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SW Grenville Province, Canada: the case against post–1.4 Ga accretionary tectonics

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Abstract

Seven accretionary sutures, formed between 1.16 and 1.03 Ga, have been identified by different authors in the Ontario–Quebec–Adirondack (OQA) segment of the Mesoproterozoic Grenville orogen in Canada. With one exception, the inferred accretionary terrane boundaries lie within, or at the margins of the Central Metasedimentary Belt (CMB), located between the Central Gneiss Belt and the Adirondack Highlands (Central Granulite Terrane). However, geological, geochronological, and petrological data suggest that the Grenville orogen on both sides of the proposed terrane boundaries (sutures) preserves a common 1.4–1.03 Ga tectonomagmatic history, inconsistent with its origin as a post-1.4 Ga collage of exotic tectonic blocks. Features which straddle the proposed 1.16–1.03 Ga 'sutures', from the Central Gneiss Belt, via the Adirondack Highlands, to the Mauricie area, include: (1) Mesoproterozoic continental crust (1.5–1.4 Ga) forming the host and/or basement to younger magmatic and supracrustal suites. (2) A 1.35–1.3 Ga continental arc, remnants of which occur from the CMB boundary zone (CMBBZ) in Ontario to the Appalachians in the United States, built on the 1.5–1.4 Ga continental crust. (3) Intrusions of 1.17–1.13 Ga age in the Central Gneiss Belt (mafic suite), and the Adirondack Highlands and their Quebec extension (AMCG suite, i.e. anorthosite massifs and related granitoids). (4) Relics of 1.18–1.14 Ga sedimentary basins in the northwestern CMB and the Mauricie area.

We propose that an alternative model can adequately account for the observed geology of this part of the Grenville orogen wherein, the rocks of the OQA segment were part of an Andean-type margin between 1.4 and 1.2 Ga. At 1.35–1.3 Ga, a continental magmatic arc was built upon the southeastern margin of Laurentia represented by the 1.5–1.4 Ga Mesoproterozoic continental crust. The arc split at 1.3 Ga forming an ensialic back arc basin, relics of which now occur in the northwestern part of the CMB, and the back arc basin was flanked to the southeast by an active 1.28–1.25 Ga arc. Collision between the Laurentian margin and another continent (Amazonia?) occurred at 1.2 Ga, resulting in closure of the back arc basin and initiation of thrusting along the CMBBZ. Post-collisional lithospheric shortening led to convective removal of thickened subcontinental lithosphere, upper mantle melting, and extension of the overlying crust, resulting in widespread magmatic activity at 1.17–1.13 Ga, including emplacement of the AMCG massifs. Crustal extension generated sedimentary basins now represented by the St Boniface sediments in the Mauricie area (1.18 to between 1.15 and 1.09 Ga), and the penecontemporaneous Flinton Group in the northwestern CMB. Renewed, post-collisional, granulite facies shortening commenced at 1.12 Ga, manifested as

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nappes in the Central Gneiss Belt, and thrusting in the Mauricie area. Continued post-collisional shortening at 1.08–1.05 Ga was more localised, resulting in reactivation of thrusting in the CMBBZ, and initiation of the kinematically compatible Tawachiche shear zone along the eastern border of the Quebec extension of the Adirondack Highlands.

The characteristics of the OQA segment of the Grenville orogen can all be accounted for in the context of: (1) a 1.4–1.2 Ga, southeast facing Andean-type margin to a Laurentian upper plate, associated with northwest dipping subduction; (2) continental collision at 1.2 Ga; and (3) subsequent, continued, post-collisional shortening, without invoking accretion of exotic terranes between 1.4 and 1.0 Ga.

Keywords: Andean margin; continental collision; Grenville; orogeny; tectonics

1. Introduction

The Grenville orogen in North America marks the southeastern margin of Proterozoic Laurentia from the southern United States to Labrador, Canada (Fig. 1). The SW Grenville Province in Ontario, western Quebec, and the Adirondack Highlands and Lowlands, referred to herein as the Ontario–Quebec–Adirondack (OQA) segment (Fig. 2) forms a relatively small component of the Grenville orogen, but comprises key elements that provide constraints for its tectonic evolution. It is traditionally divided into a Central Metasedimentary Belt (CMB), flanked by a Central Gneiss Belt (CGB) to the northwest and the Adirondack Highlands (Central Granulite Terrane) to the southeast (Fig. 1; e.g. Davidson, 1986; Easton, 1992). The tectonic development of the Grenville orogen in North America has been the subject of several recent review papers, notably those by Davidson (1995), Gower (1996), Rivers (1997) and Mosher (1998), all of which highlight the accretionary history of the orogen (see also Rivers et al., 1989; Lumbers et al., 1990 and references therein). The OQA segment, most notably the CMB, has long been interpreted in terms of the accretion of exotic terranes (e.g. Brown et al., 1975; Pride and Moore, 1983; Windley, 1986; Davidson, 1986, 1995; Corriveau, 1990; Mezger et al., 1992, 1993; Gower and Tucker, 1994; Hildebrand and Easton, 1995; McLelland et al., 1996; Culshaw et al., 1997; Busch et al., 1997; Martignole and Friedman, 1998). The CMB was initially divided into Elzevir and Frontenac 'terranes', flanked to the northwest by a Bancroft 'terrane' (see below; e.g. Davidson, 1986; Easton, 1992). Most of the published tectonic models invoke subduction zones within the exposed Grenville orogen. The number of subduction zones varies from model to model, but they are consistently shown dipping to the southeast, away from Laurentia (e.g. Condie and Moore, 1977; Windley, 1986; Corriveau, 1990; Gower and Tucker, 1994; Davidson, 1995; Smith and Harris, 1996; McLelland et al., 1996; Culshaw et al., 1997), though there are exceptions (see Rivers, 1997). Several seismic reflection experiments have been undertaken to image the inferred terrane boundaries, with varying degrees of success (e.g. Culotta et al., 1990; Hughes and Luetgert, 1992; Milkereit et al., 1992; Forsyth et al., 1994a,b; White et al., 1994; Zelt et al., 1994; Kellett et al., 1994).

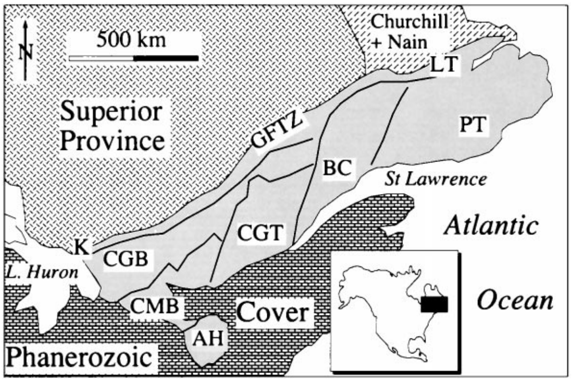

Fig. 1. Distribution of principal tectonic elements in the Grenville Province. AH, Adirondack Highlands (also part of the Central Granulite Terrane); BC, Baie Comeau region; CGB, Central Gneiss Belt; CGT, Central Granulite Terrane; CMB, Central Metasedimentary Belt; GFTZ, Grenville Front Tectonic Zone; K, Killarney arc terrane; LT, Labradorian arc terrane; PT, Pinware arc terrane. Bold lines are accretionary terrane boundaries (sutures) discussed in the text. Adapted from McLelland et al. (1996) and Rivers (1997).

Much of the geoscientific effort in studying and

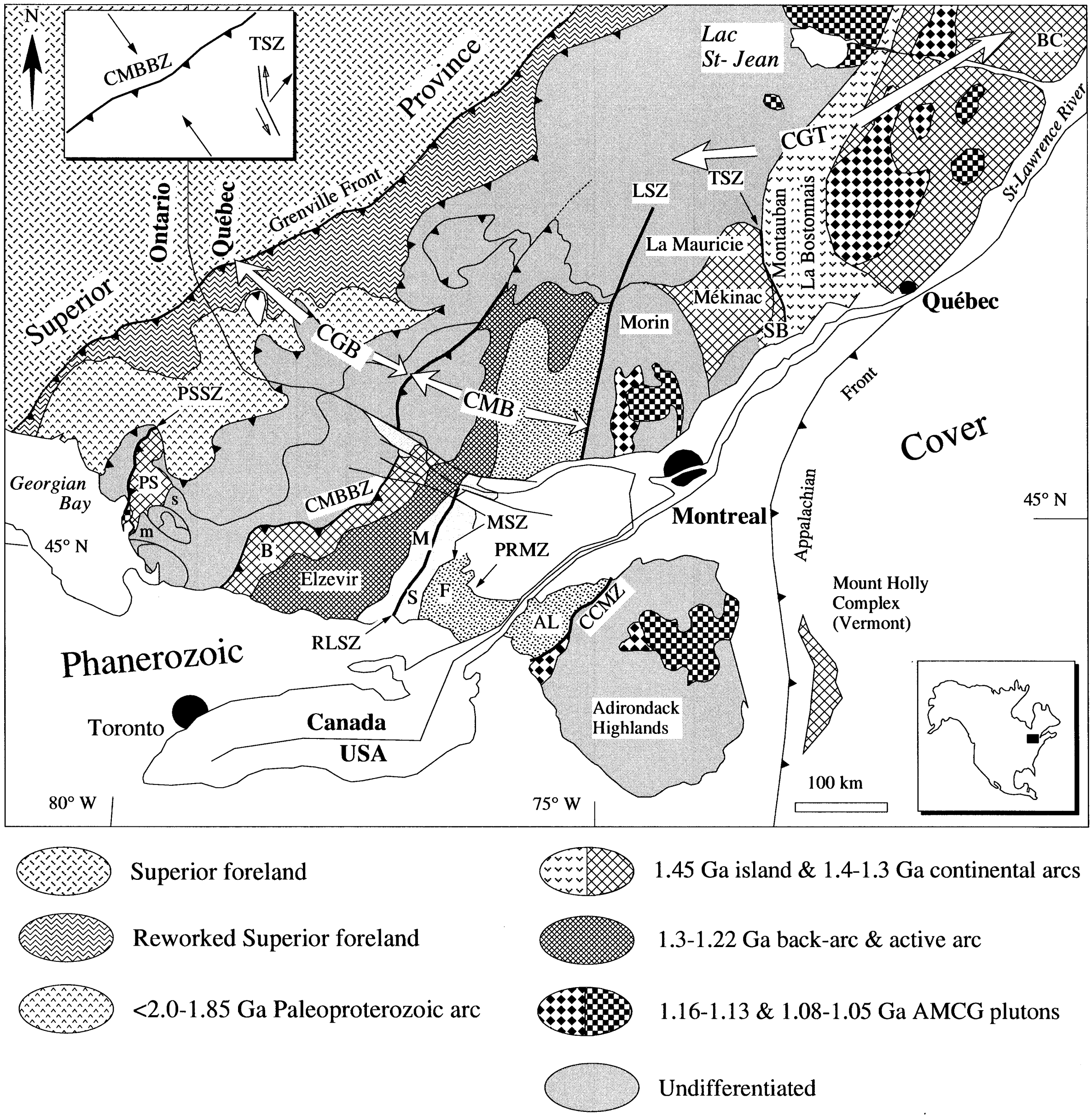

Fig. 2. Schematic distribution of principal tectonic elements in the OQA segment of the Grenville orogen, Canada. AL, Adirondack Lowlands; B, Bancroft 'terrane'; BC, Baie Comeau region; CCMZ, Carthage–Colton mylonite zone; CGB, Central Gneiss Belt; CGT, Central Gneiss Terrane; CMBBZ, Central Metasedimentary Belt boundary zone; E, Elzevir 'terrane'; F, Frontenac 'terrane'; LSZ, Labelle shear zone; M, Mazinaw 'terrane'; m, Moon River nappe; MSZ, Maberly shear zone; PRMZ, Perth Road mylonite zone; PS, Parry Sound domain; RLSZ, Robertson Lake shear zone; s, Seguin nappe; S, Sharbot Lake 'terrane'. The thick lines are the accretionary 'sutures' proposed by other workers, referred to and referenced in the in the text. Adapted from Davidson (1995). Inset illustrates how 1.08–1.05 Ga NW–SE post-collisional shortening across the CMB boundary thrust zone is kinematically compatible with localised oblique extension on the Tawachiche shear zone, as a result of partioning along a pre-existing, orogen-scale structural anisotropy.

interpreting the Grenville orogen has focused on the OQA segment. From our work within the Ontario and west Quebec parts of the segment, we have proposed that the principal tectonic components of the orogen were amalgamated by 1.2 Ga (Hanmer and McEachern, 1992; Nadeau and Hanmer, 1992; McEachern and van Breemen, 1993; Pehrsson et al., 1996), a time of continent–continent collision (Corrigan and Hanmer, 1997). However, other workers have identified seven accretionary terrane boundaries (sutures) within the OQA segment, whose interpreted ages range from 1.16 to 1.03 Ga (Fig. 3; e.g. Corriveau, 1990; Mezger et al., 1992, 1993; Davidson, 1995; Hildebrand and Easton, 1995; Smith and Harris, 1996; McLelland et al., 1996, 1997; Dickin and McNutt, 1990; Culshaw et al., 1997; Busch et al., 1997).

The aim of the present contribution is to build on our initial proposal (Hanmer et al., 1994) and to argue that geological linkages were already established across all of the proposed terrane boundaries in the OQA segment by 1.4 Ga, thereby obviating the requirement for post-1.4 Ga sutures within the SW Grenville Province. This argument will be presented in three parts. First, we briefly summarise the current understanding of the evolution of the Grenville Province. Second, after reviewing the available isotopic and geochronological data, we suggest that all parts of the OQA

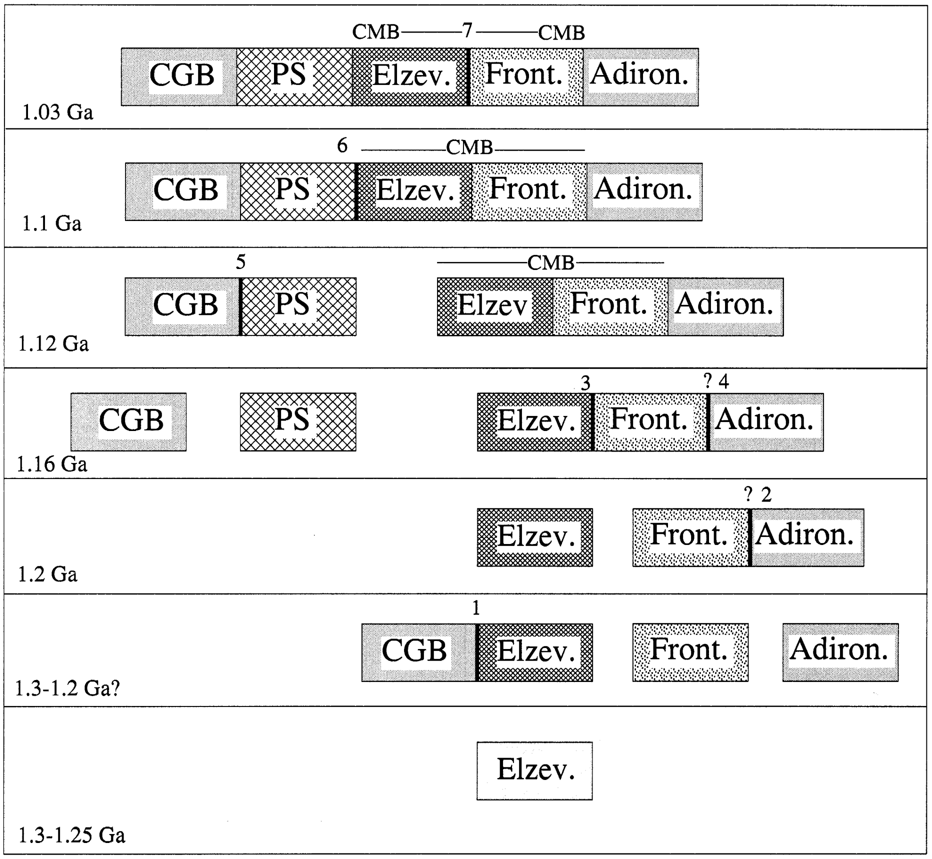

Fig. 3. Space–time diagram schematic to illustrate the locations and timing of accretionary sutures, as proposed in the literature. Thick lines are sutures, numbered and keyed to references in the text. Adirond., Adirondack Highlands; CGB, Central Gneiss Belt; CMB, Central Metasedimentary Belt; Elsev., Elzevir 'terrane'; Front., Frontenac 'terrane'; PS, Parry Sound domain.

segment shared a common tectonomagmatic history between 1.4 and 1.2 Ga. Furthermore, from the spatial and temporal distribution of tectonometamorphic and magmatic events, we suggest that no terrane accretion involving opening and closing of major ocean basins occurred within the OQA segment after 1.2 Ga. Third, we shall present a tectonic model whereby the post-1.4 Ga history of the OQA segment can be adequately interpreted in terms of: (1) an initial southeast-facing Andean-type margin (present day coordinates), whose tectonic evolution reflects the relative horizontal motion of the hinge of a northwestward subducting lower plate, followed by: (2) 1.2 Ga continent–continent collision, and subsequent post-collisional shortening within the Laurentian margin.

All cited dates were determined by U–Pb on zircon, unless otherwise specified. Note that the term 'terrane' is now entrenched in Grenvillian nomenclature, and its usage for geographical reference is unavoidable.

2. Grenville Province

In his recent summary of the Grenville Province, Canada, Rivers (1997) systematically reviewed the available evidence for accretion of juvenile crust to the southeastern margin of Laurentia during the Palaeoproterozoic and Mesoproterozoic. This includes a Penokean age accreted arc terrane (<2.0–1.85 Ga; Palaeoproterozoic arc in Fig. 2), Labradorian and Killarney accretionary arc terranes (1.7–1.63 Ga; Fig. 1), and the emplacement of juvenile arc granitoids into the newly accreted continental margin, including the Pinwarian terrane (1.5–1.4 Ga; Fig. 1). In the Labradorian terrane, the latter part of the 1.7–1.63 Ga accretionary event is associated with the Trans-Labrador batholith, interpreted by Rivers (1997) as a continental arc that formed within the Laurentian plate above a northwest-dipping subduction zone, but as a collision-related melt associated with crustal thickening by Gower (1996). The 1.5–1.4 Ga event is associated with emplacement of voluminous mantle-derived mafic melts in a back-arc setting, inboard of the Pinwarian continental-margin arc, and is also interpreted to have developed above a northwest-dipping subduction zone (see Corrigan et al., 2000). This subduction system appears to have extended from the Granite–Rhyolite belt of the mid-continental USA to southern Labrador, and is interpreted in terms of an Andean-type destructive plate margin (Gower, 1996; Rivers, 1997).

Rivers (1997) also presented a comprehensive review of post-1.4 Ga tectonic events in the Grenville Province. The Andean-type margin persisted until continent–continent collision at ca. 1.2 Ga (Corrigan, 1995; Corrigan and Hanmer, 1997). A back-arc basin that opened in the Laurentian margin is only preserved in the SW Grenville Province (1.3–1.2 Ga supracrustal and gabbroic rocks of the CMB; Fig. 2), although it may have extended to the northeast outside of the presently exposed Grenville orogen (Gower, 1996). Other volcano-sedimentary continental rift deposits were formed on, and mantle- and crustal-derived melts were emplaced within, the NE Grenville Province and the adjacent Laurentian craton during back-arc related extension. At 1.2 Ga, arc and back-arc magmatism ceased, and was succeeded by syncollisional and post-collisional magmatism, marking the evolution of the Grenville Province from Andean-type to continent-continent collisional orogeny, formally defined as the Grenvillian orogeny per se.

Rivers (1997) considered the Grenvillian orogeny (1.2–1.0 Ga) as a number of tectonothermal and magmatic pulses associated with voluminous, within-plate mantle- and crustal-derived melts. However, he does not explicitly address the numerous published tectonic models for the Grenville Province that are inconsistent with his synthesis of the Grenvillian orogeny. They are inconsistent either because they invoke different subduction polarities between 1.4 and 1.2 Ga, or because they propose continued exotic terrane accretion after 1.2 Ga (Fig. 3; e.g. Windley, 1986; Davidson, 1986, 1995; McLelland et al., 1988, 1996; Corriveau, 1990; Corriveau et al., 1990; Mezger et al., 1992, 1993; Davidson and Ketchum, 1993; Corfu and Easton 1997; Busch et al., 1997; Culshaw et al., 1997). Our intention in the rest of this contribution is to critically examine the arguments for and against accretionary tectonics during the period

1.4–1.0 Ga in the OQA segment of the Grenville orogen, SW Grenville Province.

3. Isotopic data for the OQA segment

The extent of pre-1.4 Ga Laurentian basement within the OQA segment of the Grenville orogen is revealed by orthogneisses and plutonic rocks which yield a consistent pattern of Palaeoproterozoic to early Mesoproterozoic T_{dm} model ages, from the southern part of the CGB to well east of the Adirondack Highlands (Parry Sound domain to Baie Comeau region in Figs. 2 and 4). In the northern part of the CGB, Archean model ages for orthogneisses adjacent to the Grenville Front tectonic zone are succeeded to the southeast by model ages ranging from 1.9 to 1.5 Ga, in part interpreted by Dickin and coworkers in terms of a <2.0–1.85 Ga Penokean arc, accreted to the margin of Archean Laurentia during the Palaeoproterozoic (Figs. 2 and 4; Dickin and McNutt, 1989; Dickin et al., 1990; Holmden and Dickin, 1995; Guo and Dickin, 1996; Dickin, 1998).

Southeast of the Penokean arc, model ages are more restricted in range (Fig. 4). Plutonic rocks of the Parry Sound and Muskoka domains (Seguin nappe; Fig. 2), part of the 1.45–1.42 Ga magmatism recognised throughout the CGB (see Easton, 1992), yield T_{dm} model ages of 1.5 Ga (Dickin and McNutt, 1990). Southeast of the Frontenac–Elzevir 'terrane' boundary within the CMB (MSZ in Fig. 2), Marcantonio et al. (1990) obtained

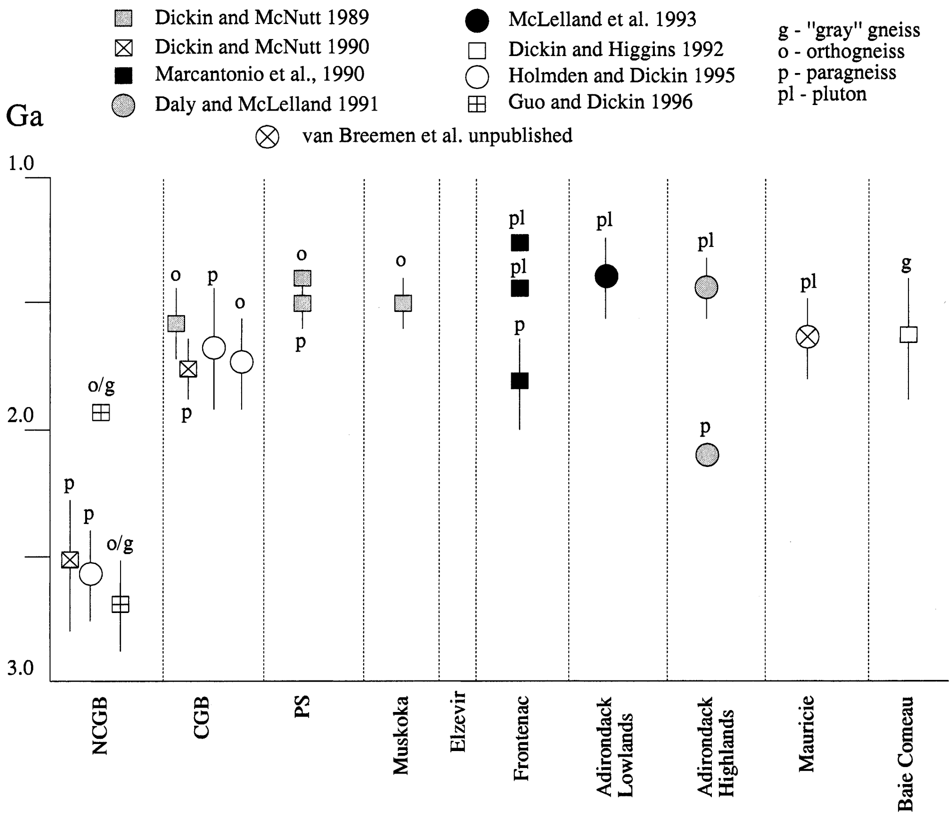

Fig. 4. Schematic diagram of the spatial distribution of T_{dm} model ages across the OQA segment of the Grenville orogen in North America. Vertical line represents span of model ages from an lithological type, identified by abbreviations, determined by the cited authors, identified by symbols. Geographical abbreviations are: CGB, Central Gneiss Belt; NCGB, northern CGB; PS, Parry Sound domain.

1.5 Ga T_{dm} model ages from 1.16 to 1.08 Ga granitic plutons within the Frontenac 'terrane', though they also obtained some significantly younger ages (>1.25 Ga; Fig. 4). In addition, DeWolf and Mezger (1994) interpreted Pb isotopic mineral data to indicate that extensive juvenile continental crust underlay the CMB and the southern part of the CGB at 1.5–1.4 Ga. Within the Adirondack Lowlands (Fig. 2), 1.17 Ga plutonic rocks (Hyde School gneiss) give T_{dm} model ages of 1.5–1.3 Ga (McLelland et al., 1993, 1997). In the Adirondack Highlands (Fig. 2), tonalites and granitoids ranging in age from 1.3 to 1.1 Ga yield model ages of 1.6–1.3 Ga (Fig. 4; Daly and McLelland, 1991).

The Mauricie area lies to the east of the Quebec extension of the Adirondack Highlands (Morin 'terrane'; Fig. 2). Recent work there (Corrigan, 1995; Corrigan and Hanmer, 1997; Corrigan and van Breemen, 1997) has shown that the 1.45 Ga Montauban Group, interpreted to be part of an island arc, was invaded at 1.4–1.37 Ga by the La Bostonnais plutonic complex of continental arc affinity (Fig. 2; Nadeau and Corrigan, 1991; Gauthier, 1993; Nadeau and van Breemen, 1994; Corrigan, 1995). These suites of arc-related rocks give 1.7–1.45 Ga T_{dm} model ages (Fig. 4; van Breemen and Nadeau, unpublished data). To the west, the 1.40–1.37 Ga Mékinac orthogneisses (Fig. 2; van Breemen and Nadeau cited in Corrigan and van Breemen, 1997) yield similar T_{dm} model ages (1.5 Ga; van Breemen and Nadeau, unpublished data), and are likely equivalents of the continental arc (Corrigan, 1995; Corrigan and Hanmer, 1995).

Throughout the Baie Comeau region in central Quebec, well east of the Mauricie area (Fig. 2), Dickin and Higgins (1992) obtained T_{dm} model ages in the range 2.0–1.5 Ga, but strongly skewed towards 1.5 Ga, in extensive 'grey' gneisses that they interpreted as orthogneisses (Fig. 4; see also Tucker and Gower, 1994). Lacking U–Pb determinations for their material, Dickin and Higgins (1992) determined a Sm–Nd isochron age of 1.53 Ga. These data do not unequivocally indicate the presence of ca. 1.5 Ga crust. However, they do show that the Baie Comeau segment presents an average Sm–Nd model age signature (Arndt and Goldstein, 1987) similar to that of known 1.45 Ga crust in other areas of the OQA segment of the Grenville orogen.

A small number of Sm–Nd model ages have also been recovered from paragneisses of the OQA segment (Fig. 4). T_{dm} model ages of 2.0–1.4 Ga were obtained from the CGB (Dickin and McNutt, 1989; Dickin et al., 1990; Holmden and Dickin, 1995; Guo and Dickin, 1996), and 2.05–1.55 Ga from the Frontenac 'terrane' (Marcantonio et al., 1990). Although they do not constitute a comprehensive provenance database, we simply note the similarity between these two data sets. In addition, there is a single 2.07 Ga model age determination from paragneiss in the Adirondack Highlands (Daly and McLelland, 1991).

We are well aware of the potential pitfalls inherent in interpreting isotopic model ages in terms of the time of crust formation, and recognise that they may represent average crustal residence times (Arndt and Goldstein, 1987). We also recognise that the cited model ages from crustally-derived granitic rocks were recovered from plutons which crystallised both before and after the 1.2 Ga continental collision. However, for the purposes of this discussion, we seek only to treat the magmatic rocks as crustal probes that reflect the nature of the materials from which they were derived. The salient point here is that the Sm–Nd signatures of the OQA segment of the Grenville orogen show a lack of provinciality across the CMB, from the CGB to well east of the Adirondack Highlands. Although this is negative evidence, it serves to focus the burden of proof for the post-1.4 Ga accretionary terrane hypothesis on the geological data.

4. Accretionary terranes and sutures?

The CMB (Fig. 2) is a key component in the accretionary terrane models of the OQA segment of the Grenville orogen (Easton and Davidson, 1994). Within the CMB, the Grenville Supergroup was defined as a suite of mafic to intermediate volcanic rocks with coeval marbles, feldspathic quartzites and pelites, all deposited between 1.3 and 1.25 Ga (see Easton, 1986, 1992 and references therein; Sager-Kinsman and Parrish, 1993; Corfu and Easton, 1995). Easton (1992) subdivided the original Grenville Supergroup into a volcano-sedimentary Grenville Supergroup, and a sedimentary Frontenac Supergroup, broadly corresponding to the Elzevir and Frontenac 'terranes'. Easton (1992) further divided the Elzevir 'terrane' into three smaller ones (Mazinaw, Elzevir and Sharbot Lake), flanked by a Bancroft 'terrane' to the northwest (Fig. 2), all of which he grouped into an Elzevir 'superterrane'. A number of accretionary sutures have been proposed in the literature, either within or in close proximity to the CMB (Fig. 2). These are presented in diagrammatic form in Fig. 3, constructed with the Elzevir 'terrane' as the central reference point. In what follows, we examine each of these accretionary events and proposed sutures in geochronological order.

4.1. Accretion at ca. 1.2 Ga ?

Several authors have speculated that the northwestern margin of the CMB might contain a suture (#1 in Fig. 3) which they relate to the docking of an arc assemblage with Laurentia, at 1.3 Ga (Dickin and McNutt, 1990), or 1.2 Ga (Davidson, 1995; McLelland et al., 1996). Building on an early attempt by Windley (1986) to draw tectonic comparisons with the western Himalaya, Davidson (1995) interpreted calc-alkaline volcanic and plutonic rocks of the Elzevir superterrane as the end-product of westward migrating arc construction, associated with southeast directed subduction, leading to obduction of the arc over the CGB and the Bancroft 'terrane' at 1.2 Ga. McLelland et al. (1996) followed Davidson, while acknowledging that they were treating the Elzevir 'terrane' as an arc, despite the evidence for its back-arc or marginal basin petrochemical signature (see below). Dickin and McNutt (1990) also adopted this model, but placed it significantly earlier, between 1.3 and 1.25 Ga.

Other authors have identified a suture at the southeastern margin of the CMB (No. 2 in Fig. 3). McLelland et al. (1996) suggested that the Adirondack Highlands docked with the CMB at 1.2 Ga, thereby terminating southeast directed subduction. Subduction beneath the Adirondacks is required to account for 1.35–1.23 Ga juvenile magmatism. Rivers (1997) accounts for it by northwest directed subduction located well to the southeast of the Adirondacks, but McLelland et al. (1996) do not explain their choice of subduction polarity.

4.2. Accretion at ca. 1.16 Ga?

An accretionary terrane boundary, or suture, has been proposed separating the volcanic and carbonate rocks of the Elzevir 'terrane' to the northwest from the quartzites, pelites and carbonates of the Frontenac 'terrane' to the southeast, based on their differing lithological and geochronological characteristics (Fig. 2, No. 3 in Fig. 3; Davidson, 1995; see also Davidson, 1986; McLelland et al., 1996). The presence of granitic plutons and tectonothermal events dated at 1.17–1.16 Ga (Marcantonio et al., 1990; Corfu and Easton, 1997) in the Frontenac 'terrane', and their absence in the Elzevir 'terrane', has been used to highlight the distinctive character of the Frontenac 'terrane', and to support the Frontenac–Elzevir boundary as a 1.16 Ga accretionary suture (e.g. Easton, 1992; Davidson, 1995, 1996; Corfu and Easton, 1997). The accretionary terrane boundary has been identified with the 1.16 Ga Maberly shear zone (MSZ in Fig. 2; Davidson, 1995; Davidson and Ketchum, 1993), although Corfu and Easton (1997) suggest that the shear zone per se may only be one component in a structurally complex boundary. However, there are alternative explanations for the different geological histories of the two 'terranes'. For example, the 1.17 Ga granitic plutons are crustal melts (e.g. Easton, 1992), which we would relate to collisional and post-collisional crustal thickening. Their spatial distribution could simply reflect the locus of the thermal anomaly responsible for melting, or the pattern of principal stresses or other factors enhancing or disfavouring the emplacement of melts into the crust (e.g. Paterson and Fowler, 1993; Corriveau at al., 1998). Similarly, tectonothermal events are commonly localised, even on a large scale (e.g. Hanmer and McEachern, 1992), as well as being depth dependent (e.g. Hanmer, 1988a). Abrupt juxtaposition of the contrasting rocks may well represent crustal-scale faulting, but need not require the suturing of exotic accretionary terranes per se. In this perspective, it is significant that the Elzevir 'terrane' registered a thermal event at 1.17 Ga (Lopez-Martinez and York, 1983), despite the apparent lack of contemporaneous plutons, and that the southeastern CGB was intruded by widespread 1.16 Ga gabbro bodies (Davidson and van Breemen, 1988; Heaman and LeCheminant, 1993). While the presence of contemporary 1.17 Ga thermal events throughout much of the OQA segment of the Grenville orogen, and on either side of the Frontenac–Elzevir boundary, does not prove a common causality, our point here is that the presence of widespread thermal events, which potentially weakens arguments in favour of the accretionary terrane model, has been ignored hitherto.

Building on an original suggestion by McLelland et al. (1988), Mezger et al. (1992) suggested that the southeastern margin of the CMB, the Carthage–Colton mylonite zone (CCMZ in Fig. 2), may be a cryptic 1.16 Ga suture (No. 4 in Fig. 3) on the basis of a 100 Ma jump in monazite and titanite ages from the Adirondack Lowlands and Highlands. Mezger et al. (1992) correlated the Carthage-Colton mylonite zone with the Labelle shear zone in Quebec (LSZ in Fig. 2), giving the proposed suture a strike length of 1000 km. However, the geology of the Carthage–Colton mylonite zone is still very poorly understood, and observations appear contradictory. For example, the mylonite zone appears to be overprinted and stitched by the 1.16 Ga Diana syenite (Geraghty et al., 1980; Mezger, 1992), yet it is interpreted as the locus of major thrusting at 1.13–1.1 Ga (Mezger et al., 1992), and of major rifting at 1.1 Ga (Mezger et al., 1993).

4.3. *Accretion at ca. 1.1 Ga?*

From a comparison with the tectonic setting of the Sunda arc, Corriveau (1990) proposed that the northwestern margin of the CMB represents a 1.1 Ga suture associated with southeast dipping subduction (Fig. 2, No. 6 in Fig. 3; however, see Corriveau et al., 1990, 1998). More recently, Culshaw et al. (1997), building on a suggestion by Davidson (1995), interpreted the CMB and the Parry Sound domain as a composite system of magmatic arcs, accreted to the Laurentian margin in two stages associated with southeast directed subduction. Their accretionary model is predicated on: (1) the absence of 1.19–1.16 Ga deformation and high-grade metamorphism in the CGB, but their presence in the rocks to the south; and (2) the absence of high-grade metamorphism in the southern part of the CGB prior to 1.08 Ga. Initial accretion occurred (No. 5 in Fig. 3) when a basin between a composite terrane including the Parry Sound domain and the CMB boundary zone (CMBBZ), already deformed at 1.16 and 1.19 Ga, and the rest of the CGB was occluded at 1.12 Ga. Subsequently, a second accretionary event occurred (No. 6 in Fig. 3) when a basin within the CMB closed at 1.08 Ga, emplacing the CMB over its boundary zone and the Parry Sound domain over the leading edge of the Laurentian cratonic margin. However, structural and geochronological studies have shown that the CMBBZ (Fig. 2) was the locus of thrusting of the CMB, including its internal components, over the CGB at 1.19 Ga, some 100 myears prior to the proposed accretionary events (McEachern, 1990; Hanmer and McEachern, 1992; Milkereit et al., 1992; McEachern and van Breemen, 1993; Pehrsson et al., 1996). Moreover, the southern part of the CGB is known to have experienced granulite facies thrusting and nappe tectonics prior to 1.1 Ga (van Breemen and Davidson, 1990; Nadeau, 1990; Nadeau and Hanmer, 1992).

4.4. *Accretion at ca. 1.03 Ga?*

The Robertson Lake shear zone is located at the boundary of the Sharbot Lake and Mazinaw 'terranes', within the CMB (RLSZ in Fig. 2). In contrast to Easton (1992), Busch et al. (1997) identify that boundary as separating the Elzevir and Frontenac (super) 'terranes'. Busch and van der Pluijm (1996) and Busch et al. (1996a,b) have shown that the shear zone acted as an extensional fault until as late as 0.9 Ga. However, it has an extended history, and was active as a contractional fault at 1.03 Ga (Busch et al., 1997). The latter authors report that titanite ages record a >100 Ma jump across the Robertson Lake shear zone; 1.05–1.0 Ga in the Mazinaw 'terrane', and 1.16–1.14 Ga in Sharbot Lake 'terrane'. Sharbot Lake 'terrane' did not experience the younger 1.03 Ga metamorphic event prevalent in the Mazinaw 'terrane'. Furthermore, the lithologies of Sharbot Lake 'terrane' are mafic to intermediate igneous rocks with marbles, as opposed to the plutonic rocks, clastic sedimentary and mafic volcanic rocks of the Mazinaw 'terrane'. Accordingly, Busch et al. (1997; see also Mezger et al., 1993) interpret the early history of the Robertson Lake shear zone in terms of a cryptic suture (No. 7 in Fig. 3) related to transpressional convergence of the two 'terranes'. However, as above, abrupt juxtaposition of the contrasting rocks may well represent crustal-scale faulting, but need not require the suturing of accretionary terranes per se. For completeness, we note that Hildebrand and Easton (1995) also proposed a suture at the Elzevir–Frontenac boundary on somewhat similar grounds, but their model involved extreme dip–lip displacements at 1.16 Ga (see Davidson and Carmichael, 1997 for detailed discussion).

5. An alternative model: Andean-type margin

5.1. Continental magmatic arcs at ca. 1.45–1.3 Ga

The tectonostratigraphic assemblage comprising the Montauban Group (1.45 Ga), and the La Bostonnais plutonic complex and Mékinac orthogneisses (1.40–1.37 Ga) in the Mauricie area (Fig. 5A), shows a petrological trend evolving from oceanic arc to continental arc affinity (Corrigan, 1995; see also Gauthier, 1993). The La Bostonnais complex and Mékinac orthogneiss, which are part of the continental arc, were intruded into an already deformed Montauban island arc, leading Corrigan and van Breemen (1997) to conclude that the Montauban Group had previously accreted to the continental margin. Accordingly, they proposed that the 1.4–1.37 Ga continental arc was built on the margin of Laurentia, that is, the upper plate of a southeast facing Andean-type margin, associated with northwest dipping subduction (Fig. 5A). The present state of knowledge does not allow determination of the plate geometry prior to 1.4 Ga. However, the presence of extensive juvenile 1.5–1.42 Ga magmatism in the CGB, Ontario (e.g. Dickin and McNutt, 1990; Easton, 1992; Rivers, 1997; Nadeau and van Breemen, 1998), located well inboard of the Mauricie area (Fig. 2), allows the speculation that an (early?) Andean-type geometry may already have been established by that time (see also Dickin and McNutt, 1990; Rivers, 1997). This is also compatible with subduction polarity inferred for the Pinwarian arc in the NW Grenville Province (Wasteneys et al., 1997; Corrigan et al., 2000). If this is valid, then locally preserved 1.45 Ga deformation and metamorphism within the CGB (Tuccillo et al., 1992; Ketchum et al., 1994; Dudas et al., 1994) could represent shortening within the upper plate.

1.35–1.3 Ga tonalite orthogneiss have been identified in the CMBBZ (van Breemen and Hanmer, 1986; Hanmer, 1988b; Lumbers et al., 1990) and the southern Adirondack Highlands (Fig. 2; McLelland et al., 1988). They have been compared with similar coeval rocks from Grenville outliers within the Appalachians of the United States (Chiarenzelli and McLelland, 1991; Ratcliffe et al., 1991; McLelland et al., 1996 and references therein), and interpreted as juvenile arc-related plutons (Fig. 5A; McLelland et al., 1993, 1996; Rivers, 1997). Given the inboard extent of the northwestern part of this younger arc with respect to the older arc rocks of the Mauricie area (Fig. 2), Corrigan (1995) suggested that it represents a migration of the locus of arc development toward the interior of the Laurentian continent, thereby conserving the polarity of subduction toward the northwest that was re-established at 1.4–1.37 Ga.

5.2. Back-arc extension at 1.3–1.2 Ga

Mafic to rhyolitic volcanic rocks of the Grenville Supergroup (i.e. the Tudor, Turriff, Kashwakamak, Harlowe, Grimsthorpe, Belmont Lake, Queensborough, and Canniff groups and complexes; see Easton, 1992; Smith and Harris, 1996) were deposited in the Elzevir 'terrane of the CMB between 1.3 and 1.24 Ga (Figs. 2 and 5B; Silver and Lumbers, 1966; Easton, 1986, 1992; Davis and Bartlett, 1988; Corfu and Easton, 1995; see also Martignole et al., 1994). They are largely flanked to the southeast by the Elzevir plutons

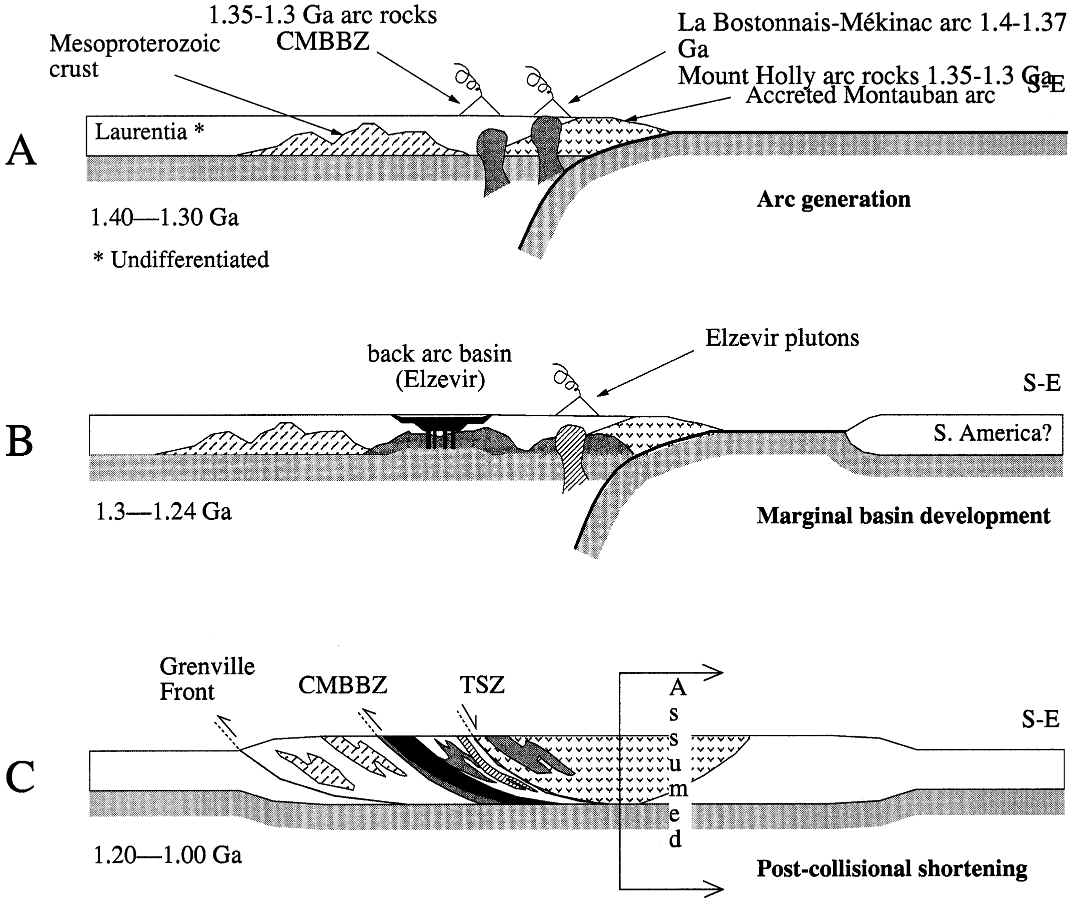

Fig. 5. Schematic sections to illustrate the tectonic evolution of a southeast facing Andean-type Laurentian margin between 1.40 and 1.20 Ga, and its subsequent collisional and post-collisional evolution. CMBBZ, Central Metasedimentary Belt boundary zone; TSZ, Tawachiche shear zone.

(Easton, 1992), a suite of 1.28–1.23 Ga tonalite/trondhjemite and granites of arc affinity (Pride and Moore, 1983; Connelly et al., 1987; Lumbers et al., 1990).

Although some workers have speculated that the volcanic rocks of the Elzevir 'terrane' could represent a fragment of an island arc (Brown et al., 1975; Pride and Moore, 1983; Windley, 1986, 1989; Davidson, 1995; McLelland et al., 1996), petrological studies consistently indicate that they formed in a back-arc basin, developed on thinned continental crust (Fig. 5B; Condie and Moore, 1977; Fletcher and Farquar, 1982; Holm et al., 1986; Smith and Holm, 1987, 1990a,b; Davis and Bartlett, 1988; Harnois and Moore, 1991; DeWolf and Mezger, 1994; Smith and Harris, 1996; Smith et al., 1997). A chain of 1.25–1.23 Ga gabbro bodies, penecontemporaneous with the volcanic rocks, and intruded into Grenville Supergroup carbonates in a tectonically active environment (Pehrsson et al., 1996), marks the present-day upper structural limit of the CMBBZ, a crustal-scale ductile thrust (Fig. 2; Hanmer, 1988b; Hanmer and McEachern, 1992). The gabbros may have formed in, and been thrust out of the back-arc basin when it was finally closed at 1.2 Ga (see below; Hanmer, 1988b; Hanmer and McEachern, 1992; McEachern, 1990; McEachern and van Breemen, 1993; Pehrsson et al., 1996). Pehrsson et al. (1996) suggested that inherited 1.44 Ga zircons within the gabbros were derived from rocks of CGB affinity, which formed the basement to the supracrustal rocks of the CMB (Fig. 5B). This interpretation derives some support from 1.41 Ga inherited zircons in 1.17 Ga granite intruded into the Grenville Supergroup in the Adirondack Lowlands (McLelland et al., 1988, 1997).

We suggest that the 1.35–1.3 Ga tonalites in the CMBBZ, on the northwest side of the volcanic rocks, represent the remnant arc, while the 1.28–1.23 Ga Elzevir plutons to the southeast represent the active arc segment during back-arc basin development (e.g. Hamilton, 1988). This configuration suggests that the associated subduction zone would have dipped to the northwest, as it had for the preceding 150 Ma, at least (Fig. 5; Hanmer et al., 1994; see also Smith and Holm, 1990a,b; Smith et al., 1997). Independent support for this geometry comes from Lambert et al. (1995) who obtained Re–Os and Sm–Nd isotope model ages of 1.2 Ga from the 106 Ma diamond-bearing Prairie Creek lamproites, in Arkansas, significantly younger than the Palaeoproterozoic crust into which they were intruded. Their interpretation calls for the northwestward subduction of lithosphere of Grenville age.

It is generally assumed that the carbonates of the Grenville Supergroup were deposited during this time period, contemporaneously with formation of the volcanic rocks (see Easton, 1992 and references therein). However, unlike reported sequences from recent back-arc and marginal basins (cf. Carey and Sigurdsson, 1984; Clift, 1995; Soja, 1996), most of the marbles of the Grenville Supergroup are remarkably clean, from the CMB boundary thrust zone to the Carthage–Colton mylonite zone. In the CMBBZ and the Adirondack Lowlands, the non-carbonate supracrustal content in the marbles largely consists of tremolite after dolomite, graphitic quartzite after algal mats with trapped quartz sand, and evaporites (see also Easton, 1992, de Lorraine and Sangster, 1997). Davidson (1995) also suggested that nepheline syenites localised along the CMBBZ were derived by metasomatic interaction with evaporites. Accordingly, the carbonates were probably deposited as platformal limestones with quartzites and local sabkha basins, in an extensive shallow shelf sea (Haynes, 1986; de Lorraine and Sangster, 1997). Similar carbonates exist in the Elzevir 'terrane', whereas shallow water quartzites are characteristic of the Frontenac 'terrane' (e.g. Easton, 1992). The salient point here is that a shallow marine environment occupied much of the CMB at some time between 1.3 and 1.23 Ga.

5.3. *Continental collision at 1.2 Ga*

By 1.19 Ga, the marginal basin on the northwest side of the Elzevir arc had closed, and arc magmatism had shut down (Hanmer and McEachern, 1992; McEachern and van Breemen, 1993). The nature of Grenville magmatism underwent a fundamental change from essentially calc-alkaline tonalite to a diverse set of intrusive suites. These range from anorthosite to gabbroic dykes to granite (e.g. Lumbers et al., 1990), and mark a fundamental change in the tectonic setting (Corrigan, 1995). Corrigan and Hanmer (1997) suggested that this represents the evolution of the Grenville from an Andean-type margin to a continent–continent collisional orogen (Fig. 5), significantly earlier than the 1.08–1.05 Ga time frame which other workers had hitherto suggested ('Ottawan orogeny' of authors; e.g. Moore, 1986; see also Windley, 1986, 1989; Rivers et al., 1989; Easton, 1992; McLelland et al., 1996 and references therein). From the arguments advanced above, we would place the site of collision between the Laurentian margin and the southern continent (Amazonia?; e.g. Rivers, 1997), well outboard of the Mauricie area (Fig. 5).

5.4. *Extension and magmatism at 1.16–1.13 Ga*

The CMB had been deformed, thickened and thrust to the northwest by 1.19 Ga (Hanmer, 1988b; Hanmer and McEachern, 1992). Subsequent deformation northwest of the CMB was initially manifested as 1.16 Ga granulite facies ductile thrusting near the base of the Parry Sound domain (PSSZ in Fig. 2; van Breemen et al., 1986; Nadeau and Hanmer, 1992 and references therein; see also Nadeau, 1984). In the Frontenac 'terrane', vertically dipping, NW–SE-striking, Kingston mafic dykes (Easton, 1992) lie adjacent to the amphibolite facies Perth Road mylonite zone (PRMZ in Fig. 2). The 1.16 Ga age (Pehrsson, unpublished data) and orientation of the dykes indicate that this kinematically complex, contractional fault (Barclay, 1985) is approximately contemporaneous with both the Parry Sound and the Maberly shear zones (Fig. 2; Davidson, 1995). From the distribution of their high strain ductile fabrics, all three of these 1.16 Ga shear zones appear to be of limited lateral extent (Davidson, 1984; Barclay, 1985; Easton and Davidson, 1994), which we infer to reflect their arrested development. Note, however, that Davidson (1995, 1998) suggests that the Maberly structure extends cryptically along the CMB into Quebec. If our inference is valid, it suggests that penetrative shortening, transitional to localised flow, was synchronously aborted across a large section of the orogen. Significantly, this would represent a modification in tectonic boundary conditions, immediately prior to the onset of voluminous AMCG magmatism.

At 1.16–1.13 Ga, anorthosite massifs and related granitoids (AMCG) intruded the Adirondack Highlands and their Quebec extension (Fig. 2; Emslie and Hunt, 1990; Doig, 1990; Chiarenzelli and McLelland, 1991). As noted above, contemporaneous thermal and magmatic events also occurred in the northwestern CMB (Elzevir 'terrane') and the CGB. Corrigan and Hanmer (1997) attributed the AMCG suite to convective removal of the subcontinental lithosphere and extension of the crust after lithospheric thickening due to continental collision at 1.2 Ga. They also held the crustal extension accountable for the deposition and/or preservation of the St Boniface sediments in the Mauricie area (1.18 to between 1.15 and 1.09 Ga), and the penecontemporaneous Flinton Group in the Elzevir 'terrane' of the CMB (Fig. 2; Sager-Kinsman and Parrish, 1993). Accordingly, the orogen-wide cessation of crustal shortening, initiation of extension, and magmatic flare-up of diverse provenance, may all be ascribed to a common 1.16–1.13 Ga tectonic event. The salient point here is that this orogenic event straddled the post-1.13 Ga sutures proposed by other workers.

5.5. *Renewed compression at 1.13–1.05 Ga*

After the cessation of widespread AMCG magmatism at 1.13 Ga, the thinned and thermally weakened continental lithosphere would once again have been susceptible to ongoing post-collisional shortening across much of the OQA segment of the Grenville orogen (Corrigan, 1995; Corrigan and Hanmer, 1997). Northwest of the CMB, the Seguin and Moon River thrust nappes (Fig. 2) were penetratively deformed at granulite facies, and emplaced over the Parry Sound klippe prior to 1.1 Ga (Nadeau and Hanmer, 1992; see also Nadeau, 1990; van Breemen and Davidson, 1990). Given that the granoblastic gneisses within the nappe had cooled slowly from granulite to amphibolite facies by that time (Nadeau, 1990; Nadeau and Hanmer, 1992), thrusting itself must have occurred well before 1.1 Ga, possibly coincident with the renewed activity at the base of the Parry Sound shear zone at 1.12 Ga (Wodicka et al., 1996, 2000; see also Timmermann et al., 1997). Westward thrusting at granulite facies also occurred in the Mauricie area during the interval 1.15–1.09 Ga (Corrigan, 1995; Corrigan and van Breemen, 1997), and Mezger et al. (1992) have suggested that the southern margin of the CMB may have been thrust onto the Adirondack Highlands at some time between 1.13 and 1.1 Ga.

In the west, the principal deformation event between 1.12 and 1.05 Ga is represented by the deep crustal thrust reactivation of the CMBBZ (Figs. 2 and 5C), as well as thrusting associated with the uplift of eclogites in the CGB and final emplacement of the Parry Sound domain, all at 1.08–1.05 Ga (Hanmer, 1988b; Hanmer and McEachern, 1992; McEachern and van Breemen, 1993; Indares, 1997; Wodicka et al., 2000). Although Hanmer and McEachern (1992; see also McLelland et al., 1996) ascribed this event to the reactivation of a pre-existing intracontinental crustal-scale weakness zone during continental collision, we would now suggest that it was a response to continued post-collisional convergence (Corrigan and Hanmer, 1997). A recent geochronological study from immediately beneath the CMBBZ has revealed the absence of a 1.2 Ga metamorphic signature in zircon from 1.45 to 1.4 Ga orthogneiss and granitoids (Timmermann et al., 1997). One way of accounting for these data is to propose that the locus of emplacement of the CMB at 1.2 Ga was far removed to the southeast of its current position, such that it had little thermal effect on the present footwall. Accordingly, the data of Timmermann et al. (1997) would be the first firm indication of the relative magnitude of displacement involved during the 1.08–1.05 Ga thrust reactivation of the CMBBZ.

In the east, the east dipping boundary between the bulk of the 1.45–1.37 Ga arcs and the Quebec extension of the Adirondack Highlands in the Mauricie area was reactivated at 1.09–1.06 Ga along the amphibolite facies, oblique-sinistral, Tawachiche extensional shear zone (TSZ in Figs. 2 and 5C; Corrigan, 1995; Corrigan and Hanmer, 1997; Corrigan and van Breemen, 1997). The north-northwest trending Tawachiche shear zone accommodated uplift of the Highlands, at about the same time as northwestward thrusting occurred across the east-northeast striking CMBBZ (Fig. 2). The kinematics of localised 1.08–1.05 Ga tectonic displacements can therefore be resolved as two components related to continued NW–SE post-collisional shortening, partitioned along the pre-existing orogen-scale structural anisotropy (see inset in Fig. 2; e.g. Lister and Williams, 1983). From the foregoing, we conclude that deformation events straddling the inferred post-1.13 Ga sutures in the OQA segment (Figs. 2 and 4) were kinematically linked during the period 1.13–1.05 Ga.

6. Discussion

6.1. Evolving Andean-type margin

The margin of Laurentia exposed in the OQA segment of the Grenville orogen appears to have been the site of accretion of juvenile Palaeoproterozoic crust to the northwest, and new Mesoproterozoic crust to the southeast. While the polarity of subduction may have varied through time (e.g. Rivers, 1997; see also Gower, 1996), the evolution from Montauban oceanic arc to La Bostonnais-Mékinac continental arc signature indicates that northwest dipping subduction beneath Laurentia was re-established by 1.4–1.37 Ga (Fig. 5). We suggest that the Laurentian margin was already transversely contiguous from the Superior Province, via the Appalachian outliers, to the Baie Comeau region at that time. Once a southeast facing convergent Andean-type margin was established at ca. 1.4 Ga, we infer that there was no requirement to alter its fundamental geometry in order to accommodate subsequent tectonic events, until continental collision at 1.2 Ga.

Alternation between compressional and extensional regimes may be a function of variation of the dip of the subducting plate, the ratio of horizontal and vertical vectors (convergence and slab sinking), and hence the migration of the hinge of the subduction zone (e.g. Hamilton, 1988, 1991). This scenario allows for construction of a 1.35–1.3 Ga Andean-type arc on the pre-1.4 Ga margin of Laurentia, splitting of the arc at 1.3 Ga to form a back-arc marginal basin environment, and closure of the basin at 1.2 Ga (Fig. 5B and C; Hanmer and McEachern, 1992; McEachern and van Breemen, 1993). Local evidence of northwestward thrusting at 1.25 Ga within the CMB (Davis and Bartlett, 1988), and at 1.23 Ga at the top of the boundary thrust zone (Pehrsson et al., 1996), could be attributed to subduction hinge migration, and consequent tectonic jostling within the marginal basin environment.

6.2. Orogen-wide events

When considered at the scale of the Grenville orogen, many geological units and events in the OQA segment can be matched and integrated, from the CGB to well east of the Mauricie area, across the CMB boundary thrust zone, Elzevir-Frontenac ‘terrane’ boundary, and the Carthage–Colton mylonite zone (Fig. 2), both before and after periods of tectonic activity on 1.16–1.03 Ga accretionary sutures proposed by other workers. These include: (1) a pre-Grenville Supergroup potential basement, composed of 1.45–1.4 Ga plutonic rocks with Nd model ages of 1.5 Ga and the remnants of a 1.35–1.3 Ga continental arc; (2) shallow water carbonates deposited on this basement between 1.3 and 1.25 Ga; and (3) closure of a marginal basin at 1.2 Ga, interpreted as the effect of continent–continent collision. Furthermore, thrusting leading to thickening, convective removal of continental lithosphere, and consequent extension and widespread magmatic events at 1.17–1.13 Ga, followed by renewed compression at 1.12 Ga and 1.08–1.06 Ga, all attributable to ongoing post-collisional shortening, have left their mark from the CGB to the Mauricie area.

We suggest that these observations indicate that there was no opportunity to accrete new terranes within the OQA segment after ca 1.2 Ga. Indeed, we see no evidence for terrane accretion after docking of the Montauban island arc at 1.4 Ga. Rather, we envisage the Grenville orogen developing by long-lived reworking of the southeast facing, Andean-type margin of Laurentia, which was transformed to a continental collisional orogen at 1.2 Ga. Furthermore, the exposed OQA segment of the Grenville orogen lies entirely within the pre-1.4 Ga Laurentian continental margin.

7. Conclusions

An accretionary terrane model is not required to account for the post-1.4 Ga development of the OQA segment of the Grenville orogen. Geological, geochronological, and petrological data and observations suggest that the principal features and events of the Grenville orogen straddle the proposed 1.16–1.03 Ga terrane boundaries from the CGB to the Mauricie area, east of the Adirondack Highlands. Rather, the southwest Grenville orogen can be explained in terms of: (1) a 1.4–1.2 Ga Andean-type margin to a Laurentian upper plate, associated with northwest dipping subduction; (2) continental collision at 1.2 Ga; and (3) continued post-collisional shortening until ca. 1.0 Ga, without invoking 1.16–1.03 Ga accretionary terrane boundaries, within the exposed Grenville orogen.

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