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Re-equilibration of primary fluid inclusions in peritectic garnet from metapelitic enclaves, El Hoyazo, Spain

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ABSTRACT

Primary-appearing fluid (FI) and melt (FI) inclusions occur in peritectic garnet from restitic enclaves from El Hoyazo (Spain). The inclusions were trapped under conditions of immiscibility during partial melting of the enclaves. Trapped fluids in Bt–Grt–Sil and Spl–Crd enclaves have been characterized by microthermometric, Raman spectroscopic, electron microprobe (EMP) and transmission electron microprobe (TEM) analyses to better constrain melt and fluid products and pressure conditions of the partial melting event. In Bt–Grt–Sil enclaves, FI are one phase and contain a CO_2-N_2 mixture, sometimes with graphite as trapped phase. In Spl–Crd enclaves, FI are two phase and contain an H_2O-rich (≤90 mol%), with minor amounts of CO_2, N_2, and traces of H_2S and CH_4. Graphite often occurs as a trapped phase in the H_2O-rich FI, and rare carbonates and other accessory minerals are also observed. Although decrepitation features are not recognized during examination with a petrographic microscope, FI densities based on mass balance constraints are always lower than expected at the inferred PT conditions of entrapment, 5–7 kbar and 800–900 °C. Extremely low densities (≈0.1 g cm^{-1}) of FI in Bt–Grt–Sil enclaves suggest a pressure ≤500 bar at 800–900 °C, while densities up to 0.53 g cm^{-1} in Spl–Crd enclaves indicate P≤3 kbar at 800–900 °C. Re-equilibration is likely to have occurred via partial decrepitation, as suggested by TEM studies that show rare partially annealed sub-μm cracks, containing small cavities, which may have been the pathways for fluid movement out of the inclusions. MI coexisting with FI have a rhyolitic, peraluminous composition, with higher H_2O contents of MI in Spl–Crd enclaves (≈9 wt.%) compared to MI in Bt–Grt–Sil enclaves (≈3 wt.%). Based on published data, peritectic garnet in Spl–Crd enclaves grew in the presence of a leucogranitic melt saturated in an H_2O-rich fluid, in good agreement with the inferred garnet PT growth conditions. The composition of the fluid phase coexisting with melt in Bt–Grt–Sil enclaves cannot be evaluated owing to the almost complete decrepitation and fluid loss from FI, and may only be inferred to have been more CO_2-rich, based on the lower H_2O content of the coexisting melt.

1. Introduction

Partially melted metapelitic enclaves are abundant in dacitic lavas from the Neogene Volcanic Province (NVP) in southern Spain, and contain anatectic melt, preserved as an amorphous phase (glass) in intergranular layers, in microfractures and in melt inclusions. Studied enclaves underwent partial melting at 9.3–9.9 Ma, after which they resided at high-temperature (HT) conditions for 3 Ma before host dacite extrusion (Cesare et al., 2003; 2009b). Because of their unusual history, they represent a unique case of "migmatites-in-progress" rapidly brought to the surface by a volcanic eruption. Rapid cooling froze the residual melanosomes and allowed the preservation of many of the features that were present at depth. Preserved glass in these samples permits a direct characterization of the anatectic melt as it forms during crustal melting. In fact, many of the typical problems related to slow cooling of leucosomes in classic migmatite terrains, such as fractional crystallization, cumulus phenomena, and mixing with other source melts (Sawyer and Brown, 2008; Marchildon and Brown, 2001), are absent or minimized in these samples. Melt inclusions (MI) occur in many minerals in these samples and their microstructural and compositional characterization (Acosta-Vigil et al., 2007; Cesare et al., 2007), along with trace element studies (Acosta-Vigil et al., 2010), support the hypothesis that glass within MI is the anatectic melt produced during peritectic reactions. Moreover, the possibility of finding anatectic melt trapped as MI in more classic high-temperature settings is supported by an increasing number of case studies on migmatites from low-pressure settings (i.e., Ronda migmatites; Cesare et al., 2009b), from medium- to high-pressure rocks (i.e., Kerala Khondalite Belt; Cesare et al., 2009a) and from ultrahigh-pressure migmatites (i.e., Ulten Zone; Braga and Massonne,

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2008). In the studied rocks, the host mineral and the melt trapped in glassy inclusions are cogenetic, i.e. products of the same dehydration melting reaction, and in this respect they differ from MI from deep-seated rocks reported in literature in terms of their origin and significance (e.g. Thomas and Klemm, 1997; Webster, 2006). In fact, most MI in deep-seated rocks reported in the literature occur in plutonic rocks, and the trapped melt has a genetic relationship with the host crystal. Moreover, granite-hosted MI normally show a compositional trend in major elements and volatiles (Webster and Thomas, 2006) caused by fractional crystallization of the melt, while the compositional variation of MI in El Hoyazo enclaves reflects the prograde history of the rock during partial melting, i.e., contributions from different minerals during the progress of dehydration–melting reactions (Acosta-Vigil et al., 2007, 2010).

Another peculiar aspect of the El Hoyazo enclaves is the occurrence of fluid–melt immiscibility. Anatectic melt was trapped along with a COH fluid phase in different minerals, including cordierite and plagioclase (Cesare et al., 2007) and garnet (Alvarez-Valero et al., 2005; this study). Fluid–melt immiscibility is a well known phenomenon that has been extensively studied using fluid inclusions (FI) (Roedder, 1992 and references therein), and has been recognized in mafic melts (Andersen and Neumann, 2001), silicic melts (De Vivo and Frezzotti, 1994), as a secondary feature accompanying the crystallization and/or outgassing of magma during cooling (Roedder, 1992), in ore-forming magmatic systems (Student and Bodnar, 2004), and has been reproduced experimentally using synthetic silicate melt and fluid inclusions (Student and Bodnar, 1999). In high grade, partially melted rocks, COH fluids are commonly reported (Touret, 2009), and the coexistence of a CO_2-rich phase and a melt is expected because experimental studies (Holloway, 1976; Tamic et al., 2001) demonstrate the low solubility of CO_2 in silicate melts. However, fluid–melt immiscibility is only seldom reported for granulites and migmatites (Touret, 1971, 1981), probably because MI and FI in HT peak minerals are likely destroyed by deformation and re-crystallization during the retrograde PT evolution. The enclaves from El Hoyazo have not experienced a long retrograde history, and therefore they preserve exceptional evidence of primary fluid–melt immiscibility that was developed during peritectic garnet growth and syngenetic origin of anatectic magma.

The PT conditions of the anatectic process at El Hoyazo are still a matter of debate. Previous studies based on classical geothermobarometers (Grt–Bt, GASP and Grt–Crd; mineral abbreviations after Kretz, 1983) determined that the peak metamorphic partial melting event occurred at 850 ± 50 °C and 5–7 kbar (Cesare et al., 1997), where the proposed P values represent minimum pressures, followed by biotite dehydration melting at 900 °C and 5 kbar. Recently, based on a pseudosection calculation for sample HO50 that is also used in this study, Tajčmanová et al. (2009) proposed that enclaves equilibrated in the cordierite field at 790–825 °C and 5 kbar. However, these conditions do not correspond to those at which garnet formed. Both textural and microchemical data (Acosta-Vigil et al., 2007, 2010) indicate that initial garnet growth began early in the melting history of the enclaves, and at temperatures lower than peak values. Given the estimated depth of the crust in the El Hoyazo region, 20–22 km (see Fig. 10, Torné et al, 2000), calculated pressures of 5–7 kbar suggest that the investigated enclaves are samples of the lower portion of the crust, ripped off from the basement close to the Moho discontinuity.

A 2 kbar interval (corresponding to a rock column approximately 6–7 km thick) represents a large uncertainty at such shallow crustal levels. In an attempt of better defining the P conditions at which anatexis took place, Cesare et al. (2007) estimated pressures based on primary FI coexisting with melt in cordierite and plagioclase. However, their microthermometric study and isochore calculations resulted in pressures of FI and MI entrapment that were low and inconsistent with their primary nature and the PT estimation based on sample petrology. These results were suggestive of extensive re-equilibration of inclusions during decompression.

In order to minimize effects of FI re-equilibration, the present work has focused on FI (and also MI) in peritectic garnet in both main types of enclaves. Primary FI in garnets were selected because it is well known that "harder" minerals are less likely to re-equilibrate, both in nature and in the laboratory (Bodnar, 2003), and more likely to preserve original formation conditions. We are aware that the P–T path suggested for the enclaves (e.g., Alvarez-Valero et al., 2007) is the less favorable for the preservation of primary FI densities, as it should normally lead to inclusion decrepitation (see Touret, 2009, Fig. 3). However our choice was supported by numerous examples of preservation of high densities in FI from both crustal and mantle xenoliths (e.g., Ladenberger et al., 2009; Ertan and Leeman, 1999; Szabó et al., 1996), and by the fact that some of these previous studies dealt with inclusions with preserved densities in garnet (Pretorius and Barton, 2003; Torok et al., 2005).

By focussing on garnet, one of the first peritectic phases to crystallize along with plagioclase (Acosta-Vigil et al., 2010), the present study aims to characterize the fluid phase during the initial stage of partial melting of the thinned crust beneath the NVP. From a more general point of view, our results add new constraints to the composition of the fluid phase coexisting with anatectic melt during partial melting of a metapelitic protolith.

2. Geological setting

The NVP is located in the Betic Cordillera, which forms the western termination of the Alpine orogen in the Mediterranean region, along with the Moroccan Rif (Fig. 1). The area is characterized by a thinned lithosphere, a consequence of the opening of the Alboran Domain in the late Tertiary (Comas et al., 1999). The upwelling of asthenospheric mantle caused anomalous heat flow, still present in the area, with partial melting of the lower crust and subsequent eruption or emplacement of large volumes of magmas of variable composition, ranging from basaltic andesites to rhyolites, between 15 and 2 Ma (Comas et al., 1999; Zeck and Williams, 2002; Duggen et al., 2004). Investigated enclaves were emplaced in a shallow submarine environment during the Upper Miocene (Zeck, 1970; Cesare et al., 1997) by upwelling high-K calc-alkaline to shoshonitic magmas. The

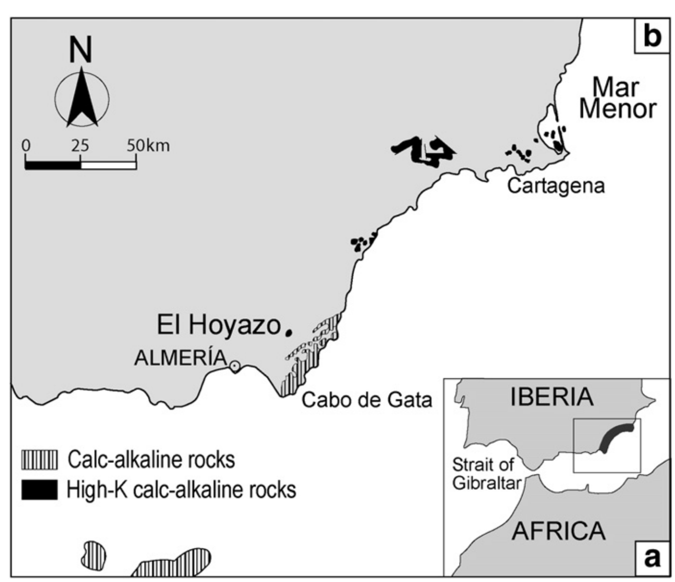

Fig. 1. The Neogene Volcanic Province, SE Spain. a) Location map of the study area in the western Mediterranean, with NVP province in black pattern (box) (redrawn after Lopez-Ruiz and Rodriguez-Badiola, 1980); b) Enlargment of the area shown by the box in (a), with locations of the main outcrops of the Neogene Volcanic Province.