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Arctic Nanogranitoids and What We Can Learn from Them

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Primary melt inclusions are small droplets of melt trapped in minerals during their growth in the presence of a melt phase (Sorby 1858; Roedder 1984; Frezzotti 2001). In magmatic rocks melt inclusions have been described since 1858, when Henry Clifton Sorby recognized them in feldspar, pyroxene, and leucite crystals in erupted lavas (Sorby 1858). Already back then, Sorby was able to observe and recognize under the microscope glassy and crystalized inclusions referring to them as “glass-cavities” and “stone-cavities”, respectively.

In metamorphic rocks, melt inclusions generally occur – as for their magmatic counterparts – either as glass or crystallized into a cryptocrystalline assemblage with a variable composition named nanorocks (Bartoli and Cesare 2020). When these polycrystalline inclusions display an assemblage similar to that of a granitoid, they are called nanogranitoids (Cesare et al. 2015). Melt inclusions in regionally metamorphosed felsic rocks were first described by Cesare et al. (2009). They were identified in the inner part of garnets in the granulites of the Kerala Khondalite Belt in India (Cesare et al. 2009). This study was groundbreaking as it was the first preserved anatectic melt analyzed in situ (Cesare et al. 2009). The study of melt inclusions in metamorphic rocks with modern techniques allows the investigation in situ of natural anatectic melts and the determination of the physico-chemical conditions at which anatexis took place (Cesare et al. 2015; Ferrero et al. 2018). Anatexis is one of the main processes responsible for crustal differentiation and thus studying melt inclusions allows its direct investigation (Cesare et al. 2009) also in terms of volatile budget (Bartoli et al. 2014; Carvalho et al. 2018; Ferrero et al. 2021, 2023; Borghini et al. 2023). Moreover, in subduction settings, where melts and fluids are responsible for the transfer of elements from the crust to the mantle, the study of melt inclusions allows the direct investigation of crust-mantle interaction and deep volatile and incompatible elements cycles (Borghini et al. 2020, 2023, 2024). Nanorocks are widespread almost all over the world, including a few localities in the Arctic (Nicoli et al. 2022; Janák et al., in review) and they are reported in different geological settings (Bartoli and Cesare 2020). In this contribution, we present two examples of melt inclusions trapped in garnets of metamorphic rocks from the Arctic in SE Greenland and NW Norway.

In SE Greenland the samples studied are part of the Mesoarchean (2800–3000 Ma) Kangerlussuaq basement surrounding the Skaergaard intrusion (Kays et al. 1989). This basement is mainly composed of felsic intrusions, tonalites-trondhjemite-granodiorite (TTG) and grey gneisses interlayered with metasediment lenses and amphibolites (Kays et al. 1989). Melt inclusions occur in stromatic migmatites which are part of a metasedimentary lens, and have a melanosome dominated by garnet and biotite (partly chloritized) and a leucosome containing feldspar and quartz with minor oxides, chlorite, apatite, and zircon (Nicoli et al. 2022). The melanosome and leucosome form alternating bands that define the main fabric of the rock. Two generations of garnets were recognized: (i) large xenoblatic garnets (up to 5 mm in size) and (ii) smaller idioblastic garnets overprinting the main fabric (Nicoli et al. 2022). Both garnet generations contain melt and fluid inclusions, with melt inclusions more abundant in the first generation and fluid inclusions more abundant in the second. Both types of inclusions are randomly distributed, forming clusters in the inner part of garnets, indicating that the garnet was growing in presence of a melt and a fluid phase (Ferrero et al. 2018). Melt inclusions are up to 15 μm in size and they were investigated by micro-Raman spectroscopy to determine the mineral assemblage that differs in the two garnet generations. In the xenoblastic garnets, melt inclusions contain quartz/cristobalite, kumdykolite ($NaAlSi_3O_8$ orthorhombic polymorph), kokchetavite ($KAlSi_3O_8$ hexagonal polymorph), and phlogopite. In the idioblastic garnets instead, the melt inclusions assemblage is made of quartz, K-feldspar, chlorite and ± H_2O. Fluid inclusions are significantly bigger, they are up to 40 μm and they contain a constant assemblage in both generations of garnet, including siderite, graphite, pyrophyllite, CO_2, and CH_4. The presence of carbonate, C-phases and hydrates in the same inclusions suggests that the fluid is COH-rich (Nicoli et al. 2022). Thermodynamic modelling suggested a supra-solidus evolution between 0.5 and 0.8 GPa. The first generation of garnet is stable at 950–1000 °C and 0.6–0.8 GPa whereas the second is stable at 825–950 °C and 0.5–0.7 GPa. The garnet/melt pairs considering the differences are snapshots of two different melting events taking place at the pressure-temperature conditions of formation of the two different garnet generations (Nicoli et al. 2022). This case study reports the oldest occurrence of preserved melt inclusions and also shows for the first time the supra-solidus history of this area. The coexistence of melt and fluid inclusions indicates fluid-melt immiscibility and, thus, partial melting in presence of a COH fluid.

In NW Norway, the samples are from the Nordmannvik Nappe – part of the Norwegian Artic Caledonides. This Nappe is made of polymetamorphic rocks, including mylonitic micaceous gneisses, garnet amphibolites, marbles, calcsilicates and ultramafic lenses (Andresen 1988). Nanogranitoids, along with diamond-bearing fluid inclusions, occur in garnet-kyanite migmatitic gneisses located in a megalens of the Nordmannvik Nappe at Heia (Janák et al. 2024). These gneisses are finely foliated and contain melanocratic and leucocratic domains.

The melanocratic domains host garnet and kyanite porphyroblasts, biotite and white mica whereas the leucocratic portion is dominated by feldspars, quartz, and garnet (Janák et al. 2024). Melt and fluid inclusions occur in the inner parts of garnets organized in clusters or isolated. Melt inclusions are up to 100 μm and their mineral assemblage was determined with an electron microprobe. They contain muscovite, paragonite, phlogopite, K-feldspar, albite, quartz, and kyanite (Janák et al. 2024). The latter however is a trapped phase as it is present in the matrix and as mineral inclusion in garnet. Fluid inclusions are 5–10 μm in diameter and were investigated with micro-Raman spectroscopy. They contain CO_2, siderite and magnesite, a minor amount of pyrophyllite, biotite, white mica, diamond, and ± graphite. The association of carbonates, C-phases and hydrates suggests that the fluid is COH. Diamond is an index mineral of ultra-high pressure (UHP) conditions and its presence in a fluid coexisting with melt suggests that partial melting in Heia gneiss took place at UHP conditions in the presence of a COH fluid. This is one of the first examples of fluid-melt immiscibility at UHP conditions (Janák et al. 2024).

Melt inclusions represent a snapshot of melt produced during anatexis in terms of major, trace elements, and volatiles. The composition of the melt can be measured in situ on glassy inclusions and experimentally re-homogenized nanogranitoids with the electron microprobe (Cesare et al. 2015; Ferrero et al. 2018). Moreover, also trace elements and volatiles concentrations can be directly obtained from the analyses of melt inclusions (see Bartoli et al. 2014; Carvalho et al. 2018; Nicoli and Ferrero 2021; Ferrero et al. 2021, 2023).

In subduction settings, the possibility of targeting melt inclusions trapped in mantle rocks involved in crust-mantle interaction allows not only to quantify the mass transferred from the crust to the mantle but also the deep volatile cycles (Borghini et al. 2020, 2023, 2024). All these processes have an influence on crustal growth, global volatile recycling, Earth habitability, and climate (Borghini et al. 2023).

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