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RESEARCH PAPER

Experimental and petrological constraints on local-scale interaction of biotite-amphibole gneiss with H_2O-CO_2-(K, Na)Cl fluids at middle-crustal conditions: Example from the Limpopo Complex, South Africa

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Abstract Reaction textures and fluid inclusions in the ~2.0 Ga pyroxene-bearing dehydration zones within the Sand River biotite-hornblende orthogneisses (Central Zone of the Limpopo Complex) suggest that the formation of these zones is a result of close interplay between dehydration process along ductile shear zones triggered by H_2O-CO_2-salt fluids at 750–800 °C and 5.5–6.2 kbar, partial melting, and later exsolution of residual brine and H_2O-CO_2 fluids during melt crystallization at 650–700 °C. These processes caused local variations of water and alkali activity in the fluids, resulting in various mineral assemblages within the dehydration zone. The petrological observations are substantiated by experiments on the interaction of the Sand River gneiss with the H_2O-CO_2-(K, Na)Cl fluids at 750 and 800 °C and

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5.5 kbar. It follows that the interaction of biotite-amphibole gneiss with H_2O-CO_2-(K, Na)Cl fluids is accompanied by partial melting at 750–800 °C. Orthopyroxene-bearing assemblages are characteristic for temperature 800 °C and are stable in equilibrium with fluids with low salt concentrations, while salt-rich fluids produce clinopyroxene-bearing assemblages. These observations are in good agreement with the petrological data on the dehydration zones within the Sand River orthogneisses.

1. Introduction

Ductile shear zones developed within high-grade metamorphic terrains are usually considered as effective pathways for external fluids (e.g. Newton, 1990; Aranovich et al., 2010). Localized over a scale of centimeters to a few meters orthopyroxene ± clinopyroxene and K-feldspar-bearing dehydration zones within biotite-hornblende(±garnet) gneisses in various transitional amphibolite-to-granulite facies terrains are the best examples of such shear zones (Pichamuthu, 1960; Friend, 1981; Janardhan et al., 1982; Hansen et al., 1984, 1987; Stähle et al., 1987; Burton and O'Nions, 1990; Santosh et al., 1990; Milisenda et al., 1991; McGregor and Friend, 1992; Raith and Srikantappa, 1993; Dobmeier and Raith, 2000; Perchuk et al., 2000; Harlov and Förster, 2002; Rajesh, 2004; Ravindra-Kumar, 2004; Harlov et al., 2006; Rajesh et al., in press). Most researchers agree that the local dehydration of biotite- and hornblende-bearing gneisses to pyroxene-bearing assemblages is a result of the passage of low-aH_2O fluid through the rocks at temperatures 700–800 °C and pressures 5–7 kbar. Instead of an H_2O-CO_2 fluid with high X_{CO_2} (e.g. Friend, 1981; Janardhan et al., 1982; Newton, 1986), preference is lately given to more complex H_2O-CO_2-salt fluids (Hansen et al., 1995; Newton, 1995; Newton et al., 1998; Perchuk et al., 2000; Ravindra-Kumar, 2004; Harlov et al., 2006; Hansen and Harlov, 2009; Harlov, 2012; Touret and Huizenga, 2012). This conclusion agrees with the data on activity of aqueous brines in many amphibolite and granulite terrains suggesting that this type of fluid is an important agent of high-grade metamorphism in the lower to middle crust (Touret, 2009; Newton and Manning, 2010; Touret and Huizenga, 2011). At granulite *p-T* conditions, aqueous brines are immiscible with CO_2 (Schmulovich and Graham, 2004; Heinrich, 2007), resulting in coexistence of two fluids with contrast mobility (Watson and Brenan, 1987; Holness, 1997; Gilbert et al., 1998). Presence of supercritical brines coexisting with CO_2-rich fluids explains in much better way textural, geochemical and thermodynamic characteristic of the rocks from the dehydration zones. Both coexisting fluids are characterized by low water activity at granulite *p-T* conditions (Aranovich and Newton, 1996, 1997, 1998), assisting to stabilization of anhydrous mineral assemblages. In addition, low water activity would prevent from the extensive partial melting (Aranovich and Newton, 1996). The relationships between passage of the low-water activity fluids (brines and CO_2) and possible melting is still under hot debate. Using mass balance calculations and/or structural evidence, several studies on the dehydration zones proposed that formation of the pyroxene-bearing assemblages via metasomatism either preceded or was accompanied by partial melting (e.g. Stähle et al., 1987; Perchuk et al., 2000). Other groups of researchers argue for the dehydration induced by fluid infiltration only, without melting (e.g. Janardhan et al., 1982; Hansen et al., 1987; Santosh et al., 1990; Raith and Srikantappa, 1993; Harlov et al., 2006).

In addition to petrological and geochemical studies, the relations between dehydration induced by the complex H_2O-CO_2-salt fluids and partial melting could be resolved using experimental approach. Nevertheless, there are only few experimental studies available on dehydration processes for metamorphic rocks. Moreover, most of them are concentrated on the fluid-absent melting of rocks of diverse composition. Formation of orthopyroxene-bearing assemblages via dehydration melting of semi-pelitic rocks at pressures 5–7 kbar proceeded at temperatures above 800–850 °C (Nair and Chacko, 2002), while tonalitic rocks produced orthopyroxene-bearing assemblages at temperatures above 900 °C (Skjerlie and Johnston, 1993). Khodorevskaya (2004) performed experiments on "granitization" of amphibolite via infiltration of chloride-bearing aqueous solutions at 5 kbar and 750 °C. Harlov (2004) published results of an episodic study on interaction of tonalite biotite gneiss with KCl and NaCl-bearing fluids at 10 kbar and 900 °C and showed that chlorides stabilize orthopyroxene and clinopyroxene after biotite and plagioclase. Alkali feldspar microveins, characteristic for granulites and charnockites, were reproduced in these runs. However, *p-T* parameters of Harlov's experiments are much higher than those for the dehydration zones in Precambrian complexes, i.e. temperatures below 850 °C at pressures 5–7 kbar (e.g. Nair and Chacko, 2002).

Because of variable bulk and mineral composition of the rocks in the dehydration zones and diverse ranges of *p-T*-fluid conditions of their formation, it is hard to propose a global model for the fluid-induced dehydration process. However, such models can be created for specific examples of the dehydration zones accounting for their chemical and thermodynamic evolution deduced from petrological data. The present study is focused on dehydration zones within the Archean Sand River biotite-hornblende tonalite-trondhjemite-granodiorite orthogneisses (ca. 3.3–3.2 Ga; Kröner et al., 1999; Zeh et al., 2007) at the Causeway locality within the Central Zone of the Limpopo Complex, Southern Africa (Fig. 1). According to Jaeckel et al. (1997), the formation of these zones occurred during the latest Paleoproterozoic D3/M3 (∼2.0 Ga) the metamorphic event in the Central Zone of the Limpopo Complex. Rajesh et al. (in press) describes in detail the geology, petrography and geochemistry of, as well as compositions of minerals and fluid inclusions of the rocks from the dehydration zones at the Causeway locality. In the present paper, we first use Rajesh's et al. data to account for the various fluid-mineral reactions and *p-T*-fluid conditions during the dehydration process. The main focus of this study is on results of experiments on interaction of the Sand River