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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.

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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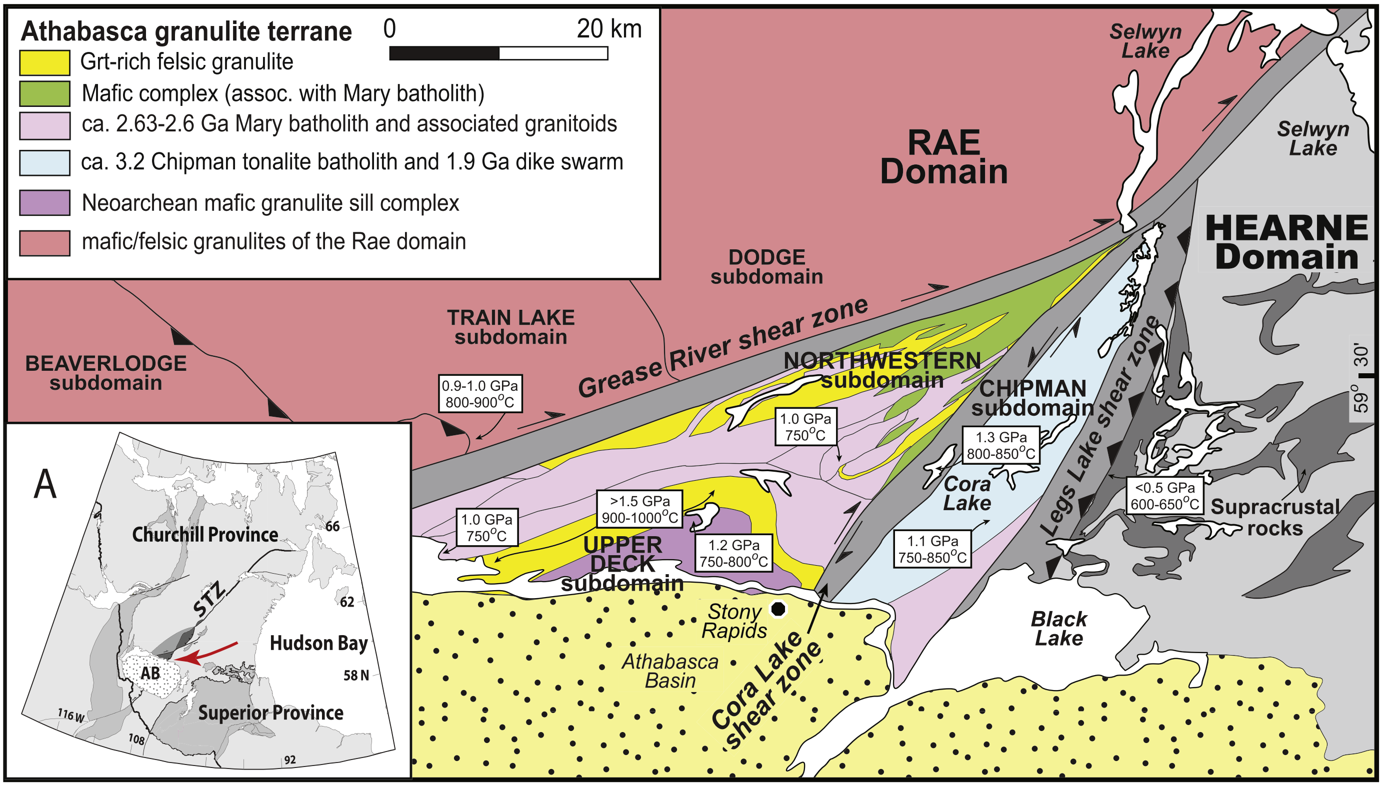

Fig. 1. Simplified geologic map of East Athabasca mylonite triangle (Tantato domain) region after Gilboy (1980), Slimmon (1989), Hanmer (1994), Mahan et al. (2003), and unpublished mapping. (A) Inset map showing general location. STZ – Snowbird Tectonic Zone; AB – Athabasca Basin. See text for discussion.

(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

Table 1
Major element composition of Mary batholith and mafic dikes/sills.

Mary granite batholith							Bohica[b]	Chipman mafic dikes (1.9 Ga)				Mafic granulite	
Sample	S182 WH	C664a ML	S230 TL	M190 C1	63 WH	71 WH	11R-112	W2-41 CAULI	M112-D	W2-26	M2479B	02M133A[a]	03-217A
SiO_2	69.7	66.2	62.8	64.5	70.73	74.14	58.01	49.26	49.69	51.52	49.61	49.9	49.23
TiO_2	0.5	0.71	0.9	0.88	0.46	0.39	1.3	3.09	1.31	1.78	0.6	1.82	0.79
Al_2O_3	13.8	14.8	14.8	14.91	13.8	12.7	16.58	12.97	13.54	13.1	16.33	14.82	3.91
Fe_2O_3T	5.2	6.9	9.4	7.86	4.43	3.04	9.42	16.95	15.34	16.05	11.8		13.49
Fe_2O_3	0.2	0.9	0.5	–	–	–	–	–	–	–	–		
FeO	4.5	5.4	8	–	–	–	–	0.22	0.21	0.22	0.19	14.06	
MnO	0.05	0.08	0.12	0.11	0.06	0.04	0.13	5.13	6.2	4.72	8.48		0.22
MgO	0.76	1.41	0.96	1.66	0.43	0.2	1.25	9.16	9.9	8.88	10.87	6.46	22.41
CaO	1.95	3.64	3.78	3.95	2.21	1.27	5.92	2.46	2.65	2.61	2.11	10.55	7.53
Na_2O	2.6	3	3.1	2.43	2.63	2.39	3.55	0.49	0.75	0.9	0.38	2.39	1.6
K_2O	4.74	3.24	3.47	2.82	4.37	5.78	2.68	0	0	0	0		0.28
H_2O	0.8	0.6	0.7	–	–	–		0	0	0	0		
P_2O_5	0.15	0.22	0.26	0.2	0.14	0.1	0.64	0.34	0.11	0.18	0.05		0.08
Total	99.75	100.2	99.39	99.32	99.25	100.04	99.48	100.07	99.7	99.96	100.42	100	99.54

[a] From Mahan et al. (2008); normalized to 100%.
[b] Bohica mafic complex, possibly related to Mary batholith.

Legs Lake shear zone, an east-verging thrust-sense shear zone that juxtaposed the high-*P* rocks against middle crustal rocks of the Hearne domain (Mahan et al., 2003, 2006a). Details of the 1.9–1.78 Ga multi-stage regional exhumation history and late-stage strike-slip disruption of the terrane during the Trans-Hudson orogeny are presented by Mahan and Williams (2005), Flowers et al. (2006a), and Dumond et al. (2013a).

The most extensively studied portion of the AGT, the East Athabasca mylonite triangle (Hanmer, 1994, 1997) or Tantato domain (Slimmon, 1989), is divided into three lithotectonic subdomains: Northwestern, Chipman, and Upper Deck (Fig. 1). All three subdomains are dominated by Meso- to Neoarchean igneous protoliths (3.2 to 2.6 Ga) that have been strongly reworked by at least two major periods of high-*P* tectonometamorphism: one in the Neoarchean at ca. 2.6–2.5 Ga and a second in the Paleoproterozoic at ca. 1.9 Ga (Hanmer et al., 1994, 1995; Snoeyenbos et al., 1995; Williams et al., 1995, 2000; Kopf, 1999; Baldwin et al., 2003, 2004, 2006, 2007; Flowers et al., 2006a, 2006b, 2008; Mahan et al., 2006b, 2008; Dumond et al., 2008, 2010). Williams and Hanmer (2006) summarized the geology of the terrane and emphasized the heterogeneity that characterizes much of the AGT.

Approximately 2.6 Ga granitoid rocks are abundant throughout the Rae Province (Hinchey et al., 2011), and are well exposed in the Northwestern subdomain of the East Athabasca mylonite triangle (Fig. 1). Bulk SiO_2 contents range from 60 to >70%, and most are formally granodiorite (Table 1) (Williams et al., 2000). The largest component of this granitoid batholith is the Mary granite (Hanmer et al., 1994; Hanmer, 1997; Williams et al., 2000). Typical exposures of the Mary granite and equivalents have a well foliated gneissic texture, although small volumes of coarse plutonic protolith are locally preserved. Most rocks contain ribbons or clusters of polycrystalline feldspar separated by a finer matrix of feldspar, quartz, and lesser amounts of hornblende, garnet, clinopyroxene, orthopyroxene, and ilmenite ± biotite (Fig. 2).

Rocks of the Northwestern subdomain, including the Mary granite, are characterized by large (meter-to-kilometer scale) F_2 folds with upright, northeast-striking axial surfaces. In many localities, the folds deform a moderate to strong gneissic to mylonitic fabric (S_1). An early mineral lineation (L_1) trends E–W or NW–SE and is folded by the upright folds (Dumond et al., 2010). In 3-D exposures, the early gneissic fabric has a consistent top-to-the-east vergence, interpreted to represent subhorizontal flow of the deep crust (Fig. 2) (Dumond et al., 2010; Regan et al., in press). The intensity of the S_2 axial plane fabric varies across the area, but is generally weakest in F_2 hinges and strongest in limbs, where it commonly is a composite S_1/S_2 foliation. Along fold limbs, S_2 can be strongly mylonitic with significant grain size reduction and predominantly dextral kinematic indicators. Both S_1 and S_2 involve garnet, clinopyroxene, quartz, plagioclase, and K-feldspar. Locally, S_2 includes small amounts of hornblende, suggesting that fluids may have infiltrated the rocks during cleavage development (Regan et al., in press), but the total amount of fluid influx was probably small as indicated by minimal evidence for partial melting of the Mary granite (Williams et al., 2000).

Thermobarometric calculations indicate pressures on the order of 0.9–1.0 GPa and temperatures above 700 °C for both the S_1 and S_2 fabric-forming events in the Northwestern subdomain (Williams et al., 2000; Dumond et al., 2010; Regan et al., in press). Calculations using multiple calibrated thermobarometers and internally consistent thermobarometry were done by Williams et al. (2000); thermodynamic modelling was done by Dumond et al. (2010) and Regan et al. (in press). Dumond et al. (2010) used in-situ monazite geochronology to constrain the age of the two fabrics, and Regan et al. (in press) carried out similar analyses on rocks near Cora Lake and Beed Lake, almost 60 km to the northeast. Both studies concluded that S_1 formed during the Archean (2.60–2.55 Ga) and S_2 formed during the Paleoproterozoic (ca. 1.9 Ga), consistent with results of Baldwin et al. (2003). These data suggest that the region existed at pressures near 1.0 GPa and temperatures >700 °C during two deformation events, approximately 700 m.y. apart. The deformation styles have been interpreted to suggest that the deep crust was relatively weak and capable of flowing during the Neoarchean, but was relatively strong, compared to the earlier event, during the Paleoproterozoic (Dumond et al., 2010).

3. Garnet-forming reaction (s)

One of the most striking characteristics of the Mary granite is its broad range of deformational and metamorphic textures. Individual outcrops display a range from medium to coarse grained igneous textures with no visible foliation or lineation to strongly compositionally banded gneisses, S-C-C′ mylonites, and fine-grained ultramylonites (Williams et al., 2000). Some of the variation is interpreted to reflect progressive phases of granite emplacement relative to the accumulating regional strain (Williams et al., 2000). However, other textural variations reflect localized heterogeneous strain within the intrusive bodies. Gradients from relatively undeformed granite to highly strained gneiss can be seen on scales from centimeters to kilometers.

The transition from igneous texture to gneissic texture/fabric in the Mary granite (Williams et al., 2000) corresponds with a char-

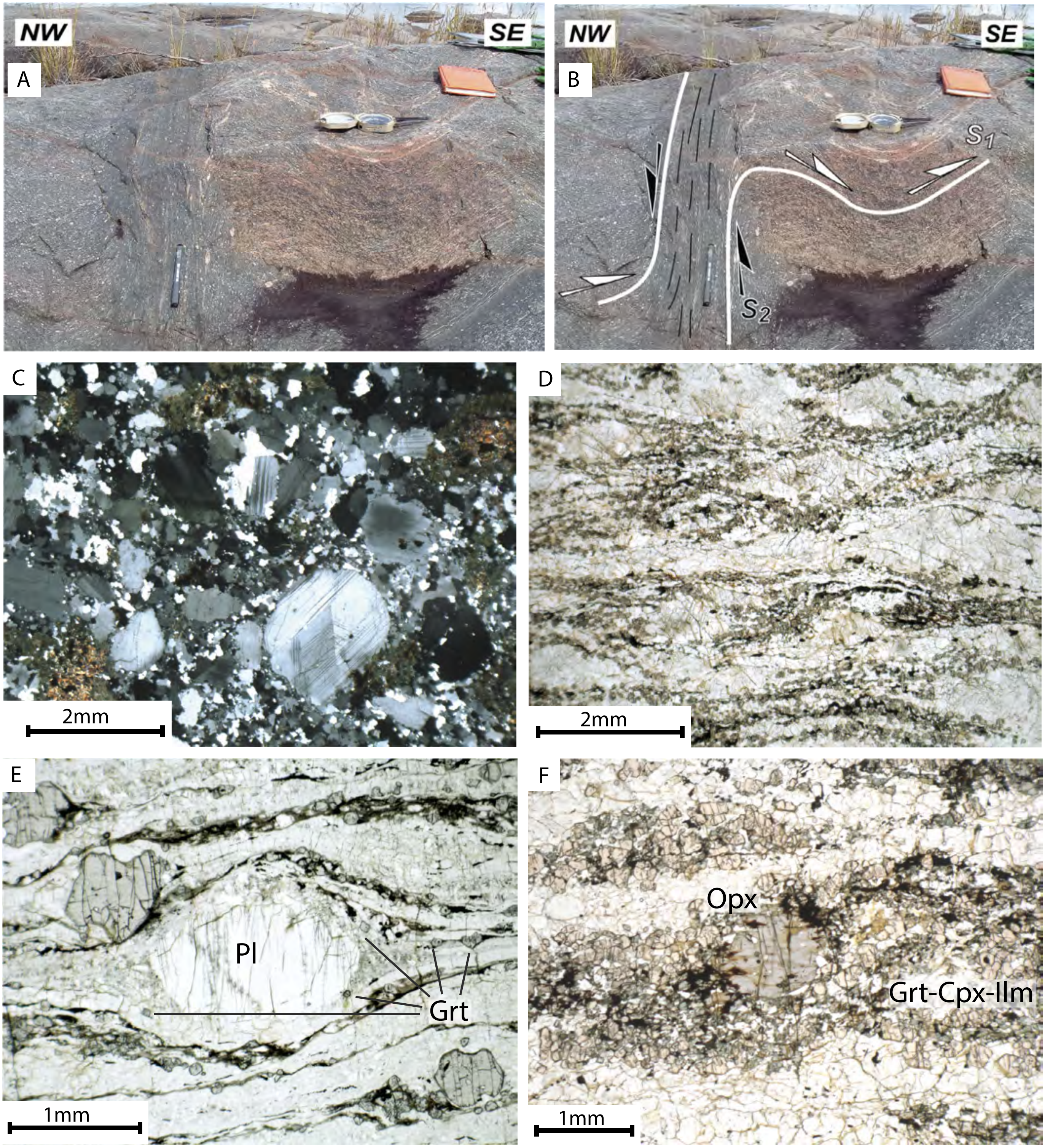

Fig. 2. Photos of garnet-bearing Mary granite: (A, B) Early subhorizontal S1 fabric cut by vertical S2 – see text for discussion (modified after Dumond, 2008). (C) Low-strain sample (S823) of Mary granite. (D) High-strain sample of Mary granite with Grt, Cpx, and Ilm in dynamically recrystallized tails of plagioclase and orthopyroxene. (E) Plagioclase porphyroclast with Grt+Ilm on dynamically recrystallized tails. Note new Grt within recrystallized tail. (F) Opx porphyroclast with Grt, Cpx, and relict Opx defining dextral sigma tails. Garnet occurs adjacent to and within plagioclase ribbons (above and below Opx).

acteristic metamorphic reaction that is common in a range of rock types in the AGT. Low-strain (igneous-texture) exposures contain quartz, K-feldspar, plagioclase, orthopyroxene, and magnetite, with small amounts of biotite and hornblende (Fig. 2C). High-strain (gneissic) exposures contain garnet, clinopyroxene, quartz, K-feldspar, Na-rich plagioclase, and relict orthopyroxene ± hornblende (Fig. 2D) (Williams et al., 2000; Dumond et al., 2010). In its simplest form, the mineralogical transition in the Mary granite is interpreted to represent the model reaction:

$$2\text{Opx} + \text{Ca-rich Pl} \rightarrow \text{Grt} + \text{Cpx} + \text{Na-rich Pl} + \text{Qz} \quad (1)$$

(abbreviations from Whitney and Evans, 2010). In felsic rocks such as the Mary granite, the reaction has been informally called

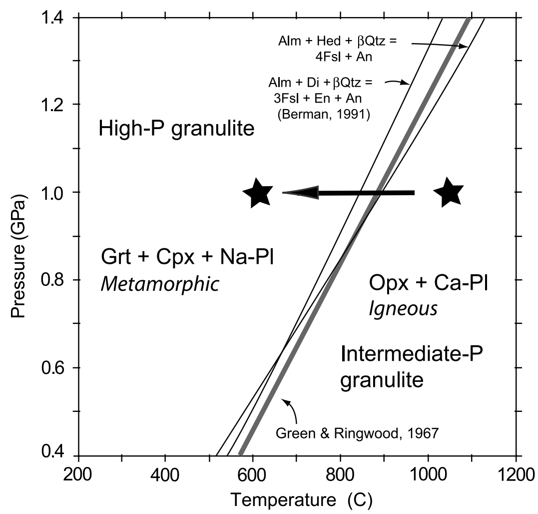

Fig. 3. Location of garnet-in ("Mary") reaction. Thin lines show reactions for Mary granite composition plotted using TWQ software of Berman (1991, 1992). Thick line is approximate location of experimental reaction of Green and Ringwood (1967). Stars show possible igneous crystallization temperature and stable geotherm temperature at 1.0 GPa (Williams et al., 2000).

"The Mary Reaction". However, the reaction is similar to the one that defines the boundary between medium-pressure and high-pressure granulites in mafic rocks (Green and Ringwood, 1967). The progress of this reaction is evident in a wide variety of mafic to felsic rock types throughout the East Athabasca mylonite triangle. For this contribution, we focus mainly on felsic compositions because they are common in the AGT and we seek to understand their relative importance for models of the density and character of the deep crust. The reaction is plotted for typical Mary granite bulk compositions in Fig. 3. Relatively dry granitic magmas, regardless of the depth of emplacement, would crystallize on the high-temperature side of this reaction. However, temperatures in the "stable" (i.e. not actively deforming and not over-thickened) deep crust on a normal geothermal gradient are expected to be on the low-*T* side of this reaction (Mareschal and Jaupart, 2013). The presence of the high-*T* assemblage in numerous low-strain exposures around the region demonstrates that the Opx-bearing assemblage can exist metastably in the Grt+Cpx stability field for long periods of time.

As described by Williams et al. (2000), progress of Reaction (1) can be directly correlated with the textural transition from igneous to gneissic texture. Plagioclase forms core-and-mantle microstructures (White, 1976; Shigematsu, 1999), and garnet is restricted to the distinctly more Na-rich recrystallized mantles (Figs. 2E and 4). Additionally, garnet and clinopyroxene occur as coronae or mantles on primary orthopyroxene crystals (Fig. 2F). Orthopyroxene is commonly fractured into tabular segments and drawn out in a domino or bookshelf microstructure. The overall abundance of garnet and clinopyroxene increases with the degree of deformation of orthopyroxene and of recrystallization of Ca-rich igneous plagioclase. The final result is a gneissic texture with three basic layer types: 1) recrystallized plagioclase layers decorated with garnet, 2) garnet-clinopyroxene layers with remnant orthopyroxene, and 3) recrystallized quartz-K-feldspar layers interpreted to be recrystallized matrix domains in the original granite (see Williams et al., 2000).

At the time that Reaction (1) was originally described in rocks from the AGT, the S_1 and S_2 fabrics were not fully differentiated. Recent work has shown that the reaction products are most abundantly and characteristically developed on the subhorizontal S_1 fabric (Dumond et al., 2010; Holland et al., 2012). However, locally, the reaction has also occurred during shearing and dynamic recrystallization associated with S_2 (Dumond et al., 2010; Regan et al., in press). Consequently, the same reaction occurred or progressed at two very different times, both associated with regional tectonism. In both cases, the reaction products are associated with the dynamic recrystallization of igneous plagioclase and orthopyroxene crystals. Hornblende is produced locally during the S_2-hosted reaction (Dumond et al., 2010; Regan et al., in press).

3.1. Modeling reaction (1)

A series of forward models were carried out to characterize Reaction (1) in *P*–*T* space and to evaluate the potential change in physical properties of granitoid rocks in the deep crust. Modeling was carried out using the software Theriak-Domino of de Capitani and Petrakakis (2010) with the JUN92 database of Berman (1988) and v. 5.5 of the internally consistent thermodynamic data set of Holland and Powell (1998). Physical properties were evaluated using the Theriak-Domino software and the spreadsheet of Hacker and Abers (2004). Bulk compositions for several samples of Mary granite were reported by Williams et al. (2000), and are presented in Table 1 along with several new analyses. Major element compositions were determined by XRF analysis at the University of Massachusetts.

Fig. 5A is an equilibrium phase diagram calculated for the composition of sample M190 (Table 1). The high-*T* starting assemblage consists of plagioclase (fsp), orthopyroxene, and quartz. Although the Mary granite also contains K-feldspar, it does not appear to affect the assemblage or reactions at these conditions, especially in the absence of H_2O. On cooling, garnet first joins the assemblage, then clinopyroxene, and finally orthopyroxene leaves. Balanced reactions for this bulk composition are shown in Table 2. The final assemblage consists of garnet, clinopyroxene, plagioclase, and quartz. Of the many relatively undeformed and unreacted samples of the Mary granite, little or no garnet has been recognized, suggesting that emplacement conditions were in excess of 1000 °C (Williams et al., 2000). Further, most of the strongly deformed samples contain little or no orthopyroxene, suggesting that final equilibration conditions were near or below 600 °C.

Fig. 5B shows contours of volume percent garnet in the modeled product assemblage. For this bulk composition, garnet modes range from zero at the garnet-in reaction to more than 20% at presumed deep crustal temperatures of approximately 500–600 °C. The amount of garnet produced will vary with the bulk composition of the starting granitoid. For the range of Mary granite compositions, the amount of garnet produced varies from approximately 10% to more the 20%, with the average composition yielding more than 18% garnet. Importantly, contours of vol% garnet (Fig. 5B) are most closely spaced in the garnet + two-pyroxene region between approximately 850 °C and 700 °C at 1.0 GPa. Thus, on cooling, the region from 850 °C to 700 °C is associated with the most extensive garnet growth. Modeled garnet compositions are similar to those measured by Williams et al. (2000), although most have slightly lower pyrope + grossular and higher almandine compositions than the model results.

Fig. 5C shows the variation in bulk density calculated for this composition (sample M190). The density increases, on cooling, from below 2.75 g/cm^3 to approximately 2.95 g/cm^3 at 500–600 °C and is relatively pressure independent. Density increases most rapidly in the 850 °C to 700 °C window where orthopyroxene decreases and garnet increases in abundance. Fig. 5D summarizes the calculated physical properties for the orthopyroxene-bearing Mary granite, the garnet–granulite, and an average diabase (Hacker and Abers, 2004). Calculations were made using the macro of Hacker and Abers (2004) and verified using the Theriak-Domino software. Calculated garnet–granulite properties are similar to those of diabase, with a density of approximately

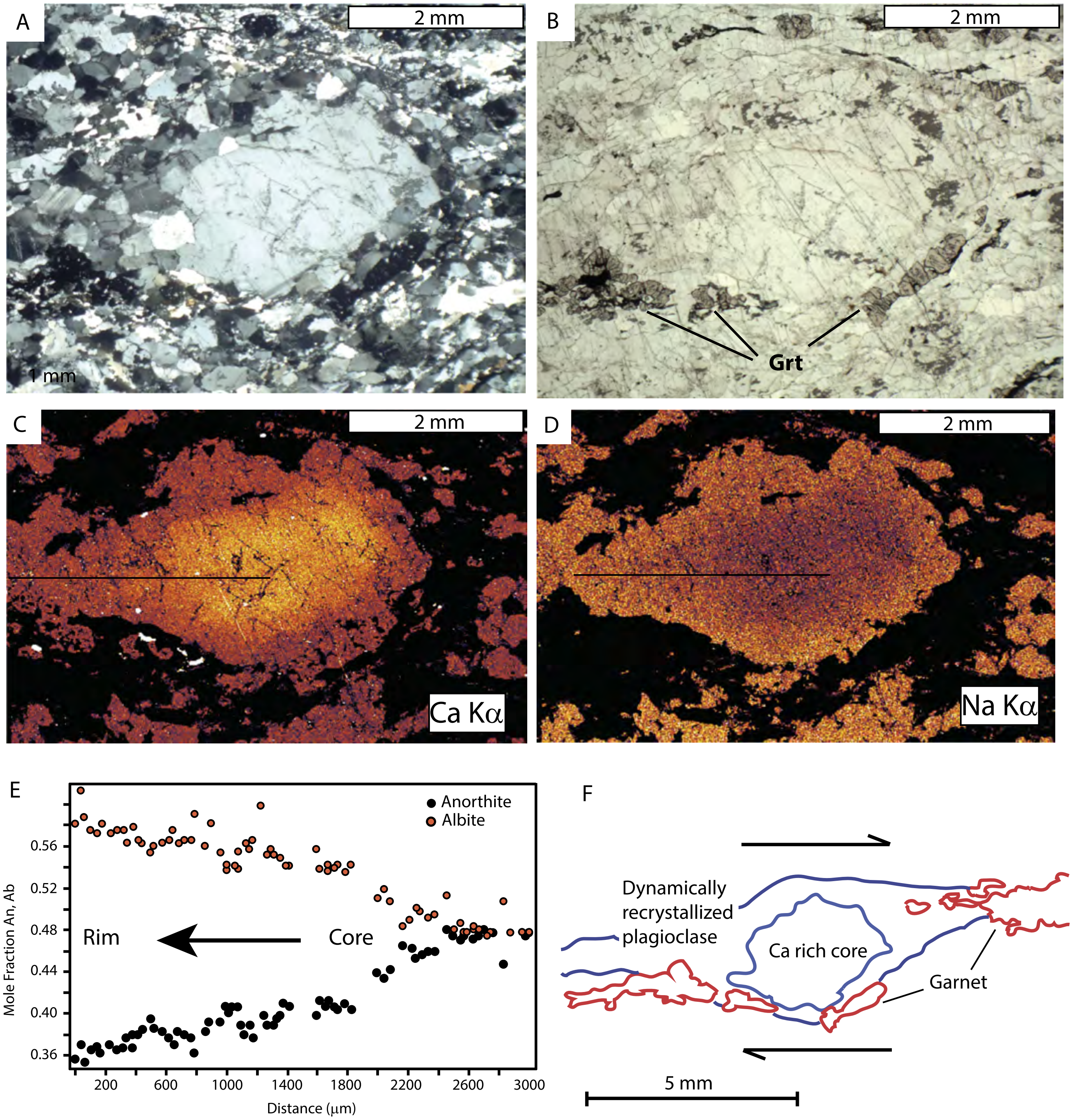

Fig. 4. (A, B) Photomicrograph of dynamically recrystallized plagioclase porphyroclast with garnet in recrystallized tails (modified after Holland et al., 2012). (C, D) Ca *Kα* and Na *Kα* WDS compositional maps of plagioclase porphyroclast showing Ca-richer core and Na-richer recrystallized rim, with garnet (mapping conditions: 330 × 515 pixels; 15 kV; 100 nA; 12 μm step). (E) Compositional traverse (core to rim) across plagioclase porphyroclast. (F) Sketch of dynamically recrystallized plagioclase porphyroclast.

3 g/cm^3, except that Vp is somewhat lower than average diabase depending on the method of calculation.

4. Other rock types associated with the Mary granite

The AGT is interpreted to be, to a first order, an isobaric terrane (Williams et al., 2009; after Mezger, 1992); essentially all rocks coexisted at similar pressures (crustal depths) despite later displacement of the deep crustal blocks during exhumation (Mahan and Williams, 2005). As such, associated rock types are of interest when considering the properties of the lower continental crust (Percival et al., 1992). Common rock types in the AGT include mafic plutonic rocks, abundant mafic dikes and sills, tonalite, felsic granulite, and migmatite. Except for tonalite, all of the other rock types developed significant amounts of garnet during tectonic events subsequent to igneous emplacement. With the exception of the garnet-bearing migmatites (see below), the primary mode of garnet growth was by reactions similar to Reaction (1), that is, gar-

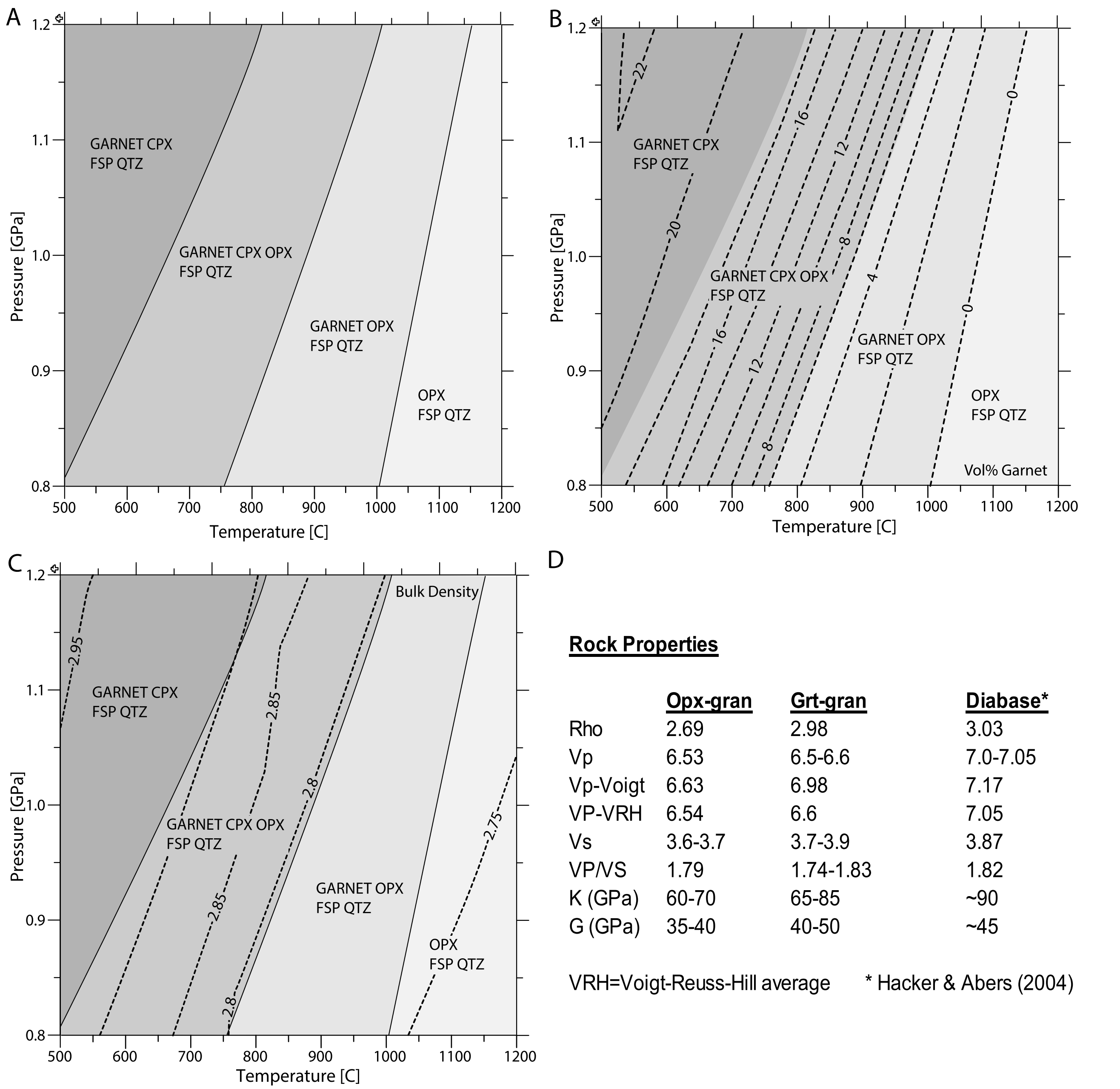

Fig. 5. Petrologic modeling of garnet-in reaction in Mary granite using Theriak-Domino (de Capitani and Petrakakis, 2010) with data base of Berman (JUN92) (Berman, 1988, 1991; Berman and Aranovich, 1996). (A) Reaction boundaries. (B) Isopleths of volume % garnet. (C) Isopleths of bulk density. (D) Approximate physical properties of rock at 550 °C, 1.1 GPa using calculations of Hacker and Abers (2004).

Table 2
Reaction sequence in Mary granitoid (Fig. 5)[a].

Garnet-in: Ilm + Fsp2 + Opx + bQz = Ilm + Garnet + 2Fsp2 + Opx + bQz
Cpx-in: Ilm + Garnet + 2Fsp2 + Opx + bQz = Ilm + Garnet + 2Fsp2 + Opx + Omph + bQz
Opx-out: Garnet + 2Fsp2 + Opx + Omph + Rt + aQz = Garnet + 2Fsp2 + Omph + Rt + aQz

[a] Reaction shown as a cooling sequence from high-*T* to low-*T* with high-*T* side on the left; Abbreviations from Theriak-Domino (de Capitani and Petrakakis, 2010).

net grew at relatively low-*T* at the expense of orthopyroxene and Ca-rich plagioclase with little or no evidence for melting.

Mafic rocks are of particular interest in studies of lower continental crust (Rudnick and Fountain, 1995), and two main varieties are present in the AGT. The first and older variety (Neoarchean) includes two-pyroxene mafic granulites and minor pyroxenites that occur as meter-to-kilometer-wide lenses up to 10 km in strike length (Baldwin et al., 2003; Mahan et al., 2008; Flowers et al., 2008). These rocks experienced a similar polymetamorphic history as the Mary granite. The earlier metamorphic event (ca. 2.55 Ga) involved growth of garnet and clinopyroxene via a reaction similar to Reaction (1) (Fig. 6A). The second variety of mafic rocks includes a large 1.9 Ga mafic dike swarm (Williams et al., 1995; Flowers et al., 2006b). These dikes are interpreted to have crystallized with a primary assemblage of hornblende, clinopyroxene, and plagioclase, and like the Mary granite, the assemblage is

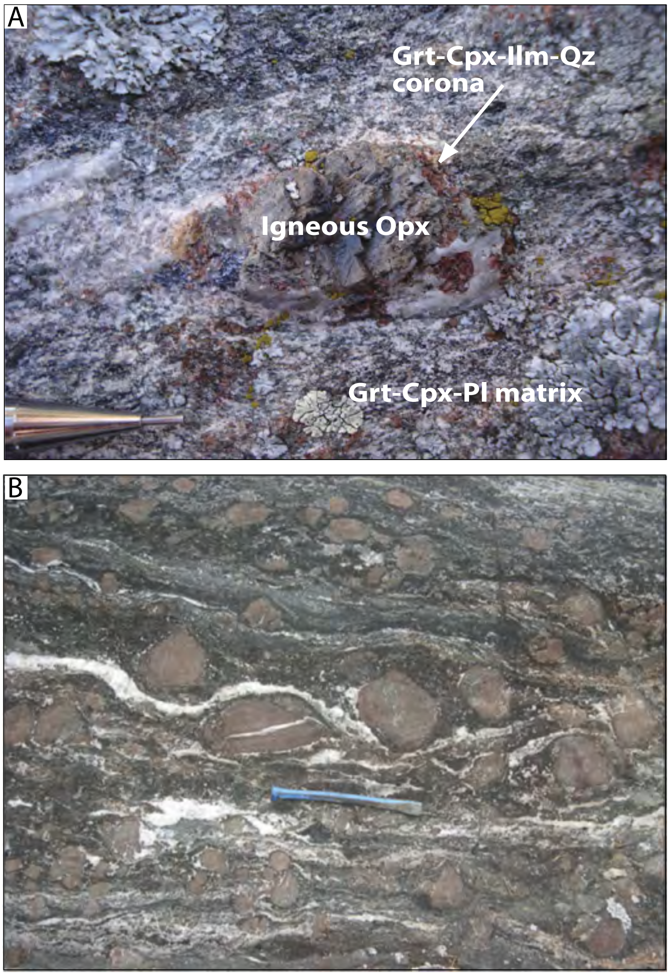

Fig. 6. Field photos of other garnet-rich rock types in the AGT. (A) Metamorphosed mafic granulite from Cora Lake, AGT. Igneous opx rimmed by metamorphic Grt–Cpx–Ilm–Qz corona in a grt-rich matrix (see Mahan et al., 2008 for discussion). (B) Metamorphosed mafic "Chipman" dike. Primary dike assemblage includes hornblende, plagioclase, and minor clinopyroxene. Metamorphic assemblage includes garnet, minor clinopyroxene, plagioclase, and quartz (see Williams et al., 1995 or Flowers et al., 2006b for discussion).

metastable (i.e. garnet would be expected) at ambient deep crustal conditions or even under deep crustal metamorphic conditions of 700–800 °C (Vielzeuf and Schmidt, 2001). Several garnet-producing metamorphic reactions have been observed. Some involving partial melting to produce tonalite, but the majority involve garnet and clinopyroxene growth without melting (Williams et al., 1995; Flowers et al., 2006b) (Fig. 6B). Modeling experiments, similar to those done for the Mary granite but using mafic dike bulk compositions, predict as much as 40 vol% garnet and densities as high as 3.4 g/cm^3 (Fig. 7). Garnet-bearing dikes have been observed in the AGT with a wide variation in garnet content from less than 10% to >90%, but dikes with 30–40% garnet are not uncommon. Two important observations are evident: (1) after metamorphism, these mafic rocks are only mildly eclogitic (i.e., clinopyroxene with up to 16% jadeite component and plagioclase still present) and (2) the dense garnet-bearing assemblage is produced on reheating, not during cooling or increasing pressure, as might be assumed for the transition from basalt to eclogite.

Partial melting of biotite-bearing felsic igneous rocks or Al-rich paragneisses in the deep crust can also lead to the development of significant amounts of garnet, and if melt is extracted, anhydrous garnet-rich restites can be produced (e.g., White and Powell, 2002). Dumond et al. (2013b, in review) investigated and modeled ultra-high *P*–*T* metamorphism and biotite dehydration melting of felsic plutonic rocks in the Upper Deck subdomain of the AGT. Models of partial melting without melt extraction predict over 13 vol% garnet (Dumond et al., in review). However, melt loss is required by field observations, mineral modes, and phase compositions. Models utilizing the residual felsic granulite bulk composition after a component of melt loss results in garnet modes that reach 20% or more (Dumond et al., in review). Layers and boudins of garnetite are locally present and certainly contributed to increases in bulk crustal density. Finally, Mahan et al. (2006a) investigated high-*T* metamorphism of felsic granulite in the Chipman domain of the AGT and also documented evidence for partial melting of felsic rocks via biotite dehydration. Importantly for both above examples, there was significant garnet growth during metamorphism of formerly felsic igneous rocks which locally produced m-scale layers consisting of >50% garnet.

In summary, most meta-igneous rock types in the AGT, from mafic to felsic, have significant amounts of garnet, and virtually all of the garnet developed after crystallization of the original igneous assemblage. Hornblende-bearing mafic dikes and biotite-bearing granites, particularly in the Upper Deck subdomain, developed significant amounts of garnet via peritectic reactions during partial melting. However, a much larger proportion of rocks in the region, such as the felsic Mary granite and mafic granulite dikes and sills, all developed large amounts of garnet via a non-melting reaction similar to Reaction (1). Assuming the AGT is a representative sample of lower continental crust, we suggest that the "Mary reaction" is a common and important mechanism for garnet growth and crustal densification. We discuss below the possible fate of igneous rocks during tectonism and subsequent residence in the deep crust, as these rocks cool into and are periodically reheated in the garnet-stability field (Fig. 3).

5. Discussion

5.1. Role of deformation in garnet growth

Felsic to intermediate 2.6 Ga plutonic rocks are abundant in the AGT. They were deformed and metamorphosed at 2.6–2.55 Ga and again at ca. 1.9 Ga during a protracted period of lower crustal residence (Williams and Hanmer, 2006; Flowers et al., 2008; Dumond et al., 2010). The garnet-producing Reaction (1) ("Mary reaction") characterizes the transition from relatively hot igneous crystallization conditions to cooler ambient conditions at high pressures in the post-tectonic deep crust. The transition is essentially a down-temperature, garnet-in metamorphic reaction. The rocks are interpreted to provide a model for the long-term evolution of lower continental crust after orogenesis and subsequent reestablishment of isostatic equilibrium.

Temperatures of rocks in the stable deep crust, i.e., not actively undergoing deformation or metamorphism, are probably on the order of 500–600 °C (Mareschal and Jaupart, 2013). As discussed above, the most significant phase of garnet production and densification due to Reaction (1) occurs at temperatures between ca. 850 and 700 °C. Thus, at ambient temperatures, Opx-bearing granitoids such as the Mary granite are predicted to have significant garnet, as much as 20% or more. However, a number of relatively low-strain exposures of mafic through felsic igneous rocks contain the original igneous assemblage, with little or no garnet or clinopyroxene. Clearly, it is possible for the high-*T* assemblage to exist metastably within the deep crust for long periods of time.

Because Reaction (1) does not involve hydration or dehydration (i.e. no hydrous minerals are involved as reactants or products), the input or removal of H_2O is not required for reaction progress. Instead, the correlation with fabric intensity suggests that deformation is one key to the forward progress of the reaction. Solid state

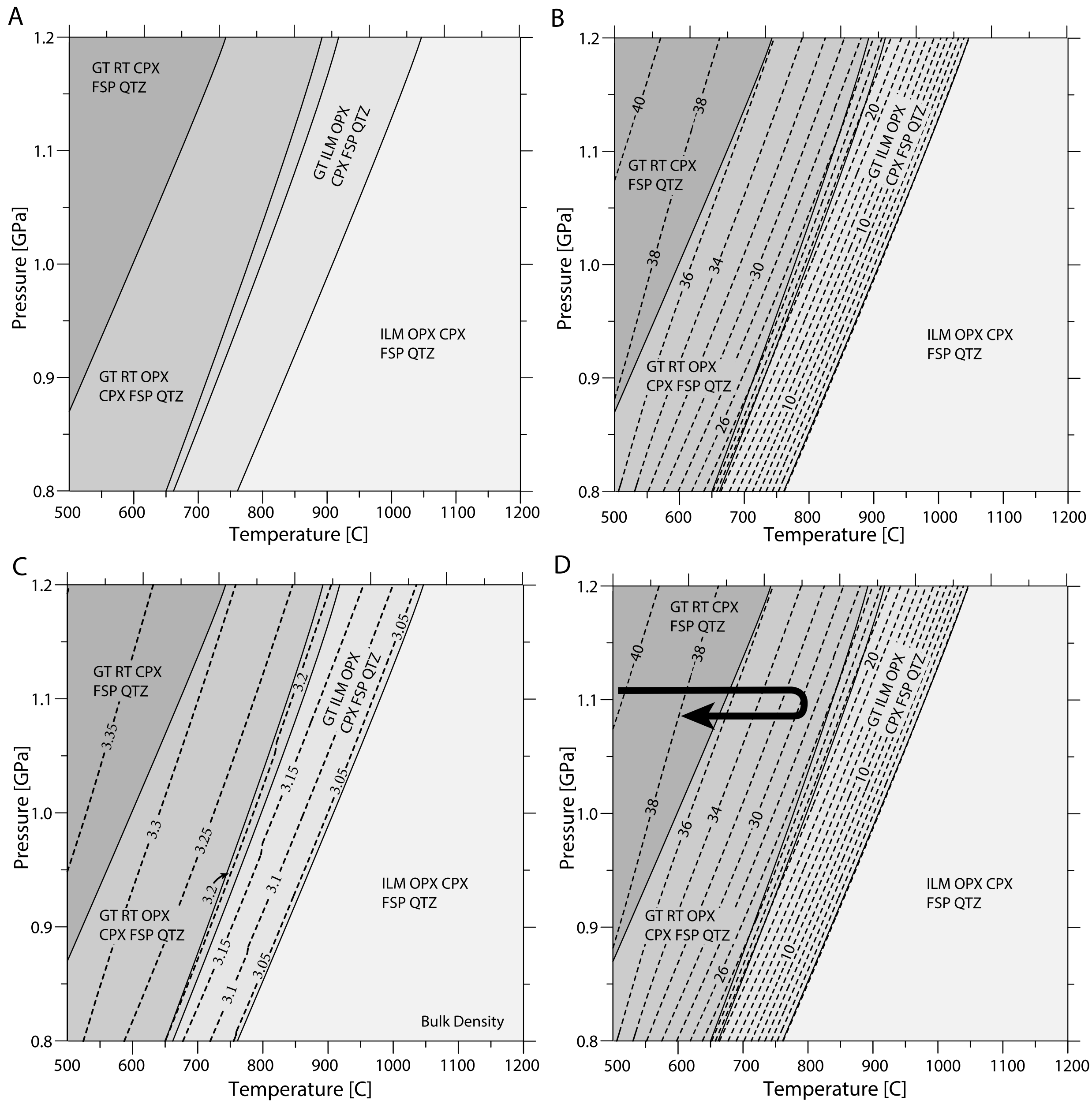

Fig. 7. Petrologic modeling of garnet-in reaction in mafic dike using Theriak-Domino (de Capitani and Petrakakis, 2010) with data base of Berman (JUN92) (Berman, 1988; Berman and Aranovich, 1996). (A) Reaction boundaries. (B) Isopleths of volume % garnet. (C) Isopleths of bulk density. (D) Arrow shows approximately 200 °C of heating of Hb+Pl dike can result in approximately growth of 30% garnet.

Ca–Na diffusion is extremely slow in plagioclase because of the coupled nature of the substitution (Grove et al., 1984; Cherniak, 2010). The consistent observation of garnet as a product phase within recrystallized, Na-rich plagioclase mantles suggest that dislocation movement, grain size reduction, and dynamic recrystallization help to facilitate the mass transfer needed for replacement of the metastable Ca-rich plagioclase by the new Na-rich plagioclase and the growth of garnet (Williams and Jercinovic, 2012). We envision the dynamic recrystallization process as involving the bulging of more stable, Na-richer plagioclase into dislocation-rich, less stable, Ca-richer plagioclase associated with Mg–Fe diffusion and garnet growth. Deformation near the orthopyroxene grain boundaries may help to overcome the activation energy required for nucleation of garnet and clinopyroxene (Whitney et al., 2008). We conclude that deformation in the Mary granite played a key role in replacement of the metastable reactant assemblage(s) and in nucleating product phases (see also Whitney et al., 2008; Goergen, 2011). In addition, because all of the new metamorphic phases have finer grain sizes and presumably lower dislocation densities than the original phases, the process of metamorphism may have enhanced the strain rate and provided a positive feedback for the deformation–recrystallization–metamorphism process.

The basic question of whether metamorphic reactions enhance deformation or deformation enhances metamorphism is relevant (Brodie and Rutter, 1985; Knipe and Wintsch, 1985; Rutter and Brodie, 1995). In this case, the fact that garnet grows within the recrystallized mantles of plagioclase feldspar suggests that dynamic recrystallization of feldspar enables or enhances the metamorphic reaction progress. This is consistent with the sluggish Ca–Na exchange in feldspar (Grove et al., 1984), particularly in the absence of a recrystallization mechanism, and the plagioclase porphyroclasts being the main reactant providing the Ca and Al necessary for garnet nucleation and growth.

5.2. Possible role of heating

Based on the phase relationships discussed above, garnet is expected to grow under ambient conditions in the stable and relatively cool lower continental crust, perhaps at 500 °C and 1.0–1.1 GPa. However, Williams et al. (2000) also suggested that, if there are kinetic barriers to garnet growth during cooling or within relatively cool rocks, garnet could also grow during periods of relatively mild reheating where peak temperatures were still within the garnet stability field. Because of the close spacing of garnet isopleths between 700 and 850 °C at 1.1 GPa (Figs. 5B, 7B), an Opx-granitoid at 500 °C could be heated by as much as 150–200 °C and would still be expected to develop approximately 15–20 vol% garnet. Such heating can occur as previously emplaced plutons are re-heated by adjacent and slightly younger intrusions, during magmatic under- and intra-plating of the crust (e.g., Bergantz, 1989), or during later metamorphic events.

Reheating is not required for the progress of Reaction (1). In fact, the lower the temperature, the greater the amount of garnet that is predicted (Figs. 5, 7). However, dynamic recrystallization of feldspar would be sluggish in the 500–600 °C range and occurs more readily at temperatures of 600–700 °C (Tullis, 2002; Passchier and Trouw, 2005). Slightly elevated temperatures would be expected to result in increased deformation of the rocks, in general, facilitating dynamic recrystallization of feldspar and increased garnet growth as kinetic barriers are overcome. We suggest that reheating events, with peak temperatures still within the garnet stability field, may be important times of garnet growth in deep crustal granitoids (see also Jull and Kelemen, 2001).

The important implication of the observations presented here is that the predicted densification of lower continental crust and subsidence would not necessarily occur as a simple function of cooling time after orogenesis. Instead, densification and subsidence would be expected to occur in stages that correspond to subsequent deformation (± heating) events in the deep crust.

5.3. Densification of the deep crust

Some of the granitoid igneous assemblages in the AGT persisted metastably for 10 s of m.y. before garnet growth during ca. 2.5–2.6 Ga tectonism (Baldwin et al., 2003; Mahan et al., 2006b; Dumond et al., 2010). Other granitoids persisted for 100 s of m.y. before garnet growth during renewed tectonism at ca. 1.9 Ga. We suspect that there may have been other periods of garnet growth and densification during less regionally significant periods of heating and deformation between 2.55 and 1.9 Ga. That is, relatively localized heating and reactivation events between larger or more significant periods of orogenesis may still be associated with garnet growth and densification.

The Athabasca granulite terrane, including the Mary granite, may provide a tangible example and mechanism for the metamorphic densification of the deep crust that has been hypothesized by Fischer (2002) and Blackburn et al. (2012). Fischer (2002) observed a deficit in buoyancy in orogenic roots, long after orogenesis, and hypothesized that retrograde metamorphism, garnet growth, and perhaps local eclogite formation could explain this deficit. We have made a number of simple isostatic calculations to investigate the significance of Reaction (1) on crustal elevation. We assume a simple 4-layer crust: upper, middle, and lower crust (∼35 km thick), with the fourth layer representing a 5–10 km-thick crustal root. If only 20% of the root participated in the reaction, elevation would diminish by approximately 110 m. If 100% of the root underwent the densification, almost 600 m of subsidence of this simple model crust would result. Blackburn et al. (2012) carried out coupled densification/erosion models and showed that densification of the deep crust could explain long-term erosion and exhumation of orogens. One of the main contributions of the present work is the observation that densification can be directly related to deformation and/or reactivation of the lower continental crust, and the time lag before densification might not be solely a function of post-orogenic cooling.

5.4. Implications for lower crustal delamination or convective instability

Recent results from deep seismic investigations such as Earthscope and focused studies such as those in the Sierra Nevada (Saleeby et al., 2003; Frassetto et al., 2011; Levandowski et al., 2013) and southwestern Colorado (Levander et al., 2011; Karlstrom et al., 2012) have brought new attention to possible recycling of lower continental crust and uppermost mantle by dripping or delamination processes. Densification of mantle lithosphere during cooling and local eclogite formation has been considered as a mechanism to create the negative buoyancy which would facilitate delamination of upper mantle lithosphere and mafic lower crust (Kay and Mahlburg Kay, 1993; Jull and Kelemen, 2001). Creating the necessary density in felsic lower continental crust is more problematic, assuming that any igneous restite has already been removed from the system.

Garnet-forming reactions such as Reaction (1) can significantly increase the density of the deep crust and thus play a potentially important role in the recycling process. The maximum density that we have calculated for felsic rocks like the Mary granite or Upper Deck migmatite is on the order of 3.0 g/cm^3, which is not enough to render the rocks negatively buoyant in a peridotitic mantle (density 3.2–3.4 g/cm^3). If, as in the AGT, other rocks types are also present, such as mafic dikes and sills or garnet-rich restite that can reach densities as high as 3.4 g/cm^3, then the bulk density may be closer to that of the mantle, especially in regions where the mantle temperature is elevated. Garnet-forming reactions such as those described here may not bring the lower crustal density to the point that it would initiate a convective instability, but these reactions could certainly explain the progressive loss of crustal root buoyancy inferred by Fischer (2002). However, if the lower crustal density is closer to that of the underlying mantle lithosphere and if stronger garnet-rich lower crust is more coupled to the underlying mantle, then it seems more likely that parts of the lower crust may be removed along with the upper mantle lithosphere during delamination or convective instability (Jull and Kelemen, 2001). The idea that Reaction (1) could progress during periods of relatively minor heating may be particularly relevant in regions such as southwestern Colorado (Levander et al., 2011; Karlstrom et al., 2012) where the crust is anomalously thin and in contact with relatively hot and buoyant mantle, making eclogite-forming reactions seem less likely.

5.5. Rheology of the deep crust

A full characterization of the rheology of the deep crustal Opx- and Grt-granitoids is beyond the scope of this paper (see Jull and Kelemen, 2001), but several observations are relevant to discussions of garnet-forming reactions and the implications for rheology. As noted above, 2.6 Ga Opx-granitoids were deformed twice, once at ca. 2.55 Ga, perhaps as young as 2.52 Ga: Baldwin et al. (2003), and again at 1.9 Ga. Both events involved similar peak *P–T* conditions (ca. 0.9 GPa and 700–800 °C) (Dumond et al., 2010; Regan et al., in press). Temperatures may have been slightly hotter during the first event. The first event resulted in a coarse-grained subhorizontal mylonitic fabric with a top-to-the-east sense of shear (Dumond et al., 2010) (Figs. 2A, B). The full thickness of the shear zone is not known, but several kilometers of shear zone width are exposed. It is not possible to quantify the exact amount of garnet produced, however, significant garnet growth occurred via Reaction (1) during the shearing event, and in many exposures, garnet exceeds 10 modal percent. The second event resulted in upright folds of the earlier fabric and localized vertical mylonitic fabric, particularly fold limbs (Dumond et al., 2010; Regan et al., in press) (Fig. 2). The second generation mylonitic fabric involved the production of new garnet via Reaction (1), but the grain sizes are typically finer than those in the earlier fabric (Regan et al., in press).

Dumond et al. (2010) suggested that the early 2.6 Ga fabric was produced during subhorizontal flow of a relatively weak deep crust, perhaps driven by topographic loads created during ca. 2.6 Ga orogenesis. The upright and much more localized second generation (1.9 Ga) fabrics were interpreted in terms of a stronger deep crust. Because the *P*–*T* conditions were similar and the bulk rock compositions nearly identical, and also because there is no evidence for a significant difference in fluid composition or fluid abundance between the two events, we suspect that the difference in behavior is due to modal mineralogy changes, primarily related to Reaction (1). We suggest that this garnet-forming reaction not only promoted densification of the deep crust, but also served to strengthen and stabilize it. Because most of the garnet was apparently produced during the earlier event, the growth of significant amounts of relatively coarse grained garnet and recrystallization of plagioclase resulted in a stronger deep crust and a significantly more localized strain and garnet growth during subsequent episodes of tectonism.

Orthopyroxene-bearing granitic to monzodioritic gneisses and granulites may be a common component of the lower continental crust at $P = 0.9–1.3$ GPa (e.g., Green and Lambert, 1965; De Paoli et al., 2012; Qian and Hermann, 2013). If so, it seems likely that garnet-forming reactions like the one described here play an important role in strengthening and stabilizing (i.e., "cratonizing") the deep crust. Subsequent heating and deformation events, unless they involve very high temperatures and possibly partial melting or fluid infiltration, probably do not result in significant garnet loss. Unless reheating is extreme enough to drive metamorphism of lower crustal rocks back into the garnet-absent intermediate-*P* granulite field of Fig. 3, the deep garnet-granitoid crust may maintain its strength and stability and resist later reactivation.

6. Conclusions

Orthopyroxene-bearing (meta-)igneous rocks are common components of the Athabasca granulite terrane and may be a significant component of the deep crust in general. The high-temperature igneous assemblage consisted of quartz, plagioclase, orthopyroxene, K-feldspar, and ilmenite ± hornblende. The stable metamorphic assemblage under ambient deep crustal conditions (ca. 500 °C) consists of garnet, clinopyroxene, quartz, K-feldspar, and plagioclase ± hornblende. However, the high-*T* assemblage can exist metastably for long periods of time. The transition to garnet granulite is, at least in part, facilitated by dynamic recrystallization and active deformation of the igneous protolith.

Petrologic modeling suggests that average Opx-granitoids can develop as much as 15–20 vol% garnet with densities as high as 3.0 g/cm^3. Associated mafic rocks and restites can have densities as high as 3.4 g/cm^3 (see also De Paoli et al., 2012). Garnet isopleths (vol%) are most closely spaced at temperatures of 700–850 °C at 1.0 GPa, allowing reheating to both facilitate deformation and promote growth of significant amounts of garnet.

Garnet growth in relatively felsic igneous rocks may account for densification of the lower continental crust long after the orogenic activity involved with the initial magmatism. The sluggishness of the reaction in the absence of deformation may explain the time lag between orogenesis and densification in some orogenic belts (Fischer, 2002; Blackburn et al., 2012). The reaction may also help to explain the discrepancy between seismic velocities suggestive of mafic/intermediate lower crustal bulk compositions and the observed abundance of felsic rocks in granulite terranes (Rudnick, 1992; Rudnick and Fountain, 1995). Finally, garnet growth in felsic rocks may provide a mechanism by which some deep crustal rocks become dense enough to allow downward recycling during delamination or foundering of lower continental crust into the underlying mantle lithosphere.

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