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Chlorine-rich fluid or melt activity during granulite facies metamorphism in the Late Proterozoic to Cambrian continental collision zone—An example from the Sør Rondane Mountains, East Antarctica

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ABSTRACT

In the granulite facies rocks, the role of low H_2O activity fluids is still unclear. The importance of understanding its role is gradually being recognized, and it enables us to help understand the process of granulite formation. Attention has been specifically focused on Cl-rich fluids and high-salinity alkaline fluids in the geochemical modification of continental crust. We have investigated the field distribution of Cl-rich biotite in the pelitic gneisses of the Sør Rondane Mountains, East Antarctica where Late Proterozoic to Cambrian granulites are widely exposed. Among 27 samples studied, a garnet-biotite-sillimanite gneiss from Balchenfjella was selected as best suited sample to constrain the *P-T-t* conditions of Cl-rich fluid or melt activity. This gneiss contains garnet porphyroblasts that have a P-rich core with oscillatory zoning in P. The garnet core includes Cl-poor biotite and fluorapatite. This core has been partially resorbed and discontinuously overgrown by a P-poor rim, in which Cl-rich biotite and chlorapatite are included. Coarse-grained, rounded zircon grains are exclusively included in the rim of the garnet porphyroblast and are also present in the matrix. This mode of occurrence suggests that the Cl-rich biotite and chlorapatite, together with coarse-grained zircon were formed almost simultaneously. The *P-T* conditions of Cl-rich biotite entrapment in the garnet rim are estimated to be ca. 800 °C and 0.8 GPa. In comparison, peak metamorphic condition is ca. 850 °C and 1.1 GPa. These pieces of observation suggest that Cl-rich fluid or melt infiltrated at the core-rim boundary of garnet. In the case of fluid infiltration, the f_{HCl}/f_{H_2O} ratio of the fluid in equilibrium with Cl-rich biotite and chlorapatite in the garnet rim are estimated to be ten times larger than that in equilibrium with Cl-poor biotite and fluorapatite in the matrix and the garnet core. The LA-ICP-MS U-Pb dating of the coarse-grained zircon included in the garnet rim gave concordia age of 603 ± 14 Ma. Therefore, Cl-rich fluid or melt infiltration took place close to the metamorphic peak condition of ca. 800 °C and 0.8 GPa at 603 ± 14 Ma. The field distribution of Cl-rich fluid or melt activity is somewhat linear in the Sør Rondane Mountains. High Cl-activity is located near the large scale ductile shear zones, suggesting its relation to high-strain zones. Regional distribution of high-grade Cl-rich fluid or melt activity in the Sør Rondane Mountains implies that it is one of the major phenomena in the continental collision processes.

1. Introduction

Metamorphic fluids play important roles in thermal transport, mass transfer (e.g., Helgeson, 1964), metasomatism (e.g., Meyer and Hemeley, 1967) and changing stability field of mineral assemblages (e.g., Powell et al., 1991). The effect of the fluid on metamorphism varies depending on the fluid composition. Nearly ubiquitous CO_2-rich fluid inclusions in granulite facies rocks have been observed by many scientists in contrast to H_2O-dominated fluids of low-grade metamorphism (e.g., Newton et al., 1998). However, high-salinity fluids also have low H_2O activity. Presence of such a fluid shifts the wet solidus to the high-temperature side, and dehydration reactions to the low-temperature side. The solubility of minerals varies depending on the X_{H_2O} of the fluid (Newton and Manning, 2010).

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Therefore, high-salinity low H_2O activity fluids play a remarkable role in fluid-present melting, chemical compositional changes, change in mineral assemblage, or mass transfer during high-temperature metamorphism (e.g., Newton et al., 1998; Van den Berg and Huizenga, 2001; Harlov and Förster, 2002). Chlorine-rich fluids are more notable than CO_2-rich fluids because they can act as a powerful solvent not just for metals but for various oxides and silicate minerals (Newton and Manning, 2010).

The main features of the phase topology of the ternary H_2O-salt-CO_2 systems are exemplified by the H_2O-CO_2-NaCl ternary system (e.g., Trommsdorff and Skippen, 1986; Skippen and Trommsdorff, 1986; Heinrich et al., 2004; Heinrich, 2007). The critical boundary between $NaCl^{liquid}$ and CO_2 is not well known but it is clear that both are extremely immiscible, even at very high temperature (e.g., Heinrich, 2007; Newton and Manning, 2010). Therefore, a brine (or hypersaline liquid) and a CO_2-H_2O-bearig fluid can coexist under the granulite-facies conditions (Heinrich, 2007).

It is important to understand how widespread such a fluid can be present in natural examples of the lower crust when we try to understand their possible role during granulite facies metamorphism. Evidence for Cl-rich fluids is often found in fluid inclusion which enables us to directly measure the Cl concentration of the fluid. In metamorphic rocks under granulite facies conditions, however, Cl-rich fluid inclusions are rarely found. This may be because brines have a high mobility due to their low viscosity and low wetting angle (Watson and Brenan, 1987; Holness, 1997). If so, this opens up the possibility that Cl-rich fluids are more general during granulite facies metamorphism than might be expected.

On the other hand, the HCl fugacity of a fluid can also be estimated from the Cl concentration in biotite and apatite (Piccoli and Candela, 1994; Selby and Nesbitt, 2000). Therefore, investigating Cl-bearing minerals helps in understanding the role of Cl-rich fluids during metamorphism, and finds more detailed evidence of Cl-rich fluid activities than from fluid inclusions alone. There have been many field-based studies that dealt with local interaction between rock and Cl-bearing fluid in cm- to km-scale shear zones (e.g., Kullerud, 1995; Harlov and Förster, 2002; Rubenach, 2005) or Cl-bearing fluid activity near the igneous complex (e.g., Hanley and Mungall, 2003). However, to our knowledge, the study that mapped the field distribution of Cl-rich minerals in the regional high-grade metamorphic complex scale is scarce.

In this study, in order to evaluate the importance of Cl fluid or melt activity in a regional metamorphic complex scale, the fluid or melt activity recorded in biotite and apatite in the pelitic lithologies of the Sør Rondane Mountains, East Antarctica is mapped. The *P*-*T* condition and the age of Cl-rich fluid or melt activity are also determined. Mineral abbreviations are after Kretz (1983).

2. Geological setting

The Sør Rondane Mountains (22°–28°E, 71.5°–72.5°S), eastern Dronning Maud Land, East Antarctica is dominated by metamorphic rocks and granitoids (Shiraishi et al., 1991; Asami et al., 1992) (Fig. 1). The Sør Rondane Mountains is thought to be a part of the collision zone between East and West Gondwana during the Pan-African event (Jacobs et al., 2003). The Sør Rondane Mountains are divided into the NE Terrane and the SW Terrane by an inferred tectonic line, the Sør Rondane Suture (Osanai et al., 1992). The NE Terrane is mainly composed of granulite-facies metamorphic rocks of pelitic (kyanite-bearing), psammitic, and intermediate compositions (Shiraishi and Kojima, 1987; Asami and Shiraishi, 1987; Grew et al., 1989), whereas the SW Terrane is composed of amphibolite facies and lower grade metamorphic rocks of mainly intermediate to basic composition, including a large volume of meta-tonalite (Shiraishi et al., 2008). Peak metamorphic conditions in Brattnipane are estimated as ca. 800 °C and 0.7–0.85 GPa (Fig. 1; Shiraishi and Kojima, 1987) though possible ultrahigh-temperature conditions are also inferred (Nakano et al., 2011).

SHRIMP zircon U-Pb dating for metamorphic and igneous rocks from the whole area of the Sør Rondane Mountains have been compiled by Shiraishi et al. (2008). The abundant and widespread growth of metamorphic zircon at ca. 600 Ma is interpreted as timing the peak of granulite-facies metamorphism and ductile deformation in the NE Terrane. Inherited and detrital zircon ages, ca. 800–750 Ma and ca. 570–550 Ma metamorphic zircon ages are reported in the NE Terrane (Shiraishi et al., 2008). However, there is an absence of ca. 600 Ma zircon age from the SW Terrane (Shiraishi et al., 2008).

The crystalline basement exposed around Balchenfjella is composed of high-grade gneissic rocks accompanied by migmatite and small intrusive bodies (Fig. 1; Asami et al., 1990, 2007). The metamorphic rocks are metasedimentary, metavolcanogenic,

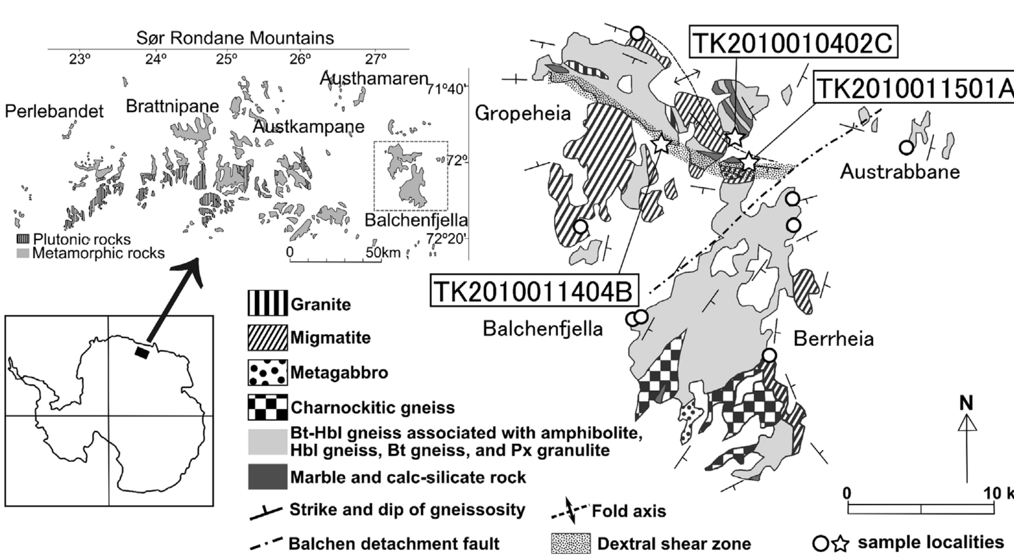

Fig. 1. Simplified map of the Sør Rondane Mountains (after Shiraishi et al., 1997) and the geological map of Balchenfjella (after Asami et al., 2007) showing the sample localities studied. Three stars are the sample localities of Cl-rich biotite-bearing rocks and open circles are the sample localities of Cl-rich biotite-absent rocks. Detailed descriptions of these rocks are given in Fig. 2 and Table 1. Balchen detachment fault and dextral shear zone are from Ishikawa et al. (2013).