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Research paper

Fluid-rock interaction in retrograde granulites of the Southern Marginal Zone, Limpopo high grade terrain, South Africa

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ABSTRACT

Fluid infiltration into retrograde granulites of the Southern Marginal Zone (Limpopo high grade terrain) is exemplified by hydration reactions, shear zone hosted metasomatism, and lode gold mineralisation. Hydration reactions include the breakdown of cordierite and orthopyroxene to gedrite + kyanite, and anthophyllite, respectively. Metamorphic petrology, fluid inclusions, and field data indicate that a low H_2O-activity carbon-saturated CO_2-rich and a saline aqueous fluid infiltrated the Southern Marginal Zone during exhumation. The formation of anthophyllite after orthopyroxene established a regional retrograde anthophyllite-in isograd and occurred at *P-T* conditions of ~6 kbar and 610 °C, which fixes the minimum mole fraction of H_2O in the CO_2-rich fluid phase at ~0.1. The maximum H_2O mole fraction is fixed by the lower temperature limit (~800 °C) for partial melting at ~0.3. C-O-H fluid calculations show that the CO_2-rich fluid had an oxygen fugacity that was 0.6 $\log_{10}$ units higher than that of the fayalite-magnetite-quartz buffer and that the $CO_2/(CO_2+CH_4)$ mole ratio of this fluid was 1. The presence of dominantly relatively low density CO_2-rich fluid inclusions in the hydrated granulites indicates that the fluid pressure was less than the lithostatic pressure. This can be explained by strike slip faulting and/or an increase of the rock permeability caused by hydration reactions.

1. Introduction

The Limpopo high-grade terrain in South Africa is well known for its classic exposures of regionally metamorphosed granulite-facies rocks. It is a late Archean ENE–WSW trending zone located between the granite-greenstone terrains of the Zimbabwe and Kaapvaal cratons (Fig. 1), subdivided into the Northern Marginal Zone, the Central Zone, and the Southern Marginal Zone (e.g., Van Reenen et al., 2011). The Northern and Southern Marginal Zones comprise high-grade granitoids and greenstone belt lithologies (e.g., Kreissig et al., 2001; Van Reenen et al., 2011), which are juxtaposed against the cratons as a result of compression-related exhumation in the interval ~2.69–2.62 Ga (Van Reenen et al., 2011).

The Southern Marginal Zone (SMZ) is particularly interesting as its metamorphic evolution is typical for subduction-related high-pressure granulites (clockwise *P-T* path), which also experienced ultrahigh-temperature conditions (Tsunogae et al., 2004; Belyanin et al., 2012). Granulites that show a clockwise *P-T* path and experienced both high-pressure and ultrahigh temperature conditions are not common (Touret and Huizenga, 2012). Further, the SMZ shows evidence of both near-peak and retrograde fluid-rock interaction during thrust-controlled exhumation in the interval 2.69–2.62 Ga (Van Reenen et al., 2011). The limit of the regionally retrogressed granulite corresponds to a rarely described retrograde

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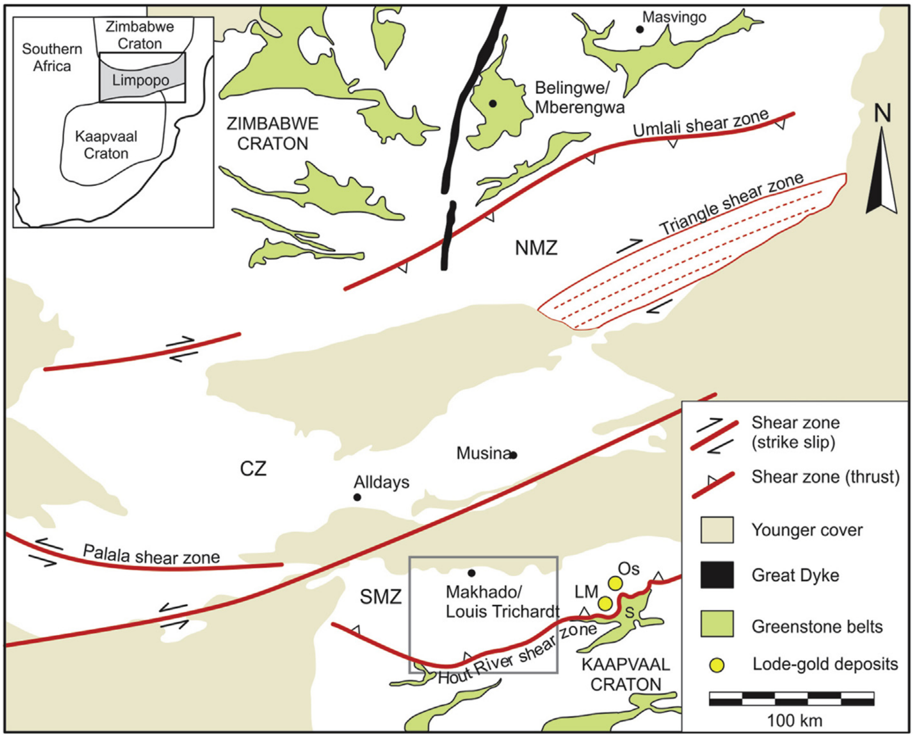

Figure 1. Geological map of the Limpopo high-grade terrain and the adjacent Kaapvaal and Zimbabwe cratons (modified after Rollinson, 1993). SMZ: Southern Marginal Zone, CZ: Central Zone, NMZ: Northern Marginal Zone, S: Sutherland/Giyani greenstone belt, LM: Louis Moore gold deposit, Os: Osprey gold deposit. Inset: see Fig. 2.

anthophyllite-in isograd (Van Reenen, 1986). The SMZ is thus an ideal terrain where the physico-chemical effects of fluid-rock interaction at deep- and mid-crustal levels can be studied.

The emphasis of this paper is to demonstrate the importance of an integrated approach of field mapping, mineralogy, fluid inclusion studies, and thermodynamic modelling in studying different aspects (i.e., *P*, *T*, fluid composition and redox state) of fluid-rock interaction in cooling granulites. We reviewed and reinterpreted mineralogical and fluid inclusions data from the literature, and applied thermodynamic model calculations within the C-O-H fluid system.

2. Geological setting of the Southern Marginal Zone

The SMZ is subdivided into a granulite zone (comprising garnet-orthopyroxene-cordierite-bearing metapelitic lithologies) in the north and a retrograde hydrated granulite zone (comprising garnet-biotite-plagioclase-anthophyllite ± gedrite ± kyanite-bearing lithologies) in the south (e.g., Van Reenen, 1986; Van Reenen et al., 2011) (Fig. 2). These two zones are chemically equivalent (Kreissig et al., 2000) and separated by the retrograde anthophyllite-in isograd (Van Reenen, 1986). Migmatitic pelitic rocks in the granulite zone show reaction textures that are associated with decompression and cooling from peak conditions at $P > 10$ kbar and $T = \sim 1000\ ^\circ\mathrm{C}$ (e.g., Tsunogae et al., 2004; Van Reenen et al., 2011; Belyanin et al., 2012). They are characterised by the following four mineral assemblages: (1) orthopyroxene-plagioclase-biotite-quartz (±garnet, ±K-feldspar), (2) garnet-orthopyroxene-plagioclase-biotite-quartz (±K-feldspar), (3) garnet-orthopyroxene-cordierite-plagioclase-biotite-quartz (±K-feldspar), and (4) orthopyroxene-cordierite-plagioclase-biotite-quartz (±K-feldspar) (e.g., Van Reenen et al., 2011). Mineral assemblages (3) and (4) formed as a result of the reaction:

$$\underset{\text{Garnet}}{2(\mathrm{Fe,Mg})_3\mathrm{Al}_2\mathrm{Si}_3\mathrm{O}_{12}} + \underset{\text{Quartz}}{3\ \mathrm{SiO}_2} \rightarrow \underset{\text{Orthopyroxene}}{2(\mathrm{Fe,\ Mg})_2\mathrm{Si}_2\mathrm{O}_6} + \underset{\text{Cordierite}}{(\mathrm{Fe,Mg})_2\mathrm{Al}_4\mathrm{Si}_5\mathrm{O}_{18}} \tag{1}$$

during decompression and cooling (e.g., Van Reenen et al., 2011). Iron-rich rocks with a Mg/(Mg + Fe) mole ratio < 0.6 do not show any sign of reaction (1) whereas this reaction has run to completion in rocks with a Mg/(Mg + Fe) mole ratio > 0.7 (Van Reenen, 1986). Rocks with a Mg/(Mg + Fe) mole ratio between 0.6 and 0.7 show reaction (1) in progress (Fig. 3a) (Van Reenen, 1986).

The rare occurrence of primary mixed saline H_2O-CO_2 fluid inclusions in orthopyroxene (Touret and Huizenga, 2011) and in quartz inclusions in garnet (Van den Berg and Huizenga, 2001) indicates that granulite facies metamorphism occurred in the presence of a CO_2 and a saline aqueous fluid (Van den Berg and Huizenga, 2001; Touret and Huizenga, 2011). These low-H_2O activity fluids coexisted under conditions of immiscibility and are considered to be typical granulite facies fluids (e.g., Newton et al., 1998).

Post-peak grain-size scale metasomatism is exemplified by perthitic feldspar rims between quartz and garnet, which is the result of the reaction Garnet + Quartz + $(\mathrm{K,Na})_{\mathrm{fluid}}$ → K-feldspar + Albite + Biotite (Touret and Huizenga, 2011). Large-scale, shear zone related metasomatism is shown by potassium alteration of tonalitic orthopyroxene-bearing gneisses in the Petronella Shear Zone (Fig. 2) (Smit and Van Reenen, 1997). Here, mesoperthite, perthite, and antiperthite are replacing precursor oligoclase (Smit and Van Reenen, 1997) while orthopyroxene remains stable. Whole-rock/garnet/quartz oxygen-isotope fractionation of the metasomatosed rocks