**MESOPROTEROZOIC EVOLUTION OF THE SOUTH-CENTRAL GRENVILLE
OROGEN: STRUCTURAL, METAMORPHIC, AND GEOCHRONOLOGIC
CONSTRAINTS FROM THE MAURICIE TRANSECT**

by

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A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfilment of

the requirements for the degree of

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and

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ABSTRACT

The Mauricie transect in south-central Québec consists of an orogen-oblique, east-dipping homoclinal sequence containing one of the most important concordant, low-angle oblique extensional shear zones (Tawachiche shear zone) in the Grenville orogen. The Portneuf—St. Maurice domain, which forms the hanging wall, is composed of relicts a *ca.* 1.45 Ga island arc (Montauban Group) intruded by *ca.* 1.40—1.37 Ga calc-alkaline plutons of continental arc affinity (La Bostonnais complex). The Portneuf—St. Maurice domain was metamorphosed and deformed under amphibolite-facies relatively high-T, low- to moderate-P conditions (550—750°C; 3.2—6.6 kb) at *ca.* 1.39 Ga.

The Tawachiche shear zone footwall is predominantly formed of relicts of this *ca.* 1.40 Ga arc. From west to east, the following lithotectonic assemblages are found: *i)* a granulite facies terrain (Mékinac domain) composed of shallowly-dipping *ca.* 1.40 Ga mafic to felsic orthogneisses, structurally interlayered with minor metasedimentary tracts and small anorthositic-gabbroic plutons; *ii)* an uppermost amphibolite- to granulite-facies terrain (Shawinigan domain) composed of *ca.* 1.37 Ga orthogneisses of predominantly intermediate composition structurally interlayered with numerous metasedimentary tracts, and concordant with an important unit of metasedimentary rocks of pelitic, quartzitic, and calc-silicic composition deposited between *ca.* 1.18 and 1.12 Ga (St. Boniface unit).

Two temporally and spatially distinct AMCG-type plutonic suites are recognized. An older suite is represented by the *ca.* 1.15 Ga Lac Paul megacrystic granite, which occurs in the Shawinigan domain, and deformed meta-anorthositic and coronitic meta-gabbro bodies located in the Mékinac domain. The older suite, along with host gneisses, was affected by W-NW-directed thrusting and granulite to uppermost amphibolite-facies metamorphism at P-T conditions of 7.5—8 kb and ≥ 800 °C, at *ca.* 1.12—1.09 Ga. The younger suite consists of unmetamorphosed, post-thrusting gabbro-norite-mangerite-jotunite-granite plutons that were emplaced between *ca.* 1.08 and 1.05 Ga in the Shawinigan and Portneuf—St. Maurice domains.

A relatively sharp transition from *ca.* 1.12—1.09 Ga collisional tectonics, to oblique extension accompanied by voluminous AMCG-type plutonism (younger suite) occurred at *ca.* 1.09—1.08 Ga, and lasted until *ca.* 1.05 Ga. Oblique extensional shear was localized between the Shawinigan and Portneuf—St. Maurice domains along the Tawachiche shear zone, and provided a mechanism for the exhumation of the high-grade

footwall. The hanging wall (Portneuf—St . Maurice domain) likely remained at high structural levels during the *ca.* 1.12—1.09 Ga collisional phase, as indicated by the preservation of concordant *ca.* 1.39 Ga monazite U-Pb ages. In contrast, monazite U-Pb ages in the footwall range from *ca.* 1.09 to 1.08 Ga, coinciding with the early stages of tectonic denudation, and represent post-metamorphic cooling through ~ 725 °C. Metamorphic reaction textures preserved in the footwall suggest that the retrograde P-T path may have consisted of isothermal decompression followed by isobaric cooling.

Data from the Mauricie transect and published data from outside the study area suggest the following tectonic evolution of the southwestern Grenville orogen:

- 1) Formation of an island arc (Montauban Group) southeast of Laurentia at *ca.* 1.45 Ga.
- 2) Accretion of this island arc to Laurentia at *ca.* 1.40 Ga, with Andean-type evolution of the Laurentian margin continuing until at least 1.20 Ga.
- 3) Continent-continent collision at *ca.* 1.19 Ga, resulting in the closure of the Elzevir back arc basin and the end of subduction-related magmatism throughout the Grenville orogen.
- 4) First phase of crustal thickening (1.19—1.16 Ga) leading to overthickening of the lithospheric root and ensuing "delamination", resulting in uplift, extensional collapse, mantle-derived magmatism (AMCG-type), and intramontane sedimentation in the orogen interior between 1.18 and 1.12 Ga.
- 5) Re-establishment of normal lithosphere thickness and resumption of contractional deformation in the orogen interior between 1.12 and 1.09 Ga, leading to the tectonic burial and high-grade overprint of mantle-derived plutons and intramontane sediments.
- 6) Second phase of lithospheric "delamination" between 1.09 and 1.05 Ga, leading to extension in the orogen interior, the emplacement of voluminous AMCG-type plutons, and the exhumation of the Central Granulite Terrain by tectonic denudation.

The above observations imply that the Laurentian margin has evolved continuously during ~ 400 m.y. in a convergent tectonic setting, and that the presently exposed Grenville Province formed a coherent "block" as early as 1.40 Ga. Models of lithospheric "delamination" presently provide the best explanation for the apparent paradox of AMCG-type magmatism, extension, and intramontane sedimentation, in an overall convergent tectonic setting.

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INTRODUCTION

In the last decade or more, the development of precise geochronological and thermobarometric methods, and the advances in structural and kinematic analysis in high-grade gneiss terrains, have significantly advanced our understanding of geological processes that affect orogenic belts. Researchers working in the deeply eroded and relatively poorly exposed Grenville orogen have greatly benefited from the applications of these new techniques. Unfortunately, the majority of published data are from the better exposed or more accessible parts of the orogen, mainly in Ontario, western Québec, the Adirondack Mountains in New York State, and in Labrador. This has led to the extrapolation of tectonic models, or terrain nomenclature from these better known regions, to the vast and less well known parts of the orogen in central Québec (cf. Wynne-Edwards 1972; Rondot 1986; Rivers et. al. 1989), and in turn, to gross misinterpretations of the geological evolution of this region.

This thesis utilises a multidisciplinary approach to constrain the lithologic, tectonic, and metamorphic evolution of the Mauricie region in central Québec, located east and northeast of the Morin Terrane and the Adirondack Highlands, and southwest of the Lac St. Jean anorthosite. Although there are still vast regions of the Grenville orogen that remain poorly known by modern geological standards, there is now a critical mass of data available to incite researchers to model either part of, or the whole of the orogen, in terms of modern tectonic processes. Accordingly, where the data permits, this thesis also attempts to evaluate the possible geological processes that were involved during the evolution of the Grenville orogen, with emphasis on the Mauricie region.

Statement of the problem

Preliminary field observations obtained during a 3 month, reconnaissance-scale mapping initiative in an area approximately 20,000 km² in the Mauricie region (Nadeau

and Corrigan 1991), provided direction for this thesis. During that first season, it was recognized that east-dipping amphibolite-facies supracrustal and metaplutonic rocks in which primary features are locally preserved, structurally overly sub-horizontal to moderately east-dipping granulite facies ortho- and paragneisses. A ductile shear zone (Tawachiche shear zone) that accommodated oblique, top-down-to-the-N-NE sinistral displacement was identified between the high-grade footwall and lower-grade hanging wall. The Tawachiche shear zone appeared to rework and facilitate retrograde metamorphism of high-grade gneisses that were formed earlier during a W-NW-directed thrusting event. An important spatial and temporal relationship between plutonic suites of highly contrasting composition was also observed.

The specific aim of this thesis was to: (1) Investigate in more detail the lithological and structural framework of the Mauricie region in a relatively well exposed transect across the N-S striking structural grain; (2) constrain the age and nature of protoliths using precise U—Pb geochronology; (3) evaluate the timing and cause of deformation and metamorphism in the Tawachiche shear zone footwall and hanging wall; (3) evaluate the role of the Tawachiche shear zone in the exhumation of the granulite facies footwall; (4) derive a model for the tectonic evolution of the Mauricie transect, and to evaluate its role and significance in the construction of the Grenville orogen.

Method of presentation

Chapter 1 locates the study area in the context of the Grenville orogen and of currently utilized lithotectonic subdivision schemes. It then provides a description of the lithological and structural framework of the Mauricie transect, and discusses possible tectonic environments that may have produced the observed lithologic assembly. For convenience, the Mauricie transect is divided into three longitudinal belts (Mékinac, Shawinigan, and Portneuf—St. Maurice domains) that share unique lithologic, metamorphic, or structural characteristics. Chapter 2 expands on the structural and

intrusive relationships outlined in the previous chapter and utilizes U-Pb, and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende geochronology (presented in Appendix 2.1) to provide new constraints on the timing of crust formation, tectonic activity, and metamorphism in this part of the Grenville orogen. This chapter highlights the fact that about 400 m.y. of geological history are preserved in parts of the Mauricie transect, significantly improving our current understanding of the evolution of the "pre-Grenvillian" margin of Laurentia. The new constraints also yield some important insights on the intricate relationship that exists between crustal thickening, extension, magmatism, and metamorphism. The post-metamorphic cooling history is also discussed. Chapter 3 documents the metamorphic response to crustal thickening followed by late- to post-thrusting extension. It also highlights the large difference in metamorphic grade and the contrasting P-T-t trajectories followed by the footwall and hanging wall of the Tawachiche shear zone. Chapter 4 integrates relevant data obtained in the previous chapters with published data from elsewhere in the Grenville orogen to derive a series of schematic tectonic cross-sections illustrating the possible geodynamic evolution of the southwestern part of the orogen.

Chapters 1 to 3 are written in the form of extended articles that will be submitted to refereed journals after the final revisions are completed. Chapter 4 has been written more as a traditional synthesis, in order to permit a larger scope for discussion. I apologize to the reader for any repetition in text. It is inherent to the "self-contained" writing style required for journal articles.

Statement of original contribution

The original proposal for this research has been to a large extent conceived by the author. Subsequent discussions with supervisors helped to refine the scope of research. The data and ideas presented in this thesis are derived from 6 months of locally detailed field work in an area of approximately 1500 km², with logistical support provided by the Geological Survey of Canada. At least 850 stations were described in detail, and rock

specimens and structural measurements were obtained from at least 95% of the stations visited. Approximately 200 thin sections were used for further petrographical and petrological investigation.

I planned and performed all electron microprobe analyses for thermobarometry. I also performed all stages of sample selection and preparation for U-Pb geochronology, for the most part, at Carleton University. However, chemical dissolution was done either entirely by, or with the assistance of the technical staff at the Geological Survey of Canada Geochronology Laboratory. Mass spectrometry and data reduction was entirely performed by the technical staff at the geochronological laboratory. Sample selection and preparation for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology was performed by the author. Sample degassing with the step-heating furnace and mass spectrometry was performed with the assistance of Fred Quigg, at the Geological Survey of Canada.

I am entirely responsible for the interpretation of laboratory and field data, for the writing of all chapters, and for the conceptualization of most of the geological models presented in this thesis.

CHAPTER 1: LITHOTECTONIC FRAMEWORK OF THE MAURICIE TRANSECT, SOUTH—CENTRAL GRENVILLE OROGEN

1.1 INTRODUCTION

Three previously published lithotectonic models of the Grenville orogen offer highly contrasting views concerning the geological nature of the Mauricie region in south-central Québec. In the first "modern" attempt at dissecting the Grenville orogen into lithologically or metamorphically distinct crustal blocks, Wynne Edwards (1972) incorporated the entire Mauricie region into the "Central Granulite Terrain" (Fig. 1.1a). However, this predominantly high-grade crustal block, which comprises the Marcy, Morin, and Lac St. Jean anorthosite massifs (Emslie and Hunt 1990) also contains a wide area of middle amphibolite-facies gneisses east of the St. Maurice River (Pyke 1967; Rondot 1978), suggesting that this subdivision scheme was grossly oversimplified. Supported by more detailed geological mapping, Rondot (1978; 1986) recognized the contrasting lithologic nature and metamorphic facies of adjacent domains in the Mauricie region, which he interpreted as a suture zone between three orogen-scale crustal blocks that he named "Laurentia", "Grenvillia", and "Québecia" (Fig. 1.1b). The margin between "Laurentia" and "Grenvillia" was tentatively interpreted as a suture of Penokean age (1.9-1.8 Ga). Between "Grenvillia" and "Québecia", the intervening "La Bostonnais complex" was interpreted as relict oceanic crust incorporated in a suture zone of Grenvillian age. However, recent geological mapping has not found true oceanic crust (i.e. ophiolites) in the region outlined by Rondot (Nadeau and Corrigan 1991), prompting a re-evaluation of his model.

More recently, and based on locally well-constrained geological, geophysical, and geochronological data (but predominantly extrapolated from Ontario and Labrador), Rivers et al. (1989) proposed a new subdivision of the Grenville orogen comprising three first-order longitudinal belts (Fig. 1.1c). The Parautochthonous Belt consists of

metamorphically upgraded and reworked lithologies belonging to the adjacent foreland (i.e. Laurentia). The Allochthonous Polycyclic Belt, which by definition contains evidence of more than one orogeny, is composed of tectonically transported terranes overlying the Parautochthonous Belt. The Allochthonous Monocyclic Belt consists of rocks apparently younger than 1.3 Ga (Lumbers, 1969; however, see McLelland et al. 1991) that were apparently subjected to a single orogenic cycle. The latter more or less corresponds to "Grenvillia" as defined by Rondot (1986). In this subdivision scheme, the Mauricie region has been interpreted as a first order tectonic boundary that includes the Allochthonous Monocyclic Belt boundary thrust zone. The region immediately east of this boundary was omitted from this model, likely due to the scarcity of data. Interestingly, both Rondot (1986) and Rivers et al. (1989) insinuate that the Mauricie region forms an important tectonic boundary within the Grenville orogen, but present highly contrasting perspectives on its nature.

The aim of this paper is to present a concise description of the lithological and structural characteristics of the Mauricie region, in order to discuss its tectonic setting and evolution, and to provide a better framework for evaluating its significance with respect to the Grenville orogen. The data presented here are based partly on reconnaissance geological mapping at 1:250,000 scale (Nadeau and Corrigan 1991), but primarily on 6 months of more detailed field work done by the author, concentrated in an east-west band across the Mauricie region, referred to in this paper as the "Mauricie transect" (Fig. 1.2).

1.2 REGIONAL FRAMEWORK

On magnetic anomaly maps (Geological Survey of Canada 1987), the Mauricie region generally separates low-amplitude curvilinear patterns to the west, corresponding to the predominantly supracrustal Allochthonous Monocyclic Belt (Rivers et al. 1989), from more "patchy", high-amplitude patterns to the east, corresponding to a vast area of

the Grenville orogen dominated by anorthositic-mangeritic-charnockitic-granitic (AMCG) plutonic complexes (Rivers et al. 1989; Emslie and Hunt 1990; Gower et al. 1991). On gravity anomalies maps (Geological Survey of Canada 1990), it separates a vast region of low Bouguer anomalies (-50 to -100 mGal) to the west, corresponding in part to the Morin anorthosite and associated granulite facies para- and orthogneisses, from a distinct area of higher Bouguer anomalies (+5 to -15 mGal) corresponding to a region dominated by ca. 1080—1055 Ma gabbroic and noritic, post-thrusting intrusions (Nadeau and van Breemen 1994; Corrigan et al. 1994), that includes the Parc des Laurentides plutonic complex (Avramtchev and Piché, 1981; Nadeau and Corrigan, 1991).

Several geological maps covering parts of the Mauricie transect have been published previously (e.g. Rondot 1978; Klugman 1963; Pyke 1967; Béland 1961). However, most are outdated, and some lack essential structural data such as extension and mineral lineations. Martignole (1978) described the tectonometamorphic and plutonic evolution of the Shawinigan area in some detail. He proposed that it forms an eastward extension of the Grenville Supergroup and related anorthosite-mangerite intrusives, i.e. the Morin anorthositic complex and associated high-grade gneisses.

Prior to this study, geochronological data in the Mauricie region was relatively sparse, with only three Rb-Sr whole rock isotopic ages reported in the surrounding area. A granitic orthogneiss located approximately 15 km northwest of Shawinigan (Fig. 1.3) yielded a 1231 ± 24 Ma whole rock Rb-Sr isochron (Barton and Doig 1974; decay constant modified after Steiger and Jäger 1977). Two different outcrops from the St-Didace quartz-monzonite complex, located southwest of Shawinigan (Fig. 1.2), yield Rb-Sr ages of 1138 ± 51 and 1074 ± 25 Ma (*ibid*). All the above were interpreted as magmatic crystallization ages. Lead isochron dates averaging 1270 Ma have been obtained from volcanogenic sulfide deposits from at Montauban (Fig. 1.3), and were

interpreted as mineralisation ages (Fletcher and Farquhar 1982). East of the map area, Rb-Sr whole rock ages of 1089 ± 33 , 1057 ± 27 , and 1043 ± 12 Ma have been obtained on charnockitic bodies belonging to the Parc des Laurentides complex (Frith and Doig 1973; 1975), (Fig. 1.2). In this text, charnockites are defined as plutonic rocks of granitic composition (Streckeisen 1976) containing magmatic orthopyroxene. Other compositional types of plutonic rocks with magmatic orthopyroxene are named after the nomenclature of deWaard (1969).

Granulite facies metamorphism has been reported for the entire western half of the Mauricie transect (Rondot 1978; Béland 1961; Klugman 1963; Martignole 1978), in an area roughly corresponding to "Grenvillia" of Rondot (1986), or to the Allochthonous Monocyclic Belt of Rivers et al. (1989). Thermobarometric constraints have only been published for two localities within the transect. The first is from a sapphirine-bearing gneiss outcropping on the eastern shore of the St. Maurice River, which yielded pressure and temperature estimates of ~ 820 °C and 9 kb (Herd et al. 1986). The second is from a Pb-Zn-Au-Ag deposit near Montauban (Fig. 1.3), which yielded pressures and temperatures of 3.5—4.5 kb and 630—660 °C (Stamatelopoulou-Seymour and MacLean 1984), and 4.5—6.5 kb and 550—620 °C (Bernier and MacLean, 1993).

1.3 THE MAURICIE TRANSECT

The Mauricie transect spans an orogen-oblique belt of shallow to moderately east-dipping, north-south trending metavolcanic, metasedimentary, and metaigneous gneisses, which are intruded by different plutonic suites that show extreme variations in tectonothermal overprint. Based on the proportion of ortho- to paragneiss, metamorphic facies, or the presence or absence of younger intrusive rocks, three distinct domains are identified. From east to west, or from highest to deepest structural level, they are named the Portneuf—St. Maurice, Shawinigan, and Mékinac domains (Fig. 1.3). The Portneuf—

St. Maurice domain contains amphibolite facies metavolcanic and metasedimentary rocks that locally preserve primary features (Montauban Group; Pyke 1967), intruded by a suite of dioritic to granitic plutons (La Bostonnais complex; Nadeau and Corrigan 1991, modified after Rondot 1986). It is separated from the underlying Shawinigan domain by a low-angle, east-dipping, lower amphibolite facies shear zone (herein named the Tawachiche shear zone) that accommodated oblique sinistral extensional displacement. Footwall rocks (Shawinigan and Mékinac domains) are regionally metamorphosed at granulite to uppermost amphibolite facies, and do not retain any primary features. In contrast, they contain evidence of regionally distributed moderate to high strains related to bulk, top-to-the-W-NW thrusting. The following text provides a lithological and structural description of the lithological units and their structural context. Mineral abbreviations are after Kretz (1983).

1.3.1 Portneuf—St. Maurice domain

In general, the Grenville orogen is formed of high-grade gneisses and migmatites whose protoliths are not easily recognizable (e.g. Wynne-Edwards 1972; Davidson 1986). However, as in the case of the Elzevir Terrane in Ontario (Easton 1992), and the Wakeham Terrane in northeastern Québec (Martignole et al. 1994), the Portneuf—St. Maurice domain (Fig. 1.3) is characterized by relatively lower grade assemblages, and a predominance of gneisses of undoubtable volcanic, volcanoclastic, and sedimentary origin. The supracrustal rocks (Montauban Group) are intruded by a suite of calc-alkaline plutons of predominantly dioritic composition (La Bostonnais Complex; Nadeau and Corrigan (1991), after Rondot (1986)).

i) Montauban Group

The Montauban Group occurs in two isolated strands ("eastern" and "western" strands; new names Fig. 1.3), that differ only in metamorphic grade. In contrast to the Mékinac and Shawinigan domains, primary sedimentary or volcanic structures are relatively abundant in the Montauban Group. Metabasalts with well preserved pillow structures are exposed near a volcanogenic massive sulfide deposit at Montauban-les-Mines (Pyke, 1967; Sangster 1972). Felsic lapilli tuff have been locally observed (Fig. 1.4a), as well as centimetre-scale graded bedding in metasediments (Fig. 1.4b) and in volcaniclastic rocks.

The metamorphosed volcanic and volcaniclastic rocks, ranging in composition from basaltic to rhyolitic, are ~ 70 % andesitic (Morin 1987; MacLean et al. 1982; Bernier and MacLean 1993). The abundance of andesite, and the relatively small volume of meta-rhyolites, is more compatible with an island arc than a continental margin setting. Trace element characteristics of the pillowed basalts are also more typical of island arcs, but do not preclude a back arc tectonic setting (MacLean et al. 1982; Bernier and MacLean 1993). However, the typically bimodal character of back arc magmatism is not observed, and we therefore prefer to interpret the Montauban Group as the remnant of an island arc. A U-Pb zircon age of 1.45 Ga (Nadeau and van Breemen 1994) obtained on metamorphosed lappili tuff precludes any correlation of the Montauban Group with the ca. 1.28—1.24 Ga Elzevir or Wakeham Terranes.

Metasediments of psammitic, pelitic, and calc-silicic composition have also been observed in the study area, as well as abundant *hbl—bt—Ksp—pl*—bearing metasediments that compositionally resemble greywackes. The thick, grey-coloured metagreywackes typically contain a few thin (~10 cm), light green calcsilicate layers, suggesting deposition in a shallow marine environment. True pelitic metasediments are relatively rare, and generally form thin layers within metasedimentary units of

quartzofeldspathic or psammitic composition. Marble and quartzite have not been observed in the study area, but rare occurrences are described further south near the Montauban area (Pyke 1967). Rare amphibolite layers up to a few tens of metres thick and composed of hornblende and plagioclase, with minor biotite and quartz, are scattered throughout the Montauban Group. They are parallel to adjacent gneisses at outcrop scale, and are laterally discontinuous. They could either represent metamorphosed mafic sills, or tectonically transposed dykes. However, due to the absence of cross-cutting features, the former interpretation is preferred. Metasedimentary and metavolcanic units are interlayered at outcrop or map scale, but it is impossible to determine whether this relation has been produced by folding, or if the interlayering is primary.

The structural base of the Montauban Group contains a zone approximately 1 km wide where abundant peraluminous pegmatitic pods and dykes composed of orthoclase, plagioclase, quartz, muscovite, biotite, garnet, and locally fibrolite, are found. The pegmatitic pods vary in size from a few centimetres to a few metres. They have thin biotite selvages around their margins (Fig. 1.5a), and enclose delicate, elongate wisps (schlieren) of host rock. The occurrence of numerous, small, spatially isolated, and undeformed pegmatitic pods suggests *in situ* development. However, true pegmatite dykes with the same composition as the pods crosscut the host rock (Fig. 1.5b). These dykes are locally derived, and were likely formed by amalgamation of smaller pegmatitic pods and their re-injection in the host rock.

ii) La Bostonnais complex

The Montauban Group is intruded by a suite of dioritic, tonalitic, granodioritic, granitic, and minor gabbroic and ultramafic plutons (Nadeau and Corrigan 1991; Gauthier 1993). U-Pb zircon ages of ca. 1.40 Ga have been obtained from two separate dioritic plutons (van Breemen, unpublished data 1995), and one quartz-diorite located

west of the Western strand of the Montauban Group yielded a U-Pb zircon age of $1371 \pm 3/-2$ Ma (Chapter 2). Plutonic rocks of the La Bostonnais complex are medium to coarse grained, and are weakly to moderately foliated. Although they have been metamorphosed at amphibolite facies, some have nearly escaped deformation and preserve relict igneous textures and minerals. Their equigranular texture contrasts with the commonly porphyritic nature of younger AMCG-type plutons. Hornblende and biotite are the primary mafic minerals, except in the granite where hornblende is locally absent. North of the study area, orthopyroxene cores rimmed by hornblende have been observed in diorite (Nadeau and Corrigan 1991), suggesting an emplacement in high-temperature, anhydrous conditions. In general, the more mafic end-members are progressively intruded by intermediate, and then by felsic members of this suite (Fig. 1.6a), which are also the least deformed. This intrusive sequence of mafic to felsic magmatism accompanied by progressive deformation suggests an emplacement in an active tectonic environment.

On the basis of chondrite-normalized rare earth element plots, Gauthier (1993) suggested that plutons from the calc-alkaline La Bostonnais complex are similar to those of mature island arcs, or transitional oceanic-continental arcs (e.g. Aleutian arc). He suggested a geodynamic model in which the La Bostonnais complex was emplaced into the previously accreted Montauban arc, drawing analogies with the Andean margin, where the Coastal Batholith of Peru has been emplaced in an older arc and back arc. Trace elements, especially Nb, Ta, Th, Y, Yb, Zr, and Hf, can be used to determine the tectonic setting into which magmas of basaltic composition were emplaced (Pearce 1983). Specifically, plots of Zr vs Zr/Y, and Ta/Yb vs Th/Yb, can be used to discriminate basalts originating in oceanic arcs, from those originating in continental arcs (Pearce 1983). In agreement with field observations, published geochemical data from Montauban Group pillowed basalt (MacLean et al. 1982) and La Bostonnais complex

gabbros and diorites (Gauthier 1993), plot in oceanic arc, and continental arc fields, respectively (Fig. 1.7).

1.3.2 Shawinigan domain

The Shawinigan domain is distinguished from the Portneuf—St. Maurice domain by the scarcity of rocks of recognizable metavolcanic or volcanoclastic origin, and by the abundance of highly aluminous metapelites. At least two distinct groups of metasediments can be identified in the Shawinigan domain. The first, named here the "St. Boniface group", is extensive, forming a thick unit dominated by metapelite with quartzite and marble (Fig. 1.3), and is restricted to the southwestern region of the study area. Metapelites of the St. Boniface group are distinctive, forming thick units composed of abundant pale pink garnets up to 6 cm in diameter (averaging 2 cm), mesoperthite, plagioclase, quartz, biotite, and up to 40% prismatic sillimanite, with accessory rutile, graphite, monazite, and locally tourmaline. Locally, garnet and sillimanite form approximately 75% of the rock volume, suggesting an unusually aluminium-rich protolith. Stromatic leucosomes (terminology of Mehnert 1968) are commonly developed, and are composed of $Ksp(perthite)-pl-qtz-grt-bt-rt \pm gr$, with accessory zircon and monazite. Locally, leucosomes lack biotite and contain abundant, coarse-grained tourmaline. St. Boniface metapelites are interlayered with quartzite layers ranging in thickness from a few centimetres to tens of metres, and with lesser amounts of calc-silicate gneiss and marble. Marble is coarse grained, granoblastic, and contains calcite, dolomite, diopside, phlogopite, rare tremolite, and serpentine (probably after forsterite). Quartzite varies from almost pure, to impure with up to a total of 20% garnet, biotite, perthite, plagioclase, rutile, and monazite.

The second group of metasediments forms much smaller, outcrop-size slivers of metapelite intercalated with orthogneiss, and contain rare quartzite and marble. They are

graphite-rich, and do not contain tourmaline. Isolated metasedimentary screens a few tens of metres thick are scattered within Shawinigan domain orthogneisses, and most are too small to plot on a 1:50,000 scale map. In general, metapelites in these screens are much less aluminous than those of the St. Boniface unit, although there are some exceptions. Some screens contain distinctive brick-red microperthite, biotite, garnet, and corundum—spinel rich streaks, and are interlayered with quartzofeldspathic gneiss that could be interpreted as metamorphosed felsic volcanic rocks.

These quartzofeldspathic gneisses are compositionally heterogeneous, and are predominantly pink with isolated white and gray streaks and layers, suggesting that they may be the highly deformed equivalent of felsic tuff. The rare presence of fine grained layered mafic gneiss with thin (mm- to cm- scale) graded compositional banding strongly resembling mafic volcanic rocks, suggests the presence of supracrustal rocks among this suite. However, identifying these highly deformed and metamorphosed rocks with a volcanic protolith is difficult, if not impossible. Therefore, their relationship to the Montauban Group cannot be determined without further isotopic dating or geochemistry.

The metasediments and the quartzofeldspathic gneisses are structurally concordant with pink to dark grey (more rarely green), fine- to medium-grained orthogneisses of dioritic to granitic but predominantly tonalitic composition, containing hornblende and biotite (and locally ortho- or clinopyroxene) as major mafic phases. In this unit, poorly preserved igneous textures are only locally found in zones of lower strain, such as fold hinges, or in rheologically competent dioritic lenses. The tonalitic, dioritic, and granitic orthogneisses are tectonically transposed and form distinctive, moderately east-dipping, grey and salmon-pink layered gneiss. A U-Pb zircon age of $1371 \pm 51/-32$ Ma (Chapter 2) was obtained from a medium-grained tonalitic orthogneiss belonging to this suite.

Metagabbro occurs throughout the Shawinigan domain as small dykes, boudins, and elongate map-scale bodies parallel to the regional foliation. Crosscutting relationships

suggest that at least two generations of metagabbro occur. The oldest are totally recrystallised and metamorphosed to amphibolite, with or without garnet, and are locally contain anhydrous assemblages (*opx* and *cpx*) along an angular net-vein array. This texture suggests infiltration of CO₂-rich fluids. Amphibolites and garnet amphibolites are coarse- to medium-grained and some also contain clino- and orthopyroxene. The older dykes form elongate map-scale bodies or boudins. The younger metagabbros form dykes up to 1 m thick, that are generally oriented east-west and, although metamorphosed, preserve chilled margins. They characteristically contain fine-grained plagioclase needles or coarse, gray-coloured labradorite phenocrysts. They are garnet-free, and composed of *opx—cpx—pl—hbl—Fe-Ti oxide ± bt*. These younger dykes are present in minor amounts in the western margin of the Portneuf—St. Maurice domain.

1.3.4 Mékinac domain

The portion of the Mékinac domain investigated in this study (Fig. 1.3) forms the eastern margin of a crustal-scale antiformal structure that extends westward to the Morin Terrane (Martignole 1994), (Fig. 1.2) and southward to the St. Didace plutonic complex (Martignole 1978). Its northern extent is presently unconstrained. This ~ 6,000 km² area is clearly outlined in residual total field aeromagnetic anomaly maps (Geological Survey of Canada 1987) as a large zone of uniform, low to moderate magnetic amplitude, and contrasts sharply with the high-amplitude magnetic signature of adjacent lithotectonic domains. As seen below, this aeromagnetic contrast is due to the absence of highly magnetic, ca. 1.08—1.05 Ga AMCG-type plutons, that are abundant in adjacent domains. Most of the Mékinac domain investigated in this study (Fig. 1.3) consists of ca. 1.39 Ga (van Breemen; unpublished data 1995) lithologically monotonous, penetratively deformed, layered granulite facies orthogneiss of granitic to dioritic composition. Feldspars are typically green on fresh surfaces and pink to beige on weathered surfaces

(e.g. Howie 1967). Mafic minerals include orthopyroxene, clinopyroxene, hornblende, biotite, and Ti-Fe oxides, which are present in various proportion and abundance. Garnet is also found locally, together with clinopyroxene and quartz. Compositional layering in the granulite orthogneisses, which is developed at centimetre to metre scale, is primarily defined by differential concentration of ferromagnesian minerals (Fig. 1.6b). Because of widespread transposition (see below), it is not clear whether the compositional layering represents primary igneous layering, or original intrusive relationships between granitoid magmas of felsic to mafic composition, or both.

Orthogneisses in the structurally deeper parts of the Mékinac domain are generally granodioritic and contain mafic bands up to several centimetres thick. At least some of the mafic bands are demonstrably transposed dykes, especially where rare cross-cutting relationships are preserved. However, the contacts of most of the mafic layers are parallel to their more leucocratic host gneiss and compositionally diffuse, and may represent primary compositional variations (Fig. 1.6c). Some areas are dominated by more compositionally homogeneous, migmatitic granitoids. In the migmatites, orthopyroxene-bearing leucosomes either form folded layers with stromatic textures (Fig. 1.6d) or undeformed, coarse grained "patches" (Fig. 1.6e).

Granulites of mafic to intermediate composition are also present in important volumes, but are more concentrated in the upper structural levels of the Mékinac domain, east of the St. Maurice River. The most abundant type is medium-grained, equigranular diorite. It contains approximately 50% andesine (An_{35}), with hornblende, orthopyroxene, clinopyroxene, and biotite as the mafic phases. Mafic to intermediate granulites are either massive, or layered at centimetre to metre scale. Most have migmatitic textures characterized by a fine to medium-grained equigranular paleosome composed of hornblende, plagioclase, biotite, and magnetite, with coarse-grained, patchy leucosomes composed of $opx-cpx-pl-mt \pm hbl \pm bt \pm qtz$ (Fig. 6e). Thinly-layered gneisses

composed of alternating ultramafic, garnetiferous, and quartzitic bands are also found in the upper structural levels, along with the mafic gneisses, and may represent supracrustal fragments. Rare and laterally discontinuous paragneiss layers, only a few metres thick and including metapelites, marble, and quartzite, are found throughout the Mékinac domain, but are generally concentrated in the upper structural levels. Metapelites are graphite-rich, and are distinguished by the high-grade assemblage containing sillimanite and perthite. Marble contain the assemblage *cal—dol—di—scp—phl* $\pm$ *fo* $\pm$ *wo*.

Ultramafic pods and dykes consisting of clinopyroxenite, websterite, and hornblendite, have been observed in the upper structural levels of the Mékinac domain. They are tectonically dismembered and form boudins that range from outcrop-size to hand sample size. The interiors of the larger-sized pods and boudins are virtually unstrained in comparison with their margins, reflecting the relatively higher competence of such lithologies in contrast to the host quartz-rich gneisses.

Late- to post-tectonic allanite-bearing pegmatite dykes (Fig. 1.6d) occur in northeast trending swarms and are common in the Mékinac domain. They rarely occur in the Shawinigan domain, and are absent from the Portneuf—St. Maurice domain.

1.4 AMCG-TYPE PLUTONISM

Apart from the ca. 1.40—1.37 Ga calc-alkaline, arc-related plutons that occur throughout the Mauricie transect, at least two plutonic suites have been emplaced during later tectonomagmatic episodes. As will be seen below, the Portneuf—St. Maurice and Shawinigan domains were emplaced over the Mékinac domain by W-NW-directed syn-metamorphic thrusting. The older group of plutons is pre- to syn-thrusting, and has been totally overprinted by high-grade deformation, whereas the younger group of plutons is post-thrusting, and has escaped the high-grade tectonothermal overprint. Interestingly, pre- to syn-thrusting plutons are restricted to the Shawinigan domain, and to a lesser

extent, to the upper structural levels of the Mékinac domain. By contrast, the younger post-thrusting plutons are absent from the Mékinac domain, and but are abundant in the Shawinigan and Portneuf—St. Maurice domains.

1.4.1 Older, pre- or syn-thrusting plutons

The Shawinigan domain contains distinctive plutonic rocks of granitic or quartz-monzonitic composition. They contain K-feldspar megacrysts up to 10 cm in diameter (Fig. 1.8a), and generally occur as augen gneiss. Modal composition is *Kfs* (*perthite*)—*qtz*—*pl*—*hbl*—*bt*—*ilm* $\pm$ *opx*, with accessory apatite and zircon. Orthopyroxene is only locally observed, and its origin cannot be readily interpreted as either igneous or metamorphic. A relatively small plutonic sheet belonging to this suite, herein named the Lac Paul granite, outcrops east of Lac Mékinac. It is strongly foliated, with K-feldspar megacrysts occurring as elongate polycrystalline aggregates (Fig 1.8b). In some portions of the Lac Paul granite, polycrystalline feldspars aggregates are green coloured, and the presence of metamorphic orthopyroxene indicates that deformation occurred at granulite facies. In other parts of the same plutons, polycrystalline feldspar aggregates are pink and the common ferromagnesian mineral is biotite and minor hornblende. A U-Pb zircon age of $1153 \pm 2/-1$ Ma has been obtained from this pluton (Chapter 2). Béland (1961) described a similar plutonic rock outcropping in the southwest corner of the study area, near Shawinigan, and correlated it with similar plutons found south of the Morin anorthosite, referred to as "Pine Hill type".

Several small bodies of anorthosite and metagabbro with sub-ophitic and coronitic textures have been observed in the study area, west and northwest of the study area (Nadeau and Corrigan 1991), and are shown in Figure 1.3. These metagabbro and anorthosite boudins occur within the Mékinac domain, and may be related to the larger

La Tuque and Langelier anorthosite bodies (Fig. 1.2) that outcrop further north, between this study area and the Lac St. Jean anorthosite.

1.4.2 Post-thrusting plutons

A younger suite of plutons composed of gabbro, norite, jotunite, mangerite, charnockite, hornblende-biotite granite, and minor anorthosite, pyroxenite, and hornblendite, occurs throughout the Shawinigan and Portneuf—St. Maurice domains (Fig. 1.3). They occur either as isolated plutons of distinctive composition, or as noritic—mangeritic complexes. U-Pb zircon ages show a progressive compositional evolution from gabbroic to granitic within the time span 1080—1055 Ma (Chapter 2). These plutons are readily identifiable in the field by their generally well preserved igneous textures, and the absence of high-grade metamorphic overprint. In contrast with the Mékinac domain metagabbros, which commonly exhibit coronitic textures (Chapter 3), gabbros and norites of this suite show no reaction textures between plagioclase and orthopyroxene, suggesting a post-metamorphic emplacement.

The oldest, and also the most mafic of these intrusions consist of the ca. 1.08 Ga Lapeyrère gabbro (van Breemen, unpublished data 1995) and the $1077 \pm 10/-2$ Ma Shawinigan norite (Chapter 2), which are the same age, within error. The petrology of the Lapeyrère gabbro and Shawinigan norite are described in detail in Gauthier (1993), and Martignole (1978), respectively. Both are unmetamorphosed, except locally along narrow sinistral shear zones (see below), and have well developed ophitic textures, with cumulate plagioclase laths and interstitial pyroxene (Fig. 1.9a). At map scale, the Shawinigan norite is parallel to the foliation developed in the host gneisses and is U shaped. At outcrop scale it has a chilled margin and contains apophyses that cut mylonitic fabrics developed in the host gneisses. Martignole (1978) has interpreted the U shape as a fold.

However, the absence of strain throughout the pluton suggests that the U shape is not the product of folding, but of its emplacement into previously deformed strata.

The LeJeune and Missionnaire plutons (named herein, Fig. 1.3), that have been previously interpreted as forming a single pluton of monzonitic composition (Rondot 1978), form two distinct plutonic masses of variable composition. Although monzonite is the predominant phase, there are also large norite masses, and smaller areas where norite, monzonite, monzodiorite, and syenite form crosscutting sets (Fig. 1.9b), with the more felsic phases intruding the more mafic ones. However, the local occurrence of norite and monzodiorite with chilled margins adjacent to an interstitial monzonitic phase suggests a more complex emplacement history. Similar magmatic relationships have been documented in the eastern lobe of the St-Didace pluton (Martignole 1978), and are thought to represent co-mingling of mafic and felsic magmas. The noritic phase of the LeJeune and Missionnaire plutons is compositionally and texturally similar to that of the Shawinigan body. Monzonite is medium to coarse grained, green or pink coloured, hypidiomorphic, and contains magmatic ortho- and/or clinopyroxene. Along the western margin of the LeJeune and Missionnaire plutons, the monzonite carries a well-developed L>>S fabric, whereas the pluton interior is entirely isotropic. A U-Pb zircon age of 1060 ± 2 Ma has been obtained for the monzonitic phase of the LeJeune pluton (Chapter 2).

The Missionnaire pluton is smaller, and compositionally more diverse than the LeJeune pluton. Apart from containing norite and monzonite as predominant phases, it also contains gabbro, monzodiorite (jotunite), and small quantities of porphyritic granite. Poor exposure strongly limits the interpretation of intrusive relationships between different compositional phases. The pluton also contains a large xenolith of probable mafic volcanic origin, with the assemblage $opx-cpx-hbl-pl-ilm \pm bt$. This mafic volcanic xenolith is similar to another small one enclosed in a minor monzonite sheet

outcropping in the Shawinigan domain near Ste. Tite, and to mafic volcanic rocks of the Montauban Group.

The Gagnon pluton (Fig. 1.3) forms a large isolated pluton within the Portneuf—St. Maurice domain. It is a coarse-grained hornblende-biotite granite that contains K-feldspar megacrystic and more rarely, rapakivi feldspars. Quartz, as well as minor plagioclase, are found in the matrix with approximately 15 % igneous hornblende and < 5 % biotite, with accessory apatite and zircon. The pluton is generally undeformed in its central portion, but has a moderately developed foliation at its margin. Along its western margin, it contains many angular enclaves that are very similar to the Montauban Group (Fig. 1.9c). It is intruded along its western margin by aplite of similar composition. On a compositional and textural basis, the Gagnon pluton is identical to some of the granitic phases of the Parc des Laurentides complex, outcropping to the east, and is therefore interpreted as a satellite pluton to this much larger complex, that extends approximately 150 km northeastwards to Chicoutimi (Avramtchev and Piché 1981).

1.5 STRUCTURAL FRAMEWORK

Relative chronology of deformation and metamorphism forms the basic framework upon which the tectonometamorphic and plutonic evolution of orogenic belts can be modeled. The overall north-south trending, homoclinal structural grain observed in the Mauricie transect suggests a relatively simple structural evolution for the entire region. However, the structural and metamorphic record preserved in plutonic suites of different age suggests a complex history of at least three major episodes of deformation that were approximately coaxial to one another. The oldest event produced structures that are uniquely preserved in the structurally shallow Portneuf—St. Maurice domain, related to arc accretion at ca. 1.4 Ga (Chapter 2). A second event, constrained by U-Pb geochronology between 1.15 to 1.09 Ga (Chapter 2), involved penetrative ductile

deformation during west-northwest-directed crustal thickening accompanied by granulite to uppermost-amphibolite metamorphism. Its effect is limited to the structurally deeper-seated Mékinac and Shawinigan domains. The third and youngest event produced a mylonitic fabric predominantly located at the contact between the Portneuf—St. Maurice and Shawinigan domains, and was formed in response to oblique sinistral extension within the Tawachiche shear zone.

1.5.1 Structures related to ca. 1.4 Ga arc accretion

In the western and eastern strands of the Montauban Group (Figure 1.3), three surfaces, and one fold generation are identified. Due to the general preservation of primary volcanic, volcanoclastic, and sedimentary structures, S_0 surfaces are commonly observed in outcrop, and outline centimetre- to metre-scale reclined similar folds (Fig. 1.10a, b). Fold tightness locally varies, but is commonly tight or isoclinal. A first tectonic fabric consists of an axial-planar foliation (S_1) outlined by prograde metamorphic minerals, indicating that peak metamorphism and deformation were synchronous. Where folds are tight or isoclinal, S_0 and S_1 are sub-parallel to one another, and are indistinguishable on fold limbs. A strong transposition foliation forms a second tectonic fabric, most commonly observed in the eastern strand of the Montauban Group. In strongly transposed outcrops, more competent layers such as quartzite and calc-silicate gneiss form rootless isoclinal folds and boudin trains, and the rheologically weaker matrix forms annealed ribbon mylonites outlining a transposition foliation (S_{tr}). There is a complete gradation between S_1 and S_{tr} , such that these fabrics become difficult to differentiate in the absence of fold closures. S_0 surfaces, as well as S_1 and S_{tr} , are generally parallel to the elongate map pattern of the two Montauban Group strands (Fig. 1.11).

Plutons of the La Bostonnais complex intrude the Montauban Group supracrustal rocks (Nadeau and Corrigan 1991), and in general are much less deformed. The interior of some of the larger plutons are locally isotropic, and show nearly pristine igneous textures. Where a foliation is developed, it is outlined by the parallel orientation of mafic minerals, and is parallel to the exterior foliation (S_{tr} or S_1) in the Montauban Group. Deformation in the La Bostonnais complex thus appears to be related to deformation in the Montauban Group, but is perhaps late-tectonic with respect to the latter.

Linear fabrics in the Portneuf—St. Maurice domain consist of mineral lineations, extension lineations, and fold axes. All three linear elements are generally parallel in outcrop. On a stereographic projection (Fig. 1.11), mineral and extension lineations form a shallow east-dipping girdle that spans from the northeast to the southeast, indicating the presence of either non-cylindrical folds, or of fold interference. Fold axes show the same geometrical distribution at outcrop scale, demonstrating the non-cylindricity of folds. However, the strong concentration of linear elements within the foliation plane also suggests an important amount of flattening.

1.5.2 Structures related to thrusting

The two most important characteristics observed in the Mékinac and Shawinigan domains, compared to the Portneuf—St. Maurice domain, are (i) a marked increase in metamorphic grade, and (ii) an increase in overall strain. In the above section, we have emphasized that the La Bostonnais complex is in general only moderately foliated, and locally preserves igneous textures and primary mineral assemblages. By contrast, plutonic rocks of similar composition and similar age in the Mékinac and Shawinigan domains are metamorphosed at uppermost-amphibolite to granulite facies, are most commonly recrystallized, and are transposed into regular to straight gneisses (terminology of Hanmer 1988). This transposition foliation (S_{tr}) is parallel to the elongate

map pattern of lithological units, and to S_1 and S_T observed in the Portneuf—St. Maurice domain. However, as will be seen below, it is approximately 280 m.y. younger.

In the Mékinac and Shawinigan domains, there are many structures indicative of regionally distributed moderate to high strain. The overall pervasiveness of the N-S-trending foliation, the widespread presence of isolated, centimetre- to metre-scale sigmoidal- or augen-shaped boudins of highly competent lithologies such as mafic or calc-silicate pods (Fig. 1.12), and local transposition, folding, and attenuation of amphibolite dykes and leucosomes into sub-parallelism with the foliation (Fig. 1.13a), indicate intense ductile deformation. Rootless, isoclinal, asymmetric folds are common (Fig. 1.13b). Fold axes are generally parallel to the widely developed east-plunging stretching lineations, but locally show varying degrees of rotation within the foliation plane. These features are taken to indicate the presence of strongly non-cylindrical folds (e.g. Brun and Merle 1988; Hobbs et al. 1976). In zones of more intense deformation, less competent units such as marble are forcefully injected in their host quartzo-feldspathic gneisses, forming marble tectonic *mélange*. Similar features have been documented in deep crustal shear zones in the southwestern Grenville orogen in Ontario (Hanmer 1988). Extension lineations within the Mékinac and Shawinigan domains are defined by elongate quartzofeldspathic aggregates, or pressure shadows enclosing porphyroblasts, and are parallel to mineral lineations. They generally plunge towards the east-southeast (Fig. 1.11), and are considered to coincide with the main vector of tectonic transport (Fig. 1.3). The extension lineation regionally contains peak metamorphic minerals, such as prismatic sillimanite, hornblende, and pyroxene, suggesting that this deformation event was accompanied by maximum pressure and temperature conditions.

Shear-sense indicators are rare, but where present, consistently indicate east-over-west reverse displacement. Shear sense criteria have been obtained from σ -shaped rotated porphyroclasts (Fig. 1.14a, b) (Passchier and Simpson 1986), sigmoidal-shaped boudins,

C-S fabrics (Berthé et al. 1979), and foliation "fish" (Fig. 1.14c; see Hanmer and Passchier 1991). In granulite-facies mylonitic orthogneiss, quartz ribbons are totally to partially annealed. The widely distributed presence of relic sigmoidal-shaped feldspar, garnet, and orthopyroxene porphyroclasts isolated in annealed quartz ribbons (e.g. Fig. 1.14d) suggests that deformation occurred at high temperature. Orthopyroxene is stable in sheared Mékinac domain rocks, attesting to the high metamorphic grade accompanying deformation ($\sim 800^{\circ}\text{C}$ at ≥ 8 kb; Chapter 3).

One of the remarkable features of the Mékinac domain is the relative absence of localized strain associated with west-northwest-directed thrusting. However, as will be discussed below, strain did appear to localize in rheologically weaker, quartz-rich lithologies during the later stages of thrusting. Although shear strain was partitioned at the outcrop scale between units of contrasting rheology, in general, strain intensity was more or less evenly distributed on a regional scale. This style of deformation involving regional distribution of shallowly dipping, moderately to highly strained rocks is commonly reported from regions of exposed lower continental crust (Coward 1973; Fountain and Salisbury 1981; Park 1981; Handy 1990; Leonov 1991; Sandiford 1989; Rutter et al. 1993; Shackelton 1993).

1.5.3 Structures related to localized oblique extension (Tawachiche Shear Zone)

The Shawinigan and Portneuf—St. Maurice domains are separated by an anastomosing array of partially annealed to unannealed east-dipping shear zones, herein named the "Tawachiche shear zone". The shear zone strands are sub-parallel to the regional S_{tr} and S_1 foliations that developed earlier. Individual shear zone strands vary in thickness from a few centimetres to a few hundred metres and can be traced along strike up to a few tens of kilometres. The total map width where shear zone strands can be found is approximately 25 km. However, most of the shearing is concentrated along the

boundary zone between the Portneuf-Mauricie and Shawinigan domains. Extension lineations within the Tawachiche shear zone are well developed, and plunge $\sim 18^\circ$ towards the N-NE at an average trend of $\sim 020^\circ$ (Fig. 1.11). Microstructures in the Tawachiche shear zone reflect deformation at lower amphibolite facies. They comprise quartz ribbons with asymmetric subgrains, feldspar porphyroclasts with undulose extinction and core and mantle texture (Fig. 1.15a), and the dynamic recrystallization of matrix grains to $\sim 10 \mu\text{m}$ (Fig. 1.15b). Hornblende is a stable phase, and is commonly recrystallized into polygonal aggregates. Undeformed, randomly oriented muscovite overprints the mylonitic fabric. Shear sense indicators are ubiquitous in the Tawachiche shear zone, and consistently show top-down-to-the-N-NE sinistral oblique extension (Figs. 1.16a, b and 1.17b).

Although a few narrow and isolated shear zone strands have been observed in the upper Mékinac domain and in parts of the Shawinigan domain, the most laterally continuous sinistral shear zone strand occurs within the eastern boundary of the Shawinigan domain. Along its entire length, it juxtaposes ortho- and paragneisses of the Shawinigan domain with a 2 to 5 km wide, elongate belt belonging to the La Bostonnais Complex. This particular strand has an average map width of 1 km and penetrates equally into the Shawinigan and Portneuf—St. Maurice domains. Another major strand occurs further east along the interface between the La Bostonnais complex metaplutonic rocks and the Montauban Group. Within this shear zone strand, strain is clearly more concentrated in the Montauban Group, which consists of rheologically weaker metasediments and metavolcanic rocks. Penetrative macroscopic deformation associated with this shear zone, predominantly in the form of porphyroclastic gneiss and mylonite (Fig. 1.17a), is observed through a cross-strike distance of approximately 1 km in the Montauban Group, and ~ 200 m in the La Bostonnais complex. Most of the metasediments from the western strand of the Montauban Group show well developed,

regularly-spaced asymmetric shear bands formed by sinistral shear. The ~1056 Ma peraluminous pegmatites found along the base of the Montauban Group are variably mylonitised. Some are completely disaggregated into porphyroclastic gneiss with ∂ -type rotated feldspar porphyroclasts (Passchier and Simpson 1986), showing sinistral, top-down-to-the-N-NE shear (Fig. 1.17b). Others form boudin trains in outcrops where earlier structures are totally transposed into straight gneiss (Fig. 1.17c; compare with Figure 1.5a which was photographed in a lower-strained zone approximately 20 metres away). Further east, shear zones are either thin and discontinuous, or are localized at the interface between units of highly contrasting rheological strength, for example at the contact between Montauban Group supracrustal rocks and ca. 1.08—1.05 Ga post-thrusting plutons.

The easternmost strand (Fig. 1.3) occurs along the western margin of the Parc des Laurentides complex, and was previously interpreted as the eastern margin of the Portneuf—St. Maurice domain (Nadeau and Corrigan 1991). It is sub-vertical with sub-horizontal stretching lineations, and accommodated sinistral displacement. Further investigations have shown that this shear zone is not a tectonic boundary between different crustal blocks, but that it merely reworked the intrusive contact between the Portneuf—St. Maurice domain and the ca. 1.06 Ga (van Breemen; unpublished data 1995) Parc des Laurentides plutonic complex. The westernmost of these shear zones, which is only a few metres thick, is located south of Lac Mékinac, and occurs within the uppermost structural level of the Mékinac domain. At this locality, moderately-dipping granulite-facies gneisses with E-SE-trending stretching and mineral lineations are abruptly overprinted by a more or less co-planar, centimetres-thick middle- to lower-amphibolite facies shear zone. It contains a shallow-plunging NNE-trending stretching lineation and numerous ∂ -type rotated feldspar porphyroclasts indicating top-down-to-the-NNE (sinistral) shear.

The juxtaposition of highly contrasting lithologies and metamorphic assemblages between the Mékinac and Shawinigan domains (footwall) and the Portneuf—St. Maurice domain (hanging wall), implies an important component of vertical displacement along the Tawachiche shear zone. This will be discussed in more detail in the following chapters.

1.5.4 Structures related to the emplacement of post-thrusting plutons

In the Portneuf—St. Maurice domain, structures related to pluton emplacement have been superimposed on earlier fabrics. Aerial photographs, map patterns, and field observations clearly show that the Montauban Group and La Bostonnais complex wrap around the Gagnon pluton, and that structures resembling foliation triple points (e.g. Brun and Pons 1981; Karlstrom and Williams 1995) were produced at the northern and southern extremities (Fig. 1.11). Granitic veins in the host rock are deformed into ptygmatic folds that record at least 50% layer-parallel shortening (Fig. 1.18), even at a distance of ~ 1km from the pluton contact. Within the pluton margin, a weakly to moderately developed foliation produced by solid-state deformation is parallel to the periphery. There, folded aplitic veins have axial-planar foliations that are parallel to the marginal foliation. Together, these features suggest that the post-thrusting plutons were forcefully emplaced during deformation (e.g. Brun and Pons 1981; Hutton 1988; Paterson and Fowler 1993). Although the specific deformation attributed to forceful emplacement is difficult to discriminate from the earlier ca. 1.4 Ga deformation, it is reasonable to assume that considerable flattening strain was superimposed on earlier structures, perhaps resulting in fold tightening, for example.

1.5.6 Brittle faults and pseudotachylite

The latest deformation event that affected the Mauricie region involved brittle faulting and the formation of cataclasite and pseudotachylite, associated with intense potassic alteration, chloritisation, epidotisation, and carbonatisation. These faults are outlined by pronounced, ≤ 1 km wide, NE-SW trending lineaments clearly visible on topographic maps and air photos, and have been previously documented by Rondot (1978) and Béland (1961). Some have been linked to the Lower-Cambrian St. Lawrence rift system (*ibid*), but it is not known if all are of that age. At many locations, the original relationship between the Mékinac and Shawinigan domains has been obscured by these late normal faults. The occasional preservation of flat-lying Ordovician sedimentary rocks on the southeast side of fault segments indicates southeast-down vertical displacement. This fault system also locally coincides with a minor metamorphic discontinuity, with Mékinac domain granulites to the northwest, and uppermost-amphibolite to granulite-facies gneisses of the Shawinigan domain to the southeast.

1.6 DISCUSSION

Recognition of protoliths and bounding shear zones is fundamental to our understanding of Grenvillian tectonics. The present configuration of the Mauricie transect consists of medium-grade, arc-related metavolcanic, metasedimentary, and metaplutonic rocks, that overly strongly transposed and thoroughly recrystallized high-grade ortho- and paragneisses. The boundary between these two contrasting blocks is a low-angle, top-down-to-the-N-NE oblique extensional shear zone, and its footwall contains evidence for top-to-the-N-NW thrusting.

1.6.1 Early phase of arc accretion, plutonism, deformation, and metamorphism

The ~ 1.45 Ga Montauban Group preserves the oldest structures and mineral assemblages in the Mauricie transect. The rather simple bedding-cleavage relationships observed locally in the western strand, and the related cleavage-parallel foliation observed in the ~ 1.40-1.37 Ga La Bostonnais complex suggests that deformation, metamorphism, and plutonism were more or less contemporaneous. The style of deformation during this period appears to be dominated by folding concomitant with regional metamorphism. Supracrustal rocks, including mafic and felsic volcanics, are locally found in the uppermost structural level of the Mékinac domain and in the Shawinigan domain, suggesting a possible but uncertain link with the Montauban Group. This observation cautions against the premature drawing of tectonic boundaries, and suggests that although the main occurrence of ca. 1.45 Ga island arc rocks is mostly confined to the Portneuf—St. Maurice domain, smaller rafts or fragments may occur further west, and were inundated by ca. 1.4 Ga plutons.

In light of the field observations and geochemical evidence presented earlier, the model of evolution that best accommodates these data is the accretion of an oceanic arc to a continental margin at ca. 1.40 Ga. The timing of peak metamorphism in the Montauban Group at ca. 1.39 Ga (see Chapter 2), is coincident with voluminous continental arc type plutonism, and supports the above model.

1.6.2 Thrusting, crustal thickening, and oblique sinistral extension

One of the greatest difficulties in establishing the magnitude of displacement of thrusting in the Mékinac and Shawinigan domains is the lack of recognizable stratigraphy, and of discrete thrust faults. The westward imbrication of structures, the high degree of parallelism of once discordant lithologies, the widespread occurrence of meso-scale boudins, and the regionally pervasive east-southeast-plunging mineral and

extension lineation, all indicate regional-scale penetrative deformation. The cause of high-grade metamorphism in the Mékinac and Shawinigan domains is still poorly known, but we may speculate on its origin. Mylonitic rocks now exposed at the surface of the Mékinac domain were formed at pressures of ≥ 8 kb (Chapter 3), corresponding to a burial depth of at least 25 km. Due to the presence of scant but consistent indicators of west-directed thrusting scattered throughout this crustal block, it can be inferred that burial occurred as a result of west-directed overthrusting of a thrust sheet or thrust system, now removed by erosion and oblique extension. The penetrative nature of deformation in the Mékinac and Shawinigan domains is likely due to the considerable depth of burial and of high temperatures accompanying thrusting.

The Portneuf—St. Maurice domain, which now overlies the high-grade block, has escaped high-grade tectonothermal overprint. We can speculate that it achieved this by remaining at a high structural level during thrusting, and was juxtaposed against the high-grade block by ca. 1.09—1.05 Ga (see Chapter 2) oblique extensional faulting along the Tawachiche shear zone. The retrogression of high-grade assemblages in the Tawachiche shear zone supports this relative timing constraint.

1.6.3 AMCG-type plutonism

The relative timing of AMCG-type plutonism with respect to thrusting and oblique extension provides valuable information on tectonomagmatic processes that have affected the Mauricie transect. On the basis of overprinting fabrics, two AMCG suites can be identified. The older AMCG suite, restricted to the Shawinigan and Mékinac domains, include the ca. 1153 Ma Lac Paul granite, and possibly anorthosite and metagabbro pods and boudins found in the upper structural levels of the Mékinac domain. The younger AMCG suite, restricted to the Shawinigan and Portneuf—St. Maurice domain, comprises the Shawinigan norite, the LeJeune and Missionnaire plutons, the Gagnon granite—

quartz monzonite, the Lapeyrère gabbro, and the Parc des Laurentides complex, which were emplaced in the interval 1.08—1.05 Ga. The older suite is concordant with host high-grade gneisses, penetratively deformed, metamorphosed at the same grade as the host gneisses, and contains an east-southeast-plunging mineral and extension lineation. This clearly indicates that it has been emplaced before the main west-directed thrusting event. However, the Lac Paul granite also crosscuts high-grade mylonites that were formed during an earlier tectonometamorphic event of unknown age and extent. By contrast, the younger suite cuts thrust-related mylonitic fabrics in the Shawinigan domain, and has not been metamorphosed nor penetratively deformed. These post-thrusting plutons are however locally reworked by oblique extensional shear in the Tawachiche shear zone and in the Portneuf—St. Maurice domain.

1.6.4 Nature of the Mauricie transect.

The notion that the Mauricie transect may contain a crustal scale boundary zone or suture in the Grenville orogen has been inferred by Rondot (1986) and Rivers et al. (1989). The model proposed by Rondot (1986) hinged on the interpretation of the "Portneuf—St. Maurice domain" as an ophiolitic sequence that had perhaps been obducted during the collision between two continents, "Grenvillia" and "Québecia". However, reconnaissance mapping by Nadeau and Corrigan (1991) and more detailed data presented in this chapter, supports the interpretation of the Montauban Group as a relict island arc, as previously inferred by geochemical data (e.g. MacLean et al. 1982; Bernier and MacLean 1993). The interpretation of the La Bostonnais calc-alkaline complex as continental arc plutons (Gauthier 1993; and this chapter) has important implications on the tectonic evolution of the southwestern margin of Laurentia. It can only imply that the Montauban island arc had been accreted to a continent (Laurentia), and subsequently evolved within a continental magmatic arc. Both the Mékinac and

Shawinigan domains are formed of orthogneisses of the same approximate composition and age as the La Bostonnais complex, and likely belong to the same continental arc. This, in turn, implies that the entire Mauricie transect formed part of the Laurentian margin as early as 1.4 Ga, and poses significant constraints on the lithotectonic model of Rivers et al. (1989), who interpret the Mauricie region as major lithotectonic boundary of Grenvillian age (i.e. 1.12—1.0 Ga). The possible tectonic evolution of the Mauricie transect during the Grenville orogeny is further discussed in Chapters 2, 3, and 4.

1.7 CONCLUSIONS

On the basis of lithology, metamorphic facies, and structure, the Mauricie transect can be subdivided into three different lithotectonic domains, namely the Portneuf—St. Maurice, Shawinigan, and Mékinac domains. The structurally highest Portneuf—St. Maurice domain contains remnants of a 1.45 Ga island arc, and was metamorphosed and deformed during its accretion to the southeastern margin of Laurentia, at ca. 1.4 Ga. The Mékinac and Shawinigan domains, as well as the younger (≤ 1.4 Ga) component of the Portneuf—St. Maurice domain, are part of a continental magmatic arc that evolved during, and after the accretion of the island arc, ca. 1.4 Ga ago.

During W-NW-directed thrusting of Grenvillian age, rocks of the Mékinac and Shawinigan domains were penetratively deformed, transposed, and metamorphosed at granulite to uppermost-amphibolite facies. At 1.09—1.05 Ga, the Tawachiche oblique sinistral extensional shear zone was active at the boundary between the Shawinigan and Portneuf—St. Maurice domains.

Two different suites of AMCG-type plutons were emplaced at different times in the Mauricie transect. The Lac Paul megacrystic granite, which belongs to the older suite (ca. 1.15 Ga), intrudes high-grade mylonites that may have formed during an earlier tectonometamorphic event of unknown nature and age. The younger AMCG suite (ca.

1.08—1.05 Ga) occurs only in the Shawinigan and Portneuf—St. Maurice domains, is unmetamorphosed, and post-thrusting. However, some plutons belonging to the younger suite are reworked by shear strands of the Tawachiche shear zone, indicating that they may have been emplaced before or during oblique extension. The field relations described above are tested by U-Pb and ^{40}Ar - ^{39}Ar geochronology in Chapter 2.

Figure 1.1 Maps showing the principal elements of the Grenville orogen in North America, after the lithotectonic division schemes proposed by: **a** Wynne Edwards (1972); **b** Rondot (1986); and **c** Rivers et al. (1989). The location of the Mauricie transect is shown for reference.

A

Subdivisions of the Grenville Province after Wynne-Edwards (1972)

- GFTZ Grenville Front Tectonic Zone
- EGP Eastern Grenville Province
- BCS Baie Comeau Segment
- CGT Central Granulite Terrain
- CGB Central Gneiss Belt
- CMB Central Metasedimentary Belt

B

Subdivision after Rondot (1986)

- Appalachian front
- Fault-bounded Paleozoic cover
- La Bostonnais complex

C

Subdivision after Rivers et al. (1989)

- Parautochthonous Belt
- Allochthonous Polycyclic Belt
- Allochthonous Monocyclic Belt

Figure 1.2 Map of the south-western portion of the Grenville orogen showing the major lithotectonic elements, and the location of the Mauricie transect. Modified after Rivers et al. (1989)

Figure 1.3 Geological map of the Mauricie region, in part modified after Martignole (1978), Nadeau and Corrigan (1991), and Nadeau et al. (1994). The Mauricie transect, which forms the focus of this study, is shown in boxes.

Figure 1.4 Outcrop photographs of Montauban group supracrustal rocks in the northern part of the western strand. **a** Metamorphosed and folded lapilli tuff with preserved lapilli bombs (light patches). Original layering is also partly preserved. **b** Pelitic metasediments with graded bedding still preserved. Coin diameter is 26 mm.

Figure 1.5 Outcrop photographs of Montauban Group supracrustal rocks in the lower margin of the Western strand. **a)** Two-mica and garnet-fibrolite-bearing pegmatitic pods in Montauban Group meta-psammities. The thin black lines at contact are melanosomes. Note the interlayered nature of pegmatites and the host rock, and the thin host rock wisps that protrude in the pegmatite. **b)** Two-mica and garnet-fibrolite-bearing pegmatite dyke intruding folded Montauban Group meta-psammities. Geological hammer for scale.

Figure 1.6 Photographs of outcrops. **a)** Multiple crosscutting relationship between diorite (dark), granodiorite (grey), and granite (light grey) in the La Bostonnais complex. **b)** Compositionally heterogeneous, shallow-dipping granulite-facies orthogneiss from the Mékinac domain. **c)** Layered migmatitic orthogneiss from the Mékinac domain. Note the isoclinally folded leucosome at the bottom left of the photograph. **d)** Migmatitic orthogneiss from the Mékinac domain showing well-developed stromatic textures. The crosscutting pegmatite dyke is allanite-bearing. **e)** Migmatitic diorite with undeformed “patch” leucosomes formed of plagioclase, orthopyroxene, and clinopyroxene.

Figure 1.7 a) Zr/Y versus Zr diagram showing the distribution of compositions from Montauban group metamorphosed pillow basalts (average of 12 analyses (★); data from MacLean et al. (1982)), and of La Bostonnais complex gabbros and diorites (data from Gauthier (1993)). b) Th/Yb versus Ta/Yb diagram showing the composition of gabbros and diorites from the La Bostonnais complex (data from Gauthier (1993)). Fields in both diagrams are after Pearce (1983). The majority of data points fall into the continental arc field.

Figure 1.8 a) Photograph of K-feldspar megacrystic granite from the Shawinigan domain, with augen texture. b) Granite of same composition as the one shown in "a", but with K-feldspar megacrysts completely recrystallized into polycrystalline aggregates, and with a more strongly developed foliation. Ca. 1153 Ma Lac Paul granite, Shawinigan domain. Coin diameter is 23 mm.

Figure 1.9 Outcrop photographs of post-thrusting plutons. **a)** Photograph of the Shawinigan norite, showing a pristine ophitic texture. Coin diameter is 26 mm. **b)** Intrusive relationship between norite (dark), jotunite (grey), and monzonite (light grey) from the LeJeune pluton. **c)** Photograph of the Gagnon pluton showing angular xenoliths derived from the Montauban group metasediments. Xenoliths exhibit primary sedimentary structures. Lens cap diameter is 65 mm.

Figure 1.10 Bedding-cleavage relationships in Montauban Group metasediments from the western strand. **a)** Folded sedimentary layers (S_0) forming close similar folds with axial-planar fibrolite bundles parallel to the axial plane (S_1), and forming small streaks. **b)** Tightly folded sedimentary layers (S_0) with axial-planar sillimanite bundles and biotite forming a strong S_1 foliation. Lens cap diameter is 65 mm.

Figure 1.11 Structural map of the Mauricie transect showing lower-hemisphere stereographic projections of structural elements. Small plots are for linear elements in specific domains. Larger plots are for regional data. Contoured according to Kamb (1959), with density percentage increments of 2%.

Figure 1.12 Photographs and line drawings of outcrops showing high finite strain produced during W-NW-directed thrusting. **a)** Lenticular metagabbro boudin, highlighted by dashed line, in granulite-facies quartzofeldspathic orthogneiss in Mékinac domain. Road cut on the east shore of St. Maurice River, looking towards the N-NE with the extension lineation almost parallel to the outcrop face. Andrea Dorval for scale.

b) Lenticular calc-silicate boudins in St. Boniface metapelites, Shawinigan domain, southwest of Shawinigan city. View looking to the W-NW, parallel to the extension lineation. Cliff face is ~ 7 metres.

Figure 1.13 **a)** Isoclinaly folded, transposed, and highly attenuated mafic dyke in granulite facies orthogneiss, Mékinac domain. Looking towards the north, orthogonal to the extension lineation. Fold axes plunge towards the northeast. **b)** Rootless isoclinal folds in highly strained granulite orthogneiss, Mékinac domain. View parallel to the extension lineation.

Figure 1.14 **a)** Mylonitic quartzite from the Shawinigan domain with garnet porphyroclasts and biotite tails showing stair-step asymmetry. Top-to-the-W-NW sense of shear. Plane polarized light. **b)** Detail of "a", showing the polygonal, recrystallized quartz matrix, and numerous rutile needles (X-nicols). **c)** Foliation "fish" in Shawinigan domain tonalitic orthogneiss, looking towards the northeast, and showing top-to-the-W-NW sense of shear. The extension lineation plunges towards the east. Lend cap (white disk) for scale. **d)** Photomicrograph of a partially annealed mylonitic metapelitic rock from the Shawinigan domain. The plagioclase porphyroclast is 0.5 mm long. See text for explanations.

Figure 1.15 Photomicrographs of mylonites from the Tawachiche shear zone.

a) Plagioclase porphyroclasts in an ultramylonite, showing relict core and recrystallized mantle. Average grain size in the matrix is $< 10 \mu\text{m}$. **b)** Ultramylonite formed of quartz ribbons and feldspar porphyroclasts in a biotite-rich matrix, showing the extreme reduction in grain size, and the absence of post-deformation recrystallization. Field of view is 2 mm.

Figure 1.16 Photomicrographs of mylonites from the Tawachiche shear zone. **a)** K-feldspar porphyroclasts with σ -type asymmetry shown by pyrite pressure shadows. Shear sense shown is top-down-to-the-N-NE. **b)** Hornblende porphyroclast with σ -type asymmetry showing sinistral, top-down-to-the-N-NE sense of shear. The field of view in both photographs is 2mm.

Figure 1.17 **a)** Typical outcrop of the Tawachiche shear zone showing the high degree of transposition of rock types. Dark layers are transposed mafic dykes. Disaggregated pegmatite dykes now form light-coloured streaks with K-feldspar porphyroclasts. **b)** δ -type rotated K-feldspar porphyroclast from the Tawachiche shear zone, showing sinistral sense of shear. View looking east. Coin diameter is 21 mm. **c)** Montauban group metapsammities transposed in the Tawachiche shear zone. Peraluminous pegmatites are disaggregated and deformed into boudins. Earlier structures such as folds (see Figure 1.5a) are now transposed into parallelism with the shear zone.

Figure 1.18 Photograph of outcrop from the Western strand of the Montauban group showing delicate primary layering, and ptygmatic folds in a granite vein. Photograph taken approximately 0.5 km from the western margin of the Gagnon pluton, and looking towards the east. Layering is sub-parallel to the pluton margin, and the vein is nearly perpendicular.

CHAPTER 2: LITHOTECTONIC AND THERMAL EVOLUTION OF THE GRENVILLE OROGEN IN SOUTH-CENTRAL QUÉBEC: U-Pb AND ^{40}Ar - ^{39}Ar AGE CONSTRAINTS FROM THE MAURICIE TRANSECT

2.1 INTRODUCTION

The accumulation of U-Pb geochronological data in recent years has had an important impact on the development of models for the geological evolution of the Grenville orogen in Canada and northeastern United States. However, the majority of published U-Pb isotopic data have been concentrated mainly in Ontario (e.g. Krogh and Davis 1968; Krogh 1970; van Breemen et al. 1986; Lumbers et al. 1990; McEachern and van Breemen 1993; Sager-Kinsman and Parrish 1993; Corrigan et al. 1994), the Adirondacks and Vermont (e.g. McLelland and Chiarenzelli 1990; McLelland et al. 1988, 1991, 1993; Chiarenzelli and McLelland 1991; Ratcliffe et al. 1991; Mezger et al. 1993), and Labrador (e.g. Schärer et al. 1986; Gower et al. 1991; Connelly and Heaman 1993; Scott et al. 1993). In contrast, fewer U-Pb geochronological data are available for the vast intervening region in Québec, with the notable exception of some of the better known anorthositic plutonic complexes (e.g. Emslie and Hunt 1990; Higgins and van Breemen 1992; Doig 1991). Therefore, constraints on the timing of protolith formation, deformation, and metamorphism remain relatively scarce. Consequently, tectonic or crustal evolution models involving the Mauricie region have been either formulated in the absence of reliable geochronological data (Rondot 1978, 1986), or extrapolated from more thoroughly studied geological regions in Ontario and the Adirondacks (e.g. Rivers et al. 1989), and thus remain highly speculative (cf. Nadeau and Corrigan 1991).

Recent data from 1:250,000 scale mapping in the Mauricie region (Nadeau and Corrigan 1991) has led to the identification of three distinct NS-striking, east-dipping lithologic associations (herein termed domains), referred to in this thesis as the Mauricie

transect (Fig. 2.1). More detailed mapping along an east-west section across the Mauricie transect (Fig. 2.2) has helped to further refine its lithologic, metamorphic, and structural framework (Chapter 1), and to redefine the domain boundaries. From west to east, and forming progressively higher structural levels, the domains studied are termed Mékinac, Shawinigan, and Portneuf—St. Maurice (Chapter 1). The latter is intruded by the voluminous Parc des Laurentides plutonic complex (Fig. 2.1), which is predominantly formed of late- to post-tectonic charnockite and mangerite (Avramtchev and Piché 1981; Emslie and Hunt 1990; Nadeau and Corrigan 1991), and extends approximately 150 km to the east and northeast of the Mauricie region.

This paper presents U-Pb zircon, monazite, and titanite data, as well as $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages from the Mauricie transect. These data support proposals that (i) the Portneuf—St. Maurice (PSM) domain, which comprises the remnant of a *ca.* 1.45 Ga island arc (Montauban Group) intruded by *ca.* 1.40—1.37 Ga calc-alkaline plutons (La Bostonnais complex) (Nadeau and van Breemen 1994; this paper), locally preserves *ca.* 1.39 Ga metamorphic assemblages that were only moderately affected by a Grenvillian tectonothermal overprint; (ii) the Mékinac and Shawinigan domains are predominantly composed of calc-alkaline metaplutonic rocks that were emplaced at *ca.* 1.40—1.37 Ga, and are possibly the westerly extension of the La Bostonnais complex; (iii) detrital zircons from a quartzite from the Shawinigan domain (St. Boniface metasediments) constrain their maximum age of deposition to *ca.* 1176 Ma, and distinguishes this unit from the *ca.* 1.45 Ga metasediments of the PSM domain, and from possibly pre-1.40 Ga metasedimentary rocks in the Mékinac and Shawinigan domains; (iv) *ca.* 1153 Ma granitic plutonism, restricted to the Shawinigan domain and possibly to the upper structural levels of the Mékinac domain, provides a maximum age for bulk, W-NW-directed thrusting and peak Grenvillian metamorphism; (v) the end of thrusting at approximately 1092 Ma generally coincides with the initiation of exhumation of high

grade metamorphic assemblages in the Mékinac and Shawinigan domains, and with the development of an important oblique extensional shear zone, the Tawachiche shear zone, between the Shawinigan and PSM domains; and (vi) tectonic denudation by oblique extension coincided with extensive high-temperature plutonism, restricted to the Shawinigan and PSM domains, in the time span 1.08—1.06 Ga.

2.2 GEOLOGICAL SETTING

2.2.1 Portneuf—St. Maurice domain

The PSM domain comprises (i) the Montauban Group, predominantly composed of metamorphosed volcanic and volcanoclastic rocks including pillow basalts and lapilli tuff, with pelites, psammites, and calc-silicate gneiss (Smith 1956; Pyke 1967; Nadeau and Corrigan 1991; this thesis, Chapter 1), and (ii) the La Bostonnais calc-alkaline plutonic complex. Trace element geochemistry suggests an island arc or back-arc tectonic environment for volcanic and associated sedimentary rocks of the Montauban Group (MacLean et al. 1982; Bernier and MacLean 1993). In contrast, hornblende-bearing dioritic to granitic plutons of the La Bostonnais complex, intruded into the Montauban Group (Nadeau and Corrigan 1991), have trace element geochemical signatures more compatible with continental magmatic arcs (Gauthier 1993; this thesis, Chapter 1). U-Pb zircon ages on lapilli tuff from the Montauban Group, and calc-alkaline plutons of the La Bostonnais complex are ca. 1.45 Ga, and 1.40 Ga, respectively (Nadeau and van Breemen 1994), suggesting that the PSM domain evolved from an island arc or back-arc to a continental arc within this period.

In the study area the Montauban Group is divided into two strands with different metamorphic facies (Fig. 2.2). The eastern strand locally contains migmatitic paragneisses with cordierite-spinel-garnet-sillimanite assemblages, yielding pressure and temperature estimates of 5—6 kb and ~750 °C (Lévesque and Nadeau 1994; this thesis,

Chapter 3). The western strand is locally migmatitic and preserves abundant examples of primary sedimentary and volcanic structures. It yields P-T estimates ranging from 3.2 to 6.5 kb and 550 to 625 °C (Stamatelopoulou-Seymour and MacLean 1984; Bernier and MacLean 1993; Lévesque and Nadeau 1994; this thesis, Chapter 3).

Rocks of the Montauban Group and La Bostonnais complex are intruded by large plutons of gabbroic, monzonitic, and granitic composition (Nadeau and Corrigan 1991), including the 1072 ± 3 Ma Lapeyrère gabbro and the ca. 1.06 Ga Parc des Laurentides plutonic complex (van Breemen, unpublished data 1995). Plutons of this age group postdate peak metamorphism and regional deformation.

2.2.2 Mékinac domain

The Mékinac domain is composed of granulite-facies orthogneisses of felsic to mafic, but predominantly intermediate composition, with minor metasedimentary screens and disrupted mafic and ultramafic pods. From west to east, and progressively up structural section, orthogneisses gradually become more mafic and contain an increasing abundance of thin, quartz-rich, and ultramafic-rich layers of probable volcanic and sedimentary origin (Chapter 1). The predominance of orthogneisses in the core of the Mékinac domain, and the general concentration of metasedimentary rocks along its eastern margin, suggests either a batholithic or arc-root origin for this domain. A charnockitic orthogneiss from this domain was dated by U-Pb zircon at $1372 \pm 39/-30$ Ma, and Nd model ages (t_{DM}) on six orthogneiss samples range from 1.44 to 1.60 Ga (van Breemen, unpublished data 1995). Therefore, isotopic data suggest that the Mékinac domain formed at ca. 1.40 Ga from a juvenile source with only minor contamination by older crust.

The Mékinac domain is entirely composed of granulite facies rocks. Orthogneisses have the assemblage $Kfs-pl-qtz \pm hbl \pm bt \pm opx \pm cpx \pm grt$, whereas the most common assemblage in metapelites is $grt-bt-sil-Kfs-pl-qtz-rf \pm opx \pm spl$. Herd et al.

(1986) obtained P - T estimates of 9 ± 0.5 kb and 820 ± 40 °C from a sapphirine-bearing paragneiss. Calculated P - T conditions from other Mékinac domain assemblages range from 8 to 11.5 kb and 800 to 900 °C (Lévesque and Nadeau 1994; and this thesis, Chapter 3).

2.2.3 Shawinigan domain

The Shawinigan domain, which structurally overlies the Mékinac domain, is predominantly composed of layered tonalitic, granodioritic, and granitic orthogneisses that are structurally concordant with metapelites, quartzites, and calc-silicate rocks. However, in the southern portion of the map area, south and west of Shawinigan, highly aluminous metapelites with minor quartzite and marble predominate. This specific map unit has been named the St. Boniface unit (Chapter 1). Ortho- and paragneisses of the Shawinigan domain were intruded by a number of small to medium size plutons, varying in composition from noritic-anorthositic to granitic. On the basis of metamorphic and structural overprinting relations, the plutons can be divided into two groups (Chapter 1). The older group, which includes the Lac Paul granite (Fig. 2.2), is overprinted by granulite to uppermost-amphibolite facies metamorphism, contains an E-SE-plunging mineral and extension lineation, and is composed of thoroughly recrystallized minerals. The younger group, which includes the Shawinigan norite, the LeJeune mangerite, and other smaller bodies, postdates regional deformation and metamorphism associated with thrusting. These post-thrusting plutons range in composition from anorthositic-gabbroic to syenitic, with norite and mangerite forming the most abundant types. They generally preserve igneous textures and crosscut annealed mylonitic fabrics in their host rocks. Some, like the Shawinigan norite, have chilled margins, suggesting relatively shallow-level emplacement.

The metamorphic facies in the Shawinigan domain is predominantly uppermost amphibolite, with local occurrences of granulite facies assemblages. Calculated P-T estimates range from 7.0 to 10 kb and 725 to 825 °C (this thesis, Chapter 3; Lévesque and Nadeau 1994). Previous geochronology consists of a single 1231 ± 24 Ma whole rock Rb-Sr age, reported from a granitic orthogneiss located approximately 15 km northwest of Shawinigan (Barton and Doig 1974).

2.2.4 Thrusting and oblique extension

All three domains were tectonically imbricated during W-NW directed thrusting (Chapter 1). This event produced a strong N-S striking, east-dipping foliation with a locally well developed, E-SE-plunging syn-metamorphic mineral and extension lineation in the Mékinac and Shawinigan domains. In the Portneuf—St. Maurice domain, transposition does not appear to have been as thorough as in the structurally lower domains, and the deformation style is dominated by folding (Chapter 1). Metamorphic facies is lower- to middle-amphibolite (Stamatelopoulou-Seymour and MacLean 1984; Bernier and MacLean 1993; Lévesque and Nadeau 1994; and this thesis, Chapter 3), and is reflected by the widespread preservation of primary textures and structures in the supracrustal rocks. The abrupt transition in structural style and metamorphic assemblages observed between the Portneuf—St. Maurice and Shawinigan domains coincides with the Tawachiche shear zone. This shear zone is nearly coplanar with the pre-existing foliation, and accommodated moderate to shallow, top-down-to-the-N-NE sense of shear (Chapter 1). Metamorphic assemblages in the Tawachiche shear zone reequilibrated at lower amphibolite facies. A 2 to 3 kb paleopressure offset is recorded between footwall and hanging wall mineral assemblages, with lower pressures observed in the hanging wall (Chapter 3).

2.3 GEOCHRONOLOGY

2.3.1 Sample selection

Sampling was designed with three objectives. The first was to constrain the age of formation of protoliths in order to characterize lithological domains. The second objective was to constrain the age of regional, high grade deformation and metamorphism in all three domains. The third objective was to constrain the age of oblique extension along the Tawachiche shear zone, and related AMCG-type plutonism.

2.3.2 Analytical method

Rock samples were prepared using standard crushing and grinding techniques. Heavy mineral separates were concentrated using a Rodgers Gemeni Gold TableTM, heavy liquids (methylene iodide), and a FrantzTM Magnetic separator. Accessory minerals were separated into a number of size fractions, using sieves immersed in ethyl alcohol. Fractions analyzed were selected on the basis of purity, clarity, and the absence of cored grains. Zircons from individual fractions were selected from grain populations of similar morphology and size. Where necessary, representative zircon grains were polished and etched in HF vapour to reveal internal structures.

All zircon fractions were air abraded (Krogh 1982), until most of the crystal faces and edges were removed. Abraded zircons, as well as monazite and titanite, were washed in warm 3N HNO₃ for a duration of 15 minutes to remove pyrite dust residue. Sample dissolution and column chemistry were performed at the Geochronology Laboratory, Geological Survey of Canada, using the methods described by Parrish et al. (1987). Model Pb isotopic compositions are derived from the growth curve of Stacey and Kramers (1975). Decay constants used are those of Steiger and Jäger (1977). Linear regressions utilize the method of York (1969). Procedures for the preparation of hornblende samples are presented in Appendix A. All U-Pb analyses in this paper are

plotted as ellipses reflecting two-sigma error limits. U-Pb analytical data is presented in Table 2.1.

2.4 SAMPLE DESCRIPTIONS AND RESULTS

2.4.1 Protolith formation and plutonism.

Sample 1) The Tawachiche Diorite; Portneuf—St-Maurice domain (91D—140).

This dioritic body forms part of an elongate plutonic complex of mutually crosscutting diorite, tonalite, granodiorite, granite, and aplite (Fig. 2.3a), which lies structurally below the western strand of the Montauban Group (Fig. 2.2). It was included in the Mékinac domain in previous studies (Rondot 1978; Nadeau and Corrigan 1991). However, from field criteria such as compositional association, and relatively weaker degree of tectonometamorphic reworking, it was thought that this plutonic belt more likely belonged to the ca. 1400 Ma La Bostonnais calc-alkaline complex (Chapter 1). The Tawachiche diorite is coarse-grained, dark grey, and generally only moderately foliated. In contrast to the migmatitic and recrystallized nature of rocks of similar composition in the Mékinac and Shawinigan domains, this rock unit still preserves igneous plagioclase and hornblende crystals that are only partially recrystallized.

Sample 1 contains abundant apatite and zircons showing very little morphological diversity. Zircons are clear, prismatic, with length to width ratios ranging from 2:1 to 6:1, and some contain a few small apatite inclusions. Igneous zoning is visible under high magnification, and metamorphic rims have not been observed. Fractions A, B, and C have been selected from this population.

On a concordia plot, the three fractions form a linear data array with one near-concordant analysis (A) (Fig. 2.4a). A York (1969) regression through fractions "A" and "C" yields an upper intercept of $1371 \pm 3/-2$ Ma, interpreted as the crystallization age of

the diorite. Fraction "B" was excluded from the regression owing to its large analytical error. However, the calculated discordia does intersect its error ellipse.

Sample 2) Tonalitic orthogneiss, Shawinigan domain (92D—388).

Sample 2 is a fine to medium grained, upper amphibolite-facies tonalitic orthogneiss from the Shawinigan domain. The purpose of dating this gneiss is two-fold, (i) it provides an age for the oldest orthogneisses of the Shawinigan domain, as determined from field relationships; and (ii) it provides a maximum age for high grade deformation and metamorphism. The sample dated is very highly strained and contains a number of centimetre-thick aplitic veins which have been rotated into sub-parallelism with the foliation plane (Fig. 2.3b). The tonalite was sampled as far away possible from the aplitic bands, and was broken into small chips in order to remove any aplite inclusions. Heavy mineral separates contains abundant apatite, and zircon that show a variety of morphologies and sizes. The most abundant zircon types consist of prisms with ~ 1:2 aspect ratios, and lacking sharp edges and faces. Etched grain mounts show igneous grains which contain numerous, euhedral apatite inclusions (Fig. 2.5). All fractions except "D" consist of multiple zircon grains with this distinctive morphology.

Two other zircon types are present. One consists of tabular- shaped grains with sub-rounded outlines, and weak igneous zoning visible under high magnification. These grains, which also contain small apatite inclusions, form fraction D. Another, less abundant morphological type consists of < 74 μm , long prismatic, clear zircons. These were not selected for dating due to the higher probability of episodic Pb-loss due to their relatively small size.

Fractions B, D, and E form a group of discordant ellipses with $^{206}\text{Pb}/^{207}\text{Pb}$ ages ranging from 1271 ± 2 to 1278 ± 6 Ma (Fig. 2.4b). Fractions A and C yield significantly older $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 1308 ± 2 Ma, and 1312 ± 9 Ma, respectively. A York (1969)

correlation through all data points yields a discordia with an upper intercept age of 1371 $\pm$ 51/-32 Ma, which can be interpreted as the crystallization age of the tonalite, and a lower intercept of 1155 $\pm$ 44/-61 Ma, interpreted as the approximate age of Pb-loss due to a thermal "event".

Sample 3) Lac Paul megacrystic granite; Shawinigan domain (92D—45).

Sample 3 is a strongly deformed and metamorphosed megacrystic granite exposed in the Shawinigan domain. It forms part of a group of plutonic rocks that were deformation and metamorphosed at high-grade. The Lac Paul granite was sampled approximately 1 km east of Lac Mékinac (Fig. 2.2). At that locality, it crosscuts folded mylonitic fabrics in a quartzo-feldspathic gneiss that contains thin amphibolite bands, which may be transposed and attenuated mafic dykes (Figure 2.3c). The Lac Paul granite is itself mylonitic, forming a distinctive augen gneiss with K-feldspar megacrysts recrystallized into fine-grained, flattened aggregates up to six centimetres in length (Figure 2.3d). Partially annealed quartz ribbons are flattened between feldspar augen. Mineral and stretching lineations in the granite are parallel to the regional E-SE-plunging lineation associated with tectonic transport to the W-NW. It was metamorphosed at uppermost amphibolite to granulite facies. Therefore, the age of the granite provides a minimum age for the development of mylonitic fabric in the host rock, and a first indication of the approximate timing of high grade metamorphism and W-NW directed tectonic transport.

Heavy mineral separates contain abundant, perfectly euhedral apatite and zircon, without or with very few inclusions. Inclusion-free, prismatic zircons with sharp crystal faces and edges were selected for dating. Fraction "A" consists of long prismatic grains with aspect ratios of up to 6:1. All other fractions consist of stubby prisms with aspect ratios of 1:1 to 3:1. A York (1969) regression through the four data points yields a discordia chord with an upper intercept of 1153 $\pm$ 2/-1 Ma, and a lower intercept of 412 $\pm$

165 Ma, with a MSWD of 0.29 (Fig. 2.6a). Fraction "D" is concordant, and fractions "A", "B", and "C" are only 0.5 to 1% discordant. The minor Pb-loss in this sample (3), in comparison to samples 1 and 2 described above, may reflect its relatively simpler metamorphic history. The upper intercept of the discordia is interpreted as the crystallization age of the granite.

Sample 4) Shawinigan Norite; Shawinigan domain (91D—11).

Sample 4 is from a post-thrusting, medium to coarse grained norite pluton occurring west of the city of Shawinigan (Fig. 2.2). It postdates regional metamorphism and has a chilled margin. Apophyses from the norite crosscut leucosomes and annealed mylonitic fabrics in the host gneisses, that formed during W-NW-directed thrusting (Chapter 1). The age of the norite provides a minimum date for W-NW directed thrusting and peak metamorphism in the Shawinigan domain. On the basis of compositional similarity, this norite pluton was interpreted by Béland (1961) and Martignole (1978) as belonging to the ca. 1155 ± 3 Ma (U-Pb zircon and baddeleyite; Doig 1991) Morin anorthosite suite (Fig. 1.1b).

A coarse-grained outcrop of the norite was sampled approximately 50 metres from its margin in order to reduce the likelihood of collecting a sample with zircons assimilated from the host rock. Separated zircons are mostly broken fragments of larger, faceted grains, and a smaller quantity of long prismatic grains with corroded surfaces. All zircons are clear, and most contain small opaque inclusions. The four fractions analyzed yield only slightly discordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1072.6 ± 2 Ma to 1075.5 ± 1 Ma. A York (1969) regression through all points yields an upper intercept of $1077 \pm 10/-2$ Ma (Fig. 3.6b), interpreted as the age of this norite. The small amount of Pb-loss is interpreted as recent, and has no geological significance.

Sample 5) LeJeune mangerite; Shawinigan domain (92D—314).

The LeJeune pluton is teardrop-shaped in map-view, and occurs in the structurally lowest part of the Shawinigan domain (Fig. 2.2). Ortho- and paragneisses surrounding the pluton are highly strained and form granulite to uppermost amphibolite facies S>L tectonites with an east-trending stretching lineation. The distribution of fabrics in the pluton is variable with little or no deformation from the core to the upper contact, and a very pronounced L>>S fabric in the structurally lower margin (Chapter 1). This composite pluton contains predominantly greasy-green clinopyroxene-hornblende bearing mangerite, with less abundant norite, granite, and syenite, and is unmetamorphosed. The norite phase locally shows a chilled margin at its contact with mangerite (Fig. 3.7a).

The mangeritic phase of the pluton was sampled for dating. Heavy mineral separates yielded abundant apatite and zircon. Zircons are prismatic with square cross-sections, they are clear, and most contain small clear inclusions. Four fractions were selected for dating. On a concordia diagram, fractions A, B, and D form a cluster of concordant to nearly concordant points at ca. 1060 Ma, and fraction C yields a 4% discordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1054 ± 2 Ma. Fraction C contains 2 to 3 times more uranium as does the other fractions, which might explain the greater amount of recent Pb-loss. Concordant fractions B and D, which yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1059 ± 2 and 1059.2 ± 4 Ma, respectively, provide the best estimate for the age of sample 5 (i.e. 1059 ± 4 Ma).

Sample 6) Hornblende-biotite granite dyke; Portneuf—St-Maurice domain (91D-125).

A post-tectonic hornblende-biotite granite dyke (sample 6) intrudes deformed and metamorphosed plutonic rocks (Fig. 3.7b) now thought to belong to the ca. 1.40 Ga La Bostonnais complex (see sample 1 above). The host rock to the *hbl-bt* granite consists of moderately to well foliated diorite, megacrystic granite, and pegmatite, which have

parallel contacts within the foliation, and contain a penetrative, east-trending stretching and mineral lineation. The hornblende-biotite granite is medium-grained, equigranular, and isotropic. The granite was dated in order to provide a minimum age for the timing of ductile deformation in the La Bostonnais complex.

The majority of zircons in sample 6 are perfectly euhedral, stubby prismatic, and contain a few microscopic apatite inclusions. Three fractions, consisting of whole euhedral grains and broken-off tips, were selected. Fraction "C" is concordant (Fig. 2.8b), with a U-Pb isotopic age of 1055 ± 2 Ma, and provides the best estimate for the age of crystallization of the granite. Fractions "B", which is concordant within error, yields a slightly younger $^{207}\text{Pb}/^{206}\text{Pb}$ age. Fraction "A" yields a slightly discordant ellipse, probably due to a small amount of recent Pb-loss. The relatively large analytical uncertainty calculated for fractions except "A" and "B" is due to the very low (0.09 to 0.37 nanogram) amount of radiogenic lead in the analyses. The greater amount of recent Pb-loss in fraction "A" may be due to its higher U content.

This granite is thus the same age (within error) as the Parc des Laurentides complex, and the Gagnon Pluton (see below). It also provides a minimum age of ca. 1055 Ma for ductile deformation associated with crustal shortening in the La Bostonnais complex.

Sample 7) Aplite; Portneuf—St-Maurice domain (91D—118).

The 20 km diameter Gagnon pluton (Fig. 2.2) is a satellite to the Parc des Laurentides complex. The Gagnon pluton is a gray to pink, coarse-grained to porphyritic hornblende-biotite granite, which locally hosts rapakivi feldspars. Although most of the pluton is isotropic, it locally contains anisotropic fabrics such as aligned K-feldspar crystals and biotite forming a penetrative foliation. This foliation is parallel to compositional layering in the pluton and could be interpreted as syn-emplacement. Along its western margin, the Gagnon pluton contains a moderately developed proto-mylonitic fabric. Sample 7 is an

aplitic phase of the Gagnon pluton that occurs along the western margin. This aplite crosscuts the syn-emplacement fabric in the pluton. Aplite outside of the pluton crosscuts tightly folded meta-supracrustal rocks of the ca. 1.45 Ga Montauban Group (Fig. 3.7c). The aplite itself contains a very fine-grained, but well developed C-S fabric (Berthé et al. 1979), not readily visible in the host pluton. The C-S fabric indicates oblique sinistral shear, compatible with that observed in the Tawachiche shear zone (Chapter 1). The fact that oblique extensional fabrics are both cut by the aplite and developed within it suggests a syn- or pre-extension emplacement. Therefore dating the aplite provides constraints on the age of: *i*) emplacement of the Gagnon pluton and its aplitic phase, and *ii*) syn- or post-magmatic extension.

The aplite contains abundant zircon and apatite. Zircons are highly enriched in uranium (up to 5000 ppm), and form a single morphological type; stubby euhedral prisms with length to width ratios of 1-2:1. Individual grains are compositionally zoned, have no optically detectable cores, and no metamorphic rims. Four multiple-grain fractions were strongly abraded and analyzed, and form a linear array of slightly discordant (1.5 to 4%) data points on a concordia plot (Fig. 2.9a). A York (1969) regression through all fractions yields an upper intercept of 1056 ± 2 Ma, interpreted as the age of crystallization of the aplite, and consequently, of the Gagnon pluton. Relationships with the oblique extension fabric suggests that deformation continued at least until that age. The discordance of fractions could be interpreted as the result of recent Pb-loss due to the high U concentration in zircons.

2.4.2- Sediment provenance age

Sample 8) Detrital zircons; Shawinigan quartzite (91D—20).

Field, compositional, and structural evidence suggest that there may be more than one age group for metasedimentary rocks in the Mauricie transect. Because of their intimate

association with metavolcanic rocks, and their probable derivation from a predominantly volcanic source (Bernier and MacLean 1993; this thesis, Chapter 1), metasedimentary rocks the Montauban Group are thought to be arc-related, and therefore deposited at ~1450 Ma. However, metasedimentary rocks in the Shawinigan and Mékinac domains are predominantly pelitic with minor quartzite and marble, and contrast sharply with those of the Montauban Group. In order to place some constraints on the time of deposition of sediments in the Shawinigan domain, a quartzite from the St. Boniface unit (Fig. 2.2) was sampled and single detrital grains of undoubtable igneous origin were extracted and analyzed. Monazite grains from the same sample were analyzed in order to constrain the age of metamorphism.

Sample 8 is from a ~ 1 metre thick quartzite layer interbedded with a volumetrically important unit of highly aluminous metapelite occurring near the city of Shawinigan. The quartzite is mylonitic and slightly impure, with a total of 5% garnet, biotite, sillimanite, plagioclase, monazite, and rutile inclusions. Prior to processing, the sample was broken in fist-sized fragments, scrubbed with a steel wire brush, and washed in water in order to remove surface contamination. Crushing and grinding equipment was thoroughly washed and cleaned a number of times, and the first sample runs were thrown away, in order to minimize any possible contamination from previously processed samples.

Heavy mineral separates yielded abundant zircon, monazite, and rutile. Zircons have a wide range of size, morphology, and degree of roundness, and are interpreted to represent multiple sources. Spherical to ovoid grains are abundant and are thought to represent detrital grains mechanically abraded during sediment transport (Fig. 2.10a, b, d). This interpretation is supported by the observation of igneous growth zoning truncated by erosional surfaces in some grains (Fig. 2.10c). Other grains show only moderately abraded, to virtually unabraded surfaces and edges, indicating either a shorter distance of sediment transport, or greater hardness due to low uranium content. Some zircons have

multifaceted surfaces, are more or less spherical, and do not reveal growth zoning when etched in HF vapor. Such grains were not analyzed due to their probable metamorphic origin.

Six grains were chosen for analysis on the basis of two criteria. The first is unequivocal igneous origin, and the second is the presence of not only one, but a few grains with identical morphological characteristics within the entire zircon population. The latter criteria reduces the likelihood that one of the analyzed grains would have been introduced during sample preparation. All grains were strongly abraded in order to minimize the effect of recent or episodic Pb-loss, or metamorphic overgrowths (if present).

Fractions "A" and "B" are composed of clear prismatic grains with internal growth zoning and slightly rounded outlines (Fig. 2.10b, e). Neither have visible cores or inclusions. They yield $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 2655 ± 1 Ma, and 2324 ± 1 Ma respectively (Fig. 2.9b), suggesting a contribution of some of the detrital material from an Archean source. Fraction "C" is a tabular-shaped grain with slightly rounded edges (Fig. 2.10f). It is colourless, clear, and contains weak igneous zoning. On a concordia plot it yields a point with a 28% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1922 ± 4 Ma. Fraction "D" is a long prismatic grain with an aspect ratio of 4:1. It is clear, colourless, with rounded edges and smoothly undulating faces (e.g. Fig. 2.10a). It shows weak igneous zoning under high magnification. This fraction yields a 10% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1672 ± 5 Ma.

Fraction "E" is a clear prismatic crystal with a square cross-section, and a length to breadth ratio of $\sim 4:1$ (Fig. 2.10h). It has prismatic faces but slightly rounded edges. It also contains a few colourless, cylindrical inclusions that are probably apatite. This grain yielded a concordant analysis of 1176 ± 18 Ma. The larger error ellipse is due to the low radiogenic Pb content, approximately 0.12×10^{-9} gm. Fraction "F" consists of a light brown, translucent, short prismatic grain with igneous growth zoning. It is slightly

fractured and has straight crystal faces with slightly rounded edges (Fig. 2.10g). HF-etched grain mounts of similar grains show a truncation of igneous zoning by the erosional surface. On a concordia plot, fraction "F" yields a slightly discordant (0.3 %) ellipse with a $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1246 ± 1 Ma. Fraction "E" yields the youngest age and constrains the maximum age of deposition of this quartzite at 1176 ± 18 Ma.

Two monazite fractions were analyzed, each consisting of a single grain. Both grains are clear, free of inclusions, and have more or less rounded outlines and slightly pitted surfaces. Based on these observations they may be interpreted as detrital grains, but they could also have acquired this shape during mylonitization (e.g. van Breemen and Hanmer 1986). Fractions "G" and "H" yield concordant U-Pb ages of 1087 ± 1.5 Ma, and 1094 ± 2 Ma, respectively. Given that volume diffusion in minerals is partly a function of grain size and shape (McDougall and Harrison 1988), the greater size and more spherical shape of fraction "H" may explain its older age in comparison to "G". Thermobarometry on nearby samples yielded near-peak P-T estimates of $\sim 725\text{--}800$ °C (Lévesque and Nadeau 1994). Fraction "H" (1094 ± 2 Ma) is therefore thought to represent the best estimate of cooling of peak metamorphic temperatures through ca. 725 °C, the estimated closure temperature for the diffusion of Pb in monazite (Parrish 1990).

2.4.3 Pegmatite emplacement

Sample 9) Late-tectonic pegmatite; Mékinac domain (91D—382).

Sample 9 is a pegmatite dyke the interior of the Mékinac domain (Fig 2.2). It is coarse grained, weakly to moderately foliated, contains pink orthoclase, greenish to grey plagioclase, hornblende poikilocrysts, quartz, and minor biotite and garnet. This pegmatite did not hydrate the granulite facies orthogneisses into which it was emplaced. On the contrary, the fact that it contains greasy-green plagioclase feldspars within its margin suggests that it was emplaced while anhydrous, granulite-facies metamorphic

conditions prevailed. Its host rock is a green-coloured, granulite-facies migmatitic granodioritic orthogneiss with a well developed transposition foliation and east-trending mineral lineation. The pegmatite crosscuts the host rock fabric at a high angle, and its internal foliation (S_i) is parallel to the external foliation (S_e). Therefore, dating this pegmatite should provide a minimum age for the regional deformation in the Mékinac domain, and also provide a constraint for granulite facies metamorphic conditions, which appear to have existed at the time of pegmatite emplacement.

Zircons from this sample are all clear, prismatic, and form stubby prisms with square cross-sections. Length to width ratios vary from 2-4:1. Although all zircons are clearly igneous in origin, none have optically visible igneous zoning. Two multi-grain fractions were analyzed and one (A) is concordant with a U-Pb age of 1057 ± 2 Ma (Fig. 2.11a), interpreted as the age of the pegmatite. Fraction "B" yields a slightly older, 0.5% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1066 ± 3 Ma, which may be due to the incorporation of one or more zircons with undetected cores containing inherited Pb.

Sample 10) Late-tectonic pegmatite; Mékinac domain (92D—4).

A late-tectonic pegmatite with similar field relationships to sample 9 was sampled in a road cut along Highway 155 near Rivière-aux-Rats (Fig. 2.7d). However, this pegmatite (sample 10) is significantly more deformed than the one described above. It is tightly folded, and contains a moderately developed axial planar fabric that is parallel to the tectonic foliation in the enclosing granulite facies gneisses. The pegmatite cuts the transposition foliation and east-plunging mineral lineation in its host rock. Therefore, this sample was analyzed in order to provide a minimum age for the major phase of deformation and metamorphism in the high grade Mékinac domain. However, the fact that the pegmatite itself is deformed, with an internal foliation parallel to that in its host

rock, signifies that deformation was still active, although less intense, at the time of its emplacement.

Zircons show a single morphology, short prisms with length to breadth ratios of 1-3:1. Most zircons are clear and inclusion-free, but some have xenocrystic cores. Three fractions of very clear, gem-like, core-free grains were selected for analysis, with one fraction (A) consisting of a single grain. All fractions were strongly abraded. On a concordia plot, all three fractions are concordant within error and yield the same $^{206}\text{Pb}/^{207}\text{Pb}$ age (Fig. 2.11b). Because fraction "B" is the most concordant and yields the smallest analytical error, its age, 1058 ± 2 Ma, is interpreted as the best estimate for the age of the pegmatite.

Sample 11) Syn-oblique extension pegmatite; Tawachiche Shear Zone (91D—298).

Sample 11 is a biotite granite pegmatite which crosscuts well developed mylonitic fabrics in the Tawachiche shear zone (Fig. 2.12a). At this locality, pegmatites of the same composition as the one sampled are found in various states of deformation. Some are totally disaggregated into isolated, coarse-grained, rotated porphyroclasts, whereas others form partially transposed dykes with internal shear bands and stretching lineations compatible with the shear sense observed in their host gneisses. The above observations suggest that the pegmatites were emplaced during shearing in this particular strand of the Tawachiche shear zone. It was sampled in order to provide an absolute age for a significant component of oblique extension along this shear zone.

Zircons consist of colourless grains with well developed facets and very few inclusions. They are short, prismatic, with length to breadth ratios of 1-2:1. Four fractions consisting of very clear, inclusion-free and core-free grains were selected for analysis. Fractions "A" and "B" are multi-grain whereas "C" and "D" are single grains. Fractions "B" and "C" overlap each other on the concordia (Fig. 2.13a). Fractions "A" and "D" are

0.1 % and 0.2% discordant, respectively. Fractions "A", "C", and "D" yield $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 1065 ± 1 Ma, interpreted as the age of the pegmatite.

Sample 12) Syn-oblique extension pegmatite; Portneuf—St. Maurice domain (91D-246).

Within the study area, the Montauban Group occurs in two distinct, eastern and western strands (Fig. 2.2). The western strand, near its contact with orthogneisses of the structurally underlying La Bostonnais complex, is intruded by a large number of muscovite-biotite-garnet $\pm$ fibrolite bearing pegmatite dykes (Chapter 1). Pegmatites form up to 30% of some outcrops and are concentrated within one kilometre at the structural base of the Montauban Group. In this area, rocks of the Montauban Group, as well as the La Bostonnais complex and the Shawinigan domain, are partially to totally transposed by the Tawachiche shear zone. Pegmatites here have the same structural relationship with their host rocks, as does sample 11, described above, and are syn-oblique extension (Fig. 2.12b, c). Sample 12 cuts mylonitic fabrics developed during oblique strike-slip shearing in the Montauban Group, but is itself only slightly foliated. It is interpreted to have been emplaced during the waning stage of oblique shearing in this particular outcrop.

Heavy mineral separates yielded only a few, small ($< 100 \mu\text{m}$) rounded zircons interpreted as xenocrystic. Because of their likely xenocrystic origin, zircons were not dated. However, large euhedral monazite grains were present. They vary in shape from multifaceted spherical grains, to prismatic grains with well developed facets and edges. Three single-grain fractions were analyzed. One (A) is multifaceted crystal, and the two others are prismatic. Selected grains are yellow and clear, without inclusions. Fraction "A" was slightly abraded to remove grit on its surface.

Fractions "A" and "B" are concordant with U-Pb ages of 1057 ± 1 Ma and 1054 ± 1 Ma, respectively, and fraction "C" yields a 0.8% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1056 ± 1

Ma (Fig. 2.13b). The $^{206}\text{Pb}/^{207}\text{Pb}$ age of fraction "A" is interpreted as the age of the pegmatite. In this sample, monazite is interpreted to have grown at the time of pegmatite emplacement. Due to the higher closure temperature of monazite ($\sim 725^\circ\text{C}$; Parrish 1990) in comparison to the calculated peak metamorphic temperature of the surrounding paragneisses ($550\text{--}600^\circ\text{C}$; Chapter 3), and the fact that the pegmatites post-date peak metamorphism, it is unlikely that the U-Pb age is metamorphic. This age is identical (within error) to that of the aplitic phase of the Gagnon Pluton, which occurs approximately 1 km east of this locality. The fact that sample 12 is syn-oblique extension, implies that the contemporaneous Gagnon pluton was emplaced during oblique extension.

Sample 13) Late-tectonic pegmatite; Shawinigan domain (91D—311).

Sample 13 is a hornblende-biotite-allanite pegmatite sampled along a gas pipeline less than 1 km east of Lac Mékinac (Fig. 2.12d). It is approximately 1 m thick, tightly folded, and cuts two co-planar tectonic fabrics in its host tonalitic orthogneiss. The oldest, high metamorphic grade fabric, consists of S>L gneissic layering formed by the transposition of mafic dykes and granitic veins previously intruded in the tonalitic gneiss. This fabric contains a weak E-SE-trending mineral lineation delineated by hornblende. The younger, low metamorphic grade fabric, is contained in a few centimetre-thick layers sub-parallel to the earlier-formed gneissosity. The younger layers are mylonitic and accommodated NNE-directed oblique strike-slip displacement, and are likely related to the Tawachiche shear zone. The sampled pegmatite cuts both of these fabrics, is tightly folded, and itself contains a weak axial-planar foliation parallel to the exterior foliation. Dating of this pegmatite should therefore constrain the waning stage of deformation due to oblique strike-slip shearing in the Shawinigan domain.

Zircons are clear, light brown, and short and euhedral with well developed facets. Crystal shapes vary from short prismatic with square cross-section, to tabular-shaped.

Four fractions, each consisting of two or more grains without cores, inclusions, or fractures, were strongly abraded and analyzed. On a concordia plot, they form a linear array of data points (Fig. 2.14a) with two overlapping analyses (B and C). Fractions "B", "C", and "D" have similar $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 1035 ± 1 Ma. A York (1969) regression through all data points yields an upper intercept of $1036 \pm 4/-2$ Ma, interpreted as the age of the pegmatite. The slight discordance of the analyses (0.8 to 1.4%) may be due to recent Pb-loss, due to the unusually high U-content of these zircons (up to ~3000 ppm).

2.4.4 Timing of metamorphism and cooling

The age of accessory minerals with different closure temperatures can be used to constrain either the timing of mineral growth, or post-metamorphic cooling (e.g. Ghent et al. 1988; Parrish 1990; Mezger 1993; and many others). The generally accepted closure temperature to Pb diffusion is ~ 725 °C in monazite (Parrish 1990), and ~ 600 °C in titanite (Ghent et al. 1988). Samples from all three domains were selected for the dating of monazite and titanite.

Sample 14) Metapelite; Portneuf—St-Maurice domain (91D-LROB).

Sample 14 is a *crd—grt—spl—sil—bt—pl—qtz* metapelite from the eastern strand of the Portneuf—St. Maurice domain (Fig. 2.2). It is strongly foliated, migmatitic, and contains folded calc-silicate and mafic boudins, indicating intense ductile deformation. Thermobarometers yield peak P-T estimates of ca. 6 kb and 775 °C for this high grade assemblage (Chapter 3).

Monazites extracted from this rock are up to 500 µm in diameter, idiomorphic, and clear. Two fractions were analyzed, each composed of two, partly euhedral grain fragments. On a concordia plot, fractions "m14A" and "m14B" yield $^{206}\text{Pb}/^{207}\text{Pb}$ ages of 1387 ± 1 Ma, and 1388 ± 1 Ma, that are 0.3% and 0.2% concordant, respectively (Fig.

2.14b). Fraction "14mB" is the least discordant and its $^{206}\text{Pb}/^{207}\text{Pb}$ age (1388 ± 1 Ma) is interpreted as the time of cooling of peak metamorphic conditions through ~ 725 °C.

Sample 15) Meta-diorite, Portneuf—St. Maurice domain (92D-327)

Sample 15 is a meta-diorite belonging to the ca. 1.40 Ga La Bostonnais calc-alkaline complex. It is medium to coarse grained, moderately foliated, and contains abundant relict igneous plagioclase and hornblende, which were only partly recrystallized during a younger thermal event. Abundant, very clear, amber-coloured titanites range in size from 100 to 400 μm . Most of the titanites are gem-like and multifaceted, but some are fragments of originally larger grains, probably broken during sample preparation.

Two fractions, each formed of approximately 40 whole grains and fragments, were analyzed. Fraction "t15A" yields a 3% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1236 ± 4 Ma, and fraction "t15B" yields a 3.2% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1235 ± 5 Ma (Fig. 2.14b). These data points plot on a discordia with an upper intercept of ~ 1.40 Ga, which is the assumed age of the parent rock, and a lower intercept of ~ 1.06 Ga. Voluminous high-temperature plutonism did occur at that time in the Portneuf—St-Maurice domain (van Breemen, unpublished data; and this paper), and may have provided sufficient heat to allow partial diffusion of Pb in titanite.

Sample 16) Metapelite, Mékinac domain (92D-400).

Sample 16 is a high grade, strongly foliated and lineated metapelite with the assemblage *sil—Ksp(perthite)—grt—bt—pl—qtz—rt—gr*, with accessory zircon and monazite. Thermobarometers applied to nearby samples yielded minimum P-T estimates of ~ 9 kb and 800 °C (Lévesque and Nadeau 1994).

Monazites are clear, yellow, and euhedral. One analysed grain (m16A) yields a very slightly discordant (0.8%) $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1081 ± 4 Ma (Fig. 2.14b), interpreted as the

time of cooling through ~ 725 °C. Peak metamorphic conditions likely occurred before this date.

Sample 17) Calc-silicate gneiss, Mékinac domain (93D-31).

Sample 17 is a calc-silicate boudin composed of calcite, scapolite, diopside, and phlogopite, with accessory titanite. It is enclosed within granulite facies quartzofeldspathic orthogneiss and is compositionally zoned, with diopside and titanite preferably concentrated along its margin. Boudinage of the calc-silicate gneiss, and the pronounced mineral and stretching lineation present in the metapelite and surrounding rocks, are thought to have been produced during WNW-directed thrusting accompanied by peak metamorphism (Chapter 1).

Titanites extracted from this sample are medium to light amber colour, very clear, multifaceted, and saucer-shaped. Two fractions were analyzed; one (t17A) is composed of approximately 50 grains ranging in diameter from 100 to 300 μm . The other (t17B) contains 12 grains with diameters ranging from 300 to 500 μm . Fraction "t17A" yields a 2.6% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1052 ± 24 Ma, and fraction "t17B" yields a 0.8% discordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1048 ± 7 Ma (Fig. 2.14b). Fraction "t17B", which is the least discordant and has the smallest analytical uncertainty, presents the best estimate for the timing of cooling through ~ 600 °C, the closure temperature of titanite (Ghent et al. 1988).

Sample 18) Tourmaline-garnet leucosome; Shawinigan domain (91D-35).

Sample 18 is from a metre-thick leucosome that formed from the partial melting of a metapelitic protolith. It is coarse-grained, white, and contains abundant tourmaline and pink garnet. At this location, leucosomes are in various stages of tectonic disaggregation. Their state of deformation ranges from totally disaggregated pods now forming

porphyroclastic gneiss, to moderately deformed pods, to virtually undeformed crosscutting dykes (Fig. 2.15a,b). Mylonitized leucosomes show a strong preferred orientation of tourmaline crystals, parallel to prismatic sillimanite in the host metapelite. Mineral and stretching lineations are parallel and plunge shallowly to the southeast. Although unequivocal shear-sense indicators were not found in this outcrop, the regional prevalence of E-SE plunging lineations and their unique association with W-NW directed reverse shearing, suggests a direct relationship (Chapter 1). Therefore, dating this moderately deformed leucosome should constrain the age of the final stages of W-NW-directed thrusting, and of metamorphism in the Shawinigan domain.

Zircons show a wide variety of sizes and shapes, which is to be expected if the leucosome incorporated detrital zircons from the metapelite. However, there are a large number of very clear, light brown euhedral grains that are very distinct from the other zircons. These are prismatic with long bi-pyramidal terminations, and all contain very small cores surrounded by a small, dark brown smokey rim (Fig. 2.15c, d). These grains are compositionally zoned, and interpreted as "igneous" zircons that nucleated on xenocrystic cores and grew in the leucosome. Fractions "A", "B", and "C" consist of tips of such zircons, that were "surgically" removed under high magnification. On a concordia plot, the three zircon fractions form a linear array of slightly to moderately discordant data points. A York (1969) regression through these points yields a well constrained chord with a mean square of weighted deviates (MSWD) of 0.07, an upper-intercept of 1087 ± 2 Ma, and a lower intercept of 193 ± 69 Ma (Fig. 2.16).

Monazites extracted from this sample range in shape from prismatic to oblong, and in size from 100 to 400 μm . Two single-grain fractions were analyzed, one consists of a long prismatic inclusion-free grain (m18D), and the other is a ~ 300 μm long ovoid grain (m18E). Fraction "m18D" yields a nearly concordant $^{206}\text{Pb}/^{207}\text{Pb}$ age of 1093 ± 1 Ma.

Fraction "18mE", which was strongly abraded, yields a concordant U-Pb age of 1092 ± 1 Ma.

There is a small discrepancy between the younger monazite age (1092 ± 1 Ma), and the zircon upper intercept age (1087 ± 2 Ma). This cannot be explained in terms of blocking temperature, since it is known to be about 100 °C higher in zircon than in monazite (Ghent et al. 1988). A likely explanation is that the monazites were formed earlier during peak metamorphism in the metapelite, and were later assimilated by the leucosomes. Monazite ages would date post-peak cooling below ~ 725 °C. In contrast, the igneous zircons may have grown later during the formation of the leucosome at ca. 1087 Ma. This interpretation implies that the leucosomes postdate peak metamorphism, and were perhaps formed during the initiation of decompression. Similar zircon and monazite U-Pb systematics were documented from syn-extensional leucosomes in paragneiss from the Valhalla metamorphic core complex in British Columbia (Carr et al. 1987).

Sample 19) Marble, Shawinigan domain (91D-313).

Sample 19 is a marble from the Shawinigan domain, collected from less than 1 km east of Lac Mékinac (Fig. 2.2). It occurs as a small pod within migmatitic granodioritic orthogneiss. It is composed of white and pink calcite, diopside, scapolite, and minor titanite. Titanite is particularly abundant at the margin of the marble, where hornblende pegmatite pods are also found. Titanites are disc-shaped and range in size from 100 to 500 μm . Two fractions were picked on the basis of clarity and purity of grains. Fraction "19tA" consists of grains 300 to 500 μm in diameter, and fraction "t19B" of grains 100 to 300 μm . On a concordia plot, fractions "t19A" and "t19B" yield concordant analyses of 1036 ± 2 Ma, and 1043 ± 3 Ma respectively (Fig. 2.14b). Fraction "t19A" provides the best estimate for the age of cooling of peak metamorphic temperatures through ~ 600 °C.

2.5 DISCUSSION OF U-Pb RESULTS

The U-Pb data presented above provide new information on the timing of protolith formation, deformation, and metamorphism in the Mauricie transect (Fig. 2.17). Moreover, it now provides the opportunity to compare the chronology of geological events in the Mauricie region with events documented elsewhere in the Grenville Province. The implications of the new geochronological results are discussed below.

2.5.1 Protolith formation.

Available data suggest that the ca. 1.45 Ga (Nadeau and van Breemen 1994) Montauban island arc forms the oldest geological unit in the Mauricie transect. The $1371 \pm 3/-2$ Ma and $1371 \pm 51/-32$ Ma U-Pb zircon ages obtained for quartz-diorite and tonalitic gneiss from the Portneuf—St. Maurice and Shawinigan domains, (samples 1 and 2, respectively), complement the ca. 1372 Ma and ca. 1400 Ma U-Pb zircon ages obtained by Nadeau and van Breemen (1994) for a felsic granulite gneiss from the Mékinac domain, and diorite from the La Bostonnais complex, respectively. This strongly suggests that mafic to felsic orthogneisses forming most of the Mékinac domain and also a large portion of the Shawinigan domain, are the same age, within error, as the ca. 1.40 Ga (Nadeau and van Breemen 1994) La Bostonnais plutonic complex. Furthermore, it suggests a continuous evolution of all three domains commencing with the formation of the Montauban island arc at ca. 1.45 Ga, followed by widespread continental arc magmatism between 1.40 and 1.37 Ga. The fact that the Montauban island arc was also intruded by ca. 1.40—1.37 Ga calc-alkaline plutons with continental arc geochemical signature (Chapter 1) suggests that it had been accreted to a continental margin by that time, and later evolved as an “Andean-type” margin.

The 1.40 to 1.37 Ga dioritic to granitic plutonic rocks and orthogneisses reported in this study and in Nadeau and van Breemen (1994) are generally older than, but overlap in

age with, 1.37-1.35 Ga trondhjemites, tonalites, and granodiorites of the Central Metasedimentary Belt boundary thrust zone in Ontario (van Breemen and Hanmer 1986; Lumbers et al. 1990). They are also slightly older than 1.33 Ga tonalites from the Adirondack highlands (McLelland et al. 1988; McLelland and Chiarenzelli 1991), and ca. 1.35-1.31 Ga tonalites from the Mount Holly Complex in Vermont (Ratcliffe et al. 1991). McLelland and Chiarenzelli (1990), and McEachern et al. (1992) have proposed that the tonalites and associated plutonic rocks were formed in an Andean-type continental magmatic arc within the southeastern margin of Laurentia. These data strongly suggest that the western margin of the Portneuf—St. Maurice domain may represent a "diffuse" ca. 1.40 Ga suture between the rifted margin of Laurentia and the accreted Montauban arc. The observed time span of calc-alkaline plutonism throughout the southwestern Grenville Province (~ 70 m.y.) is comparable with that reported from some of the batholithic calc-alkaline complexes from modern continental magmatic arcs (Bruce et al. 1991).

2.5.2 Arc-related deformation and metamorphism

The 1388 ± 1 Ma date obtained on monazite from a metapelite from the eastern strand of the Montauban Group, interpreted as the age of peak metamorphism, has important implications for the tectonothermal evolution of the Portneuf—St. Maurice domain. It suggests that high grade metamorphism and deformation in this domain was contemporaneous with the emplacement of the La Bostonnais complex at 1.40-1.37 Ga. Although it is known that high-temperature low- to medium-pressure metamorphism is not restricted to a single type of tectonic setting (e.g. Miyashiro 1973; Wickham and Oxburgh 1986; Yardley et al. 1987; Gibson 1991; Reinhardt 1992), the association of high-T low-P metamorphism with Andean-type calc-alkaline magmatism is compatible

with a continental arc tectonic environment for metamorphism and deformation of the Portneuf—St-Maurice domain.

The partial resetting of the U-Pb systematics in titanite (sample 15) suggests that a thermal perturbation occurred in the Portneuf—St. Maurice domain, perhaps during voluminous AMCG plutonism at 1080-1056 Ma. In fact, a discordia line fixed at 1400 Ma and constrained to intersect the titanite data points, yields a lower intercept of ~ 1070 Ma (Fig. 2.14b). Although the postulated thermal overprint generated up to 50% discordance in titanite, it was not sufficient to reset monazite, which has a higher closure temperature to the diffusion of Pb (~ 725 °C; Parrish 1990) than titanite (~ 600 °C; Ghent et al. 1988).

2.5.3 Age constraint on sedimentation

The maximum age of deposition of 1176 ± 18 Ma for the St. Boniface quartzite, inferred by the dating of single zircon grains from sample 8, precludes correlation with the significantly older (~ 1.45 Ga) metasedimentary rocks of the Montauban Group. Moreover, it suggests that there may be at least two different groups of pelitic, quartzitic, and calc-silicate sediments in the Shawinigan domain. The dated quartzite belongs to a thick metasedimentary unit near the city of Shawinigan, where its structural relationship with surrounding ~ 1.37 Ga gneisses (i.e. sample 2) is not exposed, but appears to be structurally concordant. Thinner bands of compositionally similar metasedimentary rocks are found further north in the Shawinigan domain, and west along the margin of the Mékinac domain, and may not be of the same age. These thin bands are enclosed by ca. 1.40—1.37 Ga orthogneisses, with which they have mutually parallel, tectonically transposed contacts. Due to the small size of some of those metasedimentary tracts (some are only a few metres thick and a few tens of metres long), they are not readily interpreted as tectonic slices. Because they are generally enclosed by ~ 1.40—1.37 Ga orthogneisses,

they are more likely fragments or screens of host rock into which the orthogneiss protoliths were emplaced. If so, these metasediments must be older than 1.40 Ga, and are thus different than those dated at $< ca. 1176$ Ma.

The only direct constraint on the minimum age of deposition of the St. Boniface quartzite is the 1094 ± 2 Ma U-Pb monazite cooling age obtained from the dated quartzite. However, this minimum age estimate may be too conservative because the quartzite had to be buried by thrusting, and brought to P-T conditions of at least 7.5 kb and 800 °C (Lévesque and Nadeau 1994; this thesis, Chapter 3) before exhumation and cooling. The beginning of peak metamorphism due to W-NW-directed thrusting is estimated at ca. 1.12 Ga. Further north in the Shawinigan domain, the $1153 \pm 2/-1$ Ma Lac Paul granite (sample 3) intrudes a band of metasedimentary rocks of similar composition, but which could belong to the older (> 1.40 Ga) group. Therefore, with the present data, the 1094 ± 2 Ma monazite age is regarded as a very conservative estimate for the minimum age of deposition of the St. Boniface metasedimentary rocks. The $1153 \pm 2/-1$ Ma Lac Paul granite may provide a more reasonable estimate.

The inferred period of deposition of the St. Boniface quartzite, between 1176 and 1153 Ma, is slightly older than the maximum age of 1150 Ma allowed for the deposition of the Flinton Group in the Elzevir Terrane (Sager-Kinsman and Parrish 1993), and the Twelve-Mile Bay quartzite in the Parry Sound domain (Wodicka 1994). Nevertheless, a correlation is still possible due to the uncertainties on the minimum age of deposition.

2.5.4 ca. 1.16—1.15 Ga plutonism

The only ca. 1.16—1.15 Ga pluton identified in the Mauricie transect is the Lac Paul megacrystic granite, located in the Shawinigan domain. It is overprinted by granulite facies metamorphism and carries a mylonitic fabric with an E-SE-plunging extension

lineation. It thus provides an indication of the maximum age for N-NW-directed thrusting and high-grade metamorphism in the Mékinac and Shawinigan domains.

This age coincides with the emplacement of anorthosite-mangerite-charnockite-granite (AMCG) massifs during the interval 1160-1130 Ma in the Adirondacks (McLelland and Chiarenzelli 1990; Chiarenzelli and McLelland 1991), in the Morin Terrane (Doig 1991; Martignole and Friedman 1992), and in the Lac-Saint-Jean area (Higgins and van Breemen 1992). Undated anorthosite and coronitic metagabbro boudins that occur along the eastern margin of the Mékinac domain (Nadeau and Corrigan 1991; this thesis, Chapter 1) bear the same tectonometamorphic overprint as the Lac Paul granite, and may be of the same age. This suggestion implies that a more or less structurally continuous belt of tectonically disrupted plutonic bodies related to the ~ 1160 Ma Morin and Lac St. Jean AMCG suites, lies within the Mauricie transect. However, more mapping is necessary to verify this hypothesis.

2.5.5 High grade deformation and metamorphism.

The data presented in this chapter provide new constraints on the tectonothermal evolution of the Mauricie transect. Prior to this study, it was inferred that the entire region was subjected to metamorphic (re-) equilibration during the Grenville orogeny at ca. 1160-1000 Ma (Martignole 1978; Herd et al. 1986; Rondot 1986). However, the preservation of nearly concordant 1388 ± 1 Ma monazite ages in sample 14 contradicts this assumption. The absolute age of W-NW-directed thrusting and associated high-grade metamorphic overprint in the Mékinac and Shawinigan domains is still unconstrained. The only age constraint is given by the 1153 ± 2 Ma Lac Paul granite, which is the youngest plutonic rock to have been tectonically and thermally overprinted during this event. However, the Lac Paul granite also cuts laterally discontinuous high-grade mylonites developed in surrounding quartzofeldspathic gneisses. There are presently no

controls on the kinematic significance or age of this mylonite, which could be penecontemporaneous to ca. 1153 Ma plutonism, or significantly older. In contrast, the minimum age for W-NW directed thrusting is well constrained by the ca. 1092 ± 1 Ma late-thrusting leucosome (sample 18). Support for this minimum age is provided by the $1077 \pm 10/-2$ Ma Shawinigan norite, which is undeformed, has a chilled margin, and intrudes mylonitic fabrics developed earlier during W-NW-directed thrusting. Since the St-Boniface metasediments had to be buried under ~ 25 km of overburden before being exhumed at ca. 1.09 Ga, and that the Lac Paul granite also had to be overprinted by this event after its emplacement at ca. 1.15 Ga, a "reasonable" estimate for the initiation of W-NW-directed thrusting is ~ 1.12 Ga. This age post-dates extension and AMCG-type magmatism in the Adirondack Highlands (Chiarenzelli and McLelland 1991), and it corresponds to renewed thrusting along the Parry Sound shear zone (Wodicka 1994).

2.5.6 Oblique extensional shear and AMCG-type plutonism.

After ca. 1.09 Ga, the tectonic regime in the Mauricie transect underwent a fundamental change from W-NW directed thrusting, to N-NE directed oblique extension accompanied by voluminous AMCG-type plutonism. As emphasized above, sample 18 dates the last gasp of deformation related to W-NW directed thrusting at 1087 ± 2 Ma. In the Shawinigan domain, mylonitic fabrics related to thrusting are crosscut by the $1077 \pm 10/-2$ Ma Shawinigan norite (sample 4), which is itself undeformed and unmetamorphosed. A similar U-Pb zircon age (~ 1080 Ma) has been obtained for the post-thrusting Lapeyrère gabbro in the Portneuf—St. Maurice domain (van Breemen, unpublished data 1995). Mangerite from the LeJeune pluton (sample 5) yielded a 1060 ± 2 Ma U-Pb age, and the aplitic border phase of the Gagnon pluton (sample 7), a 1056 ± 2 Ma U-Pb age. The age obtained for the Gagnon pluton is identical to that reported for the much larger Parc des Laurentides Complex (Fig. 2.2) (van Breemen, unpublished data

1995), and supports the suggestion that it forms a satellite pluton (Chapter 1). The above data suggests a temporal evolution from mafic, to intermediate, to felsic plutonism in the interval 1080 Ma to 1056 Ma.

The $1065 \pm 2/-1$ Ma, and 1055 ± 2 Ma ages obtained on syn-extensional pegmatites (samples 11 and 12, respectively) confirm the intimate relationship between younger AMCG-type magmatism and ongoing oblique extensional shearing. Although the oldest syn-extensional pegmatite found to this date in the Tawachiche shear zone is ca. 1065 Ma, there is no reason to believe that extension did not initiate previously, perhaps as early as 1094 Ma, as suggested by monazite cooling ages in the footwall. The 1056 ± 2 Ma aplite border phase of the Gagnon pluton contains a well developed "C-S" fabric formed during oblique extensional shear, suggesting that deformation outlasted plutonism. Evidence of oblique extensional shear has also been documented along the western margin of the 1056 ± 2 Ma (van Breemen, unpublished data 1995) Parc des Laurentides complex (Nadeau and Corrigan 1991). Oblique shearing was active at least until ca. 1056 Ma (sample 7), and possibly as late as 1036 Ma (sample 13). However, the absence of deformation in the 1055 ± 2 Ma hbl-bt granite dyke (sample 6), is indicative of localisation of shearing during progressive deformation within the Tawachiche shear zone.

The 1077-1055 Ma age range obtained in this study for post-thrusting plutons in the Mauricie transect coincides with that obtained for compositionally similar rocks from the Lac-Saint-Jean area (Hervet et al. 1990; Higgins and van Breemen 1992). In the Adirondacks, plutonic rocks of this age-range have also been reported, but are of alaskitic and trondhjemitic composition (Chiarenzelli and McLelland 1991). In the Elzevir Terrane, Corriveau et al. (1990) have documented the presence of a 1089-1076 Ma suite of undeformed and unmetamorphosed ultrapotassic to syenitic plutons. It therefore

appears that the 1089-1056 Ma period in the Southwest Grenville orogen is one of voluminous, mantle-derived plutonism spatially restricted to the Allochthonous belts.

2.5.7 Cooling history

U-Pb monazite and titanite cooling ages from this study, together with hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages presented in Appendix "2.1", provide useful information on the tectonothermal evolution of the Mauricie transect. It has been established above that oblique extension along the Tawachiche shear zone provided a viable mechanism for the exhumation of the high-grade Mékinac and Shawinigan domains (Chapters 1 and 3). Tectonic denudation may have started as early as 1094 Ma, and lasted at least until 1036 Ma, with most of the oblique extension occurring before 1055 Ma, resulting in the juxtaposition of the "colder" hangingwall (Portneuf—St. Maurice domain) against a "hotter" footwall (Mékinac and Shawinigan domains). The thermal consequence of this juxtaposition is more easily resolved for the footwall than for the hanging wall, where voluminous syn-extension plutonism also played an important role.

i) Cooling of the footwall

The earliest cooling age reported for the Tawachiche shear zone footwall is a 1094 ± 2 Ma monazite age (*sample 13*) that records cooling of uppermost-amphibolite facies metasediments from the Shawinigan domain through ~ 725 °C. In contrast, monazites from a sample 16 from the structurally deeper Mékinac domain yield a blocking age of 1081 ± 4 Ma. The difference in monazite cooling ages appears to indicate that the Shawinigan domain cooled through the blocking temperature of monazite before the Mékinac domain. This observation is supported by two $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating hornblende ages from the Mékinac domain, which are 1016 ± 3 Ma nearest to the Tawachiche shear zone, and 985 ± 5 Ma in the structurally deepest region (App. 2.1.1).

Titanites from two well-spaced samples from the footwall (*samples 17 and 19*) do not follow this younging trend, but instead have similar ages, within error (see Figure 2.2). Mezger et al. (1991) have shown that the closure temperature of titanite may vary from 550 to 650 °C, depending on grain size. This may explain the more random distribution of titanite ages in comparison to monazite and hornblende. However, more titanite analyses would be necessary in order to test whether titanite U-Pb ages reflect progressive younging away from the Tawachiche shear zone, or not.

Interestingly, both hornblende samples from the Mékinac domain yield relatively “flat” age spectra, and contrast with samples from the hanging-wall (except the Gagnon pluton), which yield disturbed spectra. Flat age spectra usually form as a result of rapid cooling (Hanes 1991), and may provide an indication of the pressure-temperature-time (*P-T-t*) evolution of the high-grade footwall, as will be discussed in Chapter 3.

Using an oversimplistic assumption of linear cooling rates, U-Pb monazite, titanite, and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages can be used to approximate maximum and minimum cooling rates experienced in the footwall (Fig. 2.18). Assuming closure temperatures of ~ 725 °C, 600 °C, and 530 °C for monazite (Parrish 1990), titanite (Ghent et al. 1988), and hornblende (McDougall and Harrison 1988), respectively, time integrated cooling rates of 3.8 to 2.5 °C/m.y. are calculated between 1.09 and 1.04 Ga. Much slower time integrated cooling rates of 1.1 to 2.5 °C/m.y. apply between ~ 1.04 and 0.99 Ga. These data show that significantly faster cooling rates were attained between ~ 1.09 and 1.04 Ga, corresponding to the period of oblique extension along the Tawachiche shear zone.

Thermal models for extending crust predict that footwall rocks at a given depth should experience less cooling during decompression, at progressively increasing distances from the detachment (England and Jackson 1987; Ruppel et al. 1988; Hodges et al. 1993). This is due to the faster rates of decompression experienced in the entire footwall, in comparison to the relatively slower rate of thermal diffusivity (Hodges et al.

1993). Effectively, decompression is felt almost instantaneously in the footwall, whereas cooling progresses slowly from the detachment surface downwards. The younging of monazite and hornblende isotopic ages in the footwall away from the Tawachiche shear zone, towards the structurally deepest part of the Mékinac domain, is therefore compatible with cooling by tectonic denudation. Erosion must also have contributed to the exhumation of the footwall, but its specific effect cannot be precisely quantified with the present data.

ii) Thermal evolution of the hanging wall

The 1013 to 1031 Ma hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the hanging wall (Appendix 2.1.1) cannot be readily explained in terms of post-metamorphic cooling. Peak metamorphic temperatures in the western and eastern strands of the Montauban Group have been calculated at $\sim 550\text{--}650\text{ }^{\circ}\text{C}$ and $700\text{--}750\text{ }^{\circ}\text{C}$, respectively (Lévesque and Nadeau 1994; this thesis, Chapter 3). The nearly concordant U-Pb monazite age of 1388 ± 3 Ma obtained from sample 14 from the eastern strand (Fig. 2.2), provides a minimum age for this metamorphic event, and suggests little or only moderate thermal overprint. However, titanites from a ca. 1.40 Ga meta-diorite (sample 15) are approximately 50% discordant, with a lower intercept of 1070 Ma indicating the approximate time of the thermal disturbance. Because this thermal disturbance did not affect the U-Pb systematics in monazite, and only partially affected titanite, it can be inferred that it occurred at conditions slightly below the closure temperature of titanite. This thermal event was however sufficient to significantly perturb $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of hornblende in all the metamorphic samples from the Portneuf—St. Maurice domain (see Appendix 2.1.1).

The sample from the interior of the 1056 ± 2 Ma Gagnon pluton (*sample 5*) yields a distinctly older hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ age (1031 ± 5 Ma), with a plateau spectrum suggesting rapid cooling. Samples from the surrounding gneisses yield disturbed

$^{40}\text{Ar}/^{39}\text{Ar}$ age spectra with the age of the disturbance estimated at approximately 1013 ± 3 , 1014 ± 8 , and 1018 ± 11 Ma, for samples 4, 6, and 3, respectively (Appendix 2.1.1). Two-dimensional thermal models for cooling plutons predict that at constant depth, the core of a large pluton should cool below a given temperature later than in the country rock (e.g. Harrison and Clarke 1979). Consequently, cooling ages are expected to be younger in the core of a large pluton than in the country rocks. The opposite is observed in $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages from the Portneuf—St. Maurice domain, with the oldest age obtained from the pluton core. However, there are perhaps other factors that have affected the thermal evolution of the PSM, such as conductive heating from the uplifted footwall, or advective heating from the voluminous Parc des Laurentides complex, which is essentially the same age as the Gagnon pluton. The contribution from each of these heat sources cannot be confidently discriminated.

2.5.8 Exhumation of the Central Granulite Terrain

The data presented above demonstrate that the footwall and hanging wall of the Tawachiche shear zone experienced different post-thrusting thermal histories. Cooling in the footwall occurred as a response to tectonic denudation, at progressively younger dates away from the shear zone surface. In contrast, the temperature in the hanging wall was already below, or near the closure temperature of hornblende before extension. Heat provided by voluminous high-temperature syn-extensional plutons, emplaced predominantly in the hanging wall, or by tectonic juxtaposition upon a "hot" footwall, was sufficient to significantly disturb the $^{40}\text{Ar}/^{39}\text{Ar}$ ages in hornblende, and to partially reset U-Pb titanite ages.

Petrographic observations and quantitative thermobarometry reported from the footwall of the Tawachiche shear zone (i.e. the Central Granulite Terrain) are compatible with models of exhumation by tectonic denudation. Metamorphic reaction textures

observed in the Mékinac and Shawinigan domains are interpreted as documenting isothermal decompression followed by isobaric cooling (Chapter 3). Similar P-T trajectories have been reported from tectonically exhumed high-grade metamorphic complexes, such as the Greater Himalayan sequence below the Southern Tibet detachment (Hodges et al. 1993), in granulites from core complexes in British Columbia (Ellis 1987), and from the Napier Complex in Enderby Land, Antarctica (Ellis 1987; Harley et al. 1990). Figure 2.19 is a schematic cross-section of the southwestern Grenville orogen, from the southeastern margin of the Parautochthonous Belt through the Central Granulite Terrain, and projected to the Mauricie transect. A table of previously published U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ data, and new ages from this study, is included in the Figure. The Mékinac and Shawinigan domains form part of the Central Granulite Terrain (Wynne-Edwards 1972), which also includes the Adirondack Highlands in New York State, and the Morin and Reservoir Taureau terrains (Martignole et al. 1994) in Québec (Fig. 2.1b). The western boundary of the Central Granulite Terrain consists of the Carthage—Colton shear zone in New York State, and the Labelle shear zone in Québec (Fig. 2.1b). The steep, westerly-dipping Carthage—Colton mylonite zone has been previously interpreted as a detachment fault with normal-sense displacement (Isachsen and Geraghty 1986). This interpretation agrees with the data of Mezger et al. (1993), who report titanite cooling ages of 1103 to 1156 Ma for the hanging wall (Adirondack Lowlands), and 1014 to 1129 Ma (average of 1058 Ma) for the footwall (Adirondack Highlands) (Fig. 2.19). Reported monazite U-Pb ages from the Central Granulite Terrain in the Adirondack Highlands are ca. 1033 Ma, and those from the Lowlands and Central Metasedimentary Belt range from 1137 to 1171 Ma (Mezger et al. 1991; 1993). It is obvious from the data presented in Figure 2.19 that the hanging walls on both flanks cooled much earlier than the Central Granulite Terrain core.

The timing of displacement along the Carthage—Colton shear zone is not directly constrained, but may be pre-1058 Ma, as inferred from titanite data published by Mezger et al. (1993). Further north along the Labelle shear zone, the direction and duration of shear are not well constrained. This shear zone has been described by Martignole and Corriveau (1991) as a steep, north-striking transcurrent sinistral shear belt which is overprinted by corridors of late mylonite with down-dip lineations, but ambiguous shear-sense. Syenitic plutons with ca. 1.08 Ga U-Pb ages are reworked and provide an approximate maximum age for movement along the Labelle shear zone (Corriveau et al. 1990). Like the Carthage—Colton shear zone, it separates the Central Granulite Terrain to the east, from predominantly upper-amphibolite facies rocks to the west.

The structural relationship between the Central Granulite Terrain and its flanking extensional shear zones and lower-grade crustal blocks thus shares some structural similarities with Cordilleran metamorphic core complexes (e.g. Coney 1980; Coney and Harms 1984; Wernicke et al. 1987). However, there are also some fundamental differences, such as the strong strike-slip component of displacement that occurred along the Tawachiche shear zone, in comparison to the generally normal sense of extension observed in Cordilleran examples. Moreover, there are indications that the Adirondack Highlands were undergoing compressional deformation during the period 1090—1070 Ma, and that extension only occurred in the period 1070—1060 Ma (McLelland 1994). This contrasts with data from the Mauricie transect, which suggests compressional deformation during the period 1153—1094 Ma, with extensional deformation possibly occurring as early as 1094 Ma, and lasting at least until ~ 1035 Ma. On a larger scale, it may indicate that while the core of the Central Granulite Terrain was under a compressional tectonic regime, unroofing by extension was taking place simultaneously at a higher (now eroded) structural level. In the United States, that structural level would

root east of the present-day Adirondack Mountains. North of the St. Lawrence Lowlands, the expression of this postulated extensional detachment is the Tawachiche shear zone.

2.6 CONCLUSIONS

(1) The Mauricie transect represents an important zone of crustal weakness within the Grenville Province, that preserves a ~ 400 m.y. history of arc accretion, crustal thickening, plutonism, and extension.

(2) *Ca.* 1.45 Ga volcanic and sedimentary rocks of the Montauban island arc are intruded by *ca.* 1.40—1.37 Ga calc-alkaline plutons, suggesting accretion of the Montauban arc to a continental margin (Laurentia) at ~ 1.40 Ga, and generation of continental arc magmatism until at least 1.37 Ga. High-temperature, low- to moderate-pressure metamorphism and deformation in the Montauban Group was contemporaneous with magmatism.

(3) Post 1176 ± 18 Ma sedimentation was followed, or was accompanied by, the emplacement of AMCG-type plutons at *ca.* 1153 Ma.

(4) Granulite to uppermost amphibolite facies metamorphism resulted from crustal thickening due to W-NW directed thrusting between 1153 and 1092 Ma. The Portneuf—St. Maurice domain was located at high structural levels during this period, and escaped significant tectonothermal overprint.

(5) An abrupt transition from compressional tectonics, to oblique extension accompanied by further voluminous AMCG-type plutonism occurred at *ca.* 1.08 Ga, and lasted until ~ 1.05 Ga. Oblique extensional shear, represented by the Tawachiche shear zone, provides a mechanism for the exhumation of the high-grade Central Granulite Terrain in the footwall.

APPENDIX 2.1: $^{40}\text{Ar}/^{39}\text{Ar}$ HORNBLLENDE AGES FROM THE MAURICIE TRANSECT.

Selection of samples

Six samples containing abundant coarse-grained hornblende were collected along the Mauricie transect (Appendix 2.1.1). U-Pb ages are known for four of the six samples, and are presented in Appendix 2.2. Two samples were taken from the high-grade footwall (Mékinac and Shawinigan domains). Sample 1 is from a late-tectonic pegmatite from the Mékinac domain, located approximately 35 km west of the Tawachiche shear zone. It has a U-Pb zircon age of 1057 ± 2 Ma (Chapter 2) and contains clinopyroxene as well as poikilocrystic hornblende. Sample 2 is from a coarse-grained hornblendite boudin approximately 5 metres in diameter, enclosed within ductilely deformed migmatitic granulite of intermediate composition. Mineral and extension lineations in the granulite are east-plunging, and were formed during west-directed thrusting between 1153 and 1092 Ma (Chapter 2). Boudinage of the hornblendite was also produced during this event. This sample is located approximately 10 km west of the Tawachiche shear zone.

Sample 3 is from a diorite that belongs to the La Bostonnais Complex, and has a U-Pb zircon age of $1371 +3/-2$ Ma (Chapter 2). It is only moderately foliated, and lies between two major strands of the Tawachiche shear zone. Sample 4 was taken from a concordant amphibolite layer within the western strand of the Montauban Group. It is not known whether this amphibolite was originally a sill, or a volcanic flow. However, its emplacement predates the ca. 1.40 Ga tectonometamorphic overprint in the PSM domain. Sample 5 was collected from the core of the Gagnon pluton (Appendix 2.1.1), which has an igneous crystallization age of 1056 ± 2 Ma (Chapter 2). This ca. 20 km diameter pluton forms part of the post-collisional suite, and is a satellite of the Parc des Laurentides mangerite-charnockite complex, which extends from the northeastern corner

of the study area, to the Lac St. Jean area, approximately 200 km northeast. Sample 6 was taken from a coarse-grained meta-quartz diorite from the ca. 1.40 Ga La Bastonnais calc-alkaline complex. This pluton, which intrudes the ca. 1.45 Ga Montauban arc, has been deformed and metamorphosed during a 1.40—1.37 Ga high-temperature, medium to low-pressure tectonomagmatic event (Chapter 3).

Analytical techniques

Hornblende samples were obtained using standard crushing techniques, followed by gravity separation using a Rodgers Gemini Gold TableTM, sieving, and magnetic separation using a FrantzTM magnetic separator. This procedure was followed by hand picking of 150 μm , inclusion-free grains in ethyl alcohol to assure a sample purity of $\geq 99\%$. Samples were dried at room temperature.

Electron microprobe analyses

Quantitative electron microprobe analyses were obtained on all six hornblende samples in polished grain mounts. Mineral analyses were performed on a Cambridge “Microscan 5” electron microprobe at the Department of Earth Sciences, Carleton University. Instrumentation consisted of a energy-dispersive X-ray spectrometer operating with a beam current of 3.0 nA, 20 kV accelerating voltage, and a beam size of 1—2 μm . X-ray spectra data were reduced to elemental weight percentages using the program EDDI (Pringle 1989). Calibrations based on natural and synthetic mineral standards were used for all analyses. Chemical analyses of hornblende are given in Appendix 2.3.

⁴⁰Ar/³⁹Ar procedures

Each sample was wrapped in aluminium foil packets for neutron irradiation. The vials containing the samples were irradiated in two separate irradiations in the research reactor at McMaster University, Hamilton, Ontario. Flux variations (2—3%) were measured with a hornblende standard (MMHb-1 hornblende; Samson & Alexander 1987) with an assumed age of 518.9 Ma (Roddick 1983), and FTC-3 biotite (a ⁴⁰Ar/³⁹Ar flux monitor prepared by the United States Geological Survey). The samples received an approximate fast neutron fluence of 3×10^{16} neutrons/cm², which results in a J factor of 2.1×10^{-4} . Errors on integrated and plateau ages take account of this uncertainty, though the individual step ages do not.

Argon extractions were performed at the Geological Survey of Canada in Ottawa, using a double-vacuum resistance-heated tantalum furnace similar in design to that described by Staudacher et al. (1978). A 3 %-25 % Re-W thermocouple was used to measure the furnace temperature, which was maintained by a Eurotherm™ three term electronic controller capable of ± 0.5 °C stability. Before step-heating, the entire system (including samples) was baked to about 150 °C under vacuum for 16 hours, followed by further degassing of the furnace (to 1600 °C) and getters. Individual samples were heated in 20-minute steps, and the evolved gas were purified in three stages of gettering. A getter (consisting of SAEST™-ST707 pellets) absorbed H₂ in the furnace section during sample heating. Gas was then transferred to a second stage, using liquid nitrogen-cooled activated charcoal. There, pellets maintained at 250 °C removed active gases. The third stage of gettering utilized SAEST™-ST707 pellets at 450 °C to ensure complete cleanup of all active gases. Charcoal traps were heated to 150 °C during gas purification to desorb hydrocarbons and ensure complete absorption of Ar on the traps when cooled with liquid nitrogen. Total extraction blanks are $\approx 7 \times 10^{-10}$ cm³ ⁴⁰Ar below 1200 °C, and 6×10^{-9} at 1550 °C, and have an uncertainty of $\pm 50\%$.

Argon was analyzed with a modified MS 10 mass spectrometer with a 0.4 Tesla permanent magnet. Sensitivity was 1.5×10^{-6} A/Pascal (or 7×10^{-8} cm³ STP/V) and additional collector slit plates resulted in abundance sensitivity of 15 ppm at 10^{-8} Pascals. Twelve scans of the ion beams were recorded by a Keithley™ 642 electrometer with a 10^{11} ohm resistor, feeding a Solartron™ DVM with output to a computer for data reduction. Peak switching intervals of 5 s delay and 4 s integration resulted in a detection limit of 1×10^{-12} cm³ STP of argon. Argon isotopic ratios, ages, and errors were calculated using formulae described in Roddick (1988).

Analytical results

Chemical analyses of hornblende are presented in Appendix 2.3. ⁴⁰Ar/³⁹Ar analytical results are presented in Appendix 2.2, and their age spectra are presented in Appendix 2.1.1. Detailed step-heating data are presented in Appendix 2.4. Age plateaus were determined for samples that released > 50% of the ³⁹Ar in two or more consecutive steps, each having ⁴⁰Ar/³⁹Ar ratios that were indistinguishable at 1 standard deviation (cf. Cosca et al. 1991). Following these criteria, samples *91D-382*, *92D-26*, and *92D-274* (or samples 1, 2, and 5) define age plateaus. Samples *91D-140*, *91D-253*, and *92D-327* (or samples 3, 4, and 6) yield disturbed spectra, with the "flatter" portion yielding the approximate age of partial thermal resetting. The hornblende ⁴⁰Ar/³⁹Ar ages range from 985 ± 5 Ma to 1031 ± 5 Ma, with four dates grouped at 1013 to 1018 Ma. The youngest age (985 ± 5 Ma) is from sample 1, taken from the structurally deepest part of the Mékinac domain, and is 31 m.y. younger than that of sample 2 (1016 ± 3 Ma) taken at higher structural levels within the Mékinac domain. This apparent younging pattern of cooling ages with increasing structural depth, below the Tawachiche shear zone, is corroborated by U-Pb monazite data (Chapter 2).

Four hornblende samples (2, 3, 4, and 6) have $^{40}\text{Ar}/^{39}\text{Ar}$ ages that fall between 1013 and 1018 Ma, and are indistinguishable within error. One is from within the Tawachiche shear zone (Sample 3), two are from the Portneuf—St. Maurice domain (samples 4 and 6), and one (sample 2) is from the Mékinac domain. Sample 5, from the 1056 $\pm$ 2 Ma Gagnon pluton, yields the oldest age with a well defined plateau at 1031 $\pm$ 5 Ma, interpreted as a magmatic cooling age. All analyses except sample 5 have excess argon, probably resulting from a high external partial-pressure of argon related to earlier metamorphism (e.g. Hanes 1991). Sample 5, from the core of a post-collisional, post-metamorphic pluton, may not have been exposed to external argon. The interpretation of results is given in Chapter 2.

Appendix 2.1.1 Geological map of the Mauricie transect showing $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age spectra and sample locations.

APPENDIX 2.2. Summary of composition and isotopic ages of selected samples.

Sample number	Field number	Rock type	U-Pb age (Ma) (1)		$^{40}\text{Ar}/^{39}\text{Ar}$ hornblende (Ma)
			zircon	titanite	
1	91D-382	pegmatite	1057 ± 2	—	985 ± 5
2	92D-26	hornblendite	—	—	1016 ± 3
3	91D-140	diotite	1371 ± 3	—	1018 ± 11
4	91D-253	amphibolite	—	—	1013 ± 3
5	92D-274	hbl-bt granite	1056 ± 2	—	1031 ± 5
6	92D-327	diorite	—	1236 ± 4	1014 ± 8

Sources are: (1) Chapter 2.

APPENDIX 2.3. Representative chemical analyses of hornblende samples.

Sample # Field #	1 92D-382	2 92D-26	3 91D-140	4 91D-253	5 92D-274	6 92D-327
SiO ₂	38.57	41.71	40.75	44.53	39.61	44.18
TiO ₂	1.91	0.89	1.31	1.27	1.75	1.02
Al ₂ O ₃	12.08	12.82	12.80	11.36	9.96	10.51
FeO	21.35	13.15	20.16	17.47	28.41	17.54
MnO	0.35	0.10	0.31	0.28	0.76	0.37
MgO	7.24	12.85	7.74	9.19	3.74	10.35
CaO	10.74	11.65	11.56	11.86	10.49	11.95
Na ₂ O	2.08	1.76	1.55	0.91	2.55	1.23
K ₂ O	1.96	1.71	1.14	0.78	1.30	1.24
Cl	1.20	0.10	0.00	0.00	0.28	0.08
Total	97.48	96.97	97.32	97.65	98.85	98.54

APPENDIX 2.4. Argon step-heating data

TEMP. (°C)	³⁶ Ar	³⁷ Ar (x10 ⁻⁹ cm ³ STP) a	³⁸ Ar	³⁹ Ar	⁴⁰ Ar	% Atmos. ⁴⁰ Ar	APPARENT Ma	AGE +/- 2fb	³⁹ Ar (%)
Sample 1. AA00-361 91D-382 HB (48.69 mg) J = .01759 ± 0.50 % 1σ									
700	.054	14.876	1.573	0.620	51.75	31.0	1261.7	10.8	0.7
800	.007	0.963	0.447	0.418	28.95	7.0	1366.3	14.8	0.5
900	.005	0.379	0.661	0.565	25.87	5.4	1021.3	8.0	0.6
1000	.011	10.824	20.978	5.549	240.10	1.3	1010.7	0.9	6.2
1020	.004	13.509	24.622	6.421	264.75	0.5	980.1	0.9	7.1
1040	.008	17.624	30.156	7.983	330.47	0.7	981.8	1.8	8.9
1060	.007	26.314	44.275	11.792	488.42	0.4	984.1	0.9	13.1
1080	.006	29.387	49.189	13.247	547.34	0.3	983.1	0.8	14.7
1120	.006	35.135	59.669	15.873	658.12	0.3	985.9	0.8	17.7
1160	.003	11.506	19.803	5.192	215.90	0.5	986.9	1.2	5.8
1200	.005	25.213	43.298	11.329	469.24	0.3	985.0	0.9	12.6
1300	.005	20.635	35.426	9.226	383.61	0.4	987.2	0.8	10.3
1500	.008	3.664	6.149	1.624	69.97	3.4	991.1	2.9	1.8
Total c	0.13	210.03	336.25	89.84	3774.5	1.0	990.4	7.6	
Conc.(/g)	2.7	4313.60	6905.84	1845.17	77521.1				

Sample 2. AA00-363 92-NKD-26B HB (51.32 mg) J = .01755 ± 0.50 % 1σ

700	.041	0.439	0.069	0.093	18.75	64.9	1457.3	68.7	0.1
800	.009	0.227	0.030	0.098	11.57	23.2	1714.0	47.0	0.1
900	.007	0.354	0.052	0.148	11.79	17.2	1389.7	27.8	0.2
975	.009	2.195	0.494	0.795	39.56	6.9	1073.5	10.2	0.9
1000	.007	2.234	0.519	0.811	38.32	5.7	1042.2	6.3	0.9
1020	.005	4.608	1.068	1.617	71.80	2.2	1022.5	2.8	1.8
1040	.003	7.682	1.764	2.647	115.48	0.7	1019.7	2.0	2.9
1060	.007	13.082	2.995	4.488	194.32	1.0	1011.7	1.0	5.0
1080	.009	21.280	4.898	7.290	315.22	0.8	1012.4	1.1	8.1
1100	.013	55.127	12.438	18.873	817.68	0.5	1016.7	1.1	21.0
1120	.009	73.028	16.143	24.967	1078.46	0.2	1016.0	1.1	27.8
1140	.003	28.301	6.167	9.677	416.88	0.2	1014.3	2.5	10.8
1160	.003	3.171	0.704	1.065	46.37	1.6	1011.6	5.9	1.2
1200	.005	11.858	2.648	4.015	174.17	0.8	1014.8	2.5	4.5
1500	.007	40.430	8.700	13.190	570.66	0.4	1016.3	1.3	14.7
Total c	0.14	264.02	58.69	89.77	3921.0	1.0	1018.5	7.8	
Conc.(/g)	2.6	5144.54	1143.58	1749.29	76403.5				

TEMP. (°C)	36Ar	37Ar (x10-9 cm3 STP) a	38Ar	39Ar	40Ar	% Atmos. 40Ar	APPARENT Ma	AGE +/- 2fb	39Ar (%)
Sample 3. AA00-N 91D-140 HB (53.04 mg) J = .01758 ± 0.50 % 1σ									
700	.066	2.037	0.229	0.422	44.69	43.5	1296.0	27.7	0.6
800	.016	0.812	0.086	0.404	35.79	13.5	1540.1	16.9	0.6
900	.013	1.133	0.132	0.599	40.83	9.3	1327.0	39.7	0.9
1000	.018	26.705	2.596	7.112	316.37	1.6	1029.2	1.4	10.9
1040	.018	83.082	7.607	20.356	883.08	0.6	1017.9	5.5	31.3
1060	.004	63.129	5.701	15.254	653.36	0.2	1011.2	1.2	23.4
1080	.007	11.584	1.043	2.906	124.14	1.6	998.6	3.5	4.5
1100	.005	5.191	0.463	1.320	57.25	2.5	1002.4	8.2	2.0
1120	.011	13.374	1.192	3.187	138.52	2.4	1005.4	4.9	4.9
1140	.003	15.154	1.334	3.513	151.03	0.5	1011.7	4.0	5.4
1160	.001	13.435	1.147	2.968	132.63	0.1	1045.0	8.4	4.6
1180	.003	9.059	0.793	2.076	94.42	1.0	1051.7	11.4	3.2
1200	.003	6.563	0.575	1.512	69.23	1.3	1055.4	8.0	2.3
1225	.002	2.598	0.228	0.614	28.63	2.0	1063.6	8.7	0.9
1250	.002	1.505	0.131	0.365	17.28	3.1	1067.2	19.2	0.6
1500	.009	10.117	0.890	2.517	122.94	2.1	1100.5	4.2	3.9
Total c	0.18	265.48	24.15	65.13	2910.2	1.8	1031.4	8.1	
Conc.(/g)	3.4	5005.20	455.26	1227.85	54867.8				

Sample 4. AA00-N 91D-253B (59.97 mg) J = .01834 ± 0.50 % 1σ

700	.034	1.698	0.059	0.408	29.06	34.7	1112.1	7.6	0.9
800	.004	2.308	0.007	0.162	13.93	8.0	1618.8	14.3	0.3
900	.003	4.277	0.012	0.297	13.49	7.3	1033.2	9.1	0.6
975	.004	6.733	0.028	0.708	30.33	3.7	1016.3	2.6	1.5
1000	.000	5.773	0.033	0.824	33.67	0.0	1008.6	4.2	1.7
1020	.003	13.820	0.087	2.088	85.25	1.1	1000.2	1.3	4.4
1040	.003	67.659	0.419	10.412	427.46	0.2	1010.8	0.8	21.8
1060	.003	64.672	0.404	10.096	417.34	0.2	1016.1	1.0	21.1
1080	.003	5.825	0.039	0.849	36.56	2.7	1028.4	3.2	1.8
1100	.002	9.186	0.060	1.284	54.72	1.0	1034.1	2.2	2.7
1120	.002	19.250	0.119	2.762	115.33	0.5	1021.8	0.9	5.8
1140	.004	23.413	0.140	3.309	138.16	0.8	1019.9	1.6	6.9
1160	.002	20.131	0.119	2.789	117.80	0.5	1030.9	1.8	5.8
1180	.001	13.252	0.082	1.930	81.28	0.4	1029.7	1.0	4.0
1220	.002	19.720	0.121	2.869	121.81	0.5	1034.5	0.9	6.0
1300	.000	28.948	0.178	4.206	177.51	0.1	1033.6	0.9	8.8
1550	.005	20.808	0.124	2.846	123.42	1.2	1046.3	1.9	5.9
Total c	0.08	327.47	2.03	47.84	2017.1	1.1	1024.7	7.8	
Conc.(/g)	1.3	5460.64	33.87	797.73	33635.8				

TEMP. (°C)	³⁶ Ar	³⁷ Ar (x10-9 cm3 STP) a	³⁸ Ar	³⁹ Ar	⁴⁰ Ar	% Atmos. 40Ar	APPARENT AGE Ma +/- 2fb	³⁹ Ar (%)
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Sample 5. AA00-N 92D-274 HB (49.36 mg) J = .01756 ± 0.50 % 1σ

700	.043	0.478	0.265	0.217	19.24	66.3	762.0	27.3	0.3
800	.007	0.315	0.179	0.226	11.85	16.4	1031.0	26.6	0.3
900	.008	1.049	0.600	0.545	26.58	8.7	1042.7	9.7	0.7
1000	.008	92.338	47.718	30.466	1347.12	0.2	1035.3	5.5	41.1
1020	.001	41.870	21.295	13.669	598.78	0.0	1029.0	2.0	18.4
1040	.004	22.096	11.280	7.263	318.18	0.3	1026.6	1.6	9.8
1060	.004	16.856	8.606	5.501	242.21	0.5	1029.2	1.1	7.4
1080	.003	14.338	7.284	4.641	204.34	0.4	1030.2	1.0	6.3
1100	.003	14.256	7.115	4.559	200.58	0.4	1029.5	1.0	6.1
1140	.004	16.594	8.275	5.328	234.16	0.5	1028.3	1.2	7.2
1180	.002	3.074	1.557	0.998	44.04	1.2	1026.0	5.4	1.3
1220	.001	0.476	0.237	0.156	6.94	4.6	1003.0	30.8	0.2
1300	.002	0.685	0.351	0.226	10.37	5.4	1021.7	23.0	0.3
1500	.004	1.129	0.544	0.358	17.00	7.2	1035.0	23.2	0.5

Total c	0.09	225.55	115.31	74.15	3281.4	0.8	1030.7	8.2
Conc.(/g)	1.9	4569.57	2336.01	1502.27	66478.5			

Sample 6. AA00-470 92D-327 (55.09 mg) J = .01844 ± 0.50 % 1σ

700	.032	1.089	0.160	0.549	32.85	28.9	1044.4	3.2	0.7
800	.009	0.384	0.071	0.589	25.61	10.9	972.4	3.0	0.8
900	.006	1.232	0.150	0.547	22.01	8.2	936.2	4.6	0.7
975	.009	15.867	1.801	4.093	168.69	1.6	1007.0	1.2	5.6
1000	.004	21.422	2.324	5.329	218.77	0.6	1012.2	1.1	7.2
1020	.005	25.734	2.711	6.265	258.69	0.6	1016.7	1.0	8.5
1040	.005	38.574	3.970	9.277	381.74	0.4	1015.4	0.8	12.6
1060	.014	86.028	8.604	20.438	839.42	0.5	1013.3	0.9	27.8
1080	.007	32.888	3.240	7.917	325.83	0.6	1013.8	1.4	10.8
1100	.002	9.937	0.963	2.367	97.34	0.6	1013.5	2.1	3.2
1120	.002	9.720	0.932	2.218	91.32	0.7	1013.9	1.7	3.0
1140	.002	25.147	2.401	5.686	234.10	0.3	1016.6	0.9	7.7
1160	.004	12.845	1.227	2.911	120.67	1.0	1016.7	1.7	4.0
1180	.001	4.020	0.384	0.902	37.51	0.5	1022.6	2.0	1.2
1220	.000	3.234	0.314	0.743	30.99	0.3	1027.1	2.3	1.0
1300	.000	6.542	0.640	1.501	62.64	0.2	1028.1	2.0	2.0
1550	.007	10.071	0.976	2.283	97.29	2.2	1028.8	1.3	3.1

Total c	0.11	304.73	30.87	73.62	3045.5	1.1	1014.3	7.8
Conc.(/g)	2.0	5531.56	560.36	1336.27	55281.8

Figure 2.1. a) Geological map of the Grenville Province in eastern North America showing the location of the major lithotectonic subdivisions after Wynne-Edwards (1972), and the location of the Mauricie region. Heavy toothed lines trace the Grenville front. **b)** Geological map of the Southwest Grenville Province; AH = Adirondack Highlands; AL = Adirondack Lowlands; B = Bancroft Terrane; CMBBTz = Central Metasedimentary Belt Boundary thrust zone; CPL = Parc des Laurentides complex; E = Elzevir Terrane; F = Frontenac Terrane; LSJ = Lac St. Jean anorthosite; M = Mékinac domain; MT = Morin Terrane; PB = Parautochthonous Belt; PS = Parry Sound domain; PSM = Portneuf—St. Maurice domain; S = Shawinigan domain. Fine stipple is Paleozoic cover. Study area is shown in box. Modified after Rivers et al. (1989).

Figure 2.2. Geological map of the Mauricie region with geochronology sample locations and interpreted ages. Only a small portion of the Parc des Laurentides complex (grid pattern) and the Lapeyrère gabbro (chequered pattern) appears in the northeast corner of the map.

Figure 2.3. Outcrop photographs. **a)** Folded La Bostonnais complex diorite (dark gray), similar to sample 1 (Tawachiche diorite), and granodiorite (lighter gray), cut by a small aplite dyke. Hammer for scale. **b)** Highly strained tonalitic orthogneiss from the Shawinigan domain. Thin, light coloured bands are transposed aplite veins. Sample 2 is from a compositionally homogeneous portion of this outcrop. Lens cap for scale is 7 cm. **c)** Folded mylonite intruded by coarse grained granite (sample 3) which also contains a weak foliation parallel to the axial planes. Hammer for scale. **d)** Detail of the Lac Paul megacrystic granite (sample 3) with recrystallized K-feldspar augen. Coin is 26 mm in diameter.

Figure 2.4. U-Pb concordia diagrams. **a)** Plot of zircon data from the Tawachiche diorite in the Portneuf—St. Maurice domain (sample 1). **b)** Plot of zircon data from a tonalitic gneiss within the Shawinigan domain (sample 2). Upper and lower intercept ages are shown. Error ellipses are given at 2σ uncertainty. U.I. = upper intercept, L.I. = lower intercept.

Figure 2.5. SEM images of polished and HF-etched zircon grain mounts from sample 2, a tonalitic gneiss from the Shawinigan domain. **a)** Igneous growth zoning is visible from core to rim, although it is more diffuse in the outer portion of the grain. Dark spots are apatite inclusions. **b)** Zircon with igneous zoning from core to rim. Apatite (dark) and zircon (high reflectivity) inclusions are present. **c)** Igneous grain with a large oval-shaped, partially metamict core. Metamorphic rims are absent in all grain mounts shown.

Figure 2.6. U-Pb concordia diagrams. **a)** Plot of zircon data from the Lac Paul megacrystic granite (sample 3). **b)** Plot of zircon data from the Shawinigan Norite (sample 4), showing slightly discordant data points. Upper and lower intercept ages are shown. Error ellipses are shown at 2σ uncertainty.

Figure 2.7. Outcrop photographs. **a)** Globular-shaped norite with chilled margins against its mangeritic host, Shawinigan domain. This textural relationship is also observed in the LeJeune pluton. **b)** Hornblende-biotite granite (sample 6) intruding deformed and metamorphosed meta-plutonic rocks of the La Bostonnais complex. **c)** Aplitic border phase of the Gagnon pluton intruding Montauban Group paragneisses. The aplite contains a delicate "C-S" fabric (visible under magnification) showing oblique strike-slip (top-to-the-NNE) sense of shear (not visible on photograph). **d)** Folded and weakly foliated pegmatite dyke intruded into planar, granulite facies orthogneisses of the Mékinac domain. Geological hammer, and coin (26 mm) for scales.

Figure 2.9. U-Pb concordia diagrams. **a)** Analyses of zircons from the aplitic border of the Gagnon Pluton (sample 7). **b)** Analyses of single detrital zircon grains from a quartzite (sample 8). $^{207}\text{Pb}/^{206}\text{Pb}$ ages of discordant grains are indicated. Fractions "E" and "F" are concordant. Monazite data are plotted in Figure 2.14b. Error ellipses are given at 2σ uncertainty.

Figure 2.10. SEM and plane-polarized photomicrographs of polished and whole zircon grains from quartzite sample 8. The U-Pb age of dated grains is shown. **a)** Curved surface of an elongate igneous zircon interpreted as natural surficial abrasion. **b)** Stubby igneous zircon (similar to "e") with planar faces and smoothed edges. **c)** SEM image of a zircon showing igneous zoning and a thin metamorphic rim, both truncated by abrasion during sediment transport. **d)** Grain similar to "b", with preserved crystal faces but highly abraded pyramidal terminations. **e)** Photomicrograph of slightly eroded clear igneous grain, as selected for fractions A and B. **f)** Triangular-shaped, tabular igneous grain selected for fraction C. **g)** Stubby, fractured igneous grain selected for fraction F. **h)** Long prismatic, clear igneous grain selected for fraction E. The dates shown are $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

Fraction "A"
2655 ± 2 Ma

Fraction "C"
1922 ± 4 Ma

Fraction "F"
1246 ± 1 Ma

Fraction "E"
1176 ± 18 Ma

Figure 2.11. U-Pb concordia diagrams. **a)** Plot of zircon data from a late-tectonic pegmatite from the Mékinac domain (sample 9). **b)** Plot of zircon data from a late-tectonic pegmatite from the Mékinac domain (sample 10). See text for interpretation.

Figure 2.12. Outcrop photographs. **a)** Apophysis from a larger pegmatite dyke (sample 11) intruded in quartzofeldspathic mylonite, looking towards southeast. Obliquity of the "S" fabric is visible in the pegmatite, with respect to the "C" fabric in the host gneiss, indicates top-to-the-left (north-northeast) sense of shear. **b)** Garnet-muscovite pegmatite (sample 12) intruded into tightly folded paragneisses of the Montauban Group. View is looking east on a vertical section. **c)** Same outcrop as in Figure 11b, but with higher strain. Here, the garnet-muscovite pegmatite is almost completely disaggregated along a shear zone strand belonging to the Tawachiche shear zone. **d)** Folded pegmatite (sample 13) cross-cutting highly strained orthogneisses of the Shawinigan domain. The pegmatite has a weak, axial-planar foliation. See text for explanations. Hammer and lens cap (7 cm) for scale.

Figure 2.13. U-Pb concordia diagrams. **a)** Plot of zircon data from a syn-extension pegmatite from the Tawachiche shear zone (sample 11). **b)** Plot of monazite data from a syn-extension two-mica pegmatite, Portneuf—St. Maurice domain (sample 12). See text for interpretation.

Figure 2.14. U-Pb concordia diagrams. **a)** Plot of zircon data from a late-extension pegmatite from the Tawachiche shear zone (sample 13). **b)** Plot of monazite and titanite data from all three domains. The discordia shown has been fixed at 1400 Ma and constrained to pass through the titanite analyses from sample 15. Inset shows an enlargement of the lower part of the concordia. Errors are given at 2σ uncertainty. Sample locations are given in Figure 2.2.

Figure 2.15. **a)** Road cut where sample 18 was extracted, showing the highly planar geometry of Shawinigan domain metasedimentary rocks. Calc-silicate boudins are visible in the center of the photograph. View is towards the west, and the stretching and sillimanite lineation plunges to the southwest. **b)** Detail of migmatitic metapelite from station 91D—35 (sample 18) showing partly disaggregated, tourmaline-garnet bearing leucosomes. Lens cap for scale. **c)** SEM image of a zircon from leucosome sample 18 showing a small elongate zircon with rounded outlines, included in a larger igneous zircon interpreted to have grown during leucosome formation. **d)** Zircon with strong igneous zoning, grown during the leucosome formation.

Figure 2.16. U-Pb concordia diagram for sample 18, a late-thrusting leucosome from the Shawinigan domain. Zircon and monazite analyses are represented by "Z" and "M", respectively. Errors are given at 2σ uncertainty. Sample location is given in Figure 2.2.

¹ (Nadeau and van Breemen 1994)

Figure 2.17. Chronology of magmatic and thermal events in the Grenville Province.

¹ Nadeau and van Breemen (1994). See text for explanations.

Figure 2.18. Time vs temperature diagram showing the thermal evolution of the Mauricie transect. Peak pressures and temperatures are after Chapter 3. See text for explanations.

Figure 2.19. Schematic cross-section of the southwestern Grenville orogen at ca. 1.09—1.05 Ga showing the major oblique extensional and thrust faults. Contemporaneous plutons are indicated with the "cross" patterns. The distribution and source of U-Pb monazite and $^{40}\text{Ar}/^{39}\text{Ar}$ data is shown. See text for explanations.

Table 2.1. U-Pb analytical data

Fraction ¹	Wt (μg)	U ppm	Pb ² ppm	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb _c ⁴	²⁰⁸ Pb (%)	²⁰⁶ Pb/ ²³⁸ U ⁵	²⁰⁷ Pb/ ²³⁵ U ⁵	R	²⁰⁷ Pb/ ²⁰⁶ Pb ⁵	Age (Ma) ⁶
Sample 1- Tawachiche diorite, Portneuf—St. Maurice domain (91D—140; z3239)											
A	61	200	48	36,842	5	8.2	0.2363 ± 0.08%	2.8490 ± 0.10%	0.96	0.08744 ± 0.03%	1370.2 ± 1.1
B	52	223	53	263	654	8.1	0.2335 ± 0.17%	2.7950 ± 0.57%	0.69	0.08680 ± 0.47%	1356.0 ± 18.2
C	12	250	58	3,417	12	6.5	0.2328 ± 0.09%	2.7980 ± 0.10%	0.90	0.08717 ± 0.05%	1364.2 ± 1.8
Sample 2- Tonalitic orthogneiss, Shawinigan domain (92D—388; z3034)											
A	97	129	30	2,483	67	12.2	0.2226 ± 0.09%	2.598 ± 0.11%	0.88	0.08466 ± 0.05%	1307.9 ± 2.1
B	51	147	33	807	124	10.9	0.2165 ± 0.10%	2.489 ± 0.20%	0.71	0.08338 ± 0.15%	1278.1 ± 5.8
C	11	155	37	545	48	12.8	0.2251 ± 0.11%	2.634 ± 0.29%	0.63	0.08486 ± 0.24%	1312.4 ± 9.3
D	29	112	26	8,193	5	11.7	0.2167 ± 0.10%	2.489 ± 0.12%	0.92	0.08330 ± 0.05%	1276.2 ± 1.8
E	20	178	40	3,674	13	10.4	0.2154 ± 0.09%	2.467 ± 0.11%	0.84	0.08308 ± 0.06%	1271.2 ± 2.3
Sample 3- Lac Paul megacrystic granite, Shawinigan domain (92D—45; z2900)											
A	43	67	13	4,145	8	9.8	0.1929 ± 0.14%	2.076 ± 0.15%	0.93	0.07804 ± 0.05%	1147.9 ± 2.1
B	66	168	33	9,080	14	8.6	0.1945 ± 0.10%	2.096 ± 0.11%	0.96	0.07817 ± 0.03%	1151.2 ± 1.2
C	86	174	35	18,679	9	9.4	0.1945 ± 0.08%	2.096 ± 0.10%	0.95	0.07816 ± 0.03%	1150.8 ± 1.2
D	35	360	71	18,558	8	7.3	0.1961 ± 0.08%	2.115 ± 0.10%	0.96	0.07825 ± 0.03%	1153.1 ± 1.2
Sample 4- Shawinigan norite, Shawinigan domain (91D—11B; z3021)											
A	132	101	20	16,780	9	16.2	0.1806 ± 0.08%	1.873 ± 0.10%	0.96	0.07521 ± 0.03%	1074.1 ± 1.2
B	37	87	17	5,978	6	16.5	0.1802 ± 0.09%	1.867 ± 0.11%	0.93	0.07515 ± 0.04%	1072.6 ± 1.6
C	73	60	12	3,382	15	14.1	0.1805 ± 0.10%	1.871 ± 0.12%	0.84	0.07518 ± 0.07%	1073.4 ± 2.7
D	108	128	26	5,757	27	16.3	0.1813 ± 0.09%	1.882 ± 0.10%	0.94	0.07526 ± 0.04%	1075.5 ± 1.4
Sample 5- Leleune mangerite; Shawinigan domain (92D—314; z3022)											
A	67	69	14	5,569	9	16.4	0.1786 ± 0.09%	1.841 ± 0.11%	0.91	0.07478 ± 0.04%	1062.6 ± 1.8
B	63	55	10	5,670	7	13.3	0.1788 ± 0.10%	1.840 ± 0.11%	0.89	0.07465 ± 0.05%	1059.0 ± 2.0
C	155	68	13	6,155	18	15.1	0.1703 ± 0.10%	1.749 ± 0.12%	0.92	0.07447 ± 0.05%	1054.3 ± 1.9
D	54	79	15	3,581	13	14.8	0.1784 ± 0.10%	1.837 ± 0.15%	0.73	0.07466 ± 0.10%	1059.2 ± 4.1
Sample 6- Hornblende-biotite granite, Portneuf—St. Maurice domain (91D—127; z2605)											
A	17	118	22	922	24	12.9	0.17546 ± 0.12%	1.7961 ± 0.20%	0.70	0.07425 ± 0.14%	1048.1 ± 5.7
B	27	86	17	668	39	15.2	0.17713 ± 0.11%	1.8159 ± 0.24%	0.68	0.07436 ± 0.18%	1051.1 ± 7.4
C	61	93	18	2,900	22	14.7	0.17783 ± 0.09%	1.8265 ± 0.12%	0.78	0.07449 ± 0.08%	1054.8 ± 3.0

¹ Fraction	Wt (μg)	U ppm	Pb ² ppm	²⁰⁶ Pb ³ ²⁰⁴ Pb	²⁰⁶ Pb _c ⁴	²⁰⁸ Pb (%)	²⁰⁶ Pb ⁵ ²³⁸ U	²⁰⁷ Pb ⁵ ²³⁵ U	R	²⁰⁷ Pb ⁵ ²⁰⁶ Pb	Age (Ma) ⁶
Sample 7- Aplite, Portneuf—St. Maurice domain (91D—118; z2604)											
A	7	2,495	454	8,315	24	11.2	0.17486 ± 10%	1.7945 ± 11%	0.94	0.07443 ± 04%	1053.2 ± 1.5
B	9	3,923	697	5,725	63	12.5	0.16835 ± 10%	1.7201 ± 11%	0.95	0.07411 ± 04%	1044.3 ± 1.4
C	5	2,470	451	4,523	29	12.1	0.17360 ± 10%	1.7794 ± 11%	0.93	0.07434 ± 04%	1050.7 ± 1.7
D	4	5,262	967	9,729	24	12.2	0.17462 ± 09%	1.7907 ± 10%	0.97	0.07437 ± 03%	1051.6 ± 1.3
Sample 8- St. Boniface quartzite, Shawinigan domain (91D—20; z3261)											
A	7	186	77	1,609	19	7.9	0.3781 ± 11%	9.3940 ± 13%	0.93	0.18019 ± 05%	2654.7 ± 1.5
B	6	251	100	2,990	11	11.9	0.3560 ± 09%	7.2710 ± 11%	0.94	0.14811 ± 04%	2324.2 ± 1.3
C	3	172	46	932	10	9.7	0.2499 ± 13%	4.0560 ± 19%	0.77	0.11771 ± 12%	1921.8 ± 4.4
D	4	131	37	936	9	9.8	0.2666 ± 12%	3.7850 ± 19%	0.71	0.10296 ± 14%	1678.2 ± 5.0
E	6	94	19	250	29	9.6	0.2009 ± 20%	2.1930 ± 54%	0.58	0.07915 ± 45%	1175.9 ± 17.8
F	11	665	147	12,319	8	10.4	0.2125 ± 10%	2.4030 ± 11%	0.96	0.08201 ± 03%	1245.9 ± 1.2
G,mnz	3	2,334	1,768	9,324	9	77.5	0.1831 ± 09%	1.9110 ± 10%	0.94	0.07568 ± 04%	1086.6 ± 1.5
H,mnz	5	3,659	1,817	21,030	10	65.5	0.1844 ± 09%	1.9318 ± 10%	0.89	0.07596 ± 05%	1094.1 ± 1.9
Sample 9- Late-tectonic hornblende pegmatite, Mékinac domain (91D—382; z2603)											
A	100	113	21	3,310	38	11.4	0.17815 ± 13%	1.8314 ± 15%	0.77	0.07456 ± 10%	1056.6 ± 3.9
B	44	107	20	1,868	28	10.9	0.17898 ± 09%	1.8487 ± 12%	0.84	0.07492 ± 07%	1066.3 ± 2.7
C	22	115	21	861	31	12.3	0.17424 ± 83%	1.7929 ± 96%	0.58	0.07463 ± 83%	1058.6 ± 34.0
Sample 10- Late-tectonic hornblende pegmatite, Mékinac domain (92D—4; z2831)											
A	23	104	21	2,594	10	16.8	0.1784 ± 11%	1.8360 ± 12%	0.79	0.07466 ± 07%	1059.3 ± 3.0
B	61	131	27	4,324	20	20.2	0.1784 ± 09%	1.836 ± 11%	0.92	0.07465 ± 04%	1059.0 ± 1.7
C	26	135	28	4,236	9	20.0	0.1783 ± 09%	1.836 ± 11%	0.89	0.07467 ± 05%	1059.5 ± 2.0
Sample 11- Syn-extension biotite-hornblende pegmatite, Tawachiche shear zone (91D—298; z2832)											
A	10	647	117	7,087	10	8.7	0.1792 ± 08%	1.849 ± 10%	0.94	0.07487 ± 03%	1065.0 ± 1.3
B	42	386	70	19,231	9	8.2	0.1796 ± 08%	1.853 ± 10%	0.96	0.07482 ± 03%	1063.7 ± 1.2
C	19	507	93	10,643	10	9.4	0.1795 ± 09%	1.854 ± 10%	0.94	0.07489 ± 04%	1065.6 ± 1.4
D	24	500	91	13,941	9	9.0	0.1789 ± 09%	1.846 ± 10%	0.95	0.07486 ± 03%	1064.9 ± 1.3
Sample 12- Syn-extension biotite-muscovite pegmatite, Tawachiche shear zone (91D—246; z2601)											
A,mnz	15	8,484	3,875	30,200	47	63.8	0.17803 ± 10%	1.8309 ± 11%	0.97	0.07459 ± 03%	1057.5 ± 1.1
B,mnz	10	6,444	3,997	17,478	39	73.4	0.17774 ± 10%	1.8250 ± 10%	0.96	0.07447 ± 03%	1054.2 ± 1.3
C,mnz	5	40,112	6,884	48,001	46	4.9	0.17664 ± 11%	1.8152 ± 12%	0.98	0.07453 ± 03%	1055.9 ± 1.1

Fraction ¹	Wt (μg)	U ppm	Pb ² ppm	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}_c$	^{208}Pb (%)	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	R	$^{207}\text{Pb}/^{206}\text{Pb}$	Age (Ma) ⁶
Sample 13- Late-tectonic biotite-allanite pegmatite, Shawinigan domain (91D—311; z2602)											
A	30	1991	357	9,711	63	11.7	0.1716 ± 0.09%	1.7450 ± 0.10%	0.96	0.07373 ± 0.03%	1034.1 ± 1.3
B	12	2937	534	7,260	53	11.2	0.1729 ± 0.09%	1.7590 ± 0.10%	0.94	0.07378 ± 0.03%	1035.4 ± 1.4
C	25	2023	360	13,116	41	10.2	0.1728 ± 0.08%	1.7570 ± 0.10%	0.96	0.07376 ± 0.03%	1034.9 ± 1.2
D	6	1726	311	7,486	14	11.6	0.1724 ± 0.08%	1.7530 ± 0.10%	0.95	0.07375 ± 0.03%	1034.7 ± 1.3
Sample 14- Metapelite, Montauban Group; Portneuf—St. Maurice domain (92D—LROB; z3141)											
A,mnz	10	2,698	1,919	36,890	11	68.3	0.2392 ± 0.08%	2.909 ± 0.10%	0.96	0.08819 ± 0.03%	1386.5 ± 1.1
B,mnz	12	662	2,335	8,646	13	93.6	0.2398 ± 0.08%	2.919 ± 0.10%	0.95	0.08827 ± 0.03%	1388.4 ± 1.2
Sample 15- Meta-diorite (La Bostonnais complex); Portneuf—St. Maurice domain (92D—327; z)											
A,ttm	123	217	59	1,440	233	29.2	0.2052 ± 0.11%	2.309 ± 0.16%	0.82	0.08162 ± 0.09%	1236.3 ± 3.6
B,ttm	106	190	56	1,391	181	35.2	0.2044 ± 0.11%	2.299 ± 0.18%	0.76	0.08156 ± 0.12%	1234.9 ± 4.6
Sample 16- Mylonitic metapelite, Mékinac domain (92D—400; z2901)											
A,mnz	5	1,985	10	1,308	83	83.9	0.1819 ± 0.09%	1.893 ± 0.14%	0.76	0.07548 ± 0.09%	1081.4 ± 3.7
Sample 17- Marble tectonite, Mékinac domain (93D—31)											
A,ttm	118	225	49	1,665	170	26.2	0.1726 ± 0.18%	1.770 ± 0.66%	0.54	0.07438 ± 0.58%	1051.7 ± 23.5
B,ttm	150	139	25	926	245	10.3	0.1752 ± 0.12%	1.794 ± 0.22%	0.63	0.07425 ± 0.17%	1048.3 ± 7.0
Sample 18- Late-thrusting tourmaline-garnet leucosome, Shawinigan domain (91D—35; z2806)											
A	11	1,428	233	3,296	55	0.5	0.1756 ± 0.10%	1.827 ± 0.12%	0.89	0.07545 ± 0.06%	1080.6 ± 2.2
B	7	1,077	181	9,584	8	0.6	0.1807 ± 0.08%	1.884 ± 0.10%	0.93	0.07562 ± 0.04%	1084.9 ± 1.5
C	5	1,255	200	2,616	27	0.6	0.1713 ± 0.09%	1.780 ± 0.12%	0.82	0.07534 ± 0.07%	1077.5 ± 2.8
D,mnz	10	2,895	1,913	7,776	42	74.0	0.1843 ± 0.08%	1.929 ± 0.10%	0.94	0.07591 ± 0.03%	1092.6 ± 1.4
E,mnz	26	3,422	2,060	20,727	49	71.5	0.1845 ± 0.09%	1.931 ± 0.10%	0.96	0.07589 ± 0.03%	1092.1 ± 1.1
Sample 19- Marble tectonite, Shawinigan domain (91D—313; z3138)											
A,ti	170	222	54	1,796	226	33.4	0.1744 ± 0.10%	1.775 ± 0.14%	0.85	0.07381 ± 0.07%	1036.2 ± 3.0
B,ti	1,848	214	54	2,197	2,004	35.5	0.1758 ± 0.15%	1.793 ± 0.17%	0.92	0.07397 ± 0.07%	1040.8 ± 2.7

Notes: ¹All analyses are zircon unless specified; otherwise, (mnz) = monazite and (ttm) = titanite; ²radiogenic Pb; ³measured ratio, corrected for spike and fractionation; ⁴total common Pb in analysis corrected for fractionation and spike; ⁵corrected for blank Pb and U; common Pb errors quoted are one sigma in percent; R correlation of errors in isotope ratios; ⁶ $^{207}\text{Pb}/^{206}\text{Pb}$ model age.

Table 2.2. Summary of U-Pb results.

Sample number	Description and field number	Interpreted age (Ma)	Interpretation
PLUTONISM			
1	Tawachiche Diorite (91D-140)	1371 $\pm$ 3/-2	crystallization age
2	Tonalite orthogneiss (92D-388)	1371 $\pm$ 51/-32	crystallization age
3	Lac Paul Granite (92D-45)	1153 $\pm$ 2/-1	crystallization age
4	Shawinigan Norite (91D-11)	1077 $\pm$ 10/-2	crystallization age
5	LeJeune Mangerite (92D-314)	1059 $\pm$ 4	crystallization age
6	Hornblende-biotite granite (91D-125)	1055 $\pm$ 2	crystallization age
7	Aplite (Gagnon pluton) (91D-118)	1056 $\pm$ 2	crystallization age
SEDIMENTATION			
8	St. Boniface quartzite (91D-20)	1176 $\pm$ 18 (z)	Maximum deposition age
PEGMATITE			
9	Late tectonic pegmatite (91D-382)	1057 $\pm$ 2	Footwall reactivation
10	Late tectonic pegmatite (92D-4)	1058 $\pm$ 2	Footwall reactivation
11	Syn-extension pegmatite (91D-298)	1065 $\pm$ 1	Oblique extension
12	Syn-extension pegmatite (91D-246)	1057 $\pm$ 1 (m)	Oblique extension
13	Late-extension pegmatite (91D-311)	1036 $\pm$ 4/-2	End of oblique extension
METAMORPHISM—COOLING			
Portneuf—St. Maurice domain			
14	Metapelite (91D-LROB)	1388 $\pm$ 1 (m)	Post-metamorphic cooling
15	Quartz diorite (92D-327)	~1236 (t)	Resetting of titanite (²⁰⁷ Pb/ ²⁰⁶ Pb age)
Mékinac domain			
16	Metapelite (92D-400)	1081 $\pm$ 4 (m)	Post-metamorphic cooling
17	Calc-silicate gneiss (93D-31)	1048 $\pm$ 7 (t)	Post-metamorphic cooling
Shawinigan domain			
13	Quartzite (91D-20)	1094 $\pm$ 2 (m)	Post-metamorphic cooling
18	Leucosome in metapelite (91D-35)	1087 $\pm$ 2 (z)	Leucosome formation
		1092 $\pm$ 1 (m)	Leucosome formation
19	Marble (91D-313)	1036 $\pm$ 2 (t)	Post-metamorphic cooling

Note: (z) = zircon; (m) = monazite; (t) = titanite.

CHAPTER 3: METAMORPHIC RESPONSE TO ARC ACCRETION, CRUSTAL SHORTENING, AND POST-COLLISIONAL EXTENSION: AN EXAMPLE FROM THE MESOPROTEROZOIC GRENVILLE OROGEN IN CANADA

3.1 INTRODUCTION

In dynamically active regions of the crust, the perturbation of geotherms has been attributed to factors such as crustal thickening (e.g. Oxburgh and Turcotte 1974; England and Thompson 1984; Sleep 1987), crustal thinning (e.g. Dewey 1988; Wernicke 1981), and magmatism (e.g. Lux et al. 1986; Sandiford et al. 1991). In the Mauricie region of the south-central Grenville orogen (Fig. 3.1), several of these processes have occurred, either simultaneously or diachronously (Nadeau and van Breemen 1994; and Chapters 1 and 2). Detailed study of a broad area across the Mauricie region (Mauricie transect) has led to the identification of three orogen-oblique, NS-striking, east-dipping lithotectonic domains (Nadeau and Corrigan 1991; Corrigan 1994; this thesis, Chapter 1). From west to east, from the structurally lowest to the structurally highest, they are the Mékinac, Shawinigan, and Portneuf—St. Maurice (PSM) domains (Fig. 3.2). Granulite to uppermost amphibolite facies gneisses from the Mékinac and Shawinigan domains are separated from the PSM domain by a low-angle, east-dipping, oblique sinistral extensional shear zone (Tawachiche shear zone) (Chapter 1). Rocks from the hanging wall (PSM domain) are lower grade and, although deformed, preserve many delicate sedimentary and volcanic structures. Geochronological constraints on deformation and thermal evolution suggest that regional metamorphism in the hangingwall occurred at ca. 1.40—1.38 Ga in an arc environment (Chapter 2). In contrast, granulite facies metamorphism in the footwall (Mékinac and Shawinigan domains), was penecontemporaneous with large-scale tectonic imbrication and thrusting towards the W-NW at ca. 1.12 Ga (Chapter 2). Cooling from peak metamorphic temperatures in the footwall was well under way by 1.09 Ga, at

approximately the same time as the onset of oblique extension along the Tawachiche shear zone, and the emplacement of an important number of norite-mangerite-granite plutons in the Shawinigan and PSM domains (Nadeau and van Breemen 1994; this thesis, Chapter 2).

In Chapter 2, it was suggested that oblique extension along the Tawachiche shear zone resulted in the tectonic exhumation of the high-grade footwall (Mékinac and Shawinigan domains), and its juxtaposition with the "cold" hanging wall, which had previously remained at high structural levels during thrusting. This chapter presents detailed petrographic data from the Mauricie transect, a summary of reaction textures, and a quantitative evaluation of pressure and temperature conditions of metamorphism in each lithotectonic domain. In addition to quantitative thermobarometry on peak or near-peak metamorphic assemblages, the deciphering of P - T paths can yield important information on the thermal and tectonic processes that affected the Mauricie region. In this paper, reaction textures are used in order to model the change of pressure and temperature (P - T vector) of the retrograde path. The results are then integrated with a model for the tectonometamorphic evolution of this part of the Grenville orogen.

3.2 GEOLOGICAL FRAMEWORK

Since the original litho-tectono-metamorphic subdivision of the Grenville orogen by Wynne-Edwards (1972), the Mauricie region has been included in the Central Granulite Terrain (Fig 3.1b). This classification was widely used despite the known occurrence of an important area of lower to middle-amphibolite facies rocks in the region surrounding the Montauban Pb-Zn-Au deposit (Smith 1956; Pyke 1966). Recent 1:250,000 scale mapping in the Mauricie region has demonstrated the northern extension of the amphibolite-facies rocks, as well as their consistent structural position overlying predominantly granulite-facies rocks (Nadeau and Corrigan 1991; see also Rondot 1978;

1986). However, until now, not much was known about the metamorphic evolution of this area, or its relationship with better studied parts of the orogen.

Recent focus on the geology of the Mauricie region in the Mesoproterozoic Grenville Province in south-central Québec has led to the recognition of three easterly-dipping lithological domains (Nadeau and Corrigan 1991), collectively referred to in this thesis as the Mauricie transect (Fig. 3.2). The structurally highest PSM domain contrasts sharply with the underlying domains. It is composed of ca. 1.45 Ga (U-Pb zircon; Nadeau and van Breemen 1994) island arc supracrustal rocks (Montauban Group), that were intruded by a suite of 1.40—1.37 Ga (U-Pb zircon; Nadeau and van Breemen 1994; this thesis, Chapter 2) dioritic to granitic calc-alkaline plutons (La Bostonnais complex) of continental arc geochemical affinity (Gauthier 1993; this thesis, Chapter 1). The Montauban Group occurs in two distinct strands (eastern and western strands) that contains abundant fine-grained rocks which preserve primary sedimentary and igneous features. Peak metamorphic assemblages outline a regional fabric, and are interpreted to have been formed during a major regional deformation event dated by U-Pb monazite at ca. 1.39 Ga (Chapter 2). The structurally lowest part of the western strand contains numerous peraluminous pegmatite pods and dykes (Chapter 1). These are thought to have been formed in-situ, and have been dated by U-Pb monazite at 1055 ± 2 Ma (Chapter 2). As will be seen in more detail below, the metamorphic facies in the Portneuf—St. Maurice domain is generally middle-amphibolite, with rare assemblages diagnostic of low-pressure granulite occurring in the eastern strand.

The structurally lower Mékinac domain is entirely formed of granulite facies rocks, whereas the Shawinigan domain contains both granulite and uppermost-amphibolite facies. The Mékinac domain consists predominantly of ca. 1.40 Ga (Nadeau and van Breemen 1994) orthogneisses derived from dioritic to granitic protoliths, structurally interlayered with a few outcrop-size lenses of supracrustal origin (Rondot 1978; Nadeau

and Corrigan 1991; this thesis, Chapter 1). The Shawinigan domain contains ca. 1.40—1.37 Ga orthogneisses of intermediate composition (Chapter 2), but comprises a larger proportion of metapelite, quartzite, and marble. In the southwestern portion of the Shawinigan domain, highly aluminous metapelite interlayered with minor quartzite and marble forms a regionally important group of metasedimentary rocks, named the St. Boniface unit (Chapter 1). U-Pb dating of single detrital zircon grains in a quartzite interlayered within this map unit yielded concordant ages as young as ca. 1.18 Ga, excluding their association with the smaller lenses that occur within the older orthogneisses (Chapter 2).

A distinct feature of the Mékinac and Shawinigan domains is the presence of an older suite of plutonic rocks of anorthositic, gabbroic, mangeritic, and granitic composition resembling the ca. 1.16—1.13 Ga anorthosite-mangerite-charnockite-granite (AMCG) suites described by Emslie and Hunt (1990), which are characteristic of the Central Granulite Terrain. One pluton belonging to this suite, the Lac Paul megacrystic granite, yielded a $1153 \pm 2/-1$ Ma U-Pb age (Chapter 2). AMCG-type plutons of this suite were overprinted at granulite facies during W-NW-directed thrusting at ca. 1.12 Ga (Chapter 2). A younger suite of AMCG-type plutons, dated at ca. 1.08—1.06 Ga (Chapter 2), are only found in the Shawinigan and PSM domains. These plutons are unmetamorphosed, and are generally undeformed. They form satellite plutons to the batholith-sized Parc des Laurentides complex (Avramtchev and Piché 1981), dated at ca. 1.06 Ga (U-Pb zircon; van Breemen, personal communication). Although the Parc des Laurentides complex is composed mainly of hornblende $\pm$ orthopyroxene granite and monzonite, smaller plutons that occur in the PSM and Shawinigan domains are composed of mainly of gabbro, norite, mangerite, jotunite, and charnockite.

The boundary between the Shawinigan and PSM domains is a moderately east-dipping, oblique strike-slip shear zone (Tawachiche shear zone) that accommodated top

down-to-the-N-NE displacement during the interval ca. 1.09—1.05 Ga (Chapter 2). Stable syn-extension mineral assemblages, and structural microtextures within the Tawachiche shear zone are characteristic of lower amphibolite facies metamorphic conditions.

3.3 METAMORPHIC ASSEMBLAGES AND TEXTURES

Lithologies of the Mauricie transect are well suited for the study of metamorphism, and their compositional diversity permits the application of several well-calibrated thermobarometers. Pelitic, mafic, and calc-silicic rocks are found in all three domains and have been examined in several hundred hand specimens, and in more detail in about 120 thin sections. Assemblages described below are presented in structural order, from the lowermost Mékinac domain to the PSM domain. Sample numbers are only indicated for rock specimens that were utilized for thermobarometry, or for documenting important assemblages or reaction textures. The numbers correspond to locations given in Figure 3.3. Mineral abbreviations used in this paper are after Kretz (1983), and migmatite nomenclature follows Mehnert (1968), unless otherwise specified. A summary of reaction textures observed in the Mauricie transect is given in Table 3.1.

3.3.1 Mékinac domain

Felsic granulite

Most of the Mékinac domain is composed of orthopyroxene-bearing felsic to mafic orthogneiss, but with a predominance of gneisses of intermediate composition (Fig. 3.3). Textures in the granulites vary from nearly massive to strongly foliated. Most of the orthogneisses are coarse-to medium-grained and granoblastic. The mineral fabric outlined by peak metamorphic phases is parallel to compositional layers and to the regional N-S-

striking structural grain. Elongate minerals are generally parallel to the E-SE-trending extension lineation, but are locally randomly oriented within the foliation plane.

The more felsic end-members are composed of $opx + hbl + bt + qtz + pl + Kfs \pm cpx \pm ilm \pm gt$, with accessory zircon and apatite. Feldspars are typically perthite and antiperthite. Quartz either forms annealed ribbons, or more rounded grains with subgrains. Biotite is typically fine grained and in textural disequilibrium in most sections examined. Garnet has only been observed locally.

Sample *M-302* is from the structurally lowermost part of the Mékinac domain investigated in this study (Fig. 3.3). It contains medium-grained mesoperthitic K-feldspar and quartz enclosed in a fine-grained plagioclase + quartz matrix. Polycrystalline streaks of mafic minerals define the foliation. In this rock, garnet occurs either as a fine-grained symplectitic intergrowth with quartz, surrounding both ilmenite and clinopyroxene (Fig. 3.4a), or as 100—300 μm porphyroblasts. Clinopyroxene occurs either as relict igneous grains (ferriferous pigeonite) or as new metamorphic grains (ferroaugite). Orthopyroxene occurs as relic cores surrounded by clinopyroxene, or as small resorbed matrix grains. Rare brown hornblende is uniquely found surrounding Fe-Ti oxides. The above textures suggest the onset of high pressure granulite facies as defined by de Waard (1965) and Green and Ringwood (1967), by metamorphic reactions such as:

Garnet, clinopyroxene, and quartz symplectites around Fe-Ti oxides are similar to those developed around clinopyroxene and orthopyroxene, indicating that all three minerals (*cpx*, *opx*, and *ilm*) were consumed during the garnet-forming reactions. However, garnet-quartz symplectites are erratic, both at outcrop and thin section scale, and most of the orthopyroxene and plagioclase grains remain in textural equilibrium,

suggesting that sufficiently high pressure and temperature conditions for the development of high-pressure granulite facies were barely attained.

Intermediate to mafic granulite

Intermediate to mafic granulites have bulk compositions varying from granodioritic to gabbro/dioritic. They are generally less strained than the more quartz-rich granulites, and have undergone a high degree of migmatization. Garnet-free, isoclinally to tightly folded stromatic leucosomes composed of coarse-grained *opx—cpx—pl (antiperthite)—qtz ± Kfs ± Bt* ($\leq 5\%$), form compositional layers parallel to the regional foliation. The absence of significant deformational microstructures in the stromatic leucosomes suggests that they were formed during deformation at high metamorphic grade. A second generation of leucosomes that have essentially the same composition as the latter occur as coarse-grained, undeformed patches (e.g. McLellan 1989) that overprint earlier fabrics (Fig. 1.6e). It is possible that the stromatic and patch leucosomes were formed during two separate tectonometamorphic events. However, because of the strong mineralogical and textural resemblance of the two sets, it is more likely that patch leucosomes—and peak metamorphic conditions—simply outlived deformation in these relatively competent rocks.

A feature common to both types of migmatite is the absence of melanosome. Hornblende only occurs in the leucosome as small xenomorphic grains or as inclusions within pyroxenes (Fig. 3.4b). At the paleosome—leucosome interface, hornblende is resorbed and replaced by oligoclase. Within the paleosome, small, subidioblastic orthopyroxene and clinopyroxene replace hornblende (Fig. 3.4c). Textural evidence suggests that two generations of plagioclase coexist. The first generation (pl 1) occurs in the paleosome as fine, inclusion-free granoblastic grains. The second generation (pl 2)

occurs as coarse, inclusion-rich (fluid *and* mineral inclusions) grains in the leucosome.

Possible generalized reactions for the formation of the leucosomes are:

Reaction (2a) and (2b) have been proposed by Martignole and Schrijver (1971) and Spear (1981), respectively, for the development of assemblages and textures similar to those described above. The absence of garnet in most of the intermediate to mafic granulites, and the widespread co-existence of orthopyroxene and plagioclase along with hornblende $\pm$ biotite, suggests medium-pressure granulite facies metamorphic conditions.

Coronitic metagabbro

A few small gabbroic and anorthositic masses occur throughout the Mékinac domain. They seem to represent tectonized fragments of larger bodies, but their true relation with host gneisses is obscured by relatively poor exposure. Most of the metagabbroic masses exhibit coronitic textures consisting of granoblastic orthopyroxene aggregates, separated from plagioclase by a rim of fine-grained idioblastic garnets (Fig. 3.4d). Yellowish-brown hornblende is ubiquitous as a retrograde phase replacing orthopyroxene. Metamorphic clinopyroxene also occurs locally, in textural equilibrium with orthopyroxene. Plagioclase occurs either as moderately recrystallized igneous laths, or as completely recrystallized granoblastic aggregates with triple-junction grain boundaries. The presence of granoblastic orthopyroxene knots in coronitic metagabbro suggests that olivine (now absent) may have been consumed in a quartz-free reaction such as:

or that the garnet moat separating pyroxenes from plagioclase may have been formed by a reaction such as (1). As stressed above, this reaction characterizes high-pressure

granulite facies as defined by Green and Ringwood (1967). Interestingly, *grt—cpx* parageneses are generally not observed in migmatitic orthogneisses of intermediate to mafic composition, in which hornblende is the predominant mafic phase. In contrast, they are commonly observed as reaction products in protoliths of more "anhydrous" composition. There is thus a general correlation between the bulk rock composition and the sporadic occurrence of garnet, clinopyroxene, and quartz. Similar observations have been documented in intermediate to mafic gneisses surrounding the Adirondack (de Waard 1965) and Morin (Martignole and Schrijver 1971) anorthosite massifs in the Central Granulite Terrain.

Metapelites

Metapelites of the Mékinac domain make up only a few discontinuous layers up to about 5 metres in thickness, and locally occur with marble, quartzite, and calc-silicate gneiss. The most common paragenesis is *grt—sil—Kfs (perthite)—bt—pl—qtz ± rt ± gr ± py*, with accessory monazite and zircon. The metapelites are highly strained diatexites, with restitic streaks formed of prismatic sillimanite, biotite, garnet, microperthite, and plagioclase. Quartz, which contains abundant rutile needles, forms annealed ribbons, with or without a late generation of subgrains. Sillimanite is strongly oriented parallel to the extension lineation and occurs either in sigmoidal-shaped bundles of coarse grains (Fig. 3.4e), with individual grains up to 1 mm thick and a few centimetres long, or as smaller grains isolated within the matrix. Prismatic sillimanite crystals are bent around garnet porphyroblasts. Garnets are pale pink and form ≤ 1 cm porphyroblasts that contain more randomly oriented fibrolite inclusions. Coarser-grained matrix sillimanite is partly engulfed within garnet, suggesting that syn-deformational garnet growth outlasted sillimanite growth. Other inclusions in garnet consist of quartz, plagioclase, perthite, and rare biotite and rutile. Biotite shows evidence of at least two

generations of growth. The earliest occurs as small, reddish-brown matrix grains intergrown with and partially replaced by sillimanite. A later generation of biotite occurs as coarser grains (up to 1 mm) preferably grown adjacent to garnet porphyroblasts. The mineral assemblage and textures in metapelites suggest that uppermost-amphibolite to granulite-facies metamorphic conditions accompanied deformation, which has been correlated with W-NW-directed thrusting (Chapter 1).

Marble and calc-silicate gneiss

A few pink to white marble and calc-silicate layers and pods are found in close spatial association with metapelites. Most are tectonically remobilized and contain highly contorted calc-silicate gneiss fragments, or are simply injected as dykes into the host granulite facies orthogneisses. Such structures can be explained by the relatively low viscosity of the marbles at high temperatures and pressures (Hanmer 1988).

The most common mineral assemblage in the marble is calcite, quartz, diopside, phlogopite, and graphite. Scapolite has also been observed in the majority of samples. The texture in marbles from the Mékinac domain is typically medium- to coarse-grained and granoblastic. The common grouping of granoblastic quartz and diopside into ~ 1 cm aggregates suggests that they may be products of a prograde reaction involving tremolite (now absent) and calcite. The notable absence of forsterite in the thin sections examined is surprising in this granulite facies domain, and may be attributable to inadequate bulk compositions.

Sapphirine-bearing gneiss

Sapphirine in rare magnesian gneiss lenses, documented in the Mékinac domain since the geological mapping of Rondot (1978), has been studied in detail by Ferguson (1974) and Herd et al. (1986). The mineral assemblage in the magnesian layers is *spr*—

opx—phl—pl—sil $\pm$ *crd* $\pm$ *grt* $\pm$ *crn* $\pm$ *spl* $\pm$ *Kfs* (*perthite*) $\pm$ *qtz*, with accessory rutile, monazite and zircon, and late chlorite. Coarse- to medium-grained phlogopite is the most abundant phase and produces a strong foliation. Plagioclase either forms minor, centimetre-thick granoblastic layers within the phlogopite “schist”; or centimetre-sized patches that are also the preferred site of sapphirine and orthopyroxene growth. Within the plagioclase-rich layers, orthopyroxene is the predominant ferromagnesian mineral, with minor interstitial phlogopite. Sapphirine and orthopyroxene within the plagioclase patches form either small sub-idiomorphic grains symplectitically intergrown with plagioclase (Fig. 3.4f), or ≤ 1 cm porphyroblasts truncating matrix phlogopite. Some sapphirine porphyroblasts contain small phlogopite inclusions oriented parallel to the matrix foliation. These textures suggest that phlogopite, and possibly plagioclase, were likely participants in the sapphirine- and orthopyroxene-forming reaction(s). The restricted presence of spinel as inclusions in sapphirine (Herd et al. 1986), suggests that it may also have formed part of an earlier, “pre-sapphirine” assemblage. The peak metamorphic assemblage is therefore interpreted as *spr—opx—phl—pl—qtz*.

Idioblastic garnet occurs in some compositionally restricted layers within the phlogopite “schist” and also along the margin of the magnesian gneiss lenses. Very fine-grained sapphirine, orthopyroxene, plagioclase, and phlogopite are all found as inclusions within garnet (Fig. 3.5a), suggesting it grew after the peak of metamorphism. The inclusion trail inside the illustrated garnet is straight and continuous with matrix foliation, suggesting post-kinematic growth. Another post-metamorphic peak and post-deformation reaction produced cordierite and sillimanite rims on sapphirine (Fig. 3.5b).

Monomineralic sillimanite rims on sapphirine (Fig. 3.5c) are also found. Coarse sillimanite prisms within the matrix contain tiny sapphirine inclusions. Cordierite also occurs as isolated porphyroblasts in the matrix, where it strongly embays phlogopite. The timing of garnet growth with respect to cordierite and sillimanite is uncertain, although it

is clear that both are post-kinematic and post-metamorphic peak. The above textures suggest a replacement of sapphirine by cordierite, sillimanite, and garnet, by the following reaction:

3.3.2 Shawinigan Domain

Orthogneiss

Orthogneisses in the Shawinigan domain vary in composition from granitic to dioritic with a predominance of tonalitic gneiss. The most common mineral composition is *hbl—bt—pl—qtz* $\pm$ *Kfs*, with accessory zircon and apatite. Clinopyroxene, and more rarely orthopyroxene, are locally present, and are generally replaced by biotite.

Hornblende is yellowish green to brownish green, and together with biotite, defines the regional N-S striking foliation and the easterly-plunging mineral lineation. Microcline is a common constituent, along with plagioclase (*An*₂₅₋₃₀). Perthite, which is a common phase in the Mékinac domain, is much less common in orthogneisses from the Shawinigan domain.

Garnet amphibolite

Garnet amphibolite pods and boudins are restricted to the Shawinigan domain. Most are medium- to coarse-grained and weakly to moderately foliated. They can be grouped into two types. Type-I garnet amphibolites contain *grt—hbl—pl* $\pm$ *bt* $\pm$ *qtz*, and type-II contain the same assemblage but also include clino- and orthopyroxene.

Sample S-355 (Fig. 3.3) is a good representative of type-II garnet amphibolite. It is massive and contains 2—5 cm thick, alternating dark green and light green layers that are hornblende- and clinopyroxene-rich, respectively. The light green layers are composed of granoblastic clinopyroxene, with ilmenite blebs and interstitial plagioclase. The dark

green layers are composed of brown hornblende, ilmenite, plagioclase, and minor ortho- and clinopyroxene. Interfaces between hornblende and clinopyroxene crystals are curved. Small resorbed garnets rimmed by plagioclase form spots up to 5 mm in diameter (Fig. 3.5d), and are evenly distributed throughout the rock. Euhedral garnets approximately 200 μm in diameter are found in some of the plagioclase moats, coexisting with the older, resorbed garnets. Orthopyroxene is more concentrated within or at the periphery of the plagioclase moats. Quartz has not been observed in this sample.

The above textures suggest that the peak metamorphic assemblage was *opx—cpx—grt—pl—hbl—ilm—mag*, which defines the field of medium-pressure granulites (Green and Ringwood 1967). The absence of quartz in this assemblage may reflect its total consumption during prograde metamorphism. Symplectic growth of orthopyroxene, clinopyroxene, and plagioclase on hornblende (Fig. 3.5e) suggests a prograde reaction such as (2a). This reaction could have occurred until the total consumption of quartz. An alternative explanation for the lack of quartz, and the replacement of garnet by plagioclase and orthopyroxene, would be its total consumption during the following decompression reactions (Mengel and Rivers 1991):

A reaction similar to (5a) may have produced the small, euhedral, second-phase garnets in the plagioclase moats. It is interesting to note that plagioclase in the moats is slightly richer in anorthite (An_{55-60}) than matrix plagioclase (An_{53-55}), which is compatible with the above reactions (Mengel and Rivers 1991).

Mafic gneiss

Fine- to medium-grained layered gneiss of probable mafic volcanic origin are locally found in the Shawinigan domain. The mineral assemblage is *opx—cpx—hbl—pl—*

ilm $\pm$ *qtz* $\pm$ *bt*. Light coloured layers contain granoblastic *pl*—*cpx*—*opx*, and dark coloured layers contain green to brown hornblende and plagioclase. Hornblende grains are xenomorphic and surrounded by small (10—20 μ m) clino- and orthopyroxene grains. This texture suggests the replacement of hornblende by pyroxenes, by dehydration reactions such as (2a, b). The absence of garnet in the meta-volcanic rocks is notable and may be due, for example, to a lower bulk (Fe / Fe + Mg) ratio of the mafic volcanic protolith in comparison with that of garnet amphibolites described above.

Metapelite

Metapelites are abundant in the Shawinigan domain and are mineralogically and texturally similar to those occurring in the Mékinac domain, with a few exceptions. On the basis of mineralogy and texture, the metapelites can be divided into three groups. Group "I" metapelites are by far the most abundant, and are represented in this study by samples *S-275* and *S-12*. They consist of *grt*—*Kfs*—*sil*—*bt*—*pl*—*qtz* $\pm$ *rt* $\pm$ *gr* $\pm$ *py*. Garnets are characteristically light pink, 5—20 mm in diameter, and have inclusion-rich cores (Fig. 3.5f). Small rutile, quartz, and plagioclase inclusions are concentrated in the garnet core area. Rare spinel have also been observed as inclusions in garnet. Fibrolite inclusion trails outlining a fine crenulation record an earlier stage in metamorphism and regional deformation (Fig. 3.6a). Coarse sillimanite prisms, which form up to 40% of the rock volume, are parallel to the regional E-SE plunging stretching and mineral lineation. They typically bend around garnet porphyroblasts and are pulled-apart into segments. Some sillimanite prisms, as well as perthitic K-feldspar, are included by garnet, suggesting that these minerals grew during the main regional tectonometamorphic event. Biotite is not an abundant phase in this assemblage (5—15%), and is more concentrated in garnet pressure shadows where it nucleated as a late syn-tectonic phase along with plagioclase and quartz (Fig. 3.6b). In the matrix, earlier biotite is strongly embayed and

shows evidence of replacement by prismatic sillimanite and microperthite, perhaps by the following reaction:

In sample *S-12*, biotite growing in garnet pressure shadows with plagioclase and quartz may have formed by a retrograde reaction such as:

The breakdown of garnet to produce biotite, plagioclase, and quartz occurs even in circumstances where garnets are physically isolated from matrix K-feldspar, suggesting ionic reactions involving K^+ , and vapor. Rutile, which does not participate in this retrograde reaction, is simply liberated from the reacting garnet and incorporated with the products.

The high-grade assemblage *opx—sil—grt—bt—Kfp (perthite)—pl—qtz* has been observed in one sample only (*S-276*). This rock has undergone minor ductile deformation at lower amphibolite facies, but orthopyroxene, garnet, and sillimanite porphyroblasts have remained stable.

Group II metapelites are much less abundant than group-I, and contain the assemblage *crd—grt—bt—pl—qtz* $\pm$ *Ksp (perthite)* $\pm$ *sil* $\pm$ *opx* $\pm$ *spl*. In contrast to the uniform size and rounded shape of garnets from group-I metapelites, those from group-II are idiomorphic and tend to be much smaller (≤ 5 mm). In sample *S-205*, resorbed orthopyroxenes are found in the matrix with biotite, plagioclase, and quartz. Some orthopyroxene grains are also found as inclusions in garnet, where they are ubiquitously replaced by chlorite (Fig. 3.6c). Cordierite occurs either as inclusion blebs in garnet and plagioclase, or as matrix grains along with biotite. Cordierite and orthopyroxene grains are not in mutual contact. Sillimanite is absent from orthopyroxene- and cordierite-bearing domains. Where present, it occurs as fibrolitic bundles replacing biotite. Perthite is always associated with fibrolite, and is absent from *crd—opx* assemblages. Idiomorphic

garnet porphyroblasts statically overprint a very weak foliation outlined by orthopyroxene streaks and biotite.

The above textures suggest that an earlier orthopyroxene-cordierite assemblage was replaced by garnet by the following retrograde reaction:

The assemblage stable on the high-temperature side of these reactions, $\text{opx} + \text{crd}$, has been described from thermal aureoles (Chinner 1962; Berg 1977) and, more rarely, from regionally metamorphosed granulite terrains (Vielzeuf 1980).

Group-III metapelites are highly migmatitic, with magnesium and aluminium-rich restites, and are generally much richer in biotite than the previous two groups. In thin section, biotite has a distinctive reddish-brown colour which contrasts with the paler brown colour of group-I and group-II biotites. The characteristic assemblage is $\text{grt} - \text{bt} - \text{pl} - \text{ilm} \pm \text{Ksp} \pm \text{qtz} \pm \text{spl} \pm \text{crn} \pm \text{rt}$. Restites are generally biotite-rich and contain either corundum or spinel, or both. Spinel and ilmenite have been locally observed as ≤ 1 mm blebs within granoblastic plagioclase aggregates that are surrounded by a rim of small idioblastic garnet. Group-III metapelites all contain a large proportion of alteration products such as fine-grained chlorite, and locally calcite, and can only be used qualitatively. Microdomains shows textural equilibrium between garnet, spinel, corundum, and plagioclase, suggesting high temperatures of metamorphism.

Marble and calc-silicate gneiss

Marble and calc-silicate gneisses are found throughout the Shawinigan domain, interlayered with metapelites, or tectonically injected into adjacent gneisses. They are either white or orangy-pink, depending on the amount of manganese substitution in calcite (Deer et al. 1966). The marbles are generally coarse-grained and granoblastic, but some samples contain rounded porphyroclasts of silicate minerals in a fine-grained,

recrystallized carbonate matrix. The most common assemblage is $cal-di-qtz-scp \pm tr \pm grs \pm wo \pm phl \pm Kfs \pm ttn$. Granoblastic aggregates of diopside and quartz are common and are locally found with scapolite. Grossular occurs either as isolated matrix grains, or forms thin rims surrounding scapolite-quartz aggregates. Wollastonite has been observed in one quartz-free sample, where it replaces diopside. The almost exclusive presence of quartz in contact with diopside suggests that diopside may have been formed by the following prograde reaction:

giving rise, with the complete consumption of tremolite, to the observed assemblage. The absence of forsterite can be explained either by the absence of dolomite or by the relatively silica-rich composition of Shawinigan domain marbles (e.g. Trommsdorf 1972). Tremolite has only been observed in one sample (S-355), where it is partially replaced by diopside. In mylonitic marble, microperthite porphyroclasts are separated from the calcite matrix by vermicular scapolite. Plagioclase exsolved from K-feldspar may have reacted with calcite and quartz to produce scapolite. Reaction (9) is characteristic of uppermost-amphibolite to granulite-facies metamorphic conditions.

3.3.3 Portneuf—St. Maurice domain

Supracrustal rocks of the Portneuf—St. Maurice domain form two physically separate strands that outcrop on either side of the Gagnon pluton (Fig. 3.2). Both strands are composed of compositionally similar volcanic, volcanoclastic, and sedimentary rocks, but contain different metamorphic assemblages. The western strand is characterized by lower to middle amphibolite-facies assemblages. In contrast, the eastern strand locally contains assemblages characteristic of high-temperature, low- to medium-pressure metamorphism (i.e. low-pressure granulite).

3.3.3a Western strand

Metapelites

True metapelites are relatively rare in the western strand, metapsammites forming the most common lithology. Because of their metamorphic significance, only aluminosilicate- and garnet-bearing rocks will be described here. Most of the metasedimentary rocks observed in the field are fine-grained and partially preserve their original sedimentary structures. This contrasts sharply with the thoroughly recrystallized and migmatitic metasedimentary rocks of the Mékinac and Shawinigan domains. The typical mineral assemblage is $grt\text{---}bt\text{---}pl\text{---}qtz \pm sil \pm Kfs \pm ilm \pm py$, with accessory zircon and apatite. Graded bedding, now inverted by the growth of garnet and biotite in the fine-grained “pelitic” layers, is locally preserved, as in sample *PSM-253* (Figure 1.4). Garnet and sillimanite are more concentrated in the “pelitic” layers. Garnets are usually small (≤ 1 mm), idiomorphic, and contain numerous plagioclase, quartz, and biotite inclusions (Fig. 3.6d). Sillimanite occurs uniquely as fibrolite bundles that are contained within the foliation plane, and are parallel to the regional, easterly-plunging lineation. In tightly folded outcrops, fibrolite forms disk-shaped bundles lying within the fold axial plane, suggesting syn-tectonic growth (Sample *PSM-111*; Fig. 3.6e). Microcline is a common constituent in fibrolite-bearing rocks, but is also present in fibrolite-free assemblages, suggesting that it is not necessarily the product of muscovite breakdown. Biotite is usually small, sub-idiomorphic, and outlines the moderately to strongly developed foliation. They are reddish-brown in thin section, but those included by garnet are greenish-brown. Rutile, which is common in the Mékinac and Shawinigan domains, has not been observed in metapelites from the Portneuf—St. Maurice domain, where the stable Ti-bearing oxide is ilmenite. The above textures suggest that regional deformation was accompanied by peak metamorphism at conditions of low- to middle-amphibolite facies.

Metagreywacke and amphibolite

Metapelites and metapsammites are interlayered with fine-grained metasedimentary rocks of intermediate composition, interpreted as metagreywacke. These rocks are texturally similar to the metapelites described above, but do not contain aluminosilicates. Instead, they contain blue-green hornblende, and garnet porphyroblasts. The matrix consists of biotite, plagioclase, microcline, and quartz. Epidote has been locally observed. Hornblende and garnet porphyroblasts occur in biotite-absent knots, together with plagioclase and quartz (Fig. 3.6f). The anorthite content of plagioclase is relatively high (An_{49}) for rocks of intermediate composition. However, assuming that chlorite was part of the reactant phases, the high An-content of plagioclase can be explained by the following end-member reaction proposed by Cooper (1972):

In some samples, hornblende inclusions are found in garnet, suggesting that garnet either grew at the same time as, or after hornblende. The coexistence of blue-green hornblende, garnet, and epidote has been noted from regions metamorphosed under lower- to middle-amphibolite facies (e.g. Graham 1974; Raase et al. 1986).

Amphibolites form concordant layers up to a few metres thick. In the absence of unequivocal evidence, it remains unclear whether they were originally sills, or mafic volcanic flows. They are fine to medium grained, foliated, and contain the assemblage $\text{hbl-pl-bt-qtz-mag} \pm \text{tn}$. Yellowish-green hornblende laths, together with minor biotite, define the foliation. Plagioclase (An_{56}) occurs either as inclusions in hornblende or as $\leq .05$ mm granoblastic matrix grains. Where present, titanite forms thin rims on ilmenite. Pyroxenes have not been observed in mafic gneisses from the eastern strand.

Calc-silicate gneiss

Layers of calc-silicate gneiss up to 10 cm thick are locally found within the metasedimentary and volcanoclastic gneisses of the Montauban Group. They are typically fine grained, with an epidote-rich outer margin giving a pale green colour, and a grossular-rich centre producing a light orange colour. Because of their relatively more competent rheology in comparison with associated gneisses, they commonly form folded boudin trains. The mineral assemblage is a granoblastic mosaic of *qtz—grs—ep—ser—hbl—cal*. Plagioclase from adjacent gneiss is progressively sericitized towards the calc-silicate layers, and is totally sericitized within a 1 cm thick band along the contact. Within the calc-silicate layer, plagioclase is absent, being totally replaced firstly by sericite, and secondly by garnet and epidote. The latter contain numerous sericite inclusions. The transition between the grossular-rich centre and the epidote-rich rim is very abrupt, and the two minerals appear to be in textural equilibrium at their mutual contact. Quartz is present throughout, as well as minor calcite. A small amount ($\leq 5\%$) of light green hornblende is present in the epidote-rich band. Scapolite, which is common in calc-silicate gneisses of the Mékinac and Shawinigan domains, is absent from this assemblage.

Peraluminous pegmatite

The structural base of the western strand of the Montauban Group contains a zone approximately 1 km wide where abundant peraluminous pegmatites are found. They occur as small pods and dykes, and are composed of orthoclase, plagioclase, quartz, muscovite, biotite, garnet, and locally, fibrolite. They have been interpreted as minimum granite melts produced in-situ (Chapter 1), from the partial melting of the host rocks. Field relationships and U-Pb monazite geochronology suggest that they were formed during oblique extension, at ca. 1055 Ma (Chapter 2).

3.3.3b Eastern strand

Metapelites

Metapelites are also rare in the eastern strand, where the most common metasedimentary rock is garnet-biotite gneiss. The metapelites are locally associated with rocks of orthopyroxene-anthophyllite-cordierite composition. One sample (*PSM-LROB*) has been studied in detail because it contains informative reaction textures. It is a medium- to fine-grained metapelite with the composition *spl—qtz—grt—crd—sil—pl—bt—ilm*, with minor apatite, monazite, and zircon. Cordierite forms porphyroblasts up to 2mm in diameter, as well as thin rims around garnet. Some cordierite porphyroblasts are almost free of inclusions, enclosing only a few sillimanite needles. Others form knots with equal proportions of randomly oriented biotite laths and sillimanite prisms, with or without spinel (Fig. 3.7a). Cordierite rims around garnet are generally not continuous, and these also contain randomly oriented sillimanite and biotite. Most of the garnet overprint fibrolite mats that are aligned parallel to the matrix foliation. Some garnets are sub-idiomorphic, while others are almost entirely consumed by cordierite-biotite-sillimanite knots. Plagioclase porphyroblasts are abundant and contain conspicuous sillimanite ($\pm$ spinel) inclusions that have grown parallel to crystallographic planes. Fine-grained spinel (5—100 μ) is locally stable with quartz, but predominantly occurs as scattered xenomorphic grains enclosed by matrix sillimanite, or by cordierite-biotite-sillimanite knots. Most of the biotite occurs as small matrix grains that define the foliation. K-feldspar has not been observed in this assemblage.

Garnet and sillimanite are interpreted as part of the peak metamorphic assemblage. A later retrograde metamorphic reaction produced cordierite-biotite-sillimanite (or spinel) knots at the expense of garnet. Staurolite may also have been part of an earlier assemblage, since spinel contains an appreciable amount of zinc ($\text{spl}_{20} \text{hc}_{55} \text{gah}_{24}$), and gahnite-staurolite is a common assemblage in Zn-rich rocks (Nichols et al. 1992). The

assemblages described above are diagnostic of high-temperature, low to medium-pressure metamorphism (i.e. low-pressure granulite), indicating that the metamorphic grade in the eastern strand is higher than that in the western strand.

3.3.4 Tawachiche shear zone

Syn-oblique extension metamorphic assemblages in the Tawachiche shear zone are retrograde with respect to earlier peak metamorphic assemblages. Fabrics within each shear zone strand vary from thin ultramylonite bands to broad zones containing shear bands and C-S planes (i.e. Berthé et al. 1979). Rocks of both the Shawinigan and Portneuf—St. Maurice domains are reworked in the Tawachiche shear zone.

Garnet-biotite bearing paragneiss

Secondary muscovite and sericite are found in all rocks of suitable composition. Muscovite replaces both biotite and microcline, and grows as coarse isolated grains. The latter either randomly overprint the foliation, or form mica “fish” structures (e.g. Lister and Snoke 1984), suggesting that retrograde metamorphism accompanied and slightly postdated D₂ deformation (Fig. 3.7c). Biotite is also locally replaced by chlorite, although only to a minor and very local extent. In mylonites and ultramylonites, both biotite and hornblende (where present) are recrystallized to $\leq 10 \mu$ grains, but are nonetheless stable. Garnet porphyroclasts have chlorite—biotite pressure shadows (Fig. 3.7d), likely a product of its metamorphic breakdown. Plutonic rocks and orthogneisses of more intermediate composition contain sericite after plagioclase, as well as epidote. In Shawinigan domain lithologies, perthite porphyroclasts are mantled by microcline, the low-temperature feldspar polymorph (Deer et al. 1966).

The relationships between mineral assemblages and fabrics presented above suggest that metamorphic facies were at the amphibolite-greenschist transition during oblique

strike-slip shearing. Retrograde metamorphism affected both the Shawinigan and PSM domain, as well as parts of the Mékinac domain, although to a much lesser extent.

3.4 *P-T* CONDITIONS OF METAMORPHISM AND *P-T* VECTORS

Various independent conventional thermobarometers and the TWEEQU thermobarometry program (Berman 1991) were applied to evaluate the *P-T* conditions of metamorphism. In addition, reaction textures were used to interpret the direction of progressive change of *P-T* conditions. Samples with appropriate compositions for thermobarometry were selected predominantly from the Shawinigan and PSM domains, because of the marked difference in metamorphic facies observed between these two crustal blocks, on either side of the oblique extensional Tawachiche shear zone. Thermobarometry was also performed on one sample from the Mékinac domain, and one from the eastern strand of the Montauban Group in the Portneuf—St. Maurice domain, in order to compare results with previously published *P-T* estimates.

3.4.1 Approach to *P-T* determinations, and thermobarometric uncertainties

The primary goal of quantitative thermobarometry in this study is to determine the peak pressures (*P*) and temperatures (*T*) achieved during metamorphism along the Mauricie transect, with an emphasis on the recorded *P* and *T* on either side of the Tawachiche shear zone. These new data are meant to verify or complement the few published quantitative thermobarometric estimates available for the Mauricie transect. Samples showing the best preserved state of textural equilibrium, and the largest grain sizes, were selected for thermobarometry. Detailed petrography provided evidence for metamorphic reactions, which provided a basis for the selection of appropriate thermometers and barometers.

Garnets from two metapelitic rocks from the Shawinigan domain, and two others from the western strand of the Montauban Group, were analyzed with the electron microprobe in order to test for elemental zoning. Results of the microprobe traverses, performed on garnets isolated from other ferromagnesian minerals, are shown in Appendix 3.1.1. All four samples show evidence of homogenization by volume diffusion, a feature commonly observed in garnets subjected to metamorphic temperatures ca. 650 °C (Woodsworth 1977; Tracy 1982). Both samples from the Shawinigan domain (*S-275* and *S-12*), and sample *PSM-111* from the Portneuf—St. Maurice domain, show evidence of retrograde zoning (Tracy et al. 1976). Near-peak *P-T* estimates for each of the pelitic samples were calculated from representative analyses of garnet porphyroclasts near-rim plateau compositions, and cores of matrix ferromagnesian grains isolated from garnet by non-ferromagnesian phases. This should minimize the effect of retrograde exchange between ferromagnesian phases in contact (e.g. Tracy et al. 1976; Spear and Florence 1992). In samples of mafic and intermediate composition, cores of ferromagnesian phases and of plagioclase were utilized for calculating *P-T* estimates. In each thin section analyzed, at least 10 well-spaced microprobe analytical points were obtained on at least one of each ferromagnesian phase selected for thermobarometry. Then, rim and core analyses were obtained on at least two other isolated grains of each species, to test for chemical equilibrium at the scale of the thin section. Chemical equilibrium was assumed if the difference in chemical composition between different grains in a given thin section did not exceed 1.00 wt%. One sample (*S-12*) partially reequilibrated during W-NW-directed thrusting, according to the retrograde reaction (7) described above. In this sample, garnet rim compositions and new biotite and plagioclase from the pressure shadow were utilized for thermobarometry.

The difficulty in obtaining peak *P* and *T* estimates in uppermost amphibolite to granulite facies rocks has been addressed by many workers (e.g. O'Hara 1977; Tracy

1982; Lasaga 1983; Frost and Chacko 1989; Spear and Florence 1992; Pattison and Bégin 1994). Due to the high metamorphic grades attained during peak metamorphism, constituent minerals may have reequilibrated with one another during post-metamorphic cooling (e.g. Lasaga 1983; Essene 1989). For example, net transfer reactions between garnet and plagioclase are more sluggish than those involving Fe—Mg exchange between garnet and biotite (e.g. Ghent et al. 1988; Frost and Chacko 1989; Harley 1989). Consequently, the garnet-biotite-plagioclase-aluminosilicate barometer (e.g. Ghent 1976), and the garnet-biotite thermometer (e.g. Thompson 1976), for example, may not close at the same temperature, leading to erroneous P - T interpretations. Some workers have assumed that overall consistency in pressure and temperature estimates between a wide range of equilibria in a given granulite terrane may signify that peak conditions are preserved (e.g. Bohlen et al. 1985; Perkins 1991). Conversely, a wide scatter in P and T values may indicate that different mineral pairs quenched-in at different metamorphic conditions, and record various steps along the cooling path.

All samples selected for conventional thermobarometry, except those selected for Al-in-hornblende barometry (Hammarstrom and Zen 1986) were also utilized for TWEEQU thermobarometry (Berman 1991). This program, which utilizes an internally consistent thermodynamic database, calculates an average pressure and temperature using all possible equilibria for a given mineral assemblage. Non-ideal mixing is assumed for garnet, plagioclase, biotite, and amphiboles (Berman 1991). Ideal two-site mixing for ortho- and clinopyroxene is modelled using the approach of Newton (1983). When utilizing the TWEEQU program, pressure and temperature of formation of mineral assemblages was estimated from the intersection of two or more reaction curves. For equilibria involving three or more reaction curves, chemical equilibrium between participating phases was assessed from the degree of dispersion of intersections between the different curves. A P - T estimate was considered valid if the standard deviation was

less than ± 0.5 kb and ± 20 °C (Berman 1991). The uncertainties of P - T estimates in conventional geothermobarometers are greater. Most uncertainties quoted by the authors for the thermometers and barometers utilized in this study are in the order of ± 25 — 50 °C and ± 0.5 — 2.0 kb. In this study, the combination of one or more conventional thermobarometer (when possible) with the internally consistent TWEEQU formulation provides a more rigorous means to evaluate calculated results, and to test for consistency of P - T estimates. The standard deviations calculated by the TWEEQU program provide a basis to assess the equilibration state of samples, but do not represent statistically valid uncertainties (Berman 1991). For this reason, the uncertainties quoted herein are ± 50 °C and ± 1 kb, which more realistically reflect the "absolute" pressure and temperature of equilibration (e.g. Essene 1989).

Representative mineral analyses from samples used in thermobarometry are presented in Appendix "3.2", and a summary of P - T results is shown in Table 3.2.

3.4.2 Analytical methods

Quantitative electron microprobe analyses were obtained on all samples on polished thin sections. Mineral analyses were performed on a Cambridge "Microscan 5" electron microprobe at the Department of Earth Sciences, Carleton University. Instrumentation consisted of a energy-dispersive X-ray spectrometer operating with a beam current of 3.0 nA, 20 kV accelerating voltage, and a beam size of 1—2 μ m. X-ray spectra data were reduced to elemental weight percentages using the program EDDI (Pringle 1989). A variety of calibrations based on natural and synthetic mineral standards were used for different mineral species analyzed. Analytical precision was randomly tested on standard samples of known composition. Results for each cation were consistently within 0.02 wt% of the analyzed standards.

3.4.3 Conventional thermobarometers

Temperatures

Temperature estimates for metapelites were obtained using the garnet-biotite (GARB) thermometer of Ferry and Spear (1978), after a correction for Mn and Ca substitution in garnet (Ganguly and Saxena 1984) was applied. In cordierite-bearing samples, the garnet-cordierite thermometer of Bhattacharya et al. (1988) was applied. For rocks of intermediate and mafic composition, temperatures were determined using the Ellis and Green (1979), and Ganguly (1979) garnet-clinopyroxene Fe—Mg exchange thermometers. In orthopyroxene-bearing granulites, the garnet-orthopyroxene Fe—Mg exchange thermometers of Harley (1984) and Powell (1978) were used. For samples containing garnet and hornblende in textural equilibrium, the garnet-hornblende Fe—Mg exchange thermometer of Graham and Powell (1984) was used. In all calibrations utilizing garnet and pyroxene, calculated Fe^{2+} values were used (Spear 1993).

Various thermometers were applied to core compositions of the intermediate composition granulite sample *M-302* from the Mékinac domain. The lowest temperatures (600 and 688 °C) were obtained from different calibrations of the *grt-opx* Fe-Mg exchange thermometer (Table 3.2). Higher temperatures (766 to 879 °C) were obtained from *grt-cpx* Fe-Mg exchange thermometers. The lower temperature obtained from *grt-opx* thermometers may reflect the textural disequilibrium shown by orthopyroxene in this sample, which seems to occur as relic igneous grains. Garnet and clinopyroxene are prograde reaction products, and may be better representatives of the peak metamorphic assemblage.

Core compositions of a mafic granulite (*S-355*), and a metapelitic rock (*S-275*), were used to obtain peak temperature estimates from the Shawinigan domain. In the mafic granulite, values obtained from *grt-opx* thermometers are 652 and 716 °C, and those obtained from *grt-cpx* thermometers range from 719 to 841 °C. The wide range of

temperatures obtained from this sample may reflect the variable effects of post-peak Fe-Mg exchange between garnet and other ferromagnesian phases (e.g. Pattison and Bégin 1994). However, as will be seen below, garnet-pyroxene equilibria obtained using the internally consistent thermodynamic database of TWEEQU are tightly constrained, suggesting that the problem may be with the estimation of solution or activity models in conventional thermometers. The Ferry and Spear (1978) garnet-biotite thermometer applied to the well-equilibrated metapelite sample *S-275* yielded a temperature of 858 °C, in agreement with the temperatures obtained from the Ganguly (1979) *grt-cpx* thermometer for Mékinac and Shawinigan domain samples.

Calculated temperatures in three samples from the western strand of the Montauban Group in the Portneuf—St. Maurice domain are consistently lower than those obtained from the Shawinigan and Mékinac domains. They are consistent with the observed metamorphic facies, and range from 540 to 616 °C. Garnet-hornblende thermometry on a metavolcanic rock (sample *PSM-241*) yields a temperature of 616 °C, in accord with garnet-biotite thermometers. By contrast, the temperatures calculated from sample *PSM-LROB* from the eastern strand are significantly higher, with GARB thermometers yielding a value of 734 °C with the formulation of Ferry and Spear (1978). The garnet-cordierite thermometer of Bhattacharya et al. (1988) yields a slightly higher temperature (758 °C).

Pressures

Pressures in metapelites were determined using the Newton and Haselton (1981) calibration of the *grt—sil—pl—qtz* (GASP) barometer. Pressures in cordierite-bearing assemblages were estimated by applying the garnet-spinel barometer of Nichols et al. (1992). The latter has been experimentally calibrated to account for the activity of gahnite in spinel coexisting with garnet and cordierite. Pressures in the mafic to intermediate

rocks were determined using the *gt—opx—pl—qtz* barometer of Bohlen et al. (1983), the *gt—opx* barometer of Harley and Green (1982), and the *cpx—pl—qtz* barometer of Ellis (1980). There has been considerable debate on the validity of thermobarometers based on Fe—Mg exchange reactions in high-grade metamorphic rocks (Spear and Florence 1992; Pattison and Bégin 1994). However, experimental results on synthetic and natural samples suggest that the diffusion of Al in pyroxenes is significantly slower than the diffusion of Fe—Mg (Anovitz et al. 1991; Pattison and Bégin 1994). Therefore, barometers based on Al solubility in orthopyroxene (e.g. Harley and Green 1982; Harley 1984) were used for comparison. The Al-in-hornblende barometer of Hammarstrom and Zen (1986) was used on a ca. 1.40 Ga plutonic rock of appropriate composition from the Portneuf—St. Maurice domain (sample *PSM-327*), in order to estimate its depth of emplacement.

Most of the conventional barometers applied to sample *M-302* from the Mékinac domain yielded more elevated pressures than those obtained from sample *S-355* from the Shawinigan domain, in agreement with its deeper structural position. The different barometers applied to sample *M-302* yielded pressures ranging from 7.7 to 12.9 kb (Table 3.2). The same barometers applied to sample *S-355* yielded pressures ranging from 7.5 to 10.2 kb. The Al-solubility barometers of Harley and Green (1982) and Harley (1984) did not systematically yield higher pressures, which instead were obtained with the *cpx—pl—qtz* barometer of Ellis (1980). This barometer, based on the reaction $\text{Anorthite} = \text{CaTs} + \text{Qtz}$, is independant of Fe-Mg exchanges, and is therefore less susceptible to reequilibration.

The GASP barometer (Newton and Haselton 1981) applied to the metapelite sample *S-275* from the Shawinigan domain yielded a pressure of 8.5 kb, in agreement with the high values obtained with barometers involving pyroxene. In contrast, calculated pressures from the western strand of the Portneuf—St. Maurice domain are significantly

lower, with two samples yielding values of 4.0 and 5.4 kb with the GASP barometer. Slightly higher pressures were obtained from the eastern strand of the Montauban Group from sample *PSM-LROB*, with the GASP barometer yielding 7.1 kb, and the grt-spl barometer of Nichols et al. (1992) yielding 6.3 kb. The Al-in-hornblende barometer (Hammarstrom and Zen 1986) was applied to a pluton belonging to the ca. 1.40 Ga La Bostonnais suite (sample *PSM-327*; Fig. 3.3). This quartz-diorite pluton, which is metamorphosed but preserves igneous hornblende, yielded a calculated pressure of 5.4 kb, interpreted as its corresponding depth of emplacement (~ 16 km). This pressure estimate is compatible with those recorded by surrounding Montauban Group metasedimentary rocks.

Retrograde P-T estimates

The GASP barometer and GARB thermometer applied to garnet rims and adjacent biotite and plagioclase from pressure shadows in a syn-thrusting mylonitic metapelite (sample *S-12*), yielded *P-T* estimates of 4.5 kb and 510 °C (Table 3.2). The peak metamorphic assemblage in this rock comprises garnet, rutile, perthite, and prismatic sillimanite, suggesting that earlier metamorphic conditions were high grade, perhaps as high as recorded in sample *S-275* (836 °C, 7.6 kb). The low values calculated from rim compositions are consistent with the syn-thrusting retrograde assemblage, and confirm that both the pressure and temperature were decreasing during W-NW-directed thrusting. It is interesting to point out the similarity in pressure and temperature values obtained in retrograde syn-thrusting mylonites in the Shawinigan domain, and peak *P-T* conditions in the Portneuf—St. Maurice domain.

3.4.4 TWEEQU thermobarometry

Pressure and temperature estimates on the samples discussed above were also obtained using the TWEEQU program of Berman (1991). This program calculates end-member reactions and plots their location in P - T space, using the up-graded thermodynamic data of Mäder and Berman (1992) for amphibole end-member phases, and the solution models of Berman (1990), Fuhrman and Lindsley (1988), and McMullin et al. (1991) for garnet, plagioclase, and biotite, respectively. Pressures and temperatures are determined from the intersection of two (preferably three) or more independent reactions in P - T space (Berman 1991), with an intersection comprising three or more curves regarded as acceptable if its standard deviation is less than ± 0.5 kb and ± 25 °C.

The end-member phases used in calculations for mafic and intermediate granulites were *ab-an-alm-py-grs-di-hd-en-fs-qtz*. The assemblage *ab-an-alm-py-grs-tr-Fetr-ts-Fets-pa-Fepa-qtz* was used for samples containing hornblende and garnet, with or without pyroxene. Average core compositions from texturally equilibrated sub-domains were used. It should also be noted that quartz ($a_{\text{SiO}_2} = 1$) was included in the TWEEQU calculation for sample *S-355*, even though it was not observed in thin section. As explained earlier, the partial replacement of garnet by [opx + pl] according to reactions (5a) and (5b) suggests that quartz may have been present in the peak metamorphic assemblage before being completely consumed by these retrograde reactions.

In metapelites, two different sets of end-member compositions were used depending on the mineral assemblages present. In the high-grade samples from the Shawinigan domain, P - T estimates were determined using the assemblage *ru-alm-py-grs-ann-phl-an-sil-qtz* for core compositions (sample *S-275*), and *alm-py-grs-an-ann-phl-sil-qtz* for rim compositions (sample *S-12*). The latter assemblage was also used for rutile-absent metapelites from the southeastern strand of the Montauban Group (*PSM-111* and *PSM-*

253). In cordierite-garnet-spinel assemblages (sample *PSM-LROB*), the end-member phases used were *alm-py-grs-Fecrd-Mgcrd-hc-an-qtz*. Hydrous cordierite was selected because analytical results show an appreciable amount of volatiles, assumed to be hydrous rather than anhydrous (CO₂-bearing). Results of pressure and temperature estimates derived from TWEEQU thermobarometry are shown in Table 3.2. Mineral equilibria used in TWEEQU calculations are shown in Table 3.3.

Mékinac and Shawinigan domains.

Pressures and temperatures obtained from TWEEQU thermobarometry range from 7.5 to 9 kb and 705 to 836 °C, and are generally lower than those obtained from conventional methods. Sample *M-302* from the Mékinac domain yielded a tight cluster of reaction intersections, giving a *P-T* estimate of 9.0 kb and 705 °C (Fig 3.9a). Diopside was excluded from the phase assemblage because equilibria involving this phase invariably fell outside of the intersections defined by other reactions. In fact, there is evidence of textural disequilibrium in clinopyroxene, such as small ilmenite exsolution lamellae, that may sufficiently alter the original Fe/(Fe + Mg) ratio of this phase. However, equilibria involving hedenbergite are compatible with other reactions that exclude clinopyroxene, suggesting that the spurious results involving diopside may reside in assumptions regarding ideal solution models (Berman 1991). Therefore, the *P-T* values recorded without diopside are interpreted to best represent actual conditions of metamorphism. However, the *P-T* estimate places this sample in the stability field of kyanite, even though sillimanite was the only aluminosilicate polymorph observed in the entire region. This suggests that although the calculated pressure estimate may be adequate, the calculated temperature may be too low.

Likewise, TWEEQU thermobarometry in Shawinigan domain samples give slightly lower values than those obtained from conventional methods, but shows consistency

between metapelitic and mafic assemblages. Core garnet compositions and matrix plagioclase and biotite from metapelite sample *S-275* yield an excellent fit, with three independent reactions intersecting at 7.5 kb and 836 °C (Fig. 3.9b), in agreement with the observed high-grade mineral paragenesis. In contrast, mafic granulite sample *S-355* yielded more spurious results. This was not unexpected, given the evidence of textural disequilibrium such as plagioclase rims surrounding garnet, and two generations of garnet growth. However, there is no notable compositional difference between matrix and rim plagioclase, nor between garnet₁ and garnet₂, and reactions involving phases in local textural equilibrium yield “reasonable” results. TWEEQU thermobarometry excluding hornblende and diopside yields a *P-T* intersection involving three independent reactions at 7.6 kb and 782 °C (Fig. 3.9c).

Compositions of garnet rims, and the core compositions of biotite and plagioclase from pressure shadows in a mylonitic, syn-thrusting metapelite (*S-12*) were used in TWEEQU thermobarometry to estimate the *P-T* conditions during the late stage thrusting. A total of eight different equilibria involving three independent reactions yielded an intersection with a small amount of scatter at approximately 3.2 ± 0.4 kb and 478 ± 22 °C (Fig. 3.9d), interpreted as the *P-T* conditions of final equilibrium in this mylonite. These values contrast with near-peak estimates of 7.5–7.6 kb and 782–836 °C obtained from non-mylonitic rocks from approximately the same structural level in the Shawinigan domain.

Portneuf—St. Maurice domain.

TWEEQU thermobarometry on three samples from the western strand of the Montauban Group yields pressure and temperature estimates that are markedly distinct from those of the underlying Mékinac and Shawinigan domains (Fig. 3.10). Two metapelites (samples *PSM-111* and *PSM-253*) yielded pressures of 3.4 and 4.9 kb,

respectively, and a metasedimentary rock of intermediate composition (*PSM-241*) yielded a pressure of 3.2 kb. Temperatures from these three samples were 638, 546, and 544 °C, respectively. The low number of phases in the two metapelitic samples permitted only two linearly independent reaction curves to be plotted. However, the intersection of these curves yielded identical temperatures, within error, but slightly lower pressures (up to 0.6 kb) as those obtained from conventional thermometers.

The *grt-crd-spl-sil-bt-pl-qtz* sample from the northeastern strand of the Montauban Group (*PSM-LROB*) yielded highly scattered reaction curves in *P-T* space when hercynite and spinel were included in the phase assemblage. However, phase equilibria involving only the major metamorphic phases *grt-crd-bt-pl-sil-qtz*, and excluding the grossular end-member, yielded a tight cluster of reaction curve intersections with three independent reactions at 6.4 ± 0.3 kb and $758 \pm 5^\circ\text{C}$ (Fig. 3.10d). These values are similar to those obtained by conventional thermobarometry. The spurious results obtained by including spinel may be either due to its persistence as a relict phase in chemical disequilibrium with the main metamorphic assemblage, or to uncertain thermodynamic properties due to its high zinc content ($X_{\text{gahnite}} = 0.24$). Grossular also yields erroneous results when added to the phase assemblage, perhaps due to its minute amount in garnet ($X_{\text{grs}} < 0.01$), and the long extrapolation necessary to determine its activity.

3.4.5 Summary of calculated *P-T* estimates, constraints from the petrogenetic grid, and timing of peak metamorphism

A model petrogenetic grid applicable to the mineral assemblages of the Mauricie transect is presented in Figure 3.8. A summary of calculated *P-T* estimates derived from this study and from other published data is presented in Figure 3.11, together with the estimated timing of peak metamorphism (Chapter 2). Reaction curves and invariant points involving sapphirine, spinel, garnet, orthopyroxene, cordierite, biotite, and quartz,

are after Goscombe (1992). Although the absolute position of reaction curves is strongly dependent on bulk composition and can vary in P - T space, their slopes are less susceptible to change (Goscombe 1992), and can therefore be used to monitor the direction of P - T evolution in a given sample. The position of the $\text{opx} + \text{pl}$ breakdown reaction in P - T space was derived from TWEEQU equilibria from sample *S-355*. The K-feldspar solvus curve is after Thompson and Tracy (1979), and provides a useful estimate of minimum pressures and temperatures attained in the Mékinac and Shawinigan domains, where perthitic K-feldspar is ubiquitous. The muscovite + quartz breakdown reaction (Helgeson et al. 1978) provides an upper temperature limit for rocks of the western strand of the Montauban Group, which locally contain primary muscovite, but also show evidence that the above reaction locally occurred (i.e. *PSM-111*). The aluminosilicate stability fields are after Holdaway (1971).

Although most calculated P - T estimates in this study are consistent with constraints imposed by the petrogenetic grid, peak temperatures appear to have been underestimated in some samples. The absence of kyanite and andalusite restricts metamorphic conditions in the western strand of the Montauban Group to the sillimanite stability field. The muscovite-quartz breakdown reaction provides a maximum temperature limit for this part of the Mauricie transect. P - T estimates derived from TWEEQU from samples *PMS-111*, *PSM 241*, and *PSM-253* range from ~ 3.2 to 4.9 kb and 560 to 640 °C. The uppermost range of calculated pressures and temperatures (~ 5 kb and 640 °C) is interpreted as the approximate maximum pressure and temperature attained in the western strand of the Montauban Group. In the southern part of the western strand near the village of Montauban (Fig. 3.3), Bernier and MacLean (1993) obtained calculated pressures and temperatures of 4.5 — 6.5 kb and 550 — 620 °C, in agreement with the above values (Fig. 3.11). Similar, but slightly higher pressures and temperatures (5 — 6 kb and 610 — 668 °C) are reported from the same region by Lévesque and Nadeau (1994) (Fig. 3.11).

TWEEQU thermobarometry applied to sample *PSM-LROB* from the eastern strand of the Portneuf—St. Maurice domain yielded P - T values of 6.4 kb and 758 °C, in agreement with the observed mineral paragenesis in this part of the research area (i.e. absence of primary muscovite). Pressures and temperatures reported from Lévesque and Nadeau (1994) range from 5.7—6.6 kb and 678—740 °C (Fig. 3.11), and are consistent with the values obtained in this study.

Peak pressures and temperatures attained in the Shawinigan domain are well represented by samples *S-275* and *S-355*, from which TWEEQU thermobarometry yielded P - T values of 7.5—7.6 kb and 782—836 °C. These P - T values agree with phase relations restricted by the petrogenetic grid (e.g. absence of kyanite; absence of muscovite + quartz; local replacement of orthopyroxene and plagioclase by clinopyroxene, garnet, and quartz; and the presence of orthopyroxene and sillimanite in metapelite (sample *S-276*)), and are interpreted as the near-peak metamorphic conditions attained in the Shawinigan domain. The range of P - T values shown above is similar to that reported by Lévesque and Nadeau (1994) (Fig. 3.11). Field constraints and U-Pb dating of accessory minerals have constrained the age of peak metamorphism in this domain at ~ 1.12—1.09 Ga (Chapter 2).

The maximum temperature estimate obtained from the Mékinac domain (sample *M-302*) using TWEEQU thermobarometry, is inconsistent with conventional thermometers, and with restrictions imposed by the petrogenetic grid (Fig. 3.8). The metamorphic parageneses within the Mékinac domain necessitate the same minimum P - T constraints as those determined for the Shawinigan domain. The temperature calculated from TWEEQU equilibria (705 ± 5 °C) is at least 75 °C lower than the minimum temperature constrained by the petrogenetic grid. Temperatures obtained from different calibrations of conventional garnet-clinopyroxene Fe-Mg exchange thermometers (Table 3.2) appear to be more “reasonable” for this granulite-facies sample. In contrast, different conventional

barometers, as well as TWEEQU equilibria, applied to sample *M-302*, yield pressures that are compatible with the observed parageneses, and with other published *P-T* data from the Mékinac domain (e.g. Herd et al. 1986; Lévesque and Nadeau 1994) (Fig. 3.11). The best estimate for peak *P-T* conditions of metamorphism in the Mékinac domain is therefore interpreted as ≥ 8 kb and ≥ 800 °C. The timing of peak metamorphism in the Mékinac domain has been constrained by field and geochronological data at ~ 1.12 – 1.09 Ga (Chapter 2).

3.4.6 *P-T* vectors

The direction of change of metamorphic conditions in *P-T* space from peak or near-peak, to retrograde *P-T* conditions (*P-T* vector) can yield important information on the tectonic evolution of metamorphic terrains (e.g. England and Thompson 1984; Thompson and England 1984; Selverstone et al. 1984; Bohlen 1987; Harley 1989; Spear et al. 1990). Details of the prograde *P-T* path followed by rocks of the Mauricie transect have not been preserved, as is typically the case in high-grade metamorphic terrains (e.g. Frost and Chako 1989; Harley 1989; Selverstone and Chamberlain 1990; Spear and Florence 1992, Pattison and Bégin 1994). However, retrograde changes from peak metamorphic conditions (*P-T* vectors) can be constrained from metamorphic reactions. Because most rocks of the Mauricie transect do not retain all of either prograde or retrograde reactions, a more or less complete metamorphic history can only be derived from a recapitulation of the complete set of data. The numbered arrows in Figure 3.8 corresponds to numbered reactions in the text, and to the direction of *P-T* change.

Retrograde P-T evolution of the Mékinac domain

The highest metamorphic grade (granulite facies) has been observed in the Mékinac domain, where peak conditions derived from quantitative thermobarometry have been

estimated at ≥ 8 kb and ≥ 800 °C. The relative scarcity of *grt*—*cpx*—*qtz* assemblages, and the predominance *opx*—*cpx*—*pl*—*hbd*—*qtz* $\pm$ *bt* assemblages suggests that regional metamorphic conditions were in the uppermost field of the medium-pressure granulite, as defined by de Waard (1965) and Green and Ringwood (1967). However, the symplectic nature of garnet and quartz in sample *M-302* is more compatible with disequilibrium brought about by rapid cooling, than with slow, progressive increase of pressure and temperature generally associated with tectonic burial and thermal reequilibration. Garnet-quartz coronas on orthopyroxene, clinopyroxene, or Fe-Ti oxide suggest the following reaction,

This reaction has a shallow positive dT-dP slope of 64 °C/kbar (Sandiford 1985), with garnet and quartz on the high pressure side, indicating that the garnet-quartz coronas probably formed during cooling, at constant or slightly increasing pressure. However, there are no constraints on the timing of this reaction, nor on the pressure at which isobaric cooling may have initiated. Isobaric cooling (IBC) immediately following peak metamorphism would have brought the *P-T* conditions of the Mékinac domain in the kyanite stability field, which is unsupported by petrological data. Therefore, if IBC did occur, it must have taken place following a substantial amount of decompression.

Disequilibrium textures related to pressure and/or temperature decrease are also preserved in sample *M-304* (Fig. 3.3, and reaction 4 in Figure 3.8). This is a sapphirine-bearing magnesian gneiss in which delicate replacement textures are preserved. This sapphirine locality has been previously studied in detail, but cordierite and sillimanite moats surrounding sapphirine (e.g. Fig. 3.5b, c) have either been interpreted as a result of “silicification” (Ferguson 1974), or (together with sapphirine and orthopyroxene) as a product of garnet-consuming reactions (Herd et al. 1986). By contrast, further petrographic observations suggest that garnet is a post-peak phase and is part of the

retrograde assemblage. The peak metamorphic assemblage in this rock was *spr—opx—pl—phl—qtz*. Quartz is now absent from most thin sections observed. Nevertheless, a quartz-rich mylonitic layer hosts ~1 mm thick plagioclase lenses with skeletal sapphirine, which is not in direct contact with the quartz grains (Fig. 3.4f). However, due to the proximity of sapphirine and quartz grains (~ 0.5 mm), both phases are interpreted as having been in equilibrium during peak metamorphism. Assuming the presence of quartz, K-feldspar, and melt, the replacement of sapphirine by cordierite, garnet, and sillimanite can be modelled in the KFMASH system (Goscombe 1992). The reaction curve has a moderate negative slope in *P-T* space (Fig. 3.8), permitting either isobaric cooling or isothermal decompression (or simultaneous *P* and *T* decrease) as possible retrograde paths (reaction 4; Figure 3.8). The position of this reaction curve in *P-T* space is strongly dependant on bulk composition, and on the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio (Goscombe 1992), and may be stable at lower *P-T* conditions.

Retrograde P-T evolution of the Shawinigan domain

Plagioclase moats surrounding garnet in mafic granulite sample S-355 have been described in section 3.3.2, and have been interpreted as a product of a decompression reaction such as (5a) or (5b), or of the retrograde reaction $[\text{pl} + 4 \text{ opx} \rightleftharpoons \text{grt} + \text{cpx} + \text{qtz}]$ as illustrated in Figure 3.8. The replacement of garnet by plagioclase has only been observed in the Shawinigan domain. Garnet is altogether absent from amphibolites in the western strand of the Montauban Group.

This study has also reported the very rare, but widely distributed occurrence of silica-undersaturated, highly aluminous and magnesian gneisses within the Shawinigan domain (Fig. 3.3). Overall disequilibrium textures prevent the usage of these samples to extract peak *P-T* conditions of metamorphism. Martignole (1978) has described *crd—opx—spl* assemblages in the thermal aureole of the ca. 1.07 Ga (Chapter 2) Shawinigan

norite, and attributed their formation to syn-magmatic thermal overprint. However, the assemblages referred to in this chapter are not restricted to pluton aureoles, and are syn-tectonic with respect to the main regional fabric. Sample *S-205* occurs near the margin of a composite mangerite-gabbro-norite pluton, and is composed of *opx—crd—grt—bt—Ksp* (*perthite*)—*pl—qtz* $\pm$ *sil*. Sillimanite occurs in that same outcrop, but not with orthopyroxene. Orthopyroxene and cordierite occur as isolated inclusions in garnet, and as corroded matrix grains separated by plagioclase, and are not in textural equilibrium. Two texturally distinct garnet phases occur. The oldest garnets (*grt*₁) contain an abundant number of small inclusions showing a preferential orientation, and are enclosed within larger, inclusion-free garnets (*grt*₂). The mutual exclusion of prismatic sillimanite and orthopyroxene in this sample suggests that the reaction:

may have occurred until the complete exhaustion of one of the reacting phases (Fig. 3.8). In the thin sections observed, sillimanite is absent and the assemblage is *opx—grt*₁—*crd*. During a further stage of metamorphism, orthopyroxene became unstable in the presence of cordierite, producing euhedral biotite and garnet (*grt*₂), possibly through the following retrograde reaction;

This reaction is near-vertical in *P-T* space (Fig. 3.8), and likely occurred during cooling. Fibrolite sprays intergrown with biotite may have been produced upon further cooling, from the following retrograde reaction between cordierite and garnet;

The position of the [*spr—spl—ged*] invariant point in KFMASH has been estimated at ~ 5 kb and 775 °C (Grant 1985). Assuming that the position of this invariant point applies to the composition of sample *S-205*, the *P-T* path permitted by reactions (5), (11), (12),

and (13) implies high-temperature, post-peak decompression to approximately 5 kb, followed by nearly isobaric cooling (Fig. 3.8).

The assemblage *crd—grt—spl—sil—qtz—pl—bt* has been observed in samples *S-396*, *S-76*, and *PSM-LROB* (Fig. 3.3). In all three samples, relict spinel is separated from quartz ribbons by prismatic sillimanite bundles and cordierite (Fig. 3.7b). Idioblastic garnets overprint matrix biotite. Sillimanite crystals are bent around tight microfolds, suggesting a pre- to syn-tectonic growth, and are elongated parallel to the regional E-SE-plunging stretching lineation. The corresponding reaction:

has a shallow positive slope in *P-T* space (Fig. 3.8), implying either isobaric cooling, or cooling with a slight increase in pressure. The coexistence of spinel and quartz also implies that a temperature increase at relatively low pressures may have occurred prior to cooling. However, the absolute position of this reaction curve in *P-T* space is strongly dependant on the gahnite component in spinel. Increasing gahnite expands the spinel-quartz stability field to lower temperatures and higher pressures (Nichols et al. 1992). Spinel from Shawinigan domain assemblages have not been analyzed for Zn, but a spinel analysis from sample *PSM-LROB* yielded up to 24 wt% ZnO. This may explain the relatively high pressure recorded by quantitative thermobarometry in this sample, in spite of the position of the reaction curve (14) shown in Figure 3.8. Nonetheless, the occurrence of this reaction implies that IBC resulted in both the Shawinigan, and Portneuf—St. Maurice domains. However, U-Pb monazite ages constrain these events at ~ 1.39 Ga in the Portneuf—St. Maurice domain, and ~ 1.09 Ga in the Shawinigan domain (Chapter 2).

Sample *S-12* from the Shawinigan domain places an important constraint on the *P-T* evolution of the Mauricie region. This metapelite sample, which belongs to the ca. 1.18—1.12 Ga (Chapter 2) St. Boniface unit (Fig. 3.3), consists of a high-grade assemblage that

equilibrated at $\sim 800^\circ\text{C}$ and 7.5—8 kb during peak metamorphism associated with W-NW-directed thrusting. However, low-temperature microstructures preserved in quartz ribbons (i.e. subgrains and neo-grains with serrated boundaries; Chapter 1) suggest that the last episode of thrust-related deformation occurred while P and T conditions were decreasing. This is corroborated by the retrograde reaction observed in garnet pressure shadows (reaction 7), whose products yielded quantitative P - T estimates of 3.2—4.5 kb and 478—510 $^\circ\text{C}$. This range of pressures and temperatures is similar to the one observed in the western strand of the Montauban Group (Table 3.2), in the Tawachiche shear zone hanging wall. Without geochronological constraints, it would appear that the hanging wall and footwall equilibrated at the same P - T conditions following oblique extension. However, the similarity is fortuitous since both crustal blocks reached their final stages of peak metamorphism ~ 300 m.y. apart.

Metamorphic evolution of the Portneuf—St. Maurice domain

Most samples from the western strand of the Montauban Group preserve peak metamorphic assemblages and are synchronous with the main regional deformation event in the PSM domain, which occurred at ca. 1.39 Ga (Chapters 1 and 2). In the P - T diagram (Fig. 3.8), two samples (*PSM-111* and *PSM-241*) yield quantitative estimates that plot near the experimentally derived stability curve of muscovite and quartz (Chatterjee and Johannes 1974), in agreement with the observed local evidence for this reaction. The water-saturated granite solidus curve of Thompson (1982) provides a minimum T estimate for anatexis in the lower structural levels of the western strand (i.e. $\geq 610^\circ\text{C}$).

Peak metamorphic conditions recorded in the eastern strand by sample *PSM-LROB* are at least 150 $^\circ\text{C}$ and 1—2 kb higher than those obtained from samples from the western strand. There is no unequivocal field evidence suggesting the presence of a fault or shear zone separating the two strands, leading to the suggestion that if such a fault

existed, it may have been obscured by the ca. 1.40—1.37 Ga intrusions of the La Bostonnais complex.

3.5 TECTONIC INTERPRETATION AND DISCUSSION

3.5.1 ca. 1.40 Ga arc-related metamorphism

Quantitative thermobarometry, reaction textures, and geochronology have demonstrated that the hanging wall and footwall of the Tawachiche shear zone have evolved along different P - T - t paths before being juxtaposed by oblique extension. Prograde mineral assemblages in the Portneuf—St. Maurice domain were formed during relatively high-temperature, low- to moderate-pressure metamorphism (amphibolite to low- P granulite-facies) at ca. 1.39 Ga, and were not overprinted by the high-grade metamorphism during thrusting at ~ 1.12 — 1.09 Ga. The association of high- T , low- to moderate- P metamorphism with magmatic arc settings has been extensively documented in the literature (e.g. England and Thompson 1986; Walcott 1987; Yardley et al. 1987; Miller and Gans 1989; Sandiford and Powell 1991), suggesting that heat advection by magmatism may have been a viable mechanism for metamorphism in the Montauban Group. The relationship between metamorphic minerals and the regional fabric in the Portneuf—St. Maurice domain also suggests that metamorphism, magmatism, and regional deformation were contemporaneous, as would be expected in a dynamic arc setting. The ~ 16 km depth of emplacement inferred for ca. 1.40 Ga calc-alkaline plutons of the La Bostonnais complex (sample *PSM-327*) is consistent with the 3.2—6.4 kb metamorphic pressures calculated from various geobarometers applied to Montauban Group samples, and supports the above interpretation.

3.5.2 ca. 1.12—1.09 Ga metamorphism related to crustal thickening

In the Mékinac and Shawinigan domains, peak metamorphic assemblages were formed during a high-grade tectonothermal event related to bulk, W-NW-directed thrusting (Chapter 1). Constraints from U-Pb dating of accessory minerals restrict this metamorphic event to ~ 1.12—1.08 Ga in the Mékinac domain, and ~ 1.12—1.09 Ga in the Shawinigan domain (Chapter 2). Thermobarometry on undeformed, or only moderately deformed metamorphic assemblages yields pressures and temperatures that are compatible with the observed mineral facies, namely ≥ 8 kb and ≥ 800 °C in the granulite-facies Mékinac domain, and 7.5—8 kb and 800 °C in the uppermost-amphibolite- to granulite-facies Shawinigan domain. Although the prograde part of the P - T path followed by these rocks is not preserved, thermobarometric constraints imply that the presently exposed rocks were buried under at least 24 km of crust. Most of the thickening may have occurred by thrusting along structurally higher thrust faults above the currently exposed high grade rocks. The Portneuf—St. Maurice domain remained at high structural levels during this event, and avoided tectonothermal overprint.

3.5.3 Exhumation of the Mékinac and Shawinigan domains

The difference between peak and retrograde metamorphic conditions calculated from thermobarometry in the Shawinigan domain (Samples *S-275* and *S-12*, respectively) is ~ 400 °C and 4 kb (Fig. 8). This suggests that at least 12 km of overburden was removed from the Mékinac and Shawinigan domains, perhaps by a combination of erosion and tectonic denudation. The retrograde path did not follow a curvilinear course from high-grade to low-grade conditions, as would be expected in overthickened crust undergoing exhumation dominated by erosion (e.g. England and Richardson 1977; England and Thompson 1984). Reaction textures observed in some of the Shawinigan domain samples reflect isothermal decompression, or decompression at high

temperatures, followed by isobaric cooling (Fig. 3.8). However, this apparently continuous P - T path has been constructed from the assemblage of reaction textures preserved in different samples, and may not reflect the “real” evolution of P and T conditions in the high-grade footwall. For example, the reaction $\text{spl} + \text{qtz} \Rightarrow \text{grt} + \text{crd} + \text{sil}$ (14) requires intense heating at relatively low pressures to first form spinel and quartz, and subsequent isobaric cooling to form garnet, cordierite, and sillimanite. Nonetheless, the general tendency shown by retrograde metamorphic reactions places important constraints on the possible P - T evolution of the Shawinigan and Mékinac domains. For example, reaction (12) documented in sample *S-205* suggests cooling below $\sim 775^\circ\text{C}$ at a maximum pressure of 5 kb (Grant 1985). Similarly, textural evidence for reaction (14) observed in samples *S-76* and *S-396* suggests cooling from high temperatures, at relatively low pressures.

Acceptance of the model of isobaric cooling at relatively low pressure requires that isothermal decompression had previously occurred, as suggested from reactions 5 and 11 shown in Figure 3.8. The P - T path for the Shawinigan domain, constrained by the combination of thermobarometry and reaction textures, can therefore only be accommodated by an early phase of isothermal decompression followed by isobaric cooling. This, of course, could only be tested by dating the individual metamorphic reactions.

The Tawachiche shear zone juxtaposes middle-amphibolite facies rocks that cooled ~ 1.39 m.y. ago in the hangingwall, with uppermost-amphibolite to granulite facies rocks that were undergoing cooling at ca. 1.09—1.08 Ga in the footwall (Chapter 2) (Fig. 3.11). Cooling of the footwall is approximately coeval with the end of thrusting (ca. 1.09 Ga; Chapter 2), and with the beginning of oblique extension at ca. 1.09 Ga. The proposed P - T path for the Shawinigan domain (decompression followed by cooling) is consistent with the observed structural and geochronological data. Unroofing by oblique extension along

the Tawachiche shear zone would result in rapid decompression in the footwall. The effect of transposition of “cold” hanging wall rocks in contact with “hot” footwall rocks would produce the retrograde overprint observed in high grade footwall rocks in proximity of the shear zone. However, structurally deeper levels would only respond to the effect of thermal reequilibration at a much later time, at a rate governed by thermal diffusivity (England and Jackson 1987). This probably explains the concentration of “frozen-in” retrograde reactions in the Shawinigan domain, their relative scarcity in the Mékinac domain where the cooling rates would have been slower, and more importantly, their absence from the western strand of the Montauban Group in the Portneuf—St. Maurice domain.

Conversely, juxtaposing higher temperature rocks of the footwall against lower temperature rocks of the western strand of the Montauban Group should have resulted in heating of the hanging wall. Peraluminous pegmatites that were produced at the base of the western strand of the Montauban Group (Chapter 1) may have formed in response to isobaric heating, at conditions of ca. 620 °C and 5 kb (Fig. 3.8). Their distinct location in the immediate base of the western strand strongly suggests that the heat source that produced the minimum melt reaction was the high-grade footwall. Anatexis under these low-T conditions probably required the presence of excess fluid (Thompson 1982), which may have been more concentrated in the western strand in proximity of the Tawachiche shear zone.

3.6 CONCLUSIONS

This study has demonstrated that the Tawachiche shear zone separates two crustal blocks that have evolved through different P-T-t histories. The Portneuf—St. Maurice domain, which forms the hanging wall, was metamorphosed at ca. 1.39 Ga under relatively high-T and medium- to low-P conditions in a magmatic arc setting.

Thermobarometric data constrain peak P and T conditions at ~ 6.4 kb and 750°C in the eastern strand of the Montauban Group, and $3.2\text{--}5$ kb and $544\text{--}638^\circ\text{C}$ in the western strand. This crustal block remained at high crustal levels during subsequent crustal thickening events. By contrast, the Mékinac and Shawinigan domains were tectonically buried during W-NW directed thrusting. Compressional deformation at ca. 1.12 Ga led to uppermost-amphibolite- to granulite-facies metamorphism and penetrative deformation in the Shawinigan and Mékinac domains, with peak metamorphic minerals outlining a strong regional foliation and E-SE-plunging lineation. Thermobarometric data constrain peak metamorphic conditions during this event at $\geq 800^\circ\text{C}$ and ≥ 8 kb in the Mékinac domain, and ~ 7.5 kb and $782\text{--}836^\circ\text{C}$ in the Shawinigan domain.

Field, geochronological, and textural evidence indicate that oblique extension along the Tawachiche shear zone resulted in the tectonic denudation of the high-grade Mékinac and Shawinigan domains, and their juxtaposition to the "cold" Portneuf—St. Maurice domain. During this event, which lasted from ~ 1.09 to 1.05 Ga, up to 12 km of overburden was removed from the high-grade footwall. In the Shawinigan domain, isothermal decompression was followed by isobaric cooling. However, there is also evidence which suggest that isobaric heating at low pressures may also have occurred, perhaps in correlation with syn-extensional high-temperature plutonism. In the structurally deeper Mékinac domain, disequilibrium textures related to rapid decrease in either P or T have only been observed in one sample (*M-304*), and are not thought to have been generally developed, perhaps due to the greater distance of the Mékinac domain from the Tawachiche shear zone.

APPENDIX 3.1: INTERPRETATION OF GARNET ZONING PROFILES

Garnet in samples *S-12* and *S-275* of the Shawinigan domain, and *PSM-111* and *PSM-253* from the Portneuf—St. Maurice domains show "flat" profiles (Appendix 3.1.1), which are characteristic of homogenization by volume diffusion (e.g. Tracy et al. 1976). Volume diffusion in garnet is thought to occur at ~ 650 °C, and is commonly observed in regions metamorphosed at sillimanite—K-feldspar facies (Woodsworth 1977; Tracy 1982). Garnet *S-275* shows a relatively "flat" profile (Appendix 3.1.1a), with an increase in Fe and corresponding decrease in Mg visible near the rim at one edge only, where the garnet grain is in contact with biotite. This diffusion pattern is interpreted as late diffusion zoning in response to Fe-Mg exchange between garnet and biotite (e.g. Tracy et al. 1976). Garnet *S-12* shows a very "flat" zoning profile with a similar increase in Fe and coincident decrease in Mg at the rim, near pressure shadows containing biotite, plagioclase, and quartz (Appendix 3.1.1b). A photomicrograph of this garnet is shown in Figure 3.6b. Petrographic evidence suggests that the pressure shadows were formed in response to the net transfer reaction $[grt + Ksp + H_2O = bt + pl + qtz]$. However, there is no noted decrease in Ca in the garnet rim, as would be expected if this reaction had taken place. This could be due to the very small amount of Ca found in pressure shadow plagioclase (An_9), or to the availability of matrix Ca^{++} by intergranular diffusion.

Both garnets from the Portneuf—St. Maurice domain show "flat", homogenized profiles. However, these two samples are from the western strand of the Montauban group where the maximum peak metamorphic temperatures did not exceed ~ 640°C, and were likely closer to ~ 620 °C. Nevertheless, the diameter of these garnets (0.75 and 1.4 mm) was probably sufficiently small to permit homogenization in spite of the lower metamorphic temperatures. Garnet *PSM-253* (Appendix 3.1.1c) shows a relatively flat profile from rim to rim, and slight variations of Mg and Ca, perhaps due to local diffusion

in proximity of plagioclase and biotite inclusions. Garnet *PSM-111* (Appendix 3.1.1d) shows a similar profile to the one observed in Garnet S-275, with Fe and Mg diffusion near the rim in proximity of biotite.

APPENDIX 3.1.1: GRAPHIC REPRESENTATION OF GARNET ZONING PROFILES

APPENDIX 3.2: Average mineral compositions used in thermobarometric calculations. Numbers in parentheses represent one standard deviation for samples that contain at least 10 analytical points.

Garnet (formulae calculated on the basis of 12 oxygens)								
Sample	M-302 (core)	S-355 (core)	S-275 (core)	S-12 (rim)	PSM-253 (core)	PSM-111 (core)	PSM-241 (core)	PSM-LROB (core)
SiO2	37.38 (1.80)	37.68 (.21)	37.41 (.37)	37.33 (.42)	37.54 (.26)	36.94 (.25)	38.15 (.33)	36.67 (.52)
Al2O3	19.77 (.59)	21.00 (.19)	21.24 (.34)	21.26 (.27)	21.10 (.18)	20.94 (.15)	21.58 (.34)	21.42 (.46)
FeO	31.60 (.99)	26.36 (.36)	32.87 (.47)	35.50 (.93)	33.74 (.24)	36.58 (.35)	31.01 (.73)	34.80 (.98)
MnO	2.36 (.16)	1.88 (.13)	0.24 (.02)	0.56 (.07)	2.55 (.08)	1.54 (.05)	2.18 (.14)	0.62 (.05)
MgO	1.31 (.09)	5.44 (.32)	6.44 (.20)	4.31 (.88)	2.27 (.19)	2.53 (.28)	4.57 (.37)	6.55 (.35)
CaO	7.02 (.17)	6.78 (.24)	1.15 (.05)	0.46 (.05)	3.26 (.11)	0.79 (.08)	4.50 (.70)	0.54 (.09)
total	99.45 (.48)	99.37 (.56)	99.51 (.45)	99.49 (.77)	99.78 (.68)	99.56 (.63)	100.03(.52)	100.51 (.49)
Xalm	0.69	0.56	0.69	0.83	0.76	0.83	0.65	0.73
Xsps	0.06	0.04	0.01	0.02	0.06	0.03	0.07	0.01
Xpy	0.05	0.22	0.26	0.14	0.09	0.11	0.18	0.25
Xgrs	0.20	0.18	0.04	0.01	0.09	0.02	0.10	0.01

Plagioclase (formulae calculated on the basis of 8 oxygens)								
Sample	M-302 (c)	S-355 (c)	S-275 (c)	S-12 (r)	PSM- 253(c)	PSM- 111(c)	PSM- 241(c)	PSM- LROB(c)
SiO2	64.73 (.61)	53.97 (1.01)	60.87 (.96)	66.12 (.33)	58.02 (.48)	63.19 (.35)	57.21 (.65)	65.26 (.42)
Al2O3	21.95 (.09)	28.64 (.54)	24.97 (.44)	20.99 (.18)	25.86 (.33)	22.73 (.10)	26.78 (.45)	21.91 (.34)
FeO	0.26 (.19)	0.22 (.17)	0.04 (.04)	0.12 (.05)	0.03 (.03)	0.05 (.02)	0.06 (.01)	0.11 (.03)
CaO	3.45 (.09)	11.03 (.34)	6.10 (.57)	1.95 (.07)	7.97 (.32)	4.28 (.19)	9.18 (.52)	2.16 (.28)
NaO	9.46 (.26)	4.70 (.22)	7.96 (.34)	10.50 (.18)	6.90 (.29)	9.17 (.16)	6.01 (.31)	10.26 (.38)
K2O	0.24 (.04)	0.03 (.02)	0.44 (.04)	0.12 (.11)	0.26 (.21)	0.14 (.03)	0.15 (.10)	0.00 (.00)
total	99.09 (.99)	98.59 (1.30)	100.38 (.39)	99.79 (.45)	98.91 (.62)	99.57 (.28)	99.44 (.26)	99.92 (.39)
Xan	0.16	0.55	0.29	0.10	0.39	0.22	0.46	0.10
Xab	0.83	0.45	0.69	0.90	0.60	0.78	0.54	0.90

Appendix 3.2, ctd...

Sample	clinopyroxene (calculation based on 6 oxygens)				orthopyroxene (6 oxygens)	
	M-302 (relic)	M-302 (meta.)	S-355 (c)	S-355 (r)	M-302 (relic)	S-355 (avg)
SiO ₂	47.48 (.12)	48.29 (.37)	49.80 (.41)	50.44	52.62 (5.12)	49.55 (.44)
TiO ₂	0.00 (.00)	0.09 (.04)	0.46 (.06)	0.39	0.00 (.00)	0.00 (.00)
Al ₂ O ₃	0.77 (.06)	1.27 (.17)	3.67 (.33)	3.35	0.60 (.09)	1.76 (.35)
FeO	39.21 (1.48)	24.81 (1.43)	11.71 (.39)	11.59	39.42 (5.84)	28.20 (.70)
MnO	1.20 (.26)	0.49 (.15)	0.39 (.08)	0.42	0.84 (.27)	0.59 (.02)
MgO	5.96 (.08)	4.92 (.16)	11.50 (.24)	11.59	6.06 (.48)	17.67 (.24)
CaO	5.52 (1.57)	18.06 (1.49)	20.76 (.37)	21.21	0.44 (.20)	0.45 (.04)
Na ₂ O	0.47 (.03)	0.79 (.21)	0.68 (.16)	0.69	0.25 (.03)	0.10 (.10)
total	100.58 (.20)	99.14 (.64)	99.05 (.75)	99.71	100.28 (1.61)	98.62 (.55)
Si	1.940	1.947	1.892	1.902	2.170	1.930
Al ^{IV}	0.037	0.053	0.108	0.098	0.000	0.070
Al ^{VI}	0.000	0.007	0.056	0.051	0.029	0.011
Ti	0.000	0.003	0.013	0.011	0.000	0.000
Fe ³⁺	0.120	0.102	0.075	0.075	0.000	0.067
Fe ²⁺	1.220	0.734	0.297	0.291	1.359	0.851
Mn	0.042	0.017	0.013	0.013	0.029	0.019
Mg	0.363	0.296	0.651	0.651	0.372	1.026
Ca	0.242	0.780	0.845	0.857	0.019	0.019
Na	0.037	0.062	0.050	0.050	0.020	0.008
Sum	4.000	4.000	4.000	4.000	4.000	4.000

Appendix 3.2, ctd...

Sample	Biotite (formulae calculations based on 22 oxygens)								Spinel 32 (O)	
	S-275 (core)	S-12 (core)	PSM-253 (core)	PSM-253 (inclusions)	PSM-111 (core)	PSM-111 (rim)	PSM-LROB (core)	PSM-LROB		
SiO ₂	35.70 (.26)	36.12 (.27)	35.11 (.28)	35.00 (.20)	35.62 (.51)	35.26	35.17 (1.85)	—		
TiO ₂	4.52 (.15)	3.81 (.50)	3.40 (.27)	3.64 (.21)	3.50 (.38)	3.85	4.50 (.58)	—		
Al ₂ O ₃	17.90 (.35)	18.16 (.81)	17.79 (.22)	17.77 (.18)	19.11 (.28)	19.14	17.90 (.73)	55.35 (.75)		
FeO	17.70 (.36)	17.44 (.36)	20.72 (.32)	20.96 (.09)	20.42 (.68)	20.57	17.02 (.93)	27.07 (.18)		
MnO	0.00 (.00)	0.00 (.00)	0.09 (.04)	0.00 (.00)	0.02 (.01)	0.04	0.02 (.02)	0.04 (.02)		
MgO	10.60 (.08)	11.07 (.48)	8.67 (.14)	8.59 (.12)	8.13 (.58)	7.95	10.82 (.77)	4.72 (.19)		
K ₂ O	9.35 (.06)	9.60 (.10)	9.41 (.14)	10.13 (.12)	9.51 (.08)	9.51	9.16 (.35)	0.00 (.00)		
NiO	—	—	—	—	—	—	—	0.08 (.05)		
ZnO	—	—	—	—	—	—	—	12.02 (.28)		
total	95.77 (.18)	96.41 (.60)	95.51 (.60)	96.67 (.18)	96.44 (.34)	96.59	94.74 (1.32)	99.67 (1.82)		
Xann	0.476	0.469	0.571	0.578	0.585	0.591	0.469	Xhc		
Xphl	0.524	0.531	0.426	0.422	0.415	0.407	0.531	Xgah		
								Xsp		

Appendix 3.2, ctd...

Amphibole (formulae calculated on the basis of 23 oxygens)					Cordierite 18 (O)	
Sample	S-355 (core)	PSM-241 (core)	PSM-327 (core)		PSM-LROB (core)	PSM-LROB (rim)
SiO2	42.84 (.72)	42.03 (1.12)	44.18 (.04)		46.71 (.43)	47.07 (.28)
TiO2	1.75 (.22)	0.50 (0.11)	1.02 (.22)		0.00 (.00)	0.00 (.00)
Al2O3	12.63 (.28)	15.23 (1.28)	10.51 (.31)		32.39 (.23)	32.73 (.15)
FeO	15.28 (.70)	17.63 (0.45)	17.54 (.19)		7.50 (.05)	6.45 (.62)
MnO	0.03 (.03)	0.09 (0.09)	0.37 (.00)		0.05 (.02)	0.04 (.04)
MgO	11.57 (.47)	9.02 (0.91)	10.35 (.19)		9.10 (.15)	9.84 (.64)
CaO	11.75 (.14)	10.88 (0.45)	11.95 (.08)		0.00 (.00)	0.00 (.00)
Na2O	1.99 (.19)	1.44 (0.21)	1.23 (.22)		0.00 (.00)	0.00 (.00)
K2O	0.76 (.06)	0.45 (0.06)	1.24 (.02)		0.10 (.03)	0.11 (.04)
total	98.62 (.36)	97.28 (1.14)	98.54 (0.33)		96.62 (.45)	96.16 (.39)
Si	6.321	6.288	6.592	XFe	0.316	0.268
Al ^{IV}	1.679	1.712	1.408	XMg	0.682	0.730
Al ^{VI}	0.516	0.973	0.440			
Fe ³⁺	0.062	0.123	0.148			
Ti	0.194	0.056	0.114			
Mg	2.544	2.011	2.301			
Fe ²⁺	1.823	2.082	2.040			
Mn	0.004	0.011	0.047			
Ca	1.857	1.744	1.910			
Na	0.569	0.418	0.356			
K	0.143	0.086	0.236			
Sum	15.712	15.504	15.592

Figure 3.1. Maps of the Grenville Province with the subdivisions of [a] Rivers et al. (1989), and [b] Wynne-Edwards (1973). The location of the Mauricie transect is shown in box.

Figure 3.2. Lithological map of the Mauricie region showing part of the Mauricie transect that was studied. Note the subdivision of the Montauban group into the eastern and western strands. Lithological boundaries are modified after Rondot (1978), Martignole (1978), Nadeau and Corrigan (1991), and Nadeau et al. (1994). Brittle faults are of Paleozoic age. U-Pb ages shown in the legend are described in Chapter 2.

Figure 3.3. Map showing the location of samples used for thermobarometry (black dots). The location of samples with important mineral assemblages is also shown, with different symbols keyed to assemblages shown in the legend. The distribution of granulite-facies assemblages is also shown.

Figure 3.4. a) Felsic granulite sample M-302 showing garnet-quartz symplectite intergrown with metamorphic clinopyroxene, surrounding relic igneous orthopyroxene and ilmenite. b) Migmatitic mafic granulite in Mékinac domain, with highly resorbed hornblende, replaced by granoblastic orthopyroxene, and plagioclase. c) Migmatitic “front” showing hornblende partially replaced by fine grained ortho- and clinopyroxene, and plagioclase. Large orthopyroxene grain is in the leucosome. Inclusions in orthopyroxene are magnetite. Mékinac domain. d) Corona texture in metagabbro, with granoblastic ortho- and clinopyroxene separated from plagioclase by a rim of idiomorphic garnet. Dark grey mineral is hornblende. Mékinac domain. e) Sigmoidal sillimanite bundles in mylonitic metapelite. Quartz ribbons are annealed. Mékinac domain. f) Sapphirine—plagioclase symplectic growth in sample M-304. Sapphirine is separated from quartz by plagioclase.

Figure 3.5. **a)** Sapphirine and phlogopite inclusions in idiomorphic garnet, sample M-304. Inclusion trail in garnet is parallel to the matrix foliation, indicating post-deformational growth. Mékinac domain. **b)** Sapphirine partially replaced by sillimanite and cordierite (M-304). **c)** Spectacular replacement of sapphirine by sillimanite (M-304). **d)** Plagioclase moat surrounding garnet in mafic granulite sample S-355. Shawinigan domain. **e)** Symplectic intergrowth of orthopyroxene, clinopyroxene, and plagioclase between hornblende and ilmenite. Sample S-355. **f)** Texturally zoned garnet in metapelite sample S-275, Shawinigan domain. Biotite patch in garnet pressure shadow also contains rutile.

Figure 3.6. **a)** Early crenulation outlined by fibrolite inclusions in garnet. Sample S-275, Shawinigan domain. **b)** Garnet porphyroblast isolated in a quartz ribbon in a mylonitic metapelite (sample S-12; Shawinigan domain). Pressure shadow is composed of biotite, plagioclase, and rutile liberated from the reacting garnet. **c)** Orthopyroxene inclusions in garnet (sample S-205; Shawinigan domain). Orthopyroxene is separated from garnet by chlorite. Cordierite inclusions are found in the adjacent garnet (out of photograph). See text for explanations. **d)** Garnet containing numerous plagioclase, quartz, and biotite inclusions. Sample PSM-253, Portneuf—St. Maurice domain. **e)** Small subhedral garnet and fibrolite bundles in metapelite sample PSM-111, Portneuf—St. Maurice domain. Fibrolite bundles are axial-planar, and restricted to specific compositional layers. **f)** Large garnet porphyroblast in metagreywacke sample PSM-241. Hornblendes included in garnet are smaller, and at a high angle to those in the matrix. Clear inclusions are plagioclase.

Figure 3.7. **a)** Photomicrograph showing sillimanite, biotite, and spinel in cordierite porphyroblasts. Spinel is locally in contact with quartz. Garnet occurs locally along with cordierite. Sample PSM-LROB; Portneuf—St. Maurice domain. **b)** Relic spinel separated from quartz by sillimanite and an outer rim of pinitized cordierite. Sillimanite outlines tight microfolds (fold hinge outside this picture). Sample S-76, Shawinigan domain. **c)** Retrograde metapelite in the Tawachiche shear zone, with muscovite “fish”. **d)** Garnet porphyroclast in mylonite from the Tawachiche shear zone. Pressure shadow and “tail” are formed of microcrystalline chlorite and biotite.

Figure 3.8. P-T diagram showing the distribution of thermobarometric estimates determined with TWEEQU (black circle with error bars). P-T fields outlined in gray tones are constrained by calculated P-T values and limiting reaction curves. Encircled numbers and arrows correspond to reactions discussed in text, and the corresponding vector of P-T change. Aluminosilicate fields are after Holdaway (1971). The water-saturated granite minimum-melt reaction curve [A] is after Thompson (1982). The muscovite breakdown reaction curve [B] is after Chatterjee & Johannes (1974). The K-feldspar solvus is after Thompson and Tracy (1979). Stability curves for the assemblage *crd—grt—spl—sil—spr—bt—opx—qtz—H₂O* in the system KFMASH are after Goscombe (1992). See text for discussion.

Figure 3.9. P-T estimates from TWEEQU thermobarometry on samples M-302, S-275, S-355, and S-12. Uncertainties represent intersections plotting within 1.5σ . IR = number of independent reactions. Mineral compositions on which the individual P-T points are based are given in Appendix 3.2. Numbers on reaction curves correspond to reactions listed in Table 3.3.

Figure 3.10. P-T estimates from TWEEQU thermobarometry on samples PSM-111, PSM-253, PSM-241, and PSM-LROB. Uncertainties represent intersections plotting within 1.5σ . IR = number of independent reactions. Mineral compositions on which the individual P-T points are based are given in Appendix 3.2. Numbers on reaction curves correspond to reactions listed in Table 3.4.

Figure 3.11. Schematic cross-section of the Mauricie transect, showing the projected location of samples. Sample numbers in bold letters have been used for quantitative thermobarometric calculations. Sample numbers in italic have constraining reaction textures, and are discussed in the text. The table above the cross-section is a compilation of calculated peak P-T estimates from the Mauricie transect derived from this study, and from previously published data. The timing of peak metamorphism in each domain has been constrained from U-Pb monazite and zircon data (Chapter 2). Arrows indicating thrusting are schematic, and do not represent mapped shear zones. Extensional movement indicated for the Tawachiche shear zone is oblique. See text for explanations.

TABLE 3.1

Summary of metamorphic reaction textures and some of the labelling numbers corresponding to those in text and figures.

<i>Prograde metamorphic reactions</i>			
M	Grt—cpx—qtz symplectites	1-	$\text{opx} + \text{pl} \rightarrow \text{grt} + \text{cpx} + \text{qtz}$
	Leucosome in mafic gneiss	2-	$\text{hbl} + \text{ilm} + \text{qtz} \rightarrow \text{opx} + \text{cpx} + \text{pl}$
	Coronitic gabbro		$\text{opx} + \text{pl} \rightarrow \text{grt}$
	Inclusions in sapphirine		$\text{spl} \rightarrow \text{sa} + \text{opx}$
S	Cpx—opx—pl symplectites		$\text{hbl} + \text{ilm} \rightarrow \text{opx} + \text{cpx} + \text{pl}$
	Consumption of biotite	6-	$\text{bt} + \text{qtz} \rightarrow \text{sil} + \text{Ksp} + \text{grt} + \text{H}_2\text{O}$
	replacement of tremolite	9-	$\text{tr} + 3 \text{ cal} + 2 \text{ qtz} = 5 \text{ di} + \text{H}_2\text{O} + 3\text{CO}_2$
PSM	Breakdown of muscovite		$\text{mu} + \text{qtz} \rightarrow \text{Ksp} + \text{sil} + \text{H}_2\text{O}$
<i>Retrograde metamorphic reactions</i>			
M	Hydration of orthopyroxene		$\text{opx} + \text{H}_2\text{O} \rightarrow \text{hbl}$
	Reactions corroding sapphirine	4-	$\text{spr} + \text{qtz} \rightarrow \text{cd} + \text{sil} + \text{grt}$
	Exsolution reactions		$\text{Kfs} \rightarrow \text{perthitic exsolution lamellae}$
	Corona replacing scapolite		$\text{scp} \rightarrow \text{grs}$
S	Reactions corroding garnet	5-	$\text{grt} \rightarrow \text{pl} \pm \text{opx}$
		7-	$\text{grt} + \text{Kfs} \rightarrow \text{bt} + \text{pl} + \text{qtz}$
	Replacement of opx and cd	11-	$\text{sil} + \text{opx} \rightarrow \text{crd} + \text{grt}$
		12-	$\text{opx} + \text{crd} \rightarrow \text{grt} + \text{bt}$
		13-	$\text{crd} + \text{grt} \rightarrow \text{sil} + \text{bt}$
	Replacement of spinel	14-	$\text{spl} + \text{qtz} \rightarrow \text{sil} + \text{crd} + \text{grt}$
<i>Retrograde reactions in the Tawachiche shear zone</i>			
	Replacement of hornblende		$\text{hbl} \rightarrow \text{bt} \pm \text{chl}$
	Replacement of plagioclase		$\text{pl} \rightarrow \text{ep} \pm \text{ser}$
	Replacement of garnet		$\text{grt} \rightarrow \text{chl} + \text{qtz}$
	Growth of muscovite		$\text{Ksp} + \text{sil} \rightarrow \text{mu} + \text{qtz}$

Note: Bold letters M, S, and PSM refer to the Mékinac, Shawinigan, and Portneuf—St. Maurice domains, respectively. This table refers to observed mineral reactions only, and does not imply that balanced reactions are known.

Table 3.2. Summary of P-T estimates using conventional thermobarometers and TWEEQU.

Sample	M-302 core	S-355 core	S-275 core	S-12 rim	PSM-253 core	PSM-111 core	PSM-241 core	PSM-LROB core	PSM-327 core
THERMOMETERS									
grt—bt (FS)			858	510	540	616	550	734	
grt—crd (BMS)								758	
grt—cpx (EG)	766	719							
grt—cpx (G) (max)	879	841							
" (min)	858	824							
grt—opx (H)	688	716							
grt—opx (Powell 78)	600	652							
grt—hbl (GP)	715	715					616		
TWEEQU	705	782	836	478	556	638	544	758	
BAROMETERS									
grt—sil—pl—qtz (NH)			8.5	4.5	5.4	4.0		7.1	
grt—spl (N)								6.3	
grt—opx—pl—qtz (BWB)	9.5	7.5							
grt—opx (H)	7.7	8.2							
grt—opx (HG)	11.8	10.1							
cpx—pl—qtz (E)	12.9	10.2							5.4
Al-in-hornblende (HZ)									
TWEEQU	9.0	7.6	7.5	3.2	4.9	3.4	3.2	6.4	

Letters in parenthesis are as follows: (BMS) Bhattacharia et al. (1988); (BWB) Bohlen et al. (1983); (E) Ellis 1980; (EG) Ellis and Green (1979); (FS) Ferry and Spear (1978), after Ganguly and Saxena (1984); (G) Ganguly (1979); (GP) Graham & Powell (1984); (H) Harley (1984); (HG) Harley & Green (1982); (HZ) Hammarstrom and Zen (1986); (N) Nichols et al. (1992); (NH) Newton & Haselton (1981); (P) Powell (1978). All Fe calculated as Fe²⁺ (Spear 1993).

Table 3.3. Mineral equilibria from TWEEQ results.

Equilibria plotted in Figure 3.9.

a) M-302

- 1: $3 \text{ Qtz} + 4 \text{ Py} + 3 \text{ Hd} = \text{Alm} + 3 \text{ An} + 6 \text{ En}$
- 2: $2 \text{ Qtz} + 2 \text{ Py} + 2 \text{ Hd} = 2 \text{ An} + 3 \text{ En} + \text{Fsl}$
- 3: $\text{Gr} + 2 \text{ Py} + 3 \text{ Qtz} = 3 \text{ En} + 3 \text{ An}$
- 4: $2 \text{ Alm} + 3 \text{ En} = 2 \text{ Py} + 3 \text{ Fsl}$
- 5: $\text{Qtz} + \text{Hd} + \text{Alm} = \text{An} + 2 \text{ Fsl}$
- 6: $\text{Gr} + 3 \text{ En} + \text{Alm} = 3 \text{ Hd} + 2 \text{ Py}$
- 7: $\text{Alm} + 2 \text{ Gr} + 3 \text{ Qtz} = 3 \text{ Hd} + 3 \text{ An}$
- 8: $6 \text{ Hd} + 2 \text{ Py} = 2 \text{ Gr} + 3 \text{ Fsl} + 3 \text{ En}$
- 9: $\text{Fsl} + \text{Gr} + \text{Qtz} = 2 \text{ Hd} + \text{An}$
- 10: $3 \text{ Hd} + \text{Alm} = 3 \text{ Fsl} + \text{Gr}$
- 11: $2 \text{ Alm} + \text{Gr} + 3 \text{ Qtz} = 3 \text{ Fsl} + 3 \text{ An}$

b) S-275

- 1: $\text{Alm} + \text{Phl} = \text{Py} + \text{Ann}$
- 2: $6 \text{ Rt} + 2 \text{ Py} + \text{Gr} + 2 \text{ Ann} = 3 \text{ An} + 6 \text{ Ilm} + 2 \text{ Phl} + 3 \text{ Qtz}$
- 3: $3 \text{ Rt} + \text{Py} + \text{Ann} = 3 \text{ Ilm} + \text{Phl} + 2 \text{ Qtz} + \text{Si}$
- 4: $6 \text{ Rt} + \text{Gr} + 2 \text{ Alm} = 3 \text{ An} + 6 \text{ Ilm} + 3 \text{ Qtz}$
- 5: $\text{Alm} + 3 \text{ Rt} + \text{Si} + 2 \text{ Qtz} + 3 \text{ Ilm}$
- 6: $3 \text{ Si} + 3 \text{ Rt} + \text{Py} + 2 \text{ Gr} + \text{Ann} = 6 \text{ An} + 3 \text{ Ilm} + \text{Phl}$
- 7: $2 \text{ Si} + \text{Qtz} + \text{Gr} = 3 \text{ An}$
- 8: $3 \text{ Si} + 3 \text{ Rt} + 2 \text{ Gr} + \text{Alm} = 6 \text{ An} + 3 \text{ Ilm}$

c) S-355

- 1: $2 \text{ Hd} + \text{En} = 2 \text{ Di} + \text{Fsl}$
- 2: $\text{Qtz} + \text{Gr} + \text{En} = \text{An} + 2 \text{ Di}$
- 3: $\text{Qtz} + \text{Py} + \text{Di} = \text{An} + 2 \text{ En}$
- 4: $\text{Qtz} + \text{Gr} + \text{Fsl} = \text{An} + 2 \text{ Hd}$
- 5: $2 \text{ Qtz} + 2 \text{ Py} + 2 \text{ Hd} = 2 \text{ An} + 3 \text{ En} + \text{Fsl}$
- 6: $\text{Qtz} + \text{Py} + 4 \text{ Hd} = \text{An} + 3 \text{ Di} + 2 \text{ Fsl}$
- 7: $\text{Py} + 3 \text{ Di} = 3 \text{ En} + \text{Gr}$
- 8: $3 \text{ Qtz} + 2 \text{ Py} + 2 \text{ Gr} = 3 \text{ An} + 3 \text{ En}$
- 9: $3 \text{ Qtz} + \text{Py} + 2 \text{ Gr} = 3 \text{ An} + 3 \text{ Di}$
- 10: $2 \text{ Py} + 6 \text{ Hd} = 3 \text{ En} + 3 \text{ Fsl} + 2 \text{ Gr}$
- 11: $6 \text{ Hd} + \text{Py} = \text{Gr} + 3 \text{ Fsl} + 3 \text{ Di}$

d) S-12

- 1: $2 \text{ Alm} + \text{Gr} + 2 \text{ Kfs} + 2 \text{ W} = 3 \text{ Qtz} + 3 \text{ An} + 2 \text{ Ann}$
- 2: $\text{Phl} + \text{Alm} = \text{Ann} + \text{Py}$
- 3: $\text{Kfs} + \text{Alm} + \text{W} = \text{Ann} + 2 \text{ Qtz} + \text{Si}$
- 4: $\text{Gr} + 2 \text{ Kfs} + 2 \text{ Py} + 2 \text{ W} = 3 \text{ Qtz} + 2 \text{ Phl} + 3 \text{ An}$
- 5: $2 \text{ Si} + \text{Qtz} + \text{Gr} = 3 \text{ An}$
- 6: $3 \text{ Si} + \text{Kfs} + 2 \text{ Gr} + \text{Alm} + \text{W} = \text{Ann} + \text{Phl}$
- 7: $\text{Kfs} + \text{Py} + \text{W} = \text{Si} + 2 \text{ Qtz} + \text{Phl}$
- 8: $3 \text{ Si} + \text{Py} + \text{Kfs} + 2 \text{ Gr} + \text{W} = 6 \text{ An} + \text{Phl}$

Equilibria plotted in Figure 3.10.

a) PSM-111

- 1: $\text{Phl} + \text{Alm} = \text{Ann} + \text{Py}$
- 2: $\text{Gr} + \text{Qtz} + \text{Si} = 3 \text{ An}$

b) PSM-253

- 1: $\text{Phl} + \text{Alm} = \text{Ann} + \text{Py}$
- 2: $2 \text{ Si} + \text{Qtz} + \text{Gr} = 3 \text{ An}$

d) PSM-LROB

- 1: $4 \text{ Si} + 5 \text{ Qtz} + 2 \text{ Alm} = 3 \text{ Fe-cd}$
- 2: $3 \text{ Cd} + 2 \text{ Ann} = 3 \text{ Fe-cd} + 2 \text{ Phl}$
- 3: $4 \text{ Si} + \text{Qtz} + 2 \text{ Py} = 3 \text{ Cd}$
- 4: $4 \text{ Si} + 5 \text{ Qtz} + 2 \text{ Phl} + 2 \text{ Alm} = 2 \text{ Ann} + 3 \text{ Cd}$
- 5: $2 \text{ Alm} + 3 \text{ Cd} = 2 \text{ Py} + 3 \text{ Fe-cd}$
- 6: $4 \text{ Si} + 5 \text{ Qtz} + 2 \text{ Py} + 2 \text{ Ann} = 3 \text{ Fe-cd} + 2 \text{ Phl}$
- 7: $\text{Phl} + \text{Alm} = \text{Ann} + \text{Py}$

c) PSM-241

- 1: $2 \text{ Gr} + \text{Py} + 18 \text{ Qtz} + 3 \text{ Prg} = 3 \text{ Tr} + 6 \text{ An} + 3 \text{ Ab}$
- 2: $2 \text{ Prg} + 8 \text{ Qtz} = 2 \text{ Ab} + \text{Tr} + \text{Tsc}$
- 3: $5 \text{ Prg} + 26 \text{ Qtz} + 2 \text{ Gr} + \text{Alm} = 5 \text{ Ab} + 6 \text{ An} + 4 \text{ Tr} + \text{FeTs}$
- 4: $6 \text{ Ab} + 8 \text{ Gr} + 4 \text{ Py} + 9 \text{ Tsc} = 6 \text{ Prg} + 3 \text{ Tr} + 24 \text{ An}$
- 5: $3 \text{ Ab} + 2 \text{ Gr} + \text{Py} + 3 \text{ Tsc} = 3 \text{ Prg} + 6 \text{ Qtz} + 6 \text{ An}$
- 6: $4 \text{ Gr} + 2 \text{ Py} + 12 \text{ Qtz} + 3 \text{ Tsc} = 3 \text{ Tr} + 12 \text{ An}$
- 7: $6 \text{ Ab} + 8 \text{ Gr} + 13 \text{ Py} + 9 \text{ FeTs} = 6 \text{ Prg} + 3 \text{ Tr} + 24 \text{ An} + 9 \text{ Alm}$
- 8: $3 \text{ Ab} + 2 \text{ Gr} + 4 \text{ Py} + 3 \text{ FeTs} = 3 \text{ Prg} + 6 \text{ Qtz} + 6 \text{ An} + 3 \text{ Alm}$
- 9: $4 \text{ Gr} + 5 \text{ Py} + 12 \text{ Qtz} + 3 \text{ FeTs} = 3 \text{ Tr} + 12 \text{ An} + 3 \text{ Alm}$
- 10: $\text{Alm} + 8 \text{ Qtz} + 2 \text{ Prg} = \text{FeTs} + \text{Tr} + \text{Py} + 2 \text{ Ab}$
- 11: $6 \text{ Ab} + 4 \text{ Alm} + 8 \text{ Gr} + 13 \text{ Tsc} = 6 \text{ Prg} + 4 \text{ FeTs} + 3 \text{ Tr} + 24 \text{ An}$
- 12: $3 \text{ Ab} + \text{Alm} + 2 \text{ Gr} + 4 \text{ Tsc} = 3 \text{ Prg} + \text{FeTs} + 6 \text{ Qtz} + 6 \text{ An}$
- 13: $2 \text{ Alm} + 4 \text{ Gr} + 12 \text{ Qtz} + 5 \text{ Tsc} = 2 \text{ FeTs} + 3 \text{ Tr} + 12 \text{ An}$
- 14: $\text{Alm} + \text{Tsc} = \text{FeTs} + \text{Py}$

CHAPTER 4: THE TECTONIC EVOLUTION OF THE GRENVILLE OROGEN; CONSTRAINTS FROM THE MAURICIE TRANSECT

4.1 INTRODUCTION

The Mesoproterozoic Grenville orogen represents one the world's largest continuous tracts of high-grade metamorphic rocks (Fig. 4.1). In comparison with younger, less deeply eroded orogenic belts, and despite its accessibility, its crustal growth and tectonic evolution has remained relatively obscure. Progress has been hampered by predominantly poor exposure, combined with the generally extreme degree of deformation and metamorphism. To date, most of the geological and geochronological investigations have been concentrated in Ontario, Western Québec, New York State, and Labrador. Much fewer data are available from the vast intervening region in south-central Québec. In consequence, crustal evolution models have been mostly extrapolated or inferred from these better known regions (e.g. Wynne-Edwards 1972; Windley 1986, 1989; Rivers et al. 1989).

As demonstrated in this thesis, the Mauricie transect in south-central Québec consists of an orogen-oblique, east-dipping homoclinal sequence containing a concordant, low-angle oblique sinistral extensional shear zone (Tawachiche shear zone). The hanging wall, which remained at high structural level during Grenvillian crustal thickening, essentially escaped tectonothermal overprint and preserves many relicts of an earlier arc accretion history that occurred at *ca.* 1.4 Ga. The footwall also consists of relic of this 1.4 Ga arc, but was penetratively deformed at granulite to uppermost-amphibolite facies during overthrusting at *ca.* 1.12 Ga. The “hot” footwall and “cold” hanging wall were then juxtaposed by oblique extension along the Tawachiche shear zone. The preservation of different crustal levels provides an opportunity to document pre-Grenvillian geological events and to monitor the effects of Grenvillian overprint. The identification of two

distinct high-temperature, mantle-derived plutonic suites associated with periodic crustal extension also provides a tectonic context for AMCG-type magmatism (e.g. Emslie 1978).

The data reported in this thesis document approximately 400 m.y. of tectonic, magmatic, and metamorphic evolution of the Grenville orogen in the Mauricie region in south-central Québec. This chapter integrates these new data with previously published data, in order to propose a model for the evolution of the southwestern Grenville orogen. It will be proposed that the southeastern margin of Laurentia (North American craton) evolved as an Andean-type convergent margin during approximately 250 Ma, from *ca.* 1.45 to 1.20 Ga, preceding the Grenville orogen. Continent-continent collision followed at *ca.* 1.20 Ga (e.g. Hanmer and McEachern 1992), with ensuing "Himalayan-type" evolution of the Grenville orogen.

4.2 EVOLUTION OF THE PRE-GRENVILLE LAURENTIAN MARGIN

Based on geological, geochronological, and geophysical data, Rivers et al. (1989) proposed a new subdivision of the Grenville orogen, comprising three first-order longitudinal belts (Fig. 4.1). The Parautochthonous Belt consists of upgraded and reworked rocks belonging to the adjacent foreland. The Allochthonous Polycyclic Belt contains evidence of more than one orogeny, and is composed of tectonically transported terranes now overlying the Parautochthonous Belt. The Allochthonous Monocyclic Belt consists of rocks apparently younger than 1.3 Ga (Silver and Lumbers 1966; Rivers et al. 1989) that were subjected to a single orogenic cycle. The Mauricie transect forms part of the Allochthonous Belts, as defined by Rivers et al. (1989), or of the Central Granulite Terrane, as defined by (Wynne-Edwards (1972), and preserves part of the pre-Grenvillian (i.e. pre-1.2 Ga; Rivers et al. 1989) tectonic history of the North American craton.

There are no dated rocks older than 1.45 Ga (U-Pb zircon) in the Mauricie region.

However, immediately preceding the formation of the Montauban arc at *ca.* 1.45 Ga (Nadeau and van Breemen 1994), the southeastern margin of the North American craton may have been the site of ocean-continent convergent margin. A large number of *ca.* 1.50 to 1.45 Ga plutons that are mostly of quartz-monzonitic and granodioritic composition, but range from gabbroic-anorthositic to syenitic, occur in the Parautochthonous Belt of the southwestern Grenville orogen (van Breemen et al. 1986; van Breemen and Davidson 1988; Lumbers et al. 1990; Corrigan et al. 1994) (Fig. 4.2a). Anderson (1983) interpreted the *ca.* 1.50—1.45 Ga magmatic event which occurred throughout the mid-continental United States, the Parautochthonous Belt of the Grenville orogen, and the Nain Province in Labrador, as "anorogenic". Based on major and trace element geochemical data (van Schmus et al. 1993; Nyman et al. 1994), and on field relationships (Duebendorfer and Christensen 1995; Kirby et al. 1995), recent publications contest this interpretation, and attribute this magmatic event to accretionary tectonics involving oceanic crust, at least in mid-continental North America. As will be seen below, data from the Mauricie transect support this view. The schematic cross-section represented in Figure 4.3a shows a tentative configuration of the southwestern margin of the North American craton at *ca.* 1.50—1.45 Ga, with shallow, northwestward subduction of oceanic crust producing relatively K-rich "I"-type magmatism in the overriding continental plate.

4.2.1 *circa* 1.45 Ga island arc magmatism and sedimentation

At *ca.* 1.45 Ga, an important spatial migration and compositional change in magmatism occurred within the Grenville Province. During this time, plutonism diminished and eventually ceased in the Parautochthonous Belt, while island arc-type volcanism began southwest of the Laurentian margin (now the Montauban arc (Fig. 4.2b)). Interestingly, neodymium t_{DM} model ages obtained on meta-pillowed basalt (~1.70 Ga; van Breemen, personal communication 1995) from the Montauban Group are

significantly older than the *ca.* 1.45 Ga U-Pb zircon age reported from an associated lapilli tuff (Nadeau and van Breemen 1994). Assuming that contamination from the subduction of older sea floor sediments is minimal, this age discrepancy could be explained by the growth of the island arc on older continental crust. This hypothetical sliver of continental crust may have been “exotic”, or more simply, was Laurentian transitional crust, as illustrated in Figure 4.3b. The Japanese arc, which was built on continental crust rifted from Siberia (Uyeda 1978), and the Chilean subduction complex (Bruhn and Dalziel 1977), provide tentative analogues for the *ca.* 1.45 Ga Laurentian Margin. The emplacement of voluminous gabbro plutons and dyke swarms in Labrador during this period, including the $1459 \pm 23/-22$ Ma Shabogamo Gabbro (Connelly and Heaman 1993), and the 1426 ± 6 Ma Michael Gabbro (Schärer et al. 1986) may be related to intra-continental extension.

An important implication of this model concerns the polarity of subduction. Subduction-related magmatism within the Parautochthonous Belt (i.e. the southeastern margin of Laurentia), and the absence of a suture between the Archean foreland and the Parautochthonous Belt, implies that oceanic lithosphere was being subducted towards the northwest. As will be seen below, this subduction polarity likely remained unchanged throughout the entire evolution of the Grenville orogen.

4.2.2 Continental arc magmatism (1.40—1.31 Ga)

Between 1.45 and 1.40 Ga, magmatism in the Mauricie region changed from oceanic to continental arc type (Fig. 4.2c). Abundant calc-alkaline plutons of predominantly dioritic-tonalitic composition were emplaced throughout the Mauricie region between 1.40 and 1.37 Ga (Nadeau and van Breemen 1994; and this study), with some of the bodies (La Bostonnais complex) intruding deformed and previously accreted Montauban Group supracrustal rocks. Contemporaneous or younger plutons are found

elsewhere in the southwestern Grenville Province, and in the Appalachians. In the Mount Holly Complex of Vermont, 1.35 to 1.31 Ga trondhjemitic and tonalitic gneisses have been recognized, and may correlate with inliers of similar composition in the Central Appalachians (Ratcliffe et al. 1991). Gneisses of similar composition and age to those from Vermont have also been found in the southern Adirondack Highlands (McLelland et al. 1988; McLelland and Chiarenzelli 1990), and in the northwestern Bancroft Terrane of the Central Metasedimentary Belt (van Breemen and Hanmer 1986; Lumbers et al. 1990). The 1.35 to 1.31 trondhjemitic-tonalitic suites have been interpreted, on the basis of trace element geochemistry, as continental arc plutons (Ratcliffe et al. 1991). McEachern et al. (1992) have also proposed that 1.37—1.35 Ma tonalitic rocks in the Central Metasedimentary Belt are relics of a continental arc formed within the southeastern margin of Laurentia. The data presented in this chapter support this interpretation, and moreover, expand the time interval of continental arc magmatism to 1.40—1.31 Ga, and extend its distribution to the Mauricie region.

In terms of plate tectonics, the transition from oceanic to continental arc magmatism, and the emplacement of *ca.* 1.40—1.37 Ga plutons within the Montauban Group implies that the Montauban arc had been accreted to a continent before ~ 1.40 Ga, and that it subsequently evolved within a continental margin (Fig. 4.3c). Relatively high-temperature and moderate- to low-pressure metamorphic assemblages found in this study in deformed Montauban Group metasediments have been dated at ~ 1.39 Ga (Chapter 2), supporting this interpretation (e.g. England and Thompson 1986; Walcott 1987; Sandiford and Powell 1991). Between 1.40 and 1.31 Ga, the southeastern Laurentian margin may have resembled an Andean-type margin, with early calc-alkaline magmatism concentrated in the Mauricie region, and later migration of the magmatic front to the northwest, deeper into the continent. Such episodicity and spatial variation of magmatic fronts are commonly observed in active continental margins and can be attributed to

various factors, such as the angle of the subducting plate (Barazangi and Isacks 1976; Lopez-Escobar et al. 1977), the rate of plate convergence (Sugisaki 1976), and the presence or absence of oceanic ridges in the subducting crust (Nur and Ben-Avraham 1982).

To date, the geographic extent of the Montauban island arc, and relics of the 1.40—1.37 Ga continental arc (La Bostonnais complex and gneissic equivalents in the Shawinigan and Mékinac domains) outside of the study area, are not precisely constrained. Paragneisses outcropping south and east of Lac St. Jean, and along the north shore of the St-Lawrence River in the southwestern Baie Comeau Segment (Wynne-Edwards 1972) yield *ca.* 1.38 Ga Rb-Sr isochrons interpreted as metamorphic ages (Frith and Doig 1973), that may correlate with metamorphism in the Montauban arc. Rondot (1986) reports the occurrence of well-preserved metavolcanic and metasedimentary rocks in that same area, suggesting that the Montauban arc extends northeastwards.

Based on Nd isotopic data, Dickin and Higgins (1992) suggested that part of the Grenville Province in Québec, east and north of this study area, is composed of 1.53 Ga island arc terranes that were accreted to Laurentia about 100 m.y. after their formation. However, without the support of U-Pb ages on igneous zircons, their model hinges on the assumption that *ca.* 1.53 Ga Nd model ages corresponded to igneous crystallization ages. Because of the similarity of these model ages with the 1.45—1.70 Ga t_{DM} ages (van Breemen, personal communication 1995) reported from the *ca.* 1.40—1.37 Ga La Bostonnais complex, and the recent identification of *ca.* 1.40 Ga gabbro in the Lac St. Jean area (U-Pb zircon; Hervet et al. 1990), a more likely interpretation is that the Nd data represent minor crustal contamination of a 1.45—1.40 Ga magmatic arc (e.g. DePaolo 1981; DePaolo and Wasserburg 1976; Nelson and DePaolo 1985).

4.2.3 *circa* 1.29—1.22 Ga: Back-arc magmatism

In the Central Metasedimentary Belt and the Adirondack Lowlands and Highlands, tonalitic-trondhjemitic plutonism had more or less ceased by ~ 1.31 Ga. A back arc basin developed within the continental arc at 1.29 Ga (Fig. 4.2d) and was characterized by the emplacement of *ca.* 1.29 to 1.24 Ga tholeiitic basalts and calc-alkaline plutonic rocks in the Elzevir Terrane (see review in Easton (1992)), and *ca.* 1.23 Ga alaskitic to tonalitic plutons in the Adirondack Lowlands (McLelland et al. 1991). Based on trace element geochemical data, Smith and Holm (1990) interpreted the Elzevir metavolcanic rocks as forming part of a back arc basin that developed behind a continental magmatic arc, in response to northwestward subduction of oceanic crust. McEachern and van Breemen (1993) added to the Smith and Holm (1990) model, and suggested that the back arc formed within the old 1.37—1.31 Ga continental arc (Fig. 4.3d). Granitic and tonalitic plutons emplaced between 1.28 and 1.22 Ga within the Adirondack Lowlands and Highlands (McLelland et al. 1991; Chiarenzelli and McLelland 1991), including the Hyde School Gneiss, may be relicts of the active arc. There are no deformational, metamorphic, or magmatic events recorded in the Mauricie transect during this period.

The inception of the Elzevir back arc basin, and the waning of subduction-related calc-alkaline magmatism at ~ 1.22 Ga, could have been produced by a mechanism such as hinge roll-back of the subduction zone. This mechanism, perhaps initiated by the subduction of “colder” oceanic crust, has been proposed in order to explain the development of marginal basins in modern arcs (Fein and Jurdy 1986). Rift-related metavolcanic and sedimentary rocks of the Wakeham Terrane (Martignole et al. 1987), dated at *ca.* 1271 to 1239 Ma (U-Pb zircon; Loveridge 1986), point to orogen-scale extension in that period. The boundary between the subducting oceanic lithosphere and the continent is interpreted to lie southeast of the presently exposed Grenville orogen.

4.3 CONTINENT-CONTINENT COLLISION (1.2—1.0 Ga GRENVILLE OROGENY)

A fundamental transformation occurred in the Grenville Province at *ca.* 1.19 Ga. This approximate date corresponds to the closure of the Elzevir back arc basin (Hanmer and McEachern 1992; McEachern and van Breemen 1993), and the concomitant orogen-scale termination of magmatism related to the subduction of oceanic lithosphere (however, see Corriveau et al. 1990). I will propose below that this period marks the transition from an Andean-type collision, to an Himalayan-type continent-continent collision. Along the Mauricie transect, tectonometamorphic and magmatic events resumed after a long period of quiescence at the level of exposure, with two pulses of syn-extensional AMCG-type magmatism (*ca.* 1.15 Ga, and 1.08—1.05 Ga), separated by a period of thrusting and crustal thickening at *ca.* 1.12—1.09 Ga. The following sections relate events in the Mauricie transect to those reported from elsewhere in the southwestern Grenville orogen. Attempts to relate these events to the northeastern Grenville orogen must remain tentative, because of the large gap in geological information that still exists east of the Mauricie area.

4.3.1 *circa* 1.19—1.13 Ga: Continent-continent collision, AMCG-type plutonism, extension, and sedimentation (phase one of extensional collapse and syn-extension magmatism in an overall convergent orogen)

Any model attempting to explain the tectonic, magmatic, and metamorphic evolution of the Grenville orogen at *ca.* 1.19—1.13 Ga has to reconcile bulk collisional tectonics with the production of anorthosite massifs and associated high-temperature plutons, the emplacement of mafic and ultramafic dykes, granulite-facies metamorphism, and the production of intramontane sedimentary basins. Evidence for deformation related to contractional tectonics appears to be confined to the interval of 1.19—1.15 Ga.

Hanmer and McEachern (1992) and McEachern and van Breemen (1993) presented evidence that northwest-directed thrusting along the Central Metasedimentary Belt boundary thrust zone (Fig. 4.2e) was well underway by *ca.* 1.19 Ga, and coincided with the closure of the Elzevir back arc basin. Evidence for granulite-facies thrusting along the base of the Parry Island thrust sheet at *ca.* 1.16 Ga (van Breemen et al. 1986; Wodicka 1994), and at the same time along the base of the Cabonga thrust sheet in western Québec (Martignole and Friedman 1992), signifies that crustal thickening may have continued until that time. In the Adirondacks, contractional deformation persisted from 1.19 to 1.15 Ga, and was immediately followed by AMCG-type magmatism (McLelland 1994). In the Mauricie region there is no unequivocal field evidence suggesting that thrusting occurred throughout the entire 1.19—1.13 Ga interval.

Magmatism appears to have both overlapped with, and outlived contractional deformation. In the Grenville orogen, plutons emplaced after the *ca.* 1.19 Ga closure of the Elzevir back arc basin are radically different from the arc-related calc-alkaline plutons emplaced at *ca.* 1.40—1.31 Ga. In the Parautochthonous belt in Ontario, numerous gabbroic and ultramafic pods and dykes were emplaced at *ca.* 1.17 Ga (van Breemen and Davidson 1990). At *ca.* 1.16 to 1.13 Ga, massif anorthosites and associated mangerites, charnockites, and granites (AMCG suites; Emslie 1978), were emplaced in the Central Granulite Terrain (Emslie and Hunt 1990), and in the Parry Sound thrust sheet (Wodicka 1994) (Fig. 4.2e). Anorthositic suites from the Central Granulite Terrain include the well-studied Marcy (Chiarenzelli and McLelland 1991; McLelland et al. 1993), Morin (Doig 1991), and Lac St. Jean (Higgins and van Breemen 1992) massifs. Monzonites, granites, and syenites were emplaced within the Frontenac Terrane between 1.18 and 1.16 Ga, and are also believed to be associated to the AMCG suites described above (van Breemen and Davidson 1988; Lumbers et al. 1990; Marcantonio et al. 1990). The Kingston gabbro dykes, emplaced at *ca.* 1.16 Ga (S. Pehrsson, personal communication 1995) also occur

within the Frontenac Terrane. In Labrador and northeastern Québec, AMCG-type plutons of that age group include the voluminous Magpie and Atikontak complexes (Emslie and Hunt 1990). The only dated pluton of this specific age in the study area is the mylonitized $1153 \pm 2/-1$ Ma Lac Paul megacrystic granite, located in the Shawinigan domain. Undated coronitic gabbroic and anorthositic megaboudins bearing the same tectonothermal overprint as the Lac Paul granite are found in the upper structural levels of the Mékinac domain, and likely belong to this suite.

In summary, evidence for thrusting and crustal thickening spans from 1.19 to 1.15 Ga, is mainly focused in Ontario and western Québec, and overlaps with the emplacement of mafic dykes from 1.17 to 1.16 Ga. The most voluminous AMCG-type plutons were emplaced from 1.16 to 1.13 Ga. Except for the Parry Island anorthosite, and the 1.18–1.16 Ga plutons in the Frontenac Terrain, AMCG-type plutons are more concentrated towards the interior of the orogen, in the Central Granulite Terrain.

In general, anorthosite plutonism is thought to be associated with ponding of olivine tholeiitic basalt at the base of the crust in an extensional tectonic setting (e.g. Barker et al. 1975; Emslie 1978; Frost et al. 1989; Emslie and Hunt 1990). However, to this date, field evidence relating anorthosite emplacement and extensional tectonics has not been clearly established in the Grenville Province, possibly due to the intensity of the younger tectonometamorphic overprint during W–NW-directed thrusting. In the absence of structural evidence, other indications should be sought to infer the existent tectonic setting during AMCG-type magmatism.

One indication of at least local extension during the 1.16–1.13 Ga period may be provided by sedimentary basins of that age. At present, three sedimentary units within the Grenville Province fall into this age group. The St. Boniface metasediments (Fig. 4.2f), formed predominantly of highly aluminous metapelite interlayered with rare, thin bands of quartzite and marble, are not older than ~ 1.18 Ga (this thesis). Their minimum age is

not very well constrained, and could either be 1.15 or 1.12 Ga, with the younger date providing the most conservative estimate (Chapter 2). The other two metasedimentary units are: *i*) the 1.14—1.12 Ga Twelve Mile Bay quartzite (Wodicka 1994), and *ii*) the 1.15—1.10 Ga Flinton Group (Sager-Kinsman and Parrish 1993). The Flinton Group, which consists of conglomerate, arenite, pelite, and marble, unconformably overlies the Grenville Supergroup (Moore and Thompson 1972; Easton and Ford 1991). Original geological relationships between the Twelve Mile Bay and St. Boniface metasedimentary rocks with underlying high-grade gneisses are unclear, due to poor exposure, in addition to later tectonic reworking. They could have either been deposited unconformably onto the underlying gneisses, or transported as “exotic” nappes. However, U-Pb dating of detrital zircon grains in all three units suggests a within-orogen source of sediments. All dated grains have possible sources in either the Parautochthonous Belt, the Elzevir, or the Frontenac Terrane (Sager-Kinsman and Parrish 1993; and this study, Chapter 2). A “local” component in the sediment provenance is also suggested by the small amount of natural abrasion on some of the dated igneous zircon grains (Wodicka 1994; and this study, Chapter 2).

The presence of relatively small, isolated patches of metasediments located within the Grenville orogen provides two possibilities regarding the tectonic setting during the 1.16—1.13 Ga period. One possibility is that the sediments represent remnants of a foreland basin developed during 1.12—1.09 Ga thrusting (e.g. Wodicka 1994), and are therefore not related to extension. The fact that foreland basins and mantle-derived magmatism are highly incompatible (e.g. Butler 1986; Dewey et al. 1986) does not support this hypothesis. Another possibility is that the sedimentary units represent remnants of pull-apart or rifted basins, similar to those developed in tectonically overthickened crust (e.g. Molnar and Tapponnier 1978; Burchfiel and Royden 1982).

The 1153 $\pm$ 2/-1 Ma Lac Paul granite intrudes folded, granulite-facies mylonitic gneiss, but the pre-intrusion kinematic history of this high-grade gneiss is unknown. There is no field evidence supporting either a compressional or extensional tectonic setting during the emplacement of this pluton. Overthrusting and erosion is regarded as an important mechanism for the uplift and exhumation of granulite-facies rocks (e.g. Percival and McGrath 1986). However, deep-crustal material can also be exhumed as a consequence of crustal extension (e.g. Brodie and Rutter 1987; Gibson 1990; Reinhardt and Kleemann 1994). The intrusion of mantle-derived plutonic rocks in granulite-facies crust is also commonly observed in lithospherically-thinned regions undergoing exhumation by tectonic denudation (e.g. Sandiford and Powell 1986; Harry et al. 1993; Rutter et al. 1993; Rey 1993). Therefore, the intrusive relationship between the Lac Paul megacrystic granite and granulite-facies mylonitic rocks, and the concomitant development of sedimentary basins is permissive of an extensional tectonic setting during ~1.16—1.13 Ga plutonism. The absence of field evidence for contractional deformation in the orogen interior during this period supports this interpretation. Further northeast in the Lac St. Jean area, Higgins and van Breemen (1992) have found field and geochronological evidence that the *ca.* 1157 Ma Lac St. Jean anorthosite massif was emplaced in a transcurrent tectonic setting, supporting this model. Examples of orogens that have undergone syn-collisional extension are numerous, and include the Himalayas (Burchfield and Royden 1985; Hodges et al. 1992), the Betic-Rif (Doblas and Oyarzun 1989; Platt and Vissers 1989), the Alps (Selverstone 1988), and the Basin and Range Province in western U.S. (Bird 1991). In the above examples, the overall structural geometry is similar, with active thrusting occurring at the outer margins of the orogen, and extension and magmatism occurring in the overthickened interior. In the Grenville orogen, a similar relationship is observed, with thrusts that have been active at 1.19—1.16 Ga (e.g. Central Metasedimentary Belt boundary thrust (van Breemen et al. 1986;

McEachern and van Breemen 1993), and Parry Island thrust sheet (van Breemen et al. 1986; Wodicka 1994), being concentrated nearer to the foreland, whereas the AMCG-type plutons and anorthosite massifs occur in the hinterland.

Tectonic model for the interval 1.19—1.13 Ga

The apparent paradox of crustal thickening associated with the emplacement of mafic dyke swarms, voluminous mantle-derived melts, and sedimentation within an intraplate setting can be best explained by replacement of the continental mantle lithosphere by asthenosphere during crustal shortening. There are three possible mechanisms capable of achieving this stage: *i*) lithospheric delamination (Bird 1979; Nelson 1992), *ii*) convective removal of the thermal boundary layer (Houseman et al. 1981; Platt and England 1993), and *iii*) slab breakoff (Davies and Blanckenburg 1995). Removal of the mantle lithosphere by either of the above mechanisms has predictable consequences which are: *i*) juxtaposition of hot asthenosphere with thinned continental lithosphere, *ii*) increase in surface elevation and therefore, in the potential energy of the crustal lithosphere, and *iii*) a detectable syn- to post-extension thermal pulse in the crust. Among the inevitable results of these processes are the production of mantle-derived melts, lithospheric extension, and the development of intramontane sedimentary basins (e.g. Dewey, 1988; Gans et al. 1989; Axen et al. 1993). Asthenospheric upwelling can produce basaltic magmas at the base of the crust (Kay and Mahlburg-Kay 1993), which in turn can induce extensive lower crustal partial melting to produce K-rich granitoid plutons.

Ca. 1.2 Ga continent-continent collision following ~ 200 Ma of Andean-type evolution must certainly have resulted in crustal shortening and thickening (Fig. 4.3e). The hiatus in magmatism observed throughout the Grenville orogen during the period 1.21—1.18 Ga may have been an artifact of this lithospheric—crustal shortening and

thickening event, and final consumption of oceanic crust. A similar hiatus in calc-alkaline magmatism was observed in the Himalayas after the final closure of the Tethys Ocean and subsequent collision of India with Asia (Searle et al. 1987).

Crustal delamination or convective removal of the thermal boundary layer may have then occurred, leading to uplift and subsequent collapse, sedimentation, and magmatism in the orogen interior (Fig. 4.3f). AMCG-type plutons of batholithic proportions, emplaced mainly in the Central Granulite Terrain at 1.16–1.15 Ga, and then less abundantly through to 1.13 Ga, reflect this stage in orogenic evolution. In modern examples of extensional overthickened crust, sedimentary basins formed in plateau rifts are characterized by nonmarine sequences (Dewey 1988). However, if extensional collapse is extreme, subsidence may continue below sea level, as is proposed for the Alboran Basin (Platt and Vissers 1989), for example. This has important implications for the interpretation of the depositional environments of the Twelve Mile Bay, Flinton, and St. Boniface sediments. The first two contain predominantly coarse siliciclastic sediments compatible with a fluvial or lacustrine environment of deposition. However, the St. Boniface sediments are mostly composed of metamorphosed mudstone with minor sandstone and carbonates. Argillaceous and siliciclastic sediments, and to a lesser degree, carbonates, can be deposited in a lacustrine basin. However, they are more common in marine environment. As illustrated above, marine sedimentation is not incompatible with deposition in an extended plateau, and does not disprove the extensional plateau model.

Models of crustal “delamination” predict that once the crust and lithosphere thicknesses are reestablished and the thermal boundary layer thickens, igneous activity decreases, as well as the geothermal gradient (Platt and England 1993; Dewey 1988). If the boundary conditions permit, compressional deformation can then resume in the interior of the thermally and rheologically reestablished orogen (e.g. Collins 1994).

4.3.2 *circa* 1.12—1.09 Ga; Crustal thickening

At approximately the same time that AMCG-type magmatism ceased throughout the southwestern Grenville orogen (*ca.* 1.13 Ga), W-NW-directed thrusting resumed in the orogen interior, leading to the development of the strong regional deformation fabric and granulite to uppermost-amphibolite metamorphism observed in the Mékinac and Shawinigan domains. The 1153 Ma Lac Paul megacrystic granite, as well as anorthosite and gabbro pods in the upper Mékinac domain, were deformed and metamorphosed at granulite facies during this tectonometamorphic event. Elsewhere in the Grenville Province, important tectonothermal activity occurred at about the same time. Sager-Kinsman and Parrish (1993) have found evidence suggesting that sillimanite—K-feldspar grade metamorphism and deformation affecting the Flinton Group occurred between 1150 and 1080 Ma. Wodicka (1994) reports two periods of northwest-directed thrusting along the base of the Parry Island thrust sheet; an early period at *ca.* 1159—1157 Ma, and a later one at *ca.* 1120 Ma that deformed and metamorphosed the 1.14—1.12 Ga Twelve Mile Bay metasediments at uppermost-amphibolite facies. In Ontario, unequivocal evidence for NW-directed thrusting is also provided by *ca.* 1.11 Ga syn-tectonic pegmatites that were emplaced at high metamorphic grade, along the sole of the Seguin thrust sheet in the southeastern Parautochthonous Belt (Nadeau 1990; van Breemen and Davidson 1990; Nadeau and Hanmer 1992). The 1.12—1.09 Ga opening of the Keweenawan rift in the Grenville foreland has also been interpreted as a far-field effect of Grenvillian collisional tectonics (Gordon and Hempton 1986).

The overall style of deformation in the Mékinac and Shawinigan domains during this period is characterized by subhorizontal to shallow-dipping penetrative shear, and more generally in the southwestern Grenville orogen, by focused deformation in broad zones around plutons (e.g. Wodicka 1994), and localized thrusting along deep-crustal ductile shear zones (Davidson et al. 1982; Culshaw et al. 1983; Hanmer 1988; Nadeau

and Hanmer 1992). In the Mauricie region, late-thrusting leucosomes from the St. Boniface metasediments date the approximate end of contractional deformation at ~ 1.09 Ga (Chapter 2).

These data suggest that after the emplacement of anorthosite massifs, and after the deposition of sediments in intramontane basins, thrusting and thickening was re-established in the Grenville orogen at *ca.* 1.12 Ga (Fig. 4.3g). Thermobarometric constraints from the Twelve Mile Bay and St. Boniface metasediments are in the order of ~ 9 kb (Wodicka 1994) and ~ 7.5 to 8 kb (Lévesque and Nadeau 1994; and this study, Chapter 3), respectively, suggesting that the presently exposed surface in these regions were tectonically buried under 22 to 30 km of crust during that thrusting event. The fact that the presently exposed southwestern Grenville orogen is underlain by normal thickness crust (Mereu et al. 1986), but that mineral assemblages at the surface locally reflect up to 30 km of tectonic burial, suggests that the 1.12—1.09 Ga thrusting event led to a total crustal thickness of ~ 70 km (e.g. Nadeau and Hanmer 1992).

4.3.3 *circa* 1.09—1.05 Ga; Second phase of extension and AMCG-type magmatism in an overall compressional orogen

This important period in the evolution of the Mauricie region is highlighted by the tectonic denudation of the high-grade Mékinac and Shawinigan domains and their juxtaposition with the "cold" Portneuf—St. Maurice domain (Chapters 2 and 3). Tectonic denudation occurred by oblique extension along the amphibolite-facies Tawachiche shear zone (Fig. 4.3h), and was coeval with voluminous AMCG-type magmatism. This younger pulse of AMCG-type magmatism produced proportionally less anorthosite than the older one at 1160—1130 Ma. Instead, large quantities of mangerite, hornblende $\pm$ pyroxene granite (locally rapakivi), and charnockite were produced, as well as gabbro, norite, and jotunite (Fig. 4.2g). The younger suite of AMCG plutons were emplaced between 1077

and 1055 Ma, and show a compositional evolution from mafic to felsic, with progressively younging age. The $1077 \pm 10/2$ Ma Shawinigan norite cuts mylonitic fabrics that were developed earlier during 1.12—1.09 Ga thrusting, and is undeformed and unmetamorphosed (Chapter 2).

A syn-extensional pegmatite from the Tawachiche shear zone yielded a U-Pb zircon age of $1065 \pm 2/1$ Ma, confirming the coeval nature of oblique extension and AMCG plutonism (Chapter 2). However, isotopic evidence suggests that oblique extension may have started earlier, perhaps as soon as ~ 1.09 Ga. Monazite ages in the footwall of the Tawachiche shear zone range from 1094 ± 2 Ma to 1081 ± 4 Ma (Chapter 2). Because these dated monazites come from rocks that had been metamorphosed at temperature conditions of ~ 800 °C (Chapter 3), and given that the closure temperature of monazite is generally accepted to be ~ 725 °C (Parrish 1990), they can be confidently interpreted as representing post-metamorphic cooling ages. In the absence of field evidence for an alternative mechanism, we can infer that the 1094 Ma monazites blocked at that age in response to cooling by denudation. This relationship implies that thrusting in the Mékinac and Shawinigan domains and oblique extension along the Tawachiche shear zone may have overlapped during a period of ~ 4 million years, in the interval 1094—1090 Ma. Contemporaneous extension and shortening are known from many orogenic belts, and have been described from the Himalayas (Hodges et al. 1992), and the eastern Alps (Ratschbacher et al. 1989). It appears to be the norm, and not an exception to orogenic processes (e.g. Molnar and Lyon-Caen 1988).

Between 1.09 and 1.06 Ga, while the Central Granulite Terrain was undergoing exhumation by tectonic denudation, thrusting at high metamorphic grade resumed along the Central Metasedimentary Belt boundary thrust zone (van Breemen and Hanmer 1986; Hanmer and McEachern 1992; McEachern and van Breemen 1993). Overthrusting of the Central Metasedimentary Belt onto the Central Gneiss Belt led to the strong

tectonothermal overprint observed in the latter (Nadeau and Hanmer 1992; Wodicka 1994; Corrigan et al. 1994). High-grade deformation and metamorphism related to the “Ottawan orogeny” (Moore and Thompson 1980) is also believed to have occurred in the Adirondack Highlands during the same period (McLelland and Chiarenzelli 1990; Mezger et al. 1991). At the present level of exposure, the orogen-scale pattern of extension and magmatism in the orogen interior and contraction at the active margin is very similar to the pattern observed at ~ 1.16 Ga, and may demonstrate the action of similar processes occurring at different periods.

4.3.4 Tectonic model for the interval 1.09—1.05 Ga

Current tectonic models for the Grenville orogen in the interval 1.09—1.05 Ga include accretion of micro-plates (Easton 1992), accretion of an Indonesia-type arc (Corriveau et al. 1990), and thrust stacking and crustal thickening induced by continent-continent collision (Hanmer and McEachern 1992). However, as suggested for the 1.19—1.13 Ga interval, the contemporaneous development of thrust faults at the active northwestern margin of the orogen, coupled with voluminous mantle-derived magmatism and extension and tectonic denudation in the orogen interior warrants a modification to the above models.

Figure 4.3h illustrates the process that I favor, which is intended as a working hypothesis that can be tested by further research. The resumption of crustal shortening and thrusting in the orogen interior at ~ 1.12 Ga led to a second phase of thickening of the lithospheric mantle that culminated at ~ 1.09 Ga. The thick root of the lithospheric mantle may have become detached and incorporated in the deeper mantle (i.e. “delaminated” in the sense of Bird 1979), or convectively removed (e.g. Houseman et al. 1981). This led to isostatic uplift of the overthickened crust and localized extension. The arrival of asthenosphere induced melting of the lower crust, and the resultant magmas were

emplaced in regions of crustal extension, forming the younger phase (*ca.* 1.09—1.05 Ga) of high-temperature, AMCG-type plutonism. Parts of the orogenic belt that had remained at high structural levels during the ~1.12—1.09 Ga collisional phase (i.e. the Portneuf—St. Maurice domain, the Adirondack Lowlands, and the Frontenac, Elzevir (?), and Wakeham Terranes), were lowered along extensional faults and juxtaposed with “hot” crust.

In the Elzevir and part of the Frontenac terranes, Corriveau et al. (1990) described a suite of post-metamorphic, *ca.* 1.09 to 1.07 Ga plutons of ultrapotassic, K-rich alkaline, and shoshonitic composition, interpreted as the products of oceanic arc magmatism.

However, data from this study, from Hanmer and McEachern (1992), and McEachern and van Breemen (1993), suggest that subduction of oceanic crust had ceased about 100 Ma earlier, at *ca.* 1.2 Ga, requiring a different explanation for the potassic intrusions.

Penecontemporaneous plutons from the Mauricie transect show a compositional evolution from gabbro—norite, to mangerite, to hornblende $\pm$ pyroxene granite, during their emplacement between 1077 and 1056 Ma. Trace element geochemical analyses of samples from the above suite (Appendix 4.1), plotted on Rb vs (Y + Nb) discriminant diagram (Pearce et al. 1984), follow a curvilinear trend with time, from the volcanic arc field (norite-mangerite) to within-plate (mangerite-granite) (Fig. 4.4a). Trace element geochemical data published in Corriveau (1990), plotted in a similar diagram also show an evolution from volcanic arc to within-plate fields (Fig. 4.4b). The observed tectonic setting during this period in the Mauricie region was extensional collapse of overthickened continental crust, strongly suggesting that the “volcanic arc” signature must have been inherited from an old subduction regime. The more evolved “within-plate” signature characterizing the more felsic end-member of these suites accurately reflects the extensional continental setting inferred from field data. This type of magmatic and trace element evolution from “volcanic arc”-type to “within-plate”-type has been

observed in modern examples of regions of continental crust undergoing post-collisional extension (Storey et al. 1988; Storey and Alabaster 1991).

Corriveau et al. (1990) have interpreted the 1.09—1.07 Ga potassic plutons outcropping in the Elzevir and Frontenac Terranes as relicts of a “Sunda-type” arc. In contrast, Windley (1986) interpreted this plutonic suite as post-tectonic, having inherited its arc geochemical signature from an old subduction regime. The data presented in this thesis agree with, and provide a tectonic context for Windley's interpretation. One of the consequences of convective removal of the mantle lithosphere predicted by McKenzie (1989) would be the production of highly potassic melts, in agreement with some of the observed plutonism in that period. Interestingly, Kay and Mahlburg Kay (1993) report the presence of recent shoshonitic and K-rich calc-alkalic volcanism in the Altiplano—Puna region of the South American Cordillera, that may provide a better analogy for 1.09—1.07 Ga magmatism in the Elzevir Terrain. Cenozoic K-rich magmatism in the Tibetan Plateau has also been interpreted as a result of lithospheric delamination (Arnaud et al. 1992).

In stark contrast with extensional tectonics, lower-crustal exhumation and the associated mantle-derived magmatism observed in the active core of the orogen during the interval 1.09—1.05 Ga, Hanmer and McEachern (1992) and McEachern and van Breemen (1993) report renewed high-grade thrusting along the Central Metasedimentary Belt boundary thrust zone during the same period. Examples of coeval development of extensional plateaus in orogen interiors, and thrusting at orogen margins are common (e.g. Molnar and Lyon-Caen 1988), specifically the Himalayas (Molnar and Taponnier 1978), the Betic-Rif (Platt and Vissers 1989), the Lachlan fold belt (Collins 1994), and the South American Cordillera (Mercier 1981). Moreover, models of collisional orogens predict that once the critical thickness of a collisional plateau is attained, mountain ranges should begin to extend laterally (Molnar and Lyon-Caen 1988; Willett et al. 1993). This

relationship has been observed in the Grenville orogen, with the latest deformation related to thrusting (and the youngest cooling ages), reported from the Parautochthonous Belt and the Grenville Front (e.g. Haggart et al. 1993; Martignole and Friedman 1992; Connelly and Heaman 1993).

Some of the data reported from the Adirondack Highlands conflict with the model presented above. According to McLelland (1994), the Adirondack Highlands experienced "anorogenic" hornblende granite plutonism during the interval 1100—1095 Ma, followed by intense deformation and high-grade metamorphism related to compressional tectonics in the interval 1090—1070 Ma, and post-collisional extension accompanied by leucogranite magmatism in the interval 1070—1060 Ma. A compressional regime in the Adirondacks in the period 1.09—1.07 Ga is difficult to reconcile with the delamination model presented above, which requires general extension in the orogen interior in that period. In addition, the paradigm among researchers in the Adirondacks is that peak granulite-facies metamorphism corresponding to depths of burial of presently exposed rocks of 20 to 25 km occurred in the interval 1080—1050 Ma (Bohlen et al. 1985; McLelland and Chiarenzelli 1990). However, Chiarenzelli and McLelland (1991; p. 587) state that most plutons of the 1080—1060 Ma Late Leucogranite suite show "variable deformation", and that "some occurrences exhibit little, if any, fabric". In addition, whereas *ca.* 1.16—1.13 Ga gabbro and anorthosite are commonly metamorphosed at granulite facies and contain metamorphic garnet and pyroxene (McLelland and Isachsen 1986), plutons of the *ca.* 1100—1090 Ga Younger Granitic suite only rarely exhibit garnet, which is restricted to the pluton margin. Moreover, *ca.* 1089 Ma fayalite-bearing granitic plutons (U-Pb zircon; Chiarenzelli and McLelland 1991), which occur at several localities throughout the northwestern Adirondack Highlands, have been interpreted as post-tectonic and intrude earlier high-grade fabrics developed in host gneisses (McKinney et al. 1989), some as young as *ca.* 1093 Ma (U-Pb zircon; Chiarenzelli and McLelland

1991). The persistence of fayalite in granite is difficult to reconcile with regional scale granulite facies metamorphic conditions.

Nonetheless, McLelland (1994) does favor a model of lithospheric thinning produced by delamination for the interval 1.07—1.05 Ga, in agreement with field and isotopic evidence for extension and mantle-derived magmatism in the Mauricie region during the same period. However, it is possible that extension as a manifestation of crustal overthickening was initiated much earlier in the structurally higher Mauricie region, at *ca.* 1.09 Ga, than in the "deeper" Adirondack region, where compressional deformation may have persisted until ~ 1.07 Ga. Syn-collisional extension, with high-level extension contemporaneous with deeper level contraction, has been inferred to occur in overthickened collisional zones (e.g. Dalziel and Brown 1989; Hodges et al. 1992).

4.4 IMPLICATIONS FOR GRENVILLE TECTONICS AND CONCLUSIONS

This thesis provides new constraints on the geological evolution of the Mauricie region, south-central Québec, and on the tectonomagmatic and metamorphic evolution of the Grenville Province. The recent trend in Grenville research has been to focus on the differences between adjacent lithological packages, and to model the evolution of the Grenville orogen in terms of accreted "exotic" terranes (e.g. Windley 1986; Corriveau, 1990; Easton 1992). The data presented in this thesis show that the presently exposed Grenville Province already formed a cohesive block as early as 1.4 Ga, and evolved as an Andean-type margin until ~ 1.20 Ga, with continuous northwestward subduction of oceanic lithosphere. Crustal growth by magmatic accretion ceased in the Mauricie region at ~ 1.37 Ga, but continued in the southwest and northeast Grenville orogen until at least 1.21 Ga, culminating with the eventual development of the Elzevir back arc basin and the Wakeham rift. Given this tectonic context, the Central Metasedimentary Belt would have

been formed of sediments deposited at ≤ 1.45 Ga on thinned continental lithosphere, between the newly formed Mauricie arc and the Early Proterozoic margin of the North American craton (the Parautochthonous Belt).

The most fundamental transformation in the Grenville orogen occurred at *ca.* 1.2 Ga, with the closure of the "pre-Grenville" ocean and ensuing continent-continent collision. This collisional event led to thickening of the lithosphere, followed by the removal of the thickened lithospheric root, and resulting uplift and extension in the orogen interior. Effects were mantle-derived magmatism and deposition of intramontane sedimentary basins.

Acceptance of the "delamination" model to explain geological events that occurred during the continent-continent collision phase of the Grenville orogeny has important implications, both for the evolution of the Grenville orogen, and for "delamination" processes. We now have geochronological evidence that there were two distinct periods of voluminous AMCG-type magmatism, that principally differ in the proportion of anorthosite. Plutonism was restricted to the orogen interior and was accompanied by strike-slip and extensional faulting. In contrast, coeval thrusting was concentrated at the active orogen margin, particularly along the Central Metasedimentary Belt boundary thrust zone. Between the two periods of AMCG-type plutonism, thrusting and crustal shortening resumed within the orogen interior. Thrusting also continued after the second period of AMCG magmatism, until about 1.00 Ga, but was mainly active along, or closer to the Grenville Front (e.g. Haggart et al. 1993; Connelly et al. 1995). Late extensional faults are also known to have occurred in the Parautochthonous Belt, along the Central Britt shear zone (Ketchum et al. 1994), and in the Central Metasedimentary Belt along the Bancroft shear zone (van der Pluijm and Carlson 1989).

The duration of lithospheric thickening and resulting "delamination" in the Grenville orogen appears to have been roughly 30 Ma for each period. The first period of

continent-continent collision and thickening lasted from ~ 1.19 to 1.16 Ga. It was followed by voluminous AMCG-type plutonism from ~ 1.16 to 1.13 Ga. Renewed thrusting and crustal thickening in the orogen interior lasted from ~ 1.12 to 1.09 Ga. The second period of AMCG-type plutonism followed from 1.09 to 1.05 Ga. Contractional deformation persisted throughout the entire period, and continued, albeit in the active orogen margin, until at least 1.00 Ga (Haggart et al. 1993; Connelly et al. 1995). The phases of lithospheric thickening, and removal of the lithosphere beneath the Grenville mountain belt, each lasting approximately 30 Ma, are consistent with the duration of lithospheric overthickening and mechanical restoration predicted by "delamination" models (Houseman et al. 1981).

APPENDIX 4.1

Whole-rock geochemistry of AMCG-type rocks from the Mauricie transect

Results of 12 whole-rock analyses, obtained from post-thrusting (e.g. 1.08—1.05 Ga) AMCG-type plutons are presented in this appendix. Powdered samples were analysed for major and trace elements at the Centre Géoscientifique de Québec. Major elements, as well as Y, Rb, Sr, Zr, Nb, Ni, Cr, and V, were measured using an X-ray-fluorescence (XRF) spectrometer. Other trace elements, as well as rare earths (REEs) were measured by neutron activation. Samples varied in weight, from ~ 2 to 5 kg. During all analyses both intralaboratory and international standards were included with the samples. Duplicate analyses of the standards indicate that analytical precision is better than 5% for the major elements, and between 5 and 10% for trace elements.

APPENDIX 4.1. Major and trace elements in post-thrusting AMCG-type plutonic rocks from the Mauricie transect.

Sample	Shawinigan norite			LeJeune pluton					Missionnaire pluton		
	N	N	M	M	M	MD	LG	G	G	MD	MD
SiO ₂	49.17	46.37	59.53	60.04	60.06	49.63	52.31	45.22	51.90	58.27	53.74
TiO ₂	0.91	2.79	1.12	1.36	3.53	1.72	0.89	4.28	1.15	0.83	2.05
Al ₂ O ₃	16.30	16.11	17.19	14.53	17.70	19.53	18.25	13.57	17.16	16.20	16.21
Fe ₂ O ₃	9.28	13.55	5.55	7.78	5.63	9.61	8.07	18.08	9.94	7.25	11.28
MnO	0.12	0.14	0.11	0.11	0.12	0.09	0.12	0.20	0.13	0.11	0.20
MgO	9.44	6.20	1.23	1.56	1.08	3.50	7.37	3.83	5.96	4.33	2.45
CaO	7.93	9.88	3.59	3.62	3.53	8.55	7.17	7.22	6.24	6.65	5.40
Na ₂ O	2.85	2.90	4.67	3.53	4.49	4.00	3.71	3.01	3.86	3.52	4.22
K ₂ O	0.98	0.75	4.59	3.97	4.84	0.90	0.83	1.49	1.20	1.71	1.87
P ₂ O ₅	0.28	1.23	0.41	0.62	0.44	0.16	0.17	2.09	0.27	0.21	1.27
LOI	0.84	0.66	0.40	0.79	0.15	0.82	0.88	0.74	0.60	0.84	0.70
Total	98.39	100.85	98.91	98.42	99.50	98.79	100.00	100.05	98.66	100.11	99.75
Ba	796	727	2,974	2,906	2,953	607	418	1,055	671	541	1,226
Rb	15	11	53	65	61	4	8	45	11	52	60
Sr	976	1,018	831	619	962	1,392	1,221	910	1,168	464	755
Y	14	19	47	62	49	11	9	48	11	24	67
Zr	119	102	1,009	951	526	89	78	147	102	112	942
Nb	< 3	< 3	14	20	20	< 3	< 3	9	< 3	< 3	21
V	158	320	42	81	23	353	149	452	166	201	135
Ta	< 3	< 3	0.935	1.19	1.25	0.309	< 3	0.967	0.367	< 3	1.32
Th	1.05	0.545	0.853	1.7	0.765	0.245	0.494	1.38	0.331	2.48	2.21
La	18	18.2	79.3	82	89.5	10.7	10.5	48.2	15	26	88.4
Ce	38.9	41.2	173	195	205	25.3	24.1	124	35.7	54	199
Nd	23.2	33.4	101	125	117	17.2	11.7	88.5	23.1	32.6	132
Sm	4.47	6.49	18.5	24	20.3	3.51	2.67	17.8	4.09	5.87	24.8
Eu	1.46	2.13	5.62	5.69	5.93	1.46	1.14	4.63	1.51	1.48	5.42
Tb	0.473	0.808	1.98	2.65	2.13	0.457	0.332	2.11	0.528	0.79	2.81
Yb	1.26	1.42	4.16	5	4.26	0.743	0.562	3.8	1.07	2.47	5.27
Lu	0.161	0.212	0.618	1	0.627	0.122	0.121	0.536	0.138	0.339	0.748

N = norite, M = mangerite, MD = monzodiorite, LG = leucogabbro, G = gabbro
Major elements and Ba, Rb, Sr, Y, Zr, Nb, and V by X-ray fluorescence; Ta—Lu by neutron activation analysis

APPENDIX 4.1, ctd...

Sample	Parc des Laurentides complex *					
	MG	MG	C	C	C	MG
SiO ₂	62.81	68.69	66.99	63.55	64.26	67.56
TiO ₂	1.26	0.79	0.81	1.33	1.21	0.76
Al ₂ O ₃	13.90	13.78	14.88	14.12	13.97	15.04
Fe ₂ O ₃	7.16	4.05	3.63	7.30	6.54	3.60
MnO	0.18	0.10	0.12	0.17	0.17	0.09
MgO	0.81	0.50	0.39	1.21	0.87	0.56
CaO	4.14	2.69	2.61	4.10	3.80	2.32
Na ₂ O	3.03	2.95	3.80	3.03	3.34	3.61
K ₂ O	3.11	4.39	4.72	3.25	3.36	4.70
P ₂ O ₅	0.67	0.31	0.29	0.65	0.54	0.27
LOI	0.26	0.33	0.27	0.22	0.24	0.40
Total	97.33	98.59	98.51	98.93	98.30	98.91
Ba	1865	1695	2380	1780	1922	2465
Rb	59	85	79	65	64	77
Sr	517	368	442	485	512	450
Y	88	77	73	87	88	65
Zr	685	528	755	714	682	730
Nb	22	18	18	22	20	17
Ta	1.5	1.1	1.1	1.4	1.4	0.82
Th	2.8	3	4.2	3.8	3.2	2.6
La	102	83	120	94	100	94
Ce	253	208	280	233	244	220
Nd	148	125	151	134	138	120
Sm	29	24	27	28	28	23
Eu	6.4	5.2	6.9	6.7	6.1	6.3
Tb	3.3	2.9	2.9	3.2	3.3	2.5
Yb	7.5	6.2	6	7.3	7.2	5.2
Lu	1.1	0.94	0.91	1.1	1.1	0.82

MG = megacrystic granite, C = charnockite

* L. Nadeau, unpublished data

Major elements and Ba, Rb, Sr, Y, Zr, Nb, and V by X-ray fluorescence;

Ta—Lu by neutron activation analysis

Figure 4.1. Map of the Grenville orogen in eastern North America. **a)** Lithotectonic subdivisions after Rivers et al. (1989). **b)** Lithotectonic subdivision after Wynne-Edwards (1972).

Figure 4.2. a to g: Sequence of maps of the southwestern Grenville orogen showing the distribution of magmatism or sedimentation, at the time-intervals shown. AH = Adirondack Highlands; AL = Adirondack Lowlands; B = Bancroft Terrane; CGT = Central Granulite Terrane; CMB = Central Metasedimentary Belt; CMBbtz = Central Metasedimentary Belt boundary thrust zone; E = Elzevir Terrane; F = Frontenac Terrane; P = Parry Sound thrust sheet; MHC = Mount Holly Complex; TMB = Twelve-Mile Bay. Paleozoic cover is shown in light gray. See text for explanations.

Figure 4.3. a to h: Series of schematic cross-sections through the southwestern Laurentian margin, and the Grenville orogen, showing the geological evolution through time. See text for explanations.

- a) ca. 1.50 — 1.45 Ga; K-rich, "I"-type magmatism in the southeastern margin of Laurentia

- b) ca. 1.45 Ga; Development of the Montauban island arc on an older fragment of continental crust

- c) ca. 1.40-1.31 Ga "Andean-type" calc-alkaline magmatism

- d) ca. 1.28-1.24 Ga; Back arc and arc magmatism

Figure 4.3. ctd...

e) ca. 1.19—1.16 Ga; Continent-continent collision

f) ca. 1.16—1.13 Ga; Syn-collisional extension, AMCG-type magmatism, and formation of intramontane sedimentary basins

g) 1.12—1.09 Ga; Resuming of lithospheric thickening

h) ca. 1.09 - 1.05 Ga; Second phase of extension and mantle-derived plutonism, and exhumation of granulite core.

Figure 4.4. $(Y + Nb) / Rb$ diagrams showing the distribution of norites and granitoid rocks from **a)** the Mauricie transect, and **b)** the Central Metasedimentary Belt. Chemical analyses for rocks of the Mauricie transect are given in Appendix "4.1". Chemical analyses for samples from the Central Metasedimentary Belt are published in Corriveau et al. (1990). The U-Pb zircon ages shown in Figure "a" are from Chapter 2. Discriminant fields are after Pearce et al. (1984).

REFERENCES CITED

- Allègre, C.J., and others (35 authors), 1984. Structure and evolution of the Himalayan-Tibet orogenic belt. *Nature*, **307**: 17-22.
- Anderson, A.T. 1983. Proterozoic anorogenic plutonism of North America. *In* Proterozoic Geology, *edited by* L.G. Medaris, D.M. Mickelson, C.W. Byers, and W.C. Shanks. Geological Society of America Memoir, **161**: 133—154.
- Anovitz, L.M. 1991. Al-zoning in pyroxene and plagioclase: window on late prograde to early retrograde P-T paths in granulite terranes. *American Mineralogist*, **76**: 1328—1343.
- Arnaud, N.O., Vidal, Ph., Tapponnier, P., Matte, Ph., and Deng, W.M. 1992. The high K₂O volcanism of northwestern Tibet: Geochemistry and tectonic implications. *Earth and Planetary Science Letters*, **111**: 351—367.
- Avramtchev, L., and Piché, G. 1981. Carte des gîtes minéraux du Québec, région de Laurentide-Saguenay; Ministère de l'Énergie et des Ressources du Québec, DPV-809.
- Axen, G.J., Taylor, W.J., and Bartley, J.M. 1993. Space-time patterns and tectonic controls of Tertiary extension and magmatism in the Great Basin of the Western United States: Geological Society of America Bulletin, **105**: 56—76.
- Baldwin, S.L., Lister, G.S., Hill, J., Foster, D.A., and McDougall, I. 1993. Thermochronologic constraints on the Tectonic evolution of active metamorphic core complexes, D'Entrecasteaux Islands, Papua New Guinea. *Tectonics*, **12**: 611—628.
- Barazangi, M., and Isacks, B.L. 1976. Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America. *Geology*, **4**: 686—692.
- Barker, F., Wones, D.R., Sharp, W.N., and Desborough, G.A. 1975. The Pikes Peak batholith, Colorado Front Range, and a model for the origin of the gabbro— anorthosite—syenite—potassic granite suite. *Precambrian Research*, **2**: 97—160.

- Barton, J.M., and Doig, R. 1974. Temporal relationships of rock units in the Shawinigan area, Grenville Province, Québec. *Canadian Journal of Earth Sciences*, **11**: 686—690.
- Béland, J. 1961. Shawinigan area. County of Champlain, St-Maurice and Lavolette. Québec Dept. of Mines, Geological Report 97, 59 p.
- Berg, J.H. 1977. Dry granulite mineral assemblages in the contact aureoles of the Nain Complex, Labrador. *Contributions to Mineralogy and Petrology*, **64**: 33—52.
- Berman, R.G. 1990. Mixing properties of Ca-Mg-Fe-Mn in garnets. *American Mineralogist*, **75**: 328—344.
- Berman, R.G. 1991. Thermobarometry using multi-equilibrium calculations: a new technique, with petrological applications. *Canadian Mineralogist*, **29**: 833—855.
- Bernier, L.R., and MacLean, W.H. 1993. Lithogeochemistry of a metamorphosed VMS alteration zone at Montauban Grenville Province, Québec. *Exploration and Mining Geology*, **2**: 367—386.
- Berthé, D., Choukroune, P., and Jegouzo, P. 1979. Orthogneiss, mylonite, and non-coaxial deformation of granites: the example of the South Armorican shear zone. *Journal of Structural Geology*, **1**: 31—42.
- Bhattacharia, A., Mazumdar, A.C., and Sen, S.K. 1988. Fe—Mg mixing in cordierite: constraints from natural data and implications for cordierite-garnet geothermometry in granulites. *American Mineralogist*, **73**: 338—344.
- Bird, P. 1979. Continental delamination and the Colorado plateau. *Journal of Geophysical Research*, **84**: 7561—7571.
- Bird, P. 1991. Lateral extrusion of lower crust under high topography, in the isostatic limit. *Journal of Geophysical Research*, **96**: 10,275—10,286.
- Bohlen, S.R. 1987. Pressure-temperature-time paths and a tectonic model for the evolution of granulites. *Journal of Geology*, **95**: 617-632.

- Bohlen, S.R., Wall, V.J., and Boettcher, A.L. 1983. Experimental investigations and geological applications of equilibria in the system $\text{FeO-TiO}_2\text{-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. *American Mineralogist*, **68**: 1049—1058.
- Bohlen, S.R., Wall, V.J., and Boettcher, A.L. 1983. Geobarometry in granulites. *In* *Kinetics and Equilibrium in Mineral Reactions*, edited by S.K. Saxena. Springer-Verlag, New York, pp. 141—171.
- Bohlen, S.R., Valley, J.W., and Essene, E.J. 1985. Metamorphism in the Adirondacks, 1. Petrology, pressure, and temperature. *Journal of Petrology*, **26**: 971-992.
- Brodie, K.H., and Rutter, E.H. 1987. Deep crustal extensional faulting in the Ivrea Zone of Northern Italy. *Tectonophysics*, **140**: 193—212.
- Bruce, R.M., Nelson, E.P., Weaver, S.G., and Lux, D.R. 1991. Temporal and spacial variations in the southern Patagonian batholith; Constraints on magmatic arc development. *Geological Society of America Special Paper*, **265**: 1—12.
- Bruhn, R.L., and Dalziel, I.W.D. 1977. Destruction of the Early Cretaceous marginal basin in the Andes of Tierra del Fuego. *In* *Island Arcs, Deep Sea Trenches, and Back-arc Basins*, edited by M. Talwani. Maurice Ewing Serial, Procedure Symposium, **1**: 55—59.
- Brun, J.P., and Pons, Strain patterns of pluton emplacement in a crust undergoing non-coaxial deformation, Sierra Morena, Southern Spain. *Journal of Structural Geology*, **3**: 219—229.
- Brun, J.P., and Merle, O. 1988. Experiments on folding in spreading-gliding nappes. *Tectonophysics*, **145**: 129-139.
- Burchfiel, B.C., and Royden, L.H. 1982. Carpathian foreland fold and thrust belt and its relation to Pannonian and other basins. *Bulletin of the American Association of Petroleum Geology*, **66**: 1179—1195.

- Burchfiel, B.C., and Royden, L.H. 1985. North-south extension within the convergent Himalayan region. *Geology*, **13**: 679—682.
- Butler, R.W.H. 1986. Thrust tectonics, deep structure and subduction in the Alps and Himalayas. *Journal of the Geological Society of London*, **143**: 857—873.
- Carr, S.D., Parrish, R.R., and Brown, R.L. 1987. Eocene structural development of the Valhalla complex, southeastern British Columbia. *Tectonics*, **6**: 175—196.
- Chatterjee, N.D., and Johannes, W. 1974. Thermal stability and standard thermodynamic properties of synthetic 2M₁-muscovite KAl(AlSi₃O₁₀(OH)₂). *Contributions to Mineralogy and Petrology*, **48**: 89—114.
- Chiarenzelli, J., and McLelland, J.M. 1991. Age and regional relationships of granitoid rocks of the Adirondack highlands. *Journal of Geology*, **99**: 571-590.
- Chinner, G.A. 1962. Almandine in thermal aureoles. *Journal of Petrology*, **3**: 316—340.
- Collins, W.J., 1994. Upper- and middle-crustal response to delamination: An example from the Lachlan fold belt, eastern Australia. *Geology*, **22**: 143-146.
- Coney, P.J. 1980. Cordilleran metamorphic core complexes: An overview. *In* *Cordilleran Metamorphic Core Complexes*, edited by M.D. Crittenden. Geological Society of America Memoir, **153**: 7—31.
- Coney, P.J., and Harms, T.A. 1984. Cordilleran metamorphic core complexes: Cenozoic extensional relics of Mesozoic compression. *Geology*, **12**: 550—554.
- Connelly, J.N., and Heaman, L.M. 1993. U-Pb geochronological constraints on the tectonic evolution of the Grenville Province, western Labrador. *Precambrian Research*, **63**: 123—142.
- Connelly, J.N., Rivers, T., and James, D.T. 1995. Thermotectonic evolution of the Grenville Province of western Labrador. *Tectonics*, **14**: 202—217.

- Cooper, A.F. 1972. Progressive metamorphism of metabasic rocks from the Haast Schist group of southern New Zealand. *Journal of Petrology*, **13**: 457-492.
- Corrigan, D., Culshaw, N.G., and Mortensen, J.K. 1994. Pre-Grenvillian evolution and Grenvillian overprinting of the Parautochthonous Belt in Key Harbour, Ontario: U-Pb and field constraints. *Canadian Journal of Earth Sciences*, **31**: 583—596.
- Corriveau, L., Heaman, L.M., Marcantonio, F., and van Breemen, O. 1990. 1.1 Ga K-rich alkaline plutonism in the SW Grenville Province: U-Pb constraints for the timing of subduction-related magmatism. *Contributions to Mineralogy and Petrology*, **105**: 473-485.
- Cosca, M.A., Sutter, J.F., and Essene, E.J. 1991. Late metamorphic cooling and inferred uplift / erosion history of the Ontario Grenville Province: Constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. *Tectonics*, **10**: 959—977.
- Coward, M.P. 1973. Flat lying structures within the Lewisian basement gneiss complex of NW Scotland. *Geologists' Association Proceedings*, **85**: 459—572.
- Crittenden, M.D., P.J. Coney, and G.H. Davis, *editors*. 1980. Cordilleran Metamorphic Core Complexes. *Memoir of the Geological Society of America*, **153**: 490 pp.
- Culshaw, N. G., Davidson, A., and Nadeau, L. 1983. Structural subdivisions of the Grenville province in the Parry Sound-Algonquin region, Ontario. *In Current Research, Part B. Geological Survey of Canada* **83-1B**, p. 243-252.
- Dalziel, I.W.D., and Brown, R.L. 1989. Tectonic denudation of the Darwin metamorphic core complex in the Andes of Tierra del Fuego, southernmost Chile: Implications for Cordilleran orogenesis. *Geology*, **17**: 699-703.
- Davidson, A. 1986. New interpretations in the southwestern Grenville Province. *in The Grenville Province*, edited by J.M. Moore, A. Davidson,, and A.J. Baer, Geological Association of Canada Special Paper **31**: 61—74.

- Davidson, A., Culshaw, N.G., and Nadeau, L. 1982. A tectono-metamorphic framework for part of the Grenville Province, Parry Sound region, Ontario. *In* Current Research, Geological Survey of Canada, Paper **82-1A**: 175—190.
- Davies, J.H., and von Blanckenburg, F. 1995. Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth and Planetary Science Letters*, **129**: 85—102.
- Deer, W.A., Howie, R.A., and Zussman, J. 1966. *An Introduction to the Rock-Forming Minerals*. Longman Group Limited, London, 528 p.
- DePaolo, D.J. 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular ranges, California. *Journal of Geophysical Research*, **86**: 10470-10488.
- DePaolo, D.J., and Wasserburg, G.J. 1976. Nd isotopic variations and petrogenetic models. *Geophysical Research Letters*, **3**: 249-252.
- Dewey, J.F. 1988. Extensional collapse of orogens. *Tectonics*, **7**: 1123-1139.
- Dewey, J.F., Hempton, M.R., Kidd, W.S.F., Saroglu, F, and Sengör, A.M.C. 1986. Shortening of continental lithosphere: the neotectonics of Eastern Anatolia: a young collision zone. *In* *Collision Tectonics*, edited by M.P.Coward. Geological Society Special Publication, **19**: 3—36.
- Dickinson, A.P., and Higgins, M.D. 1992. Sm/Nd evidence for a major 1.5 Ga crust-forming event in the central Grenville province. *Geology*, **20**: 137-140.
- Doblas, M., and Oyarzun, R. 1989. Neogene extensional collapse in the western Mediterranean (Betic-Rif Alpine orogenic belt): Implications for the genesis of the Gibraltar Arc and magmatic activity. *Geology*, **17**: 430—433.
- Doig, R. 1991. U-Pb zircon dates of Morin anorthosite suite rocks, Grenville Province, Québec. *Journal of Geology*, **99**: 729-738.

- Duebendorfer, E.M., and Christensen, C. 1995. Synkinematic(?) intrusion of the "anorogenic" 1425 Ma Beer Bottle Pass pluton, southern Nevada. *Tectonics*, **14**: 168—184.
- Easton, R.M. 1992. The Grenville Province and the Proterozoic history of central and southern Ontario. *In* *Geology of Ontario*, edited by P.C. Thurston. Ontario Geological Survey, Special Volume **4** part **2**: 714—904.
- Easton, R.M., and Ford, F. 1991. Geology of the Mazinaw area. *In* Summary of field work and other activities. Ontario Geological Survey Miscellaneous Paper, **157**: 95—106.
- Ellis, D.J. 1980. Osumilite-sapphirine-quartz granulites from Enderby Land, Antarctica: P-T conditions of metamorphism, implications for garnet-cordierite equilibria and the evolution of the deep crust. *Contributions to Mineralogy and Petrology*, **74**: 201-210.
- Ellis, D.J. 1987. Origin and evolution of granulites in normal and thickened crust. *Geology*, **15**: 167—170.
- Ellis, D.J., and Green, E.H. 1979. An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contributions to Mineralogy and Petrology*, **71**: 13—22.
- Emslie, R.F., 1978. Anorthosite massifs, rapakivi granites, and late-Proterozoic rifting of North America. *Precambrian Research*, **7**: 61-98.
- Emslie, R.F., and Hunt, P.A. 1990. Ages and petrogenetic significance of igneous mangerite-charnockite suites associated with massif anorthosites, Grenville Province. *Journal of Geology*, **98**: 213—231.
- England, P.C., and Thompson, A.B. 1984. Pressure-temperature-time paths of regional metamorphism, 1. Heat transfer during the evolution of thickened crust. *Journal of Petrology*, **25**: 894—928.

- England, P.C., and Thompson, A.B. 1986. Some thermal and tectonic models for crustal melting in continental collision zones. Geological Society of London, Special Publication, **19**: 83—94.
- England, P., and Jackson, J. 1987. Migration of the seismic-aseismic transition during uniform and nonuniform extension of the continental lithosphere. *Geology*, **15**: 291—294.
- England, P.C., and Richardson, S.W. 1977. The influence of erosion upon the mineral facies of rocks from different metamorphic environments. *Journal of the Geological Society of London*, **134**: 201—213.
- Essene, E.J. 1989. The current status of thermobarometry in metamorphic rocks. *In* *Evolution of Metamorphic Belts*, edited by J.S. Daly, R.A. Cliff, and B.W.D. Yardley. Geological Society of London Special Publication, **43**: 1—44.
- Fein, J.B., and Jurdy, D.M. 1986. Plate motion controls on back-arc spreading. *Geophysical Research Letters*, **12**: 545—548.
- Ferguson, L.J., 1974. The sapphirine-bearing and associated rocks north of Grand Mère, Québec: B.Sc. thesis, Carleton University, Ottawa, Ontario, 145 p.
- Ferry, J.M., and Spear, F.S. 1978. Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. *Contributions to Mineralogy and Petrology*, **66**: 113—117.
- Fletcher, J.R., and Farquhar, R.M., 1982. The protocontinental nature and regional variability of the Central Metasedimentary Belt of the Grenville Province: lead isotopic evidence. *Canadian Journal of Earth Sciences*, **19**: 239-253.
- Fossen, H., and Rykkelid, E. 1992. Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance. *Geology*, **20**: 737-740.
- Fountain, D.M., and Salsbury, M.H. 1981. Exposed cross-sections through the continental crust: implications for crustal structure, petrology, and evolution. *Earth and Planetary Science Letters*, **56**: 263—277.

- Frith, R.A., and Doig, R. 1973. Rb-Sr isotopic ages and petrologic studies of the rocks in the Lac St. Jean area, Québec. *Canadian Journal of Earth Sciences*, **10**: 881-899.
- Frith, R.A., and Doig, R. 1975. Pre-Kenoran tonalitic gneisses in the Grenville Province. *Canadian Journal of Earth Sciences*, **12**: 844-849.
- Frost, B.R., and Chacko, T. 1989. The granulite uncertainty principle: limitations on thermobarometry in granulites. *Journal of Geology*, **97**: 435—450.
- Frost, R.B., Lindsley, D.H., and Simmons, C. 1989. Origin and evolution of anorthosites and related rocks. *Geology*, **17**: 474—475.
- Furman, M.L., and Lindsley, D.H. 1988. Ternary-feldspar modeling and thermometry. *American Mineralogist*, **73**: 201—215.
- Ganguly, J. 1979. Garnet and clinopyroxene solid solutions and geothermometry based on Fe-Mg distribution coefficient. *Geochemica Cosmochemica Acta*, **43**: 1021-1029.
- Ganguly, J., and Saxena, S.K. 1984. Mixing properties of aluminosilicate garnets: constraints from natural and experimental data, and applications to geothermobarometry. *American Mineralogist*, **69**: 88—97.
- Gans, P.B., Mahood, G.A., and Schermer, E. 1989. Syn-extensional magmatism in the Basin and Range province; a case study from the eastern Great Basin. *Geological Society of America Special Paper*, **233**: 1—53.
- Gauthier, E. 1993. Géochimie et pétrologie du complexe de la Bostonnais et du gabbro du lac Lapeyrère. Masters of Sciences thesis, Laval University, Québec, 129p.
- Geological Survey of Canada, 1987. Magnetic Anomaly Map of Canada, fifth edition. Geological Survey of Canada, map 1255A, scale 1:5 000 000.
- Geological Survey of Canada, 1990. Gravity-Bouguer Anomalies. Geological Survey of Canada, maps NL-18-GR (BA), and NL-19-GR (BA), scale 1:1 000 000.

- Ghent, E.D. 1976. Plagioclase-garnet- Al_2SiO_5 quartz: a potential geobarometer-geothermometer. *American Mineralogist*, **61**: 710—714.
- Ghent, E.D., Stout, M.S., and Parrish, R.R. 1988. Determination of metamorphic pressure-temperature-time (P-T-t) paths. *In* Heat, Metamorphism, and Tectonics, edited by E.G. Nisbett, C.M.R. Fowler, and E.D. Ghent. Short Course Handbook, Mineralogical Association of Canada, **14**: 155—188.
- Gibson, G.M. 1990. Uplift and exhumation of middle and lower crustal rocks in an extensional setting, Fiordland, New Zealand. *In* Exposed Cross-sections of the Continental Crust. Edited by M.H. Salisbury and D.M. Fountain. Kluwer, Dordrecht, pp. 71—101.
- Gibson, R.L. 1991. Hercynian low-pressure—high-temperature regional metamorphism and subhorizontal foliation development in the Canigou Massif, Pyrénées, France — evidence for crustal extension. *Geology*, **19**: 380-383.
- Gordon, M.B., and Hempton, M.R. 1986. Collision-induced rifting: the Grenville orogeny and the Keweenawan rift of North America. *Tectonophysics*, **127**: 1—25.
- Goscombe, B. 1992. High-grade reworking of central Australian granulites: Metamorphic evolution of the Arunta Complex. *Journal of Petrology*, **33**: 917—962.
- Gower, C.F., and Tucker, R.D. 1994. Distribution of pre-1400 Ma crust in the Grenville province: Implications for rifting in Laurentia-Baltica during geon 14. *Geology*, **22**: 827—830.
- Gower, C.F., Heaman, L.M., Loveridge, W.D., Schärer, U., and Tucker, R.D. 1991. Grenvillian magmatism in the eastern Grenville Province, Canada. *Precambrian Research*, **51**: 315—336.
- Graham, C.M. 1974. Metabasite amphiboles of the Scottish Dalradian. *Contributions to Mineralogy and Petrology*, **47**: 165-185.

- Graham, C.M., and Powell, R. 1984. A garnet-hornblende geothermometer: calibration, testing, and application to the Pelona Schist, Southern California. *Journal of Metamorphic Geology*, **2**: 13—21.
- Grant, J.A. 1985. Phase equilibria in partial melting of pelitic rocks. In *Migmatites*, edited by J.R. Ashworth. Blackie, London, pp. 86—144.
- Green, D.H., and Ringwood, A.E. 1967. An experimental investigation of the gabbro to eclogite transition and its petrological applications. *Geochimica and Cosmochimica Acta*, **31**: 767—833.
- Haggart, M.J., Jamieson, R.A., Reynolds, P.H., Krogh, T.E., Beaumont, C., and Culshaw, N.G. 1993. Last gap of the Grenville orogen: Thermochronology of the Grenville Front Tectonic Zone near Killarney, Ontario. *Journal of Geology*, **101**: 575—589.
- Hammarstrom, J.M., and Zen, E-an. 1986. Aluminium in hornblende: an empirical geobarometer. *American Mineralogist*, **71**: 1297—1313.
- Handy, M.R. 1990. The solid-state flow of polymineralic rocks. *Journal of Geophysical Research*, **95**: 8647—8661.
- Hanes, J.A. 1991. K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology: Methods and applications. In *Applications of Radiogenic Isotope Systems to Problems in Geology*, edited by L. Heaman and J.N. Ludden. Mineralogical Association of Canada, short course handbook, **19**: 27—57.
- Hanmer, S. 1988. Ductile thrusting at mid-crustal level, southwestern Grenville Province. *Canadian Journal of Earth Sciences*, **25**: 1049-1059.
- Hanmer, S., and McEachern, S. 1992. Kinematical and rheological evolution of a crustal-scale ductile thrust zone, Central Metasedimentary Belt, Grenville orogen, Ontario. *Canadian Journal of Earth Sciences*, **29**: 1779—1790.
- Hanmer, S., and Passchier, C.W. 1991. Sear-sense indicators: a review. *Geological Survey of Canada, Paper 90-17*: 72 p.

- Harley, S.L. 1984. An experimental study of partitioning of Fe and Mg between garnet and orthopyroxene. *Contributions to Mineralogy and Petrology*, **86**: 359—373.
- Harley, S.L. 1989. The origin of granulites: a metamorphic perspective. *Geological Magazine*, **126**: 215—247.
- Harley, S.L., and Green, D.H. 1982. Garnet—orthopyroxene barometry for granulites and peridotites. *Nature*, **300**: 697—701.
- Harley, S.L., Hensen, B.J., and Sheraton, J.W. 1990. Two-stage decompression in orthopyroxene-sillimanite granulites from Forefinger Point, Enderby Land, Antarctica: implications for the evolution of the Archean Napier Complex. *Journal of Metamorphic Geology*, **8**: 591—613.
- Harris, N., and Massey, J. 1994. Decompression and anatexis of Himalayan metapelites. *Tectonics*, **13**: 1537—1546.
- Harry, D.L., Sawyer, D.S., and Leeman, W.P. 1993. The mechanics of continental extension in western North America: implications for the magmatic and structural evolution of the Great Basin. *Earth and Planetary Science Letters*, **117**: 59—71.
- Helgeson, H.C., Delany, J.M., Nesbitt, H.W., and Bird, D.K. 1978. Summary and critique of the thermodynamic properties of rock-forming minerals. *American Journal of Science*, **278-A**: 1—299.
- Herd, K., Ackerman, D., Windley, B.F., and Rondot, J. 1986. Sapphirine-garnet rocks, St. Maurice area, Québec: petrology and implications for tectonics and metamorphism. *In The Grenville Province, edited by J.M. Moore, A. Davidson, and A.J. Baer. Geological Association of Canada, Special Paper*, **31**: 241-253.
- Hervet, M., Higgins, M.D., van Breemen, O., and Dickin, A.P. 1990. U-Pb age and Nd constraints on the Chicoutimi Gneiss Complex (CGC) at the southeast border of the Lac St. Jean anorthosite complex (LSJAC), Grenville Province, Québec, Canada. *EOS Transactions, American Geophysical Union*, **71**: 661—662.

- Higgins, M.D., and van Breemen, O. 1992. The age of the Lac-St-Jean Anorthosite Complex and associated mafic rocks, Grenville Province, Canada. *Canadian Journal of Earth Sciences*, **29**: 1412-1423.
- Hill, E.J., Baldwin, S.L., Lister, G.S. 1992. Unroofing of metamorphic core complexes in the D'Entrecasteaux Islands, Papua New Guinea. *Geology*, **20**: 907—910.
- Hobbs, B.E., Means, W.D., and Williams, P.F. 1976. *An Outline of Structural Geology*. John Wiley and Sons, Inc., USA. 571 p.
- Hodges, K.V., Burchfiel, B.C., Royden, L.H., Chen, Z., and Liu, Y. 1993. The metamorphic signature of contemporaneous extension and shortening in the central Himalayan orogen: data from the Nyalam transect, southern Tibet. *Journal of Metamorphic Geology*, **11**: 721—737.
- Hodges, K.V., Parrish, R., Housh, T., Lux, D., Burchfiel, B.C., Royden, L., and Chen, Z. 1992. Simultaneous Miocene extension and shortening in the Himalayan orogen. *Science*, **258**: 1466—1470.
- Holdaway, M.J. 1971. Stability of andalusite and the aluminium silicate phase diagrams. *American Journal of Science*, **271**: 97—131.
- Houseman, G., McKenzie, D., and Molnar, P. 1981. Convective instability of a thermal boundary layer and its relevance to the thermal evolution of continental convergent belts. *Journal of Geophysical Research*, **86**: 6115-6132.
- Howie, R.A. 1967. Charnockites and their colour. *Journal of the Geological Society of India*, **8**: 1-7.
- Hutton, D.H.W. 1988. Granite emplacement mechanisms and tectonic controls: inferences from deformation studies. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **79**: 245—255.

- Isachsen, Y.W., and Geraghty, E.P. 1986. The Carthage-Colton mylonite zone, a major ductile fault in the Grenville Province. *Abstract*, International Basement Tectonics Association meeting, Salt Lake City, U.S., **6**: 199—200.
- Kamb, W.B. 1959. Ice petrographic observations from Blue Glacier, Washington, in relation to theory and experiment. *Journal of Geophysical Research*, **64**: 1891—1909.
- Karlstrom, K.E., and Williams, M.L., 1995. The case for simultaneous deformation, metamorphism, and plutonism: an example from Proterozoic rocks in central Arizona. *Journal of Structural Geology*, **17**: 59—81.
- Kay, R.W., and Mahlburg-Kay, S. 1993. Delamination and delamination magmatism. *Tectonophysics*, **219**: 177-189.
- Ketchum, J., Jamieson, R.A., Heaman, L.M., Culshaw, N.G., and Krogh, T.E. 1994. 1.45 Ga granulites in the southwestern Grenville province: Geologic setting, P-T conditions, and U-Pb geochronology. *Geology*, **22**: 215—218.
- Kirby, E., Karlstrom, K.E., Andronicos, C.L. and Dallmyer, R.D. 1995. Tectonic setting of the Sandia pluton: An orogenic 1.4 Ga granite in New Mexico. *Tectonics*, **14**: 185—201.
- Klugman, M. A. 1963. Boucher-Carignan area, Rapport Géologique, Ministère des Richesses Naturelles du Québec, DPV-371, 51 p.
- Kretz, R. 1983. Symbols for rock-forming minerals: *American Mineralogist*, **68**: 277-279.
- Krogh, T. E. 1970. Isotopic ages along the Grenville Front in Ontario: *Carnegie Institution of Washington Yearbook*, **68**: 309-313.
- Krogh, T.E. 1982. Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochimica and Cosmochimica Acta*, **46**: 637-649.

- Krogh, T. E., and Davis, G. L. 1968. Geochronology of the Grenville Province: Carnegie Institution of Washington Yearbook, **67**: 224-230.
- Lasaga, A.C. 1983. Geospeedometry: An extension of geothermometry. *In* Kinetics and Equilibrium in Mineral Reactions, *edited by* S.K. Saxena. Springer-Verlag, New York, pp. 81—114.
- Leonov, Y.G. 1991. Intraplate tectonics in light of tectonic layering of the earth's crust. *Geotectonics*, **25**: 459—472.
- Lévesque, S., and Nadeau, L. 1994. Regional metamorphism in the Portneuf—St. Maurice region, south-central Grenville Province. *In* Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, Waterloo '94.
- Lister, G.S., and Snoke, A.W. 1984. S-C mylonites. *Journal of Structural Geology*, **6**: 617-638.
- Lister, G.S., and Baldwin, S.L. 1993. Plutonism and the origin of metamorphic core complexes. *Geology*, **21**: 607-610.
- Lopez-Escobar, L., Frey, F.A., and Vergara, M. 1977. Andesites and high-alumina basalts from the central-south Chile High Andes: geochemical evidence bearing on their petrogenesis. *Contributions to Mineralogy and Petrology*, **63**: 199—228.
- Loveridge, W.D. 1986. U-Pb ages on zircon from rocks of the Lac de Morhiban map area, Québec. *In* Current Research, Part A, Geological Survey of Canada Paper **86-1A**: 523—530.
- Lumbers, S.B., Heaman, L.M., Vertolli, V.M., and Wu, T.-W. 1990. Nature and timing of Middle Proterozoic magmatism in the Central Metasedimentary Belt, Grenville Province, Ontario. *In* Mid-Proterozoic Laurentia—Baltica, *edited by* C.F. Gower. Geological Association of Canada Special Paper **38**: 243—276.
- Lux, D.R., DeYoreo, J.J., Guidotti, C.V., and Decker, E.R. 1986. Role of plutonism in low-pressure metamorphic belt formation. *Nature*, **323**: 795-797.

- MacLean, W.H., Stamatelopoulou-Seymour, K., and Prahbu, M.K. 1982. Sr, Y, Zr, Nb, Ti, and REE in Grenville amphibolites at Montauban-les-Mines, Québec. *Canadian Journal of Earth Sciences*, **19**: 633-644.
- Mäder, U.K., and Berman, R.G. 1992. Amphibole thermometry: a thermodynamic approach. *In* Current Research, Part E. Geological Survey of Canada, Paper **92-1E**: 393—400.
- Marcantonio, F., McNutt, R., Dickin, A., and Heaman, L. 1990. Isotopic evidence for the crustal evolution of the Frontenac Arch in the Grenville Province of Ontario, Canada. *Chemical Geology*, **83**: 297-314.
- Martignole, J. 1978. Le Précambrien dans le sud de la province tectonique de Grenville (Bouclier Canadien). Mémoire déposé à l'Université de Montréal, 405 p.
- Martignole, J., and Schrijver, K. 1971. Association of (hornblende-)garnet-clinopyroxene "subfacies" of metamorphism and anorthosite masses. *Canadian Journal of Earth Sciences*, **8**: 698-704.
- Martignole, J., and Corriveau, L. 1991. Lithotectonics studies in the Central Metasedimentary Belt of the southern Grenville Province: lithology and structure of the Saint Jovite map area, Québec. *In* Current Research, Part C, Geological Survey of Canada, Paper **91-1C**:
- Martignole, J., and Friedman, R. 1992. Age constraints on terrane assembly along the Montréal—Val-d'Or transect, Grenville Province (Québec). *In* Abitibi-Grenville Transect, Lithoprobe Report No. 33, Montréal, pp. 167—171.
- Martignole, J., Indares, A., and Kish, L. 1987. Le Supergroupe de Wakeham dans la partie nord-est de la province de Grenville. Ministère de l'Énergie et des Ressources du Québec, Report **DV 87-25**: 91—94.
- Martignole, J., Machado, N., and Indares, A. 1994. The Wakeham Terrane: a Mesoproterozoic terrestrial rift in the eastern part of the Grenville Province. *Precambrian Research*, **68**: 291—306.

- Martignole, J., Rahmani-Stiquel, A., and Reynolds, P. 1994. $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology along a western Québec transect of the Grenville Province. Lithoprobe Abitibi-Grenville Project, **41**: 99—102.
- McDougall, I., and Harrison, T.M. 1988. Geochronology and thermochronology by the $^{40}\text{Ar}/^{39}\text{Ar}$ method. New York, Oxford University Press, 212 p.
- McEachern, S.J., van Breemen, O., and Hanmer, S. 1992. Mid to Late Proterozoic evolution of the Central Metasedimentary Belt boundary thrust zone: from marginal basin closure to thrust zone reactivation. Friends of the Grenville Workshop, Program with Abstracts, **3**: 27.
- McEachern, S.J., and van Breemen, O. 1993. Age of deformation within the Central Metasedimentary Belt boundary thrust zone, southwest Grenville Orogen: constraints on the collision of the Mid-Proterozoic Elzevir terrane. Canadian Journal of Earth Sciences, **30**: 1155-1165.
- McKenzie, D.P. 1989. Some remarks on the movement of small melt fractions in the mantle. Earth and Planetary Science Letters, **95**: 53—72.
- McKinney, D.B., Cortes, A., and Miller, K.S. 1990. Wanakena fayalite granite, central Adirondacks: Results from new mapping. Geological Society of America, Abstracts with Program, **22**: p. 55.
- McLellan, E.L. 1989. Migmatite structures in the Central Gneiss Complex, Boca de Quadra, Alaska. Journal of Metamorphic Geology, **6**: 517—542.
- McLelland, J.M. 1994. Tectonic history of the Adirondack region: field, geochronological, and geochemical constraints. In An Overview of the Grenville Province, from the Great Lakes to the Labrador Sea. Lithoprobe Meeting No. 5, École Polytechnique, Montréal, *Program with Abstracts*.
- McLelland, J.M., and Isachsen, Y.W. 1986. Synthesis of geology of the Adirondack mountains, New York, and their tectonic setting within the southwestern Grenville

- Province. *In The Grenville Province, edited by J.M. Moore, A. Davidson, and A.J. Baer.* Geological association of Canada, Special Paper 31, pp. 61-74.
- McLelland, J.M., and Chiarenzelli, J. 1990. Isotopic constraints on emplacement age of anorthositic rocks of the Marcy Massif, Adirondack Mts., New York. *Journal of Geology*, **98**: 19—41.
- McLelland, J., and Chiarenzelli, J. 1990. Geochronological studies in the Adirondack Mountains and the implications of a middle Proterozoic tonalitic suite. *In Mid-Proterozoic Laurentia-Baltica, edited by C.F. Gower, T. Rivers, and B. Ryan.* Geological Association of Canada, Special Paper, **33**: 175—194.
- McLelland, J.M., Chiarenzelli, J., Whitney, P., and Isachsen, Y. 1988. U-Pb zircon geochronology of the Adirondack Mountains and implications for their geologic evolution. *Geology*, **16**: 920—924.
- McLelland, J., Chiarenzelli, J., and Perham, A. 1991. Age, field, and petrological relationships of the Hyde School gneiss, Adirondack lowlands, New York: Criteria for an intrusive igneous origin. *Journal of Geology*, **100**: 69—90.
- McLelland, J., Daly, J.S., and Chiarenzelli, J. 1993. Sm-Nd and U-Pb isotopic evidence of juvenile crust in the Adirondack lowlands and implications for the evolution of the Adirondack Mts. *Journal of Geology*, **101**: 97—105.
- McMullin, D.W., Berman, R.G., and Greenwood, H.J. 1991. Calibration of the SGAM thermobarometer for pelitic rocks using data from phase-equilibrium experiments and natural assemblages. *Canadian Mineralogist*, **29**: 889—908.
- Mehnert, K.R. 1968. *Migmatites and the Origin of Granitic Rocks.* Elsevier, Amsterdam.
- Mengel, F., and Rivers, T. 1991. Decompression reactions and P-T conditions in high-grade rocks, northern Labrador: P-T-t paths from individual samples and implications for Early Proterozoic tectonic evolution. *Journal of Petrology*, **32**: 139—167.

- Mercier, J.-L. 1981. Extensional-compressional tectonics associated with the Aegean arc; Comparison with the Andean cordillera of south Peru-north Bolivia. *Philosophical Transactions of the Royal Society of London*, **A300**: 337—355.
- Mereu, R.F., Wang, D., Kuhn, O., and Forsyth, D.A. 1986. A summary of the results of the 1982 COCRUST long range seismic experiment across the Ottawa-Bonnechère graben and western Grenville Front. *In The Grenville Province, edited by J.M. Moore, A. Davidson, and A.J. Baer. Geological Association of Canada Special Paper*, **31**: 235—240.
- Mezger, K., van der Pluijm, B.A., Essene, E.J., and Halliday, A.N. 1991. Synorogenic collapse: a perspective from the middle crust, the Proterozoic Grenville orogen. *Science*, **254**: 695—698.
- Mezger, K., Essene, E.J., van der Pluijm, B.A., and Halliday, A.N. 1993. U-Pb geochronology of the Grenville Orogen of Ontario and New York: constraints on ancient crustal tectonics. *Contributions to Mineralogy and Petrology*, **114**: 13—26.
- Miller, E.L., and Gans, P.B. 1989. Cretaceous crustal structure and metamorphism in the hinterland of the Sevier thrust belt, Western U.S. Cordillera. *Geology*, **17**: 59—62.
- Miyashiro, A. 1973. *Metamorphism and Metamorphic Belts*. George Allen & Unwin, London.
- Molnar, P., and Tapponnier, P. 1978. Active tectonics in Tibet. *Journal of Geophysical Research*, **83**: 5361—5375.
- Molnar, P. and Lyon-Caen, H. 1988. Some simple physical aspects of the support, structure, and evolution of mountain belts. *In Processes in Continental Lithospheric Deformation, edited by S.P. Clark, B.C. Burchfiel, and J. Suppe. Geological Association of America, Special Paper* **218**: 179—207.
- Moore, J.M., and Thompson, P. 1980. The Finton Group: A late Precambrian metasedimentary succession in the Grenville Province of eastern Ontario. *Canadian Journal of Earth Sciences*, **17**: 1685—1707.

- Morin, G. 1987. Gîtologie de la région de Montauban. Ministère de l'Énergie et des Ressources, Québec, MM-86-02.
- Nadeau, L. 1990. Tectonic, thermal, and magmatic evolution of the Central Gneiss Belt, Huntsville region, southwestern Grenville orogen. Unpublished Ph.D. thesis, Carleton University, Ottawa, 269 p.
- Nadeau, L., and Corrigan, D. 1991. Preliminary notes of the geology of the St-Maurice tectonic zone, Grenville orogen, Québec. *In* Current Research, Part E, Geological Survey of Canada, Paper **91-1E**: 245-255.
- Nadeau, L., and Hanmer, S. 1992. Deep-crustal break-back stacking and slow exhumation of the continental footwall beneath a thrust marginal basin, Grenville orogen, Canada. *Tectonophysics*, **210**: 215—253.
- Nadeau, L., and van Breemen, O. 1994. Do the 1,45-1.39 Ga Montauban group and the La Bostonnais complex constitute a Grenvillian accreted terrane? *In* Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, Waterloo '94.
- Nelson, K.D. 1992. Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithospheric delamination? *Geology*, **20**: 498-502.
- Nelson, B.K., and DePaolo, D.J. 1985. Rapid production of continental crust 1.7 to 1.9 b.y. ago: Nd isotopic evidence from the basement of the North American mid-continent. *Geological Society of America Bulletin*, **96**: 746-754.
- Newton, R.C. 1983. Geobarometry of high-grade metamorphic rocks. *American Journal of Science*, **283-A**: 1—28.
- Newton, R.C., and Haselton, H.T. 1981. Thermodynamics of the garnet-plagioclase- Al_2SiO_5 -quartz geobarometer. *In* Thermodynamics of Minerals and Melts, *edited by* R.C. Newton. Springer-Verlag, New York, pp. 131—147.

- Nichols, G.T., Berry, R.F., and Green, D.H. 1992. Internally consistent gahnitic spinel-cordierite-garnet equilibria in the FMASHZn system: geothermobarometry and applications. *Contributions to Mineralogy and Petrology*, **111**: 362—377.
- Nur, A., and Ben-Avraham, Z. 1982. Oceanic plateaus, the fragmentation of continents and mountain building. *Journal of Geophysical Research*, **87**: 3644—3661.
- Nyman, M.W., Karlstrom, K.E., Kirby, E., and Graubard, C.M. 1994. Mesoproterozoic contractional orogeny in western North America: Evidence from ca. 1.4 Ga plutons. *Geology*, **22**: 901—904.
- O'Hara, M.J. 1977. Thermal history of excavation of Archean gneisses from the base of the continental crust. *Journal of the Geological Society of London*, **134**: 185—200.
- Owens, B.E., Rockow, M.W., and Dymek, R.F. 1993. Jotunites from the Grenville Province, Québec: petrological characteristics and implications for massif anorthosite petrogenesis. *Lithos*, **30**: 57—80.
- Oxburgh, E.R., and Turcotte, D.L. 1974. Thermal gradients and regional metamorphism in overthrust terrains with special reference to the eastern Alps. *Schweiz Mineral Petrogr Mitt*, **54**: 641-662.
- Park, R.G. 1981. Origin of horizontal structure in Archaean high grade terrains. *Geological Society of Australia Special Publication*, **7**: 481—490.
- Parrish, R.R. 1990. U-Pb dating of monazite and its applications to geological problems. *Canadian Journal of Earth Sciences*, **27**: 1431—1450.
- Parrish, R.R., Carr, S.D., and Parkinson, D.L. 1988. Eocene extensional tectonics and geochronology of the southern Omenica Belt, British Columbia and Washington. *Tectonics*, **7**: 187—212.
- Parrish, R.R., Roddick, J.C., Loveridge, W.D., and Sullivan, R.W. 1987. Uranium-lead analytical techniques at the geochronology laboratory. *Radiogenic Age and Isotopic Studies: Report 1*, Geological Survey of Canada, Paper **87-2**: 3—8.

- Passchier, C. W., and Simpson, C. 1986. Porphyroclast systems as kinematic indicators. *Journal of Structural Geology*, **8**: 831-844.
- Paterson, S.R., and Fowler, T.K. Jr. 1993. Re-examining pluton emplacement processes. *Journal of Structural Geology*, **15**: 191—206.
- Pattison, D.R.M., and Bégin, N.J. 1994. Zoning patterns in orthopyroxene and garnet in granulites: implications for geothermometry. *Journal of Metamorphic Geology*, **12**: 387—410.
- Pearce, J.A. 1983. Role of the sub-continental lithosphere in magma genesis at active continental margins. *In* *Continental Basalts and Mantle Xenoliths*, *edited by* C.J. Hawkesworth and M.J. Norry. Shiva Publishing Limited, UK. pp.231—249.
- Pearce, J.A., Harris, N.B., Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, **25**: 956-983.
- Percival, J.A., and McGrath, P.H. 1986. Deep crustal structure and tectonic history of the northern Kapuskasing uplift of Ontario: an integrated petrological-geophysical study. *Tectonics*, **5**: 553—572.
- Perkins, D. 1991. Metamorphism of the Kiseynew gneisses and related rocks of the Raindeer Zone, Trans-Hudson Orogen, northern Saskatchewan. *Canadian Journal of Earth Sciences*, **28**: 1664—1676.
- Platt, J.P., and Vissers, R.L.M. 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and the Gibraltar arc. *Geology*, **17**: 540—543.
- Platt, J.P., and England, P.C. 1993. Convective removal of lithosphere beneath mountain belts: Thermal and mechanical consequences. *American Journal of Science*, **293**: 307—336.
- Powell, R. 1978. The thermodynamics of pyroxene geotherms. *Philosophical Transactions of the Royal Society of London*, **A288**: 457—469.

- Pringle, G.J. 1989. A Fortran computer program to produce corrected microprobe analyses of minerals using an energy dispersive X-ray spectrometer. Geological Survey of Canada, Open File Report 2127.
- Pyke, D. R. 1967. Geology of the Montauban area. Ph.D. thesis, McGill University, Montréal, Québec, 197 p.
- Raase, P., Raith, M., Ackerman, D., and Lai, R.K. 1986. Progressive metamorphism of mafic rocks from greenschist to granulite facies in the Dahrwar Craton of South India. *Journal of Geology*, **94**: 261—282.
- Ratcliffe, N., Aleinikoff, J., Burton, W., and Karabinos, P. 1991. Trondhjemitic, 1.35-1.31 Ga gneisses of the Mount Holly Complex of Vermont: evidence for an Elzevirian event in the Grenville Basement of the United States Appalachians. *Canadian Journal of Earth Sciences*, **28**: 77-93.
- Ratschbacher, L., Frisch, W., Neubauer, F., Schmidt, S.M., and Neugebauer, J. 1989. Extension in compressional orogenic belts. *Geology*, **17**: 404—407.
- Reinhardt, J. 1992. Low-pressure, high-temperature metamorphism in a compressional tectonic setting: Mary Kathleen Fold Belt, northeastern Australia. *Geological Magazine*, **129**: 41-57.
- Reinhardt, J., and Kleemann, U. 1994. Extensional unroofing of granulitic lower crust and related low-pressure, high-temperature metamorphism in the Saxonian Granulite Massif, Germany. *Tectonophysics*, **238**: 71—94.
- Rey, P. Seismic and tectonometamorphic characters of the lower continental crust in Phanerozoic areas: A consequence of post-thickening extension. *Tectonics*, **12**: 580—590.
- Rivers, T., Martignole, J., Gower, C.F., and Davidson, A. 1989. New tectonic divisions of the Grenville Province, southeast Canadian Shield. *Tectonics* **8**: 63-84.

- Roddick, J.C. 1983. High precision intercalibration of ^{40}Ar - ^{39}Ar standards. *Geochimica and Cosmochimica Acta*, **47**: 887—898.
- Roddick, J.C. 1990. ^{40}Ar - ^{39}Ar evidence for the age of the New Québec Crater, northern Québec. *in* Radiogenic Age and Isotopic Studies: Report 3, Geological Survey of Canada, Paper 89-2: 7—16.
- Rondot, J. 1978. Stratigraphie et métamorphismes de la région du St-Maurice; *in* Metamorphism in the Canadian Shield, edited by J.A. Fraser and W.W. Heywood. Geological Survey of Canada, Paper **78-10**: 329—352.
- Rondot, J. 1986. Géosutures dans le Grenville. *In* The Grenville Province, *edited by* J.M. Moore, A. Davidson, and A.J. Baer. Geological Association of Canada, Special Paper 31, pp. 313-325.
- Ruppel, C., Royden, L., and Hodges, K.V. 1988. Thermal modeling of extensional tectonics: application to pressure-temperature-time histories of metamorphic rocks. *Tectonics*, **7**: 947—957.
- Rutter, E.H., Brodie, K.H., and Evans, P.J. 1993. Structural geometry, lower crustal magmatic underplating, and lithospheric stretching in the Ivrea-Verbano zone, northern Italy. *Journal of Structural Geology*, **15**: 647-662.
- Sager-Kinsman, E.A., and Parrish, R.R. 1993. Geochronology of detrital zircons from the Elzevir and Frontenac terranes, Central Metasedimentary Belt, Grenville Province, Ontario. *Canadian Journal of Earth Sciences*, **30**: 465—473.
- Sandiford, M. 1985. The metamorphic evolution of granulites at Fyfe Hills; implications for Archean crustal thickness in Enderby Land, Antarctica. *Journal of Metamorphic Geology*, **3**: 155—178.
- Sandiford, M. 1989. Horizontal structures in granulite terranes; a record of mountain building or mountain collapse. *Geology*, **17**: 449—452.

- Sandiford, M., and Powell, R. 1986. Deep crustal metamorphism during continental extension: Modern and ancient examples. *Earth and Planetary Science Letters*, **79**: 151—158.
- Sandiford, M., and Powell, R. 1991. Some remarks on high temperature-low pressure metamorphism in convergent orogens. *Journal of Metamorphic Geology*, **9**: 333—340.
- Sandiford, M., Martin, N., Zhou, S., and Fraser, G. 1991. Mechanical consequences of granite emplacement during high-T, low-P metamorphism and the origin of “anticlockwise” PT paths. *Earth and Planetary Science Letters*, **107**: 164—172.
- Sangster, D.F. 1972. Precambrian volcanogenic sulfide deposits in Canada: a review. Geological Survey of Canada, Paper **72-22**: 44p.
- Schärer, U., Krogh, T., and Gower, C. 1986. Age and evolution of the Grenville Province in eastern Labrador from U-Pb systematics in accessory minerals. *Contributions to Mineralogy and Petrology*, **94**: 438—451.
- Scott, D.J., Machado, N., Hanmer, S., and Gariépy, C. 1993. Dating ductile deformation using U-Pb geochronology: Examples from the Gilbert River Belt, Grenville Province, Labrador, Canada. *Canadian Journal of Earth Sciences*, **30**: 1458—1469.
- Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Rex, D., Li, T-D., Xiao, X-C., Jan, M.Q., Thakur, V.C., and Kumar, S. 1987. The closing of Tethys and the tectonics of the Hymalaya. *Geological Society of America Bulletin*, **98**: 678—701.
- Selverstone, J. 1988. Evidence for east-west crustal extension in the Eastern Alps. *Tectonics*, **7**: 87—105.
- Selverstone, J., and Chamberlain, C.P. 1990. Apparent isobaric cooling paths from granulites: two counterexamples from British Columbia and New Hampshire. *Geology*, **18**: 307—310.

- Silverstone, J., Spear, F.S., Franz, G., Morteani, G. 1984. High pressure metamorphism in the SW Tauern window, Austria: P-T paths from hornblende-kyanite-staurolite schists. *Journal of Petrology*, **25**: 501—531.
- Shackleton, R. 1993. Tectonics of the lower crust: a view from the Usambara Mountains, NE Tanzania. *Journal of Structural Geology*, **15**: 663—671.
- Silver, L., and Lumbers, S. 1966. Geochronologic studies in the Bancroft-Madoc area of the Grenville Province, Ontario. *In* Abstracts for 1965. Geological Society of America, Special Publication, **87**: p. 156.
- Sleep, N.H. 1987. Lithospheric heating by mantle plumes. *The Geophysical Journal of the Royal Astronomical Society*, **91**: 1—11.
- Smith, J.R. 1956. Montauban-les-mines area. Québec Department of Mines, Geological Report **65**: 43 p.
- Smith, T.E., and Holm, P.E. 1990. The geochemistry and tectonic significance of pre-metamorphic minor intrusions of the Central Metasedimentary Belt, Grenville Province, Canada. *Precambrian Research*, **48**: 341—360.
- Spear, F.S. 1981. An experimental study of hornblende stability and compositional variability in amphibolite. *American Journal of Science*, **281**: 697—734.
- Spear, F.S. 1993. Metamorphic phase equilibria and pressure-temperature-time paths. Mineralogical Society of America, Monograph Series, 799 p.
- Spear, F.S., and Florence, F.P. 1992. Thermobarometry in granulites: Pitfalls and new approaches. *Precambrian Research*, **55**: 209—241.
- Spear, F.S., Kohn, M.J., Florence, F., and Menard, T. 1990. A model for garnet and plagioclase growth in pelitic schists: Implications for thermobarometry and P-T path determinations. *Journal of Metamorphic Geology*, **8**: 683—696.

- Stacey, J.S., and Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters*, **26**: 207—221.
- Stamatelopoulou-Seymour, K., and MacLean, W.H. 1984. Metamorphosed volcanogenic ores at Montauban, Grenville Province, Québec. *Canadian Mineralogist*, **22**: 595—604.
- Staudacher, T., Jessberger, E.K., Dorflinger, D., and Kiko, J. 1978. A refined ultrahigh-vacuum furnace for rare gas analysis. *Journal of Physics, E: Scientific Instruments*, **11**: 781—789.
- Steiger, R.H., and Jäger, E. 1977. Subcommittee on geochronology: Convention on the use of decay constants in geology and cosmochemistry. *Earth and Planetary Science Letters*, **36**: 359—362.
- Storey, B.C., and Alabaster, T. 1991. Tectonomagmatic controls on Gondwana break-up models: Evidence from the proto-Pacific margin of Antarctica. *Tectonics*, **10**: 1274—1288.
- Storey, B.C., Hole, R.J., Pankhurst, I.L., Millar, I.L., Vennart, W. 1988. Middle Jurassic within-plate granites in west Antarctica and their bearing on the break-up of Gondwanaland. *Journal of the Geological Society of London*, **145**: 999—1007.
- Streckeisen, A. 1976. To each plutonic rock its proper name. *Earth Sciences Review*, **12**: 1—33.
- Sugizaki, R. 1976. Chemical characteristics of volcanic rocks: relations to plate movements. *Lithos*, **9**: 17—30.
- Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbing, P. 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology*, **10**: 611—616.
- Thompson, A.B. 1976. Mineral reactions in pelitic rocks: II. Calculation of some P-T-X (Fe-Mg) phase relations. *American Journal of Science*, **276**: 425—454.

- Thompson, A.B. 1982. Dehydration melting of pelitic rocks and the generation of H₂O-undersaturated granitic liquids. *American Journal of Science*, **282**: 1567—1595.
- Thompson, A.B., and England, P.C. 1984. Pressure-temperature-time paths of regional metamorphism II. Their influence and interpretation using mineral assemblages in metamorphic rocks. *Journal of Petrology*, **25**: 929—955.
- Thompson, A.B., and Tracy, R.J. 1979. Model systems for anatexis of pelitic rocks II. Facies series melting and reactions in the system CaO-KAlO₂-NaAlO₂-Al₂O₃-SiO₂-H₂O. *Contributions to Mineralogy and Petrology*, **70**: 429—438.
- Tracy, R.J. 1982. Compositional zoning and inclusions in metamorphic minerals. *Reviews in Mineralogy*, **10**: 355—397.
- Tracy, R.J., Robinson, P., and Thompson, A.B. 1976. Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts. *American Mineralogist*, **61**: 762—775.
- Trommsdorf, V. 1972. Change in T—X during metamorphism of siliceous dolomitic rocks of the central Alps. *Schweizerische Mineralogisches und Petrographisches Mitteilungen*, **52**: 567—571.
- Uyeda, S. 1978. *The New View of the Earth*. W.H. Freeman & Co., San Fransisco, 235 p.
- van Breemen, O., and Hanmer, S. 1986. Zircon morphology and U-Pb geochronology in active shear zones: Studies on syntectonic intrusions along the western boundary of the CMB, Grenville Province, Ontario. *In* Current Research, Part B, Geological Survey of Canada, Paper **86-1B**: 775—784.
- van Breemen, O., and Davidson, A. 1988. Northeast extension of Proterozoic terranes of mid-continental North America. *Geological Society of America, Bulletin*, **100**: 630—638.

- van Breemen, O., and Davidson, A. 1988. U-Pb zircon ages of granites and syenites in the Central Metasedimentary Belt, Grenville Province, Ontario. In *Radiogenic Age and Isotopic Studies, Report 2*, Geological Survey of Canada Paper **88-2**: 45—50.
- van Breemen, O., and Davidson, A. 1990. U-Pb zircon and baddeleyite ages from the Central Gneiss Belt, Ontario. In *Radiometric Age and Isotopic Studies, Report 3*, Geological Survey of Canada, Paper **89-2**: 85—92.
- van Breemen, O., Davidson, A., Loveridge, W.D., and Sullivan, R.W. 1986. U-Pb zircon geochronology of Grenville granulites and igneous precursors, Parry Sound, Ontario. In *The Grenville Province*, edited by J.M. Moore, A. Davidson, and A.J. Baer. Geological Association of Canada, Special Paper, **31**: 191—207.
- van der Pluijm, B.A., and Carlson, K.A. 1989. Extension in the Central Metasedimentary Belt of the Ontario Grenville: Timing and tectonic significance. *Geology*, **17**: 161—164.
- Van Schmus, W.R., Bickford, M.E., and Turek, A. 1993. Middle Proterozoic dasement of the eastern midcontinent. In *Program with Abstracts*, American Association of Petroleum Geologists Herdberg Research Conference, Ann Arbor, Michigan, pp. 131—133.
- Vielzeuf, D. 1980. Orthopyroxene and Cordierite secondary assemblages in the granulitic paragneisses from Lherz and Saleix (French Pyrénées). *Bulletin Minéralogique*, **103**: 66—78.
- Walcott, R.I. 1987. Geodetic strain and the deformational history of the North Island of New Zealand during the late Cainozoic. *Philosophical Transactions of the Royal Society, London*, **A321**: 163—182.
- Waard, D. de. 1965. A proposed subdivision of the granulite facies. *American Journal of Science*, **263**: 455—461.
- Waard, D. de. 1969. The anorthosite problem: the problem of anorthosite-charnockite suite of rocks. New York State Museum, Sciences Service, Memoir **18**: 71—90.

- Wernicke, B. 1981. Low-angle normal faults in the Basin and Range Province—Nappe tectonics in an extending orogen. *Nature*, **291**: 645—648.
- Wernicke, B., Christiansen, R.L., England, P.C., and Sonder, L.J. 1987. Tectonomagmatic evolution of Cenozoic extension in the North American Cordillera. *In* *Continental Extension Tectonics*, edited by Coward, M.P. et al. Geological Society of London Special Publication, **28**: 203—221.
- Whitney, P.R. 1978. The significance of garnet 'isograds' in the granulite facies rocks of the Adirondacks. *In* *Metamorphism in the Canadian Shield*. Geological Survey of Canada, Paper **78-10**: 357—366.
- Wickham, S.M., and Oxburgh, E.R. 1986. A rifted tectonic setting for Hercynian high-thermal gradient metamorphism in the Pyrenees. *Tectonophysics*, **129**: 53—69.
- Willet, S., Beaumont, C., and Fullsack, P. 1993. Mechanical model for the tectonics of doubly vergent compressional orogens. *Geology*, **21**: 371—374.
- Windley, B.F. 1986. Comparative tectonics of the Western Grenville and the western Himalaya. Geological Association of Canada, Special Paper **31**: 341—348.
- Windley, B.F. 1989. Anorogenic magmatism and the Grenvillian orogeny. *Canadian Journal of Earth Sciences*, **26**: 479—489.
- Windley, B.F. 1993. Proterozoic anorogenic magmatism and its orogenic connections. *Journal of the Geological Society of London*, **150**: 39—50.
- Windley, B.F. 1991. Early Proterozoic collision tectonics, and rapakivi granites as intrusions in an extensional thrust-thickened crust: the Ketilidian orogen, South Greenland. *Tectonophysics*, **195**: 1—10.
- Wodicka, N. 1994. Middle Proterozoic evolution of the Parry Sound domain, southwestern Grenville orogen, Ontario: structural, metamorphic, U/Pb, and $^{40}\text{Ar}/^{39}\text{Ar}$ constraints. Ph.D. thesis, Dalhousie University, Halifax, 357 p.

- Woodsworth, G.J. 1977. Homogenization of zoned garnets from pelitic schists. *Canadian Mineralogist*, **15**: 230—242.
- Wynne-Edwards, H. R. 1972. The Grenville Province. *In* Variations in tectonic styles in Canada, *edited by* R. A. Price and R. J. W. Douglas. Geological Association of Canada, Special Paper 11, pp. 263—334.
- Yardley, B.W.D., Barber, J.P., and Gray, J.R. 1987. The metamorphism of the Dalradian rocks of western Ireland and its relation to tectonic setting. *Philosophical Transactions of the Royal Society of London*, **A321**: 243—270.
- York, D. 1969. Least square fitting of a straight line with correlated errors. *Earth and Planetary Science Letters*, **5**: 320—324.