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Large volumes of anatectic melt retained in granulite facies migmatites: An injection complex in northern Quebec

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ABSTRACT

The Opinaca Subprovince in the Superior Province of northern Québec is a metasedimentary belt characterized by metagreywacke rocks that record a late Archean granulite facies metamorphism and contains abundant thin veins of leucogranite. Regional-scale study of this subprovince provides insight to the net budget of anatectic melt (loss versus accumulation) in the lower middle continental crust during anatexis.

A petrological study indicates that the metagreywackes partially melted at ~820 °C and ~7 kbar and generated <10% melt with orthopyroxene ± garnet as peritectic phases. The metagreywackes contain various amounts of leucogranite in thin veins, sills and dykes injected sub-parallel to the subvertical E–W striking main foliation. Study of more than 1070 outcrops indicates that the "typical outcrop" contains ~63% of leucogranite; far more than the maximum 10% of melt produced in-situ from the host rocks. Crystallization ages obtained by U–Pb SHRIMP analysis of zircons from both the migmatites and the leucogranite veins indicate that the granulite facies metamorphism and the injection of veins were contemporary and occurred during slow cooling (6 °C My^{-1}) from the metamorphic peak at 2666 Ma to the granite solidus at 2636 Ma. The large discrepancy (about 50%) between the volume of anatectic melt produced locally (in situ) and the observed volume of leucogranite in the terrain indicates that anatectic melt accumulated in the Opinaca Subprovince; it is an injection complex. This finding that granulite facies terranes can be enriched in melt contrasts with the general view that granulite terranes are melt-depleted.

The presence of an injection complex in the deep crust has several broad implications for the continental crust. 1) H_2O released as the injected melt crystallized rehydrated the adjacent granulite facies rocks which is evident from orthopyroxene replaced by amphibole and biotite. Consequently, these deep rocks would be more fertile in a subsequent anatectic event than non-rehydrated residuum. 2) The retention of voluminous leucogranite in the injection complex has thermal consequences for the crust. First, the bulk composition of the crust containing the injection complex is necessarily more felsic, thus the budget of heat-producing elements (Th, U and K) is locally enhanced and radiogenic heat production is higher. Secondly, latent heat of crystallization is released at a deeper level where the leucogranite solidifies. The combined effect of both maintains the lower crust several tens of degrees warmer for longer period of time.

1. Introduction

Partial melting has a profound effect on the continental crust (Sawyer et al., 2011). The formation of anatectic melt of granitic composition, its extraction and ascent is the main process by which the continental crust becomes differentiated and gravitationally stable with a denser lower part. The petrological and compositional links between the deep, partially melted, granulitic crust and granite plutons in the upper crust, called the granulite–granite connection by some workers has been the subject of many studies (Brown, 1994, 2006; Brown et al., 2011; Clemens, 1990; Otamendi and Patiño Douce, 2001; Sawyer, 1998; Vielzeuf et al., 1990). In the last twenty years, attention has focused more on the mechanisms by which felsic anatectic magma moves through the continental crust. Clemens and Mawer (1992) argued that buoyancy in large dykes and not diapirism was how granitic magma traversed the middle crust to feed plutons in the upper crust. In addition, field observations from migmatite terranes show that some contain innumerable small, linked leucosomes, rather than a few large dykes. Thus, in some terranes the movement of anatectic melt may have been pervasive (Brown and Solar, 1999; Collins and Sawyer, 1996; Weinberg, 1999; Weinberg and Searle, 1998) rather than a strongly focused flow through a few large dykes.

Numerical modeling (Connolly and Podladchikov, 2007; Hobbs and Ord, 2010; Leitch and Weinberg, 2002) provides insight into the large-scale link between segregation and transport of anatectic melt in the continental crust. The flow of melt from the grain

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boundaries and pores where it formed into small, elliptical leucosomes occurs over short distances, a few centimeters, and is driven by deformation of the solid matrix (Simakin and Talbot, 2001). The larger-scale problem of how far the melt can then move up from its source is controlled by how much melt, and thus heat, is advected (Hobbs and Ord, 2010; Leitch and Weinberg, 2002) because this determines where the solidus of the melt lies in the crust. A large volume of melt rising through a wide dyke can ascend high in the crust before its heat is lost to the wall rocks, and it freezes (Petford et al., 1994). In contrast, the pervasive flow of melt through innumerable narrow channels is far more sensitive to the loss of heat to the wall rocks as soon as it rises above the solidus and so the melt cannot rise as far before it freezes; it remains much nearer to the depth of the solidus as an injection complex (Leitch and Weinberg, 2002). The temperature difference between the source and the solidus, the volume of magma and the manner in which it moves, whether focused in a few dykes, or by pervasive flow, are key factors that determine how far up in the crust anatectic melt can migrate. At one extreme melt segregates, but barely leaves its source region, at the other it separates and can rise and form a pluton in the upper crust, or even be erupted. Both separate a granitic melt from a ferromagnesian residuum, but their consequences for the overall differentiation of the continental crust are quite different. The former affects only the lower crust, whereas the latter affects virtually its full thickness.

Most studies of the middle and deep levels of the continental crust have concentrated on the petrology and geochemistry of high-grade, melt-depleted rocks (e.g. Fornelli et al., 2002; Graessner and Schenk, 2001; Guernina and Sawyer, 2003; Slagstad et al., 2004; White and Powell, 2010), or on the short-range aspects of melt segregation (Marchildon and Brown, 2003; Oliver and Barr, 1997; Sawyer et al., 1999; Solar and Brown, 2001; White et al., 2004), rather than the volume and large-scale distribution of former anatectic melt in them. The lack of information on how much anatectic melt remained at deep levels in the crust has consequences for mass-balancing the process of crustal differentiation, because estimates of the bulk composition of the lower crust are based principally on the residual rocks (Rudnick and Fountain, 1995) and not on how much melt remained behind as leucosomes and leucogranitic veins. Therefore, this study addresses an important question relevant to understanding the differentiation of the continental crust; how much of the anatectic melt that was formed in the deep crust remains there. To answer this question mapping has been conducted over a large region of granulite facies migmatites, derived from a metagreywacke (psammite) protolith in the Opinaca Subprovince of northern Quebec. The principal objectives of this paper are to: 1) document the distribution and location of leucosomes and veins of leucogranite that represent crystallized anatectic melt, 2) determine how much melt the protolith produced, 3) determine from mapping and a simple mass balance how much melt was added to, or lost from, the region and, 4) discuss some of the implications of these findings for our understanding of the continental crust.

2. Opinaca Subprovince in the Superior Province

The Opinaca Subprovince is one of four metasedimentary subprovinces that together cross the Archean Superior Province (Fig. 1). It is bounded to the west and north by the La Grande Subprovince (Fig. 2), which consists predominantly of mafic volcanic rocks intruded by plutons of tonalite and granodiorite, and to the south by the Opatica Subprovince, a plutonic belt which is dominated by tonalite, trondhjemite, granodiorite and migmatites derived from them (Sawyer, 1998, 2010). The Ashuanipi Subprovince, a granulite facies migmatite terrane (Guernina and Sawyer, 2003), lies to the east. The Ashuanipi and Opinaca Subprovinces form a contiguous sequence of siliciclastic rocks, which Percival et al. (1992) subdivided on the basis of a difference in metamorphic grade. Strong similarities in rock types, bulk compositions and ages suggest that the sedimentary detritus for the Quetico, Nemiscau, Opinaca and Ashuanipi Subprovinces had very similar sources (Card, 1990), and were deposited in similar environments. The maximum temperature and pressure recorded in the four subprovinces increases from west to east, which indicates slight tilting and a deeper erosion level in the east (Percival et al., 2006).

The age of deposition for the sedimentary rocks in the Opinaca Subprovince is constrained by intrusion of the Pluton de Bezier at 2674 ± 12 Ma (St. Seymour et al., 1989), and 2700 Ma for the Lac Taylor Granite (Goutier et al., 1999) on which the sediments were deposited. The ages of detrital zircons indicate deposition occurred between 2698 and 2687 Ma for the Quetico (Percival et al., 2006) and between 2700 and 2690 Ma for the Ashuanipi Subprovinces. The minimum age for deposition in the Nemiscau Subprovince is 2672 Ma (Davis et al., 1995).

Deposition of sedimentary rocks in the four subprovinces was quickly followed by high-grade regional metamorphism and anatexis that lasted for tens of millions of years. In the Quetico Subprovince high-temperature metamorphism lasted from ca. 2670 to ca. 2650 Ma and was coeval with intrusion of peraluminous granites (Pan et al., 1998; Percival et al., 2006; Zaleski et al., 1999). Granulite facies metamorphism occurred throughout the Ashuanipi Subprovince between 2682 and 2650 Ma (Percival et al., 2003; Simard et al., 2009a,b). To the south, amphibolite facies partial melting lasted from 2690 to 2655 Ma in the Opatica Subprovince (Davis et al., 1995). Few ages are available for the Opinaca Subprovince; zircon crystallization ages of 2671.6 ± 1.8 Ma from vein of leucogranite and 2647 Ma from a pegmatite were interpreted by David et al. (2010) to bracket regional anatexis.

3. The Opinaca Subprovince

Regional mapping (1:50,000 scale) was carried out in the western third of the Opinaca Subprovince (Fig. 2) by the Bureau de l'Exploration Géologique du Québec and successive campaigns have mapped 15,500 km^2 (Bandyayera and Fliszár, 2007; Bandyayera et al., 2010, 2011; Simard and Gosselin, 1999). Fig. 3 shows the geology of the study area; a sub-region of the 15,500 km^2 mapped in more detail by the present authors. The Opinaca Subprovince is a belt of Archean siliciclastic metasedimentary rocks in which metagreywacke (psammite) dominate over pelite in a ratio of about 10:1 (see below for petrological and metamorphic details). Scattered metamafic units ranging from a meter to hundreds of meters in thickness occur within the metasedimentary rocks, and consist of amphibole + pyroxene (mostly clinopyroxene, but locally orthopyroxene) gneisses, commonly associated with minor banded iron formation. Rare, small ultra-mafic units also occur and underwent prograde metamorphism with their metagreywacke host rocks. Late- to post-tectonic felsic intrusive bodies in the Opinaca Subprovince have granodiorite to tonalite–enderbite compositions.

3.1. Structural characteristic

The rocks are pervasively deformed throughout the study area. Nevertheless, bedding in the metasedimentary rocks is evident as a variation in the grain size and proportion of minerals. Darker, coarse-grained layers rich in garnet, cordierite and biotite indicate beds of pelitic composition compared to metagreywackes which have smaller grain size and which have higher quartz and plagioclase contents. The main schistosity (S_2) is defined by oriented biotite and is commonly parallel to the pelite and greywacke layers (S_0). The S_2 schistosity is generally sub-vertical and contains a mineral lineation that plunges gently towards the east, or to the west (Bandyayera et al., 2010). A prominent compositional layering due to the presence of many thin, white quartzo-feldspathic veins in the metasedimentary rocks is evident in most outcrops, and is the result of the injection of felsic veins parallel, or sub-parallel, to the bedding or the S_2 planes. In