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Carbonatitic and granitic melts produced under conditions of primary immiscibility during anatexis in the lower crust

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A B S T R A C T

Carbonatites are peculiar magmatic rocks with mantle-related genesis, commonly interpreted as the products of melting of CO_2-bearing peridotites, or resulting from the chemical evolution of mantle-derived magmas, either through extreme differentiation or secondary immiscibility. Here we report the first finding of anatectic carbonatites of crustal origin, preserved as calcite-rich polycrystalline inclusions in garnet from low-to-medium pressure migmatites of the Oberpfalz area, SW Bohemian Massif (Central Europe). These inclusions originally trapped a melt of calciocarbonatitic composition with a characteristic enrichment in Ba, Sr and LREE. This interpretation is supported by the results of a detailed microstructural and microchemical investigation, as well as re-melting experiments using a piston cylinder apparatus. Carbonatitic inclusions coexist in the same cluster with crystallized silicate melt inclusions (nanogranites) and COH fluid inclusions, suggesting conditions of primary immiscibility between two melts and a fluid during anatexis. The production of both carbonatitic and granitic melts during the same anatectic event requires a suitable heterogeneous protolith. This may be represented by a sedimentary sequence containing marble lenses of limited extension, similar to the one still visible in the adjacent central Moldanubian Zone. The presence of CO_2-rich fluid inclusions suggests furthermore that high CO_2 activity during anatexis may be required to stabilize a carbonate-rich melt in a silica-dominated system. This natural occurrence displays a remarkable similarity with experiments on carbonate–silicate melt immiscibility, where CO_2 saturation is a condition commonly imposed.
In conclusion, this study shows how the investigation of partial melting through melt inclusion studies may unveil unexpected processes whose evidence, while preserved in stiff minerals such as garnet, is completely obliterated in the rest of the rock due to metamorphic re-equilibration. Our results thus provide invaluable new insights into the processes which shape the geochemical evolution of our planet, such as the redistribution of carbon and strategic metals during orogenesis.

1. Introduction

Melting resulting from dynamic geological processes such as subduction and/or collision drives chemical differentiation of the crust through melt (and fluid) migration to shallower crustal levels. The latter process includes the emplacement of anatexis-related granitic plutons (Brown, 2013) as well as the metasomatization of the mantle wedge, where the incoming fluid often triggers further melting (Hermann and Rubatto, 2014). The deep nature of anatexis hampers the reconstruction of the melt-related history of high-grade terrains, as extensive re-equilibration often erases and/or modifies the original geochemical and microstructural features during exhumation. An exception is represented by nanogranitoids (Cesare et al., 2015), crystallized portions of anatectic melt which survive post entrapment changes because they are encased in robust peritectic phases, mainly garnet (Ferrero et al., 2012). They offer access to the initial, often preserved melt in the source region (see e.g. Bartoli et al., 2016), thus allowing the investigation of melting processes with well-defined spatial constraints and directly in the rocks which melted at depth, without using proxies. Nanogranitoid investigation integrates the knowledge deriving from decades of experimental and petrological studies and provides a testing ground for modeling of geological processes (Cesare et al., 2015; see also Bartoli et al., 2013).

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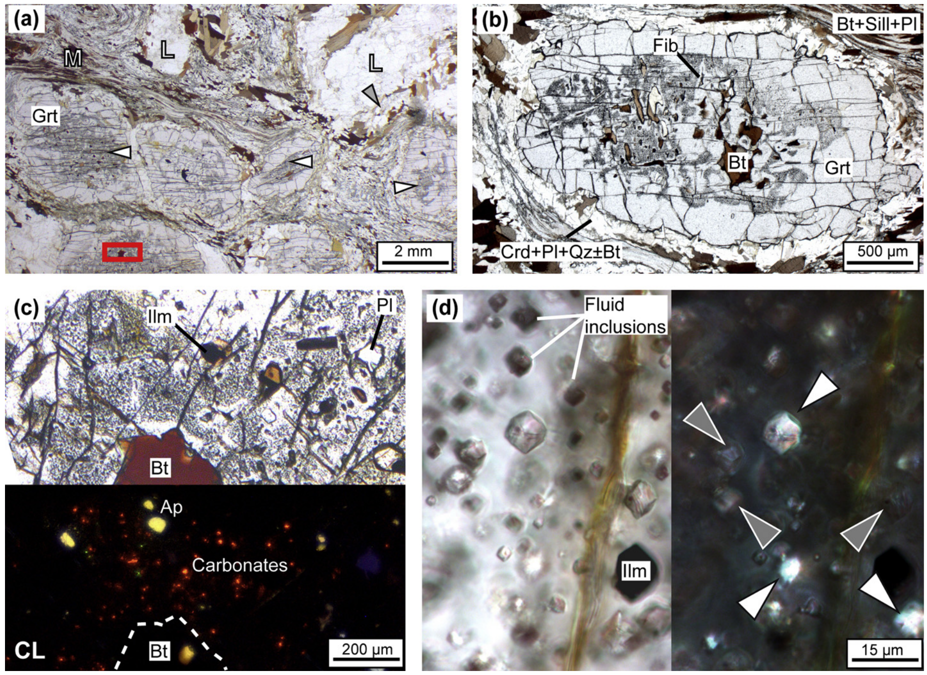

Fig. 1. Microstructural features of the Oberpfalz migmatites, microphotographs in plane polarized light and cathodoluminescence. (a) Garnet porphyroblasts (*white arrow*) occur in the melanosome (M) and show darker inner portions characterized by abundant entrained material. At the microscale, leucosome pockets (L) are irregularly distributed, with selvedges of biotite at the contact with the melanosome (*grey arrow*). Red square: area shown in (c); (b) the inclusion-rich portion of the garnet contain large residual biotite and fibrolite needles. (c) Close up of the internal portions of inclusion-bearing garnet (upper figure). Under cathodoluminescence (CL) investigation (lower figure), the same portion of garnet reveals abundance of carbonate crystals with random arrangement (recognizable for their characteristic bright orange color under CL), along with apatite crystals (in yellow). Microphotographs under plane polarized light; (d) coexistence at the microscale of calcite-rich inclusions (CRIs; white arrows), nanogranites (gray arrows) and fluid inclusions under plane polarized light (left) and under crossed polars (right) observation. Under polarized light calcite-rich inclusions are generally much brighter in color than nanogranites due to the extreme birefringence of the calcite. Mineral abbreviations are after Whitney and Evans (2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Nanogranites (Cesare et al., 2009), calcite-rich inclusions and fluid inclusions were identified in garnets from metasedimentary migmatites of the Oberpfalz area, SW Bohemian Massif (Central Europe). These rocks underwent melting at lower crustal conditions (0.5–0.8 GPa, Kalt et al., 1999) during the Variscan orogeny. A detailed petrological and geochemical investigation of these assemblage of inclusions, coupled with re-heating experiments, provide strong evidence for the novel occurrence of coexisting carbonatitic melt, silicate melt and fluid during crustal anatexis.

Carbonatites are magmatic rocks with >50% modal carbonates and <20 wt% SiO_2 (Le Maitre, 2002). Despite the fact that the most recent databases show a ten-fold increase in the number of occurrences in the last two decades (Woolley and Kjarsgaard, 2008), carbonatites are still relatively rare. These rocks and their magmas are, however, highly influential for the geochemical differentiation of the crust because of their large enrichment in Large Ion Lithophile Elements (LILE) and Light Rare Earth Elements (LREE; see also Nelson et al., 1988). Peculiar geochemical and rheological features (e.g. low viscosity; see Jones et al., 2013 for a review) make carbonatites efficient metasomatic agents able to mobilize several incompatible elements, thus promoting in turn the formation of deposits of strategic metals such as REE, Nb, U and Ta (Jones et al., 2013).

Carbonatites may form directly at mantle depth or through extreme differentiation of mantle-related silicic magmas (Mitchell, 2005). Unsurprisingly, carbonatite–silicate melt immiscibility has been so far only reported in partially melted UHP rocks (Kokchetav Massif; Korsakov and Hermann, 2006), or as the result of post-entrapment unmixing of carbonate melt inclusions in mantle xenoliths (La Gomera, Canary Islands; Frezzotti et al., 2002). Under near-surface conditions (<5 km), similar immiscibility was previously observed at Vesuvius, due to localized melting and metasomatic interaction between magmatic brines and wall-rock carbonates (Fulignati et al., 2001). However, in the present case study, evidence of mantle-related magmatism in the area is lacking and the carbonatitic melt appears to have formed directly in the metamorphic terrain where it has been identified: an unprecedented finding in metasediments melted at mid- to lower-crustal depths (20–30 km).

2. Samples and analytical techniques

The migmatites investigated in this study, a product of metamorphism during the Variscan Orogeny, belong to the Monotonous Series of the Moldanubian Zone sensu stricto, which comprises most of the southern and western portion of the Bohemian Massif, Central Europe (Matte et al., 1990). The investigated samples were collected in the southern portion of the Oberpfalz (Bavaria), in different outcrops between Waldmünchen and Furth im Wald at the border between Germany and the Czech Republic (N49.328421, E12.776270; see Fig. A1 in Appendix A). A pronounced subvertical schistosity, materialized by the alternation of leucosome-rich and melanosome-rich levels, is the result of extensive deformation in the presence of melt (Tanner, 1996; Tanner and Behrmann, 1995). The melanosome consists of anhedral plagioclase and cordierite, with a schistosity defined by iso-oriented biotite and sillimanite (Fig. 1a), locally overgrown by late spinel. Leucosome domains contain abundant plagioclase, K-feldspar and quartz. Pre-kinematic garnet porphyroblasts, ≤1 cm in diameter, are wrapped by the schistosity and display different degrees of resorption (Fig. 1b; see also Kalt et al., 1999) reflected in the formation of symmetric, post kinematic Crd + Pl + Qz ± Bt coronas in contact with melanosome (Fig. 1b). Despite their sedimentary protolith, graphite is notably absent in most of the investigated migmatites.