The High Pressure belt in the Grenville Province: architecture, timing, and exhumation[1]

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Abstract: We propose that the Grenvillian allochthonous terranes may be grouped into High Pressure (HP) and Low Pressure (LP) belts and examine the HP belt in detail in the western and central Grenville Province. The HP belt is developed in Paleo- and Mesoproterozoic rocks of the pre-Grenvillian Laurentian margin and characterized by Grenvillian eclogite and co-facial HP granulite in mafic rocks. Pressure–temperature (*P–T*) estimates for eclogite-facies conditions in well-preserved assemblages are about 1800 MPa and 850°C. In the central Grenville Province, HP rocks formed at ~1060–1040 Ma and underwent a single stage of unroofing with transport into the upper crust by ~1020 Ma, whereas farther west they underwent two stages of unroofing separated by penetrative mid-crustal recrystallization before transport to the upper crust at ~1020 Ma. Unroofing processes were comparable in the two areas, involving both thrusting and extensional faulting in an orogen propagating into its foreland by understacking. In detail, thrusting episodes preceded extension in the western Grenville Province, whereas in the central Grenville Province, they were coeval, resulting in unroofing by tectonic extrusion. In the central Grenville Province, the footwall ramp is well preserved, but any former ramp in the western Grenville Province was obliterated by later lower crustal extensional flow. Continuation of the HP belt into the eastern Grenville Province is not established, but likely on geological grounds. However, the pattern of deep crustal seismic reflection in the Lithoprobe Eastern Canadian Shield Onshore–Offshore Transect (ECSOOT) line contrasts with that father west, suggesting that, if present, the HP rocks were exhumed by a different mechanism.

Résumé : Nous proposons de regrouper les terranes allochtones grenvilliens en ceintures de haute pression (HP) et de basse pression (LP) et nous examinons en détail la ceinture HP dans l'ouest et le centre de la Province de Grenville. Elle s'est développée dans des roches paléoprotérozoïques et mésoprotérozoïques de la marge laurentienne prégrevillienne et elle est caractérisée par de l'éclogite grenvillienne et de granulite co-faciale HP dans des roches mafiques. Les estimations *P–T* pour des conditions au faciès de l'éclogite dans des assemblages bien préservés sont d'environ 1800 MPa et de 850 ºC. Dans le centre de la Province de Grenville, les roches HP se sont formées vers 1060–1040 Ma et elles ont subi un seul stage d'enlèvement de la couverture et de transport à la croûte supérieure vers environ 1020 Ma, alors que plus à l'ouest elles ont subi deux stages d'enlèvement de la couverture séparés par une recristallisation mi-crustale pénétrante avant le transport vers la croûte supérieure aux environs de 1020 Ma. Les processus d'enlèvement de la couverture sont comparables dans les deux régions, impliquant à la fois du chevauchement et des failles d'extension dans un orogène qui se propageait dans son avant-pays par empilement par le dessous. En détail, les épisodes de chevauchement ont précédé l'extension dans Province de Grenville occidentale, alors que dans la Province de Grenville centrale ils étaient contemporains, ce qui a eu comme effet d'enlever la couverture par extrusion tectonique. Dans la Province de Grenville centrale, la rampe de l'éponte inférieure est bien préservée mais toute rampe ancienne dans la Province de Grenville occidentale a été oblitérée par de subséquents écoulements d'extension dans la croûte inférieure. Le prolongement de la ceinture HP dans la Province de Grenville orientale n'est pas établi, mais c'est probable d'un point de vue géologique. Toutefois, le patron de réflexion sismique profond dans la croûte de la ligne Lithoprobe ECSOOT contraste avec celui plus à l'ouest, suggérant que, si elles avaient été présentes, les roches HP auraient été exhumées par un mécanisme différent.

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Introduction

High pressure (HP) rocks, including eclogite, retrogressed eclogite, and co-facial high pressure granulite-facies rocks, are a widespread but volumetrically minor component of most orogenic belts. Nonetheless, they have attracted considerable interest recently, especially in terms of their petrology and estimated depth of burial (e.g., Carswell 1990; Coleman and Wang 1995, and papers therein), and with respect to the mechanisms of their burial and exhumation (e.g., Platt 1986; Hynes and Eaton 1999; Hynes 2002). HP rocks are commonly poorly preserved in Precambrian orogens, and in this context the discoveries of two large areas with evidence of HP rocks in the Mesoproterozoic Grenville orogen of the Canadian Shield are of particular interest for the light they shed on Precambrian tectonic processes. Since the initial reports by Culshaw et al. (1983), Davidson (1990), and Indares (1993), the Grenvillian HP rocks have been the subject of a concerted research effort, and there now exists a considerable body of published information pertaining to their petrology, estimated *P–T* conditions, and the age of HP metamorphism, as well as tectonic models for their formation and exhumation. However, the two areas of HP rocks, located in the western and central Grenville Province, are separated by over 800 km and the only paper in which they are examined together, by Ludden and Hynes (2000), focused primarily on interpretations of crustal architecture derived from Lithoprobe cross-sections. The purpose of this paper is to provide an overview of the spatial distribution of the HP rocks in map and cross-section and to compare and contrast their petrology, age, preservation, and tectonic setting in the two areas of outcrop to evaluate their mechanisms of formation and unroofing. In so doing, we highlight the need for additional geochronological data on the timing of eclogite-facies metamorphism, especially in the western Grenville Province, and we point out important contrasts in the unroofing histories of eclogite-facies assemblages between the western and central Grenville Province. We also describe several systems of southeast-dipping, orogen-scale thrust and normal faults that we relate to the unroofing of the HP rocks. In addition, we compare the northwest-vergent architecture in the western and central Grenville Province, where HP rocks are preserved, with the doubly vergent seismic fabrics imaged in the marine Lithoprobe Eastern Canadian Shield Onshore–Offshore Transect (ECSOOT) crustal profile at the eastern end of the Grenville Province, where HP rocks have not been reported.

Terminology

In this study, we consider the Pinwarian (~1470–1450 Ma) and Elzevirian (~1250–1220 Ma) orogenies to be accretionary events that preceded collisional Grenvillian orogenesis (~1190–980 Ma), and we use the working subdivision of the Grenvillian event of Rivers (1997) into the compressional Shawinigan, Ottawa and Rigolet orogenies, with age ranges of ~1190–1140 Ma, 1080–1020 Ma, and 1000–980 Ma, respectively. Rivers (1997) originally proposed the term pulse for these events, but McLelland et al. (2001) have argued cogently for use of orogeny rather than pulse with respect to the Ottawa event, so we conform to their nomenclature here.

The term *terrane* is firmly embedded in the Grenvillian literature. It is used in the sense of a metamorphic terrane, i.e., a tectonically bounded region of metamorphic rocks that has undergone a metamorphic and structural history distinctly different from that of adjacent terranes (Rivers et al. 1989; Howell 1995). There is no connotation of an exotic origin. As described in more detail in this paper, the terranes that make up the HP belt are inferred to have been part of the Mesoproterozoic Laurentian margin prior to Grenvillian orogenesis and thus were not exotic. However, they experienced Grenvillian metamorphic histories very different from those of the terranes currently adjacent to them.

The term *high pressure* (HP) is used in this paper to encompass the Grenvillian eclogite- and co-facial HP granulite-facies rocks previously described in the literature but to exclude medium pressure granulites, which are widespread in the Grenville Province. Our aim is to focus attention on rocks that we infer developed in a deep tectonic setting near the base of the doubly thickened orogenic crust. It is well known that eclogite-facies assemblages develop at different *P–T* conditions depending upon the bulk composition of the rock (e.g., Spear 1993). However, all eclogites imply $P > {\sim}1400$ MPa, so this may be considered an arbitrary lower pressure limit for the rocks in the HP belt.

Five crustal-scale cross-sections through the Grenville orogen, largely based on the results of Lithoprobe seismic experiments, are illustrated in this paper and used to interpret the evolution of the HP rocks. Several major compressional structures visible on some of these sections were subsequently variably overprinted in extension. In naming these structures at the different stages of their evolution, we have retained the first part of the name, but changed the latter part to indicate the nature of the displacement, e.g., the compressional Allochthon Boundary thrust was reworked in extension as the Allochthon Boundary detachment.

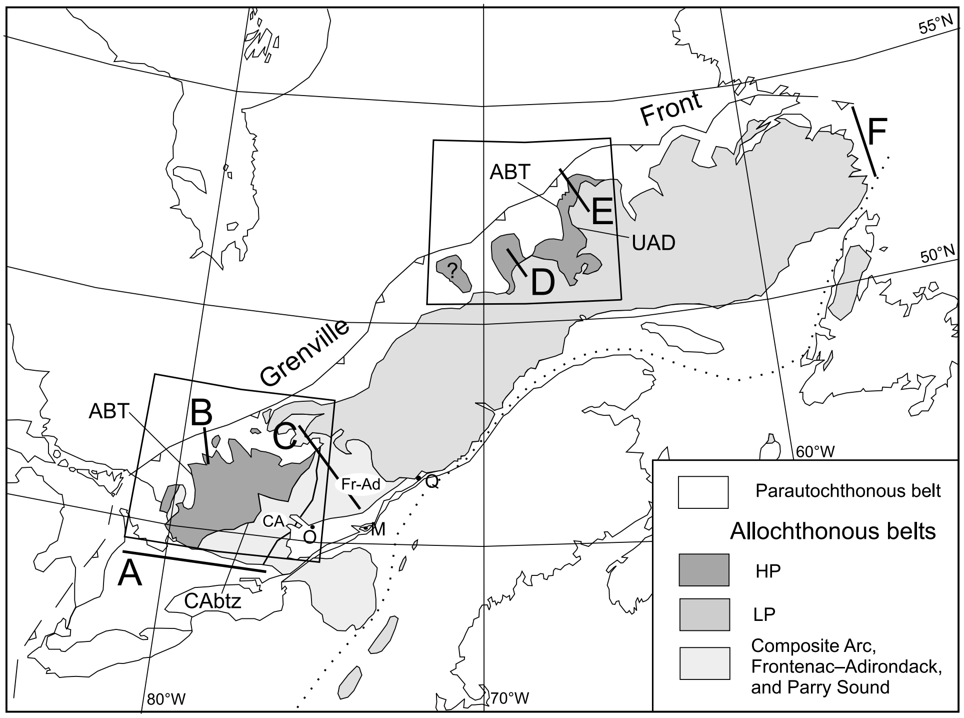
Locations of HP rocks, definition and extent of the HP belt

Known occurrences of HP rocks of Grenvillian age are ~30–150 km from the Grenville Front, the northwestern margin of the Grenville Province (Fig. 1). In Fig. 1, their locations are shown in the context of the first-order tectonic subdivision of Rivers et al. (1989, incorporating minor modifications; see figure caption). The significance of the HP rocks was not known at the time the tectonic subdivision was originally proposed, but it is clear from Fig. 1 that they occur along the interface between the Parautochthonous and Allochthonous belts. From the distribution of HP rocks in Fig. 1, we infer that they also form a continuous or semi-continuous belt along the orogen. This was referred to as the *HP belt* by Ludden and Hynes (2000), following initial use of the term by Indares et al. (1998) for the HP rocks in the central Grenville Province. We should point out that we fully expect the extent of the HP belt to be modified as a result of future work, especially in central Quebec, which has not yet been mapped in detail, and we discuss the possible continuation of the belt in the eastern Grenville Province at the end of this contribution.

Regional tectonic setting of the HP belt

It is appropriate to review current understanding of the tectonic settings of the Parautochthonous and Allochthonous

Fig. 1. First-order tectonic subdivision of the Grenville Province proposed in this paper showing locations of the High Pressure (HP) and Low Pressure (LP) belts (subdivisions of the Allochthonous Polycyclic belt of Rivers et al. 1989). Minor modifications to the location of the Allochthon Boundary thrust (ABT) in the western Grenville Province are from Davidson (1998) and Ketchum and Davidson (2000); in the central Grenville Province, the ABT is herein redefined as the lower boundary of the Molson Lake terrane, rather than the upper boundary as originally proposed, so as to include Molson Lake terrane in the HP belt. The Composite Arc belt (CA) and Frontenac–Adirondack belt (Fr-Ad) are defined by Carr et al. (2000). CAbtz, Composite Arc boundary thrust zone; UAD, Upper Allochthon detachment; M, Montreal; O, Ottawa; Q, Quebec. Boxes show the locations of Figs. 2 and 3. Heavy lines labeled A–E show locations of cross-sections in Figs. 9 and 10. Cross-section F is discussed in the text.



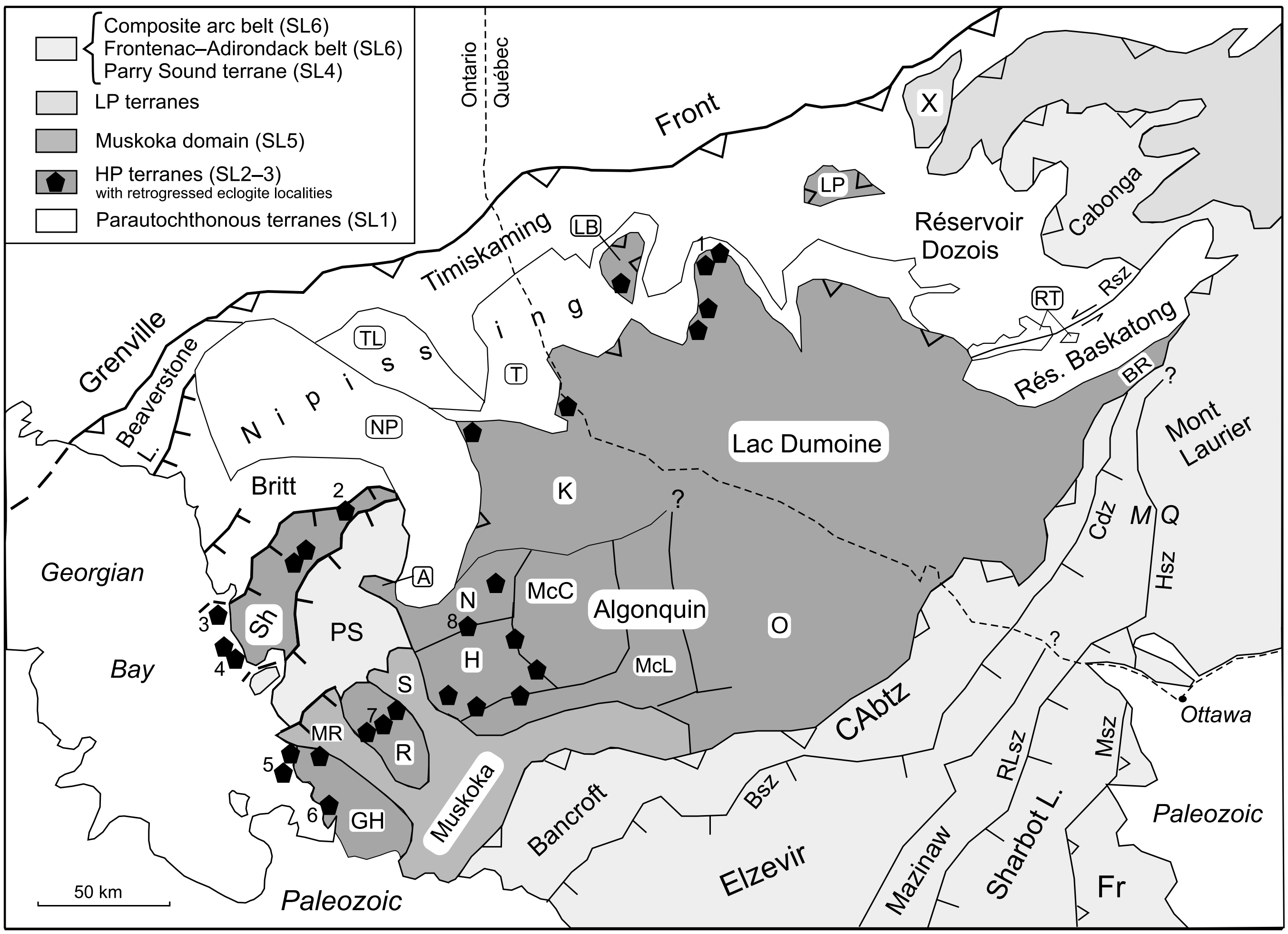
belts in the Grenville Province as they pertain to the HP belt. All three belts were defined on the basis of their Grenvillian tectonometamorphic signatures (Rivers et al. 1989; Ludden and Hynes 2000). The Parautochthonous belt, the lowest structural unit in the Grenville Province, is composed of lithologic units that locally can be correlated with less deformed and metamorphosed equivalent units in the foreland to the northwest of the orogen. Grenvillian planar fabrics in the Parautochthonous belt are generally subparallel to the Grenville Front, and contractional displacements on front-parallel structures have resulted in a rise in metamorphic grade towards the interior of the orogen (Haggart et al. 1993; Rivers et al. 1993; Jamieson et al. 1995).

The structurally overlying belts in the orogen are referred to as allochthonous, the term being used in the sense of far-traveled during Grenvillian tectonism, but not necessarily exotic. Rivers et al. (1989) originally distinguished two allochthonous belts on the basis of the presence or absence of a pre-Elzevirian and (or) Grenvillian metamorphic history. These were referred to as (*i*) the Allochthonous Polycyclic belt, comprising terranes that preserved evidence of Paleoproterozoic to early Mesoproterozoic metamorphism overprinted by Grenvillian metamorphism, and (*ii*) the Allochthonous Monocyclic belt, consisting of terranes composed of units < ~1300 Ma that carried evidence for a late Mesoproterozoic metamorphic imprint of Elzevirian and (or) Grenvillian age. Recognition of the HP belt as a first order tectonic element of the Grenville Province suggests that this subdivision can be usefully revised to facilitate understanding of Grenvillian tectonics. In Fig. 1, we have grouped the allochthonous terranes into high pressure and low pressure (LP) belts. The HP belt, as noted earlier, is defined on the basis of the presence (or inferred former presence) of Grenvillian HP rocks, whereas the structurally overlying LP belt is characterized by the absence of such rocks. This terminology is used throughout the remainder of this paper.

With respect to the tectonic subdivision of Carr et al. (2000), the Parautochthonous, HP, and LP belts are all components of their “Laurentia and Laurentian Margin.” Carr et al. (2000) subdivided the Allochthonous Monocyclic belt of Rivers et al. (1989) into the “Composite Arc belt” and the “Frontenac–Adirondack belt.” This nomenclature reflects current understanding that the arc and (or) back-arc terranes comprising the Composite Arc belt were assembled outboard of Laurentia at ~1250–1225 Ma during the Elzevirian orogeny, shortly before their accretion to Laurentia (see also Rivers 1997; Corriveau and van Breemen 2000; Rivers and Corrigan 2000; Hanmer et al. 2000). The Frontenac–Adirondack belt and contiguous parts of the Composite Arc belt carry evidence for penetrative deformation and greenschist- to granulite-facies metamorphism at 1190–1140 Ma (Shawinigan orogeny), suggesting that they were amalgamated at that time (Carr et al. 2000; Hanmer et al. 2000).

Figure 1 shows that the HP belt is sandwiched between

Fig. 2. Map of part of the Grenville Province of Ontario and western Quebec showing the distribution of parautochthonous and allochthonous terranes and domains and relict eclogite assemblages (slightly modified from Davidson 1998). Locations of garnet–clinopyroxene assemblages in Parry Sound shear zone and Muskoka domain are not shown, as they do not contain evidence for a former eclogite-facies mineralogy. A, Ahmic domain; BR, Baskatong ramp; Bsz, Bancroft shear zone; CAbtz, Composite Arc boundary thrust zone; Cdz, Cayamant deformation zone; Fr, Frontenac terrane; GH, GoHome domain; H, Huntsville domain; Hsz, Heney shear zone; K, Kiosk domain; LB, Lac Booth klippe; LP, Lac Perch klippe; McC, McCraney domain; McL, McClintock domain; MR, Moon River domain; Msz, Maberly shear zone; N, Novar domain; NP, Nipissing domain; O, Opeongo domain; PS, Parry Sound domain; R, Rosseau domain; Rés, Réservoir; RLsz, Robertson Lake shear zone; Rsz, Renzy shear zone; RT, Renzy terrane; S, Seguin domain; Sh, Shawanaga domain; T, Tomiko domain; TL, Tilden Lake domain; X, X terrane. M and Q are marble and quartzite domains from Corriveau and van Breemen (2000). Maberly shear zone is the site of the Frontenac–Adirondack boundary thrust zone in this area. SL 1–6 refer to structural levels — see text. Numbers 1–8 are dated retrogressed eclogite localities for which results are as follows (upright numerals indicate metamorphic age, italics indicate protolith age): 1, *1403* $^{+14}_{-11}$ *Ma;* 2, *1085 ± 3 Ma;* 3, *1121* $^{+12}_{-10}$ *Ma, 997 ± 4 Ma;* 4, *1093 ± 3 Ma;* 5, *1088 ± 2 Ma;* 6, *1469 ± 11 Ma, 1089 ± 2 Ma;* 7, *ca. 1450 Ma, 1063* $^{+35}_{-48}$ *Ma, 1063 ± 4 Ma;* 8, *1396* $^{+15}_{-13}$ *Ma, 1048 ± 30 Ma* (1 is from Indares and Dunning 1997, 2–8 are from Ketchum and Krogh 1998).



two belts of Laurentian crust that experienced very different styles and intensities of Grenvillian structural and metamorphic reworking. The boundaries of the HP belt are first-order structural features that were active during Grenvillian orogenesis. The lower boundary, known as the Allochthon Boundary thrust, was originally defined by Rivers et al. (1989), although its precise location has been revised slightly in Fig. 1 (see figure caption for details). The upper boundary is marked by a system of shear zones with normal-sense displacement. The continuity of the Parautochthonous, HP, and LP belts and their structural boundaries (Fig. 1) implies that there is a broad coherence to the orogen at this scale. However, there are also significant along-strike contrasts that are discussed in more detail later in the text.

Western Grenville Province

In the northwestern part of the Grenville Province in Ontario (Fig. 2), the architecture, metamorphism and interrelationships of terranes and domains have been investigated in detail and the threefold lithotectonic subdivision shown in Fig. 1 has been refined into at least six structural levels (SLs; e.g., Culshaw et al. 1997; Ketchum and Davidson 2000), with the lowest (SL1) being adjacent to the Grenville Front and the highest (SL6) including terranes and domains of the Composite Arc and Frontenac–Adirondack belts.

Parautochthonous belt

In the region shown in Fig. 2, the Parautochthonous belt (SL1 of Ketchum and Davidson 2000) comprises the reworked continuation of the adjacent Archean Superior Province and variably gneissic granitoid intrusions and subordinate metasediments of late Paleoproterozoic to Mesoproterozoic age (e.g., Easton 1992). The northwestern part of the belt, known as the Grenville Front tectonic zone (GFTZ), is characterized by front-parallel structures with dip-parallel lineations, and the various domains and terranes of the Parautochthonous belt are linked lithologically to the foreland and each other by the presence of deformed mafic dykes belonging to, or having chemical affinities with, the ~1235 Ma Sudbury swarm (Krogh et al. 1987; Dudás et al. 1994; Indares and Dunning 1997; Ketchum and Davidson 2000). In the southern Parautochthonous belt in Ontario, *P–T* conditions of ~1200 MPa / 800°C, developed at ~1060 Ma during the Ottawa orogeny, were followed by a period of isothermal decompression (Anovitz and Essene 1990; Jamieson et al. 1995). Farther east in Réservoir Dozois terrane, estimated *P–T* conditions of 900–1000 MPa and 750°C (undated) were also followed by quasi-isothermal decompression (Indares and Martignole 1990). In contrast, in the GFTZ in Ontario, evidence for two high-grade metamorphic events has been recorded at ~1060 Ma and ~980 Ma (Ottawa and Rigolet orogenies, respectively; Jamieson et al. 1995).

HP belt

The HP belt in Ontario and western Quebec, comprising SL2 and SL3 of Ketchum and Davidson (2000), is composed of a number of domains referred to here collectively as Algonquin terrane in Ontario and Lac Dumoine terrane in Quebec. In addition, there are two klippen situated northwest of the main area of outcrop (Fig. 2). The HP terranes, which appear to lack units of Archean age, consist of Paleo- and Mesoproterozoic metagranitoid rocks emplaced during two magmatic episodes at ~1715–1600 and ~1470–1430 Ma (Krogh 1991; Nadeau and van Breemen 1998; Ketchum and Davidson 2000). The HP terranes lack Sudbury metadiabase, but are characterized by the presence of the 1170–1150 Ma, coronitic Algonquin metagabbro (Davidson and van Breemen 1988; Heaman and LeCheminant 1993) and by pods and lenses of retrogressed eclogite with protolith ages of ~1470–1403 Ma (Indares and Dunning 1997; Ketchum and Krogh 1997, 1998). The mutually exclusive geographic distributions of Sudbury metadiabase in the Parautochthonous belt and Algonquin metagabbro and retrogressed eclogite relics in the HP belt have proved to be a useful tool for delineation of the boundary between the two belts in the field (Ketchum and Davidson 2000).

The Algonquin and Lac Dumoine terranes consist predominantly of upper amphibolite- and granulite-facies gneisses (Indares and Martignole 1990; Davidson 1998). Eclogite-facies relics, associated with pods and lenses of ultramafic and anorthositic rocks, are restricted mainly to high-strain zones between and within the terranes and domains (Fig. 2; Davidson 1991, 1998; Culshaw et al. 1997). Evidence for HP metamorphism in the retrogressed eclogite-facies rocks is generally indirect, due to extensive granulite- and amphibolite-facies overprinting. Petrographic relationships suggestive of the original HP character are described in more detail later in the text.

Age of HP metamorphism

The timing of HP metamorphism in the western Grenville Province remains controversial despite detailed U/Pb study. The controversy hinges on interpretation of relationships between the retrogressed eclogite and spatially associated coronitic Algonquin metagabbro. The retrogressed eclogite bodies contain undisputed evidence of their former HP character (see later in the text), whereas the question of whether the 1170–1150 Algonquin metagabbro underwent the HP event remains contentious. The metagabbro is characterized by complex coronas of orthopyroxene, clinopyroxene, and garnet–clinopyroxene symplectite, separating olivine and plagioclase. The presence of unreacted olivine and plagioclase and the absence of omphacite is open to two alternative interpretations: (*i*) that the Algonquin gabbro did not undergo the HP event, with the corollary that the HP event must therefore have predated emplacement of the gabbro; or (*ii*) that the Algonquin gabbro did undergo burial to the HP metamorphic conditions, but failed to react because of kinetic constraints imposed by the coarse grain size and dry nature of the original igneous assemblage. This second possibility is in part based on evidence from the Western Gneiss region of Norway, in which eclogitization of granulite-facies rocks is restricted to sheared and deformed zones, implying that strain and (or) hydrous fluids were essential to promote eclogite reactions despite appropriate *P–T* conditions (Austrheim 1987). The observation, noted earlier in the text, that the relict eclogite-facies rocks are restricted principally to shear zones, provides qualitative support for the second interpretation. To further complicate the problem, following the HP event, the HP belt in the western Grenville Province underwent a period of mid-crustal granulite-facies metamorphism in which the eclogite-facies assemblages were partly recrystallized. This event is well recorded by leucosome development in adjacent migmatitic gneisses (Bussy et al. 1995). Indares and Dunning (1997) and Ketchum and Krogh (1997, 1998) have attempted to date the HP metamorphism in several of the relict eclogite bodies directly by conventional isotope dilution – thermal ionization mass spectrometry (ID–TIMS) U/Pb geochronology of accessory minerals (see Fig. 2). Estimated ages include a single determination of $1121\,^{+12}_{-10}$ Ma, six determinations of 1101–1069 Ma (all ± 4 Ma or less), and two less precise determinations of $1063\,^{+35}_{-48}$ and 1048 ± 30 Ma (see Fig. 2). Of these, ages in the range 1095–1085 Ma were interpreted by Ketchum and Krogh (1998) as recording the HP event. The estimated age of metamorphism of the Algonquin gabbro is 1060–1045 Ma (Davidson and van Breemen 1988; Heaman and LeCheminant 1993), determined from metamorphic zircon overgrowths on baddeleyite. Unfortunately, many of these results are not open to unequivocal interpretation. It can be argued (*i*, earlier in the text) that the ages all record the post-HP granulite-facies overprint; or, on the other hand, that some of the calculated ages date the HP event and thus support the second alternative (*ii*, earlier in the text). However, it is undeniable that several of the ages overlap with the timing of the granulite-facies overprint, so a third possibility (*iii*) is that the age range encompasses both the eclogite- and granulite-facies events; and finally there is a fourth possibility (*iv*) that the HP metamorphism predated emplacement of the 1170 Ma gabbro, but is not recorded by the U/Pb zircon data. We consider (*iv*) to be at odds with the well-established pattern of metamorphic zircon growth during the first high *P–T* penetrative recrystallization event in mafic rocks, as no evidence of pre-1170 Ma zircon has been found in any of the analysed samples. In evaluating the remaining possibilities, it should be pointed out that there is some isotopic evidence that the Algonquin gabbro is a poor recorder of metamorphic conditions and by extension, therefore, also of zircon-producing reactions and the time of metamorphism. Both the gabbro and its host rocks underwent a later granulite-facies metamorphism, as noted earlier, which is dated by zircon formation at ~1080–1060 Ma in leucosomes in the adjacent migmatites (Bussy et al. 1995), but at 1060–1045 Ma in the gabbro (Davidson and van Breemen 1988). This age difference indicates that the gabbro was much slower to react than the host gneisses, compatible with its coarse texture, dry mineralogy and lack of penetrative strain, and so, by extension, it could have undergone a short-lived HP event that is not recorded in the major silicate mineralogy or the U/Pb systematics of zircon and baddeleyite. In conclusion, the timing of HP metamorphism in this part of the HP belt remains controversial, but the authors prefer the interpretation that it postdated intrusion of the Algonquin gabbro and slightly predated the granulite-facies recrystallization event.

Muskoka domain

Muskoka domain, SL5 of Ketchum and Davidson (2000), overlies the southern part of the HP belt (Fig. 2). It differs from Algonquin terrane in that it lacks supracrustal rocks or evidence for a polycyclic history, being composed of juvenile Mesoproterozoic (Pinwarian) units cut by Algonquin gabbro (Timmermann et al. 1997). It also appears to lack relict eclogite-facies units, although the significance of local occurrences of garnet–clinopyroxene rocks (Davidson 1991) requires further investigation. Muskoka domain underwent granulite-facies metamorphism during the Ottawa orogeny at ~1080–1065 Ma (Culshaw et al. 1997; Timmermann et al. 1997), coeval with that in the adjacent Algonquin terrane. The structural position of Muskoka domain (part of the Laurentian margin) on top of Parry Sound domain was interpreted in terms of out-of-sequence thrusting by Culshaw et al. (1997).

Overlying LP terranes

The boundary between the Composite Arc belt and the structurally underlying units is a map-scale tectonic mélange referred to here as the Composite Arc boundary thrust zone (Fig. 2; formerly Central Metasedimentary Belt boundary thrust zone, Hanmer and Ciesielski 1984; renamed to be consistent with renaming of Central Metasedimentary belt to Composite Arc belt by Carr et al. 2000). The Composite Arc boundary thrust zone includes rocks as old as ~1190–1180 Ma and may have undergone an early thrust history at about this time. However, the current geometry of the belt reflects principally thrusting and extension at ~1080–1050 Ma (Timmermann et al. 1997; Carr et al. 2000). Parry Sound domain, a complex structural assemblage comprising three distinctive packages separated by ductile shear zones, is a klippe resting on Algonquin terrane (Wodicka et al. 1996). Upper amphibolite- and granulite-facies metamorphism in Parry Sound domain has been dated at ~1160 Ma and ~1120 Ma (van Breemen et al. 1986; Tuccillo et al. 1992), predating that in the underlying Algonquin terrane, although retrogression to amphibolite-facies assemblages is widespread (Culshaw et al. 1997).

Structurally up-section to the south, metamorphism in most of the Composite Arc belt took place during the Elzevirian orogeny (except for the basal Composite Arc boundary thrust zone, noted earlier, and Mazinaw domain, which record late Ottawan ages of metamorphism, Corfu and Easton 1995), and metamorphism in the Frontenac part of the Frontenac–Adirondack belt took place in the Shawinigan orogeny (Carr et al. 2000). This implies that most of the Composite Arc belt and the Frontenac segment of the Frontenac–Adirondack belt obtained their metamorphic signatures before the Ottawa orogeny; they lack evidence for the ~1080–1040 Ma high *P–T* metamorphism that is so pervasive in their immediate footwall. We infer from this distribution that the Composite Arc and Frontenac belts were situated in the upper crust during the Ottawa orogeny. This inference is supported by recent evidence for the very high crustal level of emplacement of some ~1070 Ma granitoids in the southeastern Composite Arc belt, including narrow contact aureoles, granophyric groundmass, and miarolitic cavities (Davidson 2001).

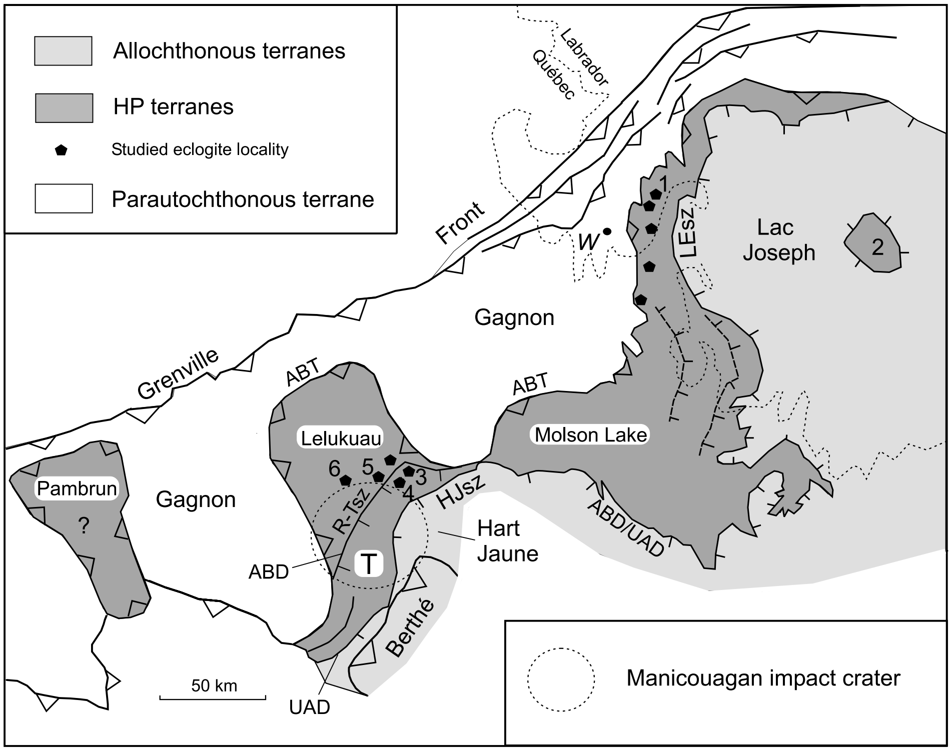
Central Grenville Province

The imbrication of terranes in the central Grenville Province (Fig. 3) shows many similarities to that farther west, although in detail the pattern appears to be simpler and only three structural levels have been identified.

Parautochthonous belt

In the central Grenville Province, the Parautochthonous belt is known as Gagnon terrane. Molson Lake terrane, formerly included in the Parautochthonous belt by Rivers et al. (1989), is now considered part of the HP belt on the basis of its metamorphic signature (see caption, Fig. 1). Gagnon terrane consists predominantly of reworked Archean gneiss and its Paleoproterozoic cover that are imbricated in a northwest-vergent, metamorphic foreland fold–thrust belt (Rivers 1983*a*, 1983*b*; van Gool 1992; Rivers et al. 1993). Subordinate rock types include deformed and metamorphosed granitoid plutons and the distinctive 1459 $^{+23}_{-22}$ Ma Shabogamo gabbro, which forms sills and dykes in the Paleoproterozoic supracrustal succession (Connelly and Heaman 1993). Paleo- and Mesoproterozoic units in Gagnon terrane display evidence for a single metamorphism that has been dated at about 1000 Ma (Connelly and Heaman 1993; Connelly et al. 1995; Schwarz 1998), i.e., Rigolet orogeny. The thrust belt exhibits a Barrovian metamorphic field gradient, with greenschist-facies rocks near the Grenville Front giving way to kyanite-bearing medium-pressure, upper amphibolite facies assemblages throughout much of Gagnon terrane. Maximum estimated *P–T* conditions in northern and central Gagnon terrane are about 1200 MPa and 750°C (Rivers 1983*b*; van Gool 1992; Schwarz 1998), but Indares (1995) has calculated higher

Fig. 3. Map of part of the Grenville Province of eastern Quebec and western Labrador showing the distribution of parautochthonous and allochthonous terranes. ABD, Allochthon boundary detachment; ABT, Allochthon Boundary thrust; HJsz, Hart Jaune shear zone; LEsz, Lac Emerillon shear zone; T, Tshenukutish terrane; UAD, Upper Allochthon detachment; *W*, Wabush. Numbers1–6 refer to dated high-pressure mafic rocks, including eclogite, for which results are as follows (upright numerals indicate metamorphic age, italics indicate protolith age): 1, *1459^{+23}_{-22} Ma*, 1006 ± 7 Ma; 2, *1452 ± 13 Ma*, 966 ± 30 Ma; 3, *1643 ± 5 Ma*, 1030 ± 12 Ma; *1629^{+17}_{-11} Ma*, 1042 $^{+22}_{-28}$ *Ma*; 4, *1170 ± 5 Ma*, 1030 $^{+11}_{-7}$ *Ma*, 1012 ± 12 Ma, 1046 ± 3 Ma; 5, *1628^{+21}_{-19} Ma*, 1049 ± 22 Ma; *1631^{+15}_{-14} Ma*, 1052 ± 19 Ma; *1214^{+48}_{-23} Ma*, 1021 ± 69 Ma; 6, *1692 ± 85 Ma*, 1007 ± 6 Ma) (1 is from Connelly and Heaman 1993, 2 is from Connelly et al. 1995; 3–4 are from Cox et al. 1998; 5–6 are from Indares et al. 1998).



pressure conditions, up to 1600 MPa at 800°C, from one locality adjacent to the tectonically overlying HP belt (see later in the text).

HP belt

The structurally overlying HP belt in the central Grenville Province consists of Molson Lake, Lelukuau, and Tshenukutish terranes, and may also include the poorly known Pambrun terrane farther west (Fig. 3). As in the western Grenville Province, the HP belt comprises units of Paleo- to Mesoproterozoic age, and rocks of Archean age appear to be absent.

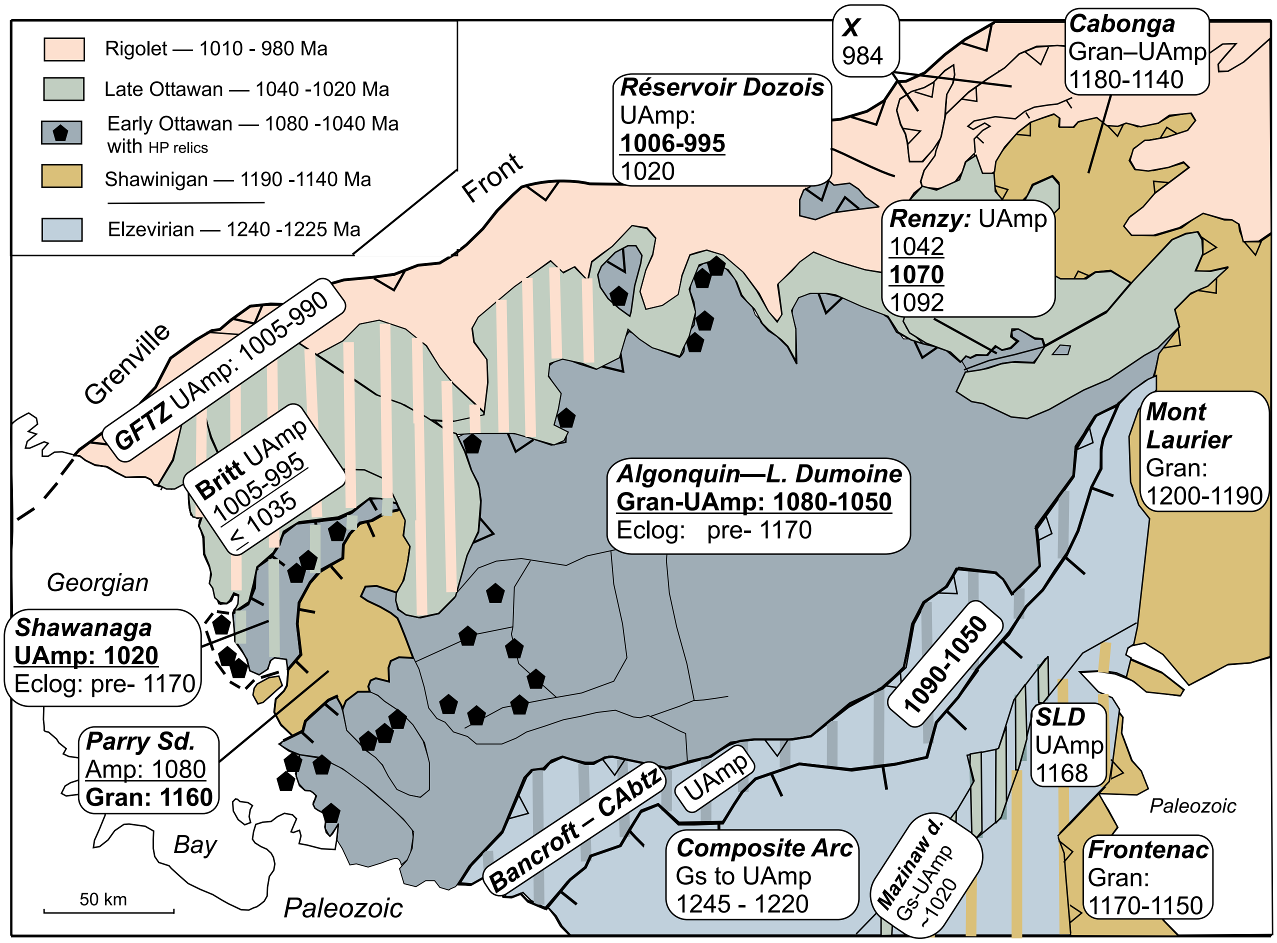
Molson Lake terrane

This terrane consists principally of 1650 Ma granitoid gneisses, part of the Paleoproterozoic Trans-Labrador batholith (Connelly and Heaman 1993; Connelly et al. 1995), cut by dykes of the Mesoproterozoic Shabogamo gabbro. Evidence for HP metamorphism is best preserved in the dry interiors of the gabbro dykes, which display a spectacular range of corona assemblages (Rivers and Mengel 1988; Indares 1993; Indares and Rivers 1995). Indares and Rivers (1995) showed that there is a regional coherence to the pattern of HP metamorphism in Molson Lake terrane and were able to map systematic variations in corona assemblages over a distance of several tens of kilometres, suggesting that there is a progressive increase in P southwards in the terrane. The age of HP metamorphism in Molson Lake terrane is not well constrained; two U/Pb (zircon) lower intercept ages of 1001 ± 10 Ma (Connelly and Heaman 1993) obtained on Shabogamo gabbro and Labradorian granite from the interior of the terrane are inferred to be minimum ages.

Lelukuau and Tshenukutish terranes

These terranes, located on the north shore of Manicouagan Reservoir, comprise the Manicouagan Imbricate zone (Indares et al. 1998, 2000), and its mapped extension into the southern part of the reservoir is described by Eaton et al. (1995) and Hynes et al. (2000). Both terranes consist primarily of Paleo- and Mesoproterozoic metaplutonic rocks that formed at ~1690–1630 Ma and ~1450 Ma (Indares et al. 2000). Subordinate Mesoproterozoic plutonic units with ages ranging from 1300 to 1020 Ma are known, including several bodies of ~1214–1160 Ma Fe–Ti gabbro and anorthosite. Lelukuau terrane, at the structural base of the Manicouagan Imbricate zone, consists of a stack of thrust slices (the Manicouagan thrust system) bounded by generally southeast-dipping shear zones (Indares et al. 2000). It is overlain by Tshenukutish terrane along a southeast-dipping normal-sense shear zone (Hynes et al. 2000). Lelukuau and Tshenukutish terranes contain widespread evidence of HP granulite- and subordinate eclogite-facies assemblages in rocks with protolith ages varying from ~1620 Ma to 1170 Ma (Indares et al. 2000).

Fig. 4. Metamorphic map of part of the Grenville Province of Ontario and western Quebec, with overprinting indicated by coloured vertical bars. Extent of Rigolet overprinting in the southern Parautochthonous belt is not well known. Numbers in boxes are ages of metamorphism in Ma determined by U/Pb geochronology on accessory minerals. Where more than one age of metamorphism has been determined, they are stacked in inverse chronological order, and the major event is shown in bold. Eclog, eclogite; Gran, granulite; Gs, greenschist facies; HP, High Pressure; Uamp, upper amphibolite facies; *CAbtz*, Composite Arc boundary thrust zone; *MD*, Mazinaw domain; *SLD*, Sharbot Lake domain; d., domain; Sd., Sound; *X*, X terrane.



This implies that HP metamorphism postdated 1170 Ma, and direct dating of metamorphism in HP granulite- and eclogite-facies rocks has yielded ages of 1060–1040 Ma (Indares et al. 1998), i.e., Ottawa orogeny, compatible with field observations.

Overlying LP terranes

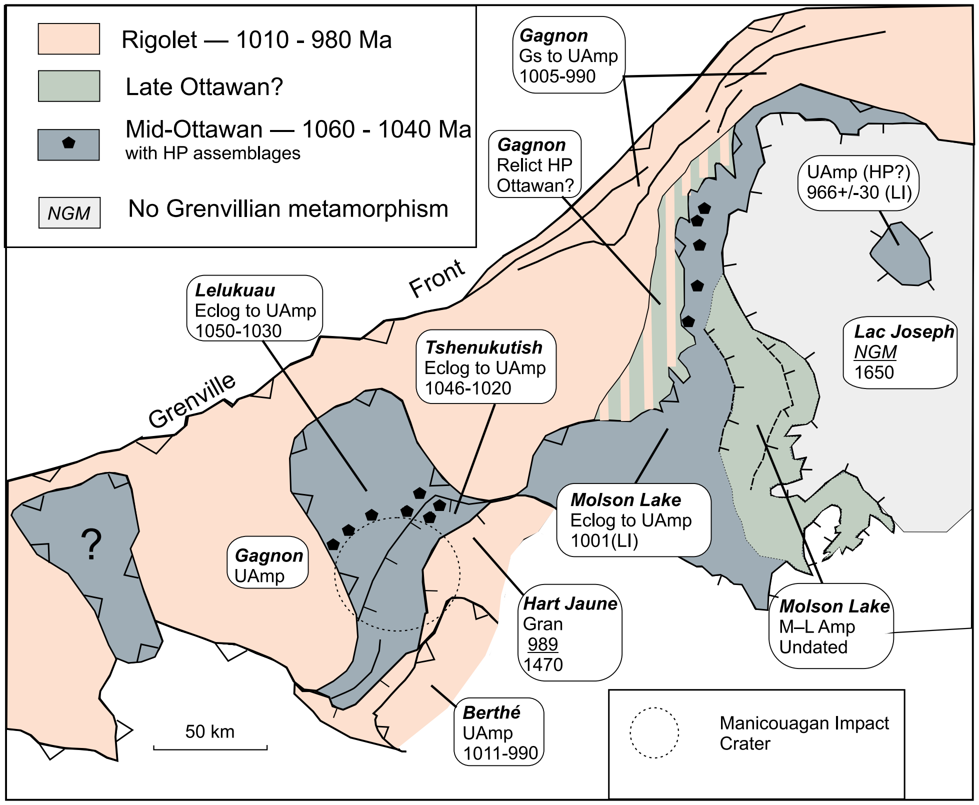
The overlying LP belt in the central Grenville Province consists of Lac Joseph, Hart Jaune, and Berthé terranes. Lac Joseph terrane comprises a thin sheet of Paleoproterozoic sedimentary and plutonic rocks metamorphosed to upper amphibolite- to granulite-facies migmatitic gneiss during the Labradorian orogeny, with a window near the centre of the terrane through which the underlying HP belt is exposed (Fig. 3; Connelly and Heaman 1993). The metasedimentary gneiss displays evidence for two generations of anatectic leucosomes, both of which are Labradorian in age (Connelly et al. 1995). There is no evidence for a high-temperature (amphibolite-facies or higher) Grenvillian metamorphic overprint, except at the structural base of the terrane. In the terrane interior, Grenvillian temperatures were sufficient to reset the $^{40}Ar/^{39}Ar$ system in muscovite, but not hornblende (Connelly 1991), implying 500°C > T > 350°C (e.g., Hanes 1991).

Hart Jaune and Berthé terranes together comprise a north-vergent, fold–thrust stack, with the Berthé anorthosite occupying the core of a km-scale sheath fold in the centre of the stack (Hynes et al. 2000). Hart Jaune terrane consists predominantly of gneisses that preserve evidence for two granulite-facies metamorphic events at 1470 Ma and 989 Ma (Pinwarian and Rigolet orogenies, respectively; Scott and Hynes 1994; Hynes and St-Jean 1997; Hynes et al. 2000). Berthé terrane consists of layered, migmatitic gneisses that have yielded evidence for a metamorphic event at 1011–990 Ma (Rigolet orogeny, Scott and Hynes 1994). Metamorphic pressure during the Rigolet orogeny was estimated to be below 700 MPa in Hart Jaune terrane and no greater than 900 MPa in Berthé terrane (Hynes and St-Jean 1997).

Summary

Figures 4 and 5 are colour-coded metamorphic maps illustrating the distribution of Elzevirian, Shawinigan, Ottawa, and Rigolet metamorphism in the western and central Grenville

Fig. 5. Metamorphic map of part of the Grenville Province of eastern Quebec and western Labrador. Numbers are ages of metamorphism in Ma determined by U/Pb geochronology on accessory minerals. Where more than one age of metamorphism has been determined, they are stacked in inverse chronological order. M-LAmp, mid- to lower amphibolite facies; LI, lower intercept on U/Pb concordia diagram; *NGM*, no penetrative Grenvillian metamorphism. Other abbreviations as in Fig. 4.



Province. They show that in both regions the most widespread Grenvillian metamorphism in the parautochthonous terranes in the *footwall* of the HP belt took place in a short-lived event from ~1010–990 Ma during the Rigolet orogeny. However, there is also evidence for Ottawan (~1060–1020 Ma) metamorphism in the southern part of the Parautochthonous belt in the western Grenville Province, which may extend across the orogen.

The *HP belt* displays evidence for a different evolution in the two areas. In the central Grenville Province, HP metamorphism took place during the Ottawa orogeny at ~1060–1040 Ma. In contrast, in the western Grenville Province, where the HP metamorphism occurred earlier but is less well dated, the HP rocks were subsequently transported into the mid-crust, where they were imbricated with Muskoka domain and underwent penetrative granulite-facies recrystallization from ~1080 to 1060 Ma (Ottawa orogeny).

Timing of the main metamorphism in *hanging wall* terranes structurally above the HP belt, i.e., the terranes composing the LP belt, most of the Composite Arc belt and the Frontenac (but not Adirondack) belt, varies from ~1650 Ma to 1470 Ma (Labradorian and Pinwarian orogenies, respectively) in the central Grenville Province and from ~1250 Ma (Elzevirian orogeny) to 1160 Ma (Shawinigan orogeny) in the western Grenville Province. Common to all the hanging-wall terranes is the preservation of pre-Ottawan metamorphic ages, with the concomitant lack of widespread, penetrative Ottawan metamorphism, implying that they must have been in the upper crust at the time their footwalls were undergoing HP metamorphism.

Occurrence, petrography, and *P–T* estimates of HP rocks

In both the western and central parts of the HP belt, preserved and relict eclogite-facies assemblages are restricted largely to mafic plutonic rocks. This restriction is probably a function of processes during the retrograde metamorphic evolution, when only the cores of structurally competent, relatively dry lithologies, such as metagabbro that had reacted to eclogite, would have withstood decompression reactions and the accompanying strain that elsewhere resulted in granoblastic granulite- or amphibolite-facies assemblages (e.g., Rubie 1990; Boundy et al. 1992). The implication is that the surrounding quartzofeldspathic gneisses also developed eclogite-facies assemblages, but that they were thoroughly reequilibrated during decompression (Davidson 1991). The only definitive report of HP assemblages preserved in a non-mafic lithology is that of Indares (1995), who described HP relics in pelitic rocks from part of Gagnon terrane in the immediate footwall of the HP belt. In the text that follows, we review the field and mineralogical characteristics of eclogite and co-facial HP granulite-facies mafic rocks in the western and central parts of the HP belt, including also the coronitic Algonquin metagabbro, for which eclogite metamorphic conditions are disputed (see earlier in the text).

Fig. 6. Outcrop patterns of HP rocks. (A) Western Grenville Province (after Davidson 1991; Ketchum and Davidson 2000). Garnet–clinopyroxene assemblages in Muskoka domain and Parry Sound shear zone (Davidson 1991) are not shown as they do not contain evidence of former eclogite-facies assemblages. Ah, Ahmic domain; GH, Go Home domain; HP, High Pressure; Sh, Shawanaga domain; R, Rosseau domain. Retrogressed eclogite-facies mafic units are tectonically disaggregated and occur in pods, boudins, and pulled apart intrusions as a result of pervasive ductile flow of the HP terrane. Note that retrogressed eclogite is restricted to the HP belt proper, whereas Algonquin metagabbros occur in both the HP belt and Muskoka domain. (B) Central Grenville Province (after Connelly et al. 1995; Indares and Rivers 1995). HP, High Pressure; LP, Low Pressure. Mafic dykes exhibit considerable along-strike continuity, and an eclogite-facies isograd has been mapped, attesting to the greater structural integrity of the HP terrane.

Western Grenville Province

In the western Grenville Province, as noted earlier, retrogressed eclogite-facies gabbro and associated ultramafic and anorthositic rocks occur in highly strained bodies up to several tens of kilometres long and in tectonically disrupted pods, lenses, and boudins, especially along domain boundaries (Davidson 1991, 1998; Culshaw et al. 1997; Fig. 6A). Their petrography has been described by Grant (1989), Davidson (1990, 1991), and Indares and Dunning (1997). The original granoblastic, eclogite-facies mineralogy is extensively overprinted by granulite- and amphibolite-facies assemblages, but compelling evidence of former eclogite parageneses is preserved locally. For instance, clinopyroxene–plagioclase symplectite replaces presumed former omphacite; pyrope-rich garnet is surrounded by decompression collars of plagioclase–pargasite symplectite; and kyanite relics are surrounded by a symplectic intergrowth of corundum–hercynite ± sapphirine, pointing to a former assemblage consisting of garnet–omphacite–kyanite in some samples. Various stages of retrogression of the original eclogite-facies assemblages are preserved; some of the complex retrograde textures are illustrated by Davidson (1991, 1998) and Indares and Dunning (1997). A representative example is reproduced in Fig. 7A. It has not proven possible to estimate the maximum *P–T* conditions attained by the retrogressed eclogites. Berman (in Davidson 1991) calculated that the *minimum* conditions of eclogite formation in mafic rocks of this bulk composition were ~1450 MPa at 700°C, and Indares and Dunning (1997) calculated a *P–T* of 1350 MPa and 720°C from the retrogressed assemblage, which they inferred to represent conditions at some stage of the unroofing.

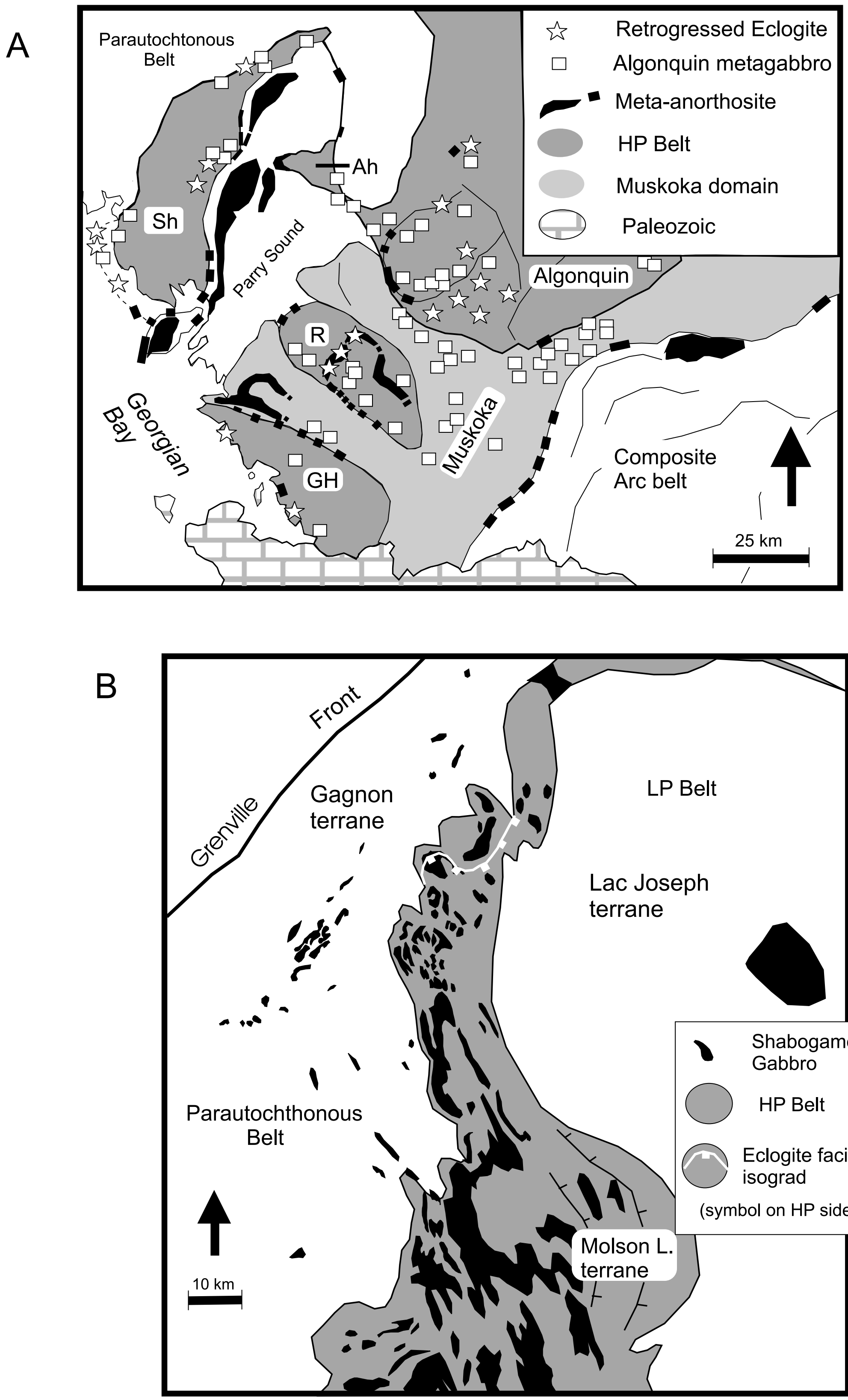
Coronitic metagabbro bodies of the Algonquin suite occur widely within the HP belt and Muskoka domain, some in close proximity to retrogressed eclogite (Fig. 6A; Davidson 1991; Ketchum and Davidson 2000). Individual bodies vary from pods and lenses to elongate forms from a few metres to over a kilometres in the longest dimension. Although tectonically dismembered, the bodies are commonly clustered, implying that they are fragments of larger intrusions (Ketchum and Davidson 2000). The characteristic preservation of relict igneous texture in this unit indicates that it is less pervasively recrystallized than the retrogressed eclogites. Typical corona mineralogy consists of shells of orthopyroxene, clinopyroxene, and garnet–clinopyroxene symplectite separating olivine and plagioclase, and spinel clouding in relict igneous plagioclase is widespread (Fig. 7B; Davidson 1991). As noted earlier, the relict igneous texture and the presence of igneous plagioclase and olivine in many samples, together with the lack of omphacite, contrast texturally and mineralogically with the relict eclogite. *P–T* estimates for the metamorphism of the Algonquin gabbro are 750–950 MPa and 650–750°C (Grant 1987), but as discussed earlier in the text, these may represent conditions attained during granulite-facies reequilibration.

Central Grenville Province

In the central Grenville Province, the metaigneous bodies with HP assemblages preserve recognizable aspects of their original intrusive shapes, albeit strongly modified by folding and ductile shearing. For example, the dyke-like shapes of bodies of Shabogamo gabbro are still evident (Fig. 6B). Furthermore, retrogression was generally less pervasive in the central Grenville Province, and jadeitic pyroxene in both coronitic and granoblastic eclogite is locally preserved, e.g., up to 51 mol.% jadeite in corona gabbro in Molson Lake terrane (Indares 1993; Indares and Rivers 1995), and 33 mol.% jadeite in granoblastic eclogite in Tshenukutish terrane (Cox and Indares 1999*a*). Garnet in these rocks pseudomorphs igneous plagioclase (Fig. 7C). However, pyroxenes in other spatially associated HP rocks have low jadeite contents due to low Na bulk compositional controls and are strictly HP granulites (Indares 1993). In Molson Lake terrane, relict igneous plagioclase in Shabogamo gabbro is commonly choked with inclusions of corundum and (or) kyanite, or less commonly spinel, and corona assemblages are widespread. In the north of the terrane, thin coronas separating igneous olivine from plagioclase are composed of orthopyroxene–pargasite, whereas farther south, where olivine is no longer present and plagioclase is largely replaced by garnet, the much wider coronas are composed of orthopyroxene–garnet and clinopyroxene symplectite (Fig. 7D; Rivers and Mengel 1988; Indares and Rivers 1995). This has been interpreted as a prograde sequence through the amphibolite-granulite transition to HP granulite- and co-facial eclogite-facies assemblages (Fig. 6B). Estimated conditions of HP metamorphism range from 1400 MPa / 750°C in the north of Molson Lake terrane to 1800 MPa and 850°C farther south (Indares 1993; Indares and Rivers 1995). Maximum estimated *P–T* conditions in Lelukuau and Tshenukutish terranes, where garnet–kyanite clinopyroxenite and subordinate true eclogite are widespread, are similar to those for Molson Lake terrane, in the range 1400 to 1900 MPa and 770 to 920°C (Indares 1997; Cox and Indares 1999*a*, 1999*b*; Indares et al. 2000).

Summary

Eclogites formed in mafic rocks with Paleoproterozoic (~1630 Ma) and Mesoproterozoic (~1470–1403 Ma) protolith ages. In addition, eclogite is well documented in ~1170 Ma gabbro in the central Grenville Province, and the authors are of the opinion that gabbro of this age also experienced the HP event in the western Grenville Province. The occurrence



of HP mafic rocks as disrupted lenses, boudins, and highly strained bodies in the western Grenville Province and as relatively coherent units in the central Grenville Province suggests that the HP belt retains a greater structural integrity in the latter region. This observation is compatible with evidence from the western Grenville Province that the HP rocks subsequently underwent granulite-facies metamorphism during the Ottawa orogeny.

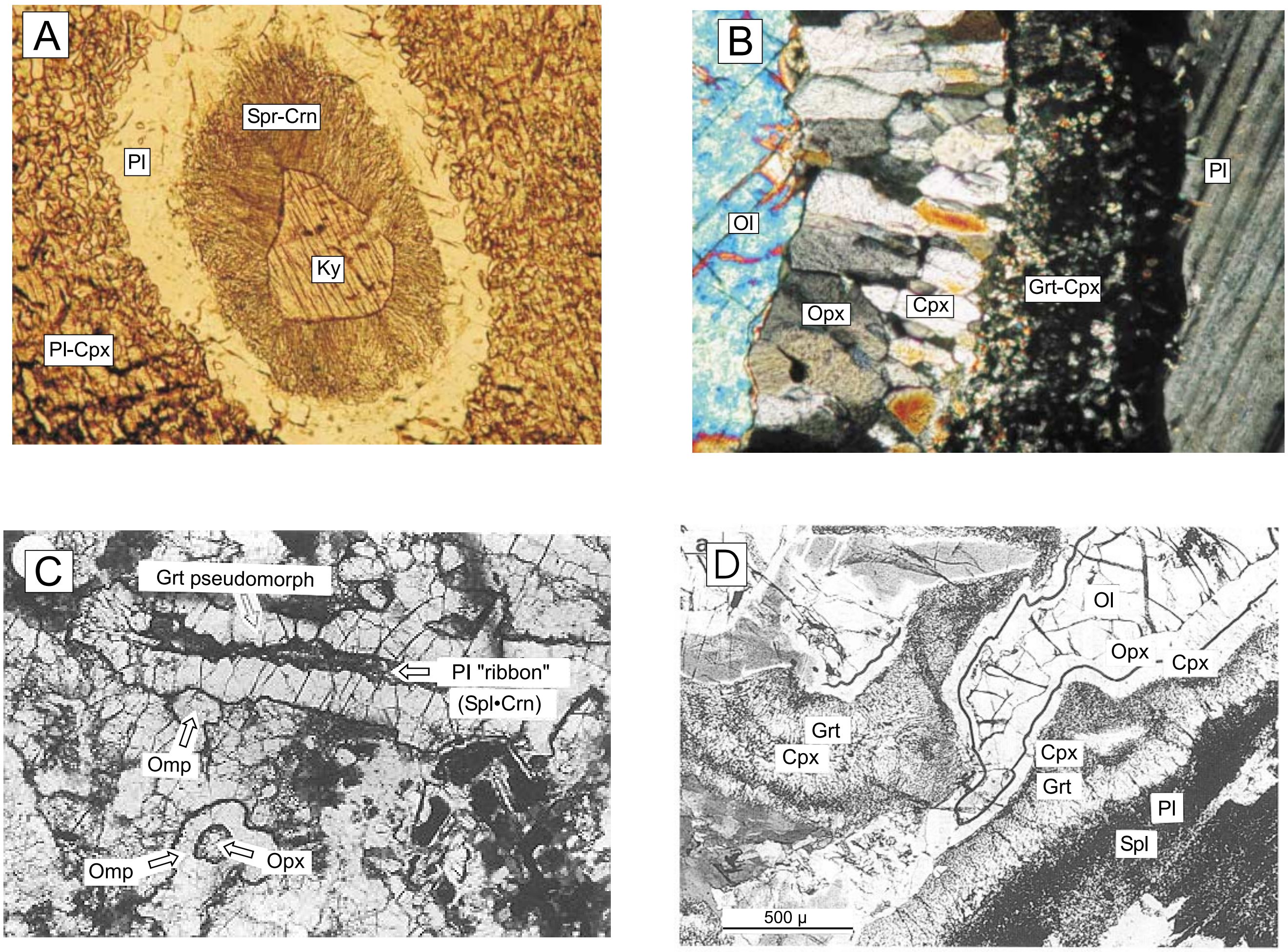


Fig. 7. Representative examples of petrographic relationships in HP rocks. (A) Retrogressed eclogite, Shawanaga domain (from Davidson 1991). A kyanite relic (Ky) is separated from plagioclase–clinopyroxene (Pl-Cpx) symplectite (former omphacite) by an inner shell of sapphirine + corundum (Spr-Crn) and an outer shell of calcic plagioclase (Pl). (B) Coronitic texture in Algonquin gabbro, GoHome domain (from Davidson 1991). (C) Eclogitic Fe–Ti gabbro, Tshenukutish terrane (from Cox and Indares 1999). Igneous plagioclase is completely pseudomorphed by garnet (Grt), which coexists with omphacite (Omp). Spl + Crn, spinel + corundum; Opx, orthopyroxene. (D) Coronitic texture in Shabogamo gabbro, Molson Lake terrane (from Indares and Rivers 1995). In B and D, coronas of orthopyroxene (Opx), clinopyroxene (Cpx), and garnet–clinopyroxene (Grt-Cpx) symplectite separate olivine (Ol) from plagioclase (Pl), which is extensively clouded with minute needles of spinel (Spl, in D only).

During unroofing, HP rocks were variably retrogressed to granulite- and amphibolite-facies assemblages. Decompression–retrogression reactions were more pervasive in the western Grenville Province, where it has not been possible to determine reliable estimates of peak *P–T* metamorphic conditions, than in the central Grenville Province, where maximum estimated conditions are in the ranges 1700 to 1900 MPa and 850 to 925°C. The presence of relatively pristine eclogite in the central Grenville Province is compatible with rapid unroofing synchronous with transport onto the Parautochthonous belt following formation. In contrast, the pervasive granulite-facies reequilibration of eclogite during the Ottawa orogeny in the western Grenville Province suggests a two-stage exhumation process involving a period of residence in the middle crust before emplacement on the Parautochthonous belt (e.g., Indares and Dunning 1997).

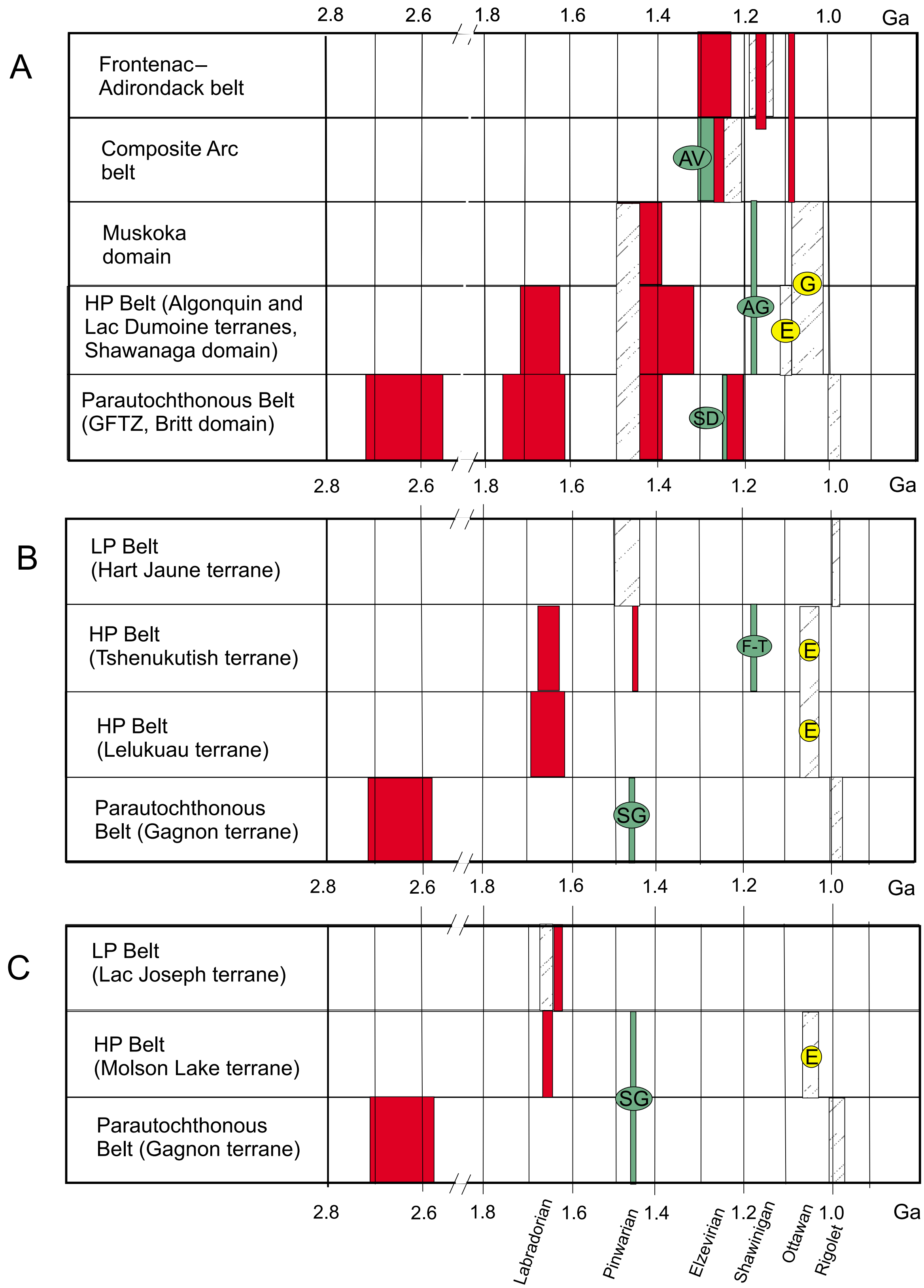
Lithologic linkages

Figure 8 summarizes the pre-Grenvillian linkages among the HP belt, the underlying Parautochthonous belt and the overlying LP, Composite Arc and Frontenac–Adirondack belts along three cross-sections. We emphasize the following points, which both shed light on the make-up of the HP belt and provide qualitative constraints on the amount of tectonic transport of the HP belt relative to adjacent belts during the Grenvillian collision.

(1) Archean rocks are restricted to the footwall (Parautochthonous belt) of the HP belt in all sections. They have not been recognized in the HP or LP terranes.

(2) The HP belt is composed of units of Paleo- and Mesoproterozoic age. Rocks of this age also occur in both the Parautochthonous belt and the LP belt (Figs. 8A, 8C).

Fig. 8. Lithologic and metamorphic linkages among the Parautochthonous belt, HP (High Pressure) belt, LP (Low Pressure) belt, Composite Arc belt, and Frontenac–Adirondack belt along three cross-sections from ~2.8 to 1 Ga; (A) western Grenville Province; (B) Manicouagan area; (C) western Labrador (in part modified from Ketchum and Davidson 2000, Indares et al. 2000). Red bars, ages of granitoid plutons; green bars, mafic dyke swarms, gabbros, and volcanic rocks. AG, Algonquin gabbro; AV, arc (or back-arc) volcanics; F-T, Fe–Ti gabbro; SD, Sudbury diabase; SG, Shabogamo gabbro; diagonal striping, metamorphic events (E, eclogite facies; G, granulite facies; note that the age of eclogite-facies metamorphism in the western Grenville Province is not well dated — see text).



(3) Sudbury diabase is restricted to the Parautochthonous belt (Fig. 8A).

(4) Algonquin metagabbro occurs in both the HP belt and Muskoka domain, whereas retrogressed eclogite is restricted to the HP belt (Fig. 8A).

(5) Fe–Ti gabbro, of similar age to the Algonquin gabbro, occurs in Tshenukutish terrane (Figs. 8A, 8B).

(6) Shabogamo gabbro is restricted to the Parautochthonous belt in the Manicouagan area, but occurs in both the Parautochthonous and HP belts in western Labrador (Figs. 8B, 8C).

(7) Tshenukutish terrane (HP belt) and Hart Jaune terrane (LP belt) both carry evidence for Pinwarian magmatism and metamorphism (Fig. 8B). Similarly, both Molson Lake terrane (HP belt) and Lac Joseph terrane (LP belt) carry evidence for Labradorian magmatism and metamorphism (Fig. 8C).

These observations imply that the HP belt shared a common Paleo- and Mesoproterozoic history with the Parautochthonous belt and the LP belt prior to the Grenvillian orogenic cycle. In detail, the presence in the central Grenville Province of Shabogamo gabbro in both the Parautochthonous belt (Gagnon terrane) and the overlying HP belt (Molson Lake terrane) suggests that these two terranes were contiguous prior to Grenvillian metamorphism, whereas in the western Grenville Province, the presence of Sudbury diabase in the Parautochthonous belt, but its absence in the overlying HP belt may imply a less intimate association. Nonetheless, in both areas the lithological evidence is compelling that the Parautochtonous, HP, and LP belts were all components of the Laurentian margin. This pre-1300 Ma history of the Laurentian margin is absent in the Composite Arc and Frontenac–Adirondack belts (see also, e.g., Wodicka et al. 1996; Culshaw et al. 1997; Carr et al. 2000). We therefore infer, with Carr et al. (2000), that the Parautochthonous, HP, and LP belts were (semi-)contiguous components of the southeastern margin of Laurentia during the Mesoproterozoic prior to the Grenvillian collision. The restriction of Archean rocks to the Parautochthonous belt is considered tectonically significant and is discussed further later in the text. In contrast to the many shared elements of their *pre-Grenvillian* history, the Parautochthonous, HP, and LP belts exhibit profound contrasts in their *Grenvillian* metamorphic history, both in terms of the time (Fig. 8) and grade of metamorphism. The spatial and temporal arrangement of these metamorphic contrasts is addressed in the next section.

Cross-sections

Figures 9 and 10 are largely based on several Lithoprobe deep seismic reflection surveys that were first assembled by Ludden and Hynes (2000). To see through the effects of widespread structural reworking, we present two figures that focus on the contractional and extensional histories separately, particularly as they pertain to the HP belt. Carr et al. (2000), Martignole et al. (2000), and Hynes et al. (2000) summarized the kinematic histories and timing of the major shear zones in cross-sections A, C, and D, respectively, and the reader is referred to these sources for details.

First-order contractional structures

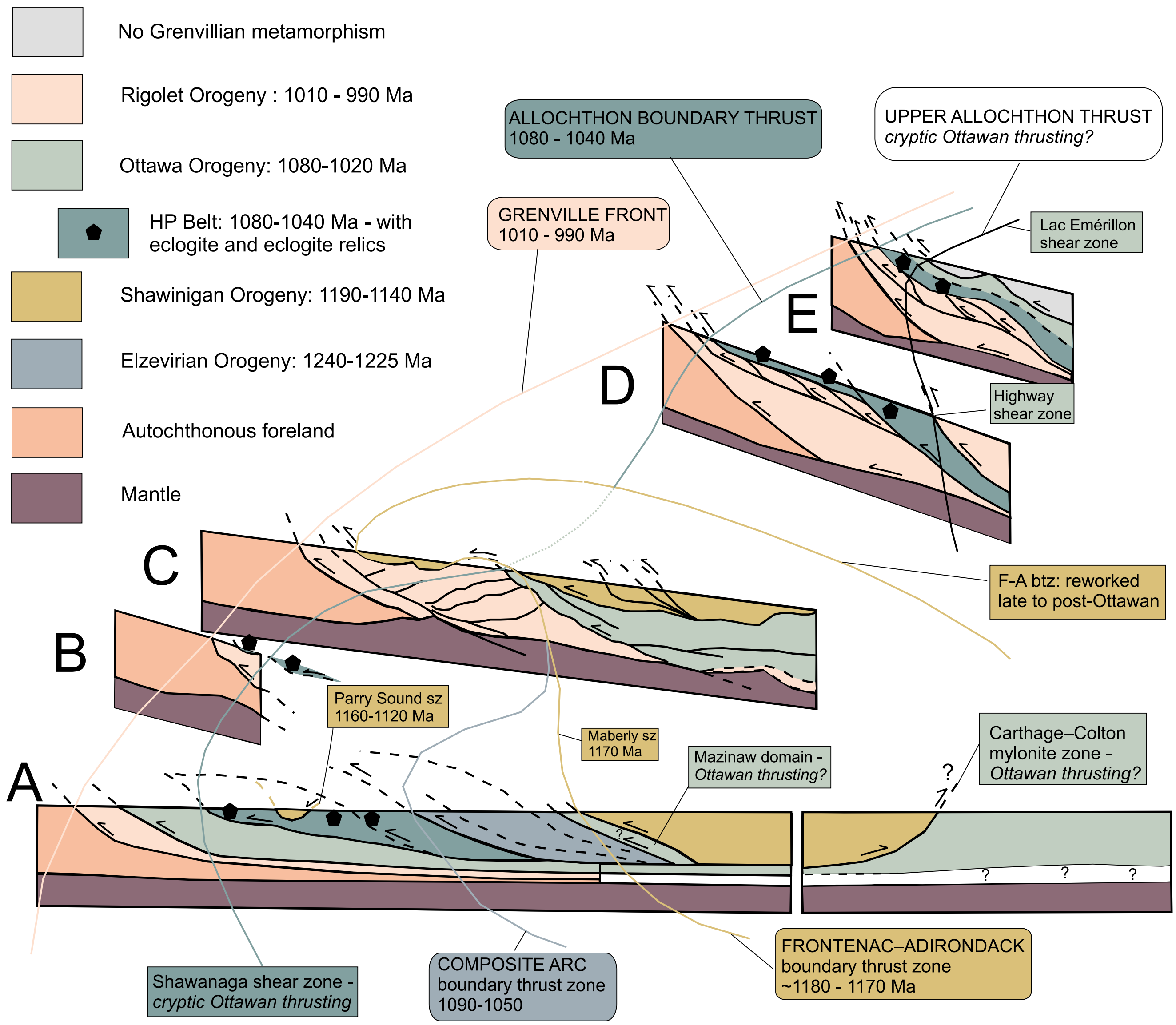
Several southeast-dipping, crustal-scale contractional structures link the cross-sections (Fig. 9) along the length of the Grenville Province, whereas others are restricted to one or two of them. The *Grenville Front* and the *Allochthon Boundary thrust* in the northwest of the orogen are crust-penetrating structures present on all cross-sections, with the latter carrying the HP belt in its hanging wall. The upper boundary of the HP belt in cross-sections A and C is marked by the *Composite Arc boundary thrust zone* and the *Frontenac–Adirondack boundary thrust zone* (new name, introduced for consistency with other terminology; Frontenac–Adirondack boundary thrust zone comprises Maberly shear zone and its northeasterly continuation, known as Heney shear zone, in cross-section C), and in cross-sections D and E by the *Upper Allochthon thrust* (new name, includes Lac Émérillon and Highway shear zones).

The *Grenville Front*, the northwestern boundary of the Grenville Province, is the trace of a series of southeast-dipping thrust or reverse faults that place higher grade rocks of the Parautochthonous belt on lower grade equivalents in the foreland to the northwest (Rivers et al. 1989). Its surface trace comprises relatively straight segments, characterized by moderately to steeply dipping, amphibolite-facies shear zones, and more gently dipping lobate segments where metamorphic, foreland fold-thrust belts are developed, the dichotomy suggesting that it has a ramp-flat geometry near the present erosion surface. At depth, it is a listric structure that soles out in the crust–mantle boundary (Hynes et al. 2000; White et al. 2000). Timing of the Grenvillian displacement on the Grenville Front has been dated at ~1005–995 Ma (e.g., Krogh 1994), i.e., Rigolet orogeny.

The southeast-dipping *Allochthon Boundary thrust*, which marks the boundary between the parautochthonous and allochthonous belts, carries the HP and LP belts in its hanging wall (Fig. 1). It lies some 30–150 km southeast of the Grenville Front, and its highly lobate surface trace is compatible with field evidence that it dips shallowly on a regional scale. The Allochthon Boundary thrust is characterized in the field by a zone of amphibolite-facies straight gneiss up to a kilometre wide. It is the site of an important, although locally cryptic, break in metamorphic grade, bringing the HP terranes in its hanging wall into contact with amphibolite-facies gneisses of the Parautochthonous belt in its footwall. Geochronological data from hanging wall rocks indicate that major displacement on the Allochthon Boundary thrust occurred during the Ottawa orogeny at ~1080–1040 Ma.

The *Composite Arc boundary thrust zone* is a 7–12 km thick, southeast-dipping, ductile thrust zone that separates the HP belt (and Muskoka domain) in its footwall from the Composite Arc belt in its hanging wall. It consists of anastomosing belts of amphibolite-facies mylonite and highly strained gneiss that surround lenses and boudins of less deformed orthogneiss (e.g., Hanmer 1988). Evidence for northwest-directed, reverse displacement is widespread and has been bracketed between 1080 and 1050 Ma (Timmermann et al. 1997). The *Frontenac-Adirondack boundary thrust zone* is a moderately southeast-dipping, amphibolite-facies shear zone that juxtaposes the Frontenac–Adirondack belt in its hanging wall over a footwall composed of the Composite Arc belt in the west and the HP and LP belts farther east

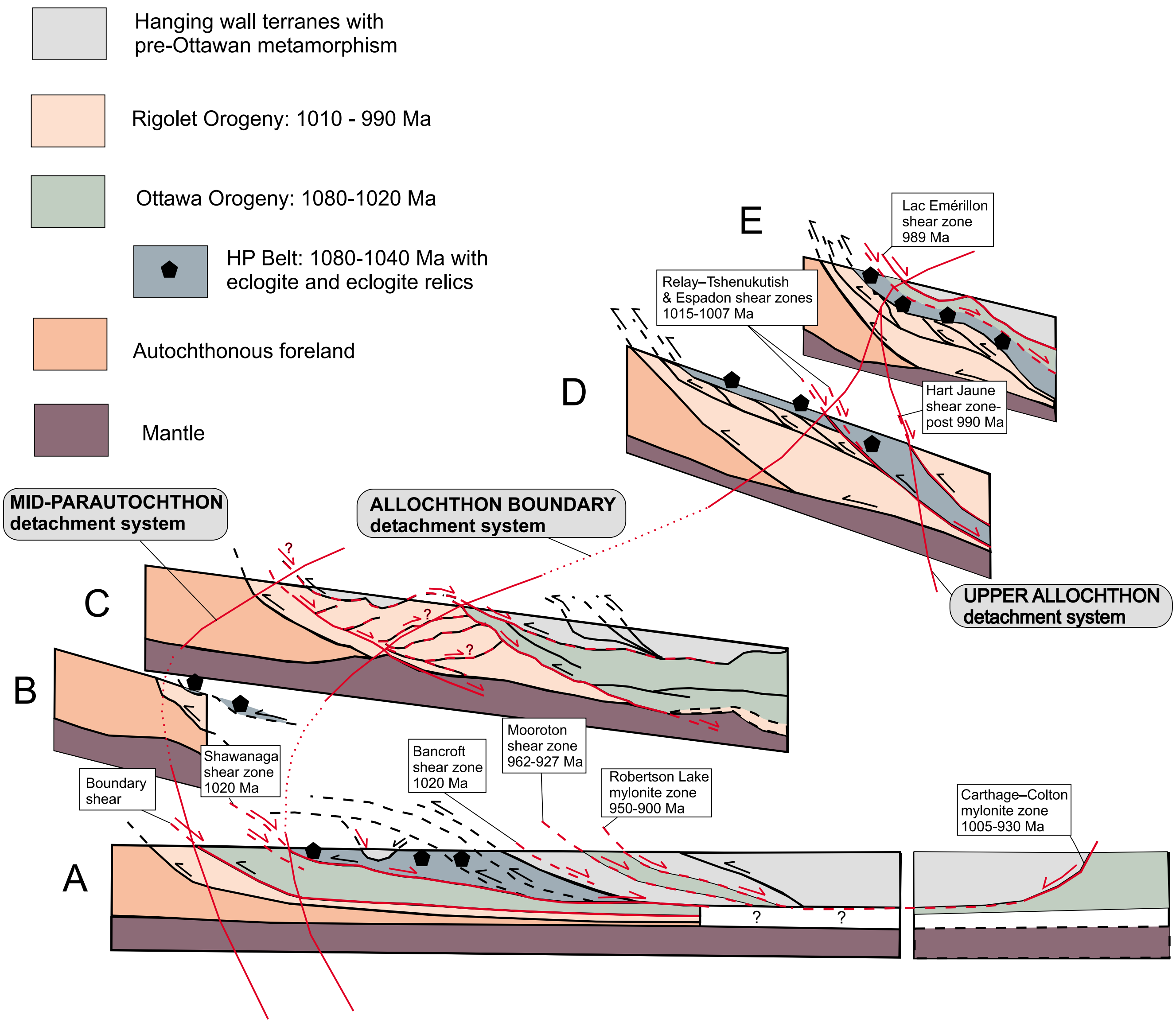
Fig. 9. Composite cross-sections of the Grenville orogen (modified from Ludden and Hynes 2000), colour-coded for the age of metamorphism as in Figs. 4 and 5 and with major contractional boundaries highlighted. Age of metamorphism in the unexposed lower crust is inferred from seismic continuity and geological arguments. Cross-sections A, B, C, and D are based on surface geology and Lithoprobe deep seismic reflection profiles; cross-section E is from Rivers et al. (1993) and is unconstrained by seismic imaging. The southeast continuation of cross-section A into the Adirondacks is schematic and based on data in Carr et al. (2000). F-Abtz, Frontenac–Adirondack boundary thrust zone; HP, High Pressure; sz, shear zone.



(Fig. 2). The eastward change in footwall units is inferred to be a result of progressive occlusion of the Composite Arc belt and the HP belt along strike. Displacement on Maberly shear zone (the southwesterly segment of Frontenac–Adirondack boundary thrust zone, Fig. 2), which has been dated at ~1170 Ma (Corfu and Easton 1997), overlaps with the age of metamorphism in the hanging wall and may be representative of the thrust zone as a whole. The *Upper Allochthon thrust* is defined from cross-sections D and E. In cross-section D, the thrust-sense Highway shear zone carries rocks in its hanging wall that were metamorphosed at ~1011–989 Ma (Hynes et al. 2000). In cross-section E, early thrust movement (undated) on Lac Émérillon shear zone (Connelly 1991) has been overprinted by later extensional displacement (see later in the text).

In summary, the dated time of displacement on the major contractional shear zones appears to young generally towards the northwest of the Grenville orogen. The Parry Sound shear zone, for which the estimated timing of thrust displacement is 1160–1120 Ma (van Breemen et al. 1986; Tuccillo et al. 1992), is an exception to this pattern. Fig. 9 shows that the age of metamorphism also generally youngs towards the northwest, such that terranes and domains with Elzevirian and Shawinigan metamorphic signatures generally lie to the southeast and structurally above those with Ottawan and Rigolet signatures. This pattern is consistent

Fig. 10. Composite cross-sections of the Grenville orogen (modified from Ludden and Hynes 2000), colour-coded for the age of metamorphism as in Figs. 4 and 5 and with major extensional detachment shear zone systems highlighted in red. For sources of information, see Fig. 9. Three major, first-order detachment systems are named. Note that shear zones of the Allochthon Boundary detachment are situated below the HP (High Pressure) belt in cross-sections A and C, within the HP belt in cross-section D, and above the HP belt in cross-section E.



with an overall *foreland- (NW-) directed, in-sequence* thrust propagation style (*understacking* in the terminology of Davy and Gillet 1986) throughout much of the Grenville Province (see also Haggart et al. 1993; Rivers et al. 1993; Culshaw et al. 1997). However, the southeast of cross-section A shows that early *southeast-directed* thrusting has been postulated along the Carthage–Colton mylonite zone (Wasteneys et al. 1999), which, if correct, implies that this part of the orogen was doubly vergent. Nonetheless, the presence of high-grade Ottawan metamorphism in the Adirondack Highlands (e.g., McLelland et al. 2001, possibly overprinting an earlier metamorphism of Shawinigan age, McLelland et al. 1996), tectonically beneath a hanging wall consisting of Frontenac terrane with older (Shawinigan) metamorphism, is compatible with the pattern farther northwest and the inference that Frontenac terrane was situated in the upper crust during the Ottawa orogeny.

Origin of the tectonic loads

The origin of the tectonic load on the HP belt that gave rise to the HP metamorphism is a matter of some significance. We infer that the terranes with pre-Ottawan metamorphic ages that are currently situated in the hanging wall of the HP belt made up part of this load, i.e., in cross-sections A and C, this would have included most of the Composite Arc belt and Frontenac terrane; and in cross-sections D and E, it would have included the LP belt. Taken overall, these units were not penetratively deformed or metamorphosed during the Ottawa orogeny and presumably were passively transported above a ductile lower crust (the HP belt) that was shortened and extruded beneath them. Similarly, noting the pre-Rigolet metamorphic ages in rocks structurally above the Parautochthonous belt, we infer that the HP belt, Composite Arc belt, Frontenac–Adirondack belt, and much of the LP belt constituted the upper crustal load during the Rigolet orogeny and were transported passively towards the northwest at that time. This indicates that the HP belt went from an active metamorphic environment in the deep to very deep crust during the Ottawa orogeny to being passively transported in the mid- to upper crust during the Rigolet orogeny, implying that it must have been tectonically transported to mid- to upper crustal levels before the onset of the Rigolet orogeny.

Architecture of the HP belt

In all cross-sections, Archean rocks are restricted to the parautochthonous footwall beneath the HP belt, and the HP belt is composed of units of Paleo- and Mesoproterozoic age (Fig. 8). However, despite this lithological similarity, Fig. 9 illustrates that there is a significant change in the two-dimensional architecture of the HP belt along the length of the Grenville orogen. In cross-sections B, C, D, and E, a ramp-flat geometry is well developed. In B, the leading, northwestern edge of a flat is present in a klippe at the southeast end of the cross-section (Fig. 9); and in C, although only the ramp is visible on the cross-section, the flat outcrops just west of the line of the cross-section. In contrast, in cross-section A, the HP belt dips relatively uniformly into the lower crust.

Formation of the ramp in cross-section D was interpreted by Hynes et al. (2000) to be due to the greater competency of the Archean crust compared to the structurally overlying Proterozoic rocks. The lack of a ramp in cross-section A is coincident with the higher proportion of Proterozoic units in the lower crust there and may therefore be a result of their inferred greater ductility (Ludden and Hynes 2000).

Another feature that may be related to the lack of a ramp in cross-section A is the extent of Ottawan metamorphism in the Parautochthonous belt. In cross-section A, there is widespread evidence of Ottawan (~1060–1020 Ma) metamorphism in the southern Parautochthonous belt prior to reworking during the Rigolet orogeny (Jamieson et al, 1995), whereas in C the evidence is more limited (see Fig. 4), and farther east there are no hard data, although the evidence for HP metamorphism in Gagnon terrane (Indares 1995) may indicate that it is present there too (Fig. 5). Hynes and Eaton (1999) considered that development of the ramp-flat geometry in cross-section D was instrumental in the unroofing of the HP rocks, and a similar architecture and evolution are inferred in cross-section E. However, in cross-section C, the time of ramp formation is uncertain (Martignole et al. 2000). The ramp may have developed during the Ottawa orogeny, as in adjacent cross-sections, or alternatively it may have formed (or been enhanced) during late Ottawan or post-Rigolet extensional faulting and southeast-directed imbrication of the Archean parautochthon. Distinction between these possibilities requires knowledge of the kinematic significance and timing of movement on northwest-dipping (apparent dip) shear zones imaged in the subsurface of cross-section C (Fig. 9).

First-order extensional detachment systems

The role of extensional detachment structures in unroofing the HP belt is examined by use of Fig. 10. Major southeast-dipping normal faults occur in all the cross-sections and three crustal-scale systems are identified that may provide links between several of the cross-sections. These are referred to here as the *Mid-Parautochthon*, the *Allochthon Boundary* and the *Upper Allochthon detachment systems*. All are ductile structures characterized by amphibolite-facies mineral assemblages.

Mid-Parautochthon detachment system

The surface expression of the Mid-Parautochthon detachment system, which is only recognized in cross-sections A and C, lies a few tens of kilometres southeast of the Grenville Front. In A, where it is known as the Boundary shear, it is a broad, moderately dipping zone of intensely flattened ductile gneiss in which oblique-normal kinematic indicators overprint older thrust structures (Jamieson et al. 1995). The amount of displacement is unknown, but the lack of field evidence for a significant change in metamorphic grade on either side may imply that it was not large. In cross-section C, in contrast, normal displacement on a structure in a similar location may have been considerable, since it is visible on Lithoprobe seismic sections and is inferred to result in crustal thinning and displacement of the crust–mantle boundary (Martignole et al. 2000). Connection of these shear zones between the two sections has not been established in the field, but their similar location suggests that they may be part of a linked detachment system, on which displacement occurred from late Ottawan to Rigolet time.

Allochthon Boundary detachment system

The Allochthon Boundary detachment system comprises several normal-sense shear zones that are known in cross-sections A, C, D, and E. In A and C, these shear zones follow the location of the Allochthon Boundary thrust at the base of the HP belt, and in C may offset the Moho (Fig. 10; Martignole et al. 2000). Farther east, however, they are located higher up the structural section; in D the Relay–Tshenukutish shear zone bisects the HP belt and in E the Lac Émérillon shear zone is situated at the upper boundary of the HP belt. Time of normal displacement has been dated at ~1020 Ma on Shawanaga shear zone in cross-section A (Culshaw et al. 1997; Ketchum et al. 1998), whereas in cross-section C, the preservation of offsets on the Moho implies that displacement probably continued until late Rigolet time there. Displacement on the Relay–Tshenukutish shear zone in the vicinity of cross-section D has been dated at 1017–1007 Ma (Cox et al. 1998) and on Lac Émérillon shear zone (cross-section E), it has been dated at 990 Ma (Connelly et al. 1995). Normal displacement thus appears to have been initiated in late Ottawan time, following unroofing of the HP belt, and to have continued episodically throughout the Rigolet orogeny.

Given the ~30 million-year spread of ages and the present lack of mapped continuity between several of the shear zones, it may be questioned whether they are part of a single detachment system. However, they are tentatively linked here because of their close spatial relationship to the HP belt. The location of the major normal-sense shear zone *beneath* the HP belt in the west, but *above* it in the east, is significant. This relationship, which places the HP belt in the hanging wall of the Allochthon Boundary detachment system in the west, but in its footwall farther east, implies that the HP belt must have been transported into the mid-upper crust prior to extensional faulting.

Upper Allochthon detachment system

The Upper Allochthon detachment system is defined in

Fig. 11. Schematic panel diagram showing tectonic evolution of the HP (High Pressure) belt in the central Grenville Province (cross-section E, Fig. 9). Dotted lines show locations of future thrusts and extensional shear zones that are active in next panel. Note the progressive migration of thrusting towards the foreland. ABD, Allochthon boundary detachment; ABT, Allochthon Boundary thrust; GF, Grenville Front; GT, Gagnon terrane; HP, High Pressure; LJT, Lac Joseph terrane; LP, Low Pressure; MLT, Molson Lake terrane; UAD, Upper Allochthon detachment; UAT, Upper Allochthon thrust. Late extensional displacements after panel D have been omitted.

the central Grenville Province from the map pattern (Fig. 3) and cross-sections D and E (Fig. 10). In cross-section D, Hart Jaune shear zone is located in the immediate hanging wall of the HP belt. Hynes et al. (2000) showed that its southwesterly continuation (known as Highway shear zone) was imaged in the Lithoprobe deep seismic reflection experiment and could be traced to at least 10 km below the present erosion surface. Farther east, the map pattern indicates that the shear zone cuts down-section and merges with the Allochthon Boundary detachment system, locally completely excising the HP belt at the erosion surface, e.g., east of Lelukuau and Tshenukutish terranes and along the northern margin of Lac Joseph terrane (Fig. 3). The existence of one or more normal-sense shear zones in eastern Molson Lake terrane immediately below and subparallel to the Upper Allochthon detachment (Fig. 3), where metamorphic grade ranges from mid- to lower amphibolite facies (Connelly 1991), is inferred on metamorphic grounds. Time of displacement on the Lac Émérillon and Hart Jaune shear zones has been dated at ~990 Ma (Scott and Hynes 1994; Connelly et al. 1995).

Other normal-sense shear zones

Other normal-sense shear zones and (or) extensional deformation can be divided into two types on the basis of scale. In the vicinity of cross-section A, regional-scale ductile extensional flow along subhorizontal fabrics in the southern Parautochthonous belt at ~1020 Ma (Culshaw et al. 1994; Ketchum et al. 1998) and in the Adirondacks at ~1060–1030 Ma (McLelland et al. 1996) indicates the presence of abnormally hot crust in these areas, and may imply bulk crustal thinning. Regional extension in the vicinity of cross-section D in the interval ~1050–1015 Ma has also been proposed; in this area extension was associated with mafic and felsic magmatism inferred to be related to delamination of the lower lithosphere (Indares et al. 1998). In contrast to these examples of regional-scale lower-crustal extension, extensional structures higher in the structural pile are discrete and vary in character, timing, and significance. In cross-section A, for instance, Bancroft shear zone comprises disconnected subparallel strands of ductile mylonite (Carr and McMullen 2000), for which time of (probably minor) displacement has been dated at ~1020 Ma (van der Pluijm and Carlson 1989); whereas displacement on the northwest-dipping Carthage–Colton mylonite zone, which marks the boundary between Frontenac and Adirondack terranes, has been dated at ~1000–930 Ma (McLelland et al. 1996; Magloughlin et al. 1997). Other normal faults separate domains of different cooling history, so must be essentially posttectonic, e.g., ~960–930 Ma displacement on the Robertson Lake and Mooroton shear zones (Mezger et al. 1993; Busch et al. 1996; Cureton et al. 1997). Taken together, these discrete extensional structures probably represent late-orogenic to post-orogenic adjustments during the final stages of crustal thickening and ongoing denudation and uplift, and they are unlikely to be part of a linked system.

Architecture and significance of the detachment systems

The general geometry of the detachment systems that emerges from Fig. 10 is that they are gently to moderately southeast-dipping structures that become listric towards the southeast and sole out at or slightly above the Moho. A ramp-flat geometry is developed in the Allochthon Boundary detachment in cross-section C (Fig. 10), but as noted earlier, it is not clear if this is an original feature or a result of later imbrication in its footwall (Martignole et al. 2000). The ramp-flat shape of the Allochthon Boundary detachment in cross-section E is inferred to be a late feature associated with cross-folding (Connelly et al. 1995). The inference that several of the detachments sole out at or near the crust–mantle boundary implies that the latter remained ductile until late Grenvillian time. Inferred offsets of the crust–mantle boundary in cross-section C suggest that latest displacements on the detachments took place after significant cooling of the crust–mantle boundary region in late Rigolet time.

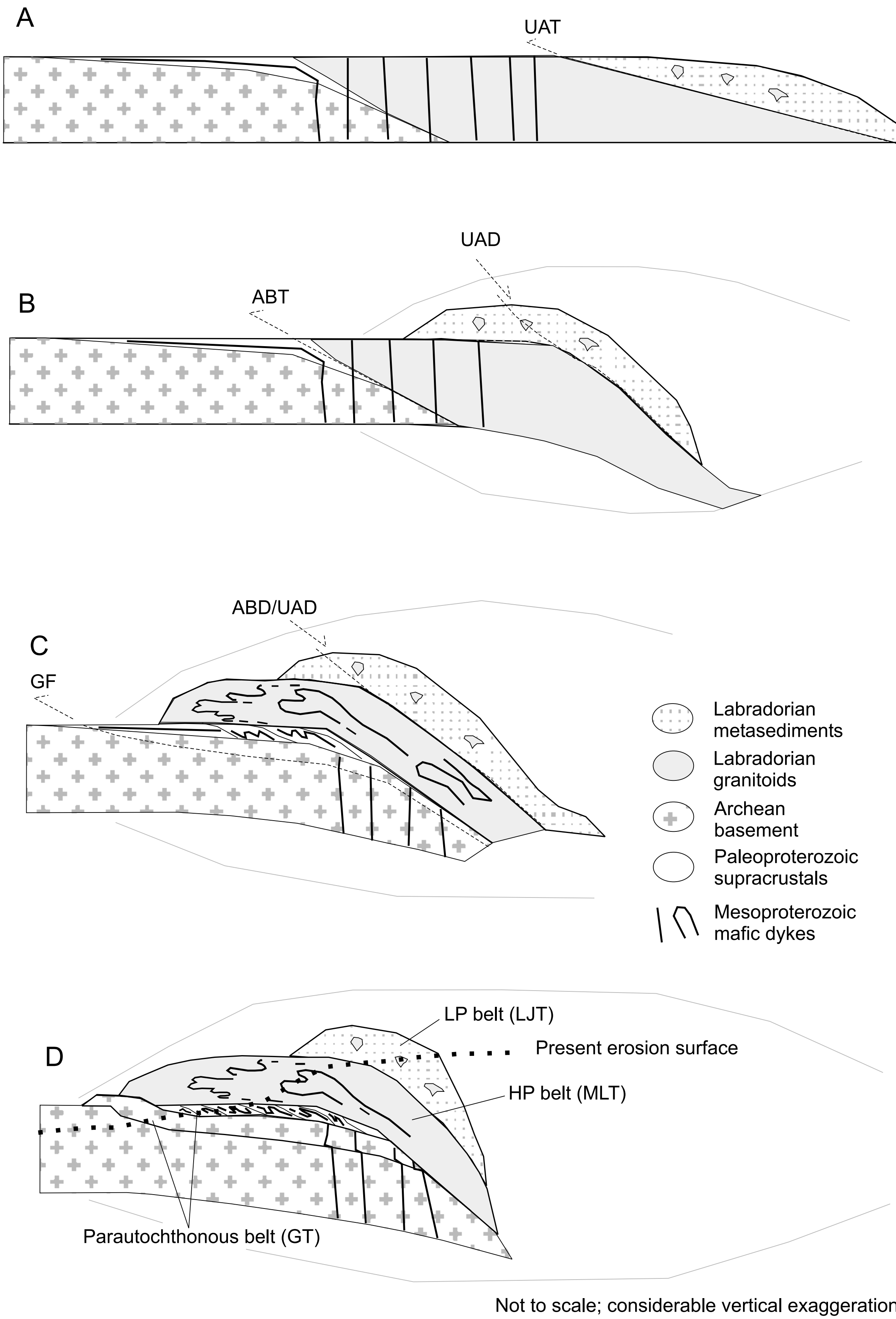
The role of the various detachment systems in contributing to the unroofing of the HP belt must now be considered. As noted earlier, the HP belt had already been transported into the mid- to upper crust by late Ottawan time, the time of earliest displacement on the detachment systems. Thus early unroofing of the HP belt was not a result of regional extension. Furthermore, the Mid-Parautochthon and Allochthon Boundary detachment systems in cross-section A are both situated beneath the HP belt, so displacement on them could not have contributed directly to unroofing of the HP rocks. On the other hand, displacement on the Allochthon Boundary detachment in cross-sections D and E could have contributed to unroofing, as the detachments lie within or above the HP belt there. In cross-section D, the HP belt occurs on both sides of the Allochthon Boundary detachment suggesting that displacement was limited there. However, in cross-section E, the marked contrast in Ottawan metamorphic grade across the Allochthon Boundary detachment suggests that it was the site of major displacement and thus could have contributed significantly to unroofing the HP terranes.

Tectonic Models

Culshaw et al. (1997), Carr et al. (2000), Hynes et al. (2000), and Martignole et al. (2000), and Wodicka et al. (2000) have discussed the evolution of the HP belt in cross-sections A, C, and D individually, and Ludden and Hynes (2000) examined cross-sections A, B, C, and D together. We present a model for the tectonic evolution of the HP belt in cross-section E here, and then compare common features and differences among the various models.

Evolution of cross-section E

The configuration of the Laurentian margin in the vicinity of cross-section E prior to the Grenvillian collision is schematically shown in Fig. 11A, with Labradorian metasediments (metamorphosed ~1660 Ma) lying outboard


A
UAT
B
UAD
ABT
ABD/UAD
C
GF
Labradorian metasediments
Labradorian granitoids
Archean basement
Paleoproterozoic supracrustals
Mesoproterozoic mafic dykes
LP belt (LJT)
D
Present erosion surface
HP belt (MLT)
Parautochthonous belt (GT)
Not to scale; considerable vertical exaggeration

of granitoid rocks comprising the Trans-Labrador batholith (emplaced at 1650 Ma), which in turn lay outboard of the Archean basement with a Paleoproterozoic supracrustal cover that in this region was undeformed. Mesoproterozoic modifications to this architecture included continental-margin arc-related intrusions and supracrustal rocks (not shown) and a prominent mafic dyke swarm (Shabogamo gabbro) that stitched several of the crustal elements (Rivers 1997; Rivers and Corrigan 2000).

The first effect of the collisional orogeny was imbrication of the future LP belt onto the HP belt along the Upper Allochthon thrust (Fig. 11B). This event is largely inferred, but may be recorded by rare thrust-sense kinematic indicators preserved in Lac Émérillon shear zone (Connelly 1991). We infer that this was a thick-skinned thrusting process because of the lack of penetrative Grenvillian deformation and metamorphism in Lac Joseph terrane in the LP belt. Understacking of the future HP belt led to eclogite-facies metamorphism near the base of the doubly thickened crust. Although ductilely deformed and penetratively recrystallized, the HP belt retains an internal structural and metamorphic coherence that can be documented from the outcrop patterns of mafic dykes. Following attainment of peak metamorphic conditions, probably at about 1080–1060 Ma, the HP belt was uplifted along the Allochthon Boundary thrust with its ramp-flat geometry (Fig. 11C). Coeval normal faulting along the Upper Allochthon detachment above the HP belt, leading to unroofing by tectonic extrusion, resulted in widespread preservation of the HP mineralogy and texture (Hynes et al. 2000). Emplacement of the HP belt on the Paleoproterozoic margin resulted in thin-skinned imbrication of the underlying parautochthonous supracrustal rocks.

In the final stage of tectonic development during the Rigolet orogeny (Fig. 11D), the adjacent foreland and upper part of the footwall were incorporated into the orogenic wedge as a foreland fold–thrust belt (van Gool and Cawood 1994). Thin-skinned imbrication of the Paleoproterozoic supracrustal rocks on top of the Archean basement contrasted with thick-skinned imbrication of the underlying Archean rocks, although total displacement of the latter was probably minor (van Gool 1992).

Orogen-scale constraints

To compare and contrast existing tectonic models for the origin of the HP belt, and in particular to examine the differences in its architecture along strike, we have placed particular importance on the following observations:

(1) HP metamorphism took place at ~1060–1040 Ma in the central Grenville Province, whereas in the western Grenville Province it was somewhat earlier, although its timing is not well constrained.

(2) HP rocks in the western Grenville Province were transported to mid-crust levels and imbricated with Muskoka domain before undergoing granulite-facies metamorphism at ~1080–1060 Ma.

(3) In the western Grenville Province, the footwall beneath the HP belt was deformed by penetrative ductile flow during the Ottawa orogeny, implying that it was hotter and weaker than in the central Grenville Province.

(4) In the western Grenville Province, HP rocks occur as variably disaggregated pods and lenses, whereas in the central Grenville Province HP units exhibit greater structural coherence.

(5) The HP belt has a ramp-flat geometry in the central Grenville Province, but dips gradually to the Moho in the western Grenville Province.

(6) Archean rocks are everywhere restricted to the footwall of the HP belt.

(7) The Allochthon Boundary detachment system formed *above* the HP terranes in the central Grenville Province, whereas it formed *below* the HP terranes in the western Grenville Province.

(8) Transport of HP terranes to mid- to upper crustal levels had taken place by late Ottawan time in both the western and central Grenville Province.

(9) There is a negative gravity anomaly, the Grenville Front gravity low, under the Parautochthonous belt in the central Grenville Province, implying that crust is about 5 km thicker than average, whereas there is no such gravity anomaly in the western Grenville Province (e.g., Rivers et al. 1989; Hynes 1994).

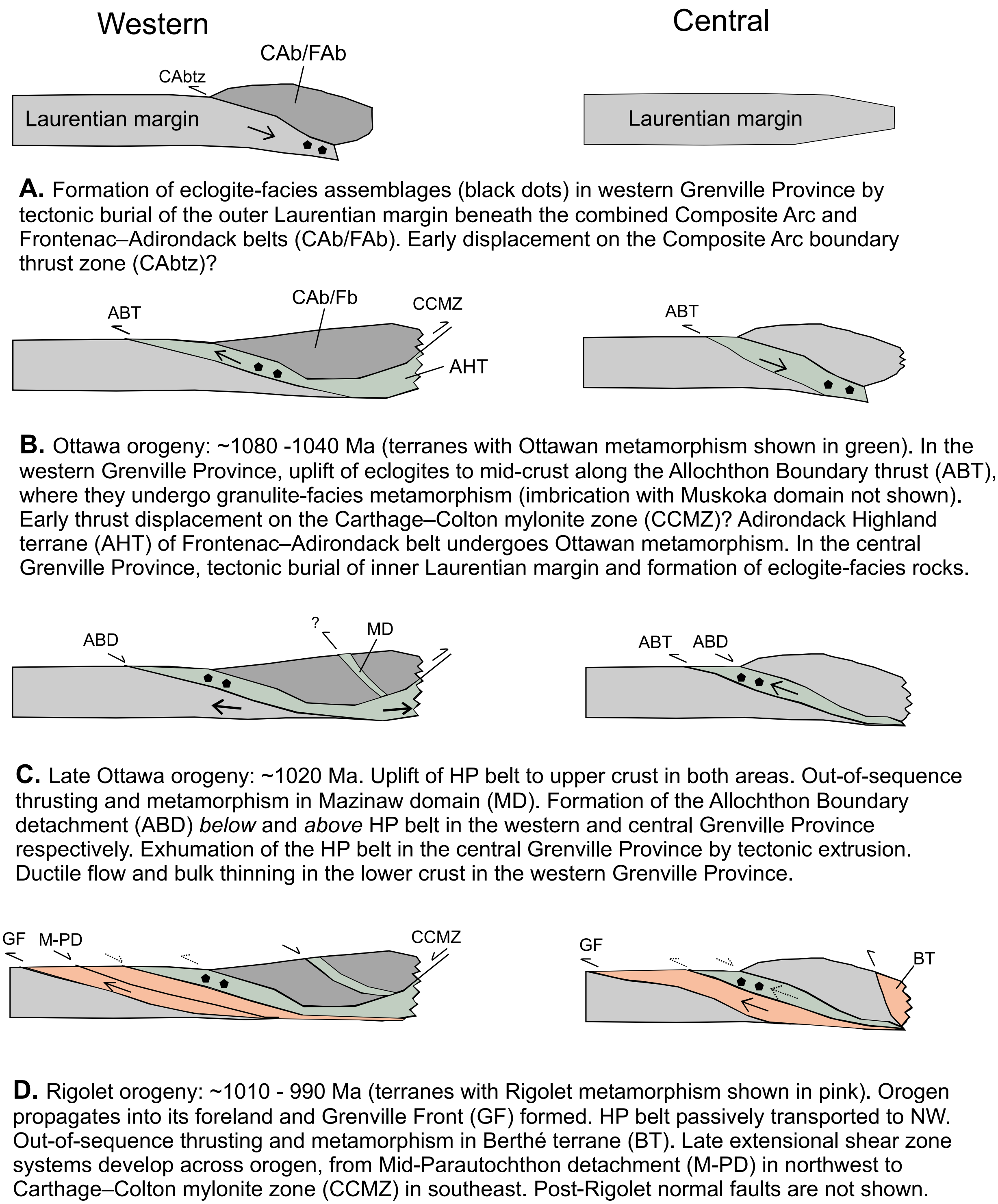
Figure 12 compares the tectonic evolution of the western and central Grenville Province. The figure begins in the western Grenville Province with the tectonic burial of the Laurentian margin accompanying approximate doubling of crustal thickness (~60 km) and the formation of the HP rocks. Other earlier pre-Grenvillian and Grenvillian orogenic activity not shown in the figure includes the offshore(?) imbrication of the components of the Composite Arc belt during the ~1250–1220 Ma Elzevirian orogeny, and imbrication of the Composite Arc belt with the Frontenac-Adirondack belt during the ~1190–1140 Ma Shawinigan orogeny (Carr et al. 2000). Fig. 12A shows that formation of the eclogite-facies rocks in the western Grenville Province occurred as a result of burial of the Laurentian margin under the Composite Arc and Frontenac–Adirondack belts. There is little evidence for this stage in the HP belt itself, however, due to the subsequent uplift of the HP rocks into the mid-crust and penetrative granulite-facies recrystallization at ~1080–1060 Ma (Fig. 12B).

At approximately the same time that the eclogite-facies rocks in the western Grenville Province were undergoing mid-crustal granulite-facies recrystallization, eclogites were forming in the deep crust in the central Grenville Province, implying that this part of the Laurentian margin had also been doubled in thickness by this time (Fig. 12B). Recognizable evidence for this stage is preserved in thrust fabrics, eclogite-facies mineral assemblages, growth-zoning patterns in slow-diffusing porphyroblastic minerals such as garnet, and U/Pb ages in accessory minerals. In rocks that underwent penetrative strain during their exhumation, this early record was more or less completely obliterated, largely restricting preserved HP assemblages to competent dry units, such as metagabbro.

Having attained their maximum depths of burial, the HP rocks in the central Grenville Province began a single-stage process of tectonic unroofing, probably along steep *P–T* gradients (Indares et al. 2000), and transport to upper crustal levels appears to have followed shortly after maximum tectonic burial.

Despite differences in the unroofing histories of the HP belt in the two areas, compressional and extensional stages

Fig. 12. Schematic diagram comparing the tectonic evolution of the HP (High Pressure) belt in the western and central Grenville Province (only the northwestern part of the orogen is shown). Solid arrows, active structures; dotted arrows, inactive structures; dark grey shading, hanging wall terranes with pre-Ottawan metamorphism. (A) and (B), The different timing of eclogite formation and the contrasting nature of the tectonic load on the HP belt (Composite Arc and Frontenac–Adirondack belts in the western Grenville Province, the outer Laurentian margin in the central Grenville Province) are shown. (C) The location of the Allochthon Boundary detachment *below* the HP belt is associated with bulk extension of the lower crust in the western Grenville Province, whereas it is located *above* or within (not shown) the HP belt in the central Grenville Province. The figure also illustrates the progressive growth of the orogen into its foreland by understacking. (D) The passive transport of the HP rocks on deeper thrust systems after late Ottawan time. Note that the ramp-flat architecture of the Allochthon Boundary thrust is not shown at this scale.



were common to both and the relative timing and spatial location of these is critical to developing a proper understanding of the overall process. Early unroofing in both areas probably took place in a thrust regime that led to transport of the HP rocks onto a footwall ramp. This resulted in incorporation of the HP belt into the orogen, a process that has been termed basal accretion to the orogenic wedge (e.g., Dahlen and Barr 1989; Royden 1993). The restriction of Archean rocks to the footwall of the HP belt in the central Grenville Province is significant and is compatible with the inference that the Archean craton comprised a mechanically competent buttress or ramp that focused extrusion of the HP rocks above it (e.g., Hynes and Eaton 1999; Hynes et al. 2000). In this context, the lack of a ramp-flat geometry beneath the HP belt in cross-section A (Fig. 9) merits attention.

As noted earlier, the Archean craton does not penetrate as far into the orogen at mid-crustal levels in cross-section A, as elsewhere. In addition, the Paleoproterozoic lower crust underlying the southern Parautochthonous belt in the western Grenville Province was unusually ductile during the Ottawa orogeny, leading to widespread distributed flow in gneissic rocks during both compressional and extensional tectonism (Fig. 12C; Culshaw et al. 1994, 1997; Ketchum et al. 1998). The abundant field evidence for ductile flow in this area shows that the process had a profound effect on the geometry of rock units, leading us to suspect that any original architecture of the ramp up which the HP rocks were transported is no longer preserved. We thus infer that the architecture in Fig. 9A represents a modification of an original ramp-flat geometry as observed in cross-sections Figs. 9B–9E. The ductile nature of the lower orogenic crust in the western Grenville Province could have several causes: (*i*) the absence of old, cold Archean rocks in the mid-crust; (*ii*) the presence of an orogenic bend in the subsurface trajectory of the Grenville orogen located over northern Georgian Bay (Fig. 1; Culotta et al. 1990), which focused thrust loading on this part of the Parautochthonous belt, thereby keeping it in compression, and thus thick, for an extended period (Ketchum 1995); (*iii*) proximity to the Mid-Continent Rift system, which was the site of voluminous magmatic activity in the interval 1109–1086 Ma (Van Schmus et al. 1993); or (*iv*) delamination or deblobbing of the lower lithosphere (McLelland et al. 1996). We are unable to choose unambiguously among these possibilities, but in any case, we infer that the lower crust in the Parautochthonous belt was hotter and more ductile in the western Grenville Province than elsewhere. The presence of a well-developed ramp in cross-section C (the Baskatong ramp, Martignole et al. 2000) may suggest that distributed ductile flow in the lower crust was restricted to the westernmost part of the Grenville Province, although, as noted earlier, it is possible that the Baskatong ramp is in part a later feature.

Following uplift of the HP belt onto its footwall in a compressional regime during the Ottawa orogeny, there is evidence for an important phase of extensional displacement along southeast-dipping detachments (Fig. 12C). As noted, Ketchum et al. (1998) have dated extensional displacement on Shawanaga shear zone in the western Grenville Province at ~1020 Ma (i.e., latest Ottawan). Shawanaga shear zone is situated *beneath* the HP belt, so displacement on it would have brought the HP rocks in its hanging wall into contact with hot lower crust in its footwall (Wodicka et al. 2000) but would not have contributed directly to unroofing of the HP belt. In contrast, in the central Grenville Province extension took place *above* the HP belt and was coeval with thrust transport of the HP belt onto the footwall ramp, leading to unroofing by tectonic extrusion (Hynes et al. 2000). The location of the extensional shear zone above the HP belt would have contributed to unroofing of the HP belt in the central Grenville Province, and may therefore partly explain the better preservation of HP assemblages there.

At the beginning of the Rigolet orogeny (~1010 Ma, Fig. 12D), the orogen again went into compression, and the orogenic wedge propagated into its foreland (Haggart et al. 1993; van Gool and Cawood 1994). At this time, the HP belt in both the western and central Grenville Province was in the hanging wall of the thrust wedge and was transported passively towards the northwest. Deformation and metamorphism were restricted principally to the foreland region in the footwall of the HP belt and by inference to the base of the orogenic wedge, although they also occurred farther to the southeast in cross-section D (Ludden and Hynes 2000). This period of thrusting appears to have been short-lived and was followed by ductile normal faulting by about 995 Ma, which continued sporadically into the brittle regime over the next 50 million years.

Gravity data suggest that crustal thickening during the Rigolet orogeny may have been considerable. The negative Bouguer gravity anomaly under the Parautochthonous belt in the central and eastern Grenville Province, one of the most conspicuous gravity anomalies in the Canadian Shield, is inferred to have developed during Rigolet time as the orogen advanced into its foreland. The presence of a residual negative Bouguer anomaly indicates that the Moho remains depressed there as a result of excess crustal thickness, whereas in the western Grenville Province any former anomaly has been completely compensated by rise of the Moho. We suggest that the depressed Moho in the central Grenville Province is consistent with a relatively cool, rigid lower crust beneath the Parautochthonous belt there, whereas, in contrast, the complete compensation of any former gravity anomaly in the western Grenville Province is compatible with the notion that the lower crust and Moho were hotter and more ductile there.

Discussion

Despite the undetermined difference in timing of HP metamorphism and the single-stage versus two-stage decompression, the overall similarity between the tectonic models for the central and western Grenville Province is striking. In both areas there is a predominant progression of thrusting towards the foreland (i.e., understacking) during orogenic evolution, and both imply transport of the HP rocks to upper crustal levels by late Ottawan time. The two-stage decompression path in the western Grenville Province involved initial transport into the mid-crust, imbrication with the mid-crustal Muskoka domain, and a period of granulite-facies metamorphism before final transport into the upper crust. In contrast, the single-stage decompression path in the central Grenville Province involved direct transport of the eclogite-facies rocks into the upper crust, at least from a metamorphic perspective. In late Ottawan time (~1020 Ma), the HP rocks were affected by development of normal-sense shear zones constituting the Allochthon Boundary detachment system. Differences resulting from the contrasting levels of the Allochthon Boundary detachment with respect to the HP belt may have been significant in the context of the preservation of the HP assemblages, but on a regional scale were probably of minor importance. Final unroofing occurred as a result of passive transport in the upper crust during the Rigolet orogeny in both areas. Overall, from an orogenic perspective, it is clear that the development of the HP belt in both the western and central Grenville Province can be accommodated in a similar tectonic setting.

Location of HP belt with respect to the Laurentian margin

Despite the similar overall tectonic setting of the HP belt in the two areas of the Grenville Province, several significant details differed. In the west, the eclogite-facies assemblages appear to have developed in lower crustal rocks originally situated near the former leading edge of the Laurentian margin as a result of accretion of the Composite Arc and Frontenac–Adirondack belts (Fig. 12). The timing of this accretionary event is, therefore, dated by the age of the eclogite-facies metamorphism, which as noted, remains contentious. Formation of the HP rocks in the central Grenville Province, on the other hand, involved tectonic burial and eclogite-facies formation in rocks well inboard from the Laurentian margin, with the tectonic load in the hanging wall formed, at least in part, from the more outboard Laurentian terranes (Fig. 11). In this setting, the impetus for crustal thickening and eclogite-facies formation is inferred to have been continental collision, with the location of the site of the inferred early fault separating the HP footwall from its hanging wall being determined by a preexisting weakness in the Laurentian crust.

One-stage and two-stage unroofing of the HP belt

It can be seen in Fig. 4 that the relict eclogite in the western Grenville Province occurs in rocks that subsequently underwent Ottawan upper amphibolite- to granulite-facies metamorphism at ~1080–1060 Ma. If the province-wide Ottawa orogeny was a result of continent–continent collision, as is commonly inferred (e.g., McLelland et al. 1996, 2001; Rivers 1997; Carr et al. 2000), the Ottawan granulite-facies metamorphism in the mid-crust in the western Grenville Province may have taken place as a result of transport of the eclogite-facies rocks from double crustal depths coeval with thrust loading associated with the collision. This notion is supported by the evidence for out-of-sequence imbrication of Muskoka domain with the HP Algonquin terrane at this time. As noted earlier in the text, uplift may have been partly suppressed by focused thrust loading as a result of the orogenic bend in this area, thereby prolonging the time available for thermal relaxation. In the central Grenville Province, on the other hand, the Ottawa orogeny was associated with the maximum burial of the HP rocks and was followed by a single-stage unroofing path. The available data thus suggest that tectonic burial to eclogite-facies conditions in one part of the orogen was approximately coeval with partial unroofing, mid-crustal imbrication and granulite-facies heating elsewhere. As noted, after this time, the major pattern of subsequent tectonism appears to have been broadly similar in the two areas.

Exhumation processes

Examination of Fig. 12 suggests that unroofing of the HP belt was the result of several sequential tectonic processes: (*i*) One- or two-stage northwest-directed tectonic transport of HP rocks along the Allochthon Boundary thrust and onto the footwall ramp in a compressional regime; (*ii*) southeast-directed transport along the extensional Allochthon Boundary detachment system, which had different effects on the HP rocks depending upon whether they were in the hanging wall or footwall of the detachment; (*iii*) northwest-directed transport and passive uplift in the upper crust; and (*iv*) southeast-directed tectonic transport in the hanging wall of late extensional faults, accompanied by tectonic erosion of hanging wall rocks (probably a minor effect). This sequence implies an overall, in-sequence forelandward progression of thrusting by understacking, which may be an essential component of the exhumation process. On a regional scale, there is little evidence for large-scale out-of-sequence thrusting by overstacking behind (to the southeast of) the HP rocks, a process that would have resulted in reburial and reheating of the previously metamorphosed rocks, thereby prolonging the unroofing process and increasing the likelihood of the retrogression of the HP assemblages. Three local examples of overstacking, and therefore exceptions to the regional pattern, are (*i*) early Ottawan out-of-sequence thrusting of the terranes overlying the HP belt in the western Grenville Province (Culshaw et al. 1997; Wodicka et al. 2000); (*ii*) late Ottawan metamorphism of Mazinaw domain in the Composite Arc belt (~1020 Ma, Corfu and Easton 1997); and (*iii*) Rigolet out-of-sequence thrusting and metamorphism in Berthé terrane in the central Grenville Province (Ludden and Hynes 2000). However, these affected relatively small segments of the orogen and do not appear to have been of major consequence for unroofing of the HP rocks. In summary, the transfer of the HP belt from the base of the lower crust to the mid- to upper crust in an understacking regime is common to both the western and central Grenville Province, although the timing was slightly different in the two areas and the process was interrupted in the western Grenville Province by a period of mid-crustal residence. This suggests that tectonic transport in a compressional regime may be central to the unroofing of HP rocks.

As noted in the western Grenville Province, major extensional shearing appears to have postdated crustal thickening by thrusting and to have taken place beneath the HP belt. In contrast, in the central Grenville Province, thrusting and extensional shearing were approximately coeval, and extension took place above the HP belt, leading to tectonic extrusion of the HP rocks (Hynes et al. 2000). The better preservation of the HP rocks in the central Grenville Province may attest to the greater efficiency of tectonic extrusion as an exhumation process (see Andersen et al. 1994; Krabbendam and Dewey 1998; Beaumont et al. 2001 for other examples).

Continuation of HP belt into the eastern Grenville Province

Although possible continuation of the HP belt into the eastern Grenville Province is speculative, it is directly relevant to the interpretation of the southern segment of the marine

ECSOOT transect, the focus of this volume. Eclogite-facies rocks have not been positively identified in the eastern Grenville Province, but we note that corona assemblages in the Mesoproterozoic Michael gabbro in Groswater Bay terrane, reported by Gower (1986), are petrographically very similar to those in the Shabogamo gabbro, for which eclogite-facies conditions have been calculated (Indares and Rivers 1995). Since the Michael and Shabogamo gabbros are chemically similar (Gower et al. 1990) and are situated along strike from one another and parallel to the regional northeast trend of the northern Grenville orogen, this leads us to suspect that the HP belt may extend out to the coast, although its exact location is unknown at this time. Furthermore, the tectonically overlying Hawke River terrane appears to have escaped Grenvillian metamorphism (Gower 1996), suggesting that it may occupy a tectonic position comparable to Lac Joseph terrane in the central Grenville Province (Fig. 11). However, although there are some lithological similarities that may suggest that the HP belt continues to the coast, the published interpretation of the marine Lithoprobe ECSOOT seismic profile indicates that the major crustal structure of the offshore Grenville Province is very different from that farther west. As seen in Fig. 9, all the on-land crustal-scale seismic lines in the Grenville Province are characterized by gently southeast-dipping structures of inferred Grenvillian age, several of which are crust-penetrating and reach the Moho. In contrast, the ECSOOT profile exhibits a doubly vergent character with southeast-dipping reflectors in the north and northwest-dipping reflectors farther south that converge in the lower crust (Gower et al. 1997). Furthermore, the seismic reflectors are interpreted to be largely of Labradorian age with only minor Grenvillian overprint (Gower et al. 1997). Exhumation of Grenvillian HP rocks from the point in the lower crust where the reflectors converge would be tectonically feasible, but only if the structures were Grenvillian in age. Clearly the present state of knowledge does not allow a satisfactory answer to this problem, but its resolution is important for proper understanding of the tectonic setting and continuity of the HP belt and for linking tectonic models across the orogen.

Conclusions

We have defined the High Pressure (HP) belt as a first-order tectonic element of the Grenville Province through examination of HP rocks from two areas some 800 km apart in the western and central parts of the province. The HP rocks comprise principally eclogite and co-facial HP granulite, and their protoliths were deeply buried units of the Paleo- to Mesoproterozoic Laurentian margin. Maximum *P–T* conditions of the eclogite-facies rocks, estimated from samples in the central Grenville Province, are about 1800 MPa and 850°C. The HP metamorphism took place at ~1060–1040 Ma in the central Grenville Province; it was somewhat earlier in the western Grenville Province, but has not yet been satisfactorily dated despite detailed study. In the western Grenville Province, HP metamorphism is inferred from field relations to have resulted from tectonic burial of the Laurentian margin, as a result of accretion of the combined Composite Arc and Frontenac–Adirondack belts. The HP rocks subsequently underwent a two-stage uplift–exhumation path separated by a period of mid-crustal residence and granulite-facies metamorphism at ~1180–1160 Ma, with final transport into the upper crust occurring in late Ottawan time (~1020 Ma). In contrast, in the central Grenville Province, HP metamorphism is dated at ~1060–1040 Ma (Ottawa orogeny) and took place inboard from the former Laurentian margin. It was followed by a single stage of uplift into the upper crust by late Ottawan time. Subsequently, the HP belt in both the western and central Grenville Province was essentially passively transported in the upper crust, first along late Ottawan extensional detachment systems and subsequently during compressional and extensional tectonics associated with the Rigolet orogeny. Compressional uplift of the HP belt in the central Grenville Province was controlled by a crustal-scale, ramp-flat geometry developed on the Archean basement that is well-imaged in Lithoprobe seismic sections, but in the western Grenville Province any former ramp has been obliterated by later widespread lower crustal extensional ductile flow. Unroofing of the HP rocks was largely a result of Ottawan compressional tectonism in a foreland-propagating orogen, but several important systems of crustal-scale, ductile detachments have been identified that may have exerted a secondary control. Evidence for approximately coeval compression and extension in the central Grenville Province implies that unroofing occurred by tectonic extrusion there. Possible continuation of the HP belt into the eastern Grenville Province is discussed. Although it appears likely on geological grounds, the published interpretation of the Grenville segment of the Lithoprobe ECSOOT profile suggests a crustal structure very different from that farther west, as well as an inferred different age of the reflector fabric, so if HP rocks are present, the geometry of their exhumation path must have contrasted to that elsewhere in the Grenville Province.

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