ANATECTIC MELT IN A METAPELITIC SYSTEM: A FLUID AND MELT INCLUSION STUDY

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INTRODUCTION

Anatexis, or partial melting, is one of the main agent of the geochemical differentiation of the continental crust (Brown & Rushmer, 2006). The result of partial melting, in fact, is a two-phase system (solid + melt) in which the less dense and less viscous melt can be easily separated from the solid residue under deformation and for differential buoyancy effects (Brown, 2007). The comprehension of the partial melting, and related processes, is a fundamental step to understand how the crust evolves in the geological time and how the presence of melt influence the geodiynamical behavior of the crust during the evolution of orogenic belts and plateaus (*e.g.*, Vanderhaeghe, 2001).

The present work is focused on the characterization of partial melting in a metapelitic system. Metapelites and metagraywackes, common in the middle crust, are very fertile (melt-producing) lithologies, and are responsible for the production of S-type granitoid magmas.

CLASSIC APPROACHES TO THE CHARACTERIZATION OF THE ANATECTIC MELT

A quantitative study of the natural melting in migmatite leucosomes has a fundamental obstacle in the unconstrained composition of the melt. In fact, although the leucosome composition is quite simple (mainly quartz, K-feldspar and plagioclase), modifications of the rock microstructures and phase assemblage of migmatites commonly occur during the retrograde path, *e.g.* cumulus phenomena, fractional crystallization, presence of xenocrysts, extensive recrystallization (Sawyer, 1996, 2008; Marchildon & Brown, 2001). For the reasons listed above, the experimental approach became in the last decades a well established tool to investigate the partial melting of metapelitic protoliths (*e.g.*, Thompson, 1982; Patino-Douce & Harris, 1998). This approach is based on the heating at controlled P-T-X conditions of both natural and synthetic samples, with the aim of reproducing the typical reactions that commonly occur in metapelites and metagraywackes during partial melting, and then characterizing the reaction products. This approach, although extremely important and powerful, suffers from problems related to: 1) the composition of the starting material, relatively simple and therefore potentially not a valid analogue for the crustal rocks, and 2) the used time scale, necessarily much shorter than the geologic time scale, that makes doubtful whether the equilibrium conditions were attained during the experimental runs.

The presence of H_2O in metasedimentary rocks is fundamental to understand the partial melting of this system, *i.e. fluid-present* versus *fluid-absent* (dehydration) melting. Since metapelites and metasedimentary granulites often contain graphite (see Cesare *et al.*, 2005 and references therein), a complex fluid in the COH system, rather than pure H_2O, is expected to be present during anatexis, as product of the interaction between graphite and the H_2O released by devolatilization reactions on the prograde path of the rock. This lead to a shift of the solidus curves toward higher temperatures, as also showed by experimental studies on granitic melts (Johannes & Holtz, 1996). The study of the COH phase in these rocks would allow the characterization of volatiles that may play an important role in the petrogenetic processes that involves partial melting of metasedimentary rocks.

Melt and fluid inclusion study in migmatites: a new approach

A novel small-scale approach to the geochemical characterization of anatectic melts was recently made possible by the detailed study of partially melted metapelitic enclaves from El Hoyazo, Neogene Volcanic Province (NVP), Spain. These enclaves represent a unique case, since they were ripped off from the basement when anatexis was still an on-going process and then rapidly brought to the surface, freezing the residual melanosomes and allowing the preservation of many of the features they had at depth. Rapid cooling caused the preservation of melt (Acosta-Vigil *et al.*, 2007, 2010; Cesare *et al.*, 2007) as an amorphous phase (glass) in intergranular layers, in microfractures and in melt inclusions in several host minerals, in particular garnet. 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 at T > 700°C. Although these enclaves represent a peculiar case, they suggest that (former) melt inclusions might be present also in more classic high-temperature settings where they must have undergone crystallization (or devetrification) to some extent because of the slow cooling (Cesare, 2008).

The possibility of finding workable MI of anatectic melt in classic high grade rocks received a first confirmation by the reported occurrence of melt inclusions in peritectic garnets from the granulite-migmatites terrain of the Proterozoic Kerala Khondalite Belt (KKB, India) (Cesare, 2008; Cesare *et al.*, 2009; present study), extensively investigated and considered as representatives of a regional anatectic crustal terrain. The MI study is a long lasting and widely accepted technique in the study of magmatic rocks, both volcanic and plutonic (Bodnar & Student, 2006). Investigation of partial melting by using this approach, made possible by the finding of MI in high-grade rocks, represents a revolutionary step forward in the understanding of natural migmatites and granulites.

As discussed above, a COH fluid phase is common in a graphite-bearing protolith during partial melting. Available FI studies in high grade rocks report the presence of a CO_2-rich fluid with variable amounts of CH_4, N_2, H_2, while H_2O may be locally present (Touret, 2009, and references therein). However, in available FI studies the genetic relationships between partial melting and trapped fluids are not clearly demonstrated on microstructural basis (*e.g.* by the occurrence of MI in the same mineral, see Roedder, 1984), but very often it is inferred. In the case of the El Hoyazo enclaves, MI coexist with FI, both considered primary based on their microstructural features (Roedder, 1984) and trapped in conditions of fluid-melt immiscibility in different minerals such as cordierite and plagioclase (Cesare *et al.*, 2007) and garnet (present work). The presence of constraints on the FI coexistence with anatectic melt suggest that the characterization of these FI will give valuable data on the composition of the fluid phase present during the partial melting of a metapelitic protolith.

PRIMARY MELT AND FLUID INCLUSIONS IN MIGMATITES FROM THE KERALA KHONDALITE BELT, INDIA

The first case study of the present work is represented by metapelites from the KKB, Southern India. Studied samples, termed "khondalites", consist of Grt-Crd-Sil-Bt-bearing melanosome and Qtz-feldspars leucosome, partially melted at T ~ 900°C and 6-8 kbar (Shabeer *et al.*, 2004; Cenki *et al.*, 2004) during the Pan-African orogeny. Peritectic garnets locally host MI, interpreted as containing anatectic melt, and this represents the first finding of this type in classic metapelitic migmatites. A detailed study was carried out to characterize the petrographic features of MI and their chemical composition by microscope observation, FESEM imaging in BSE mode, X-ray elemental mapping, EMP and MicroRaman analyses.

Peritectic garnets contain irregular clusters of hundreds of MI, from totally crystallized (*nanogranites*) to totally glassy, often negative-crystal in shape (Fig. 1a). Nanogranites are 5-25 µm across and contain a cryptocrystalline aggregate of Bt+Kfs+Pl+Qtz±Ap (Fig. 1b), along with trapped

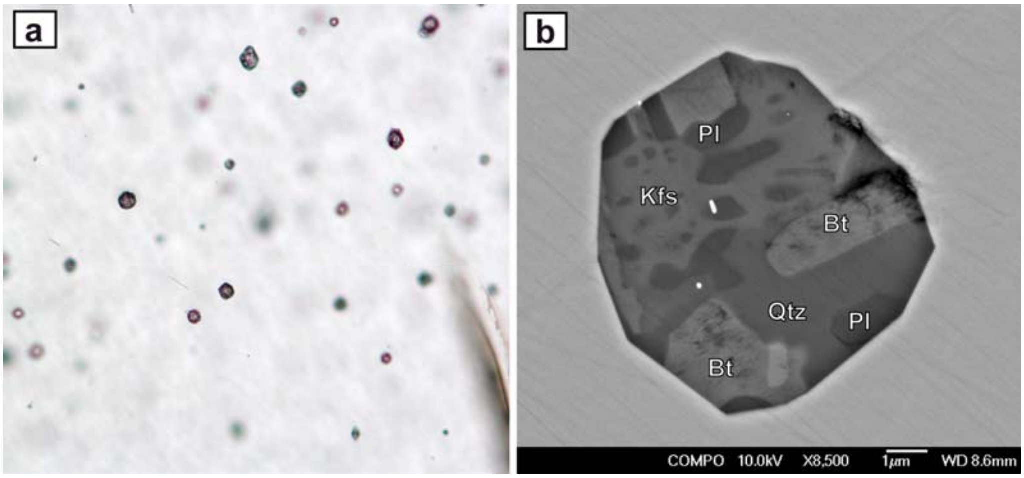

Fig. 1 - MI in garnet from Khondalites, KKB, South India. a) MI cluster in garnet; b) nanogranite, FESEM image.

phases (apatite, zircon, rutile, Zn-bearing spinel and rarely ilmenite) that are likely to have favoured the entrapment of the anatectic melt during the host growth. The grain size of crystals in nanogranite is variable, from few tens of nanometer to several microns (Fig. 2a). Glassy inclusions are usually smaller (2.5-17.5 µm) than nanogranites and represent about 15% of the total amount of MI in the clusters. They contain an amorphous phase, interpreted as glass (also confirmed by MicroRaman investigation), along with the same trapped phases found in nanogranites (Fig. 2b). EMP analysis of the glass provides an

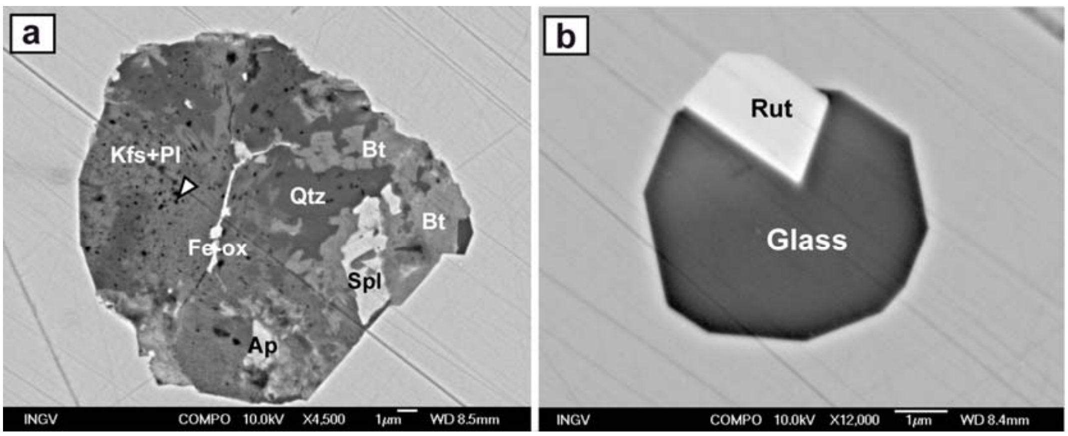

Fig. 2 - FESEM images of MI in garnet. a) nanogranite with strongly variable grain size; b) glassy inclusion with trapped rutile.

ultrapotassic and rhyolitic composition, with K_2O >> Na_2O. The EMP totals suggest a H_2O content (calculated by difference to 100%) < 3 wt.%. The occurrence of preserved glassy MI is an unprecedented finding, and since the mean diameter (8 µm) of glassy inclusions is smaller than those of nanogranites (13 µm), we propose that this difference in size was influential to the crystallization of melt droplets, so that most of the smaller inclusions remained glassy because of inhibited nucleation (Putnis *et al.*, 1995). Nanogranites were remelted using a heating stage at controlled atmosphere (He), and then analyzed, to obtain a consistent set of compositional EMP data on their bulk composition. Re-homogenized inclusions show a compositional homogeneity of the melt throughout all the different studied samples, with strong similarities to those of preserved glassy inclusions. The average composition has SiO_2 = 73 wt.%, K_2O = 6.7 wt.%, and Na_2O ~ 1 wt.%, while CaO content is low, < 1 wt.%. TiO_2 content, < 0.1 wt.%, is low and consistent with commonly reported values for anatectic melts (Patiño-Douce & Harris, 1998). Since melt composition is Na-poor, it plots very far from the "minimum melt" of the haplogranitic system in the Q-Ab-Or diagram, commonly accepted as the composition of the anatectic melt produced by partial melting of metapelites (Fig. 3). The retrieved composition, although uncommon for anatectic melts, is reported for natural rhyolites and for experimental products, and accounts for partial melting conditions with T in excess of 850°C, in agreement with the inferred PT conditions of partial melting for these rocks. The consistency of the compositional data and the careful microstructural investigation of the samples, coupled with the use of the correct techniques of MI homogenization, microchemical analyses and data correction, support for the interpretation of these data as representative of the phase trapped in MI, and the conclusion that MI in garnet from khondalites contain droplets of anatectic melt (see also Cesare *et al.*, 2009).

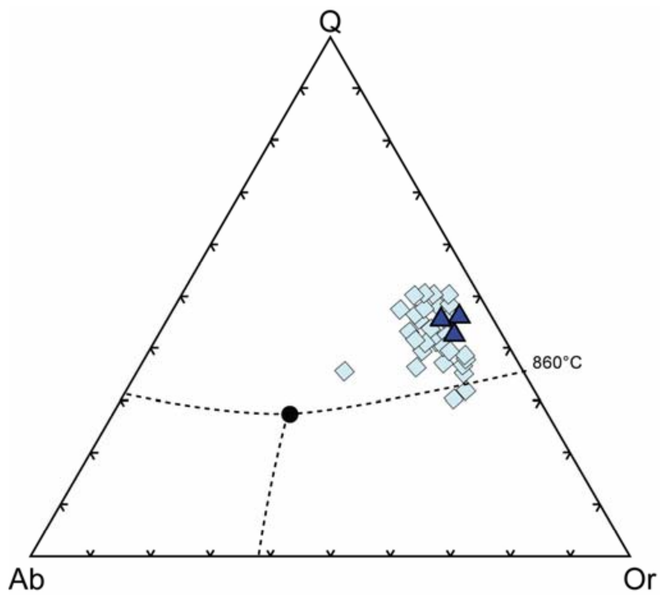

Fig. 3 - Compositions of homogenized inclusions (light-blue squares) and preserved glassy inclusions (blue triangles) in the CIPW Q-Ab-Or diagram. Dashed black lines: cotectic curves for the subaluminous haplogranitic system (5 kbar, a_{H2O} = 0.5); black dot: "minimum melt" composition for the same conditions are reported for comparison; 860°C: temperature of beginning of melting at the cotectic compositions on the Q-Or join (Johannes & Holtz, 1996).

"PRIMARY" FLUID INCLUSIONS IN PERITECTIC GARNET FROM METAPELITIC ENCLAVES, EL HOYAZO, SPAIN

The second case study is represented by the granulitic enclaves of El Hoyazo, NVP, Southern Spain. In these rocks the peritectic garnet is the first peritectic phase produced by partial melting at ~ 700°C and 5-7 kbar (Acosta-Vigil *et al.*, 2007, 2010; Cesare *et al.*, 1997). Many garnet porphyroblasts show a dark core due to the presence of MI and abundant FI, trapped during garnet growth (*i.e.* primary;

Roedder, 1984) in conditions of fluid-melt immiscibility. FI do not show any visible evidence of post-entrapment modifications, and for this reason they were investigated to characterize the fluid present along with anatectic melt during partial melting. A FI study was performed on peritectic garnets from the Spl-Crd and Bt-Grt-Sil enclaves by microscope investigation, microthermometric studies, MicroRaman analyses, mass balance calculation and TEM investigation. In Spl-Crd enclaves FI are two-phase (L+V), spherical to tubular, and often contain graphite as trapped phase (Fig. 4a). Trapped fluid is a mixture of $H_2O + CO_2 + N_2 \pm H_2S \pm CH_4$ with water up to 95 mol.%, while in Bt-Grt-Sil enclaves FI in garnet are one phase, and contain a $CO_2 + N_2$ mixtures (Fig. 4b). In both samples FI have densities that are not

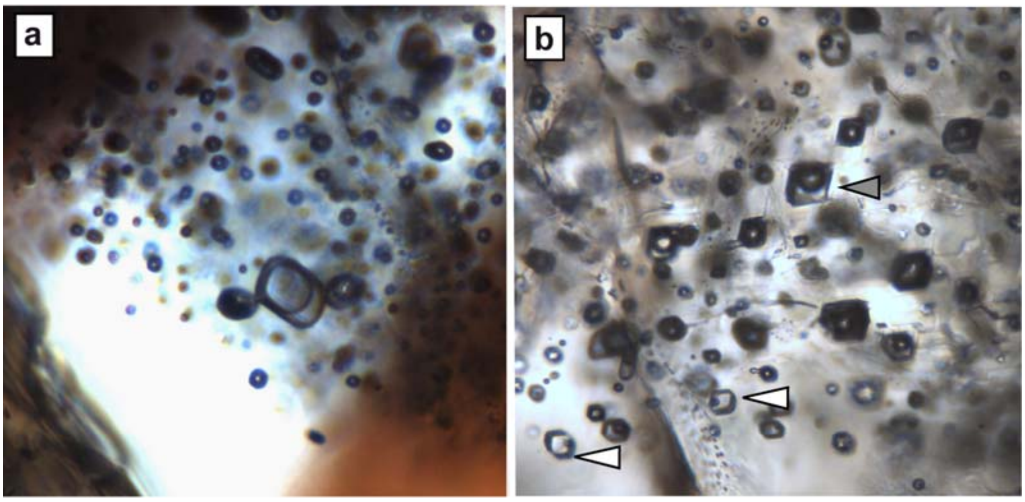

Fig. 4 - FI in garnet from metapelitic enclaves, El Hoyazo, NVP, South Spain. a) FI in Grt from Spl-Crd enclaves; b) FI in Grt from Bt-Grt-Sil enclaves. *Gray arrow:* mixed inclusions (fluid+melt); *white arrow:* melt inclusions.

consistent with the inferred trapping conditions, and suggest that despite of their primary-looking features, FI re-equilibrated during uprising. TEM investigation on Bt-Grt-Sil samples showed partially healed cracks at sub-μm scale, possible escape pathways for the leakage of fluids out of the inclusions (Fig. 5). In Spl-Crd enclaves microchemical data acquired on MI and biotite inclusions, that occur in the same cluster along with FI, demonstrate that a water-rich leucogranitic melt was trapped along with a H_2O-rich, COH phase at conditions consistent with those inferred for garnet growth (Fig. 6; Acosta-Vigil *et al.*, 2010). In garnet from Bt-Grt-Sil enclaves, the almost complete decrepitation and fluid leakage suffered by the studied FI did not allow to estimate the original composition of fluids hosted in garnet. Based on the H_2O content of coexisting melt inclusions (Acosta-Vigil *et al.*, 2007), however, the fluid is inferred to have been more CO_2-rich than the fluid in the Spl-Crd enclaves. This work adds further compositional constraints to the characterization of anatexis of metapelites in the lower crust: in fact, although final results clearly show that enclaves lost part of the original components, the composition of fluid trapped in garnet from Spl-Crd enclaves is probably very close to the original, and is consistent with the composition of the coexisting melt based on experimental data available in literature (Tamic *et al.*, 2001).

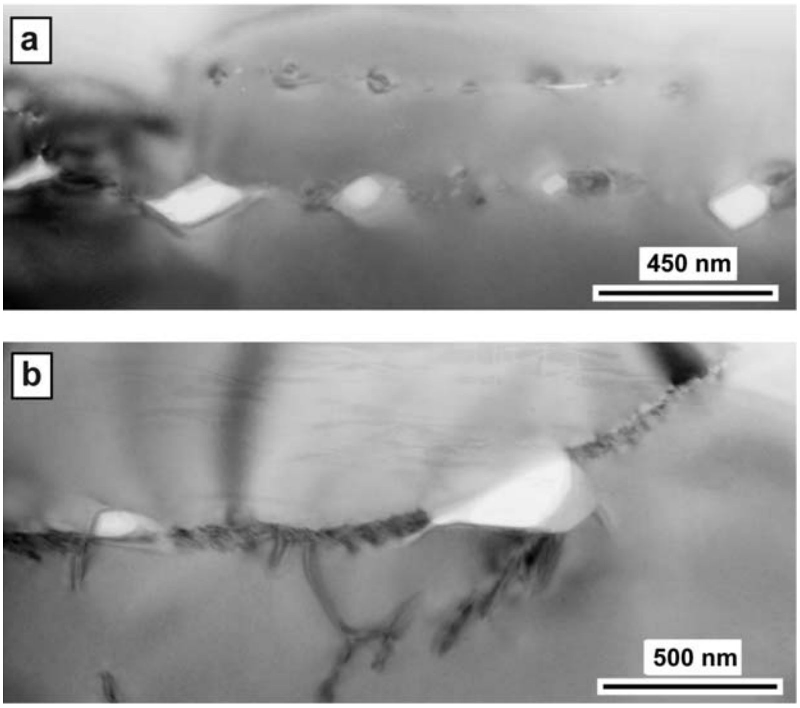

Fig. 5 - Trails of nanometer-sized FI, with structural discontinuities (*i.e.* nanofractures, dislocations), that connect all inclusions in the trail.

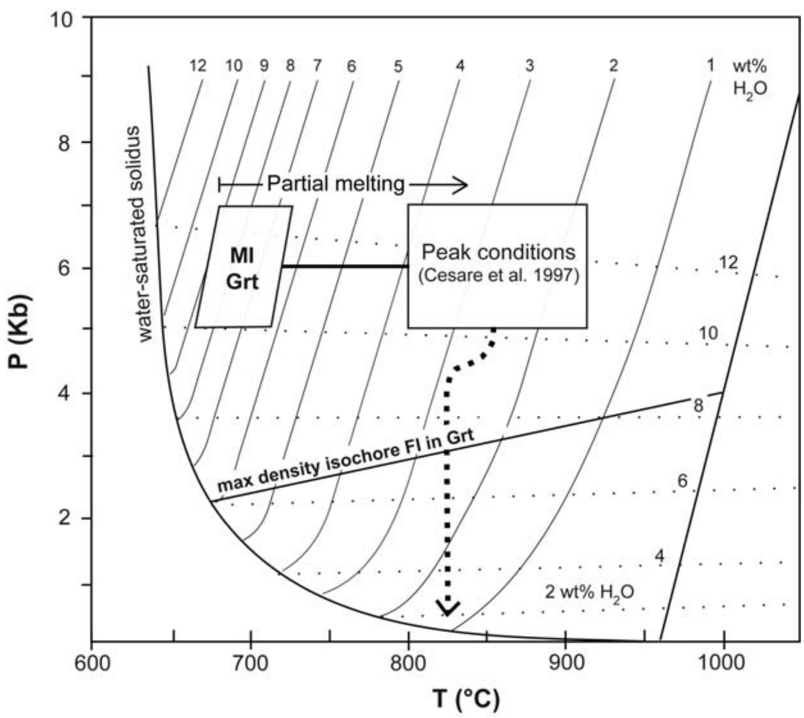

Fig. 6 - Proposed fluid-melt evolution in garnet of the El Hoyazo enclaves. *Thin lines:* liquidus curves of the system Q-Ab-Or for minimum melt compositions and specified H_2O contents; *dotted lines:* H_2O solubility isopleths for minimum and eutectic compositions in the system Q-Ab-Or (redrawn after Johannes & Holtz, 1996).

CONCLUSIONS

Research on melt and fluid inclusions in peritectic minerals represents a new approach to the problem of partial melting in natural rocks, and the present study demonstrated that reliable petrological and geochemical information on anatexis can be collected from nano- to micron-scale objects. The dataset reported in this study widens the horizons in crustal petrology, because for the first time the crustal melt composition can be analyzed rather than assumed. Moreover, MI study in migmatites is likely to have large potentials of development, as confirmed by recent findings of anatectic melt trapped in inclusions in peritectic minerals from various migmatite terrains (Himalaya, Ronda, Ulten zone, Adirondack).

REFERENCES

Acosta-Vigil, A., Cesare, B., London, D., Morgan VI, G.B. (2007): Microstructures and composition of melt inclusions in a crustal anatectic environment, represented by metapelitic enclaves within El Hoyazo dacites, SE Spain. *Chem. Geol.*, **235**, 450-465.

Acosta-Vigil, A., Buick, I., Hermann, J., Cesare, B., Rubatto, D., London, D., Morgan VI, G. (2010): Mechanisms of crustal anatexis: a geochemical study of partially melted metapelitic enclaves and host dacite, SE Spain. *J. Petrol.*, in press.

Bodnar, R.J. & Student, J.J. (2006): Melt inclusions in plutonic rocks: petrography and microthermometry. *In*: “Melt inclusions in plutonic rocks”, J.D. Webster, ed. Mineralogical Association of Canada, Short Course, **36**, 1-26.

Brown, M. (2007): Crustal melting and melt extraction, ascent and emplacement in orogens: mechanisms and consequences. *J. Geol. Soc.*, **164**, 709-730.

Brown, M. & Rushmer, T. (2006): Evolution and Differentiation of the Continental Crust. Cambridge University Press, Cambridge, 553 p.

Cenki, B., Braun, I., Bröcker, M. (2004): Evolution of the continental crust in the Kerala Khondalite Belt, southernmost India: Evidence from Nd isotope mapping combined with U-Pb and Rb-Sr geochronology. *Precambrian Res.*, **134**, 275-292.

Cesare, B. (2008): Crustal melting: working with enclaves. *In*: “Working with Migmatites”, E.W. Sawyer & M. Brown, eds. Mineralogical Association of Canada, Short Course, **38**, 37-55.

Cesare, B., Salvioli Mariani, E., Venturelli, G. (1997): Crustal anatexis and melt extraction during deformation in the restitic xenoliths at El Joyazo (SE Spain). *Mineral. Mag.*, **61**, 15-27.

Cesare, B., Meli, S., Nodari, L., Russo, U. (2005): Fe^{3+} reduction during biotite melting in graphitic metapelites: another origin of CO_2 in granulites. *Contrib. Mineral. Petrol.*, **149**, 129-140.

Cesare, B., Maineri, C., Baron Toaldo, A., Pedron, D., Acosta-Vigil, A. (2007): Immiscibility between carbonic fluids and granitic melts during crustal anatexis: a fluid and melt inclusion study in the enclaves of the Neogene Volcanic Province of SE Spain. *Chem. Geol.*, **237**, 433-449.

Cesare, B., Ferrero, S., Salvioli-Mariani, E., Pedron, D., Cavallo, A. (2009): Nanogranite and glassy inclusions: the anatectic melt in migmatites and granulites. *Geology*, **37**, 627-630.

Johannes, W. & Holtz, F. (1996): Petrogenesis and experimental petrology of granitic rocks: Springer, Berlin, 335 p.

Marchildon, N. & Brown, M. (2002): Grain-scale melt distribution in two contact aureole rocks: implications for controls on melt localization and deformation. *J. Metam. Geol.*, **20**, 381-396.

Patiño-Douce, A.E. & Harris, N. (1998): Experimental constraints on Himalayan anatexis. *J. Petrol.*, **39**, 689-710.

Putnis, A., Prieto, M., Fernandez-Diaz, L. (1995): Fluid supersaturation and crystallization in porous media. *Geol. Mag.*, **132**, 1-13.

Roedder, E. (1984): Fluid inclusions. *Rev. Mineral.*, **12**, 644 p.

Sawyer, E.W. (1996): Melt-segregation and magma flow in migmatites: implications for the generation of granite magmas. *Trans. Royal Soc. Edinburgh, Earth Sci.*, **87**, 85-94.

Sawyer, E.W. (2008): Atlas of Migmatites. Quebec. *Can. Mineral. Spec. Publ.*, **9**, 386 p.

Shabeer, K.P. (2004): Petrology and geochronology of granulite facies metamorphic rocks from Kerala Khondalite Belt, southern India: implications to partial melting and heat source: Ph.D. thesis, Osaka City University, Osaka.

Tamic, N., Behrens, H., Holtz, F. (2001): The solubility of H_2O and CO_2 in rhyolitic melts in equilibrium with a mixed CO_2-H_2O fluid phase. *Chem. Geol.*, **174**, 333-347.

Thompson, A.B. (1982): Dehydration melting of pelitic rocks and the generation of H_2O-undersaturated granitic liquids. *Am. J. Sci.*, **282**, 1567-1595.

Touret, J.L.R. (2009): Mantle to lower-crust fluid/melt transfer through granulite metamorphism. *Russian Geol. Geophys.*, **50**, 1052-1062.

Vanderhaeghe, O. (2001): Melt segregation, pervasive melt migration and magma mobility in the continental crust: the structural record from pores to orogens. *Phys. Chem. Earth*, **A26**, 213-223.