Oriented multiphase needles in garnet from ultrahigh-temperature granulites, Connecticut, U.S.A.

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**ABSTRACT**

This study investigates distinctive oriented, needle-shaped multiphase inclusions found within cores of garnets from felsic granulites of the Upper Member of the Bigelow Brook Formation and the Brimfield Schist (northeastern Connecticut, U.S.A.). The rocks crop out in the southern end of the Central Maine Terrane and thus are a part of the Acadian/Neoacadian Orogen. The typical mineral assemblage is garnet + sillimanite + K-feldspar + plagioclase + quartz + cordierite + biotite ± spinel. The sillimanite is commonly pseudomorphous after kyanite.

The multiphase needle inclusions and associated exsolved needles of rutile and ilmenite are mostly oriented parallel to <111> of garnet. The multiphase needles contain various combinations of quartz, micas, chlorite, rutile, graphite, a siliceous compositionally variable phase (“Phase-CV”), Zn-spinel, apatite, zircon, and rare ilmenite. We hypothesize that they represent inclusions of fluid that adhered to exsolving Ti±Fe oxide needles (mostly rutile) or extended along zones of weakness in garnet. This requires that multiphase needle formation occurred in response to cooling and/or decompression. The needles ultimately decrepitated during retrogression. We note that micaceous needle-shaped multiphase inclusions are rarely described; the closest analogs of which we are aware are found in UHP garnets of the Erzgebirge (Perchuk 2008).

The Brimfield Schist in this area underwent ultrahigh-temperature metamorphism (UHTM) of ~1000 °C at a minimum pressure of ~1 GPa (Ague et al. 2013). Here we provide new temperature estimates for the adjacent Upper Member of the Bigelow Brook Formation. Ternary feldspar reintegration using the activity model of Benisek et al. (2004) and Zr-in-rutile thermometry (Tomkins et al. 2007) give average temperatures of ~990 and ~1010 °C, respectively, at 1 GPa for this unit. Therefore, the recently discovered UHT zone in the Brimfield Schist of northeastern Connecticut extends to the east to include the Upper Member of the Bigelow Brook Formation. Consequently, the first confirmed regional UHT locality in the United States is larger than initially recognized, and is at least 25 km long and 5–10 km wide. The oriented, elongate multiphase inclusions and petrographically obvious oriented Ti±Fe oxide needles may be useful indicators of extreme temperature and/or pressure rocks in other field areas.

**Keywords:** Ultrahigh temperature, multiphase inclusions, garnet, metamorphism, Connecticut, rutile

**INTRODUCTION**

Garnets and other refractory minerals in mantle rocks, ultrahigh-pressure (UHP) rocks, and high-grade gneisses may contain multiphase solid inclusions that are relics of fluids entrapped during garnet growth (e.g., Stöckhert et al. 2001; van Roermund et al. 2002; Carswell and van Roermund 2005; Ferrando et al. 2005; Malaspina et al. 2006; Frewzotti et al. 2007; Perchuk 2008; Mposkos et al. 2009; Ferrero et al. 2012; Hermann et al. 2013). Common inclusion phases are quartz/coesite, feldspars, micas, chlorite, carbonates, apatite, rutile, graphite, and zircon. Microdiamond can also be found within these inclusions and by itself in garnet.

A growing number of multiphase inclusion localities have been recognized worldwide, but thus far none are in North America. Three examples are given here. (1) Multiphase inclusions ranging from ~5 to ~150 μm in diameter have been reported in garnet, orthopyroxene, and clinopyroxene from mantle-derived websterite in Fjørtoft, Norway (Carswell and van Roermund 2005). The inclusions generally contain Ti-phlogopite, kalsilite, Cr-spinel, magnesite, dolomite, Ba-Mg carbonate, Fe-Ni sulfide, Cl-apatite, rutile, zircon, and monazite; graphite or microdiamond are also found. The inclusions are interpreted to have formed from metasomatic fluids that infiltrated the peridotite. (2) Multiphase inclusions in garnets from UHP phengite-garnet-kyanite sienobachite lenses of the Saxonian Erzgebirge (Bohemian Massif) are composed mostly of phlogopite, quartz, paragonite, phengite, apatite, and rutile. In addition, graphite or microdiamond are common (Stöckhert et al. 2001, 2009). The inclusions record the presence of dense, alkali- and silica-bearing C-O-H fluids in deeply buried crust. (3) Multiphase inclusions in garnets within ultrahigh-temperature (UHT) granulites of the Barun Gneiss (Himalayas, Nepal) contain mostly quartz, biotite, muscovite, and plagioclase, together with accessory minerals...