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Highlights and Breakthroughs

Crustal melting: Deep, hot, and salty

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The transformative nature of granulite-facies metamorphism, coupled with the subsequent upheaval of the rocks during exhumation, commonly obscures much of the geologic record of deep-crustal metasomatism and anatexis. Thus, the compositions of incipient melts in orogenic settings are generally unknown and are inferred based on petrologic experiments or thermodynamic models (Bartoli 2021). The melts are expected to be peraluminous and leucogranitic (Chapman et al. 2021), but the occurrence of strongly peraluminous granitoids of moderately mafic character, such as granodiorite, calls this into question (Zen 1988). Such intermediate, peraluminous granitoids have been interpreted as reflecting entrainment of either restitic or peritectic minerals in the ascending melt (Clemens and Stevens 2012; Chapman et al. 2021). Alternatively, such melts may have attained their more mafic character by melting at higher temperature (T) (Zen 1988). The latter interpretation is supported by experimental results (Patiño Douce and Johnston 1991) but so far lacks clear evidence in the rock record. Besides, dehydration melting of metapelites (e.g., by biotite breakdown) is expected to occur mostly within a restricted T interval (~800–850 °C), and the melts produced are wet enough to rapidly expend the H_2O content of the protolith, limiting melt production at higher T (Makhluf et al. 2017). On the other hand, factors that reduce the activity of H_2O, such as saline brines, may inhibit the onset of melting until higher T (Aranovich et al. 2013). But again, direct evidence in the rock record is generally lacking.

In this issue of *American Mineralogist*, Ferrero et al. (2021) describe exceptional evidence for high-T anatexis of metasediments through direct analyses of aliquots of incipient melt trapped in peritectic garnet. Ferrero et al. (2021) analyzed melt inclusions in garnet from felsic granulites of the Central Maine Terrane (CMT), previously described by Axler and Ague (2015). These inclusions provide a unique and compelling view of the compositions of melts produced during anatexis of metasediments at ultra-high T (UHT) >1000 °C, high pressures (HP) of >1.7 GPa, and likely in the presence of saline brines. The melt compositions are peraluminous, moderately enriched in MgO+FeO, and highly enriched in Cl+F. Hence, these results effectively represent a "missing link" in the origin and evolution of peraluminous melts and underscore the diversity of crustal melts produced in the bowels of orogens.

Ferrero et al. (2021) analyzed "nanogranitoid" melt inclusions trapped in peritectic garnet. In recent years, detailed microstructural studies have shown that such nanogranitoid inclusions can record many otherwise elusive properties of deep crustal melts (Bartoli et al. 2013). Such melt inclusions are challenging to study, owing to their small size and the fact that they require high confining P for laboratory homogenization (Bartoli et al. 2013). Nevertheless, such inclusions are the best available tools to characterize the properties of the trapped melts. The inclusions studied by Ferrero et al. (2021) were trapped in peritectic garnets from sillimanite-bearing gneisses of the CMT (Acadian orogeny, northeast U.S.A.) and previously reported by Axler and Ague (2015). Ferrero et al.'s (2021) results reveal several surprises and provide a remarkable view of anatexis under extreme conditions.

The first major finding by Ferrero et al. (2021) is that anatexis of these granulites occurred at significantly higher T and P than the previous estimates based on phase equilibria. Specifically, Ferrero et al. (2021) found that the inclusions melted at 1050 °C, and that a *minimum* confining pressure of 1.7 GPa was required to prevent decrepitation. Hence, the re-melting experiments attest to both HP and UHT conditions of at least ~1050 °C and ~1.7 GPa in the CMT.

Ferrero et al. (2021) next analyzed the compositions of the homogenized inclusions and documented an enriched mafic component of the incipient melts up to >5 wt% FeO+MgO. These values are well in excess of the average concentrations in both leucogranites and other nanogranitoid inclusions (both typically contain <2 wt% FeO+MgO; Bartoli et al. 2016) and are akin to melts produced during UHT (>1000 °C) melting of metapelites in laboratory experiments (Patiño Douce and Johnston 1991). The FeO+MgO concentrations of the melts reported by Ferrero et al. (2021) even approach the values of some peraluminous granodiorites. Thus, Ferrero et al. (2021) provide direct evidence for the production of FeO+MgO-enriched melts during HP/UHT anatexis—a process previously recognized only in experiments and not seen before in natural samples. Moreover, these results imply a significantly lower degree of polymerization—and hence, substantially lower melt viscosity—compared to previously reported, leucogranitic nanogranitoids. Hence, both UHT and relatively low degree of polymerization of the melts would likely promote efficient melt extraction.

Ferrero et al. (2021) also measured volatile concentrations (H_2O, CO_2, Cl, and F) in the homogenized inclusions. The H_2O concentrations (~4 wt%) are in agreement with previous studies of melts produced during HP experiments (Makhluf et al. 2017), and the inclusions show very high CO_2 contents up to 8000 ppm (~3000 ppm on average). These H_2O-CO_2 contents imply that the melts were fluid-undersaturated at trapping conditions, consistent with the absence of fluid inclusions in the studied garnets and with petrologic models for ascent and emplacement of "S-type" plutons (Zen 1988). Moreover, the exceptionally high CO_2 contents of these inclusions, coupled with their modest concentrations of H_2O, imply that these melts would eventually

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degas a CO_2-rich fluid upon ascent and decompression, consistent with observations from mineralized greisen veins and pegmatites associated with peraluminous granitoids (Černý et al. 2005).

Perhaps the most intriguing result of Ferrero et al. (2021) is that these primary HP/UHT melts show very high concentrations of the halogens Cl and F—up to >1 wt% Cl+F, and in some cases approaching 1 wt% *each* of both Cl and F (!). These are exceptionally high values, about an order of magnitude greater than the average for most granitoids, and significant for several reasons. First, Ferrero et al. (2021) convincingly argue that these halogen contents imply melting in the presence of saline brine. For several decades, the presence, type, and role of fluids during granulite metamorphism and anatexis have been highly debated (Aranovich et al. 2013). The exceptional Cl concentrations of the melts reported by Ferrero et al. (2021) support the interpretation that chloride-rich brines played a role, inhibiting melting until UHT conditions were reached. The high F contents of the melts produced probably reflect a complementary process, in which the fluor-component of biotite was destabilized as a result of UHT, driving dehydration melting with anomalously high F. Hence, a key implication is that UHT conditions go hand-in-hand with Cl- and F-rich melts. Even more so than the high FeO+MgO contents noted above, these exceptional F contents would contribute to dramatically lower the viscosity of the incipient melt (Baker and Vaillancourt 1995), thus enhancing the potential for efficient extraction and ascent.

These results also have major implications for the genesis of magmatic-hydrothermal ores in orogenic settings. For example, the solubility of cassiterite (SnO_2) in peraluminous, granitic melts increases substantially with increasing temperatures *and* concentrations of Cl and F in the melt (Bhalla et al. 2005). Moreover, when such melts reach fluid saturation, they degas F-rich hydrothermal fluids that form greisen veins (Černý et al. 2005). Partitioning of both Cl and F from the melt into an exsolved aqueous fluid is strongly enhanced by elevated Cl and F in the melt (Webster 1997). Hence, the results of Ferrero et al. (2021) help explain the ultimate origins of F-rich, ore-forming fluids.

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