Lithos 206–207 (2014) 303–320

Contents lists available at ScienceDirect

Lithos

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

Microstructures and petrology of melt inclusions in the anatectic sequence of Jubrique (Betic Cordillera, S Spain): Implications for crustal anatexis

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ARTICLE INFO

Article history:
Received 29 May 2014
Accepted 1 August 2014
Available online 12 August 2014

Keywords:
Melt inclusions
Crustal anatexis
Kyanite
Ronda peridotites
Betic Cordillera

ABSTRACT

We report a new occurrence of melt inclusions in polymetamorphic granulitic gneisses of the Jubrique unit, a complete though strongly thinned crustal section located above the Ronda peridotite slab (Betic Cordillera, S Spain). The gneissic sequence is composed of mylonitic gneisses at the bottom and in contact with the peridotites, and porphyroblastic gneisses on top. Mylonitic gneisses are strongly deformed rocks with abundant garnet and rare biotite. Except for the presence of melt inclusions, microstructures indicating the former presence of melt are rare or absent. Upwards in the sequence, garnet decreases whereas biotite increases in modal proportion. Melt inclusions are present from cores to rims of garnets throughout the entire sequence. Most of the former melt inclusions are now totally crystallized and correspond to nanogranites, whereas some of them are partially made of glass or, more rarely, are totally glassy. They show negative crystal shapes and range in size from ≈5 to 200 μm, with a mean size of ≈30–40 μm. Daughter phases in nanogranites and partially crystallized melt inclusions include quartz, feldspars, biotite and muscovite; accidental minerals include kyanite, graphite, zircon, monazite, rutile and ilmenite; glass has a granitic composition. Melt inclusions are mostly similar throughout all the gneissic sequence. Some fluid inclusions, of possible primary origin, are spatially associated with melt inclusions, indicating that at some point during the suprasolidus history of these rocks granitic melt and fluid coexisted. Thermodynamic modeling and conventional thermobarometry of mylonitic gneisses provide peak conditions of ≈850 °C and 12–14 kbar, corresponding to cores of large garnets with inclusions of kyanite and rutile. Post-peak conditions of ≈800–850 °C and 5–6 kbar are represented by rim regions of large garnets with inclusions of sillimanite and ilmenite, cordierite-quartz-biotite coronas replacing garnet rims, and the matrix with oriented sillimanite. Previous conventional petrologic studies on these strongly deformed rocks have proposed that anatexis started during decompression from peak to post-peak conditions and in the field of sillimanite. The study of melt inclusions shows, however, that melt was already present in the system at peak conditions, and that most garnet grew in the presence of melt.

1. Introduction

Melt inclusions (MI) are small droplets of liquid, commonly a few to tens of micrometers across, trapped by minerals that grow in the presence of melt. They were first described by Sorby (1858) in igneous rocks, where they constitute a wealth of information on melt chemistry (e.g. Gurenko et al., 2005; Wanless et al., 2014; Webster et al., 1997). Many of the assumptions concerning the interpretation of fluid inclusions (FI) have been applied to MI (Bodnar and Student, 2006; Roedder, 1984; Sorby, 1858). More recently, MI have also been reported in crustal crystalline rocks (Cesare et al., 1997; Hwang et al., 2001; Stöckhert et al., 2001). Most melting reactions during crustal anatexis are incongruent (e.g. Clemens, 2006), i.e. produce melt and peritectic minerals, providing the opportunity that these minerals trap inclusions of the coexisting silicate liquid. Hence, MI trapped during melting can supply the composition of the primary anatectic melt (Cesare et al., 2009, 2011), in contrast with MI trapped during crystallization of cooling igneous rocks that provide the composition of fractionated (as opposed to primary) melts (Thomas and Davidson, 2013; Webster et al., 1997; see also discussion in Bartoli et al., 2014).

Most MI in anatectic terranes appear partially or totally crystallized due to slow cooling at depth. Owing to the granitic phase assemblage made of micron to submicron quartz, feldspars and micas, crystallized MI have been named “nanogranites” (Cesare et al., 2009). With the recent development of in situ and high spatial resolution micro-

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http://dx.doi.org/10.1016/j.lithos.2014.08.003

analytical techniques, as well as appropriate methods to remelt and rehomogenize nanogranites (Bartoli et al., 2013a, 2014), it is possible to characterize precisely MI in order to relate their information to the process of anatexis of the host rock. Hence, MI represent a new and powerful method to study anatexis, primarily because they can provide information on the parental melt compositions produced at the source region of crustal granites, including concentrations of H_2O and fluid regimes (Bartoli et al., 2013b, 2014; Cesare et al., 2011; Ferrero et al., 2012). This information can complement, and in some cases be more precise, than that provided by classical petrological and geochemical studies of anatectic terrains, for instance regarding the composition of the primary anatectic melt, which has been traditionally approximated by the composition of anatectic leucosomes. This is particularly important in cases where deformation has partially or totally erased the primary anatectic macro- and micro-structures. In these cases, the presence of MI may be the only evidence remaining in the rock for the presence and nature of melt (Cesare et al., 2011).

The number of MI occurrences in anatectic terranes reported in the literature is quite modest, and among those cases, only a few provide bulk compositional data from the MI (Bartoli et al., 2013b; Cesare et al., 2011; Ferrero et al., 2012). This is due to the relatively recent discovery of MI in crustal anatectic rocks (Cesare et al., 1997, 2009, 2011; Darling, 2013; Gao et al., 2012; Hwang et al., 2001; Korsakov and Hermann, 2006; Liu et al., 2013; Stöckhert et al., 2001, 2009) and, more importantly, the very recent development of appropriate methodologies to recover the information encrypted within these former droplets of melt (Bartoli et al., 2013a,b, 2014; Malaspina et al., 2006; Perchuk et al., 2008).

We report the presence and microstructures of MI in metasedimentary granulite-facies gneisses of the Jubrique unit, located in contact, and structurally above, the Ronda peridotite slab, in the hinterland of the Betic Cordillera (S Spain). Jubrique constitutes a complete though strongly thinned section (≤5 km) of upper to middle-lower continental crust. The studied gneisses, located at the bottom of the sequence, are strongly deformed and show a complex polymetamorphic history (Loomis, 1972; Torres-Roldán, 1981). Hence, Jubrique provides an exceptional opportunity to study partial melting in complex regional polymetamorphic and strongly deformed rocks by using the new approach of the MI (Cesare et al., 2009, 2011). In addition, crustal anatexis is a fundamental process that controls the differentiation of the continental crust (Sawyer et al., 2011), and this quite continuous section of continental crust offers the opportunity to characterize partial melting of middle-to-lower crustal levels and to study its potential effects on the compositional segregation of the crust. We start in this contribution by describing in detail the microstructures and phase assemblages of the MI present throughout the entire sequence of gneisses and discuss their bearing on the process of partial melting of the gneisses. The fundamental aims of this study consist of (i) describing a new occurrence of MI in the granulitic gneisses of Jubrique, and their microstructural evolution along the prograde metamorphic sequence, and (ii) shedding light on the timing and nature of the anatectic processes that affected these strongly deformed and polymetamorphic rocks.

2. Geological setting

The Betic Cordillera in southern Spain and the Rif in northern Morocco constitute an arcuate orogen formed during the N-S collision between Eurasian and African plates and the westward migration of the Alborán lithospheric domain, from Early–Middle Eocene to Early Miocene times (Fig. 1) (Andrieux et al., 1971; Dewey et al., 1989; Platt et al., 2013). The Alborán domain represents the hinterland of this orogen and is formed by a complex stack of nappes made of mostly supracrustal metamorphic rocks. Based on lithostratigraphic and metamorphic criteria, these nappes have been grouped into two major tectonic complexes which, in the Betic Cordillera, correspond to the Maláguide, on top, and the Alpujárride, at the bottom. In the highest-grade metamorphic areas of the Betics, the Alpujárride unit of Jubrique incorporates at its base a tectonic slab of subcontinental mantle peridotites, the Ronda peridotites (Balanyá et al., 1997; Garrido et al., 2011; Lenoir et al., 2001; Lundeen, 1978; Obata, 1980; Tubía and Cuevas, 1986).

The rocks studied in this contribution are granulite-facies gneisses pertaining to the Jubrique unit. This unit constitutes a complete though strongly thinned section (≤5 km) of upper to middle-lower continental crust, ranging from carbonates and low-grade phyllites at the top, to schists towards the middle, and to garnet-bearing gneisses at the bottom (Fig. 1). Rocks are affected by a penetrative foliation parallel to the lithological contacts. The gneisses are in contact with the underlying Ronda peridotites through a high temperature ductile shear zone; this contact is parallel to the mylonitic foliation of the crustal rocks. The peridotites constitute a slab of subcontinental mantle up to 5 km thick (Balanyá et al., 1997; Lundeen, 1978). Carbonates and phyllites are Permo-Triassic and were deformed and metamorphosed during the Alpine orogeny. Schist and gneisses are pre-Carboniferous and represent a polymetamorphic basement affected by at least the Variscan and Alpine orogenies. Rocks from all levels in the crustal section seem to record nearly isothermal decompression paths, from 14–12 kb to 4 kb at 750–800 °C in the case of the gneisses located at the contact with the Ronda peridotites. The HP-HT event has been related to the thickening of the Alborán domain. The main foliation in the rocks postdate HP-HT assemblages and predate LP-HT minerals and, hence, has been associated with the ductile thinning of the sequence. In this interpretation, Jubrique would represent a thinned and stretched remain of the Alpine collisional thickened crust (Argles et al., 1999; Balanyá et al., 1997; Platt et al., 2003; Torres-Roldán, 1981). The gneisses located at the bottom of the crustal sequence and in contact with the peridotites were above their solidus during part of the metamorphic evolution. Previous studies have concluded that partial melting occurred during decompression and in the field of sillimanite (Platt et al., 2003). Recent studies of gneisses of apparently similar composition and structural position in the Rif have described the presence of diamond and coesite included in garnet, suggesting UHP conditions of 6–7 GPa at $T > 1100$ °C (Ruiz-Cruz and Sanz de Galdeano, 2012, 2013).

3. Analytical methods

The minimum amount of material collected in the field for chemical analyses was about 8 to 10 kg per sample. Powders with a grain size ≤25 μm were obtained by crushing and milling the samples using a crusher with hardened still jaws and an agate ring mill, respectively. Bulk rock major element analyses were conducted by X-ray fluorescence spectrometry at the Instituto Andaluz de Ciencias de la Tierra (CSIC, Universidad de Granada), using a Bruker AXS S4 Pioneer instrument. The analyses were done on glass beads made by fusing the rock powder mixed with $Li_2B_4O_7$. The analytical detection limit and instrumental error were 0.1 % and <1 %, respectively.

Microstructrures of MI were characterized using conventional microscope petrography and a QUANTA 400 environmental scanning electron microscope at the Centro de Instrumentación Científica (CIC), Universidad de Granada, equipped with EDAX EDS (ultrathin window) and Li(Si) detectors. Mineral compositions were determined using a Cameca SX100 electron microprobe at the CIC. Natural and synthetic silicate oxides were used for calibration and ZAF correction was applied.

4. Sampling, petrography and composition of minerals

Most of the previous petrologic studies have divided the gneissic sequence of Jubrique into two major gneiss types, based either on the structures or mineral assemblages. Although structures, mineralogy and microstructures indicate that these rocks represent anatectic migmatites (see below), we have maintained the previous terminology