Anorthosites and related granitoids in the Grenville orogen: A product of convective thinning of the lithosphere?

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ABSTRACT

In the central and southwestern Grenville province in Canada and the northeastern United States, anorthosites and related granitoids were emplaced during two distinct pulses, at ca. 1.16–1.13 Ga and 1.09–1.05 Ga, each following major crustal thickening events. U-Pb age constraints on movement along major ductile shear zones indicate that they were emplaced within extending crust in an overall convergent orogen. We suggest that convective thinning of the lithosphere played a significant role in their emplacement and in the tectonic evolution of the Grenvillian orogeny.

INTRODUCTION

The origin of voluminous anorthosite, mangerite, charnockite, granite, and related granitoids (AMCG complexes; Emslie, 1978) in the Mesoproterozoic Grenville province is a matter of considerable debate (e.g., Ashwal, 1993). However, although there are several divergent views concerning the magma genesis and geochemical evolution of these rocks, there has been general agreement that they were emplaced in an anorogenic tectonic setting. The paradox that has emerged from recent U-Pb dates on AMCG complexes is that their ages broadly coincide with the timing of thrusting along first-order contractional shear zones. In the central Grenville province, U-Pb dating has outlined two distinct pulses of AMCG-type magmatism, at ca. 1.16–1.14 Ga and 1.08–1.05 Ga (Higgins and van Breemen, 1996; Corrigan and van Breemen, 1996). Although both periods of magmatism are locally accompanied by extension, they were synchronous with convergent tectonics at the scale of the orogen. We propose a model that accounts for both AMCG pulses in an overall convergent orogen by two consecutive cycles of crustal thickening followed by convective thinning of the continental lithosphere (e.g., Houseman et al., 1981).

GEOLOGIC SETTING

The Grenville province in Canada (Fig. 1) comprises two major lithotectonic elements: (1) a parautochthonous belt formed of Archean and Paleoproterozoic to Mesoproterozoic rocks from the foreland that were reworked during the Grenvillian orogeny, and (2) allochthonous terranes tectonically accreted onto the parautochthonous belt and separated from the latter by the southeast-dipping allochthon boundary thrust (see Rivers et al., 1989, and Davidson, 1995, for a detailed overview). In the central and southwestern Grenville Province (Fig. 2), the allochthonous terranes consist mainly of the Central Metasedimentary Belt and the Central Granulite Terrane (Wynne-Edwards, 1972). Except for minor intrusions and dikes, magmatism of Grenvillian age (1.19–1.00 Ga) is restricted to the allochthonous terranes. A summary of timing of sedimentation, deformation, and magmatism is presented in Figure 3.

Ca. 1.19 to 1.13 Ga: Crustal Thickening, Syncollisional to Postcollisional Extension, AMCG Magmatism, and Sedimentation

Any model of the tectonic, magmatic, and metamorphic evolution of the Grenvillian orogeny ca. 1.19–1.13 Ga must reconcile an overall collisional tectonic setting with the production of anorthosite massifs, the emplacement of mafic and ultramafic dikes, the metamorphism of granulite facies, and the production of intramontane sedimentary basins. Northwest-directed thrusting along the Central Metasedimentary Belt boundary thrust zone (Fig. 2) was well underway by ca. 1.19 Ga and coincided with the closure of the Elzevir back-arc basin (Hanmer and McEachern, 1992; McEachern and van Breemen, 1993). Granulite facies thrusting dated at ca. 1.16 Ga within the Parry Sound domain (van Breemen et al., 1986; Wodicka et al., 1996) and along the base of the Cabonga allochthon (Friedman and Martignole, 1995) signifies that crustal thickening may have continued until that period (Fig. 3). Thus, evidence for deformation related to contractional tectonics appears to be confined to the interval of 1.19–1.16 Ga but may have locally persisted beyond this age bracket.

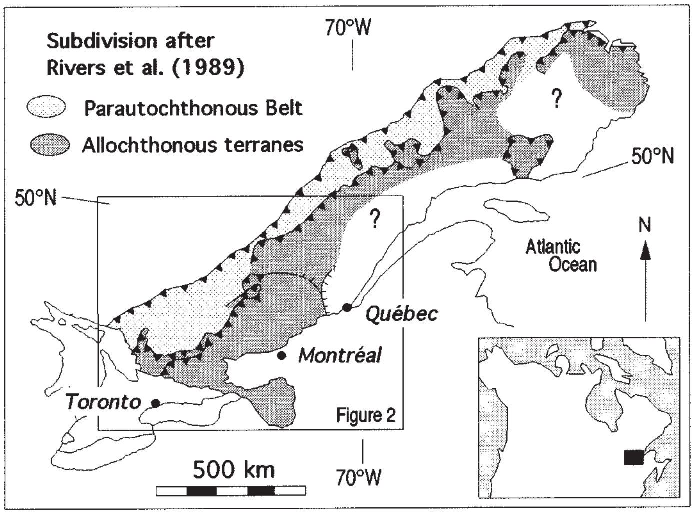

Figure 1. Map of Grenville province showing distribution of Parautochthonous Belt and overlying allochthonous terranes. Toothed line separating Parautochthonous Belt from allochthonous terranes is Allochthon Boundary Thrust. Modified after Rivers et al. (1989).

Magmatism both overlapped with and outlived crustal shortening. During the interval 1.16–1.13 Ga, the Marcy (Chiarenzelli and McLelland, 1991), Morin (Doig, 1991), and Lac St. Jean (Higgins and van Breemen, 1996) AMCG complexes were emplaced in the Central Granulite Terrane (Fig. 3). A-type monzonites, granites, and syenites emplaced within the

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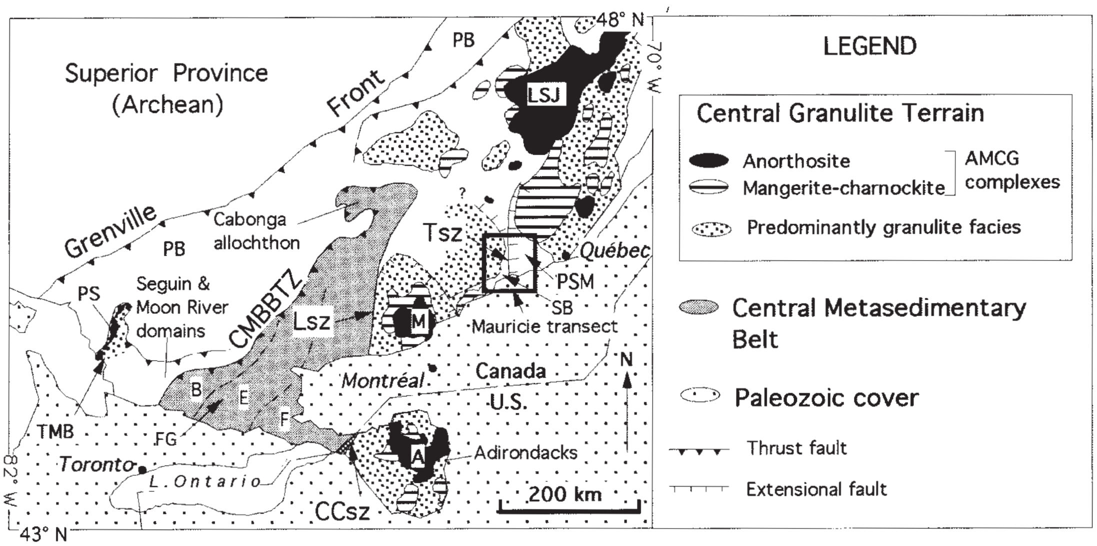
Figure 2. Generalized map of central and southwestern Grenville Province showing major geologic features. Abbreviations are as follows: A—Adirondacks; B—Bancroft terrane; CCsz—Carthage-Colton shear zone; CMBBTZ—Central Metasedimentary Belt boundary thrust zone; E—Elzevir terrane; F—Frontenac terrane; FG—Flinton Group; Lsz—Labelle shear zone; LSJ—Lac St. Jean; M—Morin; PB—Parautochthonous Belt; PS—Parry Sound domain; PSM—Portneuf–St. Maurice domain; SB—St. Boniface metasediments;Tsz—Tawachiche shear zone. Modified after Wynne-Edwards (1972) and Rivers et al. (1989).



Frontenac terrane (Central Metasedimentary Belt) between 1.18 and 1.16 Ga are related to the AMCG suites described above (van Breemen and Davidson, 1988; Lumbers et al., 1990). Crustal extension coeval with 1.18–1.13 Ga magmatism is indirectly indicated by the formation of sedimentary basins. In the Mauricie region, the St. Boniface metasedimentary rocks, which include highly aluminous metapelitic rock interlayered with rare, metre-thick bands of quartzite and marble, were deposited between 1.18 and 1.15 Ga (Corrigan and van Breemen, 1996). The 1.14–1.12 Ga Twelve Mile Bay quartzite (Wodicka et al., 1996) and the 1.15–1.10 Ga Flinton Group (Sager-Kinsman and Parrish, 1993) also fall more or less within this age range (Fig. 3). U-Pb dating of detrital zircon grains in all three basins suggests a within-orogen source of sediments (Sager-Kinsman and Parrish, 1993; Wodicka et al., 1996; Corrigan and van Breemen, 1996). Their present location well within the orogen interior suggests that they may be remnants of pull-apart or rifted basins developed on tectonically overthickened crust (e.g., Molnar and Tapponnier, 1978).

Ca. 1.12–1.09 Ga: Renewed Crustal Thickening

The cessation of AMCG-type magmatism in the southwestern Grenville province at ca. 1.13 Ga was followed by renewed northwest-directed thrusting in the orogen interior, resulting in penetrative deformation at granulite to uppermost amphibolite facies throughout most of the allochthonous belts. High-grade metamorphism and deformation affected the Flinton Group between 1.15 and 1.08 Ga (Sager-Kinsman and Parrish, 1993). Renewed northwest-directed thrusting occurred in the Parry Sound domain ca. 1.12 Ga (Wodicka et al., 1996) and along the Seguin and Moon River thrust sheets ca. 1.11 Ga (van Breemen and Davidson, 1990; Nadeau and Hanmer, 1992). Along the Mauricie transect (Fig. 2), granulite facies thrusting in the approx-

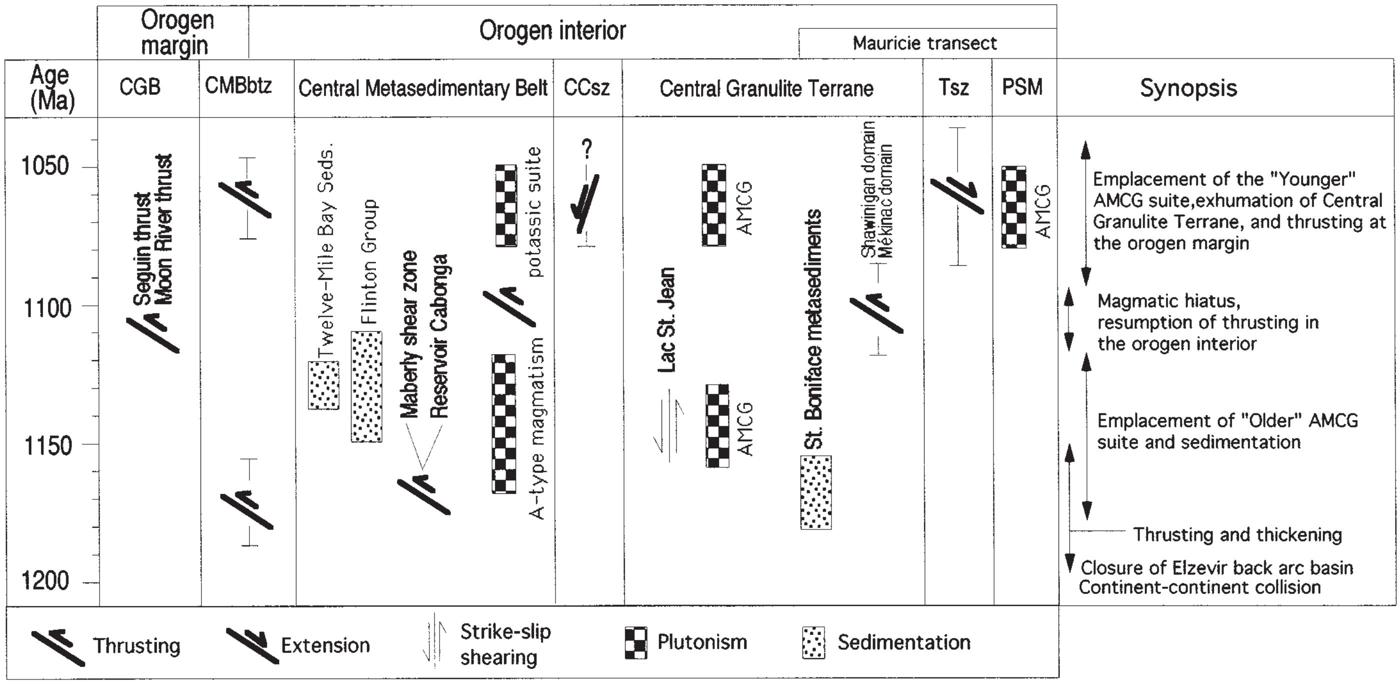


Figure 3. Summary of tectonic and magmatic events that affected central and southwestern Grenville Province from 1200 Ma to 1050 Ma. Orogen margin is interpreted as part of Grenville province lying northeast of Allochthon Boundary Thrust (CMBbtz in study area). Orogen interior includes Central Metasedimentary Belt, Central Granulite Terrane, and Mauricie transect. Orogen interior is interpreted as main region of lithospheric thickening and plateau development during Grenvillian orogeny in time interval shown.

imate interval 1.12–1.09 Ga affected both the St. Boniface metasedimentary rocks and the 1.15 Ga granitoids (Corrigan and van Breemen, 1996).

Ca. 1.09–1.05 Ga: Second Phase of Extension and AMCG-type Magmatism in an Overall Compressional Orogen

During the interval 1.09–1.05 Ga, a second pulse of AMCG-type magmatism occurred within the allochthonous terranes (Fig. 3), but produced much less anorthosite than the older one (e.g., Higgins and van Breemen, 1996; Corrigan and van Breemen, 1996). Coeval plutons of syenitic, ultrapotassic, and potassic alkaline composition were emplaced in the Elzevir terrane of the Central Metasedimentary Belt (Corriveau et al., 1990). All the above are virtually undeformed and have not been subjected to regional metamorphism.

On a broader scale, the emplacement of the younger AMCG and potassic plutons was coeval with the exhumation of the Central Granulite Terrane by tectonic denudation (Corrigan, 1995). The oblique extensional Tawachiche shear zone, which bounds the Central Granulite Terrane to the east, was active from ca. 1.09 Ga to at least 1.05 Ga (Corrigan and van Breemen, 1996). Along the western edge of the Central Granulite Terrane, extension was accommodated by the northwest-side-down Carthage-Colton shear zone (Heyn, 1990). To the northeast, the kinematic history of the Labelle shear zone is unclear, but ductile deformation along it postdates 1.08 Ga (Martignole and Corriveau, 1991). Monazite cooling ages of ca. 1.09 Ga from the eastern edge of the Central Granulite Terrane along the Mauricie transect are consistent with ages obtained for movement along the extensional faults, and hence with cooling by tectonic denudation (Corrigan and van Breemen, 1996). Between 1.09 and 1.05 Ga, as the Central Granulite Terrane was exhumed and the younger AMCG plutons were emplaced in the orogen interior, thrusting at high metamorphic grade localized at the orogen margin along the Central Metasedimentary Belt boundary thrust zone (van Breemen and Hanmer, 1986; Hanmer and McEachern, 1992).

TECTONIC MODEL

The association of crustal thickening, emplacement of mafic dikes and voluminous mantle-derived melts, sedimentation within an intraplate setting, and syncollisional extension can be best explained by replacement of the continental mantle lithosphere by asthenosphere during crustal shortening. Whether this is achieved by lithospheric delamination (Bird, 1979) or convective thinning of the lithosphere (Houseman et al., 1981), some of the consequences are similar. These are (1) juxtaposition of hot asthenosphere with thinned continental lithosphere, (2) increase in potential energy of the crust consequent upon increase in surface elevation, and (3) a detectable thermal pulse in the extended crust. The former two may produce mantle-derived melts, extension, and the development of intramontane sedimentary basins within the collisional plateau (e.g., Platt and England, 1993).

The ca. 1.19 Ga continent-continent collision that followed the Andean-type evolution of the southeastern margin of the Grenville province (McEachern and van Breemen, 1993) would have resulted in accelerated shortening and thickening of the continental lithosphere (Fig. 4A). Delamination or convective removal of the thermal boundary layer may then have occurred, leading to uplift and subsequent extensional collapse of the collisional plateau, with concomitant formation of sedimentary basins and high-temperature, mantle-derived melts (Fig. 4B). Once the normal lithosphere thickness is re-established, and if the boundary conditions permit, compressional deformation may resume in the interior of the thinned and thermally weakened orogen. This is consistent with the renewal of crustal shortening and thrusting in the Grenville orogen interior during the interval 1.12–1.09 Ga, which is inferred to have led to a second phase of thickening of the crust and lithosphere that culminated at ca. 1.09 Ga (Fig. 4C). The rethickened root of the lithospheric mantle may have again been convectively thinned, leading to a second cycle of isostatic uplift of the overthickened crust, extensional collapse, exhumation of the Central Granulite Terrane, and the generation and emplacement of the younger phase of high-temperature AMCG and potassic plutons (Fig. 4D). During this period, thrusting was again localized at the orogen margin, along the Central Metasedimentary Belt boundary thrust zone. Examples of coeval development of extensional plateaus in orogen interiors and thrusting at orogen margins are well documented in the literature about Mesozoic orogens (e.g., Molnar and Lyon-Caen, 1988), but the process has not previously been inferred for a Proterozoic orogen.

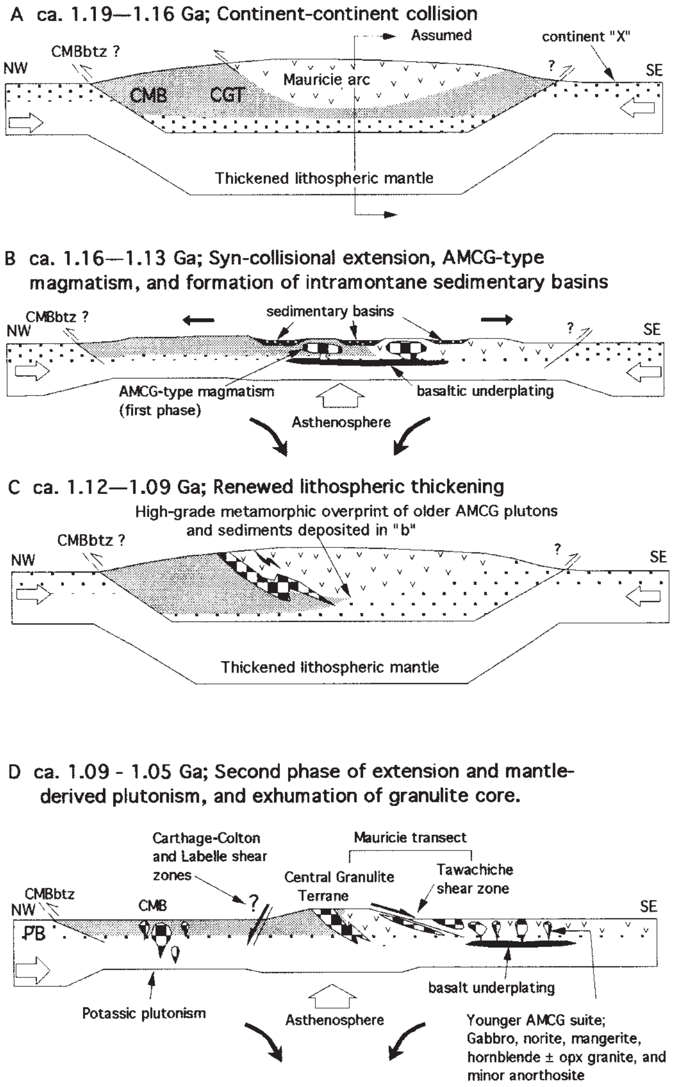


Figure 4. Series of schematic cross sections showing tectonic and magmatic evolution of Grenvillian orogeny during interval 1.20–1.05 Ga. In A, B, and C, symmetrical geometry for orogen is assumed, and collision with continent (continent x) is inferred for clarity. D shows the final configuration of orogen exposed in North America. See text for explanations. Abbreviations as in Figure 2.

DISCUSSION

Acceptance of the convective thinning model for the tectonomagmatic evolution of the Grenvillian orogeny has important implications. It has been suggested that anorthosite plutonism is associated with ponding of olivine tholeiite basalt at the base of the crust in an extensional tectonic setting (e.g., Emslie, 1978). Replacement of lithosphere by asthenosphere predicted by convective thinning models provides a viable mechanism for such a process during convergent tectonism, and does not necessitate the postulation of a mantle plume beneath a supercontinent (e.g., Hoffman, 1989) nor postcollisional extension (e.g., Windley, 1991). With respect to the Grenvillian orogeny, the convective thinning model provides a plausible way to explain the episodic nature of AMCG-type magmatism synchronous with contractional tectonics. In addition, it provides a mechanism to explain the important contribution of mantle-derived heat that is necessary for the formation of anorthosite (Emslie, 1978), which is also implied from the generally high ambient grade of metamorphism accompanying AMCG-type magmatism. The duration of lithospheric thickening and subsequent convective removal of lithosphere was ~30 m.y. for each cycle, which is consistent with the duration of lithospheric overthickening and mechanical restoration predicted by Houseman et al. (1981).

Another important consequence of convective removal of the mantle lithosphere is the production of highly potassic melts (McKenzie, 1989; Kay and Mahlburg-Kay, 1993). Shoshonitic volcanism in the Tibetan plateau, for example, is thought to be a likely product of convective thinning of the lithosphere (Turner et al., 1996). This may provide a more appropriate tectonomagmatic model for shoshonitic and other potassic plutons emplaced in the Grenville orogen that are currently interpreted on the basis of geochemistry as the product of island arc magmatism (Corriveau et al., 1990).

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