Precambrian Research 167 (2008) 237–259

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

# Assembly and preservation of lower, mid, and upper orogenic crust in the Grenville Province—Implications for the evolution of large hot long-duration orogens

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ARTICLE INFO

*Article history:*
Received 4 February 2007
Received in revised form 14 July 2008
Accepted 31 August 2008

*Keywords:*
Grenville orogen
Hot wide long-duration orogen
Orogenic plateau
Channel flow
Material focal plane
Orogenic suprastructure
Gravitational collapse

ABSTRACT

It is argued that the Grenville Province is a large hot long-duration orogen with a plateau in the hinterland, remnants of which are preserved in the hangingwall of the Allochthon Boundary Thrust and characterised by metamorphism from ca. 1090 to 1020 Ma (Ottawan phase of the Grenvillian Orogeny). Hinterland rocks are grouped into three tectonic units on the basis of their Ottawan metamorphic signatures, the allochthonous High Pressure Belt, the allochthonous Medium–Low Pressure Belt, and an orogenic lid lacking evidence for penetrative metamorphism. *P–T* and geochronological data indicate Ottawan metamorphism developed under a relatively high geothermal gradient and was followed by slow cooling, compatible with some form of channel flow. Metamorphic rocks in the Parautochthonous Belt in the footwall of the Allochthon Boundary Thrust, also divided into medium and high-pressure units, were metamorphosed from ca. 1000 to 980 Ma (Rigolet phase) under a lower geothermal gradient and underwent rapid cooling. Their evolution is interpreted to record advance of the orogen into its former foreland after channel flow had ceased. The Allochthon Boundary Thrust is thus a material focal plane separating high-grade rocks derived from opposite sides of the orogen metamorphosed at different times under different *P–T–t* gradients. Preservation of the Orogenic Lid and low pressure segments of the allochthonous Medium–Low Pressure Belt is a result of gravitational collapse of the orogenic plateau, initiated in late Ottawan time, and the formation of a crustal-scale horst-and-graben architecture. This study emphasises the importance of gravitational collapse during the prolonged compressional phase, a feature not presently accommodated in numerical models of large hot long-duration orogens.



## 1. Introduction

Advances in field mapping and integrated petrological, isotopic, and geochronological techniques have contributed to improved understanding of high-grade gneiss terranes such as those that underlie much of the Grenville Province. They are no longer seen as intractable 'seas of gneiss', but rather as information repositories on the history and evolution of the mid and lower orogenic crust. The success in documenting the tectonic history of the Grenville Province using these techniques has led to the informal suggestion that it is an ideal natural laboratory to analyse mid-crustal processes. Although not unsympathetic to this view, one of the aims of this paper is to point out that there is in fact a wide range of levels of orogenic crust preserved in the Grenville Province, including lower-crustal eclogite, mid-crustal migmatite and upper-crustal schist terranes, and an orogenic lid that largely escaped penetrative Grenvillian deformation and metamorphism. Moreover, Grenvillian metamorphism took place at different times and under different thermal regimes throughout the orogen. Once this diversity in preserved crustal levels is recognised and the temporal and spatial distribution of metamorphic rocks understood, it becomes possible to more realistically reconstruct the architecture of the orogenic crust and model its evolution.

Understanding of crustal-scale orogenic evolution in general has been significantly informed by numerical modelling experiments, including the conceptually elegant proposal that the magnitude and thermal regime of collisional orogens are related to the duration of collision (Beaumont et al., 2001a,b, 2006). Using an analogy with the temperature–magnitude diagram for stars, Beaumont et al. (2006) proposed a 'main sequence' between small cold short-duration orogens (denudation dwarfs) and large hot long-duration orogens (giants and super giants). In the former the crust remains relatively cool, whereas prolonged heating in the latter gives rise to an orogenic plateau beneath which the viscosity of the crust

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doi:10.1016/j.precamres.2008.08.005

becomes sufficiently low to flow under gravitational or tectonic forcing, giving rise to channel flow or hot nappes. The evidence is overwhelming that the Grenville Province is a candidate for a large hot long-duration orogen since: (i) it is >600 km wide (minimum estimate since the southeast margin was rifted away in the Neoproterozoic); (ii) much of the interior is underlain by Grenvillian upper amphibolite- and granulite-facies rocks implying it was hot; and (iii) collisional orogenesis continued for >100 My, from ca. 1090 to 980 Ma. These observations suggest that the Grenville Province was part of a giant or super giant orogen and the first comparisons between numerical experiments of large hot long-duration orogens and the crustal architecture of the Grenville Province were published recently (Jamieson et al., 2007). A second aim of this paper is to explore this interpretation in more detail.

## 2. Timing of the Grenvillian Orogeny and tectonic subdivision of the Grenville Province

### 2.1. Timing of regional Grenvillian metamorphism

Tollo et al. (2004) reviewed several schemes pertaining to the age limits of the Grenvillian Orogeny. Fig. 1 represents an integration of the proposals of Rivers (1997) and Gower and Krogh (2002) in which the collisional Grenvillian Orogeny is distinguished from the mid to late Mesoproterozoic Elzevirian and Shawinigan orogenies, the effects of which are restricted to accreted terranes in the southwestern Grenville Province. The Grenvillian Orogeny is defined as a late Mesoproterozoic to early Neoproterozoic collisional event between Laurentia and another continent (probably Amazonia; e.g., Hoffman, 1991; Cawood and Pisarevski, 2006; Tohver et al., 2006; Li et al., 2008) that took place from ca. 1090 to 980 Ma. Grenvillian orogenesis was diachronous however, being earlier in the orogenic core (ca. 1090–1020 Ma) than along the northwestern margin (ca. 1000–980 Ma), the two regions being separated by the crustal-scale Allochthon Boundary Thrust (Rivers et al., 1989). In order to emphasise this spatial and temporal duality, the metamorphisms are referred to as the Ottawan and Rigolet orogenic phases of the Grenvillian Orogeny respectively.

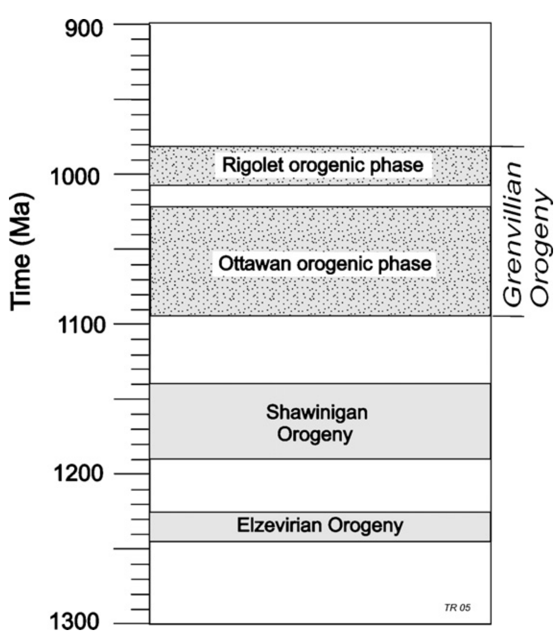


**Fig. 1.** Time scale showing middle to late Mesoproterozoic, pre-Grenvillian accretionary events and the late Mesoproterozoic to early Neoproterozoic, collisional Grenvillian Orogeny (after Rivers et al., submitted for publication). The Grenvillian Orogeny is subdivided into the temporally and spatially distinct Ottawan and Rigolet orogenic phases.

### 2.2. Tectonic subdivision of the Grenville Province

Geological mapping and geophysical sounding have shown the Grenville Province is a crustal-scale stack formed during thrusting and modified by later extension. It is composed of >1.3 Ga reworked Laurentian crust and two mid to late Mesoproterozoic (≤1.3 Ga) belts of accreted rocks in the southwest Grenville Province, the Composite Arc and Frontenac-Adirondack belts, that were accreted to Laurentia prior to the Grenvillian Orogeny (e.g., Davidson, 1984; Rivers et al., 1989; Carr et al., 2000; Fig. 2a). The first-order Grenvillian orogenic architecture is defined by the tectonostratigraphy of the imbricated crust and division into a small number of belts on the basis of the age and character of their Grenvillian metamorphism is shown in Fig. 2b. The boundaries between the belts, which are ductile shear zones a few hundred metres to a km or more in width, are predominantly SE-dipping and exhibit evidence for compressional or transpressional kinematics prior to local extensional or transtensional reworking. The belts themselves are subdivided into lithotectonic terranes and domains that are also bounded by shear zones.

The Grenville Front and the Allochthon Boundary Thrust are crustal-scale boundaries that can be traced along the length of the Grenville Province (Fig. 2b). The Grenville Front is a moderately dipping, compressional or transpressional structure that approximately coincides with the northwestern limit of penetrative Grenvillian deformation. It is defined by shear zones with variably mylonitic fabrics and is the site of a change in metamorphic grade that may be either gradual or abrupt, but it does not mark a profound lithological boundary indicating that cumulative displacement on it was limited (a few tens of km). In terms of the Grenvillian Orogeny, it is a young structure that developed at ca. 1000 Ma (Krogh, 1994; i.e., Rigolet orogenic phase).

The Allochthon Boundary Thrust is a gently dipping, high-grade shear zone southeast of (structurally above) the Grenville Front. It is ≥1 km wide and marks a major lithological break (e.g., Rivers et al., 1989; Ketchum and Davidson, 2000) implying it is the site of substantial, but unquantified displacement (hundreds of km?). Where studied in detail, it has a complex kinematic signature comprising an early phase of compression overprinted by later extension (e.g., Ketchum et al., 1998). Metamorphic grade in its hangingwall attained granulite and eclogite facies during compression, whereas it was upper amphibolite facies during later extension. Initiation of compressional displacement took place at or before ca. 1060 Ma (probably ca. 1090 Ma in the western Grenville Province; Ketchum and Krogh, 1997, 1998; Wodicka et al., 2000), whereas extensional reworking occurred at ca. 1020 Ma (i.e., early and late Ottawan respectively; Culshaw et al., 1997; Carr et al., 2000; Indares et al., 2000).

The Grenville Front and Allochthon Boundary Thrust are the principal boundaries to the tectonic belts in Fig. 2b. On an orogenic scale, the Grenville Front is the floor thrust of the Parautochthonous Belt, which is characterised by lithologic linkage with the foreland and metamorphism during the Rigolet orogenic phase from ca. 1000 to 980 Ma. The southeasterly limit of the Parautochthonous Belt, the Allochthon Boundary Thrust, is the floor thrust of a stack of overlying allochthonous belts, so called because they lack obvious lithological linkage with the underlying parautochthonous units suggesting they are far-travelled. Metamorphism in terranes above the Allochthon Boundary Thrust took place during the Ottawan orogenic phase from ca. 1090 to 1020 Ma.

With respect to terminology, Rivers et al. (2002) identified several terranes with high-pressure (≥1400 MPa) signatures of

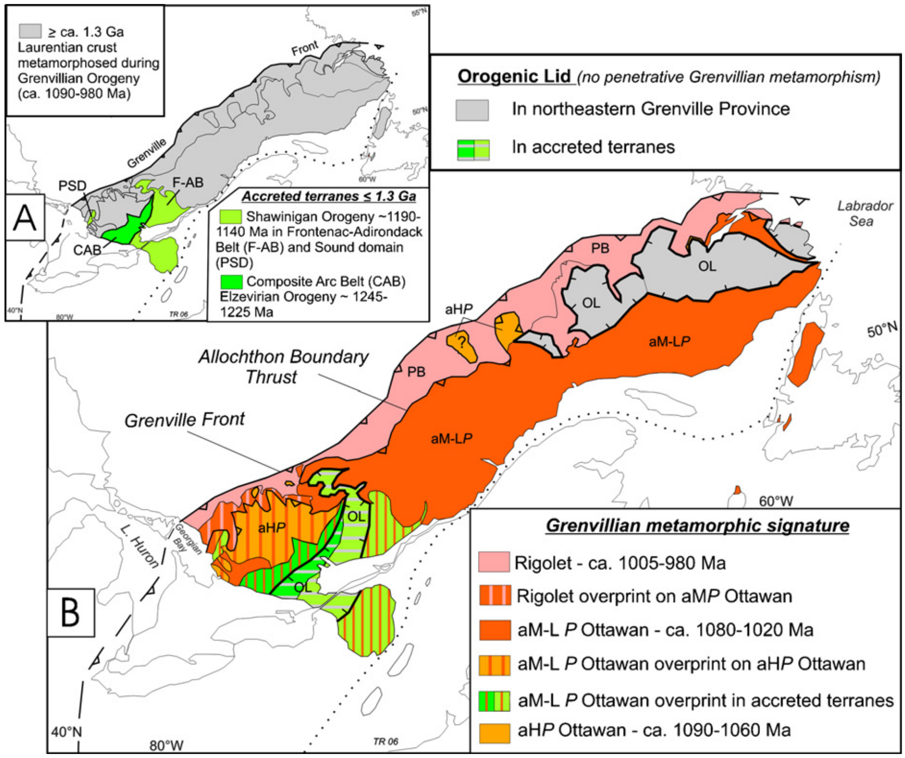


**Fig. 2.** Tectonic subdivisions of the Grenville Province: (A) distribution of reworked Laurentian crust and late Mesoproterozoic accreted terranes; (B) subdivision of the Grenville Province into belts on the basis of the time and baric character of Grenvillian metamorphism. aHP Belt—allochthonous High Pressure Belt, aM-LP Belt—allochthonous Medium to Low Pressure Belt, OL—Orogenic Lid, PB—Parautochthonous Belt (modified from Rivers et al., submitted for publication).

Ottawan age in the central and western Grenville Province directly overlying the Allochthon Boundary Thrust that they referred to collectively as the HP Belt. However, more recent work has shown that this belt is composed of two HP units situated back-to-back across the Allochthon Boundary Thrust, a structurally higher unit at the base of the allochthonous belts in which the HP metamorphism is of Ottawan age and a structurally lower unit at the top of the Parautochthonous Belt in which the HP metamorphism is of Rigolet age. In order to distinguish them and remain consistent with existing terminology, they are referred to as the allochthonous (aHP) and parautochthonous (pHP) segments of the HP Belt here.

Extending this scheme, the allochthonous belts overlying the Allochthon Boundary Thrust are subdivided into the aHP segment, noted above, and a structurally overlying Medium to Low Pressure (aM-LP) Belt characterised by granulite-, amphibolite- and locally greenschist-facies assemblages (Rivers et al., submitted for publication). It is likely that the aM-LP Belt will be subdivided into discrete MP and LP segments with more detailed mapping, but lacking the necessary data they are grouped together here. As indicated, the majority of data indicate that metamorphism in the allochthonous belts was Ottawan, but a few ages in the range ca. 1020–980 Ma have been recorded from two LP areas (not shown on Fig. 2b), indicating local metamorphism in the hinterland temporally overlapping with the Rigolet orogenic phase at the orogen margin. The extent and significance of this latter event remains poorly understood and is discussed later.

Recognition of the Orogenic Lid as a discrete tectonic element is relatively recent (Rivers and Indares, 2006; Rivers et al., submitted for publication). It lies structurally above the Allochthon Boundary Thrust and is distinguished from the underlying aM-LP Belt by its lack of evidence for penetrative Ottawan metamorphism. As discussed below, it is interpreted to comprise part of the cool, brittle suprastructure of the Ottawan orogenic crust that was subsequently dropped down on extensional faults to the same level as the aM-LP Belt. In the next section, evidence to support this tectonic subdivision is provided. More detail is provided for the aM-LP Belt and the Orogenic Lid, which are recently recognised tectonic elements that have not been described previously.

## 3. Belt characteristics

This section focusses on the Grenvillian metamorphic characteristics of the belts, especially the signatures of monocyclic units that experienced only Grenvillian metamorphism. Information on assemblages, estimated peak pressures and temperatures (i.e., $P$ at peak $T$), geochronological data and references are summarised in Tables 1–4; locations of areas discussed are shown in Fig. 3.

### 3.1. Parautochthonous Belt

The general characteristics of the Parautochthonous Belt were discussed by Rivers et al. (1989). Its northwestern boundary, the Grenville Front, is the site of a shear zone with reverse-sense kinematics, the truncation of several Proterozoic platformal sequences in the foreland, and an increase in the grade of Grenvillian metamorphism to the southeast. In Fig. 3, the Parautochthonous Belt is subdivided into pMP and pHP segments. Details of assemblages and references to original studies are given in Table 1.

In the western Parautochthonous Belt, peak Grenvillian $P$–$T$ in pMP amphibolite-facies and pHP granulite-facies assemblages in the Grenville Front Tectonic Zone ranged from ca. 600 MPa/700 °C to 1500 MPa/800 °C respectively. In the central Parautochthonous Belt, the peak Grenvillian $P$–$T$ ranged from ca. 600 MPa/450 °C to 1400 MPa/800 °C in the pMP fold-thrust belt in the Gagnon terrane, and from ca. 1400 MPa/750 °C to 1800 MPa/850 °C in the overlying pHP Molson Lake terrane. Assuming they are representative of the

**Table 1**
Assemblages, *P–T* estimates, and age of Grenvillian metamorphism in terranes and domains of the Parautochthonous Belt

| Location/tectonic setting | Lithology | Assemblage | Metamorphic facies; peak *P–T* | Age of peak metamorphism and cooling | Reference |
|---|---|---|---|---|---|
| SE of Killarney, Georgian Bay (Ontario) GFTZ | Garnet amphibolite | *Grt-Pl-Hbl-Bt-Qtz-Ilm-Spl* | ≥1100 MPa/750 °C | ca. 990–980 Ma [*Zrn*]. $^{40}$Ar/$^{39}$Ar *Hbl* ages from 980–960 Ma | Culshaw et al. (1991, 1997), Haggart et al. (1993), Krogh (1994), Jamieson et al. (1995), Reynolds et al. (1995) |
| Between Killarney and Sudbury (Ontario) GFTZ | Metabasite | *Grt-Cpx-Pl-Opx-Qtz-Hbl-Spl* | 630 MPa/710 °C ca. 7 km SE of GF, 830 MPa/730 °C ca. 16 km SE of GF | ca. 1 Ga overgrowths of metamorphic *Zrn* on igneous *Bdy* | Davidson and van Breemen (1988), Bethune (1997), Bethune and Davidson (1997) |
| Key Harbour, central Britt domain, Parautochthonous Belt south of GFTZ | Metapelite and metabasite | Metapelite: *Ky-Sil-Kfs-Grt-Pl-Bt-Qtz*; Metabasite: *Opx-Cpx-Grt* coronas separating primary *Opx* and *Pl*; *Grt-Cam-Pl* amphibolite in shear zones | Peak: HP granulite facies, retrograde: amphibolite facies | ca. 1035 Ma for metapelite [2 mg *Mnz*]; 1015 + 16/-17 Ma for leucosome [*Zrn* LI]; ca. 990 Ma for post-tectonic pegmatite [*Zrn* UI]; ca. 1003, 980–965 Ma [mg *Ttn*] | Corrigan et al. (1994) |
| Southern GFTZ and northern Britt domain | Metabasite, coronitic, foliated and granoblastic | *Grt-Hbl-Pl* ± *Qtz* ± *Cpx* ± *Opx* ± *Bt* ± *Ilm* ± *Mt* | Upper amphibolite facies: Peak: 1380 MPa/870 °C, 1260 MPa/840 °C, 1100 MPa/750 °C. Retrograde: 810 MPa/780 °C, 900 MPa/680 °C | $^{40}$Ar/$^{30}$Ar *Hbl* ages ca. 975–965 Ma; $^{40}$Ar/$^{30}$Ar *Ms* ages ca. 925–905 Ma | Culshaw et al. (1991), Jamieson et al. (1995) |
| SE of Val d'Or (W. Québec) GFTZ | Metabasite | *Grt-Cpx-Pl-Opx-Qtz-Hbl* | HP granulite facies: 1200–1500 MPa/800° to 900 MPa/700 °C | ca. 1 Ga [*Mnz*] $^{40}$Ar/$^{30}$Ar *Hbl* ages ca. 995 Ma | Childe et al. (1993), Martignole and Reynolds (1997), Martignole and Martelat (2005) |
| Gagnon terrane (near MIZ, E. Québec). MFTB | Metapelite | *Qtz-Ms-Bt-Grt-Ky-Kfs-Pl-L* | Granulite: ca. 1400 MPa/>800 °C | 995–985 Ma (*Mnz*), 960–950 Ma (*Ttn*) | Indares (1995), Jordan et al. (2006) |
| Gagnon terrane (near Wabush, W. Labrador) MFTB | Metapelite | *Qtz-Ms-Bt-Grt-Ky-Pl-L* | Lower to upper amphibolite: Upper amphibolite: ca. 600 MPa/450 °C 10 km SE of GF to ca. 1100 MPa/750 °C 30 km SE of GF | ca. 1006 ± 19 Ma [*Mnz* concordia age]. Foliated, locally cross-cutting *Hbl-Grt-Cpx* granite dyke—995 Ma [2 almost concordant mg *Zrn*]. $^{40}$Ar/$^{39}$Ar *Hbl* ages ca. 960–940 Ma. | Rivers (1983a,b), Dallemyer and Rivers (1983), van Gool (1992), Rivers et al. (1993, 2002), Schwarz (1998), van Gool et al. (2008), Cox and Rivers (in press) |
| Molson Lake terrane (E. Québec-W. Labrador) MFTB | Coronitic metagabbro, meta-granite | Cores of gabbroic bodies: *Grt-Omp-Ky* ± *Pl* ± *Prg* ± *Crn* Rims of gabbroic bodies: *Grt-Cpx- Hbl-Pl-Qtz* ± *Ep* | Eclogite facies: NW: 1400 MPa/750 °C; SE: 1800 MPa/850 °C Amphibolite facies overprint: 1200–1400 MPa/750–850 °C | ca. 1005 Ma [*Zrn* lower intercept, concordant *Ttn*] | Rivers and Mengel (1988), Connelly and Heaman (1993), Connelly et al. (1995), Indares and Rivers (1995) |
| Groswater Bay terrane; Smokey Archipelago (E. Labrador) RFZ | Mafic to intermediate orthogneiss | *Grt-Hbl-Bt-Pl-Qtz* | Middle amphibolite facies: *T*–560–630 °C, *P* - not determined | ca. 1040–1030 Ma [*Zrn* lower intercepts] | Owen et al. (1986, 1988), Krogh et al. (2002) |

Uncertainties on *P–T* estimates are ±100 MPa and ±50 °C; analytical uncertainties on U–Pb ages are ≤5 My except where stated.
*Abbreviations:* GF—Grenville Front; GFTZ—Grenville Front Tectonic Zone; MFTB—metamorphic fold-thrust belt; RFZ—reverse fault zone. *Bdy*—baddeleyite, *Bt*—biotite, *Cam*—clinoamphibole, *Cpx*—clinopyroxene, *Crn*—corundum, *Ep*—epidote, *Grt*—garnet, *Hbl*—hornblende, *Ilm*—ilmenite, *Kfs*—K feldspar, *Ky*—kyanite, *L*—leucosome (granitic liquid), *Mnz*—monazite, *Ms* – muscovite, *Omp*—omphacite, *Opx* – orthopyroxene, *Pl*—plagioclase, *Prg*—pargasite, *Qtz*—quartz, *Spl*—spinel, *Ttn*—titanite, *Zrn*—zircon.

**Table 2**
Assemblages, $P$–$T$ estimates, and age of Grenvillian metamorphism in terranes of the Allochthonous High Pressure Belt

| Location | Lithology | Assemblage | Peak $P$–$T$ | Age of metamorphism | Reference |
|---|---|---|---|---|---|
| Lac Dumoine terrane | Metagabbro | *Grt-Pl-Prg-Crn-Ky-Spl* symplectite | 1350 MPa/720 °C (retrograde) | ca. 1069 Ma [UI, 3 mg *Zrn*] | Indares and Dunning (1997) |
| Shawanaga domain | Metagabbro | *Grt-Pl-Prg-Crn-Spr-Ky-Spl* symplectite; rare relict *Omp* | Peak eclogite $P$–$T$ not determined; ca. 1100 MPa/830 °C at ca. 1080 Ma; ca. 500 MPa/580 °C at ca. 1020 Ma | Eclogite facies: ca. 1120 Ma, 1090–1050 Ma [mg *Zrn*]; <ca. 1085 Ma ages reflect post-peak $P$ granulite-facies metamorphism; extension at ca. 1020 Ma | Grant (1989), Davidson (1990), Ketchum and Krogh (1997, 1998), Ketchum et al. (1998), Wodicka et al. (2000), Jamieson et al. (2003) |
| Manicouagan Imbricate Zone | Metagabbro, meta-anorthosite | *Grt-Omp-Ky* ± *Pl* ± *Prg* | 1700–1900 MPa/750–920 °C | 1060–1040 Ma [mg *Zrn*]; extension at ca. 1015 Ma | Indares (1997, 2003), Cox et al. (1998), Indares et al. (1998), Cox and Indares (1999a,b), Yang and Indares (2005) |

Uncertainties on $P$–$T$ estimates are ±100 MPa and ±50 °C; analytical uncertainties on U–Pb ages are ≤5 My except where stated.
*Abbreviations*: mg—multi-grain analysis; UI – upper intercept on concordia. *Crn*—corundum, *Grt*—garnet, *Ky*—kyanite, *Omp*—omphacite, *Pl*—plagioclase, *Prg*—pargasite, *Spl*—spinel, *Spr*—sapphirine, *Zrn* - zircon.

range of Grenvillian metamorphic grade in the Parautochthonous Belt, these results indicate that lower-crustal rocks derived from depths of ca. 40 to 50 km structurally overlie mid-crustal rocks that underwent metamorphism at depths of ca. 16–30 km.

With respect to the age of Grenvillian metamorphism in the Parautochthonous Belt, metamorphic zircon and monazite generally yield ages of ca. 1005–980 Ma (Table 1). However, a more complex picture has been determined locally in the western Grenville Province in Ontario where Ottawan (ca. 1035 Ma) high-grade metamorphism preceding the Rigolet overprint has been recorded locally, and in western Québec the presence of relict Archean ages south of the Grenville Front indicates that conditions appropriate for growth of metamorphic zircon and monazite were not universally achieved. Hornblende $^{40}Ar/^{39}Ar$ plateau ages of ca. 990–940 Ma throughout the Parautochthonous Belt indicate the time of cooling through ca. 480–500 °C, the relatively small difference between U–Pb (zircon, monazite) and $^{40}Ar/^{39}Ar$ (hornblende) ages pointing to fast cooling after attainment of peak Rigolet metamorphic conditions.

In summary, these data indicate the Parautochthonous Belt was incorporated into the Grenville Orogen late its evolution. The lithological linkage with the foreland, the relatively low temperature of the Grenvillian metamorphism and the small difference between U–Pb (zircon, monazite) and $^{40}Ar/^{39}Ar$ (hornblende) ages suggest that it was derived from cool Laurentian crust that underwent rapid burial, heating and exhumation near the orogen margin, all features that contrast with metamorphism in the allochthonous terranes above the Allochthon Boundary Thrust described below.

### 3.2. The allochthonous High Pressure segment

The allochthonous High Pressure (aHP) segment of the HP Belt is composed of large nappes derived from pre-1.3 Ga Laurentian crust situated in the immediate hangingwall of the Allochthon Boundary Thrust. The nappes principally occur in two areas of the western and central Grenville Province where they exhibit different preservation. In the west (Algonquin–Lac Dumoine terrane, Shawanaga domain; Fig. 3), relict eclogite occurs as disaggregated pods and lenses of mafic rocks that were pervasively overprinted by granulite-facies assemblages at ca. 1085 Ma (Bussy et al., 1995; Slagstad et al., 2004), whereas in the centre (Manicouagan Imbricate Zone) mafic intrusions, although folded and dissected by shear zones, are less severely dismembered and preserved eclogite is widespread. In both areas, the upper parts of the nappes were reworked in extension (Ketchum et al., 1998; Indares et al., 2000).

In Algonquin–Lac Dumoine terrane of the western Grenville Province, relict eclogite-facies assemblages comprise texturally complex retrograde intergrowths (Table 2), the rarity of omphacite has precluded the determination of peak $P$–$T$, and metamorphic zircon has yielded ages ranging from ≥1090 Ma, interpreted as the approximate time of eclogite-facies metamorphism, to 1085–1050 Ma, the time of the granulite-facies overprint. In contrast in the Manicouagan Imbricate Zone, central Grenville Province, eclogite assemblages occur in both coronitic and granoblastic rocks for which peak $P$–$T$ estimates are 1700–1900 MPa/750–900 °C prior to their decompression to HP granulite-facies assemblages, and HP metamorphism has been dated at 1060–1040 Ma (Table 2).

Considering the data from both areas, it is apparent that metamorphism and transport of the aHP nappes into the mid crust was diachronous over the interval ≥1090–1050 Ma, with their location in the hangingwall of the gently dipping Allochthon Boundary Thrust indicating they are far-travelled. The peak $P$ estimates of 1700–1900 MPa for eclogite from the central Grenville Province imply that aHP metamorphism took place at 50–60 km depth, presumably near the base of the doubly thickened orogenic crust. The associated high $T$ (800–900 °C) is characteristic of crustal eclogite formed in the roots of continental collision zones (Carswell, 1990).

### 3.3. The allochthonous Medium to Low Pressure Belt

The allochthonous Medium to Low Pressure (aM-LP) Belt extends the full length of the interior Grenville Province from Georgian Bay to the Labrador Sea. It principally consists of upper-amphibolite- and granulite-facies terranes and domains that have undergone MP (ca. 1000 ± 200 MPa) metamorphism, but several LP (≤ca. 600 MPa) domains are known although their limits are not everywhere well defined and as a result they are not separated in Fig. 3. At this stage, the pressure distinction between MP and LP metamorphism is one of convenience based on the majority of available data. The aM-LP Belt is situated above the Allochthon Boundary Thrust and structurally overlies the aHP segment where the latter is present. It is composed of pre-1.3 Ga Laurentian crust and parts of the ≤1.3 Ga accreted terranes (Fig. 2), both of which underwent regional metamorphism during the Ottawan orogenic phase. Locations discussed in the text are shown in Fig. 3, assemblages, $P$–$T$ and geochronological data are summarised in Table 3. As this belt is described for the first time here, additional details are given in Supplementary data (Appendix 1).

**Table 3**
Assemblages, *P–T* estimates, and age of Grenvillian metamorphism in terranes of the allochthonous Medium to Low Pressure Belt

| Location MP/LP | Lithology | Assemblage | Facies/peak *P–T* | Age of metamorphism and cooling | Reference |
|---|---|---|---|---|---|
| Lake Melville terrane MP | Metapelite | *Qtz-Grt-Bt-Ky-Sil-Kf-L* | Granulite and upper amphibolite facies; 800 MPa/820 °C | ca. 1088–1046 Ma [3 sg *Mnz*] | Corrigan et al. (2000) |
| Pinware terrane MP | Meta-granite, pegmatite | | Upper amphibolite facies | ca. 1036–1020 Ma [mg *Zrn*] | Wasteneys et al. (1997), Gower and Krogh (2002) |
| Natashquan domain: Aguanish & Buit Complexes: LP (-MP?) | Granitoid gneiss, amphibolite, metagabbro; metapelite, quartzite (WG) | Metapelite, Buit Cplx: *Qtz-Crd-Grt-Ath; Qtz-Ms-Grt-Bt-And ± St ± Sil* | Mid to upper amphibolite facies; 350 MPa/550 °C | Buit Cplx: ca. 1059, 1058, 1055, 1045 Ma [4 mg *Rt*]. Buit Cplx: ca. 972 and 938 Ma [sg *Ttn*]; ca. 997, 999, 1005, 1008 Ma [sg *Mnz*]. Aguanish Cplx: ca. 1010–990 Ma [sg *Mnz* & *Ttn*]. | Madore et al. (1999), Gobeil et al. (2003), Wodicka et al. (2003) |
| Natashquan domain: LP Boulain cplx | Granitic and tonalitic gneiss, gabbro | | Amphibolite facies | ca. 1028 Ma [sg *Mnz*] | Gobeil et al. (2003), Wodicka et al. (2003) |
| Natashquan domain: LP Kataht suite | Rapakivi granite, *Qtz-Fsp* porphyry | | Amphibolite facies | 1021 ± 20 Ma [LI, sg and mg *Zrn*]; ca. 1028, 1013, and 1004 Ma [mg *Ttn*] | Gobeil et al. (2003), Wodicka et al. (2003) |
| Natashquan domain: La Romaine segment MP? | Metamorphosed felsic volcanic rocks, quartz arenite and pelite (correlated with WG) | | Amphibolite facies | ca. 1019 Ma [*Zrn* rims]; ca. 1010–1000 Ma [3 sg *Mnz*]; ca. 989 ± 11 Ma [Av. of 3 mg *Ttn*] | Bonnet et al. (2005); van Breemen and Corriveau (2005) |
| St-Jean domain MP | Metapelite and metabasite | Metapelite: *Qtz-Kf-Grt-Sil-Bt ± Gr* Metabasite: *Opx-Cpx-Pl-Grt* | Granulite to upper amphibolite facies | Metapelite: ca. 1099–1046 Ma [8 sg *Mnz*]; ca. 1077–1056 Ma [3 sg *Zrn*]; ca. 956–940 Ma [2 sg *Rt*]. Metabasite: ca. 1099–1081 Ma [4 mg *Zrn*] | Gobeil et al. (2003), Wodicka et al. (2003) |
| Berthé terrane MP | Metapelite and metabasite | *Qtz-Pl-Grt-Sil-Kf-Bt-L*; *Opx-Cpx-Pl-Grt* | Upper amphibolite to granulite facies; 1000–1100 MPa/800–900 °C. | Metapelite: ca. 1050 Ma [2 sg *Mnz*]. Metabasite: ca. 1045–1040 & 1013 Ma [mg *Zrn*] | Indares and Dunning (2004) |
| Mékinac–Taureau terrane MP | Paragneiss Pegmatite | *Spr-Opx-Sil-Crd-Pl ± Grt-Bt-Crn* | Peak: 1150 MPa/900 °C; Retrograde: 700 MPa/725 °C | Syntectonic pegmatite ca. 1087 Ma; post-tectonic pegmatite ca. 1050 Ma | Herd et al. (1986), Corrigan and van Breemen (1997) |
| Portneuf–St-Maurice LP | Paragneiss Pegmatite | *Opx-Ath-Crd-Bt-Pl; Crd-Spl-Grt-Sil-Qtz* | LP granulite to upper amphibolite facies: 500–600 MPa/750 °C | Syntectonic pegmatite ca. 1056 Ma | Corrigan and van Breemen (1997) |
| Composite Arc Belt boundary thrust zone MP | Quartzofeldspathic gneiss and amphibolite | | Upper amphibolite to granulite facies | ca. 1090–1050 Ma | Hanmer and McEachern (1992), McEachern and van Breemen (1993), Timmermann et al. (1997), Carr et al. (2000) |
| Mazinaw terrane | Amphibolite-facies pelitic schist | *Metamorphic field gradient with Ctd-St, St-And, St-Ky, Sil-Ms zones* | Mid-amphibolite facies: 350 MPa/500 °C to 500 MPa/650 °C | Northwest: Syntectonic pegmatite (2) ca. 1079–1063 Ma [mg *Zrn*]; calc-silicate 1094 Ma [sg *Zrn*]; 960–940 [mg *Rt*]; 1067 [mg *Ttn*] Central: Felsic volcanic ca. 1036 Ma [mg Zrn]; 995 Ma [mg *Ttn*] pelitic schist ca. 1022–1025 Ma [mg *Zrn*, mg *Mnz*] 1090–1050 | Moore and Thompson (1980), Corfu and Easton (1995) |
| Muskoka domain (incl. Moon River and Seguin domains) MP | Metabasite, abundant migmatite | *Opx-Cpx-Pl-Grt ± Cam* in mafic units; *Qtz-Pl-Kfs-Bt ± Grt-L* in felsic units | Granulite facies with upper amphibolite facies overprint: 1000–1150 MPa/750–850 °C | Granulite facies: ca. 1080–1050 Ma [sg and mg *Zrn*]; amphibolite facies: ca. 1044 Ma [mg *Ttn*]; ca. 980–960 Ma $^{40}Ar/^{39}Ar$ *Hbl* ages | Annovitz and Essene (1990), Cosca et al. (1991), Culshaw et al. (1997), Timmermann et al. (1997, 2002), Slagstad et al. (2004) |
| Morin terrane L-MP | Metapelite and metabasite; skarn; pegmatite | *Bt-Grt-Pl-Sil-Kf-Qtz; Opx-Qtz-Pl-Grt; Cal-An-Wo-Grs-Qtz-Ves-Gr.* | Granulite facies: 600–800 MPa/800–700 °C | Late pegmatite ca. 1070 Ma; ca. 1040 Ma $^{40}Ar/^{39}Ar$ *Hbl* ages | Indares and Martignole (1990), Martignole and Pouget (1994), Martignole and Reynolds (1997), Martignole and Friedman (1998), Peck et al. (2005) |

| | | | | | |
|---|---|---|---|---|---|
| Adirondack Highlands terrane MP | Metapelite and metabasite | *Qtz-Kf-Sil-Crd-Spl-Grt; Prs-Kf-Pl-Qtz-Tur-Crd-Grt; Grt-Pl-Opx-Cpx-Qtz* ± *Hbl* | Granulite and upper amphibolite facies: 700–800 MPa/800–915 °C | ca. 1050 Ma [mg *Zrn*]; ca. 1033 Ma [mg *Mnz*]; 996 ± 17, 990 ± 22 [Zrn rims]; 998 ± 4 [Mnz]; 1030–991 Ma [4 sg *Ttn*]; ca. 885 Ma [mg *Rt*] | Mezger et al. (1991), McLelland et al. (1996, 2001), Spear and Markussen (1997), Alcock et al. (2004), Darling et al. (2004), Heumann et al. (2006), Bickford et al. (2008) |
| Blair River inlier MP? | Metabasite, metapelite | | Granulite facies | ca. 1040 Ma | Miller et al. (1996) |
| Long Range inlier MP? | Metabasite | | Granulite and amphibolite facies | Granulite: pre-1032 Ma; amphibolite: pre-1022 Ma [mg *Zrn*] | Heaman et al. (2002) |

Uncertainties on *P–T* estimates are ±100 MPa and ±50 °C; analytical uncertainties on U–Pb ages are ≤5 My except where stated.
*Abbreviations*: sg—single grain analysis, mg—multi-grain analysis; cplx—complex; LP and MP—low pressure and medium pressure segments of M-LP Belt; WG—Wakeham Group. *An*—anorthite, *And*—andalusite, *Ath*—anthophyllite, *Bt*—biotite, *Cal*—calcite, *Cam*—calcic amphibole, *Cpx*—clinopyroxene, *Crd* - cordierite, *Crn* - corundum, *Gr* - graphite, *Grs* - grossular, *Grt* - garnet, *Hbl*—hornblende, *Kf*—K feldspar, *Ky*—kyanite, *L*—leucosome (granitic liquid), *Mnz*—monazite, *Ms*—muscovite, *Opx*—orthopyroxene, *Pl*—plagioclase, *Prs*—prismatine, *Qtz*—quartz, *Rt*—rutile, *Sil*—sillimanite, *Spr*—sapphirine, *St*—staurolite, *Ttn*—titanite, *Tur*—tourmaline, *Ves*—vesuvianite, *Wo*—wollastonite, *Zrn*—zircon.

Considering the aM-LP Belt as a whole, MP and LP metamorphism took place ca. 1080–1020 Ma, spanning the Ottawan orogenic phase. MP metamorphism locally overprinted HP metamorphism in the partially exhumed aHP segments, and was itself locally overprinted in the Parautochthonous Belt at ca. 1000 Ma during the Rigolet orogenic phase. In addition, in the LP Natashquan domain and Mazinaw terrane and elsewhere there is local evidence for metamorphism approximately coeval with the Rigolet orogenic phase at the orogen margin. We first consider the MP and LP metamorphism of Ottawan age before discussing the younger overprint.

In the MP segments of the aM-LP Belt, all reported mineral assemblages in metapelitic rocks indicate that sillimanite was the stable Al-silicate polymorph, although the kyanite → sillimanite transition is recorded in both Lake Melville terrane and in Ottawan assemblages in the parautochthonous Britt domain, implying *P–T* conditions close to the Al-silicate phase boundary at these locations. Peak *P–T* conditions for MP terranes from the length of the Grenville Province (e.g., Lake Melville terrane, St-Jean domain, Berthé terrane, Muskoka domain) lie in the range ca. 800–1100 MPa and 800–900 °C, suggesting that the present erosion surface through the MP segment exposes Ottawan orogenic crust metamorphosed at ca. 25–30 km depth, i.e., from near the middle of doubly thickened crust. Evidence for UHT metamorphism is preserved locally (e.g., Mékinac-Taureau terrane). Slightly lower peak *P* conditions in the Adirondack Highlands terrane (700–800 MPa) and Morin terrane (600–800 MPa) imply exhumation of crust from depths of ca. 18 to 25 km. In all cases, a relatively high geothermal gradient is implied by the *T* estimates of 775–900 °C, compatible with the widespread presence of sillimanite-K feldspar and abundant granitic leucosome in metapelite, and orthopyroxene and more limited tonalitic leucosome in meta-mafic rocks. The higher pressure conditions of ca. 1200–1400 MPa estimated for the Britt domain in the Parautochthonous Belt, which imply exhumation from depths of ca. 36 to 42 km, may indicate that these rocks are more appropriately included in the aHP Belt rather than the aM-LP Belt.

With regard to the LP segments of the aM-LP Belt, sillimanite is present in areas of higher temperature metamorphism (e.g., Portneuf–St-Maurice domain), but at lower grades both the kyanite → sillimanite and andalusite → sillimanite transitions are observed (in Mazinaw terrane and Natashquan domain respectively), with estimated *P–T* paths close to the Al-silicate triple point in both cases. Peak pressure estimates vary from ca. 350 MPa in Mazinaw terrane and Natashquan domain to ca. 500–600 MPa in Portneuf–St-Maurice domain, indicating that a range of crustal depths corresponding to ca. 10–18 km depth of burial is exposed. Peak temperatures range from ca. 550 °C at the lowest pressures to ca. 850 °C at the highest pressures, implying formation in a very high geothermal gradient. In Mazinaw terrane, the range of peak pressures across the metamorphic field gradient from 350 to 500 MPa implies exhumation was variable locally, even within individual terranes.

Considering the aMP and aLP segments separately, the data indicate that metamorphism in the mid-crustal aMP terranes took place from ca. 1090 to 1050 Ma, whereas that in the upper-crustal aLP terranes took place from ca. 1050 to 1020 Ma. In the aMP segment, there is evidence from several areas for more than one period of zircon and monazite growth during this 40 My interval – for instance in the Muskoka and St-Jean domains, peak granulite-facies metamorphism lasted from ca. 1080 to 1050 and from 1090 to 1050 Ma respectively (Timmermann et al., 2002; Wodicka et al., 2003) – suggesting that the crust remained sufficiently hot to generate high-grade assemblages and anatectic leucosome for a prolonged period. In the Mauricie region, peak MP metamorphism in the Mékinac–Taureau footwall terrane at ca. 1090 Ma was associated

**Table 4**
Metamorphic signature of the Orogenic Lid

| Name: Location NE/SW | Geologic/metamorphic evidence | Geochronological evidence | Reference |
|---|---|---|---|
| Hawk River terrane: (NE) | Several Labradorian plutons cross-cutting ca. ≥1670 Ma orthogneiss are undeformed and unmetamorphosed, e.g., Shoal Bay pluton | Shoal Bay granite (1663 ± 3 Ma; mg *Zrn* age), and several other almost concordant U–Pb *Zrn* ages of Labradorian plutons; Labradorian *Ttn* ages between ca. 1650–1640 Ma; ca. 1240 Ma $^{40}$Ar/$^{39}$Ar (*Hbl*) plateau age | Gower et al. (1992), Gower (1996), Gower and Krogh (2002), van Nostrand (1988) |
| Mealy Mountains terrane: (NE) | Unmetamorphosed ca. 1250 Ma Mealy dykes | $^{40}$Ar/$^{39}$Ar (*Hbl*) plateau age of 1215 Ma for the Mealy dykes | Reynolds (1989), Hamilton and Emslie (1997) |
| Gilbert River Belt, SE L. Melville, Hawke R. and Mealy Mountains terranes: (NE) | Regional amphibolite-facies metamorphism is Labradorian; Grenvillian effects are limited to non-penetrative fabrics in cross-cutting plutons and two laterally continuous, greenschist-facies mylonite zones with E- to SE-plunging stretching lineations. Unmetamorphosed ca. 974 Ma mafic dykes have amygdaloidal texture | Concordant to variably discordant pre-Grenvillian plutons (ca. 1660–1500 Ma) and local Grenvillian granite (1079 ± Ma; mg U–Pb *Zrn*) are weakly deformed; concordant to variably discordant sg *Mnz* ages (ca. 1080–1060 Ma). Greenschist-facies deformation bracketed between 1113–1062 Ma | Schärer and Gower (1988), Scott et al. (1993), Wasteneys et al. (1997), Gower and Krogh (2002) |
| Red Wine terrane: (NE) | Preserved UHT Labradorian assemblages | Granulite-facies paragneiss in Red Wine and Wilson Lake terranes (ca. 1686 ± 14 and 1666 ± 14 Ma (Rb–Sr whole-rock); ca. 1676 Ma (mg U–Pb *Zrn*) | Fryer (1983), Krogh (1983), Wardle et al. (1986) |
| Wilson Lake terrane: (NE) | Preserved UHT Labradorian assemblages, except in shear zones | Concordant to slightly discordant sg *Mnz* ages of ca. 1640–1635 Ma (i.e., Labradorian) for high-*T*, granulite-facies assemblages | Corrigan et al. (1997), Korhonen and Stout (2006) |
| Lac Joseph terrane: (NE) | Labradorian age of undeformed pegmatite cross-cutting granulite-facies pelitic gneiss; pre-Grenvillian $^{40}$Ar/$^{39}$Ar (*Hbl*) ages in terrane interior; Grenvillian $^{40}$Ar/$^{39}$Ar (*Ms*) in basal shear zone | Pre-Grenvillian $^{40}$Ar/$^{39}$Ar (*Hbl*) plateau age of 1263 Ma and a U/Pb *Ttn* age of 1281 Ma from amphibolite in terrane interior; $^{40}$Ar/$^{39}$Ar (*Ms*) plateau ages of ca. 1000 and 990 Ma from shear zone at base of terrane. Terrane cut by weakly foliated 2-mica pegmatite at 999 + 5/-3 Ma (concordant U–Pb *Mnz*) | Connelly (1991), Connelly and Heaman (1993), Connelly et al. (1995) |
| Hart Jaune terrane: (NE) | Rodot gabbro - fresh igneous texture and mineralogy, thin hydrous coronas | Rodot intrusion: concordant mg *Zrn* and *Bdy* ages of ca. 1166 ± 1 Ma | Indares and Dunning (2004) |
| Composite Arc Belt: (SW) | Granophyric groundmass, miarolitic cavities, and narrow contact aureoles in ca. 1070 Ma granitoids in SE of belt | $^{40}$Ar/$^{39}$Ar (*Hbl*) ages of ca. 1205 Ma and ca. 1150 Ma in 'Hastings metamorphic low' | Lopez-Martinez and York (1983), Cosca et al. (1991), Busch et al. (1996), Davidson (2001) |
| F-AB: Frontenac domain (SW) | Undeformed ca. 1170–1140 Ma intrusions | $^{40}$Ar/$^{39}$Ar (*Hbl*) ages of ca. 1125–1108 Ma | Cosca et al. (1992) |
| F-AB: Mont-Laurier domain (SW) | Undeformed ca. 1170–1140 Ma intrusions and ca. 1060 Ma breccia dykes, carbonatite and fenite | $^{40}$Ar/$^{39}$Ar (*Hbl*) cooling ages of ca. 1040 Ma | Martignole and Reynolds (1997), Corriveau and Morin (2000) |
| F-AB: Adirondack Lowlands domain (SW) | $^{40}$Ar/$^{39}$Ar cooling ages of various *Hbl*-bearing units, including amphibolite | $^{40}$Ar/$^{39}$Ar (*Hbl*) cooling ages of ca. 1050 Ma | Magloughlin et al. (1997), Streepey et al. (2001, 2004), Dahl et al. (2004) |

*Abbreviations*: NE/SW—location of Orogenic Lid in NE or SW Grenville Province; F-AB—Frontenac-Adirondack Belt, mg—multigrain analysis, sg—single grain analysis, UHT—ultra-high temperature. *Bdy*—baddeleyite, *Hbl*—hornblende, *Mnz*—monazite, *Ms*—muscovite, *Ttn*—titanite, *Zrn*—zircon.

with/followed by oblique extension on the Tawachiche shear zone until ca. 1040 Ma, with peak LP metamorphism in the Portneuf–St-Maurice hangingwall domain dated at ca. 1050 Ma (Corrigan and van Breemen, 1997). These results can be compared to data from the northern boundary of the Composite Arc Belt, where high-grade MP assemblages in the Composite Arc boundary thrust zone are dated at ca. 1080–1050 Ma and lower grade LP assemblages in part of Mazinaw terrane are dated at ca. 1030–1020 Ma, the latter being approximately coeval with extension on the Bancroft shear zone near the margin of the belt. Moreover, a similar pattern is also present in the data from the Côte Nord region, where M*P* metamorphism in St-Jean domain in the footwall of the Abbé Huard shear zone is dated at ca. 1080–1070 and 1060–1045 Ma and lower grade metamorphism in Natashquan domain in its hangingwall has yielded ages of ca. 1050 Ma and younger.

As discussed in Supplementary data (Appendix 1), metamorphic ages (U–Pb zircon and monazite) of ca. 1010–990 Ma in Natashquan domain and ca. 1020–1013 Ma in Mazinaw terrane, and a few ca. 1000–990 Ma zircon and monazite rims in the Adirondacks Highlands terrane are anomalous inasmuch as metamorphism of this age has not been recorded elsewhere in the aM-LP Belt. This age range overlaps with crustal thickening and prograde metamorphism in the Parautochthonous Belt at the northern margin of the Grenville Orogen, as well as with local extensional deformation in the interior Grenville Province (e.g., Carr et al., 2000) of which the Abbé Huard shear zone between the St-Jean and Natashquan domains and the Bancroft shear zone northwest of Mazinaw terrane are examples. The occurrence of some of these ages in the LP segments of the M-LP Belt suggests a relationship to upper-crustal events, but unfortunately the structural/petrological settings of the dated samples in Natashquan domain and Mazinaw terrane are insufficiently known to permit distinction between extensional and compressional fabrics so the tectonic significance of the ages cannot be resolved without additional data. Similarly, the petrologic/tectonic setting that gave rise to zircon and monazite rims in a few samples from the Adirondack Highlands terrane remains unconstrained.

Geochronological data for titanite and rutile ($T_C \approx 650–600\,^{\circ}$C; Cherniak, 1993, 2000) can be used to reconstruct part of the cooling history of the aM-LP Belt. They indicate that several MP mid-crustal

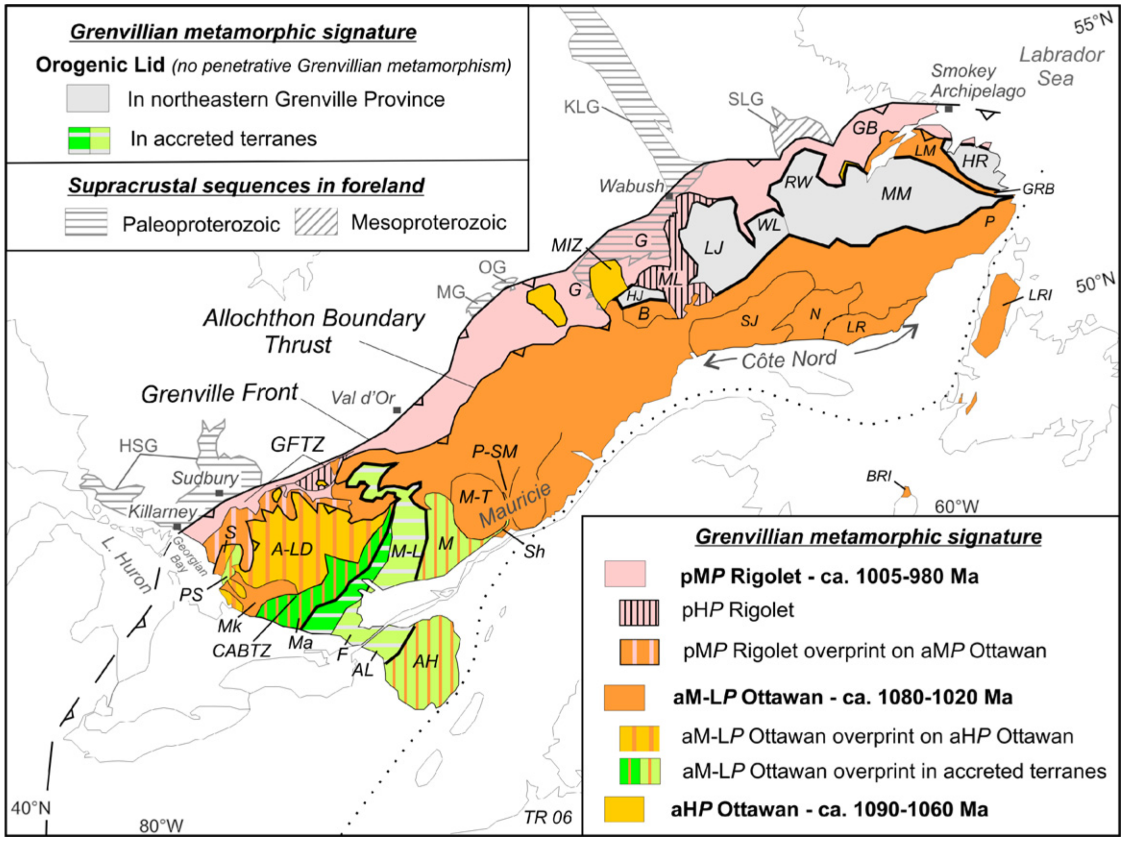


**Fig. 3.** Map showing tectonic subdivision of the Grenville Province, Paleoproterozoic and Mesoproterozoic supracrustal successions in the Grenville foreland and Parautochthonous Belt, and locations of areas discussed in the text. Proterozoic successions: HSG—Huron Supergroup, KLG—Knob Lake Group, MG—Mistassini Group, OG—Otish Group, SLG—Seal Lake Group. Other abbreviations: AH—Adirondack Highlands terrane, AL—Adirondack Lowland domain, A-LD—Algonquin–Lac Dumoine terrane, B—Berthé terrane, BRI—Blair River inlier, F—Frontenac domain, G—Gagnon terrane, GB—Groswater Bay terrane, GFTZ—Grenville Front Tectonic Zone, GRB—Gilbert River Belt, HJ—Hart Jaune terrane, HR—Hawke River terrane, LJ—Lac Joseph terrane, LM—Lake Melville terrane, LR—La Romaine segment, LRI—Long Range inlier, M—Morin terrane, Ma—Mazinaw terrane, MIZ—Manicouagan Imbricate Zone, Mk—Muskoka domain, ML—Molson Lake terrane, M-L—Mont-Laurier domain, MM—Mealy Mountains terrane, M-T—Mékinac–Taureau terrane, N—Natashquan domain, P—Pinware terrane, PS—Parry Sound terrane, P-SM—Portneuf–St-Maurice domain, RW—Red Wine Mountains terrane, S—Shawanaga domain, Sh—Shawinigan domain, SJ—Saint-Jean domain, WL—Wilson Lake terrane.

segments cooled through the closure temperatures of these minerals as early as ca. 1050 Ma, whereas the LP upper-crustal segments remained open to diffusion until as late as ca. 960 Ma. Relatively fast cooling of the mid crust and slow cooling of the adjacent upper crust implies rapid exhumation of the former and slow exhumation of the latter, corresponding to the thermal signature of extended crust with horst-and-graben architecture (i.e., fast cooling of horsts and slow cooling of graben). Such architecture is also supported by the structural evidence for extensional or transtensional shear zones separating the MP and LP terranes (e.g., the Tawachiche, Abbé Huard and Bancroft shear zones), and by the geochronological data indicating that metamorphism in the LP segments was synchronous with or post-dated extensional displacement.

In summary, the structural, metamorphic and geochronological evidence from adjacent MP and LP segments of the aM-LP Belt suggests a linked evolution between the two crustal levels. The MP segment records the formation of a hot mid crust ($\geq$800 °C at 1000–1100 MPa/30 km depth) from ca. 1090 to 1050 Ma that subsequently formed the footwall in a crustal-scale extensional fault system and underwent relatively fast cooling, whereas metamorphism in the overlying LP upper crust that formed the hangingwall to the extensional fault system took place in the interval ca. 1050–1020 Ma after extension and was followed by slow cooling. In this scenario, extension was the trigger for LP metamorphism in the upper crust after it was brought into contact with hot mid-crustal rocks in the graben.

### 3.4. Orogenic Lid

The term orogenic lid was introduced by Laubscher (1983) to describe Eoalpine metamorphic rocks occurring at high structural levels in the eastern Alps that lack evidence for the main Alpine deformation and metamorphism. Similarly, the term is used here as a collective name for terranes and domains in the interior Grenville Province above the Allochthon Boundary Thrust that escaped penetrative Ottawan metamorphism and deformation. The evidence for inclusion of terranes and domains within the Orogenic Lid varies from place to place and is summarised in Table 4. As this is a new tectonic unit of the Grenville Province, additional details are given in Supplementary data (Appendix 2).

The Orogenic Lid occurs in two areas of the Grenville Province, in the northeast where it includes the Hawk River, Mealy Mountains, Red Wine, Wilson Lake, Lac Joseph, and Hart Jaune terranes, and in the southwest where it includes parts of the Composite Arc and Frontenac-Adirondack belts (Fig. 3). Other areas of outcrop are also possible (see Supplementary data, Appendix 2). Where mapped in detail, it has been shown that the boundaries of the Orogenic Lid are normal-sense shear zones. In its northeastern segment, the Orogenic Lid consists principally of Labradorian (ca. 1670–1620 Ma) high-grade gneiss and Paleo- to Mesoproterozoic intrusions, whereas its southwestern segment is composed of parts of the accreted terranes with variable grade that were metamorphosed in the Elzevirian (ca. 1245–1225 Ma) and Shawinigan (ca.

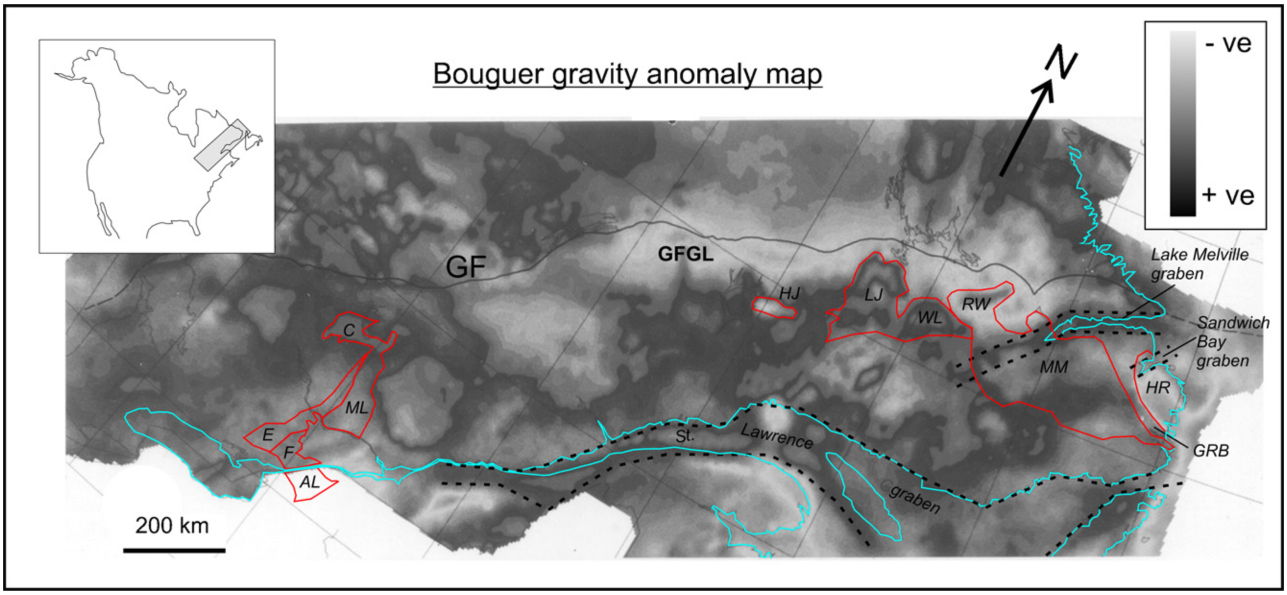


**Fig. 4.** Bouguer gravity anomaly map of the Grenville Province showing outline of the Orogenic Lid. AL—Adirondack Lowlands domain, C—Cabonga domain, E—Elzevir terrane, F—Frontenac domain, HJ—Hart Jaune terrane, HR—Hawke River terrane, LJ—Lac Joseph terrane, ML—Mont-Laurier domain, MM—Mealy Mountains terrane, RW—Red Wine Mountains terrane, WL—Wilson Lake terrane. The Lake Melville, Sandwich Bay and St. Lawrence graben are Neoproterozoic structures.

1190–1140 Ma) orogenies. In both areas, the widespread lack of an Ottawan metamorphic imprint has only recently been recognised. Although they do not exhibit a distinctive aeromagnetic signature, several terranes of the Orogenic Lid in the northeast Grenville Province are visible on Bouguer anomaly maps (Fig. 4), their less negative signatures standing out from the regional Grenville Front Gravity Low presumably due to their elevated near-surface densities. However the Orogenic Lid in the southwestern Grenville Province does not exhibit a distinctive gravity signature.

The characteristic feature of the Orogenic Lid in both of its areas of outcrop, the presence of $^{40}Ar/^{39}Ar$ hornblende cooling ages in excess of ca. 1100 Ma, implies that it was cool (<480–500 °C) during the Ottawan orogenic phase and it is inferred to have composed part of the orogenic suprastructure. The contrast between the cool Orogenic Lid lacking evidence for Ottawan deformation and metamorphism and the hot MP segment of the M-LP Belt (≥800 °C) with its extremely ductile style of Ottawan deformation is stark and implies the existence of an important rheological boundary between the mid and upper crust at that time. Linking these inferences with the presence of normal-sense shear zones bounding the terranes and domains of the Orogenic Lid leads to the interpretation that the juxtaposition of the Orogenic Lid with the aHP and aMP segments was a result of normal faulting. On the basis of available data, mostly from the southwestern Grenville Province, this may have begun as early as ca. 1050 Ma and continued until ca. 950 Ma (Connelly, 1991; Cosca et al., 1991, 1992, 1995; Busch et al., 1996; Corrigan and van Breemen, 1997; Martignole and Reynolds, 1997; Carr et al., 2000; Johnson et al., 2004; Streepey et al., 2004), and it included an important widespread event at ca. 1020 Ma (Ketchum et al., 1998; Indares et al., 2000). In the central Grenville Province, the Orogenic Lid is in direct tectonic contact with the aHP segment (e.g., the Manicouagan Imbricate Zone is in contact with Hart Jaune terrane; Fig. 3), indicating that the mid crust has been completely excised locally. This architecture may be a result of two processes: Ottawan thrust exhumation of the aHP segment into the mid crust after HP metamorphism, followed by late Ottawan and/or Rigolet normal faulting.

Although the maximum temperature of the Orogenic Lid during the Ottawan orogenic phase is constrained by the closure temperature for Ar diffusion in hornblende ($T_C \approx 480$–$500\,^{\circ}C$; McDougall and Harrison, 1999), the lack of an appropriate geobarometer precludes direct calculation of the pressure. However, maximum $P$ values can be approximated given an estimate of the Ottawan geothermal gradient. For the MP segment of the aM-LP Belt, utilising the several $P$–$T$ determinations of ca. 800–1000 MPa/850 °C and assuming an average crustal density of 3000 kg m$^{-3}$, yields an average geothermal gradient of ~28–35 °C km$^{-1}$; whereas using the $P$–$T$ determination of ca. 350 MPa/550 °C for the LP segment of the aM-LP Belt yields an average geothermal gradient of ~50 °C km$^{-1}$. These results translate into maximum depths of 9–15 km for the Orogenic Lid, supporting the inference that it formed part of the orogenic suprastructure during Ottawan time.

### 3.5. *P–T grids and T–t cooling curves for Ottawan and Rigolet metamorphism*

*P–T* determinations for the Rigolet and Ottawan metamorphisms are plotted in Fig. 5a–b. These diagrams provide visual support for the baric subdivision into low-, medium- and high-pressure terranes and domains and hence the wide range of crustal levels alluded to in the title of the paper. With regard to Rigolet metamorphism in the Parautochthonous Belt, the estimated pressures imply exhumation from depths of ca. 20 km (pMP) to 45–50 km (pHP), whereas for Ottawan metamorphism in the allochthonous belts the range is from ca. 12–20 km (aLP), through 25–30 km (aMP), to 50–55 km (aHP). The gap between the $P$ determinations for the aHP and aMP segments suggests they were derived from discrete crustal levels, whereas no such gap exists between the pMP and pHP data for the Parautochthonous Belt. Concerning the aLP segment, $P$–$T$ estimates for the higher $T$ members of this group are only slightly lower than those from the aMP segment, compatible with a relationship by variable degrees of normal faulting, as discussed above.

The contrasting thermal regimes of the Rigolet and Ottawan metamorphisms are apparent from Fig. 5a-b. Considering a reference pressure of 1000 MPa (i.e., ca. 30 km depth), the average crustal temperature at this depth during Rigolet metamorphism was ca. 750 °C, whereas during Ottawan metamorphism it was ca. 850 °C (compatible with the presence of kyanite and sillimanite respectively, and with local Ottawan UHT assemblages (e.g., sillimanite-orthopyroxene-sapphirine in Mékinac-Taureau terrane, Tables 1 and 3). This implies that, in addition to spatial and temporal contrasts, the two metamorphisms also developed under different geothermal gradients.

Two metamorphic field gradients can be inferred from the Rigolet data in Fig. 5a, one starting in the sillimanite field at relatively high temperature (ca. 700 °C at 600 MPa) and exhibiting a steep gradient into the kyanite field (GFTZ-1 to -3), the other starting at lower temperature in the kyanite field (ca. 450 °C at 600 MPa) and exhibiting a shallower gradient (G-1 to -3, ML). In both cases, the grade of metamorphism increases away from the Grenville Front. The different field gradients reflect contrasting tectonic settings, the steeper correlating with the Grenville Front Tectonic Zone and the shallower with the fold-thrust belt in Gagnon terrane. The steeper gradient in the GFTZ is interpreted to indicate variable exhumation up the moderately dipping, crustal-scale shear zone, whereas the shallower gradient in the Gagnon terrane reflects development of the metamorphic rocks on a flat on the foreland. The steeper *P*–*T* gradient in the structurally overlying pHP Molson Lake terrane may reflect exhumation up an inboard, crustal-scale ramp prior to emplacement on Gagnon terrane (van Gool et al., 2008).

With respect to the Ottawan data, Fig. 5b indicates only a small temperature difference between the mid and lower crust, both being ≥850 °C, implying that the geothermal gradient flattened out at depth. The significance of this is discussed later.

The *T*–*t* diagram in Fig. 5c illustrates cooling paths for the GFTZ, Muskoka and Natashquan domains constructed from published data and chosen as proxies for the Parautochthonous Belt, and the MP and LP segments of the aM-LP Belt respectively. Those for the GFTZ and Muskoka domain, each defined by three data points, exhibit rapid cooling following peak metamorphism and a significant reduction in cooling rate with time, qualitatively compatible with the transition from tectonically driven to erosionally driven exhumation. The fastest rates of cooling are for the GFTZ following Rigolet metamorphism, for which ≈11 °C/My for the temperature interval 775–500 °C is calculated. Cooling rates were significantly slower in the allochthonous belts following Ottawan metamorphism (≈4 °C/My over the temperature interval 800–650 °C for Muskoka domain and ≈1.5 °C/My over the temperature interval 750–650 °C for Natashquan domain). Assuming these rates are representative, the preferred interpretation for faster cooling of the MP segment (Muskoka domain) than the LP segment (Natashquan domain) is related to the development of a horst-and-graben architecture in mid- to late-Ottawan time, as discussed above.

### 3.6. Ottawan and Rigolet crustal-scale stacking sequences

In order to interpret the significance of the *P*–*T*–*t* information in Fig. 5, it is necessary to consider the data in the context of the structural stacking sequences and relative timing of metamorphism.

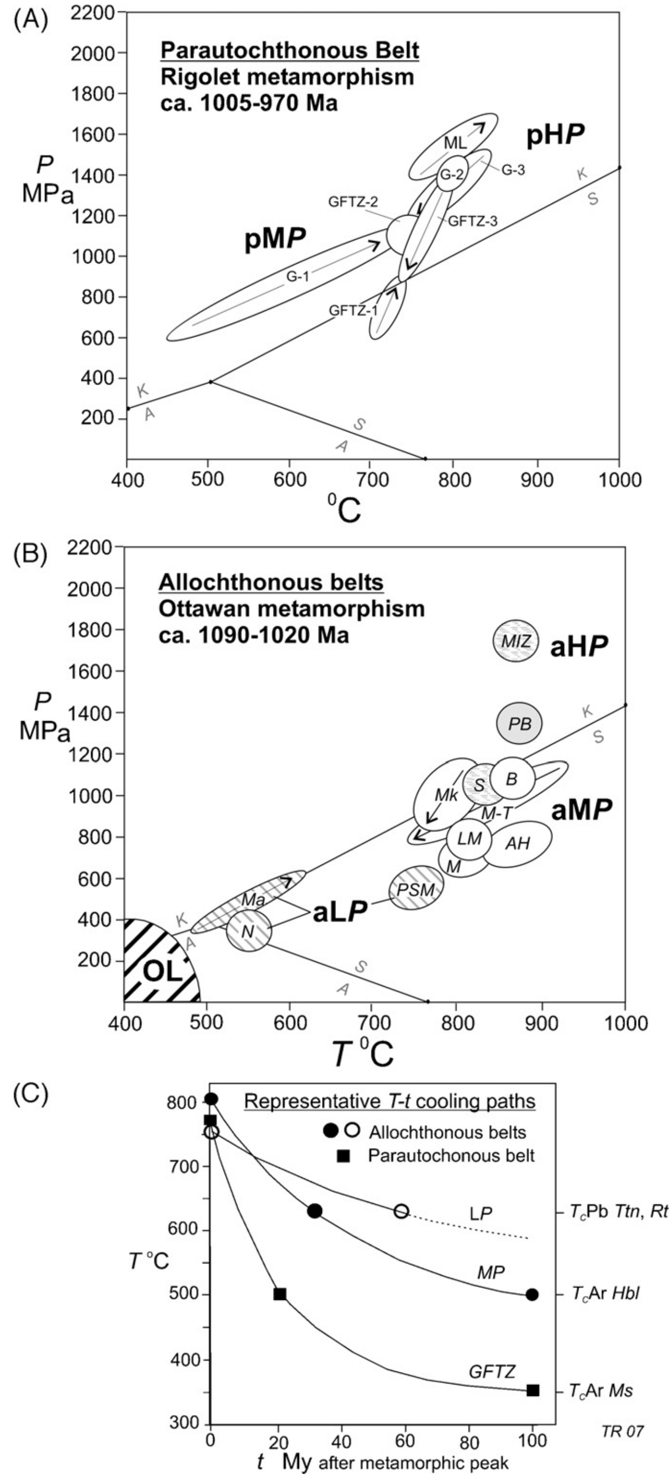


**Fig. 5.** *P*–*T* grids for peak Grenvillian metamorphism and *T*–*t* diagram illustrating post-peak cooling paths: (A) *P*–*T* grid for Rigolet metamorphism in the Parautochthonous Belt; (B) *P*–*T* grid for Ottawan metamorphism in the allochthonous belts; (C) Representative *T*–*t* cooling paths following peak Ottawan (circles) and Rigolet (squares) metamorphism in the MP Muskoka domain, the LP Natashquan domain, and the GFTZ (Parautochthonous Belt). Pb closure temperatures ($T_C$) for titanite (*Ttn*) and rutile (*Rt*) are from Cherniak (1993, 2000), $T_C$ for Ar in hornblende (*Hbl*) and muscovite (*Ms*) are from McDougall and Harrison (1999). Data and references are given in Tables 1–4. Abbreviations: pMP, pHP—Medium- and High Pressure segments of the Parautochthonous Belt, aHP, aMP, aLP—high-, medium-, and low-pressure segments of allochthonous belts, OL—Orogenic Lid. AH—Adirondack Highlands terrane, B—Berthé terrane, G—Gagnon terrane (G-1 near Wabush, G-2 southwest of Wabush, G-3 west of Manicouagan Imbricate Zone), GFTZ—Grenville Front Tectonic Zone (GFTZ-1 near Killarney, GFTZ-2 between Killarney and Sudbury, GFTZ-3 near Val d'Or), LM—Lake Melville terrane, M—Morin terrane, Ma—Mazinaw terrane, MIZ—Manicouagan Imbricate Zone, Mk—Muskoka domain, ML—Molson Lake terrane, M-T—Mékinac–Taureau terrane, N—Natashquan domain (*P*–*T* conditions shown are for Ottawan metamorphism), PB—Parautochthonous Belt (grey symbol indicates Ottawan metamorphic conditions in Britt domain prior to Rigolet overprint), PSM—Portneuf–St-Maurice domain, S—Shawanaga domain (part of HP Belt; *P*–*T* conditions shown indicate MP Ottawan overprint). In a and b, arrows for individual terranes/domains pointing to increasing *P*–*T* indicate the *P*–*T* range of a metamorphic field gradient; arrows pointing to declining *P*–*T* join the peak and retrograde conditions estimated for the terrane/domain.

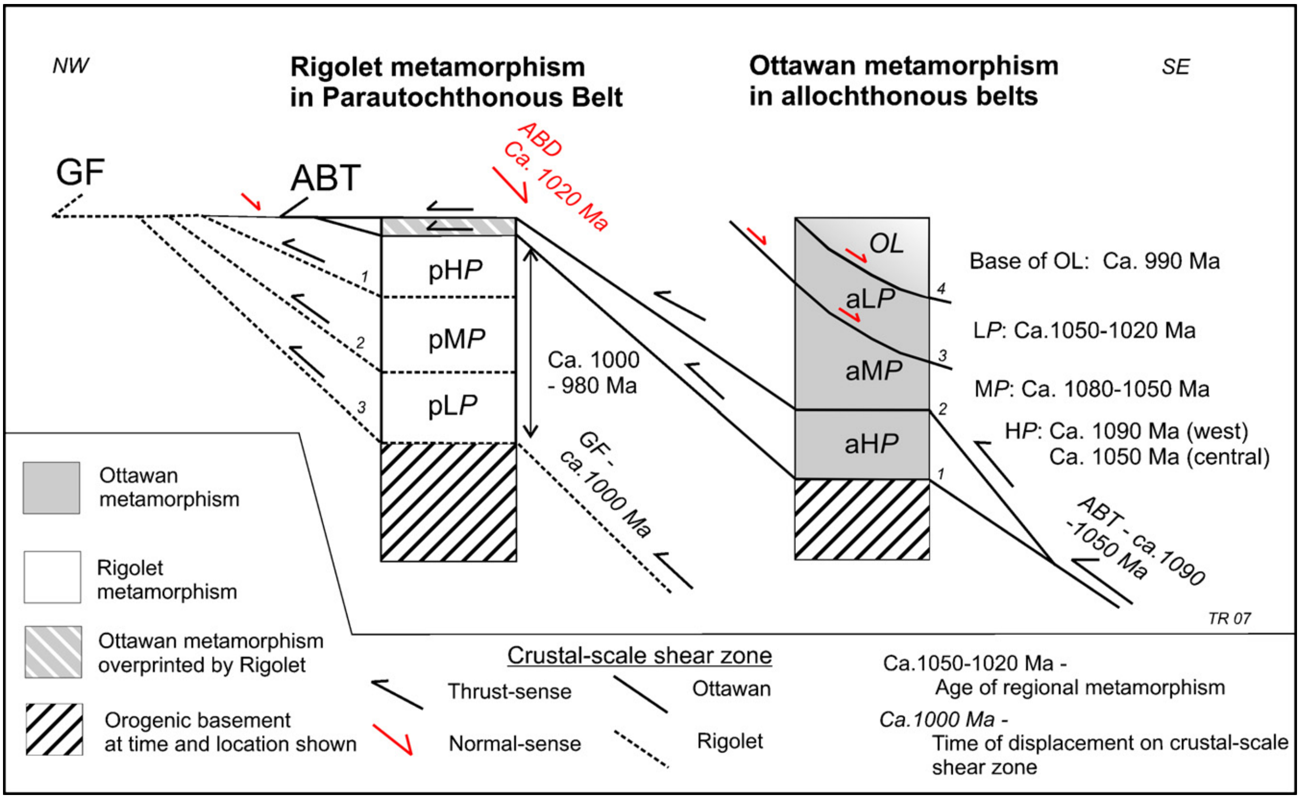


**Fig. 6.** Schematic integrated crustal sections of Ottawan orogenic crust in allochthonous belts above the Allochthon Boundary Thrust (ABT) and Rigolet orogenic crust in Parautochthonous Belt above the Grenville Front (GF). Note that metamorphism during the two orogenic phases affected different parts of the orogen and that reworking of Ottawan crust during the Rigolet orogenic phase was minor. Italicised numbers on shear zones adjacent to crustal columns indicate relative sequence of movement. aLP, aMP, aHP and OL—allochthonous low pressure, medium pressure and high-pressure rocks and Orogenic Lid above the ABT; pLP, pMP and pHP—parautochthonous low pressure, medium pressure and high-pressure rocks above the GF.

These are illustrated schematically in Fig. 6, which shows crustal sections and the inferred stacking sequences in the allochthonous belts in the interior Grenville Province and the Parautochthonous Belt at the orogen margin. In the Parautochthonous Belt, the stacking of high-pressure over medium-pressure rocks (which in turn overlie low *P*–*T* rocks near the Grenville Front locally; e.g., van Gool et al., 2008), corresponds to the typical pattern of inverted metamorphism in foreland-propagating, in-sequence thrust belts. In contrast in the allochthonous belts in the orogenic interior, the low-grade and unmetamorphosed rocks structurally overlie those metamorphosed at greater depth. Moreover, the aMP segment structurally overlies the aHP segment where the latter is present, implying out-of-sequence emplacement. As elaborated later, this arrangement is compatible with mid-crustal flow under an orogenic plateau.

With respect to the timing of metamorphism, there are important differences both within and between crustal levels. For instance, HP Ottawan metamorphism took place at ca. ≥1090 Ma in the western segment of the HP Belt, but at ca. 1060–1050 Ma in the central segment indicating a W → E diachroneity; and MP Ottawan metamorphism in the aM-LP Belt took place from ca. 1080 to 1040 Ma, whereas LP Ottawan metamorphism took place from ca. 1050 to 1020 Ma, indicating mid- to upper-crustal (↑) diachroneity. On the other hand, Rigolet metamorphism at all crustal levels appears to have been essentially coeval across the whole of the Parautochthonous Belt, with the time difference between pHP and pMP metamorphism in the lower and mid crust not resolved with the available data.

Also illustrated on Fig. 6 are the locations of normal-sense shear zones. Especially significant in this regard is the reworking of the Allochthon Boundary Thrust as the Allochthon Boundary Detachment at ca. 1020 Ma, which preceded in-sequence crustal stacking at the orogen margin. This arrangement not only illustrates the space–time duality of metamorphism in the Grenville Province noted previously, but also raises the question of tectonic linkage between the Ottawan and Rigolet orogenic phases.

## 4. Crustal-scale cross-sections

The aim of this section is to evaluate the crustal structure in light of the proposal of Culshaw et al. (1997) that the central part of the Georgian Bay transect in the southwestern Grenville Province developed under an orogenic plateau. Two approaches are followed: firstly, crustal-scale cross-sections of the Grenville Province assembled from *Lithoprobe* deep-seismic reflection experiments and surface mapping are presented; secondly, criteria for the former presence of an orogenic plateau and channel flow are evaluated with respect to data from the Grenville Province.

### *4.1. Crustal structure*

In the cross-sections (Fig. 7), the SE-dipping grain in the northwest of the orogen is apparent. Farther southeast, the shear zone boundaries become listric at depth and are gently SE-dipping to subhorizontal in the orogenic interior, except near the southeast end of cross-section A where they are NW-dipping, defining a doubly vergent orogen. Several of the major shear zone boundaries, including the Grenville Front and the Allochthon Boundary Thrust, exhibit a crustal-scale, ramp-flat architecture, with ramps coincid-

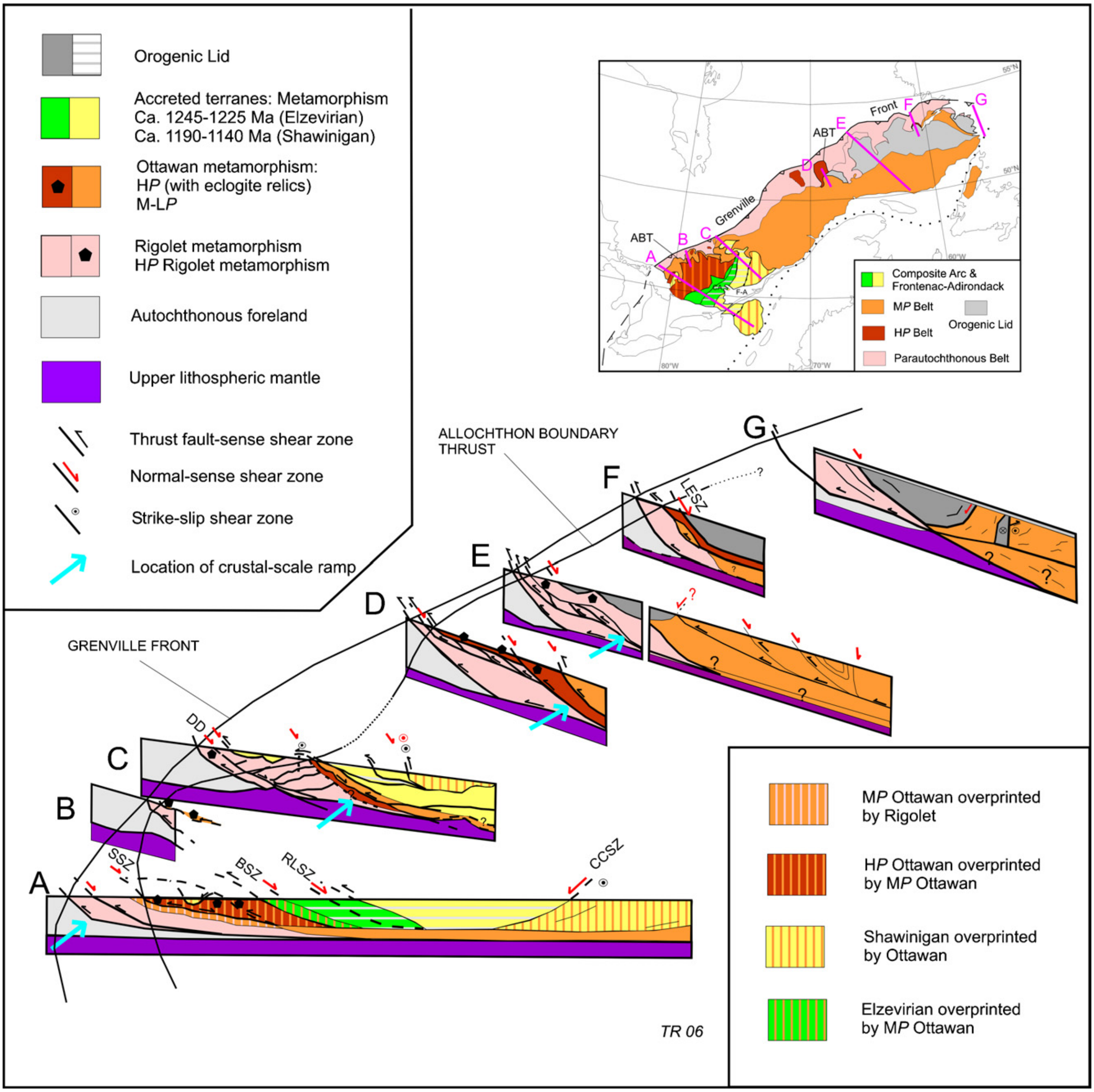


**Fig. 7.** Crustal-scale cross-sections derived from *Lithoprobe* deep seismic reflection studies (transects A–D, G; (A) from White et al., 2000, (B) from Kellett et al., 1994, (C) from Martignole and Calvert, 1996, (D) from Hynes et al., 2000, (G) from Gower et al., 1997) and extrapolation from surface geological data (E–F; from Rivers et al., submitted for publication). Cross-sections are coloured according to inferred age and baric character of Grenvillian metamorphism (Rivers et al., submitted for publication). BSZ—Bancroft shear zone, CCSZ—Carthage-Colton shear zone, DD—Dorval detachment, LESZ—Lac Émerillon shear zone, RLSZ—Robertson Lake shear zone, SSZ—Shawanaga shear zone.

ing with Archean crust suggesting that the latter was competent and formed a buttress during crustal shortening (Hynes et al., 2000; Rivers et al., 2002).

### 4.2. The relative roles of contractional and extensional events

The present orogenic architecture is a result of both contractional and extensional structures, the latter commonly located in and reworking thrust-sense shear zones in extension. Available field data do not allow accurate estimation of the amount of shortening or extension, but relative estimates can be made. For instance, ≥50% shortening is not unusual in thrust belts and the Allochthon Boundary Thrust has been shown on structural grounds to be the site of a minimum of 100 km displacement (Culshaw et al., 1997). On the other hand, there are no records of orogens in which extension exceeds shortening, which is compatible with evidence for limited extensional flow in the western Grenville Province (Culshaw et al., 1994) and with numerical simulation of the conjugate extensional fault system bounding the Orogenic Lid in the southwestern Grenville Province for which cumulative extension ca. 40 km over a distance of 300 km (≈14%) has been proposed (Streepey et al., 2004). These results imply that orogenic architecture is likely predominantly a result of contractional tectonics and we assume in the following that to a first approximation the present architecture of the Grenville Orogen resembles that developed in compression.

**Table 5**
Criteria relating to the former existence of an orogenic plateau and channel flow in the hinterland of the Grenville Province

| | Criterion | Evidence in Grenville Province | Compatibility (yes/no); significance | Source of information |
|---|---|---|---|---|
| 1. | Wide orogen | >600 km wide (minimum: SE margin rifted away) | Yes; wide orogen | See Fig. 2 |
| 2. | Duration of orogeny | ca. 110 My, from ca. 1090–980 Ma | Yes; long-duration orogen | See Fig. 1 |
| 3. | High-grade mid crust with metamorphic temperature ≥800 °C | Grenvillian upper amphibolite- and granulite-facies rocks ubiquitous in MP segment of M-LP Belt. Peak *T* estimates of 800–900 °C at 800–1100 MPa for Ottawan MP metamorphism | Yes; hot mid crust with *T* ≥800 °C throughout the 2000 km length of MP segment of M-LP Belt; implies mid crust was weak due to dehydration melting in felsic lithologies | See Table 3, Fig. 5 |
| 4. | Prolonged duration of high temperature mid crust | *T* in mid crust remained elevated (≥800 °C) from ca. 1080–1050 Ma (Muskoka domain), 1090–1050 Ma (St-Jean domain), 1090–1045 Ma (Lake Melville terrane) | Yes; implies time available for mid-crustal flow at reasonable rates (ca. 1 cm.y$^{-1}$) and that cooling was insignificant for ca. 40–50 My along the length of the Grenville Province | Corrigan et al. (2000), Timmermann et al. (2002), Wodicka et al. (2003); see Table 3. For flow rate, see Beaumont et al. (2006) |
| 5. | Subhorizontal seismic fabrics in mid crust in interior of orogen | Deep seismic sections show sub-horizontal reflectors beneath much of interior Grenville Province. However several mid-crustal ramps also present. | Yes; subhorizontal mid-crustal structure compatible with channel flow. Ramps, which coincide with strong (Archean) crust and imply exhumation of HP and MP rocks, may be late features formed when Archean crust entered orogen | See Fig. 7, *Lithoprobe* crustal-scale seismic sections |
| 6. | Small *T* difference between mid and lower orogenic crust | Peak *T* estimates for aHP and aMP crustal segments overlap (both ≥800 °C) | Yes; compatible with lateral advection of heat in mid-crustal channel | See Tables 2 and 3, Fig. 5 |
| 7. | Extensive formation of ≥10% leucosome in felsic mid-crustal rocks | Especially well documented in Muskoka domain (where leucosome abundance ≥20% locally), but field evidence for widespread leucosome is universal in MP segment of M-LP Belt. | Yes; implies low-viscosity mid crust; MCT estimated to occur at ca. 7% melt for felsic rocks, RCMP at ≥20% melt. Note estimates of leucosome abundance are minima due to possibility of drainage during metamorphism. Actual viscosity of Ottawan mid crust, and its variation over time, are unknown | For Muskoka domain, see Timmermann et al. (2002), Slagstad et al. (2004). For rheology of partial melted systems, see Arzi (1978), Rosenberg and Handy (2005), Rosenberg et al. (2007) |
| 8. | Evidence for mid-crustal flow | L-S to L»S straight gneiss is well documented in Muskoka domain, but it is widespread in all MP segments of M-LP Belt | Possibly, if straight gneiss is product of channel flow; but type of flow is dependent on knowledge of viscosity and bounding conditions, which are unknown | See Culshaw et al. (1997), Timmermann et al. (2002), Slagstad et al. (2004). For flow type, see Grujic (2006) |
| 9. | Crystallization of mid-crustal leucosomes after peak metamorphism | Evidence from Muskoka domain indicates high-grade metamorphism initiated at ca. 1079 ± 3 Ma, and leucosome crystallization took place at ca. 1067 ± 9 Ma | Possibly, but age uncertainties overlap, so although ages young in the right direction, the result is not unambiguous. If so, it would imply leucosomes remained liquid after peak metamorphism, compatible with channel flow | See Timmermann et al. (1997), Slagstad et al. (2004) |
| 10. | Mode of channel flow: Poiseuille or Couette flow, or combination | No data available from the Grenville Province | | See Grujic (2006) for flow types, Williams et al. (2006) for structural criteria |
| 11. | Base of mid-crustal channel defined by major ductile, thrust-sense shear zone | ABT (approximate lower structural limit of Ottawan metamorphism) represents base of channel | Yes; ABT is gently dipping and carries high-grade, ductile rocks in its hangingwall; ABT active as thrust from ca. 1090–1050 Ma | See Fig. 2 |
| 12. | Top of mid-crustal channel defined by coeval normal-sense shear zone | Not readily defined due to later normal faulting, but several possible candidates | Possibly, but coeval displacement on ABT and normal faults not proven | See Culshaw et al. (1997), Indares et al. (2000), Rivers et al. (2002) |
| 13. | Presence of undeformed suprastructure in upper crust | Widespread preservation of Orogenic Lid in two areas of Grenville Province | Yes; implies strong suprastructure above ductile mid crust | See Fig. 2, Table 4 |
| 14. | No inversion of crustal levels in hinterland | Stacking sequence in hinterland (OL/M-LP Belt/HP Belt) fulfills this criterion and implies crustal-scale inversion of Ottawan crust did not occur | Yes; but nature of thickening in orogen interior is not well established. Early thrusting of HP Belt onto orogen margin is compatible with in-sequence fold-thrust belt model | See Fig. 6 |
| 15. | Points # 1–12 above satisfied on orogen (not just local) scale | MP segment of M-LP Belt occurs across full width of Grenville Province | Yes; implies weak mid crust present along 2000 km length of Grenville Province | See Figs. 2 and 5, Table 3 |
| 16. | Orogenic (gravitational) collapse due to weak mid crust | Presence of OL, MP and LP segments of M-LP Belt at same level implies crustal-scale horst-and-graben architecture due to gravitational collapse; normal-sense shear zones listric in mid-crust | Yes; implies upper and middle part of overthickened crust could not support its own weight after removal or diminution of compressive stresses, resulting in extension on mid-crustal detachments due to gravity | See Fig. 7 |

*Abbreviations:* ABT—Allochthon Boundary Thrust, HP Belt—High Pressure Belt, MCT—melt connectivity transition, M-LP Belt—Medium to Low Pressure Belt, OL—Orogenic Lid, RCMP—rheologically critical melt proportion.

### *4.3. Criteria for channel flow and empirical evidence from the Grenville Province*

Criteria relevant to channel flow and an orogenic plateau, and their application to Ottawan crust in the hinterland of the Grenville Province are listed in Table 5. Application of the *large hot long-duration orogen* concept *(criteria 1–4)* to the Grenville Province was discussed in Section 1, additional data concerning the high temperature ($\geq$800 °C) of the Ottawan mid crust are given in Table 3 and Fig. 5, and the $\geq$40 My duration of the Ottawan metamorphism in the aM-LP Belt from ca. 1090 to 1050 Ma has been emphasised. With respect to the presence of *subhorizontal fabrics in the orogenic mid crust (criterion 5)*, which are implied by numerical models for channel flow, this is satisfied in cross-section A (Fig. 7) in which MP crust in the interior Grenville Province exhibits subhorizontal seismic fabrics. However in several cross-sections the Allochthon Boundary Thrust and overlying aM-LP Belt exhibit a ramp-flat architecture, implying the existence of strong lower crust over which the ductile mid crust was exhumed. In every case, these lower-crustal buttresses are composed of Archean crust (Ludden and Hynes, 2000) suggesting that, prior to entry of this rheologically strong crust into the orogen from the foreland, the mid- and lower-crustal fabrics were subhorizontal and hence also compatible with this criterion.

The *small temperature difference between the mid and lower orogenic crust (criterion 6)*, which is compatible with lateral heat advection and hence some form of channel flow (e.g., see experiments of Jamieson et al., 2007) is fulfilled by the identical *T* estimates of 850 ± 50 °C for both the mid and lower orogenic crust (aMP and aHP segments), as illustrated in Fig. 5.

*Leucosome abundance and mid-crustal flow of the mid crust (criteria 7–9).* Viscous flow of mid crust is strongly dependent on the volume of leucosome formed by dehydration melting of mica and amphibole. Although field evidence leaves no doubt that leucosome was widespread in the aM-LP Belt, whether the melt fraction ($\Phi$) was sufficient to *generally* exceed the melt connectivity transition (MCT; Rosenberg and Handy, 2005; Rosenberg et al., 2007) is less certain. According to these authors, the MCT occurs at $\Phi = 0.07$ (i.e., 7% melt fraction by volume), which was certainly exceeded *locally* as estimated leucosome volumes double this value are common (Table 5). Indeed, in some lithologies they may have approached the rheologically critical melt proportion (RCMP; $\Phi \approx 0.3$; Arzi, 1978) when the magma separates from the residual solid. It is not possible to resolve this question on the scale of the aM-LP Belt with the available data, but considering that observed leucosome volumes are likely minima due to melt drainage and that temperatures sufficient for mica dehydration melting were attained, it is likely that the MCT was exceeded in felsic lithologies with significant modal proportions of mica. In general, once the MCT is exceeded the aggregate strength of the material becomes dominated by the liquid, and since the strength of viscous liquids is dependent on strain rate, assumed to be low in orogenic mid crust, it is inferred that felsic constituents of the Ottawan mid crust would have flowed under a small differential stress. The product of such flow in the aM-LP Belt is inferred to be straight gneiss with L-S to L $\gg$ S fabrics in which the liquid was dispersed along the grain boundaries of the residual solid phases that deformed plastically in response to the geometry of flow.

Since channel flow involves the prolonged existence of liquid in the channel, *crystallization of mid-crustal leucosomes after peak metamorphism (criterion 9)* could be a diagnostic criterion. The appropriate type of data is available for Muskoka domain (Timmermann et al., 2002; Table 5) but the uncertainties on the ages overlap so the result is moot. Also unconstrained is the *mode of channel flow (criterion 10)* if it occurred. In principle, distinction between Couette and Poiseuille flow modes is possible using structural criteria (Grujic, 2006; Williams et al., 2006), but the appropriate measurements have not been systematically attempted in the Grenville Province and, moreover, any channel flow fabrics would likely be overprinted during tectonic extrusion of the channel as it approached the erosion front. As a result unequivocal evidence for channel flow of the Ottawan mid crust is not presently available.

*Limits of a mid-crustal channel* (criteria 11–12). In channel flow models, the channel is bounded by a thrust-sense lower boundary and a normal-sense upper boundary on which displacement was coeval. The Allochthon Boundary Thrust fulfills the criteria for the base of a mid-crustal channel in the Grenville Province: it is a several km thick zone of straight gneiss with thrust-sense kinematics (subsequently overprinted in extension), the site of major tectonic transport, and was active as a thrust from at least ca. 1090 to 1050 Ma. Delineation of an upper, normal-sense channel boundary in the Grenville Province is more difficult since its structural character is dependent on the flow mechanism, which as noted is undetermined, and because the upper surface of the MP segment of the aM-LP Belt was substantially reworked in extension at ca. 1020 Ma, largely obliterating evidence for earlier movement. Thus available data do not permit an unambiguous identification of the upper boundary of a putative channel or whether displacement on its upper and lower boundaries was coeval.

Channel flow models require a *strong orogenic suprastructure (criterion 13)*. It was argued previously that the Orogenic Lid represents the cool Ottawan upper crust that was dropped down on normal faults to the level of the aM-LP Belt. The data suggest that the Orogenic Lid was heated to <500 °C and not penetratively deformed at that time, compatible with the requirement for a strong suprastructure above the channel and hence also for an important rheological contrast between the mid and upper Ottawan crust.

*Mechanism of thickening during Ottawan orogenic phase (criterion 14):* The location of the aM-LP Belt structurally above the aHP segments, inferred to be the original configuration and not a result of later extension, together with the relatively younger metamorphic age of the aM-LP Belt in the western Grenville Province, indicate that crustal thickening above the Allochthon Boundary Thrust did not take place in a foreland-propagating style. The out-of-sequence style implied by the configuration is favoured if the rocks in the foreland are strong so the crust has to thicken before it can propagate into its foreland, or if the hinterland is weak such that flow is focussed there. Both factors may have been significant in the Grenville Province, where strong Archean crust underlies the Allochthon Boundary Thrust at several locations and where there is considerable evidence that the mid crust was rheologically weak (criteria 6–8). The stacking sequence and architecture in the interior Grenville Province are compatible with mid-crustal flow under an orogenic plateau, but do not provide an unequivocal answer to whether the MP segment was transported as a solid thrust sheet or by viscous flow in a channel.

*Scale of putative orogenic plateau (criterion 15):* The suggestion of Culshaw et al. (1997) that the hinterland of the western Grenville Province was the site of an orogenic plateau in Ottawan times was inspired by study of deformation in Muskoka domain in which flow was attributed to the abundant leucosomes and prolonged high-grade metamorphism. However, as shown in Tables 3 and 5, the temperature and the duration of MP metamorphism in Muskoka domain are not exceptional in the context of the aM-LP Belt and felsic lithologies are widespread, so it is likely that if a plateau existed it would have covered the aM-LP Belt as a whole rather than being limited to the southwestern Grenville Province. Such a scale would be comparable to the Tibetan Plateau in the hinterland of the Himalayas. Finally, *orogenic collapse (criterion 16)* speaks to the concept that an orogenic plateau is inherently unstable and will collapse by gravity-driven extension under its own weight due to enhanced melt-softening in the mid crust and/or diminution of the stresses holding it up below a critical level. The existence of late- to post-Ottawan extensional faults throughout the interior Grenville Province is compatible with this criterion, and has been interpreted in terms of gravity-driven orogenic collapse. Terminal collapse appears to have occurred on or close to the Allochthon Boundary Thrust at the end of the Ottawan orogenic phase (ca. 1020 Ma; Ketchum et al., 1998). On the basis of seismic evidence, the extensional fault system rooted in the mid to lower crust (Fig. 7) indicating this was a region of crustal weakness and that the system was of orogenic scale. This is consistent with (but does not prove) the former existence of an orogenic plateau.

In summary, evidence for an orogenic plateau and mid-crustal channel during Ottawan times is permissive, but not unequivocal. However, as noted under 'Compatibility' in Table 5, although some evidence is less than compelling on its own there are no criteria that refute the hypothesis and in the author's opinion the balance of evidence suggests their former existence is likely. Implications of this interpretation are investigated in the following section by comparison with the results of numerical modelling.

## 5. Comparison of crustal structure with thermal–mechanical models

In the last few years, crustal-scale numerical modelling has contributed much insight into factors controlling the evolution of large hot long-duration orogens with some form of crustal flow. Three flow modes were defined by Beaumont et al. (2006) that they referred to as homogeneous channel flow, heterogeneous channel flow, and hot fold nappes. In the case of the channel flow modes, the viscosity of the mid crust and/or part of the lower crust became sufficiently low that it flowed on a time scale of a few tens of My, contrasting with the orogenic suprastructure and remaining lower crust that, although deformable, did not flow. The driving forces for flow in their experiments were the pressure differential between the plateau and the foreland, tectonic extrusion, or some combination of the two. Jamieson et al. (2007) compared the results of a series of heterogeneous flow experiments with the architecture of the western Grenville Province (specifically cross-sections A and C, Fig. 7) and derived a remarkably close fit to both of them, from which they concluded that this flow mode provided a good explanation for the Grenvillian evolution of this part of the province. In particular, they interpreted the intercalation of lower-crustal and mid-crustal terranes undergoing channel flow in the experiments as an analogue for the distribution of the aHP Algonquin–Lac Dumoine terrane and the aMP Muskoka domain. As indicated in Section 4.3, many features of the interior Grenville Province appear broadly compatible with an evolution involving some form of channel flow, hence the intention here is not to refute their interpretation, but rather to refine it by considering other relevant data and all three flow modes proposed by Beaumont et al. (2006), and to extend interpretations to the central and eastern Grenville Province.

### 5.1. Ottawan metamorphism above the Allochthon Boundary Thrust

With regard to the Ottawan metamorphism above the Allochthon Boundary Thrust, first-order observations to be accounted for include the presence of the two aHP segments immediately above the Allochthon Boundary Thrust, the continuity of the aM-LP Belt along the length of the Grenville Province, and the long duration of high-temperature metamorphism in the mid crust. As a starting point, it is inferred that the high temperature, long duration of metamorphism in the Ottawan mid crust implies that it was able to flow efficiently and that the Allochthon Boundary Thrust represents the base of a mid-crustal channel, both of which are compatible with Jamieson et al. (2007) interpretations. The validity of these assumptions is evaluated a posteriori.

Considering the aHP segments, inferred to be exhumed lower orogenic crust from the orogenic hinterland, tectonic transport in the hangingwall of the Allochthon Boundary Thrust by either heterogeneous channel flow or as hot fold nappes appears possible, the essential differences being their rheological state and the driving mechanism. Heterogeneous channel flow would imply they had sufficiently low viscosity to flow under a pressure gradient whereas the hot fold nappe model would presume higher viscosities and emplacement by tectonic forcing. Distinguishing between these possibilities is not simple but the different structural styles in the western and central aHP segments, noted previously, may be significant in this regard. In particular, the extreme ductility exhibited in the western aHP segment (Algonquin–Lac Dumoine terrane and Shawanaga domain) may be more compatible with heterogeneous flow in which HP crustal segments were surrounded by flowing, low-viscosity mid crust (as suggested by Jamieson et al., 2007), whereas the much better preservation of the aHP segment in the Manicouagan Imbricate Zone may be more compatible with emplacement as a hot fold nappe, structurally below, but approximately coeval with homogeneous channel flow in the overlying mid crust.

Turning to the aM-LP Belt, three important attributes, continuity along the length of the Grenville Province, temperatures ≥800 °C, and the ≥40 My duration of high-grade metamorphism all indicate that conditions for widespread channel flow were probably met, with the geochronological data in Table 3 suggesting that flow may have occurred at slightly different times in different places. However, as noted direct evidence for such flow remains elusive. The relative timing of HP and MP metamorphism in the allochthonous belts is relevant to the possible flow mode(s). HP metamorphism preceded MP metamorphism by a few My in the western Grenville Province (≥1090 and ca. 1085 Ma respectively), whereas in the central Grenville Province, HP and MP metamorphism appear to have been approximately coeval (ca. 1060–1040 Ma), and in the eastern Grenville Province the aHP segment has not been recognised and MP metamorphism took place from ca. 1085 to 1050 Ma. Assuming the ages for MP metamorphism date syn-metamorphic flow, the lack of a consistent temporal relationship between HP and MP metamorphism suggests the possibility of different flow modes and/or an evolution of flow modes over time. In summary, available data permit a good case to be made that the Allochthon Boundary Thrust formed the base of a channel on which some form of mid-crustal flow occurred, but the present state of understanding clearly leaves scope for speculation concerning the type of flow and additional constraints are required before attempting to take this discussion further.

### 5.2. Rigolet metamorphism beneath the Allochthon Boundary Thrust

Rigolet metamorphism took place in the Parautochthonous Belt in the footwall of the Allochthon Boundary Thrust, the formation of which was also modelled in the heterogeneous channel flow experiments of Jamieson et al. (2007). Particle paths in these experiments show the return flow of incoming mid- and lower-crustal material from the foreland and illustrate how rocks lithologically linked to the foreland are exhumed directly beneath those in the channel that were derived from the hinterland. Such a model satisfies several important features of the Parautochthonous Belt and is also in accord with the evidence for relatively minor tectonic transport at the Grenville Front compared to the Allochthon Boundary Thrust. However, although the first-order similarity of the crustal architecture in the two cases is compelling, the model of Jamieson et al. (2007) cannot be directly applied to the Parautochthonous Belt in the Grenville Province because of the time difference between the Ottawan and Rigolet orogenic phases. In Jamieson et al. (2007) model, exhumation of the foreland beneath the channel occurs concurrently with exhumation of the channel itself, whereas in the Grenville Province exhumation of the channel ceased by 1020 Ma and metamorphism of crust derived from the foreland beneath the channel did not begin until ca. 1000 Ma. Moreover, the widespread evidence for extensional displacement on the Allochthon Boundary Thrust at 1020 Ma resulting in its reworking as the Allochthon Boundary Detachment implies collapse of the orogenic plateau and the termination of channel flow beneath it. Subsequent initiation of Rigolet metamorphism beneath the former channel suggests that collapse resulted in cooling and stiffening of the rocks in the former channel, which thereby became sub-critical for viscous flow, with the result that the final phase of convergent evolution took place nearer the foreland. If this interpretation is correct, it implies that the style and locus of orogenic activity changed over time, from some form of viscous flow in a mid-crustal channel in the orogenic hinterland above the Allochthon Boundary Thrust before ca. 1020 Ma to shortening and thickening in the Parautochthonous Belt beneath the Allochthon Boundary Thrust at ca. 1000 Ma. Thus the model of Jamieson et al. (2007) cannot be directly applied to the Grenville Province. The preferred interpretation, incorporating a phase of extension at ca. 1020 Ma and migration of the locus of metamorphism towards the foreland after that time, may also explain the difficulty encountered by Warren et al. (2006) in producing a single-stage model that accounted for both Ottawan and Rigolet crustal structure in the central Grenville Province.

### 5.3. *Preservation of the Orogenic Lid*

Progressive collapse of the orogenic plateau has been advanced as an explanation for the preservation of the Orogenic Lid at the same structural level as MP and LP segments of the aM-LP Belt. Two major graben have been identified, but the presence of the LP Mazinaw terrane within the southwestern segment of the Orogenic Lid implies the presence of smaller-scale horsts within this regional graben. Moreover, in the case of Mazinaw terrane where Ottawan isograds are at high angles to stratigraphy and peak pressures vary from 350–600 MPa across the metamorphic field gradient (Table 3), the implied differential exhumation from depths of 10 to 18 km across a distance of ca. 50 km suggests the LP horst is tilted.

With respect to formation of the horst-and-graben architecture, extensional reactivation of the Allochthon Boundary Thrust as a system of detachments at ca. 1020 Ma has already been discussed, but important extensional/transtensional displacements also occurred elsewhere during the Ottawan orogenic phase. Other examples include ca. 1050 Ma transtension on the Tawachiche shear zone separating the MP Mékinak-Taureau terrane and the LP Portneuf–St-Maurice domain, ca. 1020 Ma extension on the Bancroft shear zone at the base of the Composite Arc Belt, and ca. 1050–1020 Ma transtension on the Carthage-Colton shear zone, the latter two shear zones defining the boundaries of the Orogenic Lid in the southwestern Grenville Province (for references, see Table 3). Extension also continued during the Rigolet orogenic phase. Fig. 7 shows that most of these extensional shear zones root in the orogenic mid crust, the only known exception being a crustal-scale shear zone in the Parautochthonous Belt that offsets the Moho in cross-section C (Martignole and Calvert, 1996). The tectonic significance of these different styles of extensional faulting is discussed in the next section.

## 6. Discussion

The interpretation of an orogenic plateau in the hinterland of the Grenville Province in Ottawan times underlain by crust undergoing some form of viscous channel flow underpins the discussion in the previous section and the modelling of Jamieson et al. (2007). As noted, the interpretation is compatible with available geological data and no counter-indications are known, which although providing support for the hypothesis, falls short of a rigorous proof. Nonetheless, the compatibility is encouraging and a schematic modification to the tectonic model of Jamieson et al. (2007) incorporating the interpretations discussed in the previous section is shown in Fig. 8.

### 6.1. *Tectonic model*

Following Jamieson et al. (2007), the tectonic evolution from ca. 1080 to 1050 Ma is inferred to have involved the formation of an orogenic plateau that probably developed diachronously, but eventually extended across the full width of the orogen (Fig. 8A). As discussed, the nature of the driving force and mode of deformation beneath this plateau, whether gravitational forcing involving some form of channel flow, tectonic forcing involving the expulsion of hot nappes, or some combination, remains unknown. In any case, the Allochthon Boundary Thrust formed the approximate contemporary limit of ductile crust in the orogen. Location of the aM-LP Belt structurally on top of the aHP segments, where the latter are present, implies out-of-sequence stacking that may be a result of low-viscosity mid crust beneath the orogenic plateau. The presence of widespread, but sparse magmatism in the hinterland of the Grenville Province from ca. 1080 to 1020 Ma implies local melting of the lower crust and sub-continental mantle, compatible with evidence described above for a hot mid and lower crust.

Orogenic collapse appears to have started at least locally in the interior Grenville Province by ca. 1050 Ma and the plateau as a whole underwent terminal collapse at ca. 1020 Ma when the Allochthon Boundary Thrust was reworked in extension as the Allochthon Boundary Detachment, thereby effectively arresting flow in the channel (Fig. 8B). The result of these extensional displacements was the formation of a crustal-scale horst-and-graben architecture with the aM-LP Belt forming the horsts and the Orogenic Lid occupying the graben. In general, formation of an orogenic plateau creates a vast area of gravitational instability and the plateau can only persist if the crust at depth retains sufficient strength to support its mass and the compressional stress system is maintained. In the case of the Grenville Province, considering normal-sense displacement was initiated during the compressional Ottawan orogenic phase and the shear zones become listric in the mid crust, it is inferred that orogenic collapse was a response to melt-weakening of the mid crust with the result that it became unable to support the mass of the overlying plateau. Collapse of a compressional orogen on a weak base was referred to as 'fixed boundary collapse' by Rey et al. (2001). In such a setting, the presence of both thrust- and normal-sense structures does not imply a rapid alternation of stress regimes, but is interpreted in terms of progressive change of rheology of the zone in which the normal-sense structures root. This point was first made with respect to the Grenville Province by Corrigan and Hanmer (1995) and Corrigan and van Breemen (1997), who suggested that normal faulting on the Tawachiche shear zone in the Mauricie region during the Ottawan orogenic phase was a response to local rheological weakening

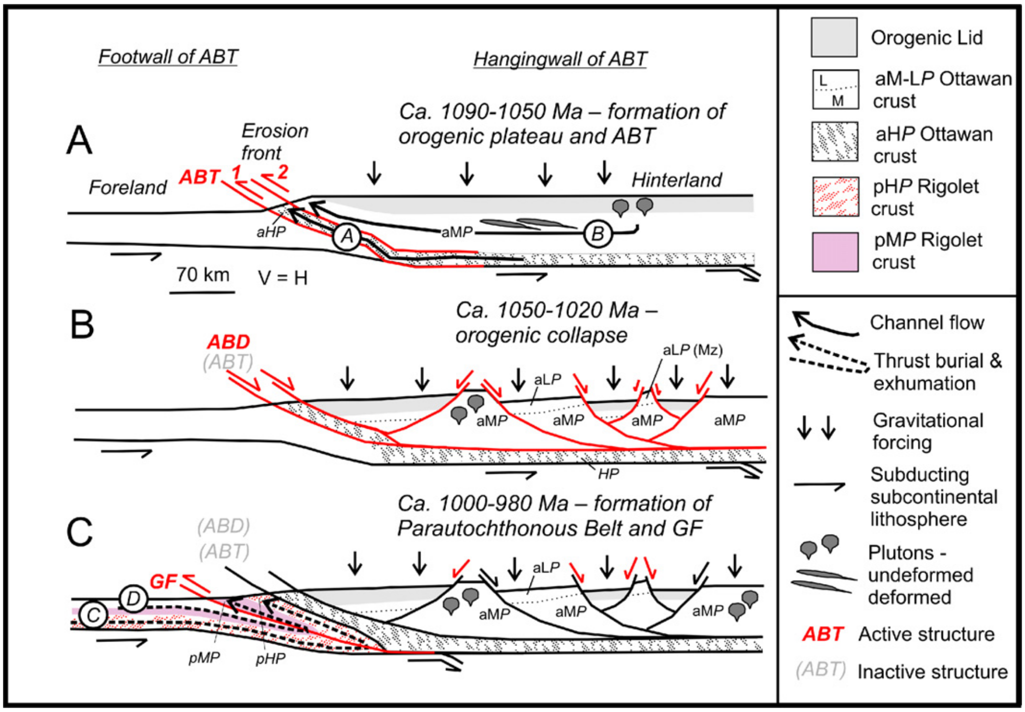


**Fig. 8.** Schematic time series illustrating the tectonic evolution of the Grenville Province assuming formation of an orogenic plateau in the hinterland during the Ottawan orogenic phase. Active structures shown in red. (A) ca. 1090–1050 Ma, metamorphism and exhumation of the allochthonous HP segment (path A) and the MP segment of the aM-LP Belt (path B) above the Allochthon Boundary Thrust (ABT), which forms the base of a mid-crustal channel. Transport mechanism of the HP segments is not well defined and may have been different in the western and central Grenville Province, but some form of channel flow of the MP segment of the aM-LP Belt is inferred. (B) ca. 1050–1020 Ma, initiation of local orogenic collapse in the upper crust at ca. 1050 Ma and widespread orogenic collapse to mid-crustal depths by ca. 1020 Ma when the ABT was reworked in extension as the Allochthon Boundary Detachment system (ABD), effectively terminating channel flow. The small tilted horst labelled aLP (Mz) situated within the larger graben defining the Orogenic Lid at the right-hand side of the figure is a schematic representation of the setting of Mazinaw terrane accounting for its location within the Orogenic Lid and the *P* variation in its metamorphic field gradient. (C) ca. 1000–980 Ma, formation of the Grenville Front (GF) and high-grade metamorphism in the Parautochthonous Belt as lower crust (path C) and mid crust (path D) from the foreland was rapidly buried and exhumed by thrusting beneath the inactive Allochthon Boundary Detachment. Continued normal faulting and local metamorphic mineral growth in the orogenic interior.

caused by advection of heat associated with mid-crustal AMCG complexes. An implication of the mid-crustal soling of the normal-sense shear zones during orogenic collapse is that the upper and mid crust became detached from the lower crust and extended together, while the lower crust presumably continued to shorten. This represents a significant change from the conditions under the active orogenic plateau when the ductile flowing mid crust was rheologically detached from the cool rigid upper crust.

The tectonic record for the 20 My from ca. 1020 to 1000 Ma is meagre. Compression presumably continued, but the paucity of metamorphic ages in this interval is inferred to correlate with the establishment of a new tectonic regime beneath the Allochthon Boundary Thrust. This would have involved crustal thickening and the construction of topography in the Parautochthonous Belt together with conductive heating of its crustal roots at depth. By ca. 1000 Ma (Fig. 8C), thrusting was widespread at the Grenville Front along the full length of the Grenville Province, indicating that the orogen had advanced into its foreland by this time. Fig. 9C illustrates that the Parautochthonous Belt was derived from rocks in the foreland that underwent a rapid cycle of burial, metamorphism and thrust exhumation, compatible with field data and numerical modelling, with the inferred particle path being restricted to the orogen margin and bypassing the hinterland under the former orogenic plateau. Schematic particle paths for pHP and pMP segments of the Parautochthonous Belt are shown, with exhumation of pHP rocks immediately beneath the inactive Allochthon Boundary Thrust compatible with their location in the Grenville Province. Evidence for metamorphism in the former hinterland at this time within the upper-crustal Natashquan domain and Mazinaw terrane and the mid-crustal Adirondack Highlands terrane has been noted. As discussed previously, the significance of these ages is not well understood, but if the kinematic interpretation in Fig. 8c is correct they may be associated with collapse of the plateau.

In western Labrador, the overlapping ages (within uncertainties) of weakly deformed, cross-cutting granite dykes in the Parautochthonous Belt (Gagnon terrane) and Orogenic Lid (Lac Joseph terrane) of $995 \pm 2$ Ma and $999 + 5/-3$ Ma respectively (Tables 1 and 4; Connelly and Heaman, 1993; Schwarz, 1998) date the final crustal assembly in this part of the orogen resulting from the exhumation of the Parautochthonous Belt and the down-dropping of the Orogenic Lid. These late-tectonic dykes currently provide the only 'pin' available anywhere in the orogen for the maximum age of juxtaposition of these orogenic elements that underwent such disparate Grenvillian evolution at the bottom and top of the orogenic crust respectively.

Tectonic evolution in the hinterland from ca. 980 to 950 Ma saw the emplacement of many small, late- to post-orogenic granitoid bodies and a few gabbro dykes in the Interior Magmatic Belt (e.g., Gower et al., 1991; Gower and Krogh, 2002), implying that the lower crust and underlying subcontinental mantle remained hot and fertile. This magmatism was approximately coeval with the development of two styles of normal-sense shear zone (not shown in Fig. 8). (1) Narrow mylonite zones with normal-sense displacement in the Orogenic Lid that have been the subject of several studies (e.g., van der Pluijm and Carlson, 1989; Carlson et al., 1990; Cosca et al., 1992, 1995; Busch et al., 1996; Streepey et al., 2001, 2004; Dahl et al., 2004). These upper-crustal structures are interpreted as high-level expressions of orogenic collapse in a fixed boundary setting discussed previously. (2) Wide crustal-scale, normal-sense ductile shear zones such as the Dorval Detachment identified seismically and at the surface in cross-section C (Fig. 7; Martignole and Calvert, 1996; Martignole and Martelat, 2005), which may link with a similar ductile structure in cross-section A (Rivers et al., 2002). This is a much more profound feature, with the seismic evidence that it displaces the Moho suggesting that it formed in a regional extensional framework (free-boundary collapse; Rey et al., 2001). This is the only known evidence for ductile regional extension following the Grenvillian Orogeny.

### 6.2. Two settings of high-pressure metamorphism in the Grenville Province

Fig. 8 provides an explanation for the empirical evidence that the HP Belt consists of two High Pressure segments located back-to-back across the Allochthon Boundary Thrust, the aHP segment above the Allochthon Boundary Thrust (Rivers et al., 2002), and the pHP segment within the Parautochthonous Belt beneath it (defined here for the first time). As is apparent from the schematic particle paths in Fig. 8, the rocks comprising the two HP segments are inferred to have originated several hundred km apart, those in the aHP segment from the hinterland beneath the plateau, those in the pHP segment from the foreland. Presently available data, summarised in Tables 1 and 2, indicate that although the peak $P$–$T$ conditions during the two HP events were similar (ca. 1700–1800 MPa/800–850 °C; Fig. 5), they were separated in time by some 60–90 My and their cooling paths were distinctive (slow cooling in the aHP segment, fast cooling in the pHP segment; Fig. 5c). This interpretation, in addition to accommodating the well known foreland-ward propagation of the Grenville Orogen from ca. 1090 to 980 Ma (e.g., Jamieson et al., 1995), for the first time also recognises and provides a tectonic context for two contrasting juxtaposed HP events in the Grenville Province, and in so doing attributes an important role to orogenic collapse on the Allochthon Boundary Thrust at ca. 1020 Ma that spatially and temporally separates them.

## 7. Conclusions

Crust metamorphosed during the Ottawan orogenic phase (ca. 1090–1020 Ma) of the Grenvillian Orogeny principally occurs above the Allochthon Boundary Thrust and has been subdivided into two allochthonous High Pressure (aHP) segments (modified term), an allochthonous Medium to Low Pressure (aM-LP) Belt (new term) and an Orogenic Lid (new term) on the basis of metamorphic and geochronological data. A range of Ottawan crustal depths is exposed at the erosion surface, from ca. ≥50 to 60 km in the aHP segments, ca. 25–33 km and 12–20 km in the MP and LP segments of the aM-LP Belt, and ≤ca. 15 km in the Orogenic Lid. Juxtaposition of these crustal levels resulted from thrust exhumation of aHP segments into the mid crust followed and down-dropping of aLP terranes and Orogenic Lid by normal faulting.

The Ottawan mid crust in the orogenic hinterland along the 2000 km length of the Grenville Province was characterised by metamorphic temperatures in excess of 800 °C for ≥40 My, a highly ductile deformation style, subhorizontal structural fabrics, and a large difference between U–Pb (zircon and monazite) ages of peak metamorphism [1090–1050 Ma] and $^{40}$Ar/$^{39}$Ar (hornblende) cooling ages [990–950 Ma]. These results are consistent with some form of channel flow and/or hot nappe emplacement beneath an extensive orogenic plateau. Gravitational collapse of the plateau began locally as early as 1050 Ma and was widespread at 1020 Ma when the former channel was reworked as the normal-sense Allochthon Boundary Detachment system thereby terminating channel flow.

Subsequent Grenvillian tectonic evolution principally occurred beneath the Allochthon Boundary Detachment in the Parautochthonous Belt at the northwestern margin of the province from 1000 to 980 Ma (Rigolet orogenic phase). Again, a range of crustal levels from pHP (new term) to pMP (new term) is exposed at the erosion surface, representing burial depths of ca. 20–45 km. The small difference between the U–Pb (zircon and monazite) metamorphic ages [1000–980 Ma] and $^{40}$Ar/$^{39}$Ar (hornblende) cooling ages [980–940 Ma] implies that Rigolet metamorphism involved rapid burial followed by thrust exhumation.

These observations lead to the interpretation that the Allochthon Boundary Thrust/Detachment system acted as a long-lived material focal plane in the Grenville Orogen across which rocks that were originally separated by several hundred km and followed very different metamorphic $P$–$T$–$t$ paths, converged and were exhumed in proximity to each other. Specifically, it separates hinterland-derived terranes with relatively high-$T$ Ottawan metamorphism in its hangingwall from foreland-derived terranes with relatively lower-$T$ Rigolet metamorphism in its footwall, implying it is a fundamental lithological and metamorphic-age boundary in the orogen. Moreover the ca. 20 My hiatus between Ottawan and Rigolet metamorphisms that followed reworking of the Allochthon Boundary Thrust as the Allochthon Boundary Detachment is inferred to correspond to the incubation time for crustal thickening, conductive heating and the redevelopment of active metamorphism at the orogen margin. In addition to terminating mid-crustal channel flow, extensional displacement on the Allochthon Boundary Detachment system led to the formation of a crustal-scale, horst-and-graben architecture in the orogenic hinterland, with the aM-LP Belt preserved in the horsts and the Orogenic Lid occupying the graben.

Several critical features of the crustal architecture and evolution described in this paper accord with the large hot long-duration orogen model of Jamieson et al. (2007) derived for the western Grenville Province. Specifically, the interpretation that the Allochthon Boundary Thrust corresponds to the base of an exhumed mid-crustal channel and that the orogenic hinterland was the site of an orogenic plateau is supported by data presented in this paper, although neither inference can yet be considered proven. However, no single numerical experiment involving channel flow is currently capable of explaining all the data for the Grenville Province. It is argued that although the first-order features of the Ottawan orogenic history in the hinterland of the Grenville Province, including prolonged high-$T$ metamorphism and pervasive ductile mid-crustal deformation, may be reasonably reproduced by some combination of the published channel flow mechanisms, the particular feature of the Grenvillian evolution that has so far eluded modellers is the collapse of the mid-crustal channel followed by a ca. 20 My hiatus before continued thrust evolution in its former footwall. In conclusion, this paper proposes the first regional tectonic model to integrate the Ottawan and Rigolet orogenic phases into a single prolonged collision involving an intervening period of orogenic collapse and furthermore the model also accommodates two episodes of high-pressure metamorphism in contrasting tectonic settings and the preservation of low-pressure metamorphic rocks and an orogenic lid in the hinterland, as required by the field data.

## Acknowledgements

The quantitative database of $P$–$T$ conditions and timing of Grenvillian metamorphism that forms the basis of this paper was assembled from the published results of many researchers over the last 20 years or so, including several former graduate students, post-doctoral fellows, and colleagues who worked with me. It is a pleasure to acknowledge the many discussions with them and others whose published contributions made this overview possible. The interpretations in this paper owe an obvious debt to the insight provided by the thermal–mechanical modelling experiments of Chris Beaumont and colleagues, which is acknowledged with gratitude. In addition, I thank Beckie Jamieson for a pre-print of her recent paper, and Beckie Jamieson, Jacques Martignole and Aphrodite Indares for perceptive and helpful comments on a previous version of the manuscript. This paper is an outcome of the *Lithoprobe* project, from which financial support is acknowledged, and in addition my research in the Grenville Province has been supported by NSERC Discovery Grants for many years.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2008.08.005.

## References


Alcock, J., Muller, P., 1999. The ca. 1144 Ma Dresden Station metagabbro, a re-evaluation. Northeastern Geology and Environmental Sciences 21, 275–281.

Alcock, J., Isachsen, C., Livi, K., Muller, P., 2004. Unraveling growth history of zircon in anatectites from the northeast Adirondack Highlands, New York: Constraints on pressure–temperature–time paths. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic Tectonic Evolution of the Grenville orogen in North America, 197. Geological Society of America Memoir, Boulder, CO, pp. 267–284.

Annovitz, L.M., Essene, E.J., 1990. Thermobarometry and pressure–temperature paths in the Grenville Province of Ontario. Journal of Petrology 31, 197–241.

Arima, M., Kerrich, R., Thomas, A., 1986. Sapphirine-bearing paragneiss from the northern Grenville Province in Labrador, Canada: Protolith composition and metamorphic *P–T* conditions. Geology 14, 844–847.

Arzi, A., 1978. Critical phenomena in the rheology of partially melted rocks. Tectonophysics 44, 173–184.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., Lee, B., 2001a. Himalayan tectonics explained by extrusion of a low-viscosity channel coupled to focused denudation. Nature 414, 738–742.

Beaumont, C., Jamieson, R.A., Nguyen, M.H., Lee, B. 2001b. Mid-crustal channel flow in large hot orogens: Results from coupled thermal–mechanical models. In: Slave – Northern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran Tectonics Workshop, Lithoprobe Secretariat, UBC, Vancouver, BC, Lithoprobe Report 79, pp. 112–170.

Beaumont, C., Nguyen, M.H., Jamieson, R.A., Ellis, S., 2006. Crustal flow modes in large hot orogens. In: Law, R.D., Searle, M.P., Godin, L. (Eds.), Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones, vol. 268. Geological Society, London, pp. 91–145 (special publication).

Bethune, K.M., 1997. The Sudbury dyke swarm and its bearing on the tectonic development of the Grenville Front, Ontario, Canada. Precambrian Research 85, 117–146.

Bethune, K.M., Davidson, A., 1997. Grenvillian metamorphism of the Sudbury diabase dyke-swarm: from protolith to two-pyroxene–garnet coronite. Canadian Mineralogist 35, 1191–1220.

Bickford, M.E., McLelland, J.M., Selleck, B.W., Hill, B.M., Heumann, M.J., 2008. Timing of anatexis in the eastern Adirondack Highlands: Implications for tectonic evolution during ca. 1050 Ottawan orogenesis. Geological Society of America Bulletin 120, 950–961, doi:10.1130/B26309.1.

Bonnet, A.-L., Corriveau, L., La Flèche, M.R., 2005. Chemical imprint of highly metamorphosed volcanic-hosted hydrothermal alterations in the La Romaine supracrustal belt, eastern Grenville Province, Quebec. Canadian Journal of Earth Sciences 42, 1783–1814.

Busch, J.P., van der Pluijm, B.A., Hall, C.M., Essene, E.J., 1996. Listric normal faulting during postorogenic extension revealed by $^{40}Ar/^{39}Ar$ thermochronology near the Robertson Lake shear zone, Grenville orogen, Canada. Tectonics 15, 387–402.

Bussy, F., Krogh, T.E., Klemens, W.P., Schwerdtner, W.M., 1995. Tectonic and metamorphic events in the westernmost Grenville Province, central Ontario: new results from high-precision zircon geochronology. Canadian Journal of Earth Sciences 32, 660–671.

Carlson, K.A., van der Pluijm, B.A., Hanmer, S., 1990. Marble mylonites near Bancroft, Ontario: evidence for crustal extension in the Canadian Grenville. Geological Society of America Bulletin 102, 174–181.

Carr, S.D., Easton, R.M., Jamieson, R.A., Culshaw, N.G., 2000. Geologic transect across the Grenville orogen of Ontario and New York. Canadian Journal of Earth Sciences 37, 193–216.

Carswell, D.A., 1990. Eclogites and eclogite facies: definitions and classification. In: Carswell, D.A. (Ed.), Eclogite Facies Rocks. Blackie, Glasgow and London, pp. 1–13.

Cawood, P.A., Pisarevski, S.A., 2006. Was Baltica right-way up or upside-down in the Neoproterozoic? Journal of the Geological Society, London 163, 753–759.

Cherniak, D.J., 1993. Lead diffusion in titanite and preliminary results on the effects of radiation damage on Pb transport. Chemical Geology 110, 177–194.

Cherniak, D.J., 2000. Pb diffusion in rutile. Contributions to Mineralogy and Petrology 139, 198–207.

Childe, F., Doig, R., Gariépy, C., 1993. Monazite as a metamorphic chronometer, south of the Grenville Front, western Quebec. Canadian Journal of Earth Sciences 30, 1056–1065.

Connelly, J.N. 1991. The thermotectonic history of the Grenville Province of western Labrador. PhD thesis. Memorial University, St. John's, Nfld.

Connelly, J.N., Heaman, L.M., 1993. U–Pb geochronological constraints on the tectonic evolution of the Grenville Province, western Labrador. Precambrian Research 63, 123–142.

Connelly, J.N., Rivers, T., James, D.T., 1995. Thermotectonic evolution of the Grenville Province of western Labrador. Tectonics 14, 202–217.

Corfu, F., Easton, R.M., 1995. U–Pb geochronology of the Mazinaw terrane, an imbricate segment of the Central Metasedimentary Belt, Grenville Province, Ontario. Canadian Journal of Earth Sciences 32, 959–976.

Corrigan, D., Hanmer, S. 1995. Arc accretion, thickening, post-collisional extension and plutonism in the Grenville orogen: constraints from the Mauricie region, south-central Québec. Precambrian 95, International Conference on Tectonics and Metallogeny of Early-Mid Precambrian Orogenic Belts, Montréal, QC. Program and Abstracts, p. 106.

Corrigan, D., van Breemen, O., 1997. U–Pb age constraints for the lithotectonic evolution of the Grenville Province along the Mauricie transect, Québec. Canadian Journal of Earth Sciences 34, 299–316.

Corrigan, D., Culshaw, N.G., Mortensen, J.K., 1994. Pre-Grenvillian evolution and Grenvillian overprinting of the Parautochthonous Belt in Key Harbour, Ontario: U–Pb and field constraints. Canadian Journal of Earth Sciences 31, 583–596.

Corrigan, D., Rivers, T., Dunning, G., 1997. Preliminary report on the evolution of the Allochthon Boundary Thrust in eastern Labrador: Mechin River to Goose Bay. Report of 1997 Transect Meeting, Lithoprobe report 61, pp. 45–56.

Corrigan, D., Rivers, T., Dunning, G., 2000. U–Pb constraints for the plutonic and tectonometamorphic evolution of Lake Melville terrane, Labrador and implications for basement reworking in the northeastern Grenville Province. Precambrian Research 99, 65–90.

Corriveau, L., Bonnet, A.-L., 2005. Pinwarian (1.50 Ga) volcanism and hydrothermal activity at the eastern margin of the Wakeham Grooup, Grenville Province, Quebec. Canadian Journal of Earth Sciences 42, 1749–1782.

Corriveau, L., Morin, D., 2000. Modelling 3D architecture of western Grenville from surface geology, xenoliths, styles of magma emplacement, and Lithoprobe reflectors. Canadian Journal of Earth Sciences 37, 235–251.

Cosca, M.A., Sutter, J.F., Essene, E.J., 1991. Cooling and inferred uplift/erosion history of the Grenville orogen, Ontario: constraints from $^{40}Ar/^{39}Ar$ thermochronology. Tectonics 10, 959–977.

Cosca, M.A., Essene, E.J., Kunk, M.J., Sutter, J.F., 1992. Differential unroofing within the Central Metasedimentary Belt of the Grenville Orogen: Constraints from $^{40}Ar/^{39}Ar$ geochronology. Contributions to Mineralogy and Petrology 110, 211–225.

Cosca, M.A., Essene, E.J., Mezger, K., van der Pluijm, B.A., 1995. Constraints on the duration of tectonic processes: Protracted extension and deep-crustal rotation in the Grenville orogen. Geology 23, 361–364.

Cox, R., Indares, A., 1999a. High pressure and temperature metamorphism of the mafic and ultramafic Lac Espadon suite, Manicouagan Imbricate Zone, eastern Grenville Province. Canadian Mineralogist 37, 335–357.

Cox, R., Indares, A., 1999b. Transformation of Fe-Ti gabbro to coronite, eclogite and amphibolite in the Baie du Nord segment, eastern Grenville Province. Journal of Metamorphic Geology 17, 537–555.

Cox, R., Indares, A., Dunning, G., 1998. Petrology and U–Pb geochronology of mafic, high-P metamorphic coronites from the Tshenukutish domain, eastern Grenville Province. Precambrian Research 90, 59–83.

Cox, R.A., Rivers, T. Reconnaissance laser ablation (LA)-ICP-MS U–Pb zircon and monazite geochronology in reworked Archean basement and Paleoproterozoic supracrustal rocks, Gagnon terrane, Grenville Province of Québec and Labrador. Precambrian Research, in press.

Culshaw, N.G., Jamieson, R.A., Ketchum, J.W.F., Wodicka, N., Corrigan, D., Reynolds, P.H., 1997. Transect across the northwestern Grenville orogen, Georgian Bay, Ontario: Polystage convergence and extension in the lower orogenic crust. Tectonics 16, 966–982.

Culshaw, N., Reynolds, P.H., Check, G., 1991. A $^{40}Ar/^{39}Ar$ study of post-tectonic cooling in the Britt domain of the Grenville Province, Ontario. Earth & Planetary Science Letters 105, 405–415.

Culshaw, N.G., Ketchum, J.W.F., Wodicka, N., Wallace, P., 1994. Deep ductile extension following thrusting in the southwestern Grenville Province, Ontario. Canadian Journal of Earth Sciences 31, 160–175.

Dahl, P.S., Pomfrey, M.E., Foland, K.A., 2004. Slow cooling and apparent tilting of the Adirondack Lowlands, Grenville Province, New York, based on $^{40}Ar/^{39}Ar$ ages. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic tectonic evolution of the Grenville orogen in North America, 197. Geological Society of America Memoir, Boulder, CO, pp. 299–323.

Dallemyer, D., Rivers, T., 1983. Recognition of extraneous argon components through incremental-release of $^{40}Ar/^{39}Ar$ analysis of biotite and hornblende across the

Grenvillian metamorphic gradient in southwestern Labrador. Geochimica et Cosmochimica Acta 47, 413–428.
Darling, R.S., Florence, F.P., Lester, G.W., Whitney, P.R., 2004. Petrogenesis of prismatine-bearing metapelitic gneiss along the Moose River, west-central Adirondacks, New York. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic Tectonic Evolution of the Grenville Orogen in North America, 197. Geological Society of America Memoir, Boulder, CO, pp. 325–336.
Davidson, A., 1984. Identification of ductile shear zones in the southwestern Grenville Province of the Canadian Shield. In: Kröner, A., Greiling, R. (Eds.), Precambrian Tectonics Illustrated. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 263–280.
Davidson, A., 1990. Evidence for eclogite metamorphism in the southwestern Grenville Province. Current Research, part C, Geological Survey of Canada, Paper 90-1C, 113–118.
Davidson, A., 2001. Evidence for and significance of high-level plutonism in the southeast Composite Arc Belt, Grenville Province, Ontario. Geological Association of Canada – Mineralogical Association of Canada (GAC-MAC) annual meeting, St. John's, NL, Abstract volume 26, p. A34.
Davidson, A., van Breemen, O., 1988. Baddeleyite-zircon relationships in coronitic metagabbro, Grenville Province, Ontario: implications for geochronology. Contributions to Mineralogy and Petrology 100, 291–299.
Fryer, B.J., 1983. Report on geochronology—Labrador mapping: summary of geochronological results obtained on samples collected from central Labrador between 1978 and 1980. Geological Survey of Newfoundland and Labrador, Department of Mines and Energy, Open File LAB 617, 35 p.
Gobeil, A., Brisebois, D., Clark, T., Verpaelst, P., Madore, L., Wodicka, N., Chevé, S., 2003. Géologie de la moyenne Côte-Nord. In: Brisebois, D., Clark, T. (Eds.), Géologie et resources minerals de la partie est de la Province de Grenville. Ministère de Richesses Naturelles, Québec, pp. 59–117, DV2002-2003.
Gower, C.F., 1996. The evolution of the Grenville Province in eastern Labrador, Canada. In: Brewer, T.S., Atkin, B.P. (Eds.), Precambrian Crustal Evolution in the North Atlantic region. Geological Society of London, pp. 197–218 (special publication no. 112).
Gower, C.F., Krogh, T.E., 2002. A U–Pb geochronological review of the Proterozoic history of the eastern Grenville Province. Canadian Journal of Earth Sciences 39, 795–829.
Gower, C.F., Hall, J., Kilfoil, G.J., Quinlan, G.M., Wardle, R.J., 1997. Roots of the Labradorian orogen in the Grenville Province in southeast Labrador: Evidence from marine, deep-seismic reflection data. Tectonics 16, 795–809.
Gower, C.F., Heaman, L.M., Loveridge, W.D., Schärer, U., Tucker, R.D., 1991. Grenvillian granitoid plutonism in the eastern Grenville Province. Precambrian Research 51, 315–336.
Gower, C.F., Schärer, U., Heaman, L.H., 1992. The Labradorian orogeny in the Grenville Province, eastern Labrador, Canada. Canadian Journal of Earth Sciences 29, 1944–1957.
Grant, S.M., 1989. Tectonic implications from sapphirine-bearing lithologies, southwest Grenville Province, Canada. Journal of Metamorphic Geology 7, 583–598.
Grujic, D., 2006. Channel flow and continental collision tectonics: an overview. In: Law, R.D., Searle, M.P., Godin, L. (Eds.), Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones. Geological Society, London, pp. 25–37 (Special Publication 268).
Haggart, M.J., Jamieson, R.A., Reynolds, P.H., Krogh, T.E., Beaumont, C., Culshaw, N.G., 1993. Last gasp of the Grenville orogeny—thermochronology of the Grenville Front Tectonic Zone near Killarney, Ontario. Journal of Geology 101, 575–589.
Hamilton, M.A., Emslie, R.F., 1997. Mealy dykes, Labrador: U–Pb badelleyite age and implications for the eastern Grenville Province. Geological Association of Canada—Mineralogical Association of Canada, Program with Abstracts, 22, A62.
Hanmer, S., McEachern, S., 1992. Kinematical and rheological evolution of a crustal-scale ductile thrust zone, central Metasedimentary Belt, Grenville Orogen, Ontario. Canadian Journal of Earth Sciences 29, 1779–1790.
Heaman, L.M., Erdmer, P., Owen, J.V., 2002. U–Pb geochronologic constraints on the crustal evolution of the Long Range Inlier, Newfoundland. Canadian Journal of Earth Sciences 39, 845–865.
Herd, R.K., Ackerman, D., Windley, B.F., Rondot, J., 1986. Sapphirine-garnet rocks, St. Maurice area, Québec: petrology and implications for tectonics and metamorphism. In: Moore, J.M., Davidson, A., Baer, A.J. (Eds.), The Grenville Province, 31. Geological Association of Canada, pp. 241–253 (Special Paper).
Heumann, M.J., Bickford, M.E., Hill, B.M., McLelland, J.M., Selleck, B.W., Jercinovic, M.J., 2006. Timing of anatexix in metapelites from the Adirondack lowlands and southern highlands: A manifestation of the Shawinigan orogeny and subsequent anorthosite-mangerite-charnockite-granite magmatism. Geological Society of America Bulletin 118, 1283–1298, doi:10.1130/B25927.1.
Hoffman, P.F., 1991. Did the breakout of Laurentia turn Gondwanaland inside out? Science 252, 1409–1412.
Hynes, A., Indares, A., Rivers, T., Gobeil, A., 2000. Lithoprobe line 55: integration of out-of-plane seismic results with surface structure, metamorphism, and geochronology, and the tectonic evolution of the eastern Grenville Province. Canadian Journal of Earth Sciences 37, 341–358.
Indares, A., 1995. Metamorphic interpretation of high-pressure–temperature metapelites with preserved growth zoning in garnet, eastern Grenville Province, Canadian Shield. Journal of Metamorphic Geology 13, 475–486.
Indares, A., 1997. Garnet-clinopyroxenites and garnet-kyanite restites from the Manicouagan Imbricate Zone: a case of high-*P*–high-*T* metamorphism in the Grenville Province. Canadian Mineralogist 35, 1161–1171.
Indares, A., 2003. Metamorphic textures and *P*–*T* evolution of high-P granulites from the Lelukuau terrane, NE Grenville Province. Journal of Metamorphic Geology 21, 35–48.
Indares, A., Dunning, G., 1997. Coronitic metagabbro and eclogite from the Grenville Province of western Quebec: interpretation of U–Pb geochronology and metamorphism. Canadian Journal of Earth Sciences 34, 891–901.
Indares, A., Dunning, G., 2004. Crustal architecture above the high-pressure belt of the Grenville Province in the Manicouagan area: new structural, petrologic and U–Pb age constraints. Precambrian Research 130, 199–228.
Indares, A., Dunning, G., Cox, R., Gale, D., Connelly, J., 1998. High-pressure, high-temperature rocks from the base of thick continental crust: geology and age constraints from the Manicouagan Imbricate Zone, eastern Grenville Province. Tectonics 17, 426–440.
Indares, A., Dunning, G., Cox, R., 2000. Tectono-thermal evolution of deep crust in a Mesoproterozoic continental collision setting: the Manicouagan example. Canadian Journal of Earth Sciences 37, 325–340.
Indares, A., Martignole, 1990. Metamorphic constraints on the tectonic evolution of the allochthonous monocyclic belt, Grenville Province, western Quebec. Canadian Journal of Earth Sciences 27, 371–386.
Indares, A., Martignole, J., 1993. Étude régionale du Supergroupe de Wakeham, Province de Grenville. Ministère de l'Énergie et des Ressources, Québec, MB 91–21, 73 pp.
Indares, A., Rivers, T., 1995. Textures, metamorphic reactions and thermobarometry of eclogitized metagabbros: a Proterozoic example. European Journal of Mineralogy 7, 43–56.
Jamieson, R.A., Culshaw, N.G., Corrigan, D., 1995. North-west propagation of the Grenville orogen: Grenvillian structure and metamorphism near Key Harbour, Georgian Bay, Ontario, Canada. Journal of Metamorphic Geology 13, 185–207.
Jamieson, R.A., Ketchum, J.W.F., Slagstad, T., Rivers, T., Culshaw, N.G., 2003. Omphacite and zircon in high-pressure metabasite, Shawanaga domain, western Grenville Province: the truth about some beauties? GAC-MAC Annual Meeting, 28, abstract #325.
Jamieson, R.A., Beaumont, C., Nguyen, M.H., Culshaw, N.G., 2007. Syn-convergent ductile flow in variable-strength continental crust: Numerical models with application to the western Grenville Province. Tectonics 26, TC5005, doi:10.1029/2006TC002036.
Johnson, E.L., Goergen, E.T., Fruchey, B.L., 2004. Right lateral oblique slip movements followed by post-Ottawan (1050–1020 Ma) orogenic collapse along the Carthage-Colton shear zone: Data from the Dana Hill metagabbro body, Adirondack Mountains, New York. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic Tectonic Evolution of the Grenville Orogen in North America, 197. Geological Society of America, Boulder, CO, pp. 357–378 (Memoir).
Jordan, S.L., Indares, A., Dunning, G., 2006. Partial melting of metapelites in the Gagnon terrane below the high-pressure belt in the Manicouagan area (Grenville Province): pressure-temperature (*P*–*T*) and U–Pb age constraints and implications. Canadian Journal of Earth Sciences 43, 1309–1329.
Kellett, R.L., Barnes, A.E., Rive, M., 1994. The deep structure of the Grenville Front: a new perspective from western Quebec. Canadian Journal of Earth Sciences 31, 282–292.
Ketchum, J.W.F., Davidson, A., 2000. Crustal architecture and tectonic assembly of the Central Gneiss Belt, southwestern Grenville Province, Canada: a new interpretation. Canadian Journal of Earth Sciences 37, 217–234.
Ketchum, J.W.F., Krogh, T.E., 1997. U–Pb constraints on high-pressure metamorphism in the Central Gneiss Belt, southwestern Grenville orogen. Geological Association of Canada— Mineralogical Association of Canada, Program with Abstracts, 22, A78.
Ketchum, J.W.F., Krogh, T.E., 1998. U–Pb constraints on high-pressure metamorphism in the southwestern Grenville orogen. Goldschmidt Conference 1998, Abstracts. Mineralogical Magazine 62A, 775–776.
Ketchum, J.W.F., Heaman, L.M., Krogh, T.E., Culshaw, N.G., Jamieson, R.A., 1998. Timing and thermal influence of late orogenic extension in the lower crust: a U–Pb geochronological study from the southwest Grenville orogen, Canada. Precambrian Research 89, 25–45.
Korhonen, F.J., Stout, J.H., 2006. Labradorian orogenesis in the Grenville Province: age constraints from the Wilson Lake terrane, central Labrador. Geological Association of Canada – Mineralogical Association of Canada, Annual Meeting, Montréal, QC, Program with Abstracts, 31, p. 79.
Kretz, R., 1983. Symbols for rock-forming minerals. American Mineralogist 68, 277–279.
Krogh, T.E., 1983. Report on U–Pb zircon and sphene geochronology, Labrador and Newfoundland. Geological Survey of Newfoundland and Labrador, Department of Mines and Energy, Open File LAB 708, 79 p.
Krogh, T.E., 1994. Precise U–Pb ages for Grenvillian and pre-Grenvillian thrusting of Proterozoic and Archean metamorphic assemblages in the Grenville Front tectonic zone, Canada. Tectonics 13, 963–982.
Krogh, T.E., Kamo, S., Gower, C.F., Owen, J.V., 2002. Augmented and reassessed U–Pb geochronological data from the Labradorian–Grenvillian front in the Smokey archipelago, eastern Labrador. Canadian Journal of Earth Sciences 39, 831–843.
Laubscher, H.P., 1983. Detachment, shear and compression in the central Alps. Geological Society of America Memoir 158, 191–211.
Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochob, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natopov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008.

Assembly, configuration and breakup of Rodinia: a synthesis. Precambrian Research 160, 179–210.
Lopez-Martinez, M., York, D., 1983. Further thermochronometric unravelling of the age and paleomagnetic record of the southwest Grenville Province. Canadian Journal of Earth Sciences 20, 953–960.
Ludden, J., Hynes, A., 2000. The Lithoprobe Abitibi-Grenville transect: two billion years of crust formation and recycling in the Precambrian Shield of Canada. Canadian Journal of Earth Sciences 37, 459–476.
Madore, L., Verpaelst, P., Brisebois, D., Hocq, M., Dion, D.J., 1999. Géologie de la région du lac Allard (SNRC 12L/11). Ministère de Richesses naturelles, Québec, RG 96-05, 30 pp.
Magloughlin, J.F., van der Pluijm, B.A., Essene, E.J., Hall, C., 1997. $^{40}Ar/^{39}Ar$ ages from hornblendes in the western Adirondacks (Highlands and Lowlands), New York: Implications for the history of the Carthage-Colton shear zone. Geological Association of Canada – Mineralogical Association of Canada, Program with Abstracts, 22, A97.
Martignole, J., Calvert, A.J., 1996. Crustal-scale shortening and extension across the Grenville Province of western Quebec. Tectonics 15, 376–386.
Martignole, J., Martelat, J.-E., 2005. Proterozoic mafic dykes as monitors of HP granulite facies metamorphism in the Grenville Front Tectonic Zone (western Quebec). Precambrian Research 138, 183–207.
Martignole, J., Friedman, R., 1998. Geochronological constraints on the last stages of terrane assembly in the central part of the Grenville Province (Quebec). Precambrian Research 92, 145–164.
Martignole, J., Pouget, P., 1994. A two-stage emplacement for the Cabonga allochthon (central part of the Grenville Province): evidence for orthogonal and oblique collision during the Grenville orogeny. Canadian Journal of Earth Sciences 31, 1714–1726.
Martignole, J., Reynolds, P., 1997. $^{40}Ar/^{39}Ar$ thermochronology along a western Québec transect of the Grenville Province, Canada. Journal of Metamorphic Geology 15, 283–296.
Martignole, J., Machado, N., Indares, A., 1994. The Wakeham Terrane: a Mesoproterozoic terrestrial rift in the eastern part of the Grenville Province. Precambrian Research 68, 291–306.
McDougall, I., Harrison, T.M., 1999. Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method, second ed. Oxford University Press, Oxford, UK, 212 pp.
McEachern, S.J., van Breemen, O., 1993. Age of deformation within the Central Metasedimentary Belt boundary thrust zone, southwest Grenville orogen: constraints on the collision of the Mid-Proterozoic Elzevir terrane. Canadian Journal of Earth Sciences 30, 1155–1165.
McLelland, J., Daly, J.S., McLelland, J.M., 1996. The Grenville orogenic cycle (ca. 1350–1000 Ma): an Adirondack perspective. Tectonophysics 265, 1–28.
McLelland, J., Hamilton, M., Selleck, B., McLelland, J., Walker, D., Orrell, S., 2001. Zircon U–Pb geochronology of the Ottawan Orogeny, Adirondack Highlands, New York: regional and tectonic implications. Precambrian Research 109, 39–72.
Mezger, K., Rawnsley, C.M., Bohlen, S.R., Hanson, G.N., 1991. U–Pb garnet, sphene, monazite, and rutile ages: Implications for the duration of high-grade metamorphism and cooling histories, Adirondack Mtns, New York. Journal of Geology 99, 415–428.
Miller, B.V., Dunning, G.R., Barr, S.M., Raeside, R.P., Jamieson, R.A., Reynolds, P.H., 1996. Magmatism and metamorphism in a Grenvillian fragment: U–Pb and $^{40}Ar/^{39}Ar$ ages from the Blair River Complex, northern Cape Breton Island, Nova Scotia. Geological Society of America Bulletin 108, 127–140.
Moore, J.M., Thompson, P.H., 1980. The Flinton Group: a late Precambrian metasedimentary succession in the Grenville Province. Canadian Journal of Earth Sciences 17, 221–229.
Owen, J.V., Rivers, T., Gower, C.F., 1986. The Grenville Front on the Labrador coast. In The Grenville Province. In: J.M. Moore, A. Davidson, A.J. Baer (Eds.), Geological Association of Canada Special Paper 31, pp. 95–106.
Owen, J.V., Dallmeyer, R.D., Gower, C.F., Rivers, T., 1988. Metamorphic conditions and $^{40}Ar/^{39}Ar$ contrasts across the Grenville Front zone, coastal Labrador, Canada. Lithos 21, 13–35.
Peck, W.H., DeAngelis, M.T., Meredith, M.T., Morin, E., 2005. Polymetamorphism of marbles in the Morin terrane, Grenville Province, Quebec. Canadian Journal of Earth Sciences 42, 1949–1965.
Rey, P., Vanderhaegue, O., Teyssier, C., 2001. Gravitational collapse of the continental crust: definition, regimes and modes. Tectonophysics 342, 435–449.
Reynolds, P.H., 1989. $^{40}Ar/^{39}Ar$ dating of the Mealy dykes of Labrador: paleomagnetic implications. Canadian Journal of Earth Sciences 26, 1567–1573.
Reynolds, P.H., Culshaw, N.G., Jamieson, R.A., Grant, S.L., McKenzie, K.J., 1995. $^{40}Ar/^{39}Ar$ traverse—Grenville Front Tectonic Zone to Britt domain, Grenville Province, Ontario, Canada. Journal of Metamorphic Geology 13, 209–221.
Rivers, T., 1983a. The northern margin of the Grenville Province in western Labrador—anatomy of an ancient orogenic front. Precambrian Research 22, 41–73.
Rivers, T., 1983b. Progressive metamorphism of pelitic and quartzofeldspathic assemblages in the Grenville Province of western Labrador—tectonic implications of bathozone 6 assemblages. Canadian Journal of Earth Sciences 20, 1791–1804.
Rivers, T., 1997. Lithotectonic elements of the Grenville Province: review and tectonic implications. Precambrian Research 86, 117–154.
Rivers, T., Indares, A., 2006. Assembly of a 60 km crustal section through the Grenville orogen from eclogites through granulites to the non-metamorphic lid—implications for Grenvillian tectonic evolution. Geological Association of Canada – Mineralogical Association of Canada, Abstracts, 31, 128.
Rivers, T., Mengel, F.C., 1988. Contrasting assemblages and petrogenetic evolution of corona and non-corona gabbros in the Grenville province of western Labrador. Canadian Journal of Earth Sciences 25, 1629–1648.
Rivers, T., Martignole, J., Gower, C.F., Davidson, A., 1989. New tectonic divisions of the Grenville Province, southeast Canadian shield. Tectonics 8, 63–84.
Rivers, T., van Gool, J.A.M., Connelly, J.N., 1993. Contrasting tectonic styles in the northern Grenville Province: implications for the dynamics of orogenic fronts. Geology 21, 1127–1130.
Rivers, T., Ketchum, J., Indares, A., Hynes, A., 2002. The High Pressure belt in the Grenville Province: architecture, timing and exhumation. Canadian Journal of Earth Sciences 39, 867–893.
Rivers, T., Culshaw, N., Hynes, A., Indares, A., Jamieson, R., Martignole, J. The Grenville Orogen. In: Variations in Tectonic Styles Revisited: A Lithoprobe Perspective, submitted for publication.
Rosenberg, C.L., Handy, M.R., 2005. Experimental deformation of partially melted granite revisited: implications for the continental crust. Journal of Metamorphic Geology 23, 19–28.
Rosenberg, C., Medvedev, S., Handy, M.R., 2007. Rheological effects of very small melt fractions (0.01–0.07) in crustal rocks. Geophysical Research Abstracts 9, 03421.
Schärer, U., Gower, C.F., 1988. Crustal evolution in eastern Labrador: Constraints from precise U–Pb ages. Precambrian Research 38, 405–421.
Schwarz, S., 1998. Structural, metamorphic and tectonic studies in central Gagnon terrane. MSc thesis, Memorial University, St. John's, NL.
Scott, D.J., Machado, N., Hanmer, S., Gariépy, C., 1993. Dating ductile deformation using U–Pb geochronology: examples from the Gilbert River belt, Grenville Province, Labrador. Canadian Journal of Earth Sciences 30, 1458–1469.
Slagstad, T., Hamilton, M.A., Jamieson, R.A., Culshaw, N.G., 2004. Timing and duration of melting in the mid orogenic crust: Constraints from U–Pb (SHRIMP) data, Muskoka and Shawanaga domains, Grenville Province, Ontario. Canadian Journal of Earth Sciences 41, 1339–1365.
Spear, F.S., Markussen, J.C., 1997. Mineral zoning, *P-T-X-M* phase relations, and metamorphic evolution of some Adirondack granulites. Journal of Petrology 38, 757–783.
Streepey, M.M., Johnson, E.L., Mezger, K., van der Pluijm, B.A., 2001. The early history of the Carthage–Colton Shear Zone, Grenville Province, New York. Journal of Geology 109, 479–492.
Streepey, M.M., Lithgow-Bertelloni, C., van der Pluijm, B.A., Essene, E.J., Magloughlin, J.F., 2004. Exhumation of a collisional orogen: A perspective from the North American Grenville Province. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic Tectonic Evolution of the Grenville Orogen in North America, 197. Geological Society of America Memoir, Boulder, CO, pp. 391–410.
Timmermann, H., Parrish, R.R., Jamieson, R.A., Culshaw, N.G., 1997. Time of metamorphism beneath the Central Metasedimentary Belt Boundary Thrust Zone, Grenville Orogen, Ontario: Accretion at 1080 Ma? Canadian Journal of Earth Sciences 34, 1023–1029.
Timmermann, H., Jamieson, R.A., Parrish, R.R., Culshaw, N.G., 2002. Coeval migmatites and granulites, Muskoka domain, southwestern Grenville Province, Ontario. Canadian Journal of Earth Sciences 39, 239–258.
Tohver, E., Teixeira, B., van der Pluijm, B., Geraldes, M.C., Bettencourt, J.S., Rizzotto, G., 2006. Restored transect across the exhumed Grenville orogen of Laurentia and Amazonia. Geology 34, 669–672.
Tollo, R.P., Corriveau, L., McLelland, J., Bartholemew, M.J., 2004. Proterozoic evolution of the Grenville orogen in North America: An introduction. In: Tollo, R.P., Corriveau, L., McLelland, J., Bartholomew, M.J. (Eds.), Proterozoic Tectonic Evolution of the Grenville Orogen in North America, 197. Geological Society of America Memoir, Boulder, CO, pp. 1–18.
van Breemen, O., Corriveau, L., 2005. U–Pb age constraints on arenaceous and volcanic rocks of the Wakeham Group, eastern Grenville Province. Canadian Journal of Earth Sciences 42, 1677–1697.
van der Pluijm, B.A., Carlson, K.A., 1989. Extension in the Central Metasedimentary Belt of the Ontario Grenville: timing and tectonic significance. Geology 17, 161–164.
van Gool, J.A.M., 1992. The Grenville Front foreland fold-thrust belt in southwestern Labrador: mid-crustal structural and metamorphic development of a Proterozoic orogenic thrust wedge. PhD thesis. Memorial University, St. John's, Nfld.
van Gool, J.A.M., Rivers, T., Calon, T., 2008. The Grenville Front zone, Gagnon terrane, southwestern Labrador: configuration of a mid-crustal foreland fold-thrust belt. Tectonics 27, 35, doi:10.1029/2006TC002095.
van Nostrand, T.S., 1988. Geothermometry–geobarometry and $^{40}Ar/^{39}Ar$ incremental release dating in the Sandwich Bay area, Grenville Province, eastern Labrador. MSc thesis, Memorial University, St. John's, NL, 203 pp.
Verpaelst, P., Madore, L., Brisebois, D., Hocq, M., Dion, D.J., 1999. Géologie de la région du lac Jérôme, du lac Sanson et de la petite rivière de l'Abbé-Huard (SNRC 12L/13, 12/L14, 12M/03). Ministère de Richesses Naturelles, Québec, RG 96-05, 38 pp.
Wardle, R.J., Rivers, T., Gower, C.F., Nunn, G.A.G., Thomas, A., 1986. The northeastern Grenville Province: New insights. In: The Grenville Province, J.M.Moore, A. Davidson and A.J. Baer (Eds.), Geological Association of Canada, Special Paper 31, 13-29.
Warren, C.J., Jamieson, R.A., Beaumont, C., Nguyen, M., 2006. Does east meet west? Insights into the thermal-tectonic evolution of the Central Gneiss Belt and Manicouagan Imbricate Zone from numerical modelling. Geological Association of Canada – Mineralogical Association of Canada, Montreal 2006, Abstracts, 31, 160.

Wasteneys, H.A., Kamo, S.L., Moser, D., Krogh, T.E., Gower, C.F., Owen, J.V., 1997. U–Pb geochronological constraints on the geological evolution of Pinware terrane and adjacent areas, Grenville Province, southeastern Labrador, Canada. Precambrian Research 81, 101–128.

White, D.J., Forsyth, D.A., Asudeh, I., Carr, S.D., Wu, H., Easton, R.M., Mereu, R.F., 2000. A seismic-based cross-section of the Grenville Orogen in southern western Quebec. Canadian Journal of Earth Sciences 37, 183–192.

Williams, P.F., Jiang, D., Lin, S., 2006. Interpretation of deformation fabrics of infrastructure zone rocks in the context of channel flow and other tectonic models. In: Law, R.D., Searle, M.P., Godin, L. (Eds.), Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones, 268. Geological Society, London, pp. 221–235 (special publication).

Wodicka, N., Ketchum, J.W.F., Jamieson, R.A., 2000. Grenvillian metamorphism of monocyclic rocks, Georgian Bay, Ontario: implications for convergence history. Canadian Mineralogist 38, 471–510.

Wodicka, N., David, J., Parent, M., Gobeil, A., Verpaelst, P., 2003. Géochronologie U–Pb et Pb-Pb de la région de Sept-Îles–Natashquan, Province de Grenville, moyenne Côte-Nord. In: Brisebois, D., Clark, T. (Eds.), Géologie et resources minerales de la partie est de la Province de Grenville. Ministère de Richesses Naturelles, Québec, pp. 59–117 (DV2002-2003).

Yang, P., Indares, A., 2005. Mineral zoning, phase relations, and *P*–*T* evolution of high-pressure granulites from the Lelukuau terrane, northeastern Grenville Province. Canadian Mineralogist 43, 443–462.