re-equilibration due to focused fluid flow reflecting large fluid-rock ratios (Fig. 9c) (Hoernes et al., 1995).

4.4.5. Narrowing of the zone of retrograde hydrated granulite in the western part of the SMZ

The dramatic narrowing of the hydration zone in the western part of the SMZ compared with the central part (Fig. 1) is mainly explained by the fact that: (1) the NE-directed dip of the HRSZ changes from near-horizontal in the central part of the SMZ to ~20° in the western part. This change in dip explains the vast exposure of sheared retrograde hydrated gneisses that occur in the hanging wall of the near horizontally north-dipping HRSZ in the central part of the SMZ (Fig. 1, 2). In the area west of the Matok granite (Fig. 1) a much narrower zone of sheared and retrogressed granulite occupies the hanging wall of the much steeper dipping section of the HRSZ (see Smit et al., under review, for a more detailed discussion).

4.5. High-temperature metasomatism

4.5.1. Introduction

The SMZ offers the opportunity to study high-temperature shear zone-hosted metasomatism. This process includes transformation of (1) dark grey homogenous metamorphic enderbite and banded migmatitic enderbitic gneiss (Baviaanskloof gneiss) into pink Grt-bearing potassium-enriched granite in the granulite zone, (2) banded and retrogressed migmatitic tonalitic gneiss into potassium-enriched granite in the zone of hydrated granulite, and (3) high-temperature shear zone-hosted lode-gold mineralization located both in the footwall and hanging wall sections of the HRSZ. Detailed case studies of shear zone-hosted metasomatic phenomena are the focus of separate papers (Dubinina and Aranovich, under review; Tsunogae and Van Reenen, under review).

4.5.2. Shear zone-hosted metasomatic transformation of enderbitic gneiss

Excellent continuous outcrops of metasomatically altered and unaltered enderbitic Baviaanskloof gneiss occur within the Petronella Shear Zone on Farms Petronella (Fig. 10a-c) and Commissiedraai (Fig. 10d,e), both located in the granulite zone (Fig. 1). The Petronella locality comprises metapelitic, mafic, and ultramafic granulite, and large volumes of leucocratic anatectic granitoid (Fig. 5d). The locality also provides evidence for numerous local Opx-Pl-Qz-bearing dehydration zones (veins and small bodies) developed within metasomatically altered and unaltered enderbitic gneiss (Fig. 10a) and mafic granulite (Du Toit et al., 1994). Moreover, evidence for hydraulic fracturing under granulite facies conditions is documented by the presence of numerous narrow enderbitic sills that are oriented nearly perpendicular to the principal load (Fig. 10b), and by the presence of granulite-facies breccia (Roering et al., 1995). Roering et al. (1995) interpreted these features as evidence for "deep crustal embrittlement" that resulted from hydro fracturing associated with fluid/melts that infiltrated deep crustal rocks under granulite facies conditions.

Grey enderbitic Baviaanskloof gneiss is uninterruptedly altered into a pink metasomatic potassium-enriched granitoid that outcrops continuously over a distance of more than 100 meters in the dry riverbed. The alteration process is easily recognized by the change in color from the unaltered dark grey enderbitic gneiss (Fig. 10a,b) into a pink granitoid characterized by growth of small grains of optically unzoned Mn-rich Grt(~$Alm_{54}Prp_{27}Sps_{15}Gr_4$) (Fig. 10c). Orthopyroxene is preserved in the pink gneiss and seems not to be affected by the alteration process. The metasomatic alteration process involves infiltrating fluids transforming oligoclase in precursor enderbitic gneiss into homogenous ternary K-rich feldspar at temperatures above the ternary feldspar solvus ($T >$ ~680°C) (Du Toit, 1995). The relatively high temperature of metasomatism is confirmed by Grt-Qz O-isotope fractionation indicating a temperature between 710 and 850°C (Hoernes et al., 1995). Depending on the degree of fluid infiltration, cooling of the homogenous ternary feldspar resulted in antiperthite, mesoperthite or perthite, while microcline is completely absent. Antiperthite typically occurs in the less altered rocks while the more altered rocks are characterized by mesoperthite and perthite (Du Toit, 1995). The isocon diagram (Grant, 1986) shows that metasomatism is accompanied by an increase of K_2O and, to a lesser extent, Na_2O, and a decrease in MgO, FeO, CaO, and TiO_2 (Fig. 11) whereas SiO_2 and Al_2O_3 were immobile (Du Toit, 1994; Smit and Van Reenen, 1997). The alteration process was triggered by a low $a_{\mathrm{H_2O}}^{\mathrm{fluid}}$ Na-K bearing brine fluid that infiltrated the rock under near-granulite facies conditions to produce a homogenous ternary K-rich feldspar that subsequently exsolved during cooling to produce antiperthite in the less altered, and mesoperthite in the most altered rocks (Du Toit, 1994; Smit and Van Reenen, 1997). The low $a_{H_2O}^{fluid}$ of the metasomatic fluid in the Petronella Shear Zone is supported by the observation that Opx remained stable in narrow metapelitic zones that occur interlayered within metasomatic potassium-enriched granitoid (Du Toit, 1994). Also, the numerous small and near-horizontal oriented Opx-bearing enderbite sills (Fig. 10b) and Opx-Pl-Qz-bearing dehydration zones that occur within the altered rocks show no evidence for interaction with a fluid phase.

The Commissiedraai locality shows some differences with the Petronella locality. The precursor enderbite at Commissiedraai is a dark-grey homogenous metamorphic rock (Fig. 10d) without any leucocratic veins in contrast to Petronella. Ghost gneissic structures of are preserved within the enderbite and can be traced uninterruptedly into the pink granitoid. Further, alteration is, similar to the Petronella locality, typically characterized by Mn-Grt (~$Alm_{75}Prp_{15}Sps_{9}Gr_{1}$) bearing granitoid and narrow foliation zones comprising Sil and Qz (Fig. 10e) whereas microcline is absent (Tsunogae and Van Reenen, under review). Intrusive leucocratic anatectic bodies are absent.

Phase equilibrium modeling in the system NCKFMASH using Thermocalc suggested that metasomatic alteration at this locality occurred at ~900°C, which corresponds to post-peak metamorphic conditions reached during the initial stage of exhumation in the SMZ (Tsunogae and Van Reenen, under review).

4.5.3. Shear zone-hosted metasomatic transformation of hydrated tonalitic gneiss

Intense metasomatism of Baviaanskloof gneiss within the retrograde hydrated portion of the SMZ is associated with the D2 Klipbank Shear Zone (locality 3 in Fig. 1). Excellent outcrops in the abandoned dimension stone Klipbank quarry offer the opportunity to study the continuous transformation of precursor retrograde hydrated tonalitic gneiss comprising mainly oligoclase, Bt, Qz and small amounts of Kfs, into intensely altered pink Mn-rich Grt-Sil-bearing potassium-enriched granitoid (Mokgatlha, 1995; Smit and Van Reenen, 1997).

Potassium metasomatism is characterized by interstitial growth of fine-grained crosshatched microcline at the expense of oligoclase in slightly altered grey-pink gneiss, and by growth of coarse crosshatched microcline replacing oligoclase in most altered pink gneiss. Interstitial microcline in the least altered grey-pink gneiss reflects limited fluid migration along grain boundaries, whereas replacement microcline perthite in the intensely altered pink gneiss suggests the action of a more pervasive K-bearing fluid (Mokgatlha, 1995). Mn-rich Alm-Grt (~$Alm_{63}Prp_{13}Sps_{24}$) in the highly altered pink gneiss occurs as large zoned porphyroblasts with dark cores due to numerous inclusions mainly of Mag and Ilm. A second generation of small idioblastic Grt crystallized during the retrograde growth stage (Mokgatlha, 1995). Similar to Petronella, metasomatism results in an increase of K_2O and Na_2O, and a decrease of MgO, FeO, CaO and TiO_2 whereas SiO_2 and Al_2O_3 remained unchanged (Mokgatlha, 1995). The composition of plagioclase varies from ~An_{20} in the unaltered rocks to ~An_8 in the most altered rocks (Mokgatlha, 1995).

Sillimanite needles in the intensely metasomatized rock are associated with rod-shaped Qz in discrete (mm-wide) shear planes that are oriented parallel to but at high angles relative to the steeply oriented gneissic foliation. Sillimanite needles and Qz rods define a stretching mineral lineation that suggests southwards movement during metasomatism (Smit and Van Reenen, 1997), suggesting a direct link between metasomatism and thrust-controlled exhumation of the SMZ.

Complete re-equilibration of intensely altered rocks as the result of interaction with an externally derived fluid is revealed by whole-rock mineral O-isotope fractionation data (Hoernes et al., 1995). The whole-rock/mineral O-isotope fractionation for a metasomatic gneiss from the Klipbank Shear Zone shows that all mineral phases, including Mn-rich Grt, plot reasonably close to a straight line, corresponding to O-isotope equilibration at T = ~630°C (Fig. 9c, sample KK15, locality 3 in Fig. 1). This temperature is similar to that of the Opx hydration on the isograd, suggesting a direct link with the regional hydration event. Whereas pervasive regional hydration was probably controlled by low CO_2-rich fluid-rock ratios, shear zone-hosted metasomatism was most likely controlled by a high brine fluid-rock ratio at similar temperature conditions (Huizenga et al., 2014).

Summarizing, metasomatism at Klipbank and Petronella involved similar precursor enderbitic/tonalitic gneisses that were transformed into pink Mn-Grt-bearing potassium-enriched granitoid by infiltrating brine fluids. Metasomatic rocks in the Klipbank Shear Zone are characterized by microcline in contrast to those in the Petronella Shear Zone, which show antiperthite, mesoperthite, and perthite. This difference is due to a different temperature of metasomatism: > 710°C along the Petronella Shear Zone and ~630°C along the Klipbank Shear Zone (Mokgathla, 1994; Du Toit, 1995; Hoernes et al., 1995; Smit and Van Reenen, 1997). Unfortunately, previous studies have mainly focused on the CO_2 rich inclusions in metasomatic rocks in both the Petronella and Klipbank Shear Zones, i.e. a systematic study to identify brine fluid inclusions was not done and will be the subject of a separate study.

4.5.4. Shear zone-hosted lode gold mineralization

Shear zone-hosted lode gold mineralization has been studied at four localities in the footwall (Giyani greenstone belt in NKVC) (Fig. 1, Birthday, Fumani, Klein Letaba, Frankie), and three localities in the hanging wall (SMZ) (Fig. 1, New Union/Osprey, Louis Moore, Doornhoek) of the HRSZ (Pretorius et al., 1988; Sieber et al., 1991; Van Reenen et al., 1994; Gan and Van Reenen, 1995a,b; Stefan, 1997). The syntectonic ore bodies are located within east west-trending, steeply northward-dipping ductile satellite shear zones of the HRSZ with an oblique to reverse southwest vergence (McCourt and Van Reenen, 1992; Van Reenen et al., 1994). The minimum age obtained from Rb/Sr dating of Ms in pegmatite that intrudes the mineralized shear zones at varies localities is ~2.65 Ga (Barton and Van Reenen, 1992). The HRSZ is the first-order control of gold mineralization; more than 90% of known gold deposits in the Giyani greenstone belt (Fig. 1) are situated close to the contact with the HRSZ. The geological characteristics of gold mineralization at these different localities (Table 1) are summarized below.

The ore bodies are located within altered mafic (Birthday, Klein Letaba), ultramafic (Louis Moore), and BIF (Fumani, Frankie, Osprey, Doornhoek). Gold occurs either as free milling (inclusions in silicates, e.g. Birthday, Louis Moore) or closely associated with sulphides in syntectonic Qz veins (Table 1).

Au mineralizing fluids infiltrated wall-rock at lower- to upper amphibolite facies *P-T* conditions as is indicated by the associated wall-rock alteration (Table 1). Wall-rocks at all deposits are typically enriched in CO_2, K_2O, and S, resulting in extensive Bt and carbonate alteration, which is common to many Archean lode-gold deposits (Table 1) (e.g., Groves et al., 2003). Sulphide mineralization (Apy, Po and Lo) is similar for all deposits despite major differences in wall-rock lithology (Table 1).

Structural and metamorphic/metasomatic features that characterize gold mineralization in both the footwall and hanging wall sections of the HRSZ are similar to those of the unmineralized metasomatism in the Klipbank and Petronella Shear Zones. This implies a direct link between the thrust-controlled exhumation of the SMZ in the interval 2.69-2.62 Ga and fluids involved in (1) lode-gold mineralization in both the footwall and hanging wall of the HRSZ, (2) metasomatism in the unmineralized Klipbank and Petronella Shear Zones, and (3) the establishment of the retrograde isograd and associated zone of retrograde hydrated granulite (Van Reenen et al., 1994).

Syntectonic gold-bearing Qz veins in all gold deposits typically comprise CO_2-rich (H_2O is not visible, i.e. $X_{H_2O}^{fluid} < 0.2$) and aqueous fluid inclusions of varying salinities, respectively. These inclusions are similar to those documented for granulite and their retrograde hydrated equivalents (Van Reenen and Hollister, 1988; Van Reenen et al., 1994; Van den Berg and Huizenga, 2001), and for the metasomatic enderbitic gneiss at Petronella and Commissiedraai (Du Toit, 1994; Huizenga et al., 2014), and the tonalitic gneiss at Klipbank (Mokgatlha, 1995; Huizenga et al., 2014).

Summarising, with the present tectono-metamorphic SMZ model in mind, it is likely Au was dissolved from the underlying greenstone belts in brine fluids during prograde metamorphism. The Au-bearing fluid was subsequently focused into the HRSZ and its satellite shear zones. Gold mineralization in the hanging wall of the HRSZ (i.e., retrograde hydrated part of the SMZ: Louis Moore, Osprey/New Union, see Fig. 1) occurred during the regional hydration event. Densities of CO_2-rich inclusions at these localities are relatively low (Th > −5°C) (Fig. 12a,b). On the other hand, gold mineralization occurred at peak metamorphic conditions in the HRSZ footwall (Birthday, Fumani, Klein Letaba). Densities of CO_2-rich fluid inclusions at these localities are significantly higher (Th as low as −20°C have been recorded) (Fig. 12c-e).

5. Time constraints on fluid infiltration

Kreissig et al. (2001) dated the onset of exhumation of the SMZ at ~2.69 Ga based on U/Pb monazite data acquired from Grt-Opx-Crd-bearing granulite sampled at the Bandelierkop quarry locality in the SMZ (Fig. 1). In contrast, the peak metamorphic event linked to burial in the root zone of the orogeny has been dated at ~2.72 Ga (Retief et al., 1990; Rajesh et al., 2014). SMZ granulites rarely retains evidence for peak metamorphic conditions being reached in the root zone of the orogeny at ~2.72 Ga due to the effect of the superimposed decompression-cooling event (Tsunogae et al., 2004; Belyanin et al., 2012). Therefore, the upper time limit for fluid-flux is constrained by the early stage of exhumation that commenced at ~2.69 Ga, which is supported by the timing (2.68-2.69 Ga) of initial thrusting along the HRSZ (Kreissig et al., 2001; Perchuk et al., 1996, 2000b). The maximum age for the infiltrating fluid is confirmed by the emplacement age of the ~2.68 Ga Matok granitic complex that intrudes the Matok Shear Zone (Laurent et al., 2013) (Fig. 1). Fluid inclusions (Touret and Huizenga, 2011) and whole-rock/mineral O-isotope data (Fig. 4a) (Hoernes et al., 1995) support a scenario in which rocks at granulite grade already interacted with low $a_{H_2O}^{fluid}$ fluids (CO_2-rich and brine fluid) at $T > 800°C$. The lower time limit for fluid infiltration at $T = 600-630°C$, $P = \sim 6$ kbar is constraint by different data. Rb/Sr age data obtained from Ms constrain the time of emplacement of Ms-bearing pegmatite, which intrudes gold-mineralized shear zones at numerous localities along the HRSZ at ~2.65 Ga (Barton and Van Reenen, 1992). On the other hand, Ar^{39}/Ar^{40} age data (2.62-2.63 Ga) (Kreissig et al., 2001) obtained from syn-tectonic Hbl developed in sheared Baviaanskloof gneiss as the result of near isobaric out-of-sequence thrusting associated with the HRSZ, shows that hydration mainly occurred during emplacement of the SMZ onto the Kaapvaal Craton (Van Reenen et al., 2011; Smit et al., under review). Moreover, Belyanin et al. (under review) present new Ar-Ar age data that provide evidence for an extended period of hydration that affected the SMZ during and after its emplacement onto the NKVC.

6. Discussions and conclusions

Evidence that high-temperature immiscible low $a_{H_2O}^{fluid}$ immiscible CO_2-rich and brine fluids interacted with cooling granulite during the thrust-controlled emplacement of the SMZ of the LC onto the granite-greenstone terrain of the NKVC is sustained by a large dataset. This dataset includes geological-, petrological-, fluid inclusion-, geochemical-, geochronological-, geophysical-, and stable O isotope data.

Evidence for pervasive infiltration of high-temperature CO_2-rich fluids is revealed by a regional retrograde (Opx-out/Anth-in) isograd that cuts across major folds and different lithologies. This clearly shows that granulite facies metamorphism in the SMZ was overprinted by a regional amphibolite facies event at P = ~6 kbar, T = 600-630°C. Pervasive retrogression established ~4500 km^2 of retrograde hydrated crust that is located in the hanging wall section of the shallow north-dipping shear zone (the HRSZ) that bounds the SMZ in the south. Emplacement of hot granulite over cool granite-greenstone material resulted in devolatilization of the underthrusted material that caused large volumes of CO_2-rich and brine fluids to infiltrate hot overriding granulite. This proposed fluid source is strongly supported by geophysical data showing that greenstone belt material at depth presently underlies more than 60% of the SMZ surface area (De Beer and Stettler, 1992; Smit et al., under review).

The low $a_{H_2O}^{fluid}$ fluids interacted with rocks in the SMZ at temperature conditions that varied between ~600. and ~900°C. This is indicated by: (1) High-temperature metasomatic Kfs micro-veins between Grt and Qz in metapelitic Opx-bearing rocks in the granulite zone; (2) Mixed brine-CO_2 fluid in Opx and in Qz blebs in Grt in metapelitic granulite; (3) Whole-rock/mineral O-istope fractionation data indicate that granulite interacted with a fluid phase at T > 800-870°C; (4) Brine-fluxed partial melting at T > 900°C, P > 7.5-9 kbar, and (5) Shear zone-hosted metasomatism of quartzo-feldspathic gneiss that occurred at temperatures that ranged from > 710 up to 900°C in the granulite zone to ~600°C within the zone of retrograde hydrated granulite.

The relatively low densities of the CO_2-rich fluid inclusions in the retrograde hydrated part of the SMZ suggest that the fluid pressure was below the lithostatic pressure. This can be expected in the SMZ because (Huizenga et al., 2014) it comprises relatively high density of strike slip shear zones, which are characterized by fluid pressures below the lithostatic pressure (e.g., Roering et al., 1995). Further, an increase of rock permeability is also expected due to volume changes associated with the hydration reactions (Huizenga et al., 2014).

The main pulse of anatexis resulted in final emplacement of large bodies of anatectic material of granodioritic-trondhjemitic composition at the mid-crustal level into the high-grade gneissic D2 fabric of already migmatitized granulite. This process is explained by a mechanism of brine-induced decompression melting during exhumation. Fluids released by crystalizing granitic melt at mid-crustal level in the granulite zone resulted in hydration reactions involving Crd, Ky, and Ged in the host metapelitic granulite that are identical to regional hydration reactions observed at the retrograde isograd. Finally, near-isobaric cooling reflected by *P-T* paths that commenced at the mid-crustal level during the thrust-controlled emplacement of granulite onto the NKVC, is best explained by the cooling effect of infiltrating fluids.

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FIGURE CAPTIONS

Figure 1

Geological map of the SMZ/NKVC contact area that highlights major features: (1) the shallow southwest-verging terrain-bounding HRSZ and related southwest-verging high-grade shear zones within the SMZ; (2) opposing tectonic transport directions of rocks at ~2.72 Ga within the NKVC and at ~2.69 Ga within the SMZ (grey and white arrow, respectively); (3) the position of the retrograde isograd that subdivides the SMZ into a northern granulite zone and southern zone of retrograde hydrated granulite located in the hanging wall section of the HRSZ; (4) ~2.68 Ga granitoid intrusives (Matok) in both the SMZ and NKVC. Localities referred to in the text: 1-Bandelierkop Quarry, 2-Petronella and Commissiedraai locality (Petronella Shear Zone), 3-Klipbank locality (Klipbank Shear Zone), 4-Sample locality DR45, 5- Sample locality DV81, 6- Sample locality DR19, 7- Sample locality DV101, 8- Sample locality DV400, 9- Sample locality DR191. Gold deposit localities: a-Birthday, b-Fumani, c-Klein Letaba and Frankie, d-Louis Moore, e-New Union/Osprey, f-Doornhoek. SZ: shear zone; GB: greenstone belt.

Figure 2

Schematic crustal section (see Fig. 1 for cross section locality) demonstrating the relationship of the SMZ with the underthrusted granite-greenstone terrain of the NKVC (modified after Roering et al., 1992a, Smit et al., under review). Lines with solid arrow heads indicate general movement of crustal segments in the SMZ as represented by samples DR45 and DR 19 (see Fig. 3). HRSZ: Hout River Shear Zone.

Figure 3

(a) *P-T-t* diagram demonstrating the dynamic and thermal interaction of underthrusted greenschist (black dotted arrow) with overriding granulite. Indicated are the prograde, peak and initial retrograde *P-T* loop (grey dotted arrrow) (Belyanin et al., 2012; Belyanin et al., in press), and the composite retrograde *P-T* paths (solid black arrow). (b) Detailed retrograde *P-T* paths (samples DR19, DR45, DV81 and DV101, see Fig. 1 for sample localities) for the SMZ and *P-T* loop for underthrusted greenschists (Giyani Greenstone Belt) (Perchuk et al., 2000a). DR45 indicates a DC path reflected by reaction (1a). DR19, DV81, and DV101 record an intervening IC, reflected by reaction (1b) between early and final DC paths. Geochronological data after Retief et al. (1990), Kreissig et al. (2001) and Belyanin et al. (under review). The subdivision of the granulite facies into different *P-T* regimes is after Brown (2007): HT = high temperature; UHT = ultrahigh temperature; HP = high pressure. The Al-silicate system is after Holdaway (1971). See text for discussion.

Figure 4

Illustration of successive anatectic events in the SMZ. (a) Small anatectic veins and melt patches (Petronella locality, Fig. 1) enhance the gneissic fabric of metapelitic granulite. (b) Concordant veins of granodioritic/trondjhemitic composition developed within metapelitic granulite at Bandelierkop locality (Fig. 1). The major vein dated at ~2.64 Ga (Kreissig et al., 2001) intruded the migmatitic metapelitic host rock dated at ~2.69 Ga (Kreissig et al., 2001). (c) Intrusive relationship of granodioritic body (light-coloured) with metapelitic granulite (dark-coloured) at Bandelierkop locality. The granodiorite comprises metapelitic xenoliths (not visible in the photograph) and crosscuts the darker metapelite. A weak gneissic foliation developed within the leucocratic body suggests emplacement during deformation. (d) Large body (~1 km in width) of leucocratic trondjhemitic dated at ~2.67 Ga (Belyanin et al., under review) that intruded and partially assimilated metapelitic granulite (Petronella locality). Note the presence of a narrow metapelitic xenolith (centre) and of a partially digested metapelitic xenolith (centre left) defined by Grt-Bt-Crd trails near the country rock.

Figure 5

Plane-polarised light microphotographs demonstrating hydration reactions involving Crd within the granulite zone. See text for discussion. (a) Localised cordierite hydration at the Petronella locality (Fig. 1). Cordierite is replaced by fine-grained intergrowths of Ged and Ky, and by coarser-grained Bt and Ky. Opx remains unaltered. (b) Regional hydration of Crd north of the retrograde isograd. Here, initial hydration of Crd is shown by its replacement at the edges by needle-shaped fine-grained Ged and Ky. Note that Opx is stable, confirming the low $a_{H_2O}^{fluid}$ of the hydrating fluid.

Figure 6

Plane-polarised light microphotographs showing petrographic features of metapelitic granulite (a, b) and their hydrated equivalent (c, d). See text for discussion. (a) Granoblastic texture of cordierite-free Grt granulite. (b) Reaction texture preserving evidence for the decompression cooling reaction Grt + Qz → Crd + Opx (photo from Huizenga et al., 2014). (c) Isograd reaction (2) developed in Crd-free granulite on the retrograde isograd. (d) Completely hydrated Ath±Ged±Ky±Grt gneiss from the hydrated granulite zone.

Figure 7

Changing compositions of (a) Grt and (b) Bt in metapelitic gneiss, and (c) Ca-amphibole in ultramafic rocks from the granulite zone (open circles), the retrograde isograd (solid black circles), and retrograde hydrated granulite zone (grey circles). (a) and (b) modified after Van Reenen (1986), (c) modified after Van Schalkwyk and Van Reenen (1992). Note that no ultramafic isograd samples were found. Grey arrow indicates the mineral compositional trend from the granulite to the retrograde hydrated granulite zone.

Figure 8

(a) Composition of the hydrating fluid constrained by *P*-*T* conditions of ~6 kbar, 600-630°C calculated for the retrograde isograd reaction (3) (assuming Mg-end members). The reaction curve was calculated using Holland and Powell's dataset (1998). (b) Composition of infiltrating CO_2-rich fluid phase constrained by petrological modeling of partially hydrated and carbonated ultramafic assemblages in sample DR191 (see Fig. 1 for sample locality). Reaction curves are calculated using the dataset by Holland and Powell (1998). Mineral compositions are from Van Schalkwyk and Van Reenen (1992). Activities for the end members were calculated using the program AX developed by T. Holland. See text for discussion. For both (a) and (b) $a_{H_2O}^{fluid}$ was recalculated to $X_{H_2O}^{fluid}$ using the H_2O-CO_2 activity-composition model from Aranovich and Newton (1999).

Figure 9

Fractionation coefficient versus $\delta^{18}O$ diagrams (FCD diagrams) for (a) metapelitic gneiss from the hydrated granulite zone (sample P50C in Hoernes et al., 1995), (b) metapelitic gneiss from the granulite zone (sample P19C in Hoernes et al., 1995), and (c) metasomatized tonalitic gneiss from the Klipbank Shear Zone (sample KK15 in Hoernes et al., 1995) (see Fig. 1 for locality) (a) Near-peak T (~820°C) is derived from whole-rock/Grt fractionations. Whole-rock/Ath fractionation defines a secondary linear array with a flatter slope corresponding to Ath formation at T = ~635°C. (b) Whole-rock/Qz/Pl/Opx fractionation indicates fluid-induced re-equilibration at T = ~670°C. Whole-rock/Grt fractionation gives an unrealistically high temperature (1230°C) (Hoernes et al., 1995). (c) All phases plot reasonably close to a straight line, suggesting re-equilibration at T = 630°C due to fluid infiltration. Note the close correspondence of this temperature to that of the retrograde hydration on the isograd. Figure modified after Hoernes et al. (1995).

Figure 10

Shear zone-hosted metasomatism at the Petronella (a-c) and Commissiedraai (d-e) localities (Fig. 1). (a) General view of strongly foliated altered pink rocks (straight gneisses, Smit and Van Reenen, 1997) in the Petronella Shear Zone. The precursor grey enderbitic gneiss (dark-grey bands alternating with pink bands in b) is altered into light-pink metasomatic potassium-enriched metasomatic rocks (c). (b) Selective metasomatism of leucocratic veins within the enderbitic gneiss. Note the presence of a narrow near-horizontal enderbitic sill (pen) that intrudes both the enderbitic gneiss and the metasomatized leucocratic veins. (c) Intensely altered enderbitic gneiss transformed into pink Mn-rich Grt-bearing potassium-enriched granitoid. (d) Dark grey homogenous metamorphic enderbite (HE) metasomatized into pink Grt-Opx-bearing potassium enriched enderbite (ME). Ghost gneissic structures of the precursor gneiss is preserved within the metamorphic enderbite and can be traced uninterruptedly into the pink granitoid. (e) Intense metasomatism resulting in Sil-bearing (Opx absent) sheared granitoid.

Figure 11

Isocon diagram showing gains and losses of major oxides with increasing metasomatic alteration from the least-altered (open circles) to the most-altered enderbitic (solid circles) gneiss at Petronella. Assuming constant $A1_2O_3$ (e.g., Newton and Tsunogae, under review), volume and mass have not changed during the metasomatic process. TiO_2, P_2O_5, CaO, FeO, and MgO are lost during metasomatism whereas Na_2O and K_2O are gained. Dotted lines indicate the relative gains and losses. For example, the relative concentration decrease of MgO is ~81%. Figure modified after Smit and Van Reenen (1997) using data by Du Toit (1994).

Figure 12

Bar plots (bar width: 2°C) of *T*h for CO_2-rich fluid inclusions in gold-bearing Qz veins in shear zone-hosted lode-gold mineralization in the hanging wall (a, b) and footwall (c-e) of the HRSZ. See Fig. 1 for gold deposit localities. Figure modified after Van Reenen et al. (1994). See text for discussion.

TABLE CAPTIONS

Table 1.

Characteristics of Au mineralization related to the tectono-metamorphic evolution of the SMZ using data from Pretorius et al. (1988), Van Reenen et al. (1994), Gan and Van Reenen (1995a,b), and Stefan (1997). See Fig. 1 for gold deposit localities.

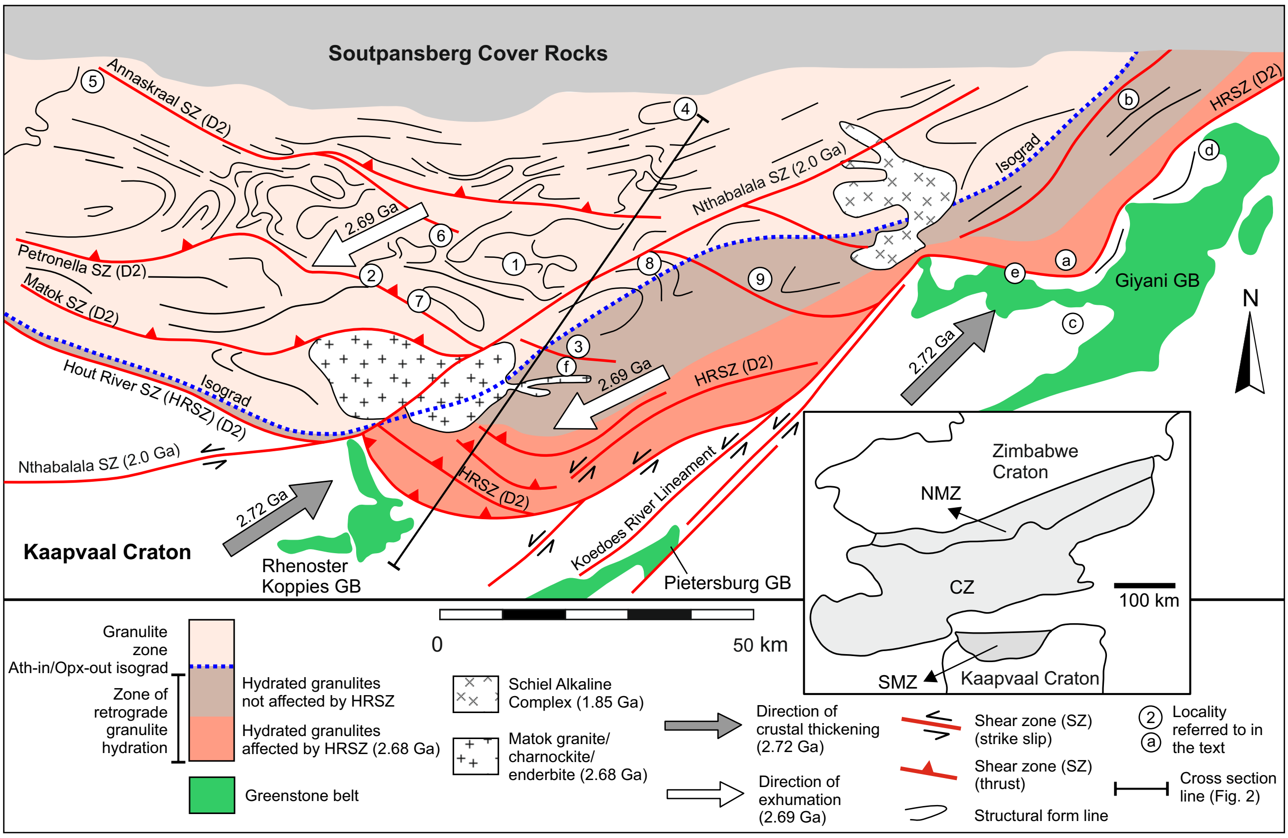


Figure 1 (colour)

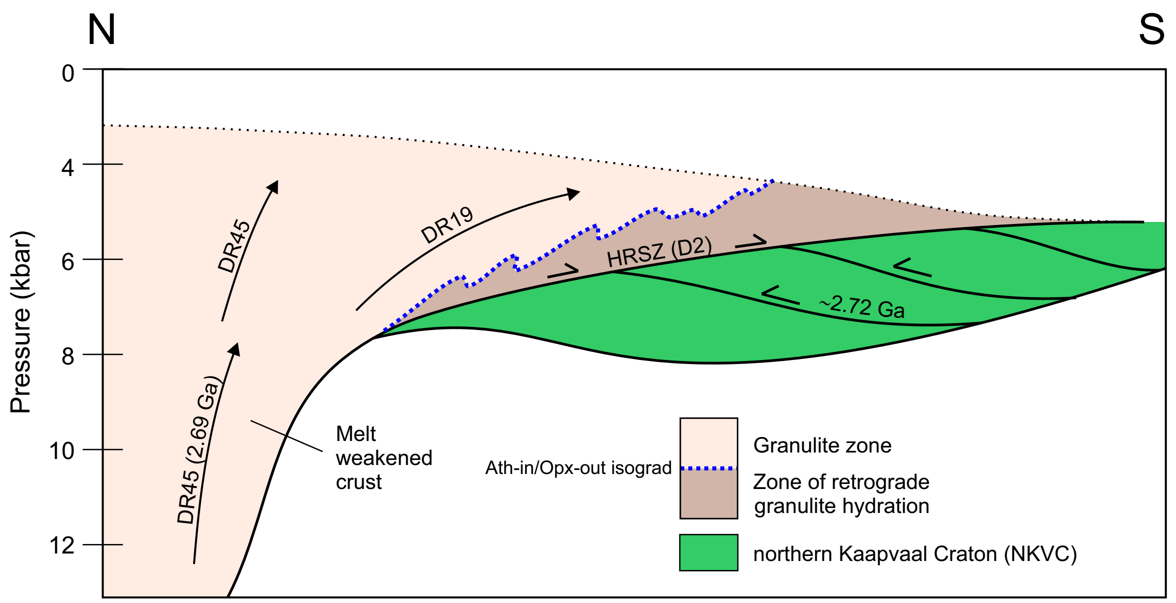


Figure 2 (colour)

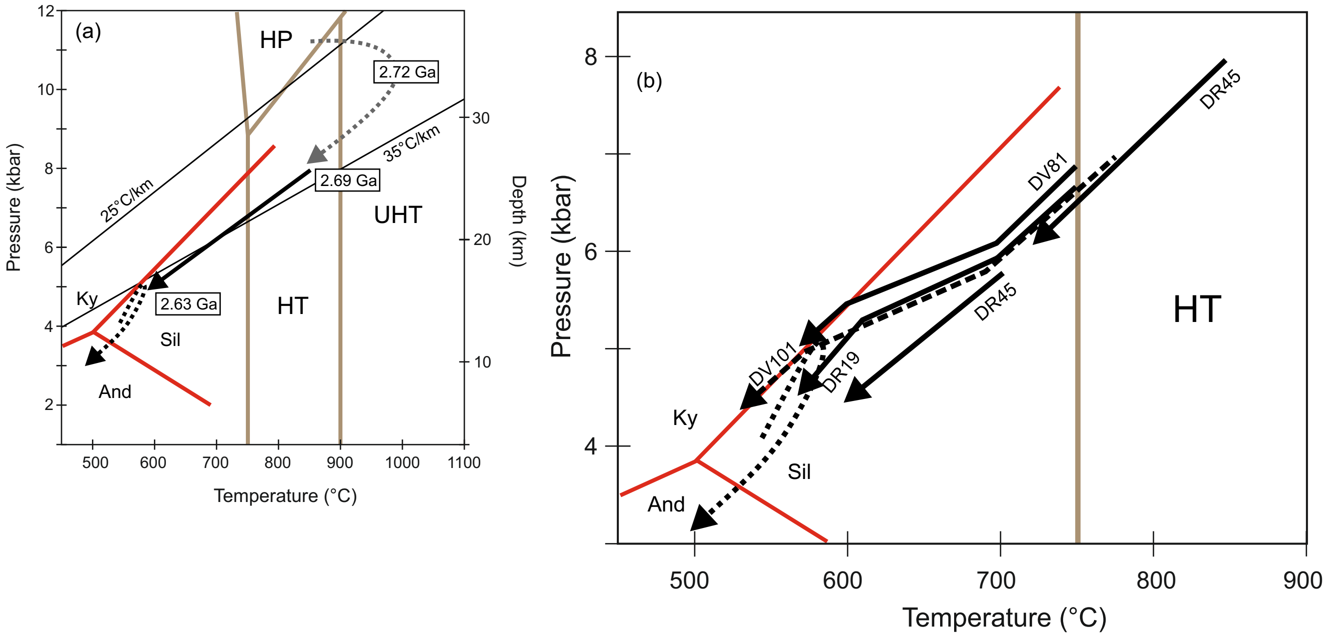
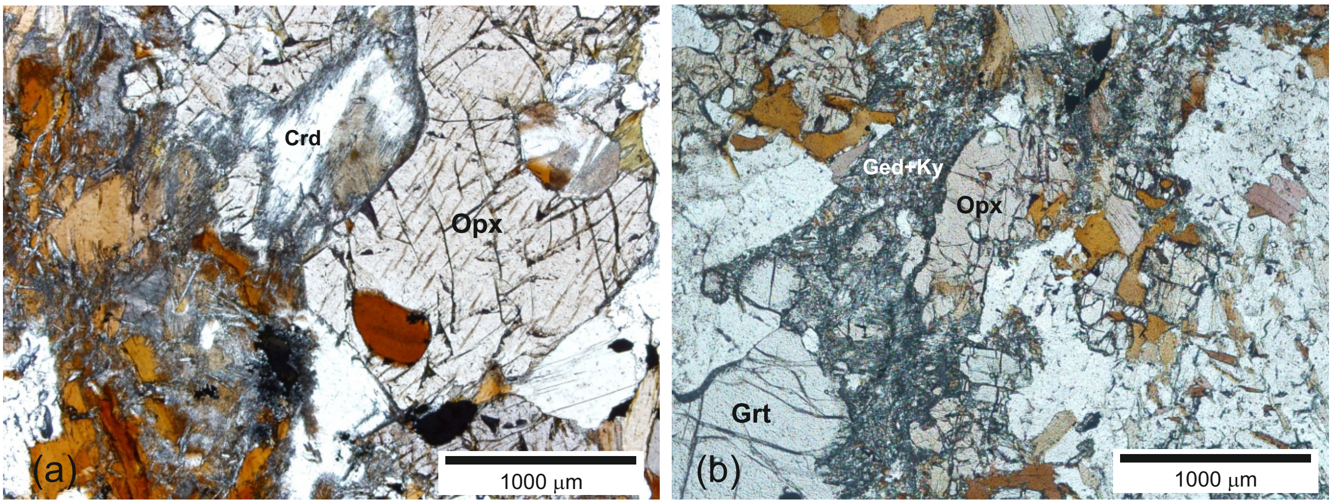


Figure 3 (colour)

Figure 4 (colour)


Crd
Opx
(a)
1000 μm
Ged+Ky
Opx
Grt
(b)
1000 μm

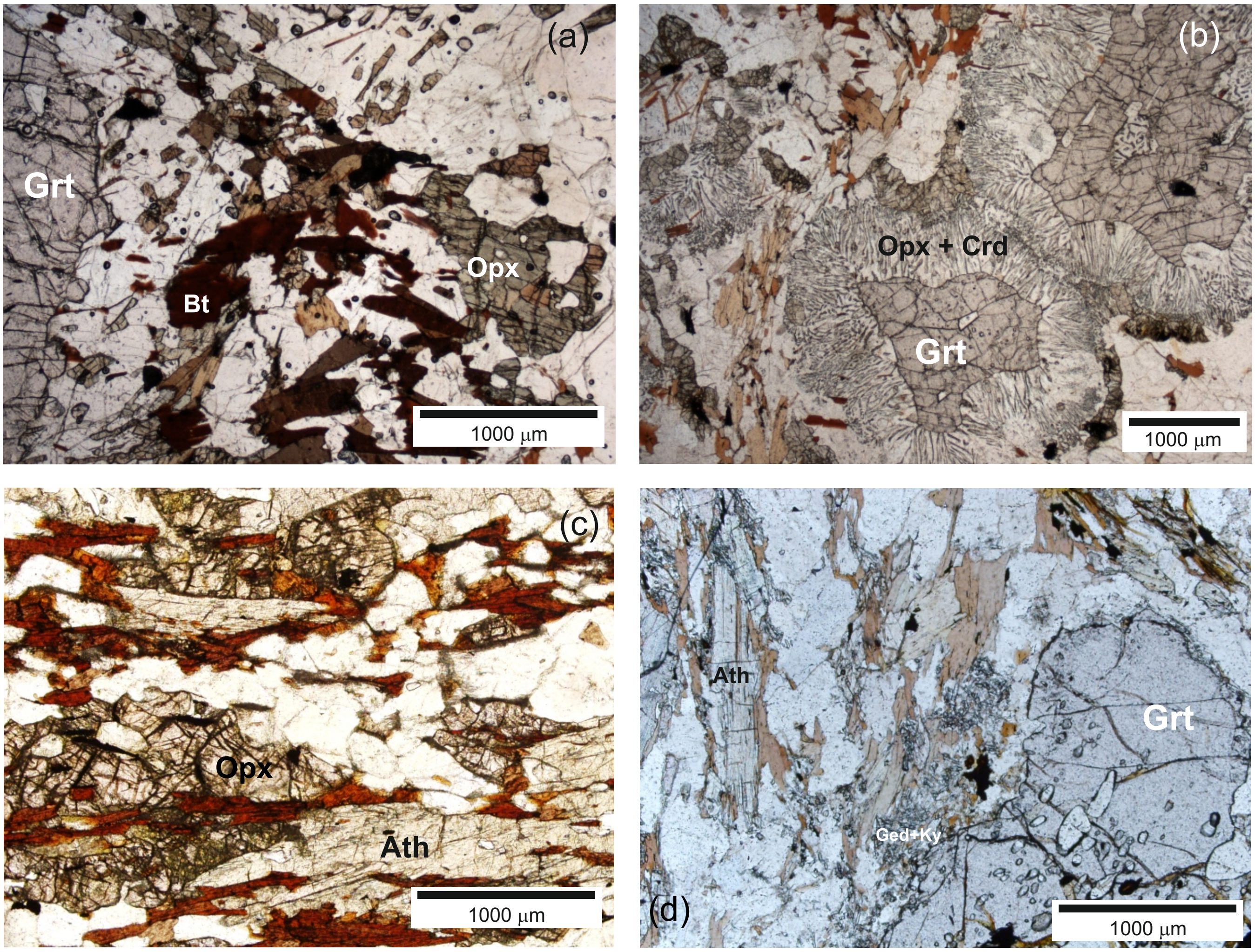
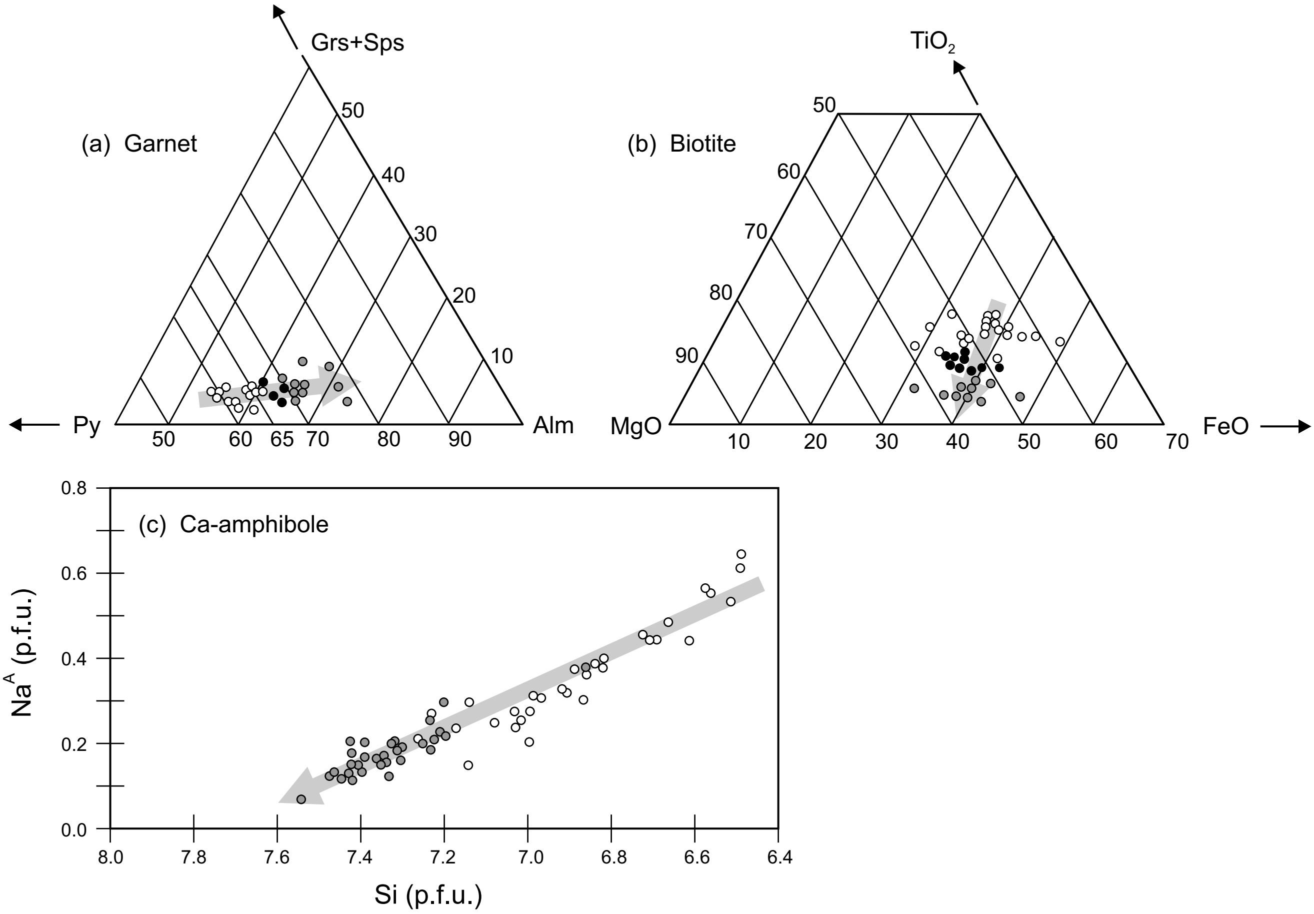
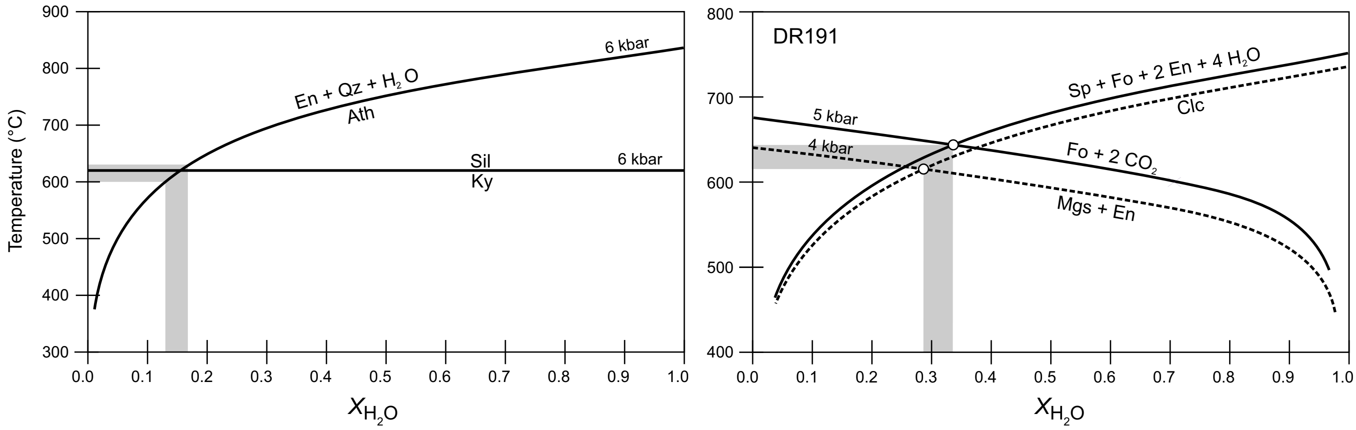


Figure 6 (colour)



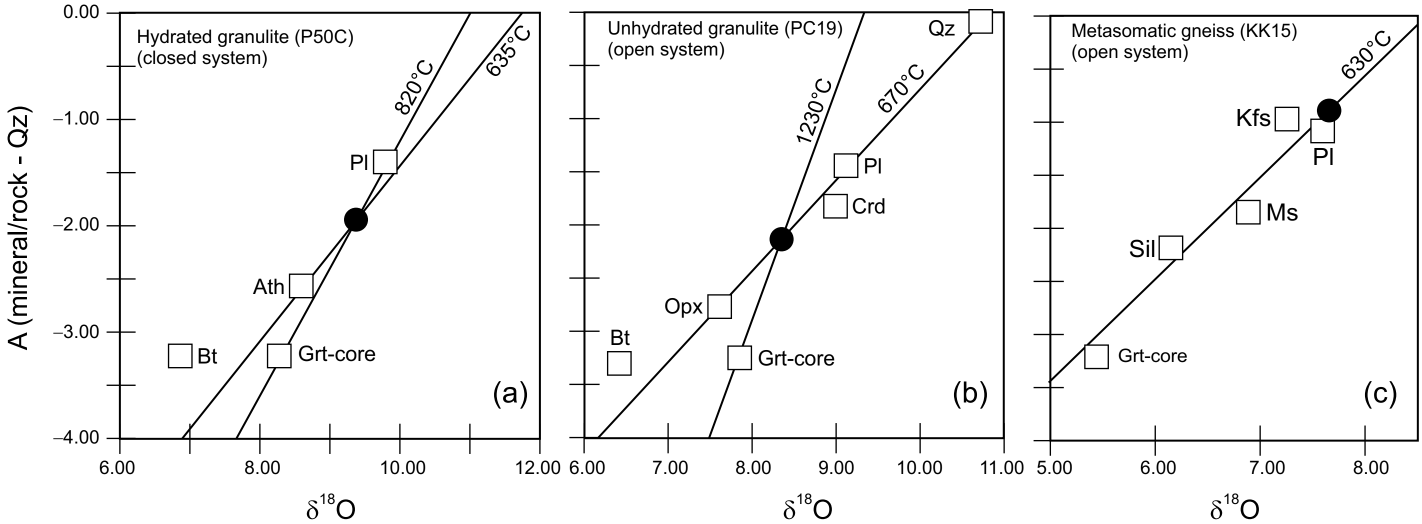
Grs+Sps
(a) Garnet
50
40
30
20
10
Py
Alm
50
60
65
70
80
90
TiO2
(b) Biotite
50
60
70
80
90
MgO
FeO
10
20
30
40
50
60
70
(c) Ca-amphibole
NaA (p.f.u.)
Si (p.f.u.)
0.8
0.6
0.4
0.2
0.0
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4

Figure 7



Temperature (°C)
En + Qz + H2O
Ath
6 kbar
Sil
Ky
6 kbar
X_{H_2O}
DR191
Sp + Fo + 2 En + 4 H2O
Clc
5 kbar
4 kbar
Fo + 2 CO2
Mgs + En
X_{H_2O}

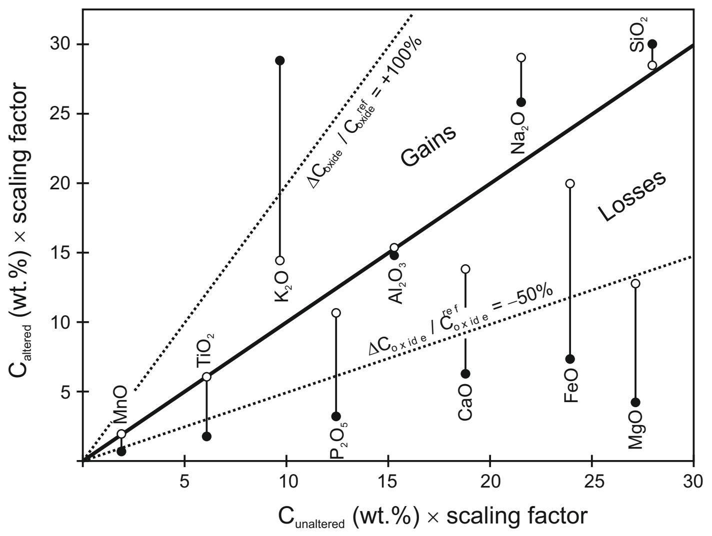
Figure 8



Hydrated granulite (P50C)
(closed system)
820°C
635°C
Pl
Ath
Bt
Grt-core
(a)
Unhydrated granulite (PC19)
(open system)
Qz
1230°C
670°C
Pl
Crd
Opx
Bt
Grt-core
(b)
Metasomatic gneiss (KK15)
(open system)
630°C
Kfs
Pl
Ms
Sil
Grt-core
(c)
A (mineral/rock - Qz)
0.00
−1.00
−2.00
−3.00
−4.00
6.00
8.00
10.00
12.00
6.00
7.00
8.00
9.00
10.00
11.00
5.00
6.00
7.00
8.00
δ18O
δ18O
δ18O

Figure 9

Figure 10 (colour)



C_altered (wt.%) × scaling factor
C_unaltered (wt.%) × scaling factor
Gains
Losses
ΔC_oxide / C_oxide^ref = +100%
ΔC_oxide / C_oxide^ref = −50%
MnO
TiO2
K2O
P2O5
Al2O3
CaO
Na2O
FeO
MgO
SiO2
0
5
10
15
20
25
30

Figure 11

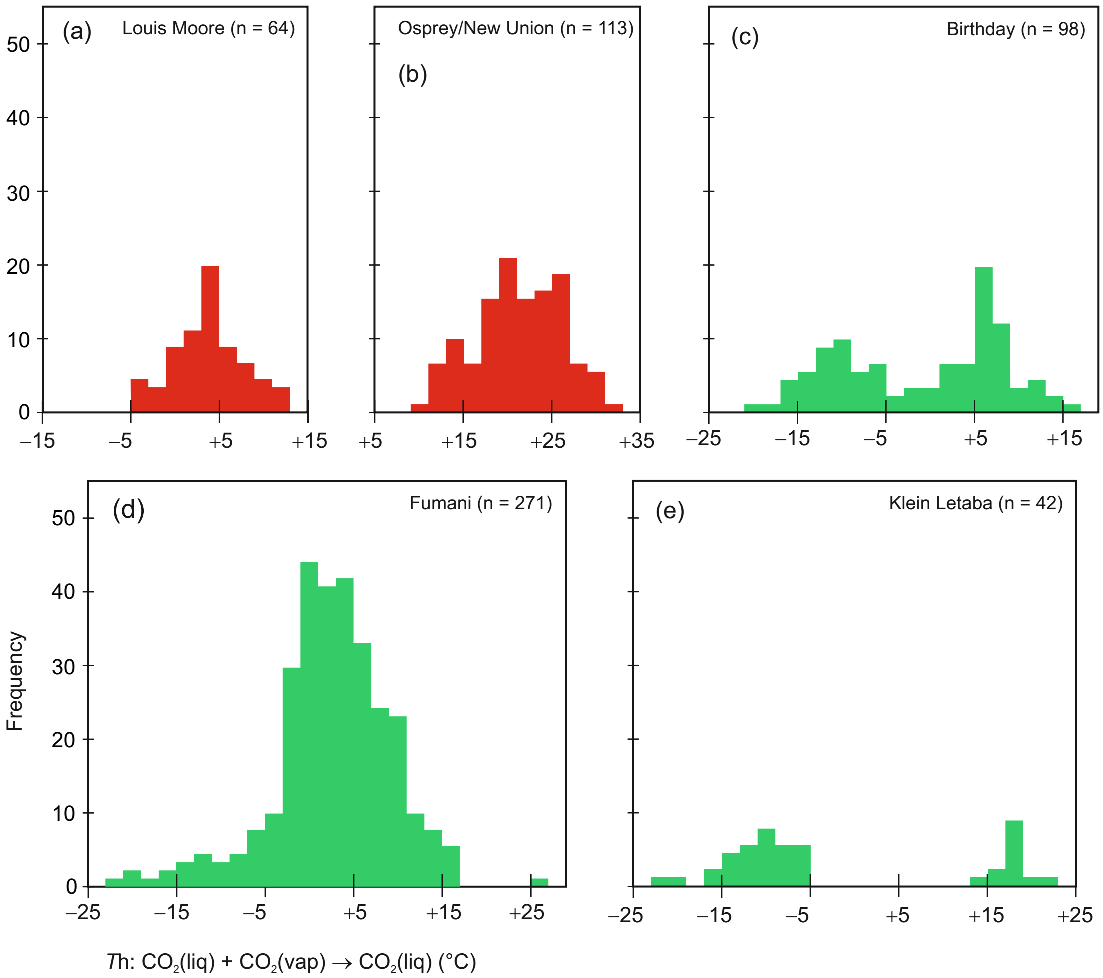


Figure 12 (colour)

Table 1

Deposit and age	Structure and metamorphism	Ore body and Au mineralization	Wall-rock alteration
Birthday (> 2.43 Ga)	SW-verging lower-amphibolite facies thrust shear zone in amphibolite schists	Hbl-Bt-Pl-Cc-Qz schist. Au (free milling) occurs in Qz veins and silicate minerals	Bt, Cc, sulphides
Fumani (> 2.63 Ga)	SW-verging upper-amphibolite facies thrust shear zone (HRSZ) in (ultra) mafic schists and BIF	Ca-Grt+Gru+Bt+Pl+Cc+Qtz schist. Au occurs as inclusions in Apy, Po, and as free milling in Qz veins and silicate minerals	Bt, Cc, sulphides
Klein Letaba (> 2.66 Ga)	SW-verging upper-amphibolite facies thrust shear zone (HRSZ) in (ultra) mafic schists, metapelites and BIF	Hbl-Bt-Qz schist. Au occurs as inclusions in Apy, Po and Lo, and as free milling in Qz veins and silicate minerals	Bt, Cc, sulphides
Frankie (> 2.43 Ga)	SW-verging middle-amphibolite facies thrust shear zone (HRSZ) in (ultra) mafic schists and BIF	Mag-Grt-Bt-Pl gneiss. Au occurs as inclusions in Apy, Po and Lo, and as free milling in Qz veins and silicate minerals	Bt, Cc, sulphides
Osprey, no age data available	SW-verging upper-amphibolite facies thrust shear zone in retrograde hydrated mafic and pelitic granulites, and BIF	Grt-Hbl-Qz-Pl±Cc gneiss and BIF. Au occurs as free milling in Qz veins and silicate minerals	Bt, Cc, Kfs sulphides
Louis Moore (> 2.5 Ga)	SW-verging upper-amphibolite facies thrust shear zone in partially retrograde hydrated ultramafic granulites	Ol-Opx-Chl-Bt-Cc schist. Au (free milling) occurs in Qz veins and silicate minerals	Bt, Cc, sulphides
Doornhoek (> 2.4 Ga)	Upper-amphibolite facies strike slip shear zone in partially retrograde hydrated ultramafic and metapelitic granulites, and BIF	Qz veins associated with sheared BIF. Au occurs as inclusions in Apy, Po and Lo, and as free milling in Qz veins and silicate minerals	Bt, Cc, Kfs sulphides