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Magma-driven hydraulic fracturing and infiltration of fluids into the damaged host rock, an example from Dronning Maud Land, Antarctica

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Abstract

Excellent outcrops in Dronning Maud Land, Antarctica, provide unique insight into the mode and extent of fluid infiltration into metamorphic and plutonic rocks in the middle crust. The fluids are liberated from pegmatitic veins and give rise to alteration halos. In the alteration halos, the conspicuous change in colour is correlated with (1) hydration mineral reactions, and (2) high density of microcracks in quartz and feldspar exceeding that observed in the unaltered host rock by an order of magnitude. The field relations indicate that the veins originated as melt-driven hydraulic fractures, sealed by pegmatite and aplite crystallising from volatile-rich melts, with the alteration halo being the wake of the process zone formed at the tip of the propagating fractures. It is proposed that (1) the size of the alteration zone and the width of the vein are correlated, resulting in higher values of both these quantities for cracks propagating at higher velocities and consequently higher crack propagation toughnesses; (2) the damage zone is characterised by a transient state of high permeability which was short-lived due to rapid healing and sealing of microcracks; (3) the infiltration and retrogression of the high-grade rocks can be considered as a quasi-instantaneous process on geologic time scales with a duration of hours to weeks.

Keywords: Alteration halo; Antarctica; Damage zone; Fluid infiltration; Hydraulic fracture; Process zone

1. Introduction

Pegmatite veins are supposed to form from hydraulic fractures driven by the excess pressure of intruding hydrous melts (e.g. Brisbin, 1986). For tensile cracks to form by hydraulic fracturing, the fluid pressure must exceed the magnitude of the least principal stress by the tensile strength of the rock (e.g. Secor, 1965; Shaw, 1980) or, in fracture mechanics terminology, exceed the fracture toughness of the rock. Upon cooling and crystallisation, the portion of volatiles in the pegmatitic melt that is not incorporated into minerals is liberated as a fluid phase (Burnham, 1979). Transport of this fluid phase away from the crystallising magma is governed by the porosity and permeability of the host rock of the pegmatite vein.

Metamorphic and magmatic rocks in central Dronning Maud Land, East Antarctica, provide an outstanding insight into these phenomena due to the excellent quality of the exposures. In this area, pegmatitic veins were emplaced in high-grade metamorphic rocks and the fluids liberated from crystallising pegmatitic melt infiltrated the host rock on both sides of the central vein causing alteration. The extent of the infiltrated zones is conspicuous owing to the marked change of the rock colour from dark brown to light. This reveals a characteristic width of the alteration halo and a sharp boundary. Similar alteration zones around veins were described by Segall and Pollard (1983), Segall (1984a,b),

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Austrheim (1990) and Kostenko et al. (2002), for example. In the present paper, the basic geometric properties of the alteration halos flanking the pegmatitic veins in central Dronning Maud Land are described. Microscopic evidence for crack-controlled fluid infiltration controlling the extent of the alteration halos is presented. Alternative concepts for the origin of the damage zone flanking the pegmatite veins are discussed. Based on mechanical considerations, it is proposed that the damage zone that gave rise to the conspicuous alteration halo represents the wake of the advancing crack tip process zone of the hydraulic fracture, which developed into the pegmatite vein. The width of the light alteration zones hence reflects the radius of the process zone at the tip of the main fracture. Finally, it is suspected that the entire alteration process took place during a short period, rapidly halted by healing and sealing of the microcracks in the wake.

2. Geological setting and petrography of unaltered rocks

The mountain range of Dronning Maud Land, East Antarctica, was a part of Gondwana formed in late Neoproterozoic to early Paleozoic times (Jacobs et al., 1998; Fitzsimons, 2000). In Dronning Maud Land, Mesoproterozoic (ca. 1.1–1.0 Ga) rocks were intruded by voluminous intrusions and underwent granulite facies metamorphism and deformation during the Pan-African event (Elworthy, 1982; Ohta et al., 1990; Moyes, 1993; Mikhalsky et al., 1997; Jacobs et al., 1998). Mühlig-Hofmannfjella and Filchnerfjella consist of a series of granitoid intrusives, which are emplaced in granulite and upper amphibolite facies metamorphic host rocks (Ohta, 1999). In the area of 5–8°E three principal rock complexes of banded gneisses, charnockite and quartz syenite are distinguished (Fig. 1). The present study focuses on samples collected from three localities representing each of the different lithologies.

2.1. Banded gneisses

Banded gneisses include brown orthopyroxene-bearing gneiss, leucocratic gneiss, metapelite and garnet amphibolite. The gneisses have experienced granulite facies metamorphism and widespread anatexis. Peak metamorphic temperatures reached >850 °C at intermediate pressure, followed by a stage of near-isothermal decompression (Engvik and Elvevold, 2004). Granulite facies metamorphism in central Dronning Maud Land is dated as 590–515 Ma (Mikhalsky et al., 1997; Jacobs et al., 1998).

The migmatitic garnet–orthopyroxene gneiss of Kubusfjellet (locality 1) reveals a variable grain size on the sample scale, being characteristic for the different layers defining the foliation. The granoblastic matrix is made up of anhedral quartz and feldspar grains. The feldspars comprise plagioclase, orthoclase, perthite, and minor antiperthite. Myrmekite is common. Biotite flakes show a preferred orientation and are concentrated in thin layers together with orthopyroxene. Garnet is evenly distributed throughout the rock. Apatite, monazite, zircon, and ilmenite are accessory minerals.

2.2. Charnockite

The charnockite complex comprises massive, coarse-grained granite with igneous textures and granitic gneiss with well-developed banding and foliation. All gradations between preserved magmatic and gneissic textures are observed, all varieties revealing granulite facies mineral assemblages with orthopyroxene and biotite. The unfoliated granite commonly displays a weak preferred orientation of the euhedral tabular perthite megacrystals and locally diffuse dark bands enriched by orthopyroxene and biotite.

Reddish brown orthopyroxene-bearing charnockite of Svarthamaren (locality 2) displays a heterogranular texture and a fine- to medium grain size. Feldspars and quartz dominate the charnockite with minor myrmekite. The feldspars comprising perthite and plagioclase commonly

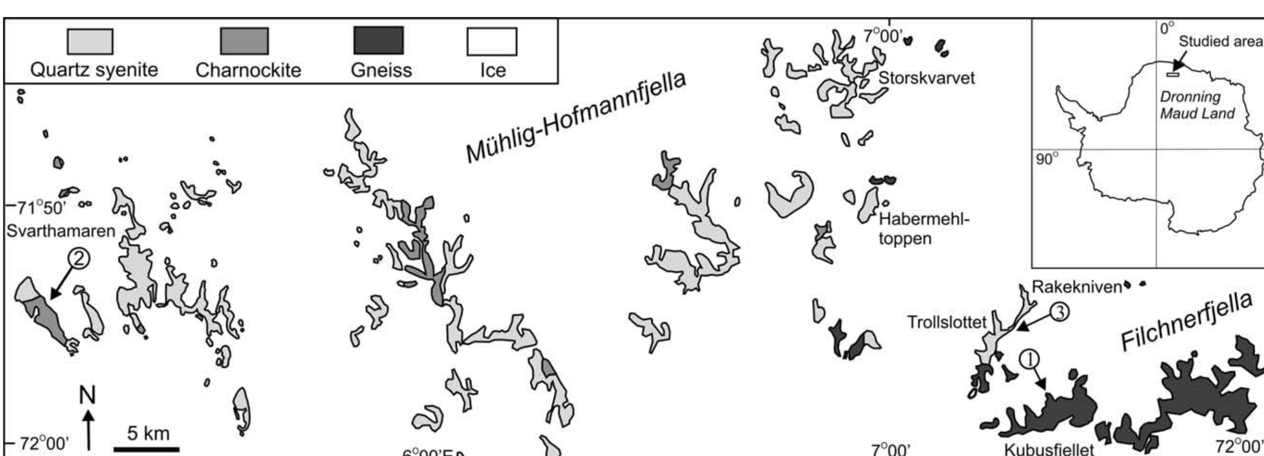

Fig. 1. Geological map of Mühlig-Hofmann and Filchnerfjella, Dronning Maud Land, Antarctica. The sample locations 1–3 are marked by encircled numbers.