MITT.ÖSTERR.MINER.GES. 159 (2013)

MELT INCLUSIONS IN MIGMATITES AND GRANULITES

by

Bernardo Cesare

Dipartimento di Geoscienze, Università di Padova
Via Gradenigo 6, 35131 Padova, Italy
e-mail: bernardo.cesare@unipd.it

The study of melt inclusions is a recent, small-scale approach to a better understanding of melting in the continental crust. It builds on the discovery of glassy inclusions (CESARE et al., 1997) and their crystallized counterparts (*"nanogranites"*, CESARE et al., 2009) in garnet and other host minerals from anatectic crustal enclaves in lavas and from regional migmatites.

By producing a melt of broadly granitic composition and a silica-poor solid residue, crustal anatexis is of paramount importance in shaping the continental lithosphere: on one hand it determines the geochemical differentiation of the crust; on the other it allows easier and faster deformation of the crust, with important tectonic and geodynamic implications. Among the several aspects of crustal melting that are still poorly known to scientists, one is the composition of the *natural* melts produced during anatexis, as both leucosomes in migmatites and allochthonous crustal granites aren't representative of primary melts.

Such gap of knowledge has led to a new approach to characterize the composition of natural crustal melts: the study of melt inclusions. Building on the extensive work and literature on fluid and melt inclusions in mafic rocks, we realised that tiny droplets of the melt phase produced during crustal anatexis can be trapped by, and preserved within, those minerals that grow simultaneously with the melt, i.e. the *peritectic* phases produced during incongruent melting. For example, a garnet crystal that forms during the incongruent melting of biotite has the potential of trapping *primary* inclusions of the melt that is in contact with. Albeit straightforward, this perspective has found little application to migmatites and granulites in the past, until our first works in the crustal enclaves and xenoliths from El Hoyazo, SE Spain (CESARE et al., 1997). In these fragments of crustal rocks entrained in lavas that rapidly ascended, extruded and cooled on the Earth surface, the inclusions of anatectic melt could solidify to, and be preserved as, rhyolitic glass. The mineralogical and chemical composition of these rocks is comparable to that of residual melanosomes in migmatites, but here abundant glass is present, particularly as melt inclusions in all the minerals.

Glass inclusions were studied in particular in garnet and plagioclase (ACOSTA-VIGIL et al., 2007, 2010, 2012). They range in size between 5 and 50 µm, have a primary texture, contain fresh and undevitrified glass, and show very little evidence of melt crystallization upon cooling.

The peraluminous leucogranitic and close-to-eutectic compositions of glasses support the conclusion that they represent natural anatectic melts. Zircon and monazite saturation temperatures of 665-750°C suggest that melts were produced by muscovite breakdown melting early in a process of rapid anatexis, and mostly under H_2O-undersaturated conditions. The analysis of trace elements in the glass inclusions also allowed the first precise evaluation of the extent of chemical equilibrium between felsic melt and crystalline residuum during the anatexis of metasediments in a natural context.

Crustal enclaves such as at El Hoyazo are extremely unusual and rare. Nonetheless, they boosted an important development of melt inclusion studies by raising the question: *"Why shouldn't inclusions formed by the same process occur also in "normal" migmatites and granulites?"*

We (re)examined migmatite and granulite localities worldwide looking for garnet-producing incongruent reactions, until the first occurrence of melt inclusions was found in the slowly cooled granulites of the Kerala Khondalite Belt (KKB), India (CESARE et al., 2009). There, the inclusions are hosted within garnet: those in the range of 15-25 μm are fully crystallized to a cryptocrystalline aggregate of quartz, alkali feldspar, biotite and plagioclase (Fig. 1), locally showing micrographic intergrowths of quartz and feldspars. Inclusions generally have a negative crystal shape, and grain-size of crystals ranges from hundreds of nm to a few μm. Given the microstructural and chemical features, the cryptocrystalline aggregate found within these inclusions was named "nanogranite"

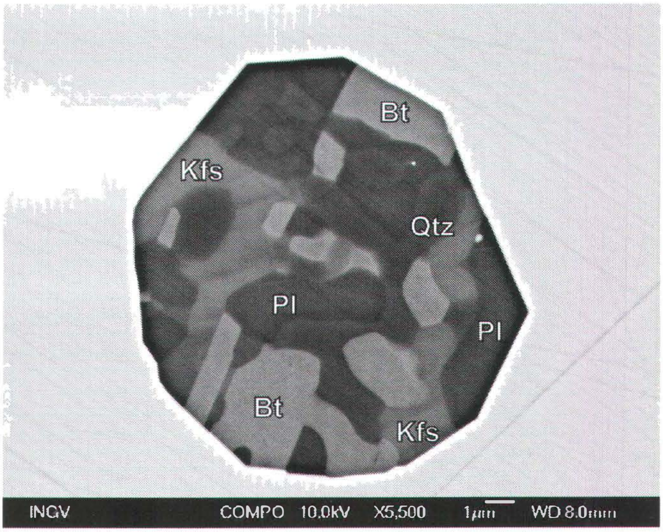

Figure 1:
Backscattered SEM image of a nanogranite inclusion hosted in garnet from a granulitic migmatite of the Kerala Khondalite Belt, India. (From HOLNESS et al., 2011).
Bt: biotite; Kfs: K-feldspar
Pl: plagioclase; Qtz: quartz

Another exceptional and intriguing discovery was that, despite the very slow cooling rate of the host rock, some inclusions <15 μm are still completely glassy. This has been explained by inhibition of nucleation in the inclusions with the smallest volumes, by analogy with the behavior of aqueous solutions in sediments or of glass in films and pores of contact meta-morphic rocks. Since the first finding, nanogranite and glassy inclusions have been identified also in regional metamorphic migmatites from other geological settings of various P-T conditions, such as the Ivrea Zone and the Ulten Zone (Italy), Ronda (Spain), the Barun Gneiss (Nepal), the Kaligandaki valley (Tibet), and south-central Massachusetts (U.S.A.).

Inclusions are hosted in garnet at all these localities, and also in ilmenite at Ronda. Their peculiar microstructural features (FERRERO et al., 2012) make nanogranites one of the most reliable indicators for the former presence of melt in a rock. Moreover, their appropriate characterization and analysis can provide the missing information on the composition of natural anatectic melts before these undergo modification processes. But while glassy inclusions can be directly analysed with minimal sample preparation, nanogranites need to be remelted to a homogene-ous liquid and then quenched: to prevent the decrepitation of inclusions and loss of volatiles, remelting is achieved in a piston cylinder apparatus (BARTOLI et al., 2013a).
EMP, Raman and nanoSIMS analysis of major elements and H_2O contents of remelted nanogranites shows that despite being all leucogranitic, compositions of natural anatectic melts generally plot away from those of minimum melts, and display systematic differences among samples, particularly concerning Qtz-Ab-Or relationships (Fig. 2).

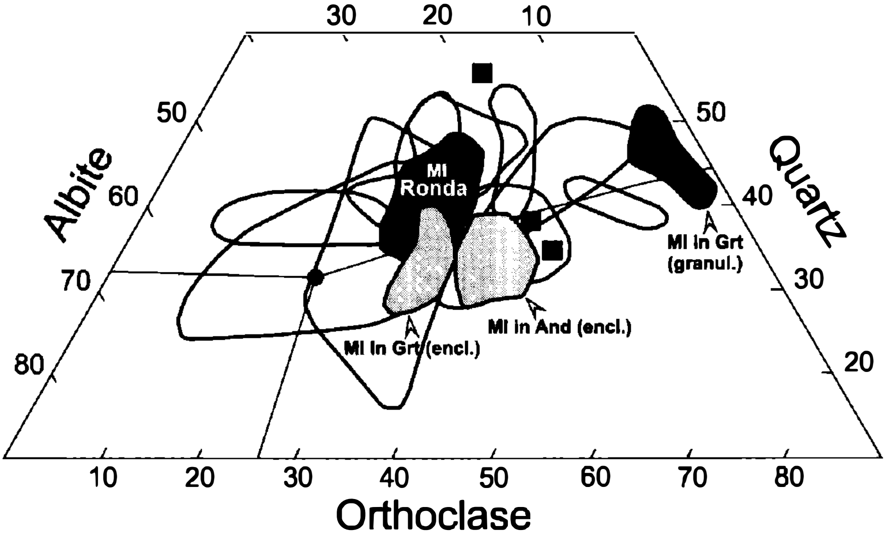

Figure 2:

Composition of remelted nanogranites (dark grey fields), of melt inclusions (MI) in garnet (Grt) and andalusite (And) from spanish enclaves (encl.; light grey fields), and of experimental melts produced from metasedimentary starting materials (white fields), plotted in the CIPW Q-Ab-Or diagram. Gray squares are leucosomes in the migmatite from Ronda. Black dot and lines show the eutectic point and cotectic lines for the subaluminous haplogranite system at 5 kbar and $a_{H2O} = 1$.

Redrawn after BARTOLI et al. (2013b), where details of the sources of data of experimental melts can be found.

The analysis of H_2O in the rehomogenized inclusions demonstrates that nanogranites preserve the primary fluid contents and that melts produced at Ronda were mainly H_2O-undersaturated even at low degree of melting (BARTOLI et al., 2013b). Since H_2O is one of the main parameters determining melt viscosities and, in turn, the strength of partially melted rocks, our characterization of the fluid contents of nanogranites is key for obtaining more realistic constraints to the rheological behaviour of the deep crust, and to the timescales of melt extraction from it.

Melt inclusions should be targeted in the most chemically inert and mechanically strong mineral hosts (e.g., spinel, ilmenite, zircon) from the least deformed rock domains. A major problem associated with this research is analytical and relates to the small size of the objects of study, enhancing the possibility of contamination by the host phase and loss of alkalis (in particular Na) due to the use of focused beams during analysis. Another problem is methodological and resides in the necessity of determining, case by case, the extent to which inclu-sions preserve their primary features, including the degree of chemical interaction with the host and the degree of crystallization upon cooling.

Because the composition of anatectic melts can now be analysed rather than assumed, we foresee that our investigation will stimulate further research on melt inclusions in migmatites and granulites. With extension to melting of mafic protoliths and to HP to UHP conditions of anatexis, our approach promises important impacts on a wide spectrum of disciplines including petrology, geochemistry, mineralogy, volcanology and geodynamics. As many occurrences of melt inclusions have been overlooked because they simply were not searched for, they will be uncovered by careful re-investigation of migmatite and granulite samples worldwide. In addition, the small size of inclusions (often <10 µm) and crystals within nanogranite (often <1 µm) offers new challenges and applications for cutting-edge micro-analytical techniques such as field emission gun-based SEM and EMP, LA-ICP-MS, nanoSIMS, synchrotron-based micro-XRF and micro-XRD. The fast technological development is likely to eliminate all analytical obstacles in a few years.

ACOSTA-VIGIL, A., CESARE, B., LONDON, D., MORGAN VI, G.B. (2007): Chem. Geology, 237, 450-465.

ACOSTA-VIGIL, A., BUICK, I., HERMANN, J., CESARE, B., RUBATTO, D., LONDON, D., MORGAN VI, G.B. (2010): Journal of Petrology, 51, 785-821.

ACOSTA-VIGIL, A., BUICK, I., CESARE, B., LONDON, D., MORGAN VI, G.B. (2012): Journal of Petrology, 53, 1319-1356.

BARTOLI, O., CESARE, B., POLI, S., ACOSTA-VIGIL, A., ESPOSITO, R., TURINA, A., BODNAR, R.J., ANGEL, R.J., HUNTER, J. (2013a): Nanogranite inclusions in migmatitic garnet: behavior during piston-cylinder remelting experiments. Geofluids (in press)

BARTOLI, O., CESARE, B., POLI, S., BODNAR, R.J., ACOSTA-VIGIL, A., FREZZOTTI, M.L., MELI, S. (2013b): Geology, 41:115-118.

CESARE, B., SALVIOLI MARIANI, E., VENTURELLI, G. (1997): Mineralogical Magazine, 61. 15-27.

CESARE, B., FERRERO, S., SALVIOLI-MARIANI, E., PEDRON, D., CAVALLO, A., (2009): Geology, 37, 627-630.

FERRERO, S., BARTOLI, O., CESARE, B., SALVIOLI-MARIANI, E., ACOSTA-VIGIL, A., CAVALLO, A., GROPPO, C., BATTISTON,S. (2012): Journal of Metamorphic Geology, 30, 303-322.

HOLNESS, M.B., CESARE, B., SAWYER, E.W. (2011): Elements, 7, 245-250.