Geoscience Frontiers 5 (2014) 683–695

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Deciphering fluid inclusions in high-grade rocks

Alfons van den Kerkhof*, Andreas Kronz, Klaus Simon

Geowissenschaftliches Zentrum der Universität Göttingen, Goldschmidtstr. 1-3, D 37073 Göttingen, Germany

A R T I C L E I N F O

Article history:
Received 31 October 2013
Received in revised form
27 February 2014
Accepted 14 March 2014
Available online 29 March 2014

Keywords:
Fluid inclusions
Granulite
Charnockite
Cathodoluminescence
LA-ICPMS
Quartz

A B S T R A C T

The study of fluid inclusions in high-grade rocks is especially challenging as the host minerals have been normally subjected to deformation, recrystallization and fluid-rock interaction so that primary inclusions, formed at the peak of metamorphism are rare. The larger part of the fluid inclusions found in metamorphic minerals is typically modified during uplift. These late processes may strongly disguise the characteristics of the "original" peak metamorphic fluid. A detailed microstructural analysis of the host minerals, notably quartz, is therefore indispensable for a proper interpretation of fluid inclusions. Cathodoluminescence (CL) techniques combined with trace element analysis of quartz (EPMA, LA-ICPMS) have shown to be very helpful in deciphering the rock-fluid evolution. Whereas high-grade metamorphic quartz may have relatively high contents of trace elements like Ti and Al, low-temperature re-equilibrated quartz typically shows reduced trace element concentrations. The resulting microstructures in CL can be basically distinguished in diffusion patterns (along microfractures and grain boundaries), and secondary quartz formed by dissolution-reprecipitation. Most of these textures are formed during retrograde fluid-controlled processes between ca. 220 and 500 °C, i.e. the range of semi-brittle deformation (greenschist-facies) and can be correlated with the fluid inclusions. In this way modified and re-trapped fluids can be identified, even when there are no optical features observed under the microscope.

1. Introduction

Fluid inclusions in high-grade metamorphic rocks have been studied much later than for other lithologies such as hydrothermal and magmatic rocks, which have been systematically described since the 19th century. Pioneering studies on geological fluids in high-grade rocks dated back to the early 1970's (Touret, 1981, 2001) and awakened a lively interest, which continues until today. The study of fluid inclusions in metamorphic rocks was particularly stimulated by the recognition of their role in stabilizing metamorphic mineral assemblages from autoclave experiments coupled with thermodynamic calculations (e.g. Winkler, 1965). Relic fluids, preserved as inclusions in natural rocks, are the only direct evidence of the role of fluids during metamorphism. However, fluid inclusions in metamorphic rocks are normally strongly modified during retrograde conditions such that the corresponding microtextures are complex. They therefore pose a challenge for unravelling the role of the metamorphic fluid during rock evolution. The fluid inclusion inventory within one rock sample may show a large variation in compositional and density, which must reflect different stages of rock evolution to investigate. In some granulites the fluid inclusions are extremely difficult, consisting only of small, highly transposed inclusions. In other granulites, they are much easier to investigate consisting of relatively large and abundant fluid inclusions in many of the rock-forming minerals. It should be emphasized that since fluid inclusions are a part of the rocks, they must be studied as much as any other rock constituent (Jacques Touret pers. comm.).

Carbonic fluid inclusions are typical for many granulite rocks and were recorded for the first time in the Bamble Sector, southern Norway (Touret, 1971a, b), i.e. within the zone delimited by the orthopyroxene-in isograd. The CO_2 is assumed responsible for the low H_2O activities required for the stabilization of orthopyroxene in these rocks. Following this first discovery, carbonic fluid inclusions were found in many other granulite-facies rocks worldwide. The

* Corresponding author.
E-mail address: akerkho@gwdg.de (A. van den Kerkhof).

Peer-review under responsibility of China University of Geosciences (Beijing)

Production and hosting by Elsevier

1674-9871/$ – see front matter
http://dx.doi.org/10.1016/j.gsf.2014.03.005

number of fluid inclusion studies in granulite rocks rose steadily from <5 to ca. 15 to 35 publications per year in the late 1980's and early 1990's (Fig. 1). In the early 1980's the introduction of Laser Raman micro-spectrometry for geological studies allowed for the fast detection of CO_2 and therewith stimulated the study of micron-scale "gas inclusions" in rocks. The somewhat lower number of studies nowadays can be explained by the general acceptance of CO_2 being the dominant fluid phase in granulite-facies rocks. Still some scepticism persists for a number of geologists who consider a proper interpretation of fluid inclusions in high-grade metamorphic rocks problematic, or at the best "difficult", due to the strongly modified character of the majority of fluid inclusions with only a few (if any at all) preserved unchanged from peak-metamorphic conditions.

In addition to CO_2, high-salinity brines are known as an important constituent of many high-grade metamorphic rocks. These fluids also help to reduce the rock H_2O activity and stabilize "dry" mineral assemblages (Touret, 1985). Brines are found in many granulite-facies rocks along side carbonic inclusions.

For more than two decades, fluid phase petrology, i.e. the study of fluid inclusions and related microtextures, has made good use of cathodoluminescence (CL) techniques in order to visualize fluid-induced textures, which cannot be observed otherwise (e.g. van den Kerkhof and Hein, 2001). In the present paper we give an overview and a guideline for fluid inclusion studies in quartz from high-grade metamorphic rocks, from microscopic observations including detailed fluid inclusion mapping to microthermometry, CL and trace element analysis.

2. Carbonic fluid inclusions in granulite rocks

Fluid inclusions in granulite-facies rocks are almost always preserved in quartz as the host mineral. Some granulite-facies rocks also show carbonic inclusions in other minerals like garnet, plagioclase, pyroxene, apatite, and zircon, besides fluid inclusions in quartz. Examples are the Doddabetta charnockite complex, Southwest India (Touret and Hansteen, 1988), the East African charnockites (Coolen, 1980; Herms and Schenk, 1998), Victoria Land, Antarctica (van den Kerkhof et al., 1998) and Varberg charnockite, SW Sweden (Harlov et al., 2013). The reason that carbonic inclusions are sometimes preserved in all the rock-forming minerals and in other cases only in quartz only, has not been fully explained so far, but suggests a high CO_2 activity during the growth of these minerals. Comparison between examples from the literature suggests that igneous charnockites tend to contain fluid inclusions in more than one rock-forming mineral (e.g. garnet, plagioclase, and quartz), whereas metamorphic charnockites normally have fluid inclusions in quartz only. However, there are exceptions and the distinguishing features between igneous vs. metamorphic charnockites have not been completely resolved (Touret and Huizenga, 2012).

The first studies of carbonic inclusions in metamorphic rocks already demonstrated large variations in fluid inclusion densities on the micron scale (e.g. Touret, 1971a, b). Normally few high-density CO_2 inclusions (>1 g/cm^3), originating from the peak-metamorphic conditions, are preserved and the majority of inclusions show densities down to the critical density of CO_2 (0.47 g/cm^3), or lower. Inclusions with highest density often show primary characteristics, i.e. they are isolated, or part of a cluster, as a group of inclusions formed by partial fluid re-trapping during uplift. However, fluid inclusions with the highest density are earliest only in the case of decompression paths, not always in the case for HT-granulites. Inclusion geochronology should be exclusively deduced from the inclusion morphology, i.e. the relation with the host mineral, and then the density evolution can be discussed in the light of this timing. We will see in the present study that the

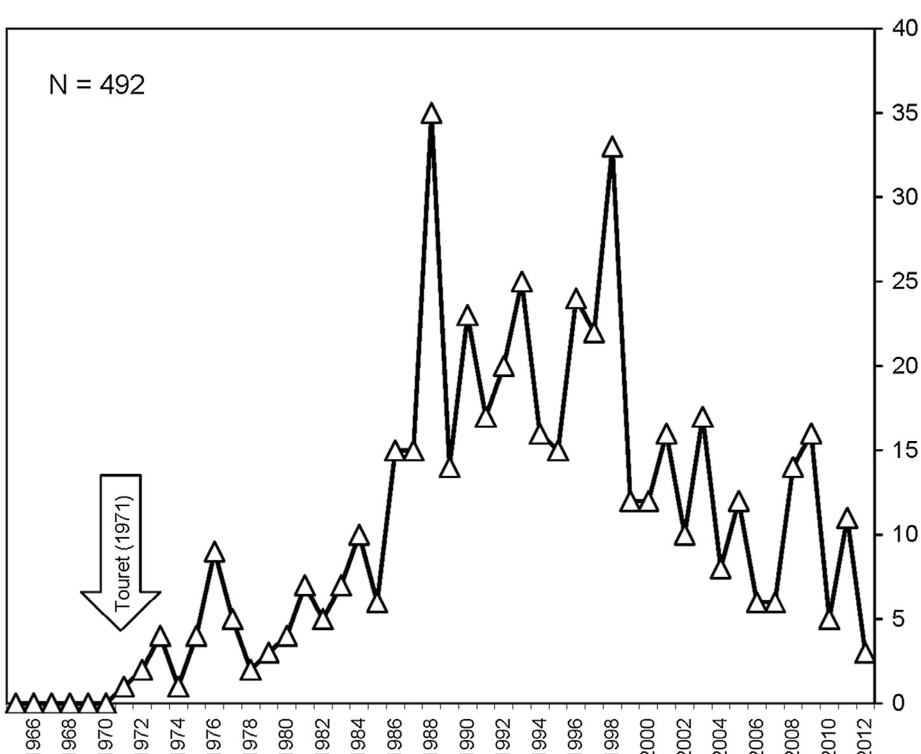

Figure 1. Graphic presentation of the number of publications on fluid inclusions in granulite-facies rocks as obtained from the GeoRef data base (American Geosciences Institute). Total number of items = 492, from the first publication (Touret, 1971a, b) until 2012.