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Invited review article

What can we learn from melt inclusions in migmatites and granulites?

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ABSTRACT

With less than two decades of activity, research on melt inclusions (MI) in crystals from rocks that have undergone crustal anatexis – migmatites and granulites – is a recent addition to crustal petrology and geochemistry. Studies on this subject started with glassy inclusions in anatectic crustal enclaves in lavas, and then progressed to regionally metamorphosed and partially melted crustal rocks, where melt inclusions are normally crystallized into a cryptocrystalline aggregate (*nanogranitoid*).

Since the first paper on melt inclusions in the granulites of the Kerala Khondalite Belt in 2009, reported and studied occurrences are already a few tens. Melt inclusions in migmatites and granulites show many analogies with their more common and long studied counterparts in igneous rocks, but also display very important differences and peculiarities, which are the subject of this review. Microstructurally, melt inclusions in anatectic rocks are small, commonly 10 μm in diameter, and their main mineral host is peritectic garnet, although several other hosts have been observed. Inclusion contents vary from glass in enclaves that were cooled very rapidly from supersolidus temperatures, to completely crystallized material in slowly cooled regional migmatites. The chemical composition of the inclusions can be analyzed combining several techniques (SEM, EMP, NanoSIMS, LA–ICP–MS), but in the case of crystallized inclusions the experimental remelting under confining pressure in a piston cylinder is a prerequisite. The melt is generally granitic and peraluminous, although granodioritic to trondhjemitic compositions have also been found.

Being mostly primary in origin, inclusions attest for the growth of their peritectic host in the presence of melt. As a consequence, the inclusions have the unique ability of preserving information on the composition of primary anatectic crustal melts, before they undergo any of the common following changes in their way to produce crustal magmas. For these peculiar features, melt inclusions in migmatites and granulites, largely overlooked so far, have the potential to become a fundamental tool for the study of crustal melting, crustal differentiation, and even the generation of the continental crust.

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Prologue

The reader may be interested in a "historical" background to the birth and development of research in this topic.

Everything began by a serendipitous encounter with G. Venturelli (University of Parma, Italy), who owned some extraordinary thin sections of metapelitic enclaves from the dacite of El Hoyazo (Betic Cordillera, SE Spain) and offered the senior author (BC) to take part in a research project on those volcanic rocks and their crustal enclaves. The enclaves turned out to contain abundant, undevitrified glassy inclusions in most of their minerals, and in particular in garnet; for such peculiarity they can be considered unique in the world. Although El Hoyazo is visited by dozens of geologists yearly, this aspect had been completely neglected. The melt inclusions (MI) in the enclaves of El Hoyazo, and subsequently of Mazarrón, have turned out to shelter a small geological treasure and are still undergoing a thorough microstructural and chemical characterization (Acosta-Vigil et al., 2012a and references therein). Having recognized that MI were trapped by the growing host minerals during melting of the enclaves (Cesare and Maineri, 1999), and that they could be analyzed to gain information on the chemical composition of crustal anatectic melts (e.g., Cesare et al., 2003a), the consequential following step has been to look for similar MI in regionally metamorphosed anatectic rocks such as migmatites and granulites, in order to understand if MI entrapment was an exceptional feature of enclaves or a common process during crustal anatexis.

After a few years of search, the first finding of MI (*nanogranites*) in regionally melted rocks came from a granulite of the Kerala Khondalite Belt (India, Cesare et al., 2009a). Since then, some tens of occurrences have been recorded in metapelitic, metapsammitic and metagranitoid migmatites and granulites worldwide, providing the justification for this paper.

1. Introduction

This is a review of the state of the art of knowledge on melt inclusions (MI) in migmatites and granulites. Research on MI in high-grade anatectic rocks would have started earlier if the report of inclusions in garnet and the insightful interpretations made by Hartel et al. (1990; unknown to the writers until 1999) had been followed by further, detailed studies. But it was not the right time, yet, and the first paper where MI are extensively described and discussed appeared a few years later (Cesare et al., 1997).

Although MI are well known since Sorby (1858) and have been extensively used in igneous petrology, geochemistry, volcanology and economic geology (reviews in Roedder, 1984; Frezzotti, 2001; Audétat and Lowenstern, 2014), until recently they have been observed and studied exclusively in intrusive and extrusive igneous rocks. Conversely, apart from a few notable exceptions (e.g., Chupin et al., 1998, 2001), they have been overlooked in partially melted crustal rocks such as migmatites, granulites and enclaves or xenoliths in lavas.

Such lack of recognition of MI outside igneous systems is still so well established that MI are defined as "droplets of silicate melt that are trapped in minerals during their growth in a magma" (Audétat and Lowenstern, 2014; Clocchiatti, 1975). This incomplete definition needs to be modified, and the perspective on related processes widened, as MI also occur in crustal rocks that have undergone partial melting, and in host minerals (e.g., garnet, hercynite, ilmenite) from rocks which clearly do not have an igneous origin. A review about a novel topic such as MI in high-grade anatectic rocks is therefore timely and useful for crustal petrology and related disciplines.

Reviewing the literature produced mainly by the research group of the writers, this paper discusses in detail the origin by incongruent melting of MI in migmatites, granulites and anatectic enclaves, outlining the fundamental differences between these inclusions and those formed during magma crystallization. It provides an exhaustive description of the optical and electron microscope features of MI, from totally glassy to fully crystallized, and reviews the analytical techniques adopted for the microstructural and chemical characterization of MI, discussing analogies and differences with respect to analysis of MI in igneous rocks. Then the paper outlines the key microstructural and chemical information that can be obtained from MI, and reports some significant examples of how this new approach has impacted on our views of crustal anatexis. Finally, after a comment on the problems and pitfalls of studies on MI and of data interpretation, and a reply to the main objections raised in the recent literature against our approach, we highlight some of the directions where research on MI in crustal rocks should focus in the next decade.

2. What are melt inclusions?

Research on MI has a long history, and continues to provide key information for our understanding of, among others, igneous processes, volcanism, ore formation, and even the origin of the solar system. Being by far more common in igneous rocks, especially volcanic, it is easy to understand why MI have been fully exploited in these systems, and why conversely they have been neglected in granulites and migmatites where they are more rare, difficult to recognize, and were not expected to occur until recently.