Fluid fluxes through the reaction zones and fractures in metamorphic rocks revealed by reactive-transport model coupled with phase equilibrium: Evidence from fluid–rock reaction zones, Sør Rondane Mountains, East Antarctica

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Introduction

Aqueous fluid flow in the Earth's crust cause hydration reactions, which induce mass transport, and changes rheology of rocks. Recent geophysical observations have revealed a relationship between cyclical fluid infiltration and seismic events (e.g., Obara, 2002; Ohmi and Obara, 2002). The periodic seismic cycles are explained by the accumulation of fluids, followed by an increase in fluid pressure, and subsequent fracturing. The fracturing enhances permeability and provides fluid transport pathways. As such, dynamic changes in the fluid pressure and permeability in the middle–lower crust are key to further understanding the relationship between fluid infiltration and fracturing. However, quantitative constraints on fluid pressure gradients and crustal permeability are limited, particularly with regards to its temporal evolution. Therefore, it is important to constrain timescales of fluid infiltration to understand fluid pressure gradient, permeability, and fluid fluxes. Here we constrain the permeability evolution in the middle–lower crust, based on metamorphic processes associated with fluid infiltration and crustal fracturing and discuss fluid fluxes through the fractures and perpendicular to it, leading to the hydration reaction zones formation.

Samples

We investigated fluid-rock reaction zones in hydrated metamorphic rocks samples from the Mefjell (Fig.1 a) and Brattnipene (Fig.1 b) Sør Rondane Mountains (SRM), East Antarctica. Millimetre-scale reaction zones occur along fractures (Fig.1). We investigated mafic granulite, opx–hbl schist samples (Fig.1 a) from Mefjell that are partially hydrated along fractures due to hydration reactions. Opx–hbl gneiss samples (Fig.1 b) collected from Brattnipene also hydrated. In the opx–hbl gneiss samples schistosity is well developed, reaction zones with width from several mm to cm crosscut the schistosity.

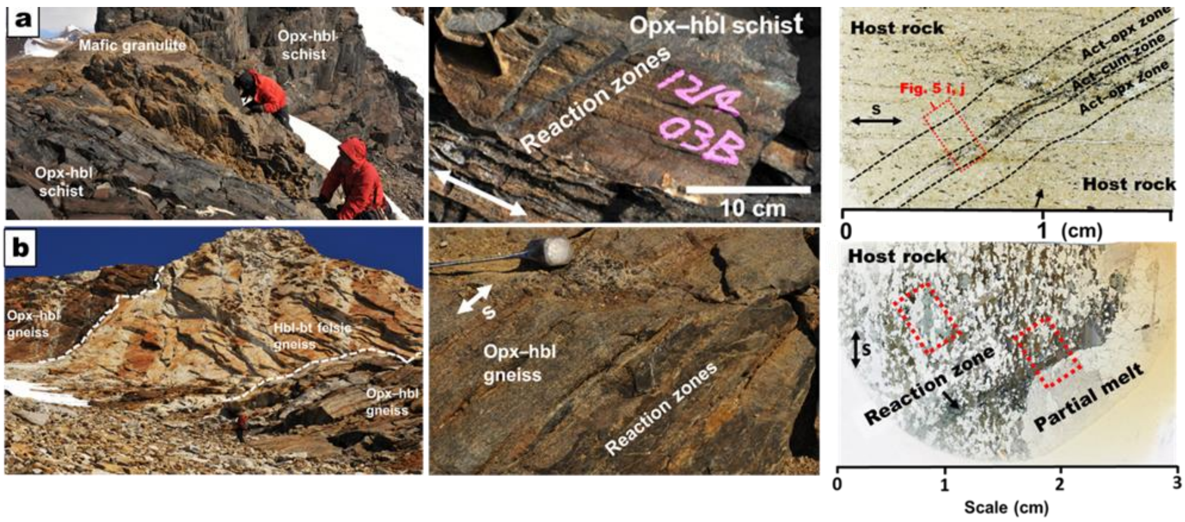

Figure 1. Photographs of partly hydrated mafic granulite, opx–hbl schist (a) and opx–hbl gneiss (b). Opx–hbl schist and opx–hbl gneiss with the white arrow showing the schistosity and close-up of the reaction zones and thinsection scans.

Methods

Previous studies (e.g., Higashino et al., 2013; Kawakami et al., 2017; Uno et al 2017) suggested Cl-bearing fluid infiltration in the SRM. Chlorine concentrations in apatite and amphibole grains show a gradual decrease from the fractures toward the host rocks. Chlorine concentration profiles were analyzed by a reactive-transport model to define transport mechanism.

We will discuss time-integrated fluid flux through the reaction zone Q_{hyd} (m) and $Q_{cl\ tr}$ (m) and compare to fluxes through the fracture Q_{fr} (m) estimated by Darcy's law and from chemical alteration ($Q_{ch\ al}$). Fluid flux through the reaction zone Q_{hyd} was estimated applying Darcy's law. We assumed that the total amount of fluid flux passing through the cross-section area in the direction toward the host rock is parallel to the fracture (Fig.2 a). The time-integrated hydration fluid flux equivalent to the volume of fluid consumed to form reaction zones along the fractures. It was compared to fluid flux required for Cl transport $Q_{cl\ tr}$. To estimate $Q_{cl\ tr}$ we applied fluid velocities, assumed porosity and timescales of fluid infiltration (Fig.2 a). Fluid flux through the fracture was calculated from the parameters estimated by thermodynamic modelling applying Darcy's law Q_{fr}. We will also discuss fluid flux through the fractures estimated from the chemical alteration and mass balance.

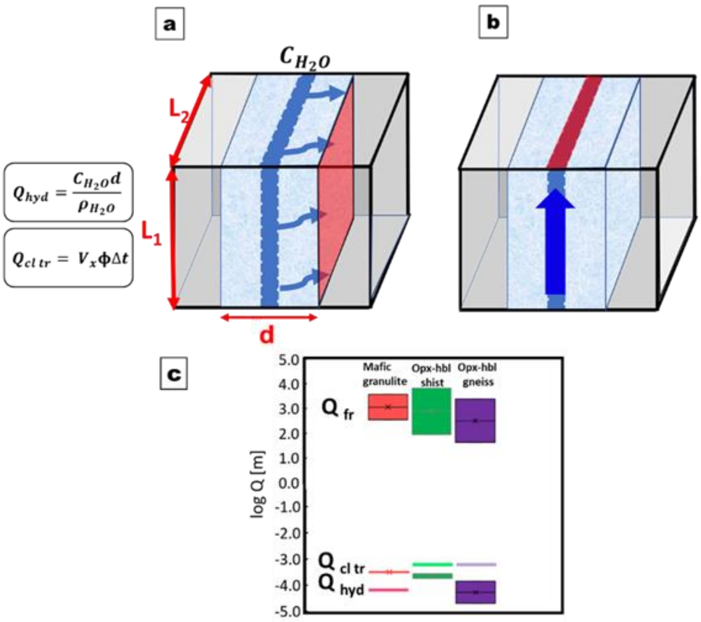

Figure 2. Schematic model used for the estimation of time-integrated fluid flux through the reaction zone (a) and through the fracture (b). Time integrated hydration fluid flux Q_{hyd} and flux required for Cl transport $Q_{cl\,tr}$ through the reaction zone compared to time-integrated fluid flux through the fracture Q_{fr} estimated by Darcy's law (c).

Results

Fitting results suggest that advection with minor diffusion is dominant. The timescales of fluid infiltration are constrained to tens of hours. The fluid pressure gradient across the reaction zones was estimated from the H_2O activity to be 0.4–1.4 MPa/mm. The permeability of the wall rock and fractures were estimated to be 10^{-20}–10^{-22} and 10^{-8}–10^{-9} m^2, respectively.

Time-integrated fluid fluxes log Q_{hyd} are -4.2 m for the mafic granulite, -3.8 m for the hbl–opx schist, and -3.3 m for the hbl–opx gneiss (Fig 2 c). log $Q_{cl\,tr}$ are same order compare to Q_{hyd}, -3.5 m for the mafic granulite, -3.6 – -3.7 m for the hbl–opx schist, and -3.9 – -4.7 m for the hbl–opx gneiss (Fig 2 c).

Discussions

Our results show that rapid infiltration of Cl-bearing fluids occurred due to a limited fluid flux. Low permeable wall rock (10^{-20}–10^{-22} m^2) was fractured due to fluid accumulation and rising of the fluid pressure. The spatio-averaged permeability then significantly increased (10^{-10}–10^{-16} m^2). The contrasting permeability reveals enhancements associated with crustal fracturing on timescales comparable to geophysical observations. Time- integrated fluid flux through the fracture is much higher compare to reaction zone, suggesting that much amount of fluid was transported through the fracture, and less was stored in the reaction zones (Fig 2 c).

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