Grenville Province and Monteregian carbonatite and nepheline syenite distribution related to rifting, collision, and plume passage

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ABSTRACT

Stimulated by the recognition of a rifted continental margin to pre-Grenville Laurentia, we interpret the deformed alkaline igneous rocks and carbonatites (DARCs) adjacent to that margin in the Bancroft domain of Ontario, Canada, to be rocks initially erupted as alkaline rocks and carbonatites (ARCs) in an intra-continental rift. When an ocean began to form, rupturing Laurentia on the site of that rift, the newly formed Laurentian rifted continental margin contained ARCs that had erupted into the intra-continental rift. Later in a Wilson cycle of ocean opening and closing, those ARCs became DARCs during a collision that sutured the Grenville province composite arc belt and Bancroft domain rocks against the margin of Laurentia on the Central Meta-sedimentary Belt boundary thrust zone. Using this interpretation we show that DARCs of the down-dip Bancroft domain suture zone in the mantle at a depth of ~100 km are likely sources of the Early Cretaceous ARC rocks in the Monteregian province.

INTRODUCTION

An association of nepheline syenites, kindred alkaline igneous rocks, and carbonatites (ARCs) with intra-continental rifts has been recognized (e.g., Bailey 1974, Doig 1970) and deformed rocks of the same compositions (DARCs) have been shown to characterize suture zones (Burke et al., 2003) in regions in Asia (Leelanandam et al., 2006), Europe (Burke et al. 2007), Africa (Burke et al., 2003, Lytwyn et al., 2006; Ashwal et al. 2007) and North America (Johnston 2008). DARCs in suture zones are ARC rocks that erupted into intra-continental rifts that became involved in a Wilson cycle of ocean opening and closing (Wilson, 1968). DARCs lie on the tectonized rifted continental margin of the closed ocean and within the coincident suture zone formed when that ocean closed. The identification of a rifted margin to pre-Grenville Laurentia formed post ca. 1450 Ma (Carr et al., 2000, their Fig. 5) provides an opportunity to test the ARC-DARC model on rocks of the Grenville Province and the Monteregian Hills in Ontario and Quebec, Canada (Fig. 1). We have extended the ARC-DARC model (that explained intracontinental ARCs as having been erupted in active rifts following decompression melting of DARCs in the underlying mantle lithosphere) to accommodate the idea that ARCs may also erupt above an underlying mantle plume as it traverses below a suture zone carrying DARCs in the lithospheric part of the mantle. ARCs have been suggested to originate in either of (1) the subcontinental lithospheric part of the mantle (e.g., Burke et al., 2003), or (2) the underlying convecting mantle (e.g., Bell and Tilton, 2002).

We here show that in the Cretaceous Monteregian province of Quebec, Canada (Fig. 1), mantle of both kinds played a role in the eruption of a population of ARCs. Source rocks were DARCs in the lithospheric part of the mantle on a suture zone related to Grenville collision. At ca. 130 Ma, during Cretaceous time, a plume in the underlying convecting mantle supplied the heat needed to generate new ARCs by partly melting those DARCs.

We integrate information from: (1) studies on Grenville province rocks, especially the tectonic syntheses of Davidson (1998), Carr et al. (2000), and White et al. (2000); (2) the carbonatite and alkaline rock catalog of Woolley (1987), as well as a version digitized and put into a geographic information system (GIS) with rift and suture distributions by Mart (2007); (3) the record of the passage of a mantle plume across Canada and New England (Heaman and Kjarsgaard 2000; Ernst and Buchan 2003; Woolley and Kjarsgaard, 2008); and (4) the petrology, geochemistry, and ages of the alkaline rocks and carbonatites of the Monteregian Hills (Woolley 1987; Eby 1984, 1985; Cox and Wilton, 2006).

TECTONIC SETTING OF DARCS IN THE GRENVILLE PROVINCE OF CANADA

The geology of nepheline syenite gneisses and deformed carbonatites (DARCs) of the Grenville province in Ontario and Quebec was succinctly described, on the basis of a comprehensive literature review, by Woolley (1987). More recently, the structure of the Grenville province in Ontario and in nearby New York has been characterized by Carr et al. (2000) and by White et al. (2000), who distinguished three tectonic elements: (1) metamorphosed pre-Grenvillian Laurentia and its margin with ca. 1740 Ma and ca. 1450 Ma continental arc plutons and associated supracrustal rocks; (2) a composite arc belt (formerly the Central Metasedimentary Belt) of allochthonous ca. 1300–1250 Ma metamorphosed volcanic arc igneous and sedimentary rocks; and (3) a Frontenac-Adirondack belt characterized by metamorphosed supracrustal rocks, granitoid rocks, and anorthosites (Fig. 1).

DARCs from Mart's (2007) North American database were plotted on maps from Carr et al. (2000) and were found to lie within the Bancroft domain of the Grenville Province, parallel to, and close to, the postulated rifted margin (Fig. 1). That result is consistent with the interpretation of Carr et al. (2000) because, in the ARC-DARC hypothesis, that is where the parent ARCs of Grenville Province DARCs are expected to have lain. Here we develop some implications of that finding.

Figure 1 is simplified from Figures 2A and 2B of Carr et al. (2000) showing the tectonic structure of the Grenville province of southeastern Ontario and neighboring areas. The Bancroft domain lies between the Central Metasedimentary Belt boundary thrust zone (CMBbtz) and the composite arc belt. The CMBbtz is an ~7-km-thick mylonite that occupies a thrust zone which experienced major deformation between 1090 Ma and 1050 Ma, juxtaposing and partly reworking rocks of the Bancroft domain against rocks of ancient Laurentia (Carr et al., 2000). The location of the carbonatite- and nepheline syenite–rich Bancroft domain adjacent to what has been suggested to be a rifted continental margin to Laurentia (Carr et al. 2000, their Figure 5c and their Tables 1 and 2) is also consistent with the suggestion that although the Bancroft domain has historically been considered to be part of the composite arc belt, "large parts of the Bancroft domain may be from the…Laurentian margin rather than the composite Arc Belt" (Carr et al., 2000, p. 199). That interpretation is consistent with the ARC-DARC model in which the carbonatite and nepheline syenite parents of the Bancroft DARCs (having been initially erupted into an intracontinental rift) had, by post ca. 1450 Ma time, come to occupy a rifted continental margin to Laurentia (Figs. 2A and 2B). The abundant carbonate metasediments of the Bancroft domain would also be appropriate rocks in a rifted continental margin environment, especially if that margin had lain in tropical latitudes, as paleomagnetic estimates (admittedly for a somewhat later time than 1450 Ma), have indicated (Weil et al., 1998). The ARC-DARC model requires: (1) the edge of Laurentia now adjacent to the CMBbtz and, at least part of, the Bancroft domain to have occupied a rifted continental margin, and (2) a suture zone within or near to the boundary of the Bancroft domain to

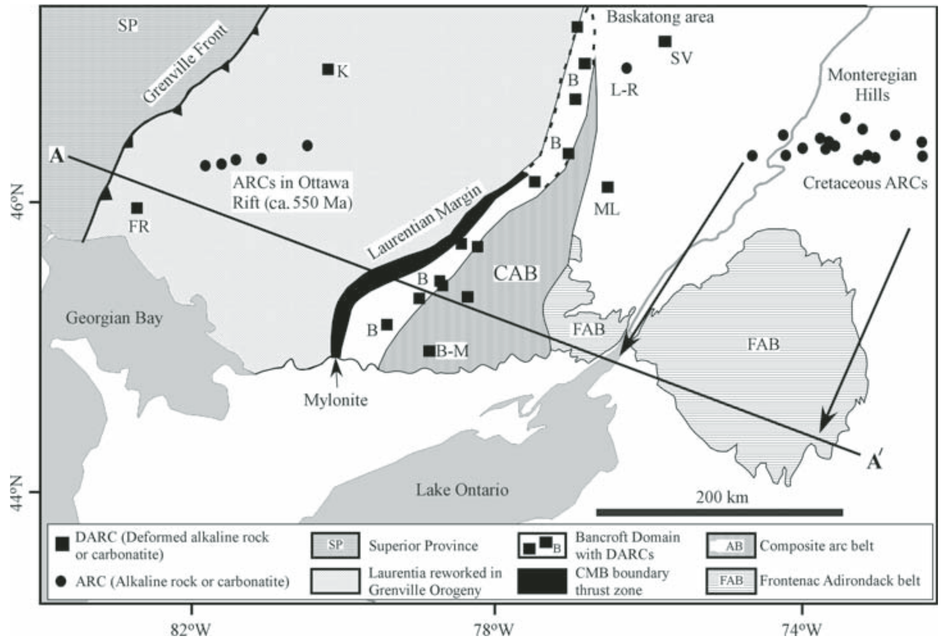

Figure 1. Sketch map (based on Figs. 2a and 2b of Carr et al., 2000) showing distribution of ARCs (alkaline igneous rocks and carbonatites) and DARCs (deformed alkaline igneous rock and carbonatites) in the Grenville province of Ontario and neighboring Quebec, as well as the distribution of Cretaceous ARCs in the Monteregian province of Quebec. DARCs (concentrated in the Bancroft domain and plotted as black squares; from Mart, 2007) are deformed ARCs that had occupied the rifted continental margin of Laurentia, which formed in post-1450 Ma time. Haliburton-Bancroft district occupies the central 100-km strike length of the 300-km-long Bancroft domain. During the Grenville collision, ARCs of the rifted Laurentian margin became DARCs lying in a suture zone dipping to the southeast. Central Metasedimentary Belt (CMB) boundary thrust zone (black) separates the Bancroft domain from the tectonized Laurentian continental margin, and occupies part of the suture zone that formed during the continental collision. The part of Laurentia reworked in the Grenville collision contains the K (Kipawa) and FR (French River) pre-Grenville ARCs that had been emplaced into intracontinental rifts and were deformed to become DARCs during the Grenville collision. ARCs with ages of ca. 550 Ma lie within the Ottawa rift, which formed when the Iapetus Ocean was initiated. Monteregian ARCs with Cretaceous ages (ca. 130–120 Ma) that form an east-west line near the northeast corner of the map are products of partial melting of DARCs at a depth of ~100 km in the down-dip Bancroft domain suture zone. Those DARCs melted in response to the passage of a mantle plume at ~200 km depth. Two arrows trending SSE indicate how the Monteregian ARCs were projected along the Grenville strike to draw Figure 2C. B-M—Blue Mountain; L-R—Lac Rouge; SV—Sainte Veronique; ML—Meach Lake.

mark the region of the collision of rocks of the composite arc belt with the Bancroft domain and with its adjacent Laurentian margin. The possible existence of such a suture zone, termed a cryptic thrust or obduction boundary, was envisaged by Carr et al. (2000, their Table 2 and p. 199). Not only is the occurrence of a 7-km-thick mylonite zone in the CMBbtz compatible with the occurrence of a suture zone, but the relative abundance of mafic and ultramafic metamorphosed igneous rocks in the part of the composite arc belt adjacent to, and southeast of, the Bancroft domain (Davidson, 1998) lends support to the idea of the occurrence of such a zone.

The Bancroft domain emerges from beneath a Paleozoic unconformity in Ontario and extends for more than 300 km along strike to the neighborhood of Baskatong reservoir in Quebec (Fig. 1, Carr et al., 2000, their Fig. 2). Many DARC occurrences lie within the domain (Fig. 1), including the Haliburton-Bancroft district which, being almost continuous for more than 100 km, is the greatest concentration of DARCs yet recognized anywhere in the world. The abrupt termination of the Bancroft domain and the absence of an immediate along-strike extension to the northeast indicates a tectonic style similar to that of younger mountain belts in which arc assembly has been followed by continental collision. Belts of that kind include the Panafrican (Burke et al., 2003) and the Altaids of Central Asia (Şengör and Natalin, 1996), in both of which orogenic collapse features, especially strike-slip and normal faults, have locally cut out and removed huge volumes of newly assembled continental material and left a frustratingly incomplete record (Dewey, 1988). Some Grenville Province DARCs lie farther to the southeast than the mapped Bancroft domain of Carr et al. (2000), for example at Blue Mountain (B-M in Fig. 1). We suggest that those rocks represent parts of the Bancroft domain tectonically incorporated into the composite arc belt.

Carr et al. (2000, their Fig. 2) defined the Bancroft domain in Ontario. Extending into Quebec models conceived to work well in Ontario does not always succeed, and the Grenville-age Meach Lake DARC (ML in Fig. 1) exemplifies that. The Meach Lake body (Hogarth, 1966; Fig. 2) and those of the Lac Rouge and Sainte Veronique (L-R and S-V in Fig. 1) lie to the east of the composite arc belt and would seem to indicate greater tectonic complexity, perhaps Altaid in style.

MONTEREGIAN PROVINCE

ARCs of the Monteregian Hills are indistinguishable from those typical of intracontinental rift environments in their sizes, compositions, and subvolcanic structures, which expose close to circular and annular outcrop patterns as well as such shallow sub-volcanic features as cone sheets (Woolley, 1987; Eby, 1984). Although the Monteregian ARCs are reminiscent of those in a rift environment, there is no evidence of Cretaceous rift activity in the region. The explanation of the origin of the Monteregian Hills ARCs comes from the observation that the rocks of the province lie in a straight line for a distance of ~100 km (Fig. 1), and from the continuity of that line with the White Mountain igneous rocks of New England and the New England Seamounts in the Atlantic Ocean. This alignment has led many to suggest that the Monteregian province occupies part of a hotspot track generated in response to the passage of an underlying mantle plume (e.g., Foster and Symons, 1979; Adams and Basham, 1991) but this idea has been criticized on the basis of the published isotopic ages of Monteregian rocks, although alkaline igneous rocks are notoriously difficult to date accurately. That has certainly been true of rocks in the Monteregian Hills, where ages are commonly cited only as being in the range of "130 Ma to 110 Ma" (e.g., Heaman and Kjarsgaard, 2000, their Fig. 4, p. 261). Farther northwest, Heaman and Kjarsgaard (2000), using high-precision U-Pb ages for 29 perovskites from kimberlites, have demonstrated the existence of a hotspot track that extends in a line across Canada for more than 1000 km and ranges progressively in age from ca. 200 Ma (Triassic-Jurassic) to ca. 130 Ma (Early Cretaceous). Because that line of kimberlites projects to join the Monteregian Hills, evidence that the Monteregian ARCs represent part of a hotspot track has become even stronger since the work of Heaman and Kjarsgaard (2000). A recently published U-Pb age of 130 Ma (Cox and Wilton, 2006) on a perovskite from the Oka carbonatite at the western end of the Monteregian province reinforces that conclusion. The ARCs of the

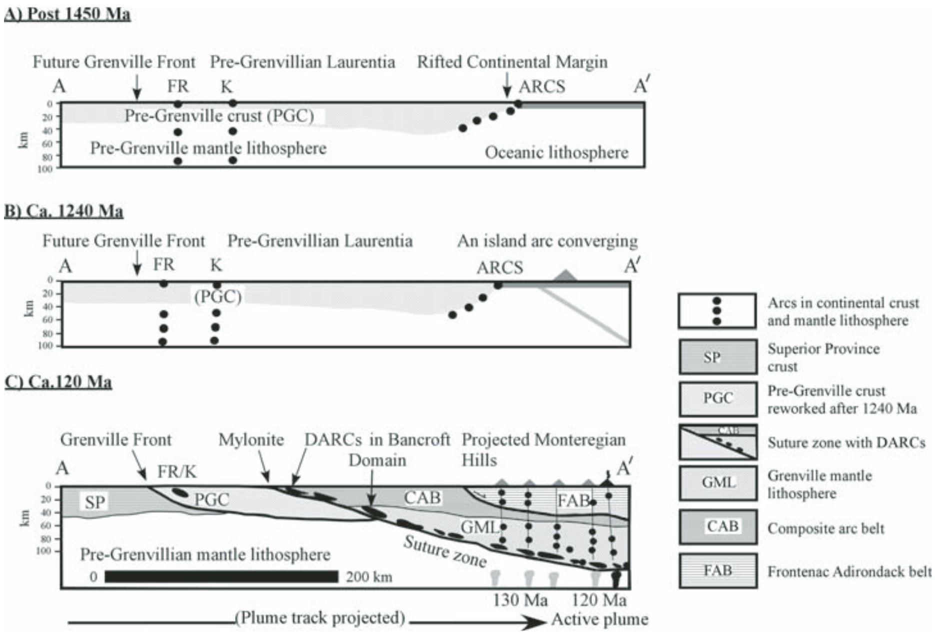

Figure 2. Sketch cross sections (based on Figure 5 of Carr et al., 2000) along the line A–A′ of Figure 1 showing alkaline igneous rock and carbonatite (ARC) to deformed alkaline igneous rock and carbonatite (DARC) evolution in the Grenville province and the derivation of Monteregian province ARCs from Grenville-aged DARCs in the underlying mantle lithosphere. A: Post-1450 Ma. The continental margin of Laurentia with two ARCs (black circles, FR—French River, K—Kipawa) and other ARCs on the rifted margin of the continent that had originally been erupted into the intracontinental rift on which the continental margin formed. B: Ca. 1240 Ma. Convergence with an island arc approaching the continent. C: Ca. 120 Ma. Structure established by the end of the Grenville collision at ca. 950 Ma (modified from Carr et al., 2000, their Fig. 5e) with the effects of the passage of a mantle plume at a depth of ~200 km added to show the postulated origin of the Monteregian ARCs. The Central Metasedimentary Belt (CMB) boundary thrust zone (labeled mylonite) and Bancroft domain DARCs (black lenses) occupy a suture zone coincident with the former rifted boundary of Laurentia. The pre-Grenville Crust (PGC) of Laurentia has been tectonized and metamorphosed between ca. 1240 Ma and ca. 950 Ma so that the Kipawa (K) and French River (FR) ARCs have become DARCs. The composite arc belt (CAB) and underlying Grenville mantle lithosphere (GML), as well as the Frontenac-Adirondack belt (FAB), have been thrust to the northwest over pre-Grenvillian mantle lithosphere. In the Cretaceous, as a mantle plume passed at a depth of ~200 km., DARCs of the Bancroft domain on the suture zone in the mantle lithosphere partly melted to generate the Monteregian ARCs. The most southeasterly of those ARCs is shown erupting.

Monteregian province are subvolcanic hotspot rocks generated in response to the passage of an underlying mantle plume.

RELATIONSHIP OF THE MONTEREGIAN ARCS TO THE GRENVILLE PROVINCE DARCS OF THE BANCROFT DOMAIN

Because of their proximity (Fig. 1), it is natural to consider whether and how Grenville DARCs and Monteregian ARCs, which are compositionally so similar, might be related. Monteregian Cretaceous igneous rocks occupy <10% of the length of a >2000-km-long hotspot track (Ernst and Buchan, 2003). Rocks marking other parts of that track include granites in New England, basalts on the ocean floor, and kimberlites in the Canadian shield, but nowhere else on the track are there ARCs. Here the occurrence of ARCs only in the Monteregian province and their proximity to the DARC-rich Bancroft domain is explained to result from partial melting over the mantle plume responsible for the hotspot track. DARCs of the Grenville province at the level of today's exposure cannot be the sources of the Monteregian ARCs because those DARCs occur as slivers within continental crustal rocks. If continental crustal rocks, which in large volume typically average roughly granodioritic composition, are subjected to the thermal influence of a passing plume, then, as in the Jos plateau of Nigeria (Burke, 2001), minimal-melt granites forming at temperatures lower than those at which DARCs minimally melt form the principal igneous products. ARCs are therefore unlikely to be generated from older DARCs in continental crust. DARC sources, if they are to be capable of generating younger ARCs, have to be in the lithospheric part of the mantle where melting, as a result either of decompression under an extending rift or of heating by a passing plume, can generate ARCs at temperatures lower than those at which basalt, which is commonly the first product of the melting of mantle rocks, can be generated (Lee and Wyllie, 2000). If, as we suggest, the DARCs of the Grenville Bancroft domain lie in the suture zone marking the collision of the composite arc belt of Carr et al. (2000) with the Laurentian continental margin, the ARC-DARC model requires that DARCs also occur on the part of the suture zone marking the Grenville collision in the lithospheric part of the mantle (Fig. 2C). The eastward offset of the Monteregian ARC outcrops with respect to the Grenville DARC outcrops (Fig. 1) is consistent with that requirement because the suture zone, like the major thrusts of Carr et al. (2000, their Fig. 5e) is expected to dip at a low angle into the mantle under the Frontenac-Adirondack belt (Figs. 1 and 2).

To estimate where in the mantle the DARC sources of the Monteregian ARCs lie, we took the outcrop distribution of the Monteregian ARCs from Woolley (1987), estimating a total length embracing the ARC rock outcrops to be ~100 km long, and projected those outcrops in a SSE direction along the regional Grenville strike onto the line of section A–A′ (see two arrows in Fig. 1). Our interpretation of Cretaceous conditions (in Fig. 2C) is a slightly modified version of Figure 5e of Carr et al. (2000). That cross section shows the structure at the end of Grenville tectonic activity, ca. 950 Ma. We modified that figure by showing the DARC-rich Bancroft domain and the CMBbtz mylonite as occupying a suture zone that marks the juxtaposition of composite arc belt rocks against the former continental margin of Laurentia. We have drawn the suture zone as an ~20-km-thick zone with a uniform ~30° dip in both crust and mantle. The ARC-DARC model requires that DARCs in the mantle be at a suitable depth (estimated here to be at ~100 km) to generate new ARCs in response to heating (Lee and Wyllie, 2000). We have also therefore sketched the passage of a plume head in Cretaceous time between ca. 130 Ma and ca. 120 Ma at the base of the lithosphere (at a depth of ~200 km; Rondenay et al., 2000; White et al., 2000). The most southeastern Monteregian Hills volcano is shown as actively erupting.

DISCUSSION

ARCs of a variety of ages that occur in the general area addressed in this paper are interpreted to indicate the widespread, but not abundant, occurrence of DARCs in the underlying mantle lithosphere of pre-Grenville Laurentia. Some ARCs in the area have been shown to have erupted in specific rifting events, such as a population with isotopic ages in the 550 ± 50 Ma range that matches the time of the opening of the Iapetus Ocean (Doig, 1970), but others have not. Some, such as Kipawa and French River

(K and FR in Fig. 1) were erupted in pre-Grenville Laurentia although they yield "typical Grenville ages" (Woolley, 1987, p. 46). Those ages, on the ARC-DARC model, are interpreted to result from having been involved in the Grenville collision.

We consider that the parent ARCs of Bancroft domain DARCs were parts of the population of pre-Grenvillian Laurentian ARCs. It might be possible to obtain isotopic ages from some Grenville DARCs that record both initial eruptions and later collisions (cf. Ashwal et al., 2007).

CONCLUSIONS

1. DARC occurrences in southeastern Ontario and neighboring Quebec lie in high concentration (Fig. 1) within the Bancroft domain of Carr et al. (2000).

2. That finding is compatible with both the suggestion of Carr et al. (2000) that the rocks in the Bancroft domain may mark a rifted margin to Laurentia, and the ARC-DARC hypothesis (Burke et al., 2003) in which ARCs erupted into intra-continental rifts can come to occupy rifted continental margins as the rifts later become involved in the early stages of the Wilson cycle process of ocean opening and closing.

3. In the ARC-DARC hypothesis, the ocean closing phase of the Wilson cycle is marked by deformation of the ARCs of a rifted margin to form DARCs in a suture zone. The possibility of the existence of such a suture zone was envisaged, using very different kinds of evidence, by Carr et al. (2000, their Table 2 and p. 199) who wrote "…a cryptic composite Arc Belt-Laurentian obduction boundary may be present in the Bancroft domain."

4. DARCs in the lithospheric part of the mantle on the down-dip extension of the Bancroft domain suture zone responded to heat from a plume as it passed underneath between 130 Ma and 120 Ma. When they melted, those DARCs generated the Monteregian ARCs. This explanation represents an extension of the ARC-DARC hypothesis that was originally conceived only to accommodate the idea of ARC eruption in actively extending rifts from decompression melting of underlying DARCs.

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