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Garnet-forming reactions in felsic orthogneiss: Implications for densification and strengthening of the lower continental crust

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ABSTRACT

Growth of garnet and pyroxene in orthogneiss from the Athabasca granulite terrane (AGT), northern Saskatchewan, provides a model for progressive densification and strengthening of the lower continental crust with implications for the recycling and long-term evolution of continental crust. Two distinct assemblages and textures are preserved in granitic and granodioritic gneiss. Low-strain orthogneiss displays igneous textures and assemblages of Opx+Kfs+Pl+Mag+Qz (± Bt, Hbl, Ilm). High-strain, dynamically recrystallized tectonites have additional garnet, clinopyroxene, and a more Na-rich plagioclase, along with relict orthopyroxene. The reaction (Opx+Ca-rich Pl=Grt+Cpx+Na-rich Pl+Qz) is informally called the "Mary reaction" after documented occurrences in the Mary granitoid batholith. The reaction represents the transition from medium-pressure to high-pressure granulite (Green and Ringwood, 1967), but reaction progress was achieved in these deep crustal rocks along an isobaric cooling path at ca. 1 GPa (35–40 km-depth). Ambient *P–T* conditions were well within the product (low-*T*-side) stability field. The abundance of the product assemblage (Grt+Cpx+Na-rich Pl) increases with deformation. Metastable igneous assemblages are widely preserved in low-strain samples. With increasing strain, garnet occurs within recrystallized mantles of plagioclase porphyroclasts, and clinopyroxene occurs in the deformed tails of orthopyroxene crystals. Deformation is interpreted to aid in the breakdown of plagioclase and/or the nucleation of garnet and clinopyroxene. Garnet and pyroxene modes have been observed to exceed 10 vol% in the AGT, but larger amounts are possible because Ca-rich plagioclase and orthopyroxene remnants are widely preserved. Densities increase from ca. 2.6 to ca. 3.0 g/cm^3 and modeled P-wave velocities approach 7.0 km/s in felsic rocks. Densities in mafic rocks approach 3.4 cm^3. The reaction occurred at least twice in the AGT, 2.6 and 1.9 Ga, and may have occurred at other times during long-term deep crustal residence. Thus, densification can occur incrementally and correspond with the time and intensity of tectonism and concomitant recrystallization. The reaction provides a mechanism for significant densification and strengthening of lower continental crust long after initial stabilization. It may explain the discrepancy between seismic velocities suggestive of mafic/intermediate compositions at lower crustal depths and the observed abundance of felsic rocks in exposed granulite terranes.

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1. Introduction

The composition and rheology of lower continental crust is important for models of orogenesis, for constraining the geochemical evolution of Earth, and for understanding the evolution and stabilization of continents. Geophysical properties, xenolith studies, heat flow data, and geochemical considerations suggest that the bulk continental crust has the composition of an intermediate igneous rock, and that the lower crust may have a more mafic bulk composition (Rudnick and Fountain, 1995; Christensen and Mooney, 1995; Rudnick and Gao, 2003). This is supported by the abundance of mafic xenoliths believed to be sourced in the deep crust (Rudnick and Fountain, 1995). However, there is considerable uncertainty in the mineralogy and geochemistry of the deep crust, and it is possible that parts of the middle to deep continental crust are considerably more felsic than commonly interpreted (Hacker et al., 2011, 2014). Incomplete sampling and alteration during transport to the surface are two among many reasons to suspect that the xenolith record may not be completely reflective of lower crust composition (McLeod and Sparks, 1998; Ferri et al., 2007). Further, evidence from isobaric granulite terrains

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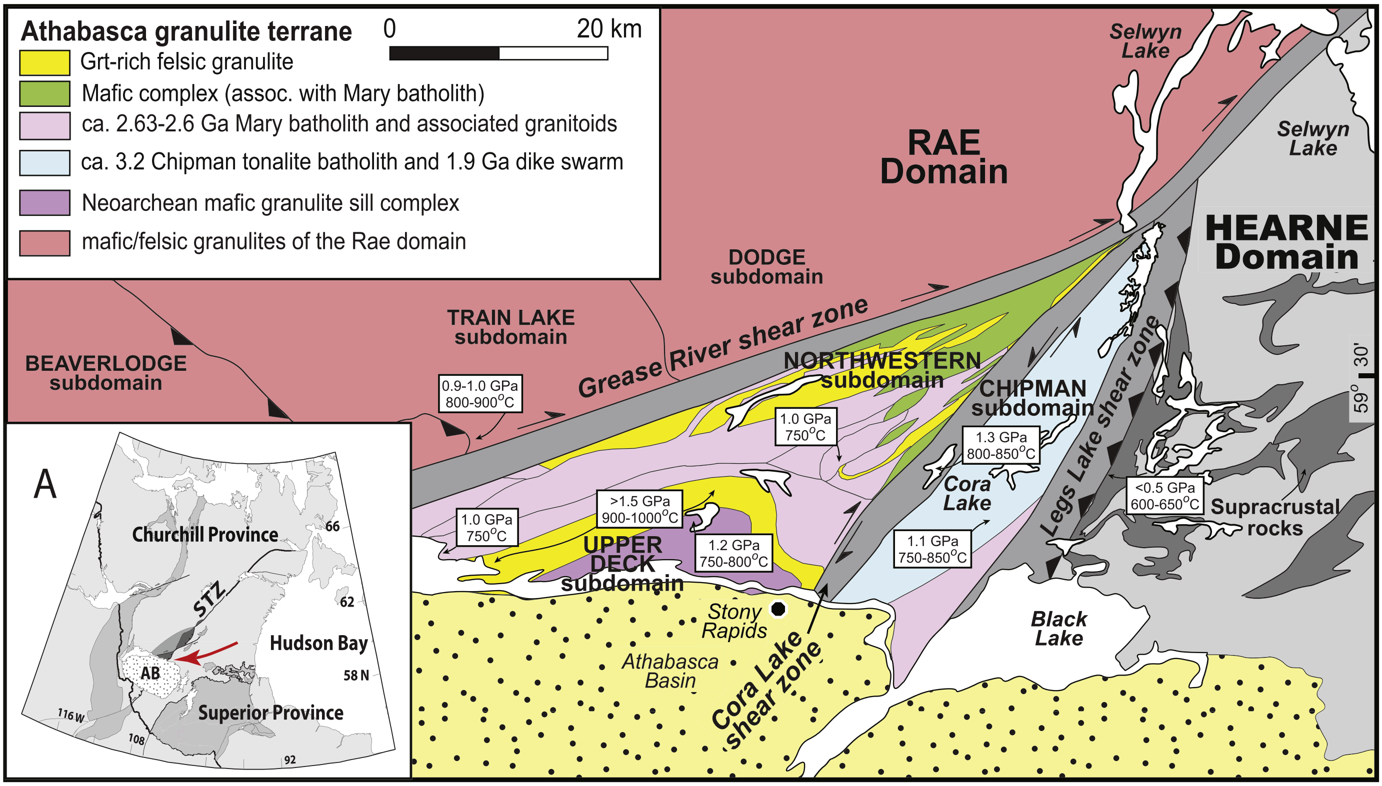

Fig. 1. Simplified geologic map of East Athabasca mylonite triangle (Tantato domain) region after Gilboy (1980), Slimmon (1989), Hanmer (1994), Mahan et al. (2003), and unpublished mapping. (A) Inset map showing general location. STZ – Snowbird Tectonic Zone; AB – Athabasca Basin. See text for discussion.

(inferred exposures of deep crust) suggest that the deep crust is heterogeneous in composition, major mineralogy, texture, and geologic history, and that felsic rocks are potentially abundant components of the deep crust (Ellis, 1987; Rudnick and Fountain, 1995; Williams and Hanmer, 2006).

Three issues underscore the importance of constraining the character and variability, in time and space, of lower continental crust. The first is that, at least in some areas, the composition and/or character of the deep crust has been interpreted to vary through time. Fischer (2002) documented a consistent decline in buoyancy of continental roots with increasing thermo-tectonic age (i.e., time since the last orogenic activity), consistent with a diminishing density contrast between the root of previously-thickened continental crust and its underlying mantle. Erosion rates show a similar decline with age (Blackburn et al., 2012). The increase in density and the corresponding secular changes in erosion rate and topography, in some cases long after orogenesis, are interpreted in terms of metamorphic reactions in the lower continental crust, particularly the growth of garnet (Fischer, 2002; Blackburn et al., 2012). Second, under certain conditions, blocks or layers of deep continental crust are interpreted to have delaminated and sunk into the mantle. A number of workers have called upon lower crustal delamination in order to account for thin crust or the lack of a relatively mafic deep crust (Nelson, 1991; Kay and Mahlburg Kay, 1993; Meissner and Mooney, 1998; Ducea, 2011; Krystopowicz and Currie, 2013). These models generally require either the presence of a dense residuum (from partial melting or fractional crystallization) or metamorphism and densification in order to generate a density inversion between the deep crust and underlying mantle (Kay and Mahlburg Kay, 1991; Jull and Kelemen, 2001; Karlstrom et al., 2012). A third issue concerns the wide variation in lower crustal rheology implied by geodynamic models and geodetic observations (e.g., Jamieson et al., 2007; Bürgmann and Dresen, 2008; Wernicke et al., 2008). Although this variation in strength may reflect the uncertainty in model parameters, an alternative interpretation is that the strength of lower continental crust is capable of significant variation, and metamorphic reactions may play an important role in strengthening and/or weakening the lower crust (Steffen et al., 2001; Rutter and Brodie, 1991; Thatcher and Pollitz, 2008; Dumond et al., 2010).

High-pressure granulite facies rocks in the Athabasca granulite terrane (AGT), northern Saskatchewan are interpreted to represent a nearly isobaric slice of the lower continental crust (Mahan and Williams, 2005; Williams and Hanmer, 2006). Extreme heterogeneity is an overriding characteristic of this sample of deep crust, and is manifest by a wide variety of mafic to felsic rock types and a broad range of deformation states, from pristine granitoid to ultramylonite to annealed granulite gneiss. Two important and consistent observations are: (1) the progressive development of garnet in many rocks, of widely varying composition, through time and (2) an apparent relationship between garnet formation and strain in the rocks. The purpose of this paper is to describe a type of garnet-producing reaction that occurs in a variety of rock types in the AGT and to discuss how this reaction provides a viable mechanism for progressive densification and strengthening of lower continental crust.

2. Background

The Athabasca granulite terrane is a >20,000 km^2 exposure of granulite facies rocks located north of the 1.7 Ga Athabasca intracratonic basin in the western Canadian Shield (Fig. 1) (Mahan and Williams, 2005; Williams and Hanmer, 2006; Dumond et al., 2008). The terrane is located along the central segment of the Snowbird Tectonic Zone (Hoffman, 1988; Hanmer, 1997), the boundary between the Rae and Hearne domains of the Churchill cratonic province. The AGT is bounded on the southeast by the

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