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Fluid-assisted interaction of peraluminous metapelites with trondhjemitic magma within the Petronella shear-zone, Limpopo Complex, South Africa

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ABSTRACT

The principal problem concerning the evolution of Precambrian granulite complexes located between granite-greenstone cratons is their interaction with the underthrusted greenstone belts during exhumation from the lower crust. Besides evidence for pervasive and localized fluid fluxes arising from devolatilization of the greenschist and amphibolite-facies rocks in the course of their burial underneath the granulites, this interaction might also be expressed in formation of diverse magmas of granitic, trondhjemitic and granodioritic composition. We present results of a petrological, fluid inclusion and thermobarometric study of interaction between fluidized trondhjemitic magma and peraluminous metapelitic granulites associated with the regional high-grade Petronella shear zone located in the Southern Marginal Zone (SMZ) of the Limpopo Granulite Complex (South Africa). The hot ($T \sim 1000\,^{\circ}$C) trondhjemitic magma, which, presumably, originated from partial melting of a basaltic (amphibolite) material at the base of the granulite complex or at the top of the underthrusted greenstone blocks, intruded granulites at $P \sim 8.0$–9.5 kbar (24–28 km depth) at 2.667 ± 0.9 Ga during the exhumation of the SMZ. The magma heated and assimilated orthopyroxene-cordierite metapelites and dragged them to a depth of 18–20 km (6.3–6.5 kbar). The magma was heterogeneously saturated with MgO, FeO, Al_2O_3 by the dissolved metapelites. This process provoked crystallization of several garnet generations from the trondhjemitic melt. Various mineral assemblages included in the different generations of garnet allowed application of TWQ method combined with PERPLE_X pseudo sections to trace sub-isobaric cooling of the magma from $T \sim 900$–$600\,^{\circ}$C at 5.5–6.5 kbar. The isobaric cooling also affected the associated metapelites. Fluid inclusions trapped in garnet and quartz in the trondhjemite show that the magma transported carbonic fluid with densities corresponding to the late stages of magma cooling (600–650 °C and 5.5–6.5 kbar). Carbonic fluids coexisted with aqueous-salt fluids (preserved as inclusions with salinity up to 20.58 wt.% NaCl eq.). These low water activity fluids ($a_{H_2O} < 0.3$) bearing Na, K and Ca salts, being exsolved from the magma on cooling and solidification, provoked formation of complex Na-gedrite + biotite + sillimanite + quartz ± staurolite ± plagioclase-bearing assemblages after cordierite in metapelites at temperatures 630–570 °C and pressures 5.5–6.5 kbar. These data provide evidence that hot trondhjemitic melts played a critical role in the exhumation of granulites onto the adjacent granite-greenstone craton. The trondhjemite transferred heat from the lower to the middle crust and transported large volumes of external aqueous-carbonic-salt fluids that participated in the rehydration of a significant portion of the SMZ.

1. Introduction

A much discussed issue regarding the evolution of Precambrian granulite complexes located between granite-greenstone cratons is their interaction with the underthrusted greenstone belts during exhumation from the lower crust. Although the direct relations

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Ab	albite
Alm	almandine
AlOpx	alumino-orthopyroxene end-member ($AlAlO_3$)
An	anorthite
And	andalusite
Ann	annite
Anth	anthophyllite
Bt	biotite
Cel	celadonite
Cor	corundum
Crd	cordierite
Eas	eastonite
En	enstatite
fCrd	Fe-cordierite
Fs	ferrosillite
Fsp	ternary feldspar
Ged	gedrite
Grs	grossular
Grt	garnet
Hc	hercinite
Ilm	ilmenite
Kfs	K-feldspar
Ky	kyanite
Mu	muscovite
Opx	orthopyroxene
Or	orthoclase
Phl	phlogopite
Pl	plagioclase
Prp	pyrope
Qtz	quartz
Ru	rutile
Sid	siderophillite
Sil	sillimanite
Spl	spinel
Sps	spessartine
St	staurolite
Zo	zoisite
Zrc	zircon
Compositional parameters	
X_{Mg}	Mg/(Mg + Fe + Mn)
X_{Al}	Al/(Si + Al + Ti + Mg + Fe + Mn) (for biotites and orthopyroxenes)
X_{Ca}	Ca/(Ca + Na + K) (for plagioclase)
X_{Ca}	Ca/(Ca + Mg + Fe + Mn) (for garnet)
X_K	K/(K + Na + Ca) (for alkali feldspar)

of the granulite complexes with the greenstone belts are rarely exposed, detailed petrological studies of prime examples from the Limpopo Complex (South Africa), Lapland Granulite Belt (Russia-Finland), and Enisey Range (Russia) proved that the *P*–*T*–*t* and geodynamic evolution of the greenstone cratons and juxtaposed granulite complexes are closely interrelated (Perchuk et al., 1996, 2000; Smit et al., 2000; Van Reenen et al., 2011). Exhumation of the granulite complexes from the lower crust always results in underthrusting of the cratonic rocks followed by their subsequent joint exhumation toward the surface (see Van Reenen et al., 2011 and references therein). The tectonic juxtaposition of the granulite belts with the cratonic complexes should not only be expressed by their joint *P*–*T*–*t* paths, but also by interrelated fluid and magmatic activities. Volatile-rich cratonic rocks (greenschists, amphibolites, tonalite-trondhjemite gneisses) evidently served as strong sources for various fluids and magmas that might have invaded the overriding granulites from below (e.g. Huizenga et al., 2014).

Such relations are best studied for the Neoarchean Limpopo Complex (LC) where a large geological, structural, petrological, geochemical, geochronological, and isotopic database (e.g. Van Reenen et al., 1992, 2011 and references therein; Huizenga et al., 2014) demonstrated that the evolution of the granulite facies Southern Marginal Zone (SMZ) of the Limpopo Complex was strongly influenced by externally derived aqueous-carbonic and aqueous-salt (brine) fluids of reduced water activity. The source of these fluids is assumed to be underthrusted greenstone rocks of the northern Kaapvaal Craton (NKVC). This assumption is sustained by geophysical data showing that more than 60% of the SMZ at depth is presently underlain by greenstone belts (e.g. De Beer and Stettler, 1992). Fluids being derived from devolatilization of the underthrusted greenstone material infiltrated overriding granulites during the thrust-controlled exhumation onto the adjacent granite-greenstone belts of the northern Kaapvaal Craton (NKVC) within the time period 2.69–2.62 Ga. At pressures about 6 kbar and temperatures 650–620 °C, these fluids established a so called “orthoamphibole isograd” in the hanging wall of the shallow north-dipping Hout River Shear Zone (HRSZ) (age 2.69 Ga) that bounds the SMZ in the south (Van Reenen et al., 2011; Huizenga et al., 2014). This isograd, defined in metapelites (Fig. 1*a*) by the disappearance of orthopyroxene (and the first appearance of anthophyllite) owing to the univariant reaction Opx + Qtz + H_2O = Anth, subdivides the SMZ into a northern granulite zone in which orthopyroxene is always a stable phase in metapelites, and a southern zone of rehydrated granulite in which orthopyroxene is completely absent from metapelites. However, the late hydration of metapelites caused by infiltrating fluids is most clearly reflected by the divariant reaction Crd + H_2O = Ged + Sil (or/and Ky) + Qtz. This reaction is not restricted to the position of the isograd, but also affected cordierite in metapelites within the granulite zone. Orthopyroxene also disappears from quartz-feldspathic gneisses (Baviaanskloof gneisses) more or less at the position of the isograd, but is often still preserved as a relict phase in mafic, ultramafic gneisses and banded ironformation south of the isograd. In addition to re-hydration, similar fluids also provoked extensive shear zone-hosted potassic metasomatic alteration of the Baviaanskloof gneisses and formation of lode-gold mineralization in other rock types (e.g. Huizenga et al., 2014).

Fluids that resulted from devolatilization of the greenstone rocks are also considered to have triggered partial melting either at the top of the underthrusted greenstone pile or at the base of the overthrusted granulites. Such partial melting of amphibolite and tonalitic gneisses produced fluidized melts of granodioritic–trondhjemitic composition that were able to intrude and interact with granulites, which had already been migmatized at the peak of metamorphic conditions (e.g. Du Toit et al., 1983). Du Toit et al. (1983) first suggested, on the basis of intrusive relationships with migmatized granulite, that the major pulse of anatexis in the SMZ must have been linked to partial melting that occurred at depth below the granulite pile. In contrast, Stevens and van Reenen (1992) and Stevens (1997) claimed that all anatectic events, including the major pulse of anatexis could be explained by a mechanism of in situ dehydration melting of metapelitic rocks involving muscovite and biotite prior to the metamorphic peak at ∼2.72 Ga (Retief et al., 1990). However, dehydration melting as a viable mechanism to explain granite–granulite relations in the SMZ has been questioned by a number of authors. Kreissig et al. (2001) first showed that the timing ∼2.64 Ga of the major anatectic event exposed in the Bandelierkop quarry locality in the SMZ (Fig. 1*a*) was significantly later than the time of initial exhumation (∼2.69 Ga) and also than the time of peak metamorphism in the SMZ (∼2.72 Ga) (Retief et al., 1990). These authors also argued that