

Transect across the northwestern Grenville orogen, Georgian Bay, Ontario: Polystage convergence and extension in the lower orogenic crust

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Abstract. The Grenville orogenic cycle, between ~ 1190 and 980 Ma, involved accretion of magmatic arcs and/or continental terranes to the Laurentian craton. A transect across the western Central Gneiss Belt, Georgian Bay, Ontario, which crosses the boundary between parautochthonous and allochthonous units at an inferred orogenic depth of 20-30 km, offers some insights on the thermal and mechanical behavior of the lower crust during the development of the Grenville orogen. Prior to Grenvillian metamorphism, this part of Laurentia consisted largely of Mesoproterozoic (~ 1450 Ma) granitoid orthogneisses, granulites, and subordinate mafic and supracrustal rocks. Grenvillian convergence along the transect began with transport of the previously deformed and metamorphosed (~ 1160 Ma) Parry Sound domain over the craton sometime between 1120 Ma and 1080 Ma. This stage of transport was followed by out-of-sequence thrusting and further convergence along successively deeper, foreland-propagating ductile thrust zones. A major episode of extension at ~ 1020 Ma resulted in southeast directed transport of allochthonous rocks along the midcrustal Shawanaga shear zone. The final stage of convergence involved deformation and metamorphism in the Grenville Front Tectonic Zone at ~ 1000-980 Ma. Peak metamorphism along most of the transect at 1065-1045 Ma followed initial transport of allochthonous rocks over the craton by 15-35 m.y. Regional cooling, which postdated peak metamorphism by >70 m.y., was probably delayed by the combined effects of late-stage extension and convergence. Transport of allochthons at least 100 km over the craton was accomplished along a weak, migmatitic decollement; further propagation of the orogen into the craton followed partial melting and weakening of parautochthonous rocks below this decollement. Extensional deformation was associated with distributed ductile flow, the formation of regional transverse folds with axes parallel to the stretching direction, and reactivation of the allochthon-parautochthon thrust boundary as an extensional decollement. The extensional lower crustal flow was likely the primary cause of the subhorizontal attitude of many structures and seismic reflectors in this part of the Central Gneiss Belt.

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1. Introduction

The behavior of the lower orogenic crust during convergence and extension is an important but poorly constrained factor in models of orogenesis [e.g. Coward, 1983; Meissner *et al.*, 1991; Malavielle, 1993; Beaumont *et al.*, 1994; Westaway, 1995; Northrup, 1996]. Rather than the lower crust acting as a passive basement to overriding thrust sheets, ductile flow at this level may well influence the progress of the orogeny itself. However, the linkages between rheological properties, thermal history, and style and timing of compressional and extensional deformation are not well understood. Progress on these problems is hampered by our relatively sparse knowledge of the structural and metamorphic style of the deep levels of orogens, especially large orogens which become hot during protracted crustal thickening. In modern orogens the lower crust cannot be observed directly, and exhumed crustal sections in ancient orogenic belts are typically fragmentary and/or overprinted by later effects.

The Mesoproterozoic to Neoproterozoic Grenville Province of the southeastern Canadian Shield (Figure 1) is widely regarded as a large, deeply eroded, convergent orogen (hereafter "Grenville orogen") developed as a result of collision between Laurentia and magmatic arcs and/or continental terranes lying to the southeast [e.g., Rivers *et al.*, 1989; Easton, 1992; McLelland *et al.*, 1996]. Along the northwestern flank of the orogen, rocks of the Laurentian craton were variably overprinted by multiple episodes of Grenvillian tectonism between ~ 1190 and 980 Ma [e.g., Rivers *et al.*, 1989; Davidson, 1995]. The deep level of exposure, with large areas deformed at inferred Grenvillian depths of 20-30 km, means that these rocks offer an opportunity to examine features formed in the lower continental crust during the development of a Himalayan-scale convergent orogen [e.g., Windley, 1986; Hanmer, 1988].

This paper summarizes the results of a transect across the western Central Gneiss Belt and adjacent parts of the Grenville Front Tectonic Zone along the well-exposed shoreline of Georgian Bay, Ontario (Figures 1 and 2). Our interpretation is based on regional geological mapping combined with detailed structural, metamorphic, and geochronological studies of key parts of this belt. A crustal-scale cross section, based on structural data and seismic reflection profiles from the transect and adjacent regions, is interpreted in terms of propagation of the orogen toward the Laurentian craton. Variations in structural style, metamorphic grade, and thermal history spanning ~ 200 m.y. of Grenvillian tectonism provide constraints on the thermal and

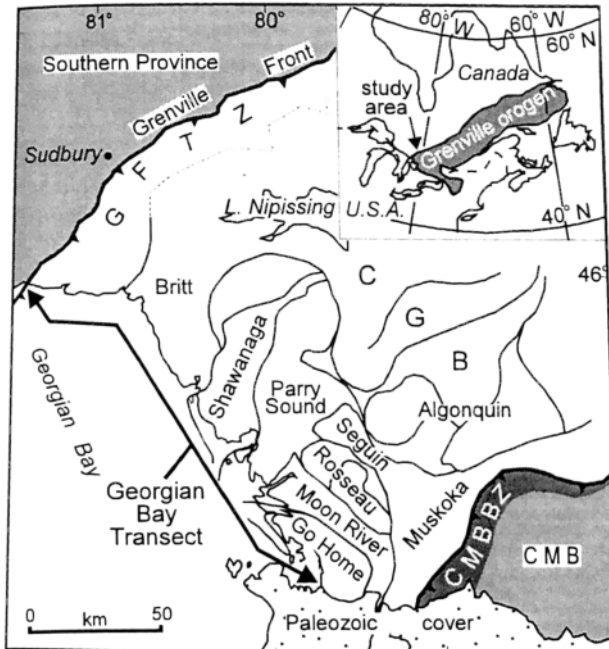


Figure 1. Location of study area and lithotectonic domains discussed in text. Abbreviations are as follows: GFTZ, Grenville Front Tectonic Zone; CGB (unshaded region), Central Gneiss Belt; CMBBZ, Central Metasedimentary Belt boundary thrust zone; CMB, Central Metasedimentary Belt. Heavy barbed lines indicate major thrust boundaries. Thin lines represent domain boundaries after Davidson [1984] and Davidson and van Breemen [1988], with some modifications as discussed in the text. Geology of Georgian Bay transect is shown in Figure 2.

mechanical effects of polystage convergence and extension in the deep orogenic crust.

2. Geological Setting

2.1. Regional Framework

Wynne-Edwards [1972] described the Grenville Province in Ontario in terms of three major divisions. The Grenville Front Tectonic Zone (GFTZ), which marks the northwestern boundary of the orogen, and the Central Gneiss Belt (CGB) consist largely of reworked high-grade rocks of the Laurentian craton (pre-1400 Ma) and younger supracrustal sequences deposited on its margin. To the southeast, the Central Metasedimentary Belt (CMB) represents a post-1400 Ma composite system of magmatic arcs and marginal basins [e.g., Windley, 1989; Easton, 1992; Davidson, 1995] accreted to Laurentia during the Grenville orogeny. The CMB overlies the CGB along the crustal-scale Central Metasedimentary Belt boundary thrust zone [Hanmer and McEachern, 1992] (CMBBZ, Figure 1).

Although Rivers *et al.* [1989] proposed a regional nomenclature based on distinctions between and within orogen-scale parautochthonous and allochthonous belts, their subdivisions are difficult to apply in the study area; we have therefore retained the terminology of Wynne-Edwards [1972]. In this paper, we describe lithotectonic units affected by both pre-Grenvillian and

Grenvillian tectonism as "polycyclic" and those affected only by Grenvillian tectonism as "monocyclic" [e.g., Rivers *et al.*, 1989]. We use the term "parautochthonous" for units that retain some lithologic continuity with the Grenville foreland, despite a strong Grenvillian overprint. The term "allochthonous" is used to refer to any far-traveled tectonic element now completely detached from its presumed original basement, whether or not it is inferred to have originated on the Laurentian side of the system. The term "domain" is used here in preference to "terrane" [cf. Rivers *et al.*, 1989; Davidson, 1995] because some tectonic connotations of the latter term do not apply in the study area. Moreover, important lithotectonic boundaries do not everywhere correspond to the obvious, and in some cases relatively late, structural breaks that define domain boundaries.

The Georgian Bay transect crosses the GFTZ and most of the western CGB (Figures 1 and 2). Contrasts in geological, metamorphic, and structural histories along the length of the Georgian Bay transect have been used to distinguish a number of lithotectonic units in the study area [Davidson and Morgan, 1981; Davidson *et al.*, 1982; Culshaw *et al.*, 1983, 1988, 1989, 1990, 1994]. Documenting the tectonic evolution of each of these has allowed us to place some constraints on their pre-orogenic settings and their roles in the accretionary history of the Grenville orogen. The following section summarizes the most important features of the GFTZ and five first-order subdivisions of the CGB (Britt, Shawanaga, Parry Sound, Moon River, and Go Home domains; Figures 1 and 2).

2.2. Grenville Front Tectonic Zone

The GFTZ is a composite crustal-scale thrust zone that abuts the older Precambrian foreland along the Grenville Front (Figures 1 and 2) [Green *et al.*, 1988; Davidson and Bethune, 1988; Jamieson *et al.*, 1995; Bethune, 1997]. It is dominated by moderately dipping late Grenvillian structures (≤ 1000 Ma) [Haggart *et al.*, 1993; Krogh, 1994]. Rock types include a variety of migmatitic orthogneisses and paragneisses, Mesoproterozoic megacrystic granitoid rocks [Davidson and van Breemen, 1994], and granulites formed ~ 1450 Ma [Dudas *et al.*, 1994; Krogh, 1994]. A suite of distinctive diabase dykes, termed the Sudbury swarm (~ 1235 Ma) [e.g., Dudas *et al.*, 1994], can be traced across the Grenville Front into the GFTZ [Bethune, 1997].

2.3 Britt Domain

Originally defined by Davidson and Morgan [1981] to include rocks lying between the GFTZ and the Parry Sound domain, recent work suggests that this region comprises two contrasting lithotectonic units separated by the Shawanaga shear zone (Figures 2 and 3) [Culshaw *et al.*, 1994; Ketchum, 1995]. In this paper, we retain the name Britt domain for polycyclic rocks in the north and use the term Shawanaga domain for the monocyclic rocks south of the Shawanaga shear zone. The Britt domain includes a variety of granitic to tonalitic orthogneisses with subordinate paragneiss. Although protolith ages are poorly known, some migmatitic gneisses predated the intrusion of ~ 1690 Ma granitoid metaplutonic rocks [Corrigan *et al.*, 1994]. At ~ 1450 Ma, these rocks were intruded by voluminous megacrystic granitoid plutons (1460-1430 Ma) [van Breemen *et al.*, 1986; Corrigan *et al.*, 1994], strongly deformed, and affected by granulite facies metamorphism (~ 1450 -1430 Ma) [Tuccillo *et al.*, 1992;

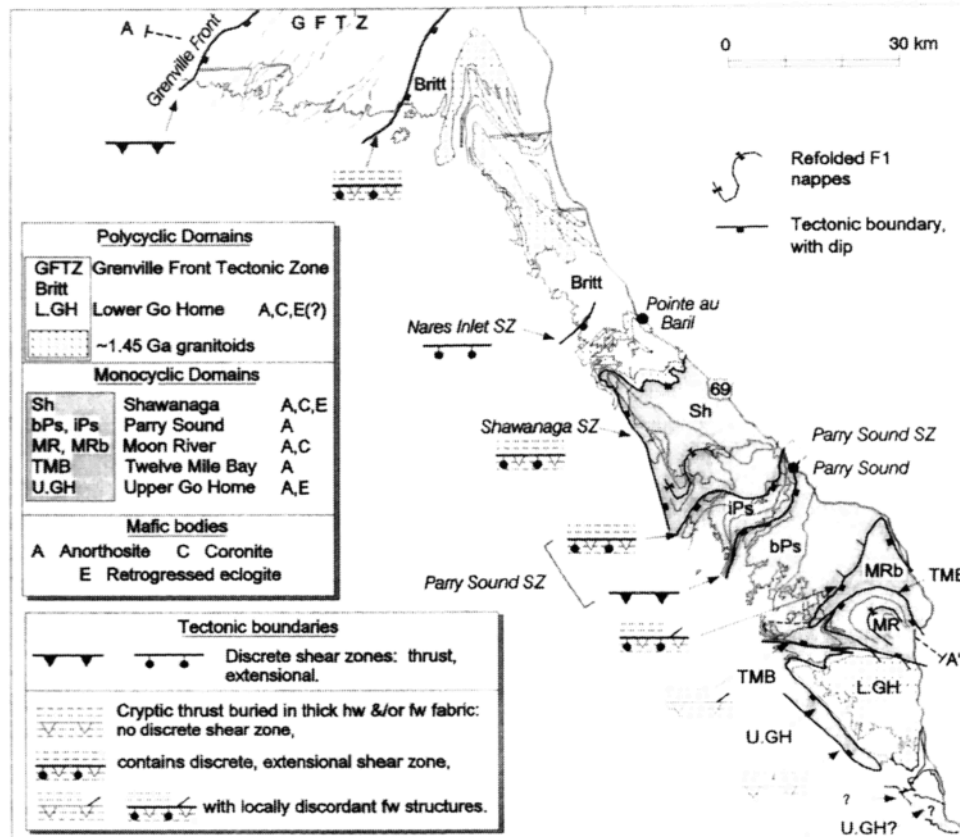


Figure 2. Geology of the Georgian Bay transect, showing distribution of polycyclic rocks (unshaded), ~ 1450 Ma metaplutonic complexes (stippling), and post-1430 Ma monocyclic rocks (light shading). Polycyclic domains are interpreted as parautochthonous units that were part of the Laurentian craton prior to Grenvillian tectonism; monocyclic rocks of the Shawanaga and upper Go Home domains are interpreted as allochthonous rocks originally formed along the Laurentian margin; monocyclic rocks of the Parry Sound domain are interpreted as allochthonous rocks originally associated with the CMB magmatic arc(s); Twelve Mile Bay assemblage (part of Parry Sound domain) includes supracrustal rocks deposited after 1120 Ma; Moon River domain consists of monocyclic rocks, including reworked rocks from adjacent units; heavy lines in Go Home domain represent marbles. Refolded F1 nappes are confined to allochthonous units; regional transverse folds are shown in more detail in Figure 4. The presence of distinctive mafic bodies (A, anorthosite; C, coronite; E, retrogressed eclogite) within units or their bounding shear zones are noted beside unit names. The nature of the complex tectonic boundaries separating the various domains is also noted schematically, as discussed in the text (hw, hangingwall; fw, footwall). Thin dashed lines in the GFTZ represent discrete thrust-sense shear zones. Simplified cross sections across these boundaries along A-A' are shown in Figure 3.

Ketchum et al., 1994]. Similar rock types, protolith ages, metamorphic histories, and Nd model ages older than 1.8 Ga [*Dickin and McNutt*, 1989] indicate that the GFTZ and Britt domain are lithotectonically equivalent units. Comparable rocks found from Labrador to the southwestern United States [e.g., *Gower and Tucker*, 1994; *Nyman et al.*, 1994] provide clear evidence that both the GFTZ and the Britt domain were part of the Laurentian continent prior to the Grenville orogeny.

2.4. Shawanaga Domain

The Shawanaga domain (Figure 2) is dominated by quartzofeldspathic paragneiss, amphibolite, and migmatitic granitoid orthogneiss [*Davidson et al.*, 1982; *Culshaw et al.*, 1994]. Single crystal zircon dating of the paragneisses shows that they were

deposited sometime after 1420 Ma (T. E. Krogh and N. G. Culshaw, unpublished data, 1992). The southern limit of the Shawanaga domain coincides with a narrow zone of migmatitic paragneisses and amphibolites previously assigned to the Parry Sound domain (Figure 2) [*Wodicka et al.*, 1996; cf. *Davidson et al.*, 1982]. These monocyclic rocks are interpreted to represent a supracrustal suite deposited on the Laurentian margin following the ~ 1450 tectonism.

2.5. Parry Sound Domain

Mafic granulites and associated high-grade gneisses of the Parry Sound domain are clearly allochthonous with respect to underlying quartzofeldspathic migmatitic gneisses [e.g., *Davidson*, 1986]. Geological and geochronological data suggest that

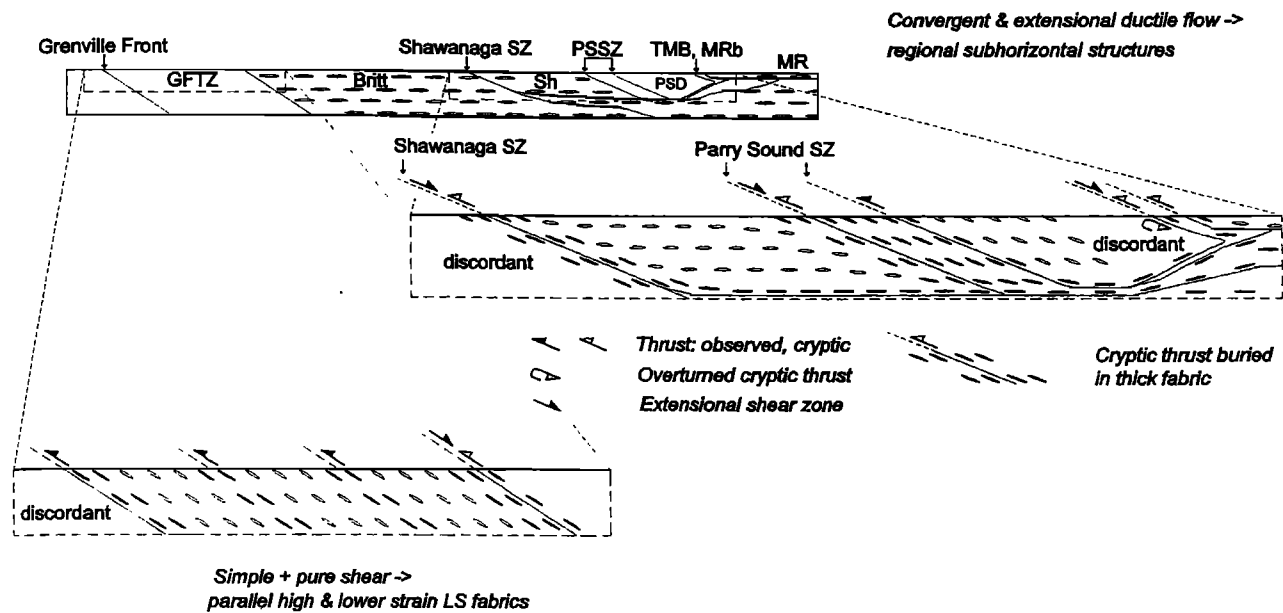


Figure 3. Schematic cross section along A-A' of Figure 2. Relationships between distributed shear, discrete lithotectonic breaks, and fabrics in the (middle) central and (bottom) northern parts of the transect. Unit abbreviations are the same as for Figure 2. Solid lines represent the boundaries between lithotectonic units shown in Figure 2. Closed arrows show observed shear sense (generally later, except for upper boundary of Parry Sound shear zone (PSSZ)); open arrows represent inferred shear sense (generally earlier); hooked arrow represents an inferred folded thrust. Open and solid ellipses represent traces of LS fabrics at lower and higher strain states, respectively. Discordant fabrics are present at the Shawanaga-Britt, Moon River-Parry Sound, and GFTZ-foreland boundaries. The diagram shows how discrete lithotectonic breaks, identified from geological criteria, may be cryptic within thick zones of tectonite (e.g., Parry Sound SZ), and how some important early thrusts have been pervasively overprinted by extensional shear (e.g., Shawanaga SZ). The GFTZ includes panels of high strain (shear zones) within domains of lesser strain, interpreted to result from a combination of pure and simple shear.

the allochthon comprises three distinctive packages separated by ductile shear zones [Wodicka, 1994; Wodicka et al., 1996]. The basal Parry Sound assemblage [Culshaw et al., 1994] includes post-1436 Ma quartzites, a substantial volume of ~ 1400-1330 Ma orthogneiss, and anorthosite intruded at ~ 1350 Ma and ~ 1160 Ma [van Breemen et al., 1986; Wodicka et al., 1996], all intruded by mafic dykes. It is separated from underlying paragneisses, here assigned to the Shawanaga domain, by a high-temperature shear zone bearing extensional kinematic indicators (Figure 2) [Wodicka, 1994]. The interior Parry Sound assemblage comprises Mesoproterozoic (~ 1400-1200 Ma) [van Breemen et al., 1986; Wodicka et al., 1996] granulite facies metaplutonic rocks ranging from gabbro to granite, with subordinate metasedimentary rocks [Culshaw et al., 1989, 1994; Wodicka, 1994]. Nd model ages of 1.5-1.4 Ga [Dickin and McNutt, 1991] are significantly younger than those from parautochthonous rocks, and their similarity to protolith ages suggests a mainly juvenile magmatic source. In the south, the Twelve Mile Bay assemblage [Wodicka et al., 1996] comprises a thin sequence of supracrustal rocks, structurally overlain by granitoid orthogneiss and anorthosite cut by mafic dykes. These rocks resemble those of the basal Parry Sound assemblage, but the quartzite is younger (deposited ≤ 1140 -1120 Ma) [Wodicka et al., 1996]. The Parry Sound domain has clear lithologic and age affinities with

magmatic arc rocks of the CMBBZ and eastern CMB [Wodicka et al., 1996].

2.6. Moon River Domain

The Moon River domain structurally overlies the Parry Sound and Go Home domains (Figures 2 and 3) [Davidson et al., 1982; Culshaw et al., 1990; Schwerdtner and van Berkel, 1991]. Although on its northern flank it has discordant tectonic boundaries with subjacent rocks, it includes a significant proportion of material derived from underlying units. A highly attenuated extension of the distinctive Twelve Mile Bay assemblage can be traced from the Parry Sound domain into the Moon River structure (Figure 2) [e.g., Schwerdtner and van Berkel, 1991], where it marks a clear lithotectonic break. North of this boundary, the Moon River domain includes retrogressed granulite derived from the Parry Sound domain cut by pegmatite, as well as mafic to ultramafic metaplutonic rocks and orthogneisses of unknown age and affinity [Culshaw et al., 1990]. South of the boundary, a distinctive lithological suite dominated by migmatitic granitoid and supracrustal gneisses can be traced around the Moon River synform (Figure 2). We interpret the Moon River domain to be a relatively late structural feature developed by ductile reworking of adjacent allochthonous units.

2.7. Go Home Domain

The Go Home domain, at the southern end of the transect (Figure 2), includes two distinctive units separated by a boundary marked by pods of anorthosite, garnet amphibolite, and retrogressed eclogite [Davidson, 1990; Culshaw *et al.*, 1990]. Below this boundary, voluminous Mesoproterozoic megacrystic granitoid rocks (~1460 Ma) [Krogh, 1991] and minor mafic bodies cut older migmatitic granitoid gneisses (~1600 Ma) [Krogh, 1991]. Strongly deformed metaplutonic rocks, minor pelitic gneiss and marble, and coronitic metagabbro are also present [Davidson *et al.*, 1985; Culshaw *et al.*, 1990]. These features, along with Nd model ages as old as 1.9 Ga [Dickin and McNutt, 1991], show that the lower Go Home domain originated as part of the Laurentian craton. Above the boundary lies a mainly supracrustal assemblage dominated by leucosome-rich granitoid migmatite with pink felsic gneiss and calcsilicate [Culshaw *et al.*, 1990] (Figure 2). Although protolith ages are not known, lithological characteristics and structural position suggest that it is equivalent to the allochthonous rocks of the Shawanaga domain. Further work on the diverse geological components of the Go Home domain will probably justify its future separation into two or more domains.

2.8. Minor Intrusions

Metamorphosed equivalents of the ~1235 Ma Sudbury diabase dyke swarm are present in the GFTZ [Davidson and Bethune, 1988; Bethune, 1997] and in the Britt domain as far south as the Shawanaga shear zone [Culshaw *et al.*, 1994; Ketchum, 1995]. Distinctive podiform coronitic metagabbros (~1170–1150 Ma) [Davidson and van Breemen, 1988; Heaman and LeCheminant, 1993] are found in the Shawanaga, Moon River, and Go Home domains but do not occur in the Britt or Parry Sound domains (Figure 2). Anorthosite is confined to the Parry Sound domain and to tectonic inclusions along important lithotectonic boundaries, including the Shawanaga and Parry Sound shear zones. Mafic bodies interpreted as retrogressed eclogites [Davidson, 1990, 1991] probably originated as gabbroic intrusions [Needham, 1992], although their contacts are now tectonic. These bodies are present in major shear zones, where they are commonly associated with anorthosite, and in the Shawanaga and Go Home domains (Figure 2). Undeformed to mylonitic pegmatite dykes and sheets, spanning a wide range of Grenvillian ages, are common along the Georgian Bay transect. A suite of late tectonic to post tectonic pegmatites, dated in several localities at ~990 Ma [e.g., Corrigan *et al.*, 1994; Ketchum, 1995; Bussy *et al.*, 1995], is present in all units except the western GFTZ.

3. Structure

3.1. Fabrics

Rocks throughout the transect were deformed by penetrative ductile flow. Within the CGB, lithological boundaries are generally parallel to the dominant Grenvillian fabric, a gneissic foliation (dominantly $S \geq L$), with a shallow, SE-dipping enveloping surface associated with a SE-plunging lineation (Figure 4). Local variations in strain between fabrics that are parallel suggest that the fabric commonly represents the combined effects of pure

and simple shear (Figure 3). Steeper fabrics are present within the GFTZ and locally in the Parry Sound and Britt domains. An earlier (?) NE-trending lineation is preserved within the Parry Sound domain and immediately beneath the Shawanaga shear zone [Gower, 1992; Wodicka, 1994; Ketchum, 1995].

3.2. Shear Zones

Ductile shear zones occur within, and can be difficult to distinguish from, gneissic tectonites along the CGB part of the transect (Figures 2 and 3). Important criteria include the presence of kinematic indicators, localized zones of high strain, and local truncation of structures in adjacent rocks. In most cases, the shear zones coincide with independently recognizable, sharp lithological contacts. Where geological relationships across them are stratigraphically incompatible (e.g., mafic dykes restricted to the hanging wall), these boundaries have been interpreted as thrusts [e.g., Culshaw *et al.*, 1994]. Lithologically defined cryptic thrusts of this type, with few thrust-sense kinematic indicators, are commonly overprinted by discrete shear zones with clear extensional kinematics (Figures 2 and 3). Although domain boundaries in this part of the CGB have been described as ductile thrust zones [e.g., Davidson, 1984; Gower, 1992], this interpretation is clearly oversimplified.

Nowhere is this problem more apparent than in the case of the "Parry Sound shear zone" (Figures 2 and 3) [Davidson *et al.*, 1982; Davidson, 1984]. Originally defined as the tectonic boundary separating the granulite facies Parry Sound domain from underlying amphibolite facies gneisses, subsequent detailed mapping west of Parry Sound has shown that the shear zone widens to include a distinctive rock package, the basal Parry Sound assemblage (bPs, Figure 2). At its west end, the lower boundary of this package is a cryptic thrust that is overprinted by a discrete extensional shear zone developed within very thick, older tectonites [Culshaw *et al.*, 1991a, 1994; Wodicka, 1994]. The upper boundary is a thrust-sense shear zone that coincides with a sharp lithological break. Geochronological data suggest that displacements along the thrusts were not contemporaneous. The thrust separating the interior Parry Sound assemblage from the basal Parry Sound assemblage has been dated at ~1160 Ma [van Breemen *et al.*, 1986; Wodicka, 1994]. Though not dated directly, thrusting along the shear zone that separates the basal Parry Sound domain from the Shawanaga domain was probably active at ~1120 Ma [Tuccillo *et al.*, 1992; Wodicka, 1994]. This boundary was reactivated between 1020 and 970 Ma [Wodicka, 1994] to form the discrete high-temperature extensional shear zone that now marks the Parry Sound-Shawanaga contact.

The allochthonous Shawanaga domain is separated from the parautochthonous Britt domain by the shallow to moderate dipping, upper amphibolite facies Shawanaga shear zone [Culshaw *et al.*, 1994; Ketchum, 1995]. It extends northeast to the eastern limit of the Parry Sound domain (Figure 1) and coincides with an important seismic reflector that dips gently southeast beneath the Parry Sound domain [White *et al.*, 1994]. The Shawanaga shear zone and the underlying Nares Inlet shear zone display extensional kinematic indicators along Georgian Bay (Figure 3) [Ketchum *et al.*, 1993; Culshaw *et al.*, 1994; Ketchum, 1995]. However, tectonostratigraphic evidence and thrust-sense kinematics along its inland extension suggest that it originated as a thrust [Ketchum *et al.*, 1993; Culshaw *et al.*, 1994]. Zircon U-Pb

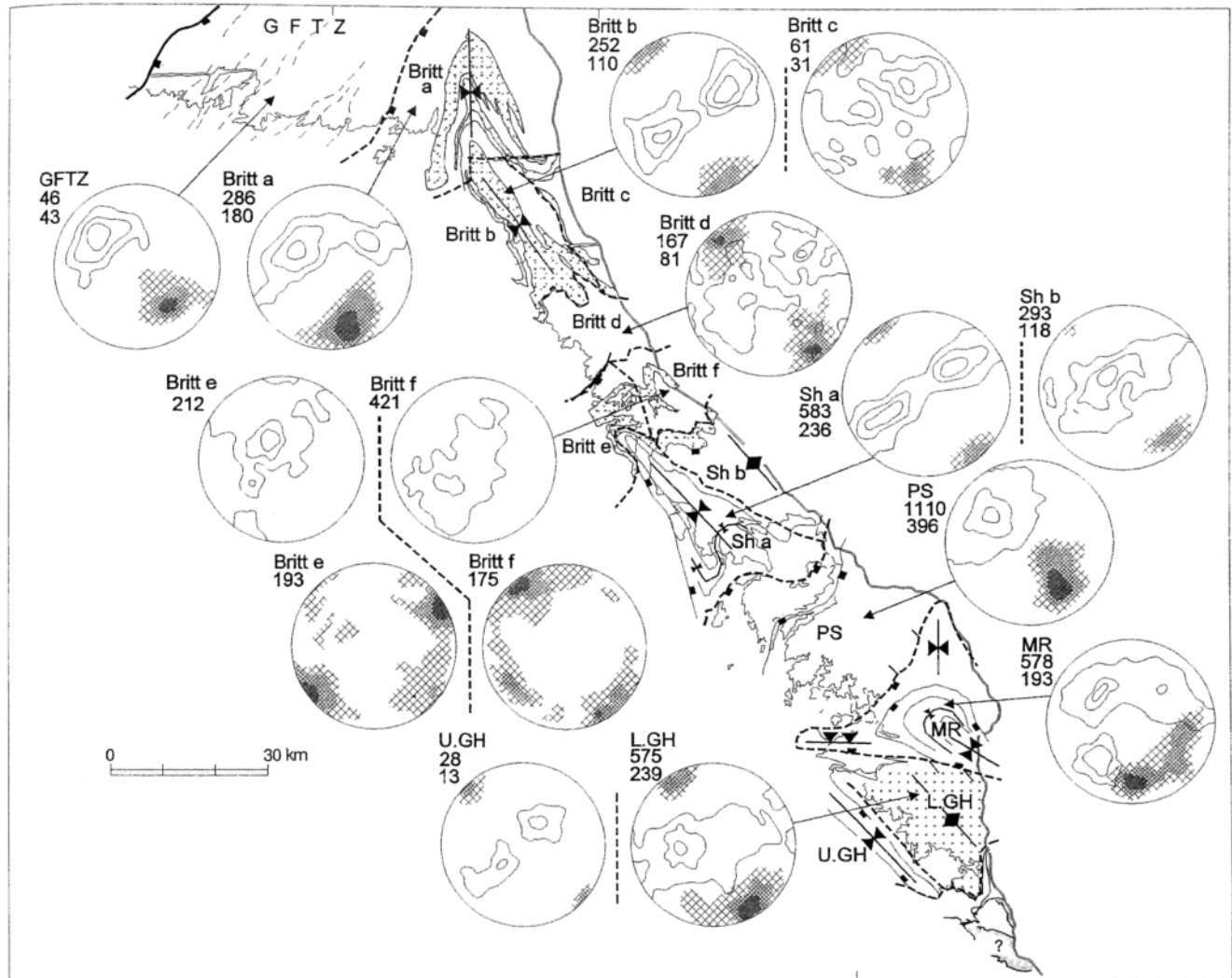


Figure 4. Structural data from the Georgian Bay transect, showing axial traces of principal transverse folds. Traces of refolded F1 nappe-like folds and dips of tectonic boundaries are as in Figure 2. Thin dashed lines in GFTZ represent traces of internal shear zones. Foliation (lines) and lineation (cross hatch) geometry are shown on contoured stereonets (lower hemisphere). Contour intervals (percent per 1% area) are slightly different from net to net: for foliations, intervals are 1, 2-5, 3-6; for lineation nets with three contours, intervals are 1-2, 2-5, 3-10; for lineation nets with two contours, intervals are 1-5, 5-10. Boundaries of structural domains are indicated by heavy dashed lines. Domain names are as for Figure 2.

dates from late synkinematic pegmatites indicate that extension was active at ~ 1020 Ma [Ketchum *et al.*, 1993; Ketchum, 1995].

South of the Parry Sound domain, the boundary between monocyclic and polycyclic elements of the Go Home domain is marked by pods of anorthosite, amphibolite, and retrogressed eclogite. Although a discrete shear zone has not been recognized, this contact is interpreted as a cryptic thrust. The Moon River domain is bounded by high-strain zones that cut earlier structures in adjacent units (Figures 2 and 3) [Davidson *et al.*, 1982]. The Moon River - Parry Sound contact locally displays strong discordance between hanging wall amphibolite facies tectonites and moderately retrogressed granulites in the footwall; scattered extensional indicators are present [Klemens and Schwerdtner, 1991]. A deformed pegmatite near this boundary has been dated at ~ 1100 Ma [van Breemen and Davidson, 1990].

The boundary between the GFTZ and the Britt domain is an amphibolite facies shear zone. The earliest fabric, which is SE-dipping with a steep down-dip lineation, appears to be thrust-related; this was overprinted by oblique-normal (top down to the SSE) movement [Jamieson *et al.*, 1995]. Ages of deformation in this boundary shear have not been determined directly, but thrusting before 1035 Ma and extension between 1035 and 1000 Ma have been inferred from geological evidence. Within the GFTZ, exclusively thrust-sense, NE-striking shear zones are separated by wider panels of less strained rock with a parallel LS fabric, that locally contain relics of an older fabric [Jamieson *et al.*, 1995]. The Grenville Front (Figures 1 and 3) is a SE-dipping mylonitic thrust fault with kinematic indicators consistently indicating tops to the NW [Davidson and Bethune, 1988]. Geochronological data indicate that metamorphism and thrusting in

the western GFTZ occurred at 1000-980 Ma [Haggart *et al.*, 1993; Krogh, 1994; Dudas *et al.*, 1994].

3.3. Folds

Recumbent, nappe-like folds (F1, Figure 2) are present in the Shawanaga [Culshaw *et al.*, 1989, 1994] and Moon River domains [Schwerdtner and van Berkel, 1991]. Isolated, isoclinal, reclined folds are present in the interior Parry Sound assemblage [Culshaw *et al.*, 1989], and repetition of quartzite in the basal Parry Sound assemblage may also be related to this type of structure [Gower, 1992], although a fold closure has not been demonstrated [Culshaw *et al.*, 1994]. Comparable folds have not been found in polycyclic rocks of the Britt domain or the lower Go Home domain.

The dominant map-scale structures along the transect are transverse folds (Figure 4) with subhorizontal or gently SE-plunging hinges that trend parallel to the regional stretching lineation [Culshaw *et al.*, 1994]. Fold sets with axial traces about 30 km long are separated by areas with distinctly steeper fabrics that have not been folded (Figure 4). The folds are disharmonic, with steeper plunges at their terminations and sigmoidal longitudinal cross sections. They are interpreted to have formed with hinges approximately parallel to their present orientation (but possibly plunging more steeply; see below), since their open profiles are incompatible with substantial rotation of hinges into the transport direction. In the Pointe-au-Baril area, transverse folding accompanied extension along the Shawanaga shear zone [Culshaw *et al.*, 1994]. These folds postdate both the nappe-like

folds in the Shawanaga and Moon River domains and thrust-related fabrics beneath the Parry Sound domain at the Moon River - Parry Sound domain boundary and at the GFTZ - Britt boundary. Consequently, extension may have played a dominant role in their formation.

4. Metamorphism and Cooling

4.1. Pre-Grenvillian Metamorphism

Prior to the onset of Grenvillian tectonism, the parautochthon consisted of Paleoproterozoic to Mesoproterozoic plutonic and high-grade metamorphic rocks. Migmatitic gneisses cut by ~1690 Ma granitoid rocks in the northernmost Britt domain [Corrigan *et al.*, 1994] are the oldest metamorphic rocks so far documented along the transect. Granulite facies metamorphism in the parautochthon, dated at 1450-1430 Ma in the southernmost Britt domain [Tuccillo *et al.*, 1992; Ketchum *et al.*, 1994], was spatially and temporally associated with voluminous granitoid plutonism.

4.2. Early Grenvillian Metamorphism

Upper amphibolite to granulite facies metamorphism in the Parry Sound domain has been dated at ~1160 Ma and ~1120 Ma [van Breemen *et al.*, 1986; Tuccillo *et al.*, 1992; Wodicka, 1994]. Metamorphism in the interior Parry Sound assemblage is generally at granulite facies [Anovitz and Essene, 1990; Wodicka, 1994], although retrogression to amphibolite is extensive in the

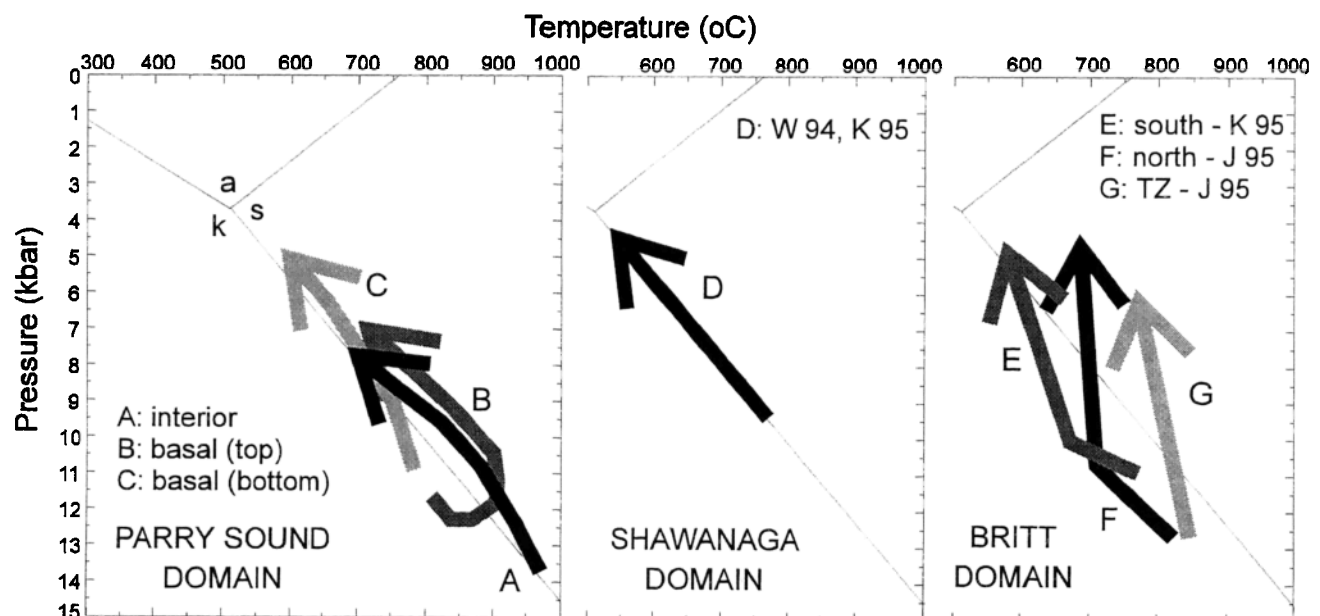


Figure 5. Metamorphic P-T-t paths from the transect; stability fields of andalusite (a), kyanite (k), and sillimanite (s) shown for reference. Parry Sound domain data are from Wodicka [1994], supplemented by data from Anovitz and Essene [1990]. A denotes interior Parry Sound assemblage; B denotes upper part of basal Parry Sound assemblage; C denotes lower part of basal Parry Sound assemblage. Shawanaga domain data are from Wodicka [1994] and Ketchum [1995] (W 94 and K 95, respectively), supplemented by data from Tuccillo *et al.* [1990, 1992]. Britt domain data are from Ketchum *et al.* [1994] and Ketchum [1995] (E denotes southern Britt domain, K 95) and Jamieson *et al.* [1995] (F denotes northern Britt domain, J 95; G: transition zone (TZ) between Britt domain and GFTZ).

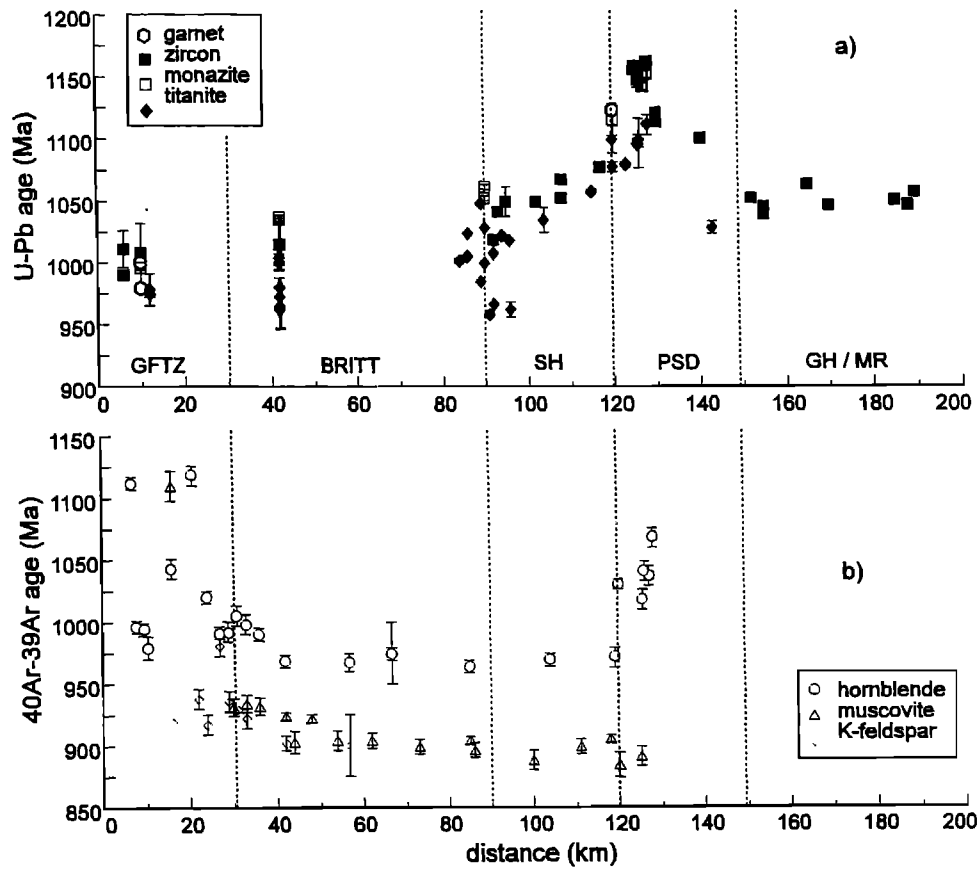


Figure 6. Age data, with errors, from the Georgian Bay transect and immediately adjacent areas along strike. Dashed vertical lines show domain boundaries. (a) U-Pb data bearing on times of peak metamorphism, cooling, and synmetamorphic ductile shear. (b) ⁴⁰Ar-³⁹Ar cooling ages. Note 50 m.y. shift in scales between Figure 6a and Figure 6b. Data are from *van Breemen et al.* [1986], *Davidson and van Breemen* [1988], *van Breemen and Davidson* [1990], *Cosca et al.* [1991], *Culshaw et al.* [1991b], *Tuccillo et al.* [1992], *Haggart et al.* [1993], *Heaman and LeCheminant* [1993], *Mezger et al.* [1993], *Corrigan et al.* [1994], *Dudas et al.* [1994], *Wodicka* [1994], *Ketchum* [1995], *Reynolds et al.* [1995], *Bussy et al.* [1995], *Wodicka et al.* [1996], and *Bethune* [1997].

southeast [*Hanmer*, 1988; *Culshaw et al.*, 1989]. Peak P-T conditions have been estimated at 800°-900°C and 10-13 kbars [*Anovitz and Essene*, 1990; *Wodicka*, 1994]. Retrograde P-T paths have been interpreted to show isobaric cooling [*Anovitz and Essene*, 1990] or decompression during cooling [*Wodicka*, 1994] (path A, Figure 5).

Upper amphibolite facies assemblages are characteristic of supracrustal rocks in the basal Parry Sound assemblage [*Wodicka*, 1994]. Both kyanite and sillimanite are typically present, although sillimanite is later than kyanite in some places. Peak P-T conditions have been estimated at 700°-800°C and 10-12 kbars [*Wodicka*, 1994]. Textural observations suggest that decompression (paths B and C, Figure 5) was linked to thrusting, which has been dated at ~ 1120 Ma [*Tuccillo et al.*, 1992; *Wodicka*, 1994].

4.3. Main Grenvillian Metamorphism

The dominant Grenvillian metamorphism along the transect is both younger and lower grade than that recorded in the Parry Sound domain. Migmatitic upper amphibolite facies assemblages

are characteristic, although orthopyroxene is present in anhydrous mafic rocks like coronitic metagabbro and Sudbury metadiabase. In the Britt and Shawanaga domains, kyanite and sillimanite are present in pelitic rocks, and peak metamorphic conditions in supracrustal rocks and metabasites have been estimated at 700°-800°C and 10-12 kbars [*Tuccillo et al.*, 1990; *Ketchum et al.*, 1994; *Ketchum*, 1995]. In the Pointe-au-Baril area, decompression during cooling (paths D and E, Figure 5) has been linked to extension on the Shawanaga shear zone [*Ketchum*, 1995]. In the northernmost Britt domain, near-isothermal decompression in metadiabase (paths F and G, Figure 5) [*Jamieson et al.*, 1995] has been attributed to the combined effects of thrusting and extension. Amphibolite and migmatite in the Go Home and Moon River domains have been dated at 1065-1045 Ma (Figure 6) [*Bussy et al.*, 1995], consistent with metamorphism of coronitic metagabbro at 1060-1045 Ma [*Davidson and van Breemen*, 1988; *Heaman and LeCheminant*, 1993]. Somewhat older zircon ages (1080-1078 Ma) [*Bussy et al.*, 1995] have been obtained from rocks at higher structural levels immediately beneath the Parry Sound domain, and some-

what younger monazite cooling ages (~ 1035 Ma) [Corrigan *et al.*, 1994] have been obtained from rocks at lower structural levels in the northernmost Britt domain (Figure 6).

4.4. Late Grenvillian Metamorphism

In the GFTZ, U-Pb data point to a short-lived episode of metamorphism and cooling at ~ 1000-980 Ma (Figure 6) [Haggart *et al.*, 1993; Mezger *et al.*, 1993; Krogh, 1994; Dudas *et al.*, 1994] that produced upper amphibolite to granulite facies assemblages in Sudbury metadiabase [Jamieson *et al.*, 1995; Bethune, 1997]. The degree of metamorphic recrystallization increases into the orogen; metamorphism in the eastern GFTZ probably began earlier and was more protracted than in the western GFTZ [Jamieson *et al.*, 1995; Bethune, 1997]. The abrupt rise in metamorphic grade across the Grenville Front results from late Grenvillian exhumation of ~ 1450 Ma high-grade metamorphic rocks [Haggart *et al.*, 1993; Krogh, 1994; Dudas *et al.*, 1994].

4.5. High-Pressure Metamorphism

Garnet + clinopyroxene - rich metabasites, interpreted as retrogressed eclogites [Davidson, 1990, 1991], are rare but potentially important for understanding the full regional metamorphic and tectonic history. Characteristic features include coarse pyrope-rich garnet, clinopyroxene riddled with exsolved plagioclase, and corundum- and sapphirine-bearing symplectite. Minimum pressures have been estimated at 13 kbars [Grant, 1989; Davidson, 1991]. Although the relict eclogitic rocks are most common in shear zones, they are not restricted to them, implying that some or all of the allochthonous units that contain them experienced similarly high-pressure conditions [Davidson, 1991]. New U-Pb data [Ketchum and Krogh, 1997] indicate that high-pressure metamorphism occurred at ~ 1120 and 1085-1090 Ma.

4.6. Cooling History

Throughout the Britt and Shawanaga domains, remarkably consistent $^{40}\text{Ar}/^{39}\text{Ar}$ data from hornblende (970 ± 10 Ma) and muscovite (900 ± 20 Ma) indicate slow, regionally uniform cooling at $1^\circ\text{-}3^\circ\text{C}/\text{m.y.}$ (Figure 6) [Culshaw *et al.*, 1991b; Cosca *et al.*, 1991, 1992; Reynolds *et al.*, 1995], interpreted to reflect postorogenic erosional unroofing. In contrast, $^{40}\text{Ar}/^{39}\text{Ar}$ data from hornblende, muscovite, and K-feldspar in the western GFTZ suggest that rapid cooling over the temperature range $500^\circ\text{-}350^\circ\text{C}$ followed a short-lived thermal event in the final stages of the Grenville orogeny (1000-980 Ma) [Haggart *et al.*, 1993; Krogh, 1994]. U-Pb titanite and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende data from the Parry Sound domain (Figure 6) record cooling at 1080-1030 Ma [Tuccillo *et al.*, 1992; Wodicka, 1994], but muscovite ages of 910-890 Ma resemble those from the Britt and Shawanaga domains [Reynolds *et al.*, 1995]. This unit appears to have cooled relatively rapidly from $>600^\circ\text{C}$ to $<500^\circ\text{C}$ some 50-80 m.y. earlier than the underlying CGB, but cooled slowly thereafter. These data are consistent with transport of the Parry Sound allochthon over CGB rocks by ~ 1080 Ma [Bussy *et al.*, 1995; Wodicka *et al.*, 1996] and suggest that it remained at a relatively high structural level after that time.

Titanite data from the central part of the transect (Figure 6) reflect the variable effects of partial resetting, cooling, strain,

retrograde growth, and late-stage fluid flow [Wodicka, 1994; Ketchum, 1995]. A detailed study across the Britt - Shawanaga boundary [Ketchum, 1995] revealed three texturally distinct populations. Concordant titanite ages of 1028-1018 Ma, 1008-1000 Ma, and 967-956 Ma are interpreted to represent the times of cooling, late shearing, and static recrystallization, respectively. Monazite and titanite in the Parry Sound domain [Wodicka, 1994] and hornblende in the GFTZ [Reynolds *et al.*, 1995] show similar complexity.

5. Tectonic Synthesis

5.1. Cross Section

A NW-SE cross section (Figure 7b) representing the present-day crustal-scale architecture of the Grenville orogen between the CMB and the Grenville Front in western Ontario has been compiled from seismic reflection profiles [Green *et al.*, 1988; White *et al.*, 1994] and the geological and structural evidence summarized above. Also shown are the times of peak metamorphism and initial cooling along the section (Figure 7a). The cross section shows a crustal-scale duplex with contrasting structural styles at upper and lower levels. At lower levels, the GFTZ and Britt domains comprise tectonically equivalent rocks of the Laurentian craton, now separated from each other and from the Laurentian foreland by dominantly thrust-sense shear zones (Figure 3) developed late in the orogenic history. The structural level immediately above the parautochthonous Britt domain is occupied by the polycyclic lower Go Home, southern Rosseau, and Algonquin domains (IGH-RA), which are interpreted as transported elements of the Laurentian craton [Ketchum, 1995].

At higher structural levels, the Parry Sound domain (PSD) and immediately underlying Shawanaga (SH) and upper Go Home (uGH) domains (Figure 7) form thin allochthonous sheets that originated as parts of the CMB composite arc(s) and the Laurentian margin, respectively. Widespread leucosome-rich migmatite in these units may have facilitated transport of the allochthons over the Laurentian craton (Figure 8) [Jamieson *et al.*, 1992]. Although the Parry Sound domain has age and lithologic affinities with the CMBBZ [Wodicka *et al.*, 1996], it is now separated from these rocks and is structurally overlain by the Moon River (MR) and Muskoka (MU) domains, which have Laurentian affinities. Allochthonous units within the Moon River domain are interpreted to have been emplaced over the Parry Sound domain along an out-of-sequence ductile thrust zone.

Although most of the tectonic boundaries shown in Figure 7b are interpreted to have originated as NW-directed thrusts, many of them have been partly or pervasively overprinted by SE-directed extensional fabrics (Figure 3). The pre-extension configuration of the orogen, in particular the original northwestern limit of thrust sheets, is not known. It is possible that Grenvillian allochthons may have overridden most of the Britt domain, perhaps extending as far as its boundary with the GFTZ.

5.2. Tectonic Evolution

An interpretation of the Grenvillian tectonic evolution responsible for the present-day crustal architecture and age distribution along the transect is shown in Figure 8. The various lithotectonic elements identified in this study are shown in their postulated (simplest) pre-Grenvillian positions relative to the fixed

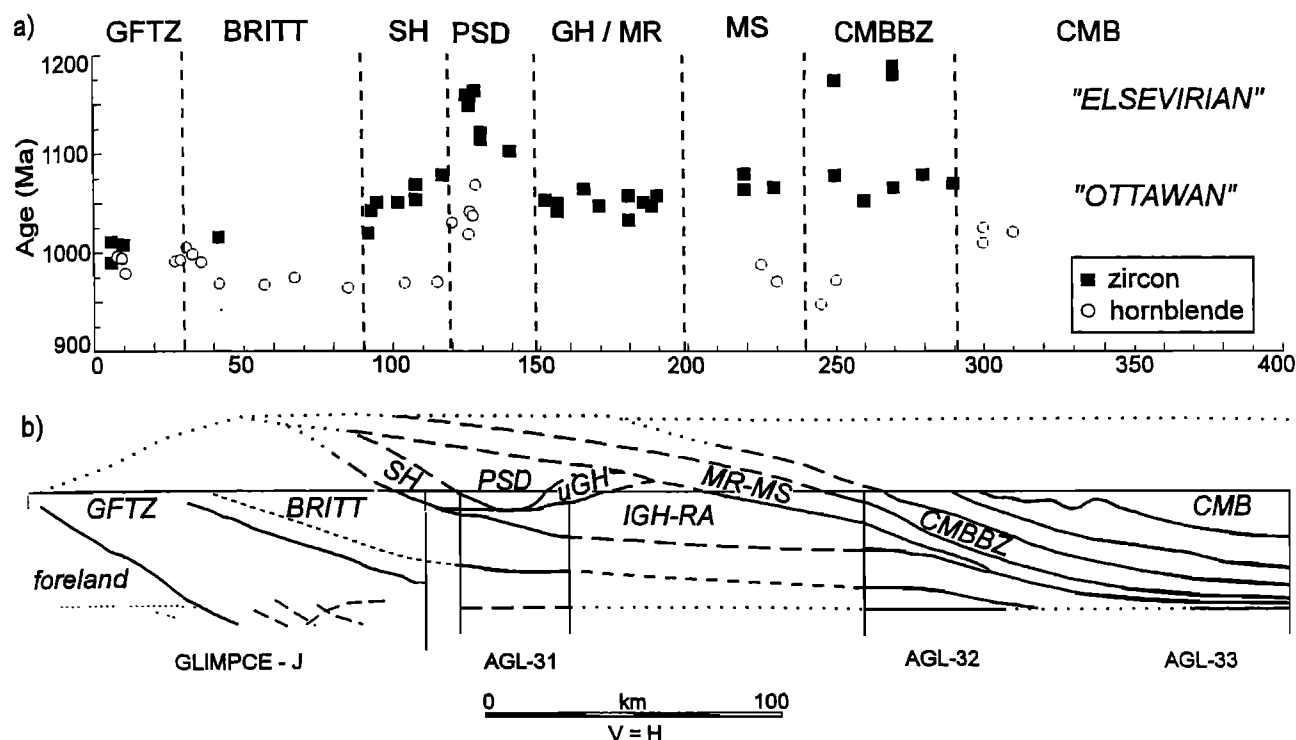


Figure 7. (a) Compilation of U-Pb zircon and ^{40}Ar - ^{39}Ar hornblende data, indicating the times of peak metamorphism and cooling through 500°C , respectively, summarized from Figure 6 and extended into the Muskoka domain (MS) and CMBBZ (Figure 1). Error bars and spurious ages (e.g., excess Ar in GFTZ [Reynolds *et al.*, 1995]) are omitted for clarity. Data sources are as for Figure 6, with additional data from Cosca *et al.* [1992], McEachern and van Breemen [1993], Burr and Carr [1994], and Timmermann *et al.* [1997]. (b) Crustal-scale cross section extending from the Grenville Front to the CMB (Figure 1), based on geological and structural data summarized in the text and Figures 2 and 3 and seismic reflection profiles from immediately east of the transect region (AGL-31 and AGL-32) and adjacent parts of the orogen (AGL-33 and GLIMPCE-J) [Green *et al.*, 1988; White *et al.*, 1994; S. Carr, personal communication, 1996]. Because it is based on the seismic profiles, this section is generally parallel to, but not exactly coincident with, A-A' in Figure 2 and the middle diagram of Figure 3. In particular, the GFTZ in Figure 7b is wider than that shown in Figure 7a because profile GLIMPCE-J is oblique to the transect and considerably along strike to the SW. Line weights in cross section indicate degree of confidence based on field data, extrapolation of surface structure to depth, along-strike projections, and seismic reflectors. Abbreviations are as follows, GFTZ, Grenville Front Tectonic Zone; BRITT, Britt domain; SH, Shawanaga domain; PSD, Parry Sound domain; uGH, upper Go Home domain; IGH-RA, lower Go Home and tectonically equivalent southern Rosseau and Algonquin domains; and MR-MS, Moon River and tectonically equivalent Muskoka and Seguin domains. CMBBZ and CMB are as for Figure 1; "foreland" corresponds to Southern Province in Figure 1.

Laurentian craton (Figure 8e). This schematic reconstruction is based on a template that incorporates systematic variations in pre-Grenvillian protolith ages, groupings of lithotectonic units with similar intrusive suites, and the pattern of Nd model ages, which decrease from NW to SE along the transect. The lower Go Home domain and its equivalents (IGH-RA) are shown southeast of the Britt-GFTZ assemblage, since although they have a polycyclic Laurentian history, they lack Sudbury diabase and contain coronitic metagabbro [Ketchum, 1995]. The Moon River domain and its equivalents in the southern Rosseau and Muskoka domains (MR-MS) contain coronitic metagabbro but lack unequivocal evidence for a polycyclic history [e.g., Timmermann *et al.*, 1997]. These are shown between the polycyclic Laurentian

rocks and the monocyclic Shawanaga and upper Go Home domains (SH-uGH), which are interpreted to represent the remnants of an active, post-1450 Ma Laurentian margin. The Parry Sound domain is shown as contiguous to the CMBBZ, which is the simplest interpretation based on geological and geochronological evidence detailed by Wodicka *et al.* [1996]. The amount of separation, if any, between the CMB composite magmatic arc(s) and this part of the Laurentian craton at this time is unknown.

Between 1190 and 1160 Ma, deformation and high-grade metamorphism affected both the Parry Sound domain and the CMBBZ (Figure 8) [e.g., van Breemen *et al.*, 1986; McEachern and van Breemen, 1993]. This tectonism was coeval with the late

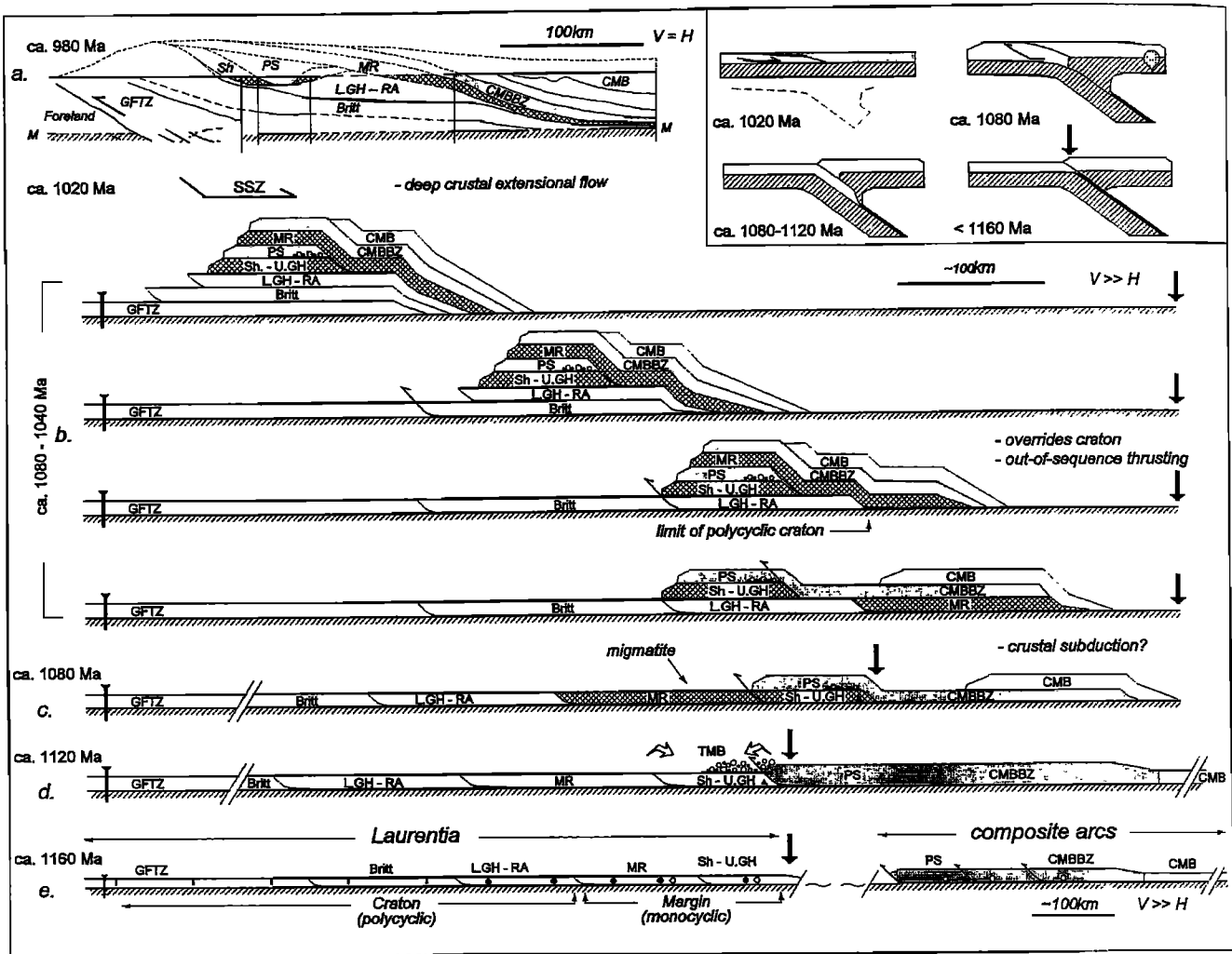


Figure 8. Tectonic evolution of the transect, (a) ~980 - 1020 Ma, (b) ~1040 - 1080 Ma, (c) ~1080 Ma, (d) ~1120 Ma, and (e) ~1160 Ma, based on the cross section in Figure 7b and geological and geochronological data discussed in the text. Unit abbreviations are as for Figure 7. "Nail" indicates fixed point on Laurentian craton at approximate position of present Grenville Front; solid arrow indicates position of SE limit of Laurentia prior to Grenvillian convergence. Note change in scale between Figure 8e and all others. Heavy barbed lines extending above section surface show thrust faults active at time indicated on panel. Figure 8e shows simplest ~1160 Ma reconstruction for units discussed in the text, based on the distribution of Sudbury metadiabase dykes (short vertical lines), coronitic metagabbro (solid circles), and anorthosite (open circles), polycyclic versus monocyclic histories, and other lithotectonic characteristics discussed in the text. Intrusive rocks are omitted for simplicity in other panels. As noted in text, the positions of the Parry Sound domain (PS), CMBBZ, and CMB with respect to Laurentia at this time are not known. Figure 8d shows the initial encounter of PS with Laurentia, formation of eclogitic rocks (triangle) and deposition of Twelve Mile Bay (TMB) supracrustal unit; this unit was subsequently overridden by, and incorporated into, the Parry Sound domain. At ~1080 Ma, the Parry Sound domain was thrust over the Laurentian craton. Between ~1080 and ~1040 Ma, NW-directed thrusting resulted in substantial telescoping of the Laurentian margin and craton; the out-of-sequence Moon River (MR) structure formed at an early stage of this process. Extension on the Shawanaga shear zone at ~1020 Ma is indicated schematically; the amount of extension is not known. A final stage of thick-skinned, NW-directed thrusting at 1000-980 Ma formed the GFTZ. Shaded units are PS and CMBBZ, contiguous at ~1160 Ma but separated by out-of-sequence thrusting soon after 1080 Ma. Cross hatching indicates leucosome-rich migmatite formed as Laurentian units were buried during post-1120 Ma convergence; these weak migmatitic zones facilitated emplacement of PS allochthon and development of out-of-sequence Moon River structure. Inset at upper right shows possible lithosphere-scale reconstruction for important stages in tectonic evolution of the region. Evidence for SE dipping subduction at 1080-1120 Ma is discussed in text.

stages of the "Elsevirian" orogeny recognized to the southeast [e.g., Moore and Thompson, 1980; McLelland et al., 1996]. The only tectonic activity of this age known from the Laurentian craton along the transect is the intrusion of coronitic gabbro at 1170-1150 Ma. Grenvillian high-grade metamorphism did not affect the parautochthon or the Muskoka domain, which occupies the immediate footwall of the CMBBZ, prior to ~ 1080 Ma (Figures 1 and 7a) [Timmermann et al., 1997]. It is therefore unlikely that the ~ 1160 Ma event represents transport of the Parry Sound domain into its present position [Wodicka et al., 1996; Timmermann et al., 1997]. This stage of tectonism is shown schematically in Figure 8 as taking place an unspecified distance to the southeast of the CGB.

At ~ 1120 Ma, metamorphism, deformation, exhumation and cooling affected the basal Parry Sound assemblage. At about the same time, the Twelve Mile Bay quartzite was deposited from a varied source that included Laurentian rocks [Wodicka et al., 1996]. It is probable that this marked the initial encounter of the Parry Sound - CMBBZ allochthons with the outer margin of Laurentia (Figure 8). This stage of convergence did not involve reworking of polycyclic Laurentian rocks, although pegmatites near the boundaries of the Moon River and Seguin domains have yielded ages of ~ 1100 Ma [van Breemen and Davidson, 1990; Nadeau, 1990]. Further work is needed to assess the significance of these data, which are difficult to reconcile with ~ 1080 Ma metamorphism and deformation in tectonically equivalent rocks of the Muskoka domain and in the Parry Sound domain footwall [Bussy et al., 1995; Timmermann et al., 1997].

Although there is little evidence for regionally significant deformation or metamorphism along the transect between 1120 and 1080 Ma, tectonic activity was occurring both to the southeast and to the northwest at this time. The recent recognition of ~ 1120-1090 Ma high-pressure metamorphism in allochthonous rocks underlying the Parry Sound domain [Ketchum and Krogh, 1997] suggests that subduction was occurring somewhere to the southeast of the transect; SE-dipping subduction beneath the CMB at 1089-1076 Ma has been postulated by Corriveau [1990]. Northwest of the transect, formation of the Midcontinent rift between 1109 and 1087 Ma [Van Schmus, 1992; Cannon, 1994] was followed by thrusting between 1080 and 1040 Ma [Cannon, 1994], coincident with the main phase of Grenvillian thrusting and metamorphism along Georgian Bay. These features suggest that some sort of plate re-organization affected the western Grenville orogen between 1120 and 1080 Ma.

The entire transect, with the exception of the GFTZ and the Parry Sound domain, was affected by high-grade metamorphism and deformation between 1080-1035 Ma (Figures 6 and 7a), corresponding broadly to the "Ottawan" orogeny [e.g., Moore and Thompson, 1980; McLelland et al., 1996]. Metamorphic ages of 1080-1070 Ma have been determined from mafic rocks at the structural level immediately underlying the CMBBZ and the Parry Sound domain (Figure 7a) [Bussy et al., 1995; Timmermann et al., 1997]. These ages are coeval with the initiation of renewed thrusting and metamorphism within the CMBBZ (Figure 7a) [McEachern and van Breemen, 1993; Burr and Carr, 1994] and titanite dates from the basal Parry Sound assemblage (Figure 6) [Tuccillo et al., 1992; Wodicka, 1994]. We interpret these data to indicate exhumation and transport of the Parry Sound domain and other deep-seated rocks over the Laurentian craton at or shortly before 1080 Ma. Metamorphism at 1065-

1045 Ma, widespread from the Shawanaga domain to the CMBBZ (Figure 7a), is interpreted as a response to the ~ 1080 Ma thrusting. After initial allochthon emplacement but before cooling of the Parry Sound domain below ~ 500°C (<1068 Ma) [Wodicka, 1994], out-of-sequence thrusting emplaced the Moon River domain (Figure 8), causing reworking and retrogression of the southeastern Parry Sound domain. Monazite cooling ages suggest that thrusting affected the northernmost Britt domain at or shortly before 1035 Ma [Corrigan et al., 1994; Jamieson et al., 1995]. It is not clear whether convergence along the transect between 1080 and 1035 Ma was continuous or episodic.

Extension on the Shawanaga shear zone, dated at ~ 1020 Ma [Ketchum et al., 1993; Ketchum, 1995], may have overlapped with compression in the northern Britt domain [Jamieson et al., 1995] but in general appears to have postdated thrusting. Ductile extensional fabrics are present along most of the transect except the GFTZ, and extension was accompanied by transverse folding in the northern and central parts of the transect. The subhorizontal structural attitude dominant along the transect (Figure 7b) is largely attributable to the effects of late orogenic extension superimposed on a complex, crustal-scale, ductile thrust belt.

The final stage of convergence along the Georgian Bay transect resulted in metamorphism and exhumation of the GFTZ at 1000-980 Ma [Haggart et al., 1993; Bethune, 1993; Krogh, 1994]. Deformation was exclusively thrust-sense within the GFTZ, although extensional fabrics are found along the older GFTZ-Britt boundary shear [Jamieson et al., 1995]. This event, which affected the northwestern flank of the Grenville orogen from Georgian Bay to Labrador [Krogh, 1994], marked the final stage of propagation of the Grenville orogen into its foreland [Haggart et al., 1993]. Between 100 and 300 km of shortening, principally constrained by likely source of Parry Sound domain within or beyond the CMB, was accommodated by multiple stages of convergence along the transect (Figure 8).

6. Implications for Flow in the Lower Orogenic Crust

The transect crosses the allochthon-parautochthon boundary at an inferred orogenic depth of 20-30 km. It therefore offers an unusual opportunity to investigate the thermal and mechanical behavior of the footwall beneath a major decollement during a protracted orogenic episode that involved both regionally significant thrusting and extension. The results of this investigation potentially shed light on some long-standing questions about the style and timing of lower crustal flow during collision (Figure 9).

6.1. Lower Crustal Flow During Convergence

Some models of thrust belts have treated the lower orogenic crust as an inactive substrate [e.g., Coward, 1983] (Figure 9a), while others have viewed ductile flow in the lower crust as an important factor accommodating substantial convergence [e.g., Westaway, 1995]. A change in the rheological behavior of the lower crust during collision is likely as the lower crust gets hotter and weaker in response to crustal thickening. Numerical models of convergent orogens involving sub-orogenic subduction suggest that the tectonic style of an orogen is strongly influenced by the strength of the lower crust [e.g., Beaumont et al., 1994]. Where the lower crust is relatively strong, deformation is focused

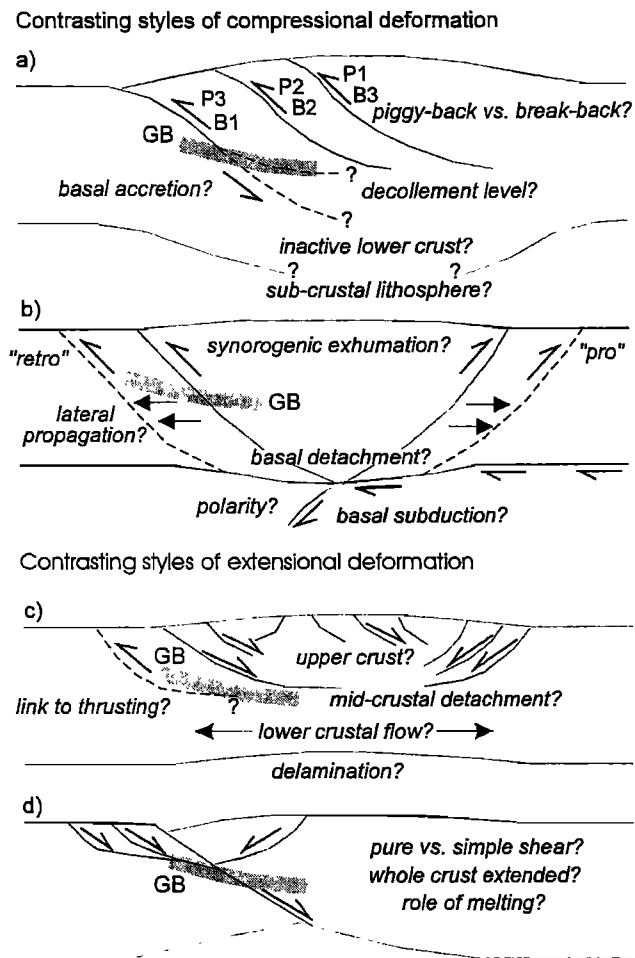


Figure 9. Questions concerning styles of extensional and compressional deformation in the middle to lower orogenic crust. Neither the structural styles shown nor the associated questions are intended to be exhaustive or mutually exclusive. Shaded line marked "GB" indicates approximate synorogenic level represented by the Georgian Bay transect. (a) Accretion of thrust sheets above inactive lower crust [e.g., Coward, 1983]; P1, P2, P3 are the sequence of thrust movement for "piggyback" style; B1, B2, B3 are the sequence for "break-back" style. (b) Thick-skinned deformation above basal detachment and outward propagation of orogen associated with subduction of suborogenic lithosphere [e.g., Beaumont et al., 1994]; (c) "Pure shear" extension rooted in midcrust, with contrasting structural styles in upper and lower crust [e.g., Malavieille, 1993]; (d) Simple shear extension with crustal-scale offset [e.g., Wernicke, 1985].

along moderately-dipping crustal-scale shear zones, and lower crustal rocks are exhumed (Figure 9b). Where the lower crust is relatively weak, the models predict detachment and substantial lateral migration of the orogen into its foreland, accompanied by pervasive subhorizontal lower crustal flow; lower crustal rocks are not likely to be exhumed except where lateral strength contrasts serve to focus deformation [e.g., Ellis et al., 1997].

Observations from the Georgian Bay transect provide constraints on the style and geometry of lower crustal flow in con-

vergence, the role of rheological heterogeneities and influence of various syncollisional weakening mechanisms, and the sequence of structural development. Among the earliest convergence-related structures are nappe-like folds within allochthonous units (Figure 2) and discrete lithotectonic boundaries, interpreted as cryptic thrusts, separating various allochthonous units from each other and from the underlying parautochthon (Figure 3). These early structures were overprinted by the penetrative ductile fabrics that characterize the upper amphibolite facies gneissic tectonites along the transect; in parautochthonous rocks these ductile fabrics are the earliest Grenvillian compressional structures. This pattern suggests a progression from accretion of allochthonous thrust sheets to distributed ductile flow [cf. Northrup, 1996] as the orogen propagated into the craton. We suggest that the out-of-sequence emplacement of the Moon River rocks occurred in response to the changing geometry of the orogen as it propagated into the craton. In general, the times of metamorphism and thrusting appear to young to the northwest; exceptions include the out-of-sequence emplacement of the Moon River rocks and the thrust separating the basal from the interior Parry Sound assemblages, which was transported into its present relative position, along with its allochthonous host rocks, on a younger, deeper-level structure (probably the Shawanaga shear zone). The sequence of thrust propagation thus more closely resembles a "piggyback" style than the "break-back" style inferred by Nadeau and Harmer [1992] (Figure 9a).

The Georgian Bay transect is dominated by rheologically weak granitoid rocks, and their ductility was enhanced by widespread partial melting. This is particularly evident in the spectacular leucosome-rich migmatites of Shawanaga and Muskoka domains. Field and geochronological data suggest that these migmatites were formed and deformed during NW-directed transport at ~ 1080 Ma [Timmermann et al., 1997] during the time that Parry Sound allochthon was transported at least 100 km over the Laurentian craton. It has been suggested that Shawanaga domain migmatite facilitated this transport [Jamieson et al., 1992], acting as a thin, extremely weak, intracrustal decollement; out-of-sequence thrusting above the relatively strong Parry Sound granulites (Figure 8) apparently also reflects the extreme ductility of the migmatitic rocks. Given the probable preorogenic setting of their monocyclic protoliths (Figure 8), we suggest that the leucosome-rich migmatites may have formed in response to deep burial or partial subduction of the Laurentian margin beneath the CMB composite arc(s) at 1120 to 1080 Ma. Less well-developed migmatite is present throughout the parautochthon in rocks of suitable bulk composition, with peak metamorphism at 1065-1045 Ma (Figure 7a) postdating allochthon emplacement by 15-35 m.y. In the northern Britt domain, where leucosomes are clearly associated with thrust-sense fabrics, the migmatite appears to be younger (1035 Ma) [Corrigan et al., 1994] than that in the overlying Shawanaga domain. The relative ages and styles of compressional structures suggest that, following allochthon emplacement, deformation propagated toward the northwest as strong rocks of the Laurentian craton were weakened by heating and partial melting beneath the decollement. The style of deformation along the transect supports the idea that partial melting is an important weakening mechanism for quartzofeldspathic lower crust in collisional orogens [e.g., Davidson et al., 1994].

Granulites in both the Parry Sound domain and the parautochthon remained relatively strong during Grenvillian deforma-

tion, preserving structures and mineral assemblages that predate the main phase of Grenvillian convergence. Penetration of fluid, particularly along major shear zones, facilitated weakening of these granulites by partial melting and retrograde hydration, for example, along the Moon River - Parry Sound domain boundary. Granulite is less abundant than granitoid orthogneisses, but its distribution is clearly reflected in the map pattern (Figures 2 and 4). Although generally weak, the lower Grenvillian crust was therefore "lumpy," with rheological heterogeneities, particularly zones of strong granulite, influencing regional ductile flow patterns.

On the northwestern flank of the orogen, the GFTZ lacks Grenvillian migmatite and has very little Grenvillian pegmatite. The highest-grade metamorphic rocks are pre-Grenvillian [e.g., Krogh, 1994; Dudas *et al.*, 1994]. This region never reached the high metamorphic grade of the interior and was therefore relatively strong during convergence. This is reflected in the moderate dips, discrete thrust-sense shear zones especially in the western GFTZ, and seismic reflectivity pattern indicating that moderately dipping structures extend into the lower crust, perhaps to the Moho [Green *et al.*, 1988] (Figure 7b). We interpret the GFTZ as a step-up shear zone separating weak orogenic crust from strong foreland. It has been suggested that the GFTZ was a retro-shear zone (e.g., Figure 9b) associated with NW-directed suborogenic subduction [Haggart *et al.*, 1993]. However, in large, weak orogens where lateral strength contrasts focus exhumation, the polarity of any associated subduction may be indeterminate [e.g., Ellis *et al.*, 1997], so the geometry of the GFTZ may provide no information on the behavior of the suborogenic lithosphere.

6.2. Lower Crustal Flow During Extension

Synorogenic extension in large orogens is generally attributed to a combination of high topography and thermal weakening associated with crustal thickening [e.g., Dewey, 1988; England and Houseman, 1989; Malavieille, 1993], although changes in convergence rate or direction are also likely to be important [e.g., Willett, 1993]. Although the style of upper crustal extension is well documented from many orogens, its expression in lower crustal rocks is not nearly as well understood. Ductile extensional flow in extremely weak lower crust ("pure shear," Figure 9c) has been postulated to explain observations like subhorizontal lower crustal and Moho seismic reflections, gravity signature, large plateaus, and apparent structural decoupling between the upper and lower crust in orogens that have evolved from thickening to extension [e.g., Meissner *et al.*, 1991; Malavieille, 1993; Masek *et al.*, 1994]. Alternatively, the crust may extend asymmetrically along gently dipping, crustal-scale normal faults ("simple shear," Figure 9d) [e.g., Wernicke, 1985; Malavieille, 1993]. The increasing recognition of transverse folds in extended terranes, with hinges formed parallel to the stretching direction and a high ratio of axial stretching to amplification, suggests that this style of folding may be characteristic of extension [e.g., Malavieille, 1987; Chauvet and Sérrane, 1994; Culshaw *et al.*, 1994; Fletcher and Bartley, 1994; Mancktelow and Pavlis, 1994].

Ductile fabrics with normal-sense kinematic indicators are widely distributed along the Georgian Bay transect and dominate over thrust-related fabrics. A significant, perhaps predominant, component of the strain that formed the predominantly subhorizontal fabrics is attributable to extension [Culshaw *et al.*,

1994]. The Shawanaga shear zone, which may be one of the best examples anywhere of a synorogenic extensional shear zone in the lower crust, is the most obvious product of extensional ductile flow in the southwestern Grenville orogen. Outcrop and seismic evidence indicates that it is a generally shallow dipping structure that overprints an earlier cryptic thrust (Figure 3) [Culshaw *et al.*, 1994]. Extensional displacement on the Shawanaga shear zone at ~ 1020 Ma postdated peak metamorphism, although growth of sillimanite parallel to the extensional stretching lineation indicates that these rocks were hot during extensional shear [Ketchum, 1995]. Extension also generally postdated thrusting, although it may have overlapped with convergence in the northernmost Britt domain [Jamieson *et al.*, 1995].

The regional-scale transverse folds that dominate the map pattern formed during ductile extensional flow (Figure 4). In some places, these folds clearly postdate contractional structures, and in the Pointe-au-Baril area, transverse folding was contemporaneous with extensional displacement on the Shawanaga shear zone [Culshaw *et al.*, 1994]. Transverse folding in extensional terranes has been widely attributed to oblique external boundary conditions that result in *Y*-axis shortening [e.g., Mancktelow and Pavlis, 1994]. However, the relative scarcity of oblique structures along the Georgian Bay transect suggests an intrinsic cause for folding. Culshaw *et al.* [1994] suggested that flow perturbations in the rheologically heterogeneous lower crust within the transect area controlled the nucleation and growth of the transverse folds. The absence of transverse folds in granulite-facies gneisses of the Parry Sound domain and of the Algonquin domain (east of the transect area Figure 1) contrasts with their abundance in amphibolite-facies rocks along Georgian Bay. This suggests that regional contrasts in metamorphic grade, or associated differences in rheology linked to mineralogy or fluid content, may have influenced the distribution of these late folds.

Fletcher and Bartley [1994] suggested that transverse, upright folds can be initiated in dipping layers by *Y*-axis shortening in the uniaxial stress state that is expected for extension ($\sigma_3 < \sigma_2 = \sigma_1$, σ_1 horizontal). Under these conditions, plunging transverse folds form initially and become subhorizontal with continued extension. This is consistent with structures along Georgian Bay, where steeper fabrics in nonfolded domains (Figure 4) predate the formation of the regional transverse folds, which have gently inclined enveloping surfaces. The activity of this mechanism proposed by Fletcher and Bartley [1994] would imply that extension played a paramount role in forming subhorizontal structures in the CGB. This folding mechanism may have operated in concert with rheological heterogeneities to form the transverse folds along Georgian Bay.

Extensional displacement on the Shawanaga shear zone at ca. 1020 Ma postdated peak metamorphism in the transect area by 25-30 m.y. This is consistent with thermally activated extension related to weakening of the lower crust [e.g., Dewey, 1988]. It could also reflect a decreased rate of convergence [e.g., Willett, 1993], which is consistent with regional geochronologic data [Ketchum, 1995]. Footwall decompression (Figure 5) and cooling through titanite closure temperature accompanied extension [Ketchum, 1995], but the crust remained above ~ 500°C along most of the transect for another 40-50 m.y. (Figures 6 and 7). It is not clear whether delayed cooling was related to extreme crustal thickness, additional mantle heat, blanketing by sedimentary

basins, or renewed crustal thickening associated with late-stage thrusting in the GFTZ [Reynolds *et al.*, 1995].

Observations from the Georgian Bay transect show that this part of the CGB extended by distributed, subhorizontal ductile flow in extremely weak lower crust (Figure 9c). This style of extension contrasts with the narrow, steeply dipping, late-orogenic to postorogenic extensional faults in the CMB [e.g., Carlson *et al.*, 1990; Busch and van der Pluijm, 1996] which have been inferred to resemble those shown in Figure 9d. These differences presumably reflect contrasting levels of exposure between the two regions. In addition, unlike other well-documented cases of syn-orogenic normal faulting that is synchronous with thrust faulting at lower structural levels [e.g., Hodges *et al.*, 1992; Northrup, 1996], there is no clear temporal or spatial link between extension on the Shawanaga shear zone and thrusting. It is not clear whether the deep crustal level exposed along Georgian Bay explains these contrasts with synorogenic extensional faults exposed at higher crustal levels.

7. Conclusions

1. The Georgian Bay transect crosses a number of distinctive lithotectonic units representing elements of the Laurentian craton, an active margin developed on its southeastern boundary (≤ 1430 Ma), and "Grenvillian" magmatic arcs farther to the southeast. The lithotectonic units were assembled into their present relative positions during NW-directed convergence that began at or shortly before 1080 Ma.

2. The Parry Sound domain records an episode of early Grenvillian tectonism (~ 1160 - 1120 Ma) not seen in underlying rocks and includes a supracrustal unit deposited after ~ 1140 - 1120 Ma. These rocks were not transported into their present relative position until after 1120 Ma.

3. The main episode of high-grade metamorphism along the transect occurred at 1065-1045 Ma. Rocks at higher structural levels were affected somewhat earlier (≤ 1080 Ma) and at lower

structural levels somewhat later (≥ 1035 Ma). Peak metamorphism was followed by ductile extension along the Shawanaga shear zone at ~ 1020 Ma. A short-lived episode of thrusting and metamorphism affected the GFTZ at the northern end of the transect at 1000-980 Ma.

4. Transport of allochthons across the Laurentian craton was initially accomplished along a weak decollement developed in leucosome-rich migmatite. Subsequent penetrative ductile deformation involving parautochthonous rocks and propagation of the orogen into the craton were associated with thermal weakening and partial melting beneath this decollement.

5. Extensional deformation was associated with distributed ductile flow, formation of regional transverse folds, and reactivation of the allochthon-parautochthon thrust boundary as a shallowly dipping, midcrustal, extensional decollement (Shawanaga shear zone). Transverse folding is attributed to the combined effects of fold nucleation and growth in a rheologically heterogeneous medium and Y -axis shortening on inclined surfaces in a uniaxial stress field. The regional map pattern and shallowly dipping enveloping surfaces of the transverse folds were mainly produced during extensional flow.

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