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# A review of the Grenville orogen in its North American type area

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In a reconstructed supercontinent assembly at ~0.9 Ga, the Grenville orogen extends from Scandinavia through North America and Antarctica to Australia. Part of it, the 2000 km long Grenville Province, exposed in the southeastern Canadian Shield, is large enough to allow a comprehensive view of its tectonic character. It has an orogen-parallel zonation: older, reworked crust, representing Archaean and Palaeoproterozoic orogens exposed in adjacent parts of the shield, is restricted to its northwest side; supracrustal and plutonic rocks of Grenvillian age (~1.3–0.95 Ga) are limited to the southeastern half. The latter lie on or within late Palaeoproterozoic and earlier Mesoproterozoic crust, which is the deformed, temporal equivalent of terranes that form a substantial part of the buried North American craton south of the shield. A pre-Grenvillian period of quiescence at ~1.5 Ga may have followed an earlier continental assembly. Grenvillian calc-alkaline igneous rocks, limited in volume and distribution, represent arc accretion that terminated with ocean closure by ~1.2 Ga. New crust was added after continent–continent collision and attendant crustal thickening by emplacement of large gabbro–anorthosite massifs of mantle origin, associated with, and in part responsible for, granitoid magma derived from the lower crust. This magmatism, beginning at ~1.18 Ga, was accompanied or followed by high-grade metamorphism, except in parts of the Grenvillian supracrustal terranes, and by low-angle, thrust-sense, ductile deformation directed toward the north and northwest. Ductile followed by brittle extensional deformation between 1.05 and 1.0 Ga, along with terminal thrust-uplift along the northwest margin of the orogen, represent the closing stages of tectonic activity, leading to unroofing and cooling by ~0.9 Ga. There is little evidence in the Grenville Province for supercontinent break-up until ~600 Ma.

## Introduction

According to recently published reconstructions (Moores 1991; Dalziel 1991; Hoffman 1991; Borg & DePaolo 1994), plate interactions during Neoproterozoic supercontinent assembly[1] produced an interconnected, global orogenic system (Fig. 1). Part of this system, the Grenville Province of the Canadian Shield, has given its name to this worldwide orogeny, active between ~1.3 and 0.95 Ga. The Grenvillian orogeny occurred between two relatively quiescent periods of Earth history, namely at ~1.5 and 0.8 Ga; the older of these was preceded by major orogeny in various parts of the world, between 1.9 and 1.6 Ga (Penokean, Hudsonian, Yavapai–Mazatzal, Ketilidian, Labradorian, Svecofennian, etc.), and the younger was succeeded by latest Proterozoic to early Phanerozoic events (Pan-African, Avalonian, Caledonian–Appalachian, etc.).

The purpose of this paper is to provide an up-to-date review of the Grenville orogen in its type area, the Canadian Shield, so that others may compare it with crust of similar age exposed in the Musgrave Block of central Australia, at the other end of the reconstructed Grenvillian orogen. The Grenville Province (Gill 1948) is defined as that part of the Grenville orogen which is exposed in the southeastern Canadian Shield. In North America, the Grenville orogen is known to extend, mainly in the subsurface, southwestward from the Shield to Texas and Mexico (Ruiz et al. 1988; Rankin et al. 1993) (Fig. 2). Precambrian rocks affected by Grenvillian orogeny occur as basement windows and slices throughout the Appalachian orogenic system, emerging in the foreland of this Palaeozoic belt in Texas (notably in the Llano uplift). In eastern Mexico, however, Grenvillian rocks may lie within or on the opposite side of the southward continuation of the Appalachian–Ouachita orogenic system (Ruiz et al. 1988). The Sveconorwegian Province in southwest Scandinavia is the trans-Atlantic counterpart, east of the Caledonides (Gower 1985, 1990), and must continue in the subsurface south of the Baltic Sea. Grenvillian remnants have also been recognised in Scotland and northern Ireland. Other orogenic belts of Grenvillian age can be fitted into reconstructions of continental plate configurations at ~0.8 Ga (e.g. Hoffman 1991). Such reconstructions show a Grenvillian connection with the Albany–Fraser Belt in southwest Australia via Antarctica, also incorporating Madagascar and eastern India (Fig. 1). It is curious that reconstructions (e.g. Moores 1991) show the northeast extension of the Albany–Fraser Belt to pass south of the central Australian Musgrave Block, in which metamorphism, deformation and plutonism in the Grenvillian range have been identified. Sun & Sheraton (1992) noted that the Musgrave Block and Albany–Fraser Belt appear to show contrasting tectonic styles (intraplate vs collisional, respectively), although tectonic activity was similar in age; they inferred (op. cit., p. 11) that central and western Australia may have undergone a more complex Grenvillian evolution than is usually portrayed. The Musgrave Block is therefore included in the Grenvillian system in Figure 1.

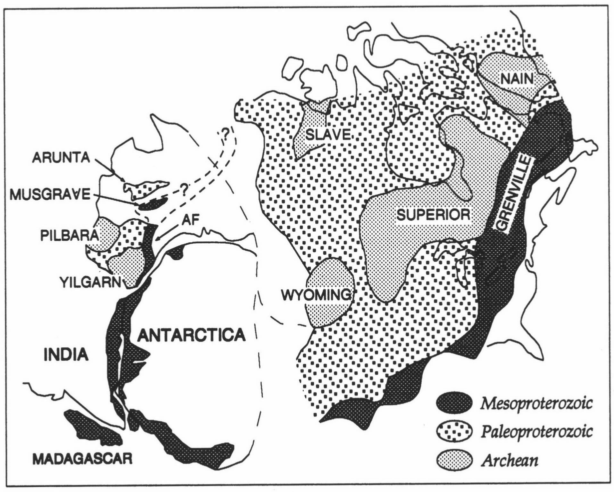


**Figure 1. Distribution of Mesoproterozoic Grenvillian belts in post-Grenvillian supercontinent reconstruction, after Moores (1991). AF is Albany–Fraser belt. Palaeoproterozoic in North America includes reworked Archaean blocks.**

The volume of literature on the Grenville Province and related topics has increased several fold in the last decade, and a fully comprehensive bibliography would run to many hundred references. In the following review, much information has been drawn from summary volumes and key papers, such as Moore et al. (1986), Rivers et al. (1989), Gower et al. (1990), Rankin et al. (1993) and, in particular, Hoffman (1989a). Many references are to recent papers reporting results of tracer isotope and geochronological studies linked to assessment of both specific and regional field relationships, without which understanding of the Grenville Province might

[1] *McMenamin & McMenamin (1990, p. 95) proposed the name 'Rodinia' for this supercontinent, but their reconstruction differs from that shown in Figure 1.*

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not be much further ahead than it was at the time of the first attempt to synthesise its geology and tectonic history as a whole (Wynne-Edwards 1972).

Before the Grenville Province and its component parts are described, two terms require clarification. The first is *Grenvillian*, used in the chronological sense. Traditionally, the Grenvillian orogeny is considered to have culminated by ~1.0 Ga, but a record of earlier events has been recognised for some time. Moreover, pre-1.0 Ga deformation has affected <1.3 Ga supracrustal rocks restricted to the Grenville orogen; these rocks therefore carry a tectonic signature which is not recognised in Shield orogens outside the Grenville Province. On this basis, Moore & Thompson (1980) suggested the terms Elzevirian and Ottawan orogenies for older and younger events in Ontario; they combined these in their term 'Grenvillian orogenic cycle', alluding to the Wilson cycle concept for development of the Grenville orogen. Modern geochronological studies, though far from complete, have provided a firm basis for assigning ages to various events in different parts of the province. As will be described later below, calc-alkaline

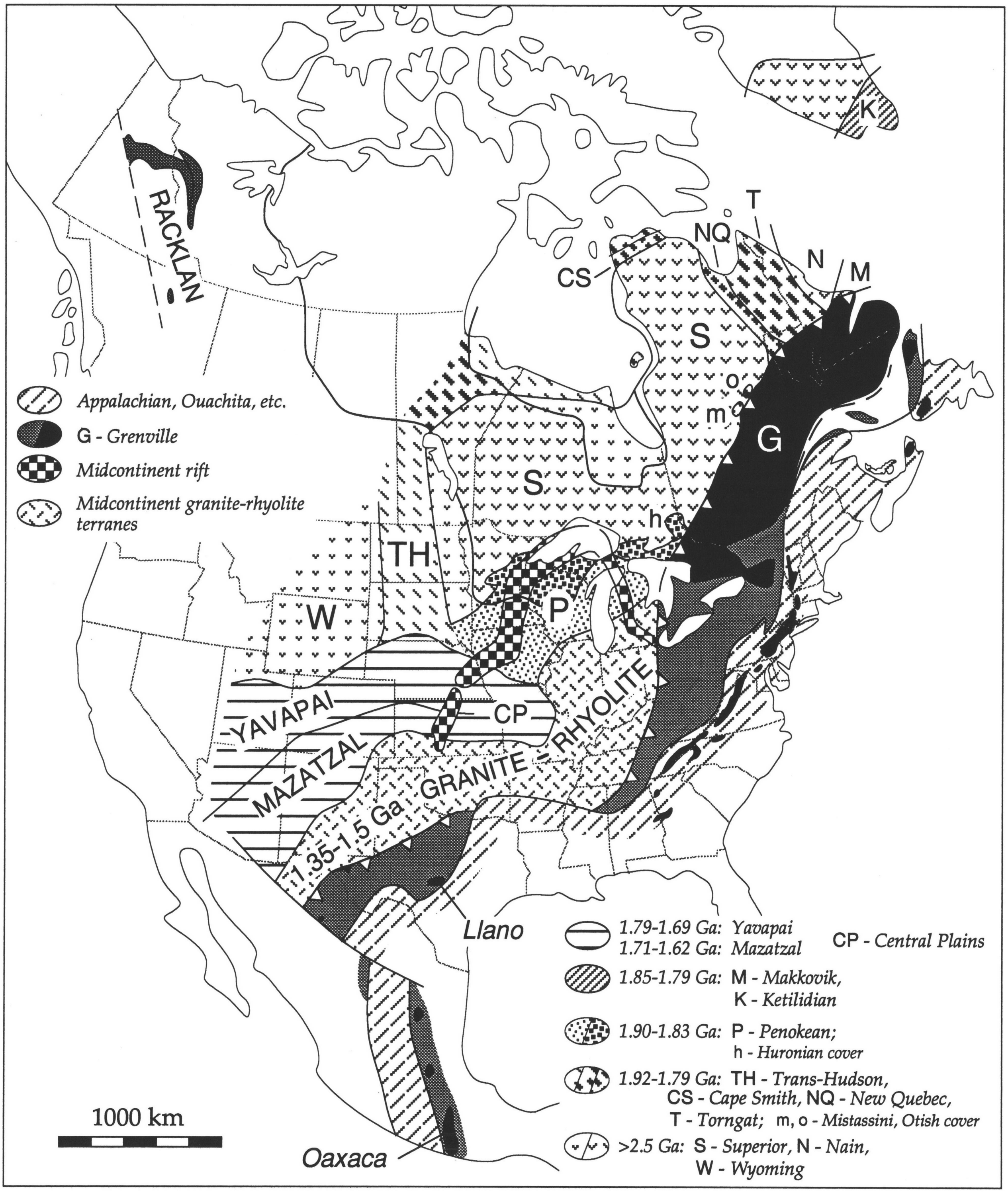


**Figure 2. The Grenville orogen in North America. Parts of Superior, Wyoming, Trans-Hudson and Penokean provinces identified by smaller patterns, and grey part of the Grenville orogen, are covered by Phanerozoic rocks. The Grenville Front is marked with white teeth. The Racklan orogen is also Grenvillian in age. Data abstracted principally from Hoffman (1989a), Ruiz et al. (1988), and Van Schmus et al. (1992).**

volcanic and plutonic rocks in the type area of the Elzevirian orogeny, considered to represent arc accretion (Windley 1986) and dated between 1.29 and 1.23 Ga, are an early manifestation of the Grenvillian orogenic cycle. There is evidence, however, for somewhat earlier, juvenile, calc-alkaline plutonic activity (1.35–1.30 Ga) in the Adirondack region of New York (McLelland & Chiarenzelli 1990) and inliers of the northern Appalachians (Ratcliffe et al. 1991), and of an even earlier volcanic arc (1.45–1.39 Ga) in central Quebec (Nadeau & van Breemen 1994), but their relationships to the Grenvillian orogenic cycle are at present uncertain. At the younger end of the Grenvillian time span, plutonism continued until ~1.06 Ga in the southwest part of the province, and until ~0.95 Ga in the east. High-grade metamorphism is recorded at ~1.05 - 1.02 Ga in several parts of the province. The Grenville Front was terminally active at ~1.0 Ga; cooling ages (U-Pb titanite, rutile, and $^{40}Ar/^{39}Ar$ hornblende) are of the same order or somewhat younger, with some exceptions of earlier cooling, noted below. In this paper, therefore, the term *Grenvillian* is used for rocks and events within the range ~1.3–0.95 Ga, with the proviso that this may be expanded in the future to include somewhat earlier events.

The second involves the term *terrane*, employed widely in the last decade for convenient description of segments of crust in the Grenville Province which, on the basis of lithology, structure, metamorphism, age of events and geophysical signature, are sufficiently distinct to set them apart from adjacent segments. The term *domain* has been used in the same sense (e.g. Davidson et al. 1982). Such distinctive segments are usually separated by continuous zones of high strain, in places amounting to well-defined ductile shear zones or faults. Rivers et al. (1989) suggested a non-genetic terminological hierarchy in which continuous *belts* within the Grenville Province may contain several terranes, themselves divisible into domains where appropriate. If the term *terrane* is considered in the narrower plate tectonic sense to define an out-of-place segment of crust bounded by sutures (e.g. Coney et al. 1980), then there are few viable candidates within the Grenville Province; discrete sutures have not been identified with certainty in the field, although some have been inferred on the basis of indirect evidence such as crust-formation ages (e.g. Dickin & McNutt 1989). It would be surprising indeed if terranes, in the plate tectonic sense, do not exist in an orogen such as the Grenville. Moreover, since much of the province is underlain by rocks of older orogens reworked during the Grenvillian orogeny, it is probable that pre-Grenvillian sutures are present as well. In deep crust such as characterises the exhumed Grenville orogen, however, terrane-bounding sutures are likely to be both cryptic and deformed, rendering their identification difficult and subject to circumstantial evidence. Nevertheless, it is quite clear that many of the named terranes within the Grenville Province are *not* bounded by sutures. The term *terrane* will therefore be used here in the non-genetic sense to avoid confusion with published nomenclature.

## The Grenville Province

The Grenville Province, as defined above, underlies a belt, about 400 km wide, extending from the Atlantic coast of Labrador 2000 km southwestward to Lake Huron, beyond which rocks affected by the Grenvillian orogeny are covered by Phanerozoic platform sediments (Michigan Basin) of the continental cratonic interior (Fig. 2). The original width of the Grenville orogen is not known. The southeast margin of the Grenville Province is mostly covered by a narrow strip of unmetamorphosed and little-disturbed Early Palaeozoic sediments, but it abuts the Appalachian front along the east side of the Adirondack Mountains of New York, the southern part of which is nearly 600 km southeast of the Grenville Front. Throughout the Appalachian system of Canada and the eastern United States, Grenvillian rocks in tectonic windows and thrust slices attest to a considerably wider orogen than is now preserved in the Grenville Province itself.

In contrast, its northwest margin, the Grenville Front, is a remarkably sharp tectonic lineament. It cuts across several cratonic provinces, truncating their boundaries and internal structures, a feature that is expressed convincingly on regional aeromagnetic maps (see Fig. 2 *in* Rivers et al. 1989). It is the locus of moderately to steeply southeast-dipping thrust faults and mylonite zones, whose hanging walls generally carry uplifted and reworked rocks that represent deeper levels of the adjoining older Shield provinces; for this reason, the Grenville Front itself cannot be a suture.

Mid to deep crustal levels are exposed throughout most of the Grenville Province, as shown by the prevalence of granulite or upper amphibolite-facies gneiss and migmatite, and by the ductile style of deformation. Exceptions are restricted to the southeast part of the province in terranes containing supracrustal rocks of Grenvillian age. In the past, it was tacitly assumed that an overwhelming proportion of the structure and metamorphism within the province resulted from Grenvillian orogeny. However, it is obvious that rocks of older shield orogens, where recognised southeast of the Grenville Front, must have been previously deformed and metamorphosed. Although this was realised thirty years ago by Stockwell (1964), thanks to modern geochronology the full extent and significance of preserved pre-Grenvillian high-grade rocks and structures is only now beginning to be appreciated fully. In some parts of the province, Grenvillian remobilisation has effectively obscured or erased the record of earlier metamorphism and deformation. In other parts, however, interpretation of Grenvillian tectonic history as a whole is complicated by large tracts of crystalline crust in which an earlier orogenic record is the dominant one preserved and, at present, by uncertainty about the distribution of such tracts in poorly exposed or less well mapped parts.

Before the more specific geologic attributes of the Grenville Province and its component parts are discussed, the nature of the foreland immediately northwest of the Grenville Front is reviewed briefly. This is important with respect to recognition of older Laurentian rocks within the Grenville orogen.

## The Grenville foreland

Along two-thirds of the exposed Grenville Front (Fig. 3), the Grenville Province abuts late Archaean rocks of the Superior Province, comprising east-trending, alternating metavolcanic (greenstone) and metasedimentary belts, each with its complement of granitoid rocks, and, in the northeast, granulite-facies rocks of the Ashuanipi complex (Card 1990). To the northeast, mid-Palaeoproterozoic sedimentary rocks (Kaniapiskau Supergroup) overlying the Superior craton are thrust westward in the fold-thrust belt (Labrador Trough) of the New Quebec orogen (Hoffman 1988); probable correlatives of these rocks (Otish and Mistassini groups) unconformably overlie Archaean rocks southwest of this orogen, and are undisturbed except where folded and faulted adjacent to the Grenville Front. Farther east, the hinterland of the New Quebec orogen (Rae Province), comprising reworked Archaean rocks, Palaeoproterozoic supracrustal rocks and ~1.83 Ga granites, and the adjacent Archaean Nain Province to the east are cut by voluminous, anorogenic plutons of anorthosite, gabbro and granitoid rocks of two age groups (~1.45 and ~1.3 Ga). Plutons of the older group are overlain by red beds and basalts of the Seal Lake Group (~1.25 Ga), which are preserved in a north-directed fold-thrust belt, probably late Grenvillian in age, adjacent to the Grenville Front. Farther east again, mid-Archaean granulites of the Nain Province are succeeded by late Palaeoproterozoic volcanic rocks (Aillik, Bruce River groups) and granites of the Makkovik Province, ranging in age and younging southeastward from ~1.9 (Ketilidian) to 1.65 Ga (Labradorian) (Kerr et al. 1992).

Adjoining the southwest part of the Grenville Province, Archaean rocks of the Superior Province are overlain unconformably by the early Palaeoproterozoic Huron Supergroup (<2.48 to >2.22 Ga). This thick succession (~12 km) is folded and metamorphosed in the Southern Province of Ontario, tectonism being ascribed to the Penokean orogeny (1.90–1.83 Ga). Granitoid rocks of two ages, ~1.74 and ~1.47 Ga, intrude the Huron Supergroup (van Breemen & Davidson 1988a; Davidson & van Breemen 1994). The former are age-correlative with Yavapai plutonism in the western mid-continent, also represented in the Central Plains orogen (Sims & Peterman 1986); the latter lie within the age range of the older of two groups of Mesoproterozoic anorogenic plutons (~1.45 and ~1.37 Ga; Bickford et al. 1986) (Fig. 2). It is interesting that Proterozoic plutonic suites, both orogenic (late Palaeoproterozoic) and anorogenic (early Mesoproterozoic), occur at both ends of the exposed Grenville Front. This has important implications for the derivation of deformed and metamorphosed plutonic suites within the Grenville Province.

## Interior of the Grenville Province

Following the early attempt by Stockwell (1964) to identify the distribution of superposed orogenic events within the Grenville Province using the geochronologic data available at that time, Wynne-Edwards (1972) divided the Grenville Province into subprovinces on the basis of lithologic assemblage and character of metamorphism, although boundaries between these were poorly defined. More recent structural studies and a burgeoning database of more sophisticated geochronology (see Moore et al. 1986; Hoffman 1989a) have prompted reassessment of Wynne-Edwards' scheme. It is now considered more convenient to view the Grenville Province in terms of three orogen-parallel belts in the manner of Rivers et al. (1989), namely (1) a northwestern parautochthonous belt, closest to the front, in which rocks can be reasonably correlated with those in the adjacent foreland: (2) a central allochthonous belt of rocks that have undergone pre-Grenvillian orogeny, but which do not appear to directly correlate with those in the parautochthon or foreland: and (3) a southeastern, discontinuous allochthonous belt of supracrustal and associated plutonic rocks that have undergone only the Grenvillian orogenic cycle (Figs 3 and 4).

Plutonic rocks of Grenvillian age are present in parts of the central, allochthonous polycyclic belt, but are extremely rare in the parautochthon. The three belts are delimited by moderately to shallowly southeast to south-dipping ductile shear zones. For the most part these exhibit northwest to north-directed thrust sense (Rivers & Chown 1986; Wardle et al. 1986, 1990; Hanmer 1988), but extensional tectonics have been documented for part of the southeastern belt (Rivers et al. 1989), and recognised as succeeding or overprinting earlier ductile thrusting elsewhere (van der Pluijm & Carlson 1989; Carlson et al. 1990; Culshaw et al. 1994).

Although useful as a first approach, this division is,

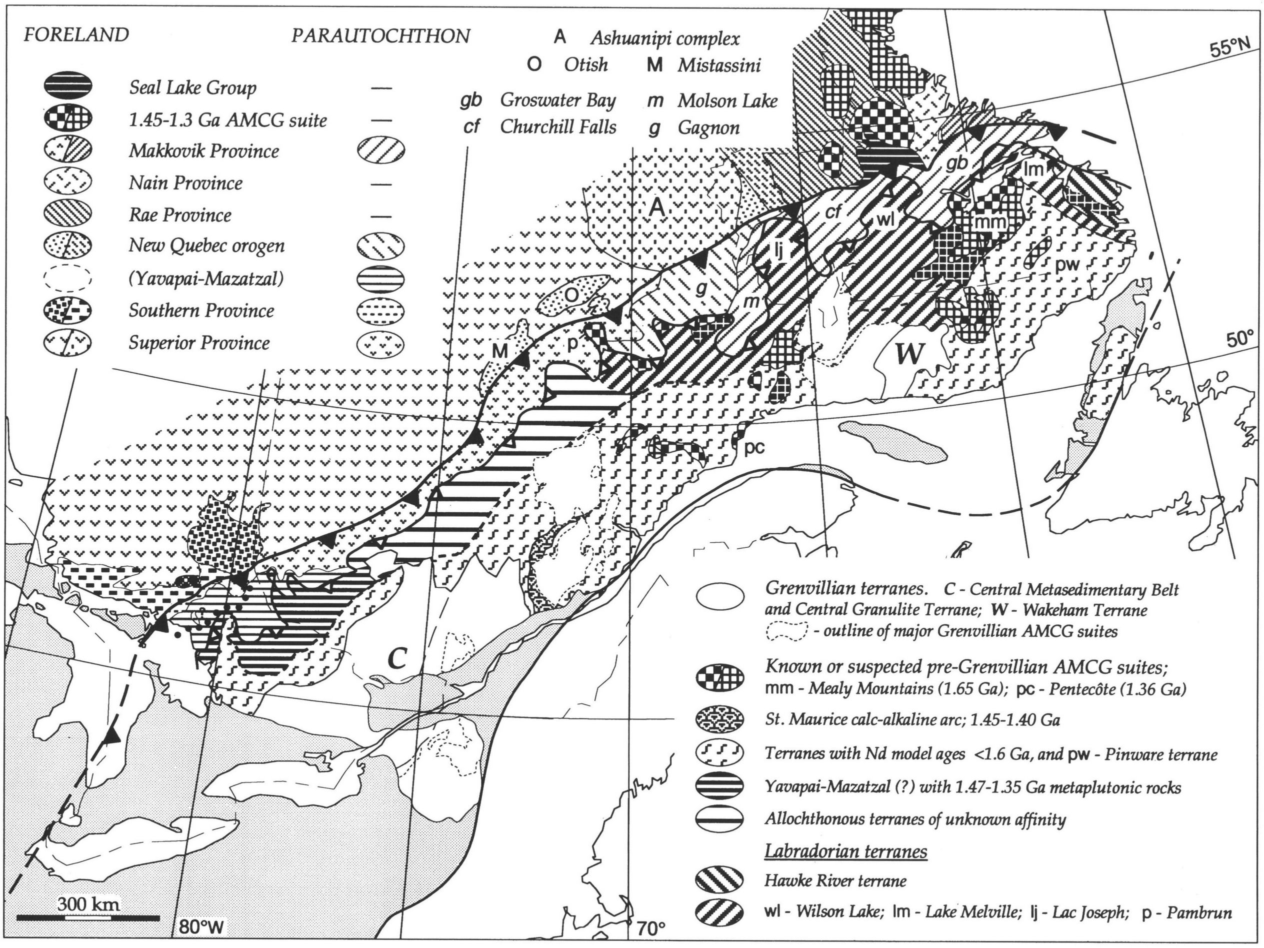


**Figure 3. Principal tectonic elements of the Grenville Province. Solid toothed line is the Grenville Front, open teeth mark the internal allochthon boundary thrust system (modified after Rivers et al., 1989); dotted line in the southwest is proposed Penokean suture of Dickin & McNutt (1989). The diagram shows the distribution of reworked foreland provinces within the northwestern parautochthonous belt, and of Palaeoproterozoic units in the central allochthonous belt, including pre-Grenvillian AMCG suites. Grenvillian terranes and the main Grenvillian AMCG suites are unpatterned.**

admittedly, simplistic; it is complicated by changes in pre- and syn-Grenvillian lithology and apparent differences in age and succession of events along the length of the belts, and also by recent recognition of major boundaries within each of the belts. A further concern is that much of the central belt may indeed have foreland correlatives beyond the confines of the exposed Shield (e.g. in the buried mid-continent) and, thus, that some boundaries within the province may be pre-Grenvillian in origin, though reactivated in Grenvillian time.

### *The northwestern parautochthonous belt*

There is little doubt about the correlation across the Grenville Front of at least three major rock associations: namely, Archaean rocks of the Superior Province, Proterozoic supracrustal rocks of the Kaniapiskau Supergroup, and Proterozoic plutonic rocks in the northeast (~1.65 Ga Trans-Labrador batholith) and southwest (1.75 and 1.45 Ga granites) (Fig. 3). In addition, metamorphosed and deformed equivalents of Proterozoic mafic rocks and dyke swarms in the foreland (e.g. 1.46 Ga Shabogamo and 1.43 Ga Michael gabbro in Labrador, 1.24 Ga Sudbury diabase dykes in Ontario) have also been recognised in the Grenville Province.

Tracking these units southeast of the front to where they are tectonically buried beneath allochthonous rocks gives at least a minimum estimate of how much of the Grenville Province was derived from pre-Grenvillian Laurentia. U–Pb geochronology has been the key to correlation in many cases, as the foreland rocks are commonly deformed and metamorphosed southeast of the front to the extent that their protoliths are physically unrecognisable. This is not true, however, for the Kaniapiskau Supergroup in Labrador and eastern Quebec, where a particularly diagnostic stratigraphic succession of dolostone, orthoquartzite and iron formation (Denault, Wishart, and Sokoman formations) is recognisable within the Grenville Province for well over 100 km south of the front (Rivers & Chown 1986). In contrast, it is surprising that the Huron Supergroup in the east-trending Southern Province fold belt, characterised by thick quartzite formations, cannot likewise be traced across the front with confidence (e.g. Frarey 1985). However, the absence immediately southeast of the front of pre-Grenvillian cratonic cover (Seal Lake, Otish and Mistassini groups, and northeastern part of the Huron Supergroup; Fig. 3) can be accounted for by relatively deep exhumation of the frontal hanging wall; there is no evidence for large-scale lateral offset. It is of interest that there are no known occurrences of large plutons belonging to the 1.45 and 1.3 Ga anorogenic suites of the Rae and Nain Provinces within the adjacent parautochthonous belt in Labrador, although it is possible that the Shabogamo and Michael gabbro intrusions are related to the older suite, with which they are coeval (Gower 1990).

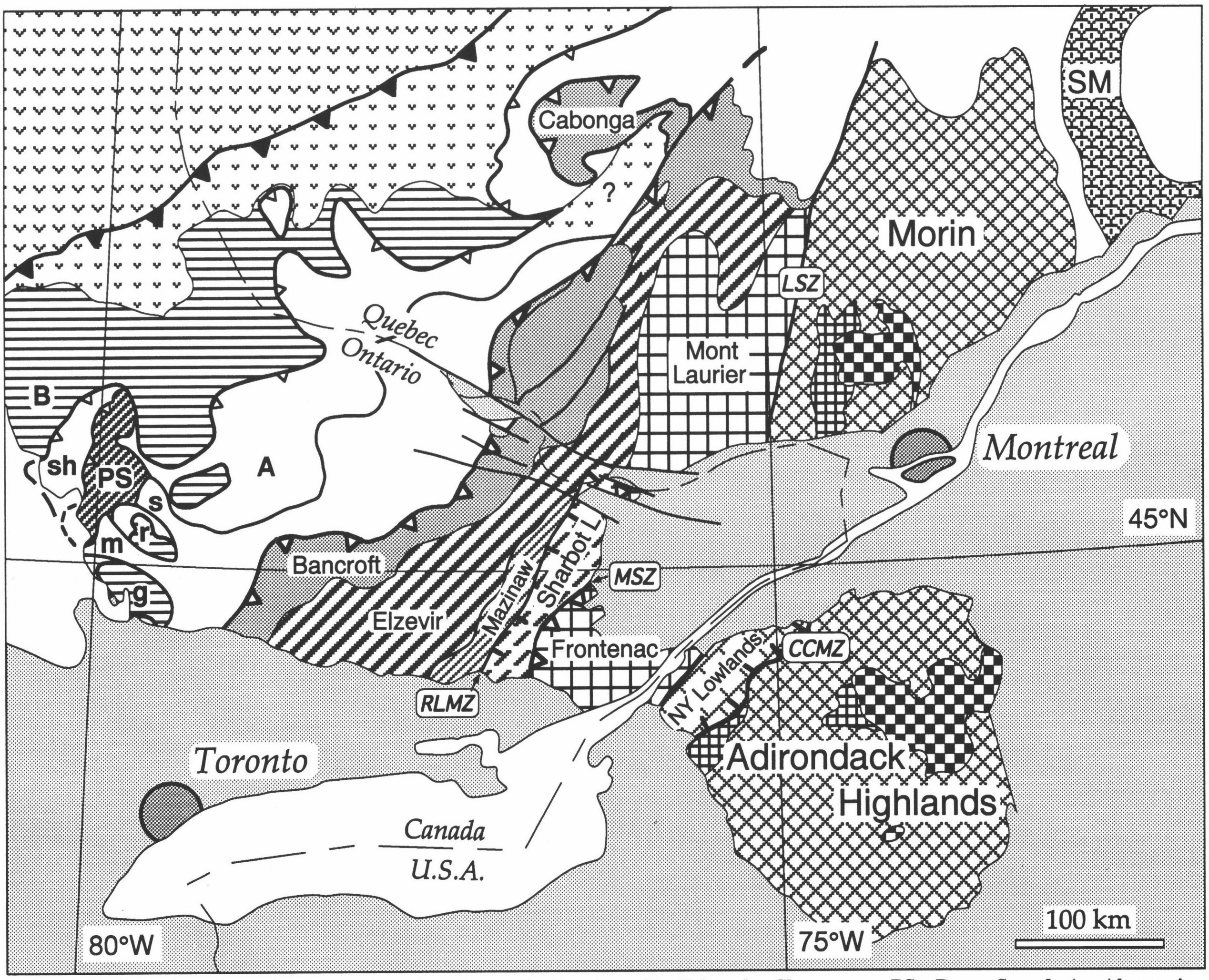


**Figure 4. Detail of terranes in the southwestern Grenville Province. B—Britt, sh—Shawanaga, PS—Parry Sound, A—Algonquin, g—Go Home, m—Moon River, r—Rosseau, s—Seguin, SM—St. Maurice. Morin and Adirondack Highlands terranes, with Grenvillian AMCG suites, comprise the Central Granulite Terrane of Wynne-Edwards (1972). Patterned terranes immediately to the west make up the Central Metasedimentary Belt, within which labelled terrane boundaries are: *RLMZ*—Robertson Lake mylonite zone, *MSZ*—Maberly shear zone, *CCMZ*—Carthage–Colton mylonite zone, and *LSZ*—Labelle shear zone. The northwest boundary of Bancroft terrane (Central Metasedimentary Belt boundary thrust zone of Hanmer & McEachern, 1992) passes into a zone of oblique shear to the north in Quebec (Hanmer & Ciesielski, 1984), almost isolating the Cabonga allochthon (Martignole & Pouget, 1993).**

Many of the metamorphosed plutonic rocks in Wynne-Edwards' (1972) 'Central Gneiss Belt' in Ontario are now known to have primary ages of ~1.46 Ga and to lie within gneisses among which older granitoid rocks give ages of ~1.7 Ga (van Breemen et al. 1986; Davidson et al. 1992; Corrigan et al. 1994a). In the southeastern part of the extent of these rocks, the enveloping gneisses have Nd depleted mantle model ages (DePaolo 1981) that are too young (≤1.98–~1.7 Ga; Dickin & McNutt 1989, 1990) for them to correlate with rocks of either the Superior or Southern provinces in the adjacent foreland. Similar crust-formation ages, however, are recorded for plutonic rocks within the Yavapai and Mazatzal orogens in the United States mid-continent southwest of the shield, and also for younger granites of the granite–rhyolite terranes farther south (Nelson & DePaolo 1985; Patchett & Arndt 1986). It is, therefore, reasonable that much of this gneiss terrane in Ontario correlates with terranes beyond the Grenville Front which are mainly buried south of the shield, but which form part of the pre-Grenvillian Laurentian craton.

Significant boundaries are now being recognised, by observation or by inference, within the northwestern parautochthonous belt. Two major terranes have been defined within the parautochthon in west-central Labrador (Fig. 3). The structurally lower one (Gagnon terrane; Rivers et al. 1989) corresponds to the foreland of the New Quebec orogen, namely the Palaeoproterozoic Kaniapiskau Supergroup and its Archaean basement; the effect of Grenvillian orogeny has been to produce a fold-thrust belt involving the previously undeformed foreland cover, in which Grenvillian metamorphic facies increase rapidly southeast of the Grenville Front (Rivers 1983; Brown et al. 1992). The Gagnon terrane is structurally overlain by younger rocks (Molson Lake terrane; Connelly et al. 1989, 1993), comprising mostly granitoids of Labradorian age (~1.65 Ga). Shabogamo metagabbro occurs within both terranes, suggesting that they had been together before ~1.46 Ga. High-pressure metamorphism of Shabogamo gabbro, approaching eclogite facies (Indares 1993) in the lower level of the Molson Lake terrane, attests to extensive Grenvillian uplift along the boundary between the two terranes. In this area, it is implied that the Molson Lake thrust plate has overstepped the whole of the hinterland (Rae Province) of the New Quebec orogen, as well as the Archaean rocks of the Nain Province on its eastern flank, a distance of several hundred kilometres; the relative amounts of displacement due to Labradorian and Grenvillian orogeny (respectively, lateral vs orthogonal with respect to the Grenville Front) are unknown.

A pre-Grenvillian crustal boundary is inferred from Nd model ages in the southwestern Grenville Province (Dickin & McNutt 1989, 1990) (dotted line in Fig. 3). It corresponds to an abrupt change in model ages from Archaean and early Palaeoproterozoic (≥2.2 Ga) to ≤1.98–1.7 Ga, and has been equated with the eastward projection into the Grenville Province of the Niagara fault, a suture within the Penokean orogen south of Lake Superior (Van Schmus et al. 1993). Its trace has not been identified on the ground, however, and its projection to the northeast appears to coincide with a boundary between post-Penokean metasedimentary rocks (~1685 Ma detrital zircons; Krogh 1989) and reworked Archaean basement. At present, it is uncertain if part of this boundary is in fact the allochthon boundary thrust.

In the same region (Fig. 3), the boundary in the foreland between folded and metamorphosed Huron Supergroup of the Southern Province and its Archaean ramp to the north (Superior Province and undeformed Huronian cover) has yet to be identified in the Grenville parautochthon. Reworked Archaean rocks in the frontal hanging wall give way southward to gneisses in which the metasedimentary component has Nd model ages too young (2.4–2.15 Ga) for them to have been derived from the Huron Supergroup (model age >2.5 Ga). Metaplutonic rocks in this region are dated at ≤1.75 or ~1.47 Ga, the same ages as post-Penokean plutonic suites west of the Grenville front. This region is interpreted in Figure 3 as being equivalent to Yavapai–Mazatzal crust (Fig. 2) with the addition of early Mesoproterozoic plutonic rocks equivalent to those of the midcontinental granite-rhyolite terranes; it also carries evidence for ~1.45 Ga metamorphism (Ketchum et al. 1994; Dudàs et al. 1994). If this is correct, any former eastward continuation of the Southern Province (Penokean orogen) into the Grenville Province would appear to have been occluded by northwestward translation of post-Penokean rocks.

The foregoing serves to illustrate the complexity of the history of shield rocks that have been 'caught up' (telescoped) in the marginal zone of the Grenville orogen, particularly at its northeast and southwest ends. If the southeastern Superior Province was flanked by early to mid-Palaeoproterozoic orogens (southern extension of the New Quebec orogen and its reworked Archaean hinterland; eastern extension of the Penokean orogen), they were either rifted away before or overridden by younger rocks during late Palaeoproterozoic orogeny (Yavapai-Mazatzal and Labradorian), Mesoproterozoic Grenvillian shortening, or both.

### *The central, polycyclic allochthonous belt*

The central belt, comprising metamorphosed sedimentary and plutonic rocks, underlies most of the Grenville Province. Its northwestern 'leading edge' against the parautochthon describes a sinuous trace for the whole length of the province (Fig. 3). Much of this boundary (central Labrador to western Quebec) is marked by an abrupt change in aeromagnetic signature, from relatively flat over the parautochthon to short-order, high-relief patterns. The latter reflect the prevalence of high-grade granulites in the hanging wall of the 'allochthon boundary thrust' (Rivers et al. 1989) compared to middle to upper amphibolite grade in the parautochthonous footwall. Wherever examined, the boundary itself is the locus of moderate to low-angle, generally southeast-dipping ductile mylonite and 'straight gneiss' (continuously and commonly thinly layered, fine-grained gneiss of ductile tectonic origin; Davidson 1984a; Hanmer 1988). Metamorphic inversion and shear-sense indicators accord with northerly to northwesterly directed thrust tectonics along this boundary. Large-scale undulations in its attitude account for much of its irregular trace, but in places these may be due to overlapping thrust slices. In a few places, granulite blocks are isolated, or nearly so, from their southeastern sources (e.g. the Wilson Lake terrane in central Labrador, the Pambrun lobe in Quebec, the Parry Sound allochthon in Ontario; Figs. 3 and 4), and in others, northwest-projecting lobes are known to be thin (e.g. the Lac Joseph terrane in western Labrador has a central window to underlying the Molson Lake terrane; Connelly et al. 1993).

There is no evidence for Archaean or early to mid-Palaeoproterozoic rock (i.e., >1.85 Ga, Nd model ages >2.0 Ga) in the terranes of the central polycyclic belt in the hanging wall of the allochthon boundary thrust. In Labrador, metamorphism and deformation internal to the allochthonous lobes have been found to be Labradorian in age (~1.65 Ga), with relatively minor Grenvillian thermal overprint (Connelly & Heaman 1993). This late Palaeoproterozoic tectonism is thus coeval with Labradorian magmatism in the underlying parautochthon in this area. The metasedimentary gneisses that host the parautochthonous Trans-Labrador batholith are similar to those at granulite grade in the overriding slices (both have pelitic and arenitic progenitors), but there is a distinct difference in the respective magmatic rocks: the Trans-Labrador batholith is a juvenile granodiorite–granite suite with calc-alkaline affinity, whereas plutonic rocks in the allochthons are mainly noritic gabbro, anorthosite, and associated pyroxene monzonite and granite; the suites are in part coeval at ~1.65 Ga, although calc-alkaline Trans-Labradorian magmatism began somewhat earlier (~1.7 Ga). The recorded timing of allochthon displacement, however, is Grenvillian; thus, although both footwall and hanging wall record Labradorian orogeny, they may represent quite different parts of the Labrador orogen. Connelly & Heaman (1993) suggested that the initial juxtaposition of these disparate terranes occurred during Labradorian orogeny, the juncture being modified by Grenvillian shortening. A similar two-stage history was expressed earlier by Wardle et al. (1986), and has been confirmed along the same thrust system 400 km farther east (Philippe et al. 1993). Hoffman (1989a, p. 498) pointed out that the geochronology '... is consistent with the central zone having been contiguous with the protocraton since about 1.65 Ga ...', but, in fact, this does not preclude extensional separation following Labradorian orogeny and reamalgamation with marked overstepping during the Grenvillian.

West of the Lac Joseph allochthonous lobe (Fig. 3), the allochthon boundary thrust oversteps the Molson Lake terrane and places high-grade granulites and their attendant gabbro–anorthosite massifs (not dated) over the southwestern continuation of the Kaniapiskau Supergroup in the parautochthonous Gagnon terrane. Farther west again, the boundary thrust passes across reworked Archaean rocks and, in the Pambrun lobe, almost oversteps them as far as the Grenville Front south of the autochthonous Otish basin. Beyond this, the allochthon boundary thrust can be traced to western Quebec on the basis of aeromagnetic contrast and scattered field observations, but the position of its continuation into Ontario is not resolved. Near Georgian Bay (Lake Huron), Rivers et al. (1989) placed it at the western thrust boundary of the Parry Sound granulite allochthon (Davidson 1986), but more recent evidence suggests that it may lie at a lower structural level to the northwest along a shear zone carrying remnants of eclogite (Davidson 1991; Culshaw et al. 1994). This location would be in accord with demarcation near the Quebec–Ontario border of granulite-facies rocks that structurally overlie a Proterozoic metasedimentary assemblage (quartzite, meta-arkose, pelitic gneiss, iron formation and minor marble) which contains the 1685 Ma detrital zircons already mentioned, and which lies structurally above the Archaean parautochthon. This metasedimentary unit has no counterpart in the adjacent foreland, and may also be separated from the Archaean part of the parautochthon by a structural discontinuity. The map pattern in this region may well be complicated by windows of parautochthonous rocks to the south, not yet delineated in the field. This trace of the allochthon boundary shown in Figures 3 and 4, to date not resolved by mapping, may pass southeast of the complex region of the southwesternmost parautochthon discussed in the last section.

Rivers et al. (1989) identified a large part of the Grenville interior in Ontario as parautochthonous on the basis that it contains ~1.75 Ga and 1.47–1.34-Ga orthogneissic rocks (deformed batholiths), making it comparable in age to the substrate of the mid-continent south of the shield. Some of this terrane lies southeast of the redefined allochthon boundary thrust (Fig. 3), and the situation may be analogous to that of the Labradorian in the northeast part of the province, complicated by structural culminations that provide windows to the underlying parautochthon (Rosseau, Go Home and parts of Algonquin domains south and east of the Parry Sound allochthon; Fig. 4). Within the same region, Nd model age determination (Dickin & McNutt 1990) has identified significantly younger crust derivation within the Parry Sound allochthon and in synformal lobes that overlie it to the southeast (1.6–1.4 Ga vs 2.0–1.7 Ga to the north), conforming to the map pattern and order of stacking deduced from field studies (Davidson 1984b). Dated metaplutonic rocks in areas with the older crust-formation ages include units belonging to the ~1.45 Ga suite. The few plutonic ages available in areas with crust-formation ages of <1.6 Ga appear to be younger, ~1.35 Ga. It seems, therefore, that the central belt in Ontario may conceal a pre-Grenvillian crustal boundary. Whether or not this boundary is present in the buried mid-continent beyond the Grenville Front is uncertain; most of the Mesoproterozoic igneous rocks there (1.5–1.35 Ga) have 1.9–1.7 Ga Nd depleted mantle model ages, but there is new evidence that some in the southern mid-continent are entirely juvenile (see Van Schmus et al. 1993, p. 290, and references therein).

The same duality of crust-forming age is becoming apparent in the central and northeastern parts of the polycyclic belt. Dickin & Higgins (1992) have documented a large region in the southern part of the belt in which 'grey gneisses', tentatively interpreted in terms of subduction-related arc terranes, have Nd model ages between 1.60 and 1.46 Ga (Fig. 3); the igneous crystallisation ages of their precursors is not known, but they can be no older than their model ages, making them younger than the Labradorian rocks that lie above the allochthon boundary thrust to the north and northeast. The boundary between Labradorian and younger crust has yet to be defined in this poorly exposed and generally inaccessible part of the province, where only regional reconnaissance mapping is available. It is noted that granitic rocks with ages between 1.49 and 1.47 Ga have been identified recently in east of the Pinware terrane, just south of the Labradorian Hawke River terrane (Fig. 3) (Tucker & Gower 1994), and also that 1.40 Ga monazite in migmatite leucosome in the south of the Lac Joseph terrane suggests regional heating at that time (Connelly & Heaman 1993).

Important with respect to the younger crustal terrane in the central belt is the recent recognition of a deformed volcano-plutonic arc (St. Maurice terrane, Figs 3 and 4), for which preliminary dating indicates an age in the range 1.45–1.39 Ga (Nadeau & van Breemen 1994; Hervet et al. 1994). Supracrustal rocks (Montauban group) include pelitic gneiss and layered amphibolite that locally preserves pillow structure. Plutonic rocks (La Bostonnais complex) range from gabbro to granodiorite, have a calc-alkaline character, and Nd model ages of ~1.6 Ga (L. Nadeau, pers. comm. 1994).

Also important in this general region is the presence of pre-Grenvillian anorthosite–mangerite–charnockite–granite (AMCG) suites of two ages. In Labrador, a large massif of anorthosite, gabbro and related granitoid rocks in the Mealy Mountains terrane, the White Bear Arm suite in the Hawke River terrane, and large gabbro masses (Ossokmanuan suite) in the Lac Joseph terrane all have late Labradorian ages (1645–1625 Ma; Emslie & Hunt 1990; Gower et al. 1992; Connelly & Heaman 1993). In Quebec, Mesoproterozoic, but pre-Grenvillian, AMCG magmatism is represented by the Pentecôte anorthosite–charnockite pluton west of Sept Iles (1.35 Ga; Emslie & Hunt 1992; Martignole et al. 1993); this is the only complex so far dated that is roughly coeval with the anorogenic AMCG magmatism in Labrador north of the Grenville Front. The fact that these pre-Grenvillian AMCG rocks are as well preserved as younger Grenvillian suites of the same type, and are petrographically indistinguishable from them, means that assignation of age to the several undated plutons in this region must await isotopic analysis.

In the foregoing, emphasis has been placed on the nature and age of the plutonic rocks in the central belt, and although these may be volumetrically dominant, a large proportion of the rocks are supracrustal in origin. Supracrustal assemblages vary from place to place, and distinctive assemblages may characterise individual terranes (e.g. layered mafic granulite and marble in the Parry Sound allochthon). Recognisable mafic volcanic rocks are rare (Labradorian Hawke River terrane (Gower et al. 1991), early Mesoproterozoic Montauban group (Rondot 1986)), as are tracts of amphibolite. It is possible, however, that felsic volcanic, pyroclastic and hypabyssal rocks are unrecognised precursors of leucocratic quartzofeldspathic gneiss units. Sillimanite- and garnet-bearing paragneiss, in places with abundant pyrite and graphite, is common in many areas, and may be associated with subordinate quartzite, impure calcareous rocks and rare metaconglomerate. Deformation and metamorphism, however, have rendered any form of stratigraphic analysis and regional correlation impossible.

In summary, the central polycyclic allochthonous belt contains several terranes bounded by shear zones, together embracing two belts of Proterozoic crust, mid to late Palaeoproterozoic to the northwest and early Mesoproterozoic to the southeast. Windows of the earlier crust appear in the southeastern part, and plutonic rocks of early Mesoproterozoic age (1.9–1.7 Nd model ages) occur in the northwestern part. The former relationship between these two units and their distribution have been modified during northwest-compressional Grenvillian tectonism. This is the setting in which the southeastern Grenvillian belt must be considered.

## *The southeastern Grenvillian belt*

Two regions near the southeastern margin of the Grenville Province are underlain by supracrustal rocks younger than ~1.3 Ga: namely, the Wakeham Supergroup in eastern Quebec and the Grenville Supergroup in eastern Ontario and southwestern Quebec (Fig. 3). These two assemblages, at least in part coeval, are represented by entirely distinct facies, indicating different depositional regimes. Although both are deformed and exhibit a wide range in metamorphic grade, the least deformed parts, particularly in the Wakeham Supergroup, allow recognition of primary sedimentary and volcanic structures and of stratigraphic relationships.

***Wakeham Supergroup.*** The Wakeham Supergroup underlies an area of ~15 000 km$^2$ in eastern Quebec near the north shore of the St. Lawrence (Fig. 3; also see Fig. 6). It has been divided into two groups, the older Aguanus Group being unconformably overlain by the Davy Group; both deposited in continental extensional environments (Martignole et al. 1987, 1994). The Aguanus Group is composed primarily of orthoquartzite and feldspathic sandstone with minor argillaceous units, intercalated with bimodal volcanic rocks (rhyolite flows and tuffs with subordinate basalt). On the basis of its peralkaline chemistry, Bourne (1986) suggested an 'anorogenic' environment for this magmatism. Rhyolite from this group has been dated at 1.27 Ga (Loveridge 1986). Associated with the felsic volcanic rocks are hypabyssal granite intrusions, two of which have been dated at ~1.24 Ga (Martignole et al. 1994). Cobbles of these granites, as well as quartzite, are present in the basal conglomerate of the Davy Group, which overlies folded Aguanus strata and is composed predominantly of cross-bedded arkose and hematite-rich siltstone. Both groups were intruded by gabbro sills (1.18 Ga; Martignole et al. 1994) before a second period of folding affected the whole assemblage. The Wakeham Supergroup has some environmental affinity with the 1.32 Ga Letitia Lake Group (peralkaline volcanic rocks) and ~1.25 Ga Seal Lake Group in the foreland of the Grenville Province 300 km to the north.

Much of the Wakeham Supergroup is only metamorphosed to greenschist facies, and in some parts, particularly in the north, is at sub-greenschist grade. West and southeast of the main exposure, however, remnants of quartzite and amphibolite within quartzofeldspathic gneisses may represent more thoroughly deformed and metamorphosed Wakeham Supergroup rocks. High-grade migmatitic gneisses, including orthogneiss of Labradorian age (Loveridge 1986), lie structurally beneath the Wakeham Supergroup along its northern margin, and although an undisturbed contact has not been observed, it is possible that it is a profound unconformity. Along the northwest flank, highly foliated rocks dipping moderately to the southeast display extensional kinematic indicators against older granite gneiss, itself intruded by younger (1.08 Ga) charnockitic rocks, part of a large AMCG plutonic mass lying to the west (Romaine River complex). The Wakeham Supergroup itself is cut by several small plutons of undeformed granite, one of which has been dated at 993 Ma (Loveridge 1986; Bourne 1991).

***Grenville Supergroup.*** Replacing the earlier name 'Grenville series' (Logan 1863), the term Grenville Supergroup applies collectively to all the sedimentary and volcanic strata that underlie the 'Central Metasedimentary Belt' in Ontario and southwest Quebec (Wynne-Edwards 1972) (Fig. 3). A characteristic and volumetrically important rock type common to all parts of this belt is marble, by contrast rare in all other parts of the Grenville Province except the 'Central Granulite Terrane' immediately to the east (Adirondack and Morin terranes of Rivers et al. (1989), but now considered to be part of the southeastern zone). This whole region, about 135 000 km$^2$, consists of a number of terranes (Fig. 4), defined on the basis of differences in supracrustal assemblages, type and age of plutonic rocks, internal structure, and the nature of their mutual boundaries (Easton 1992; Easton & Davidson 1994). It seems increasingly likely that the Grenville Supergroup, as defined by Wynne-Edwards (op. cit.), includes rock groups that are not stratigraphically and perhaps not even temporally related. Although well preserved at upper greenschist grade in parts of Ontario, in most places these rocks have been intensely deformed and metamorphosed (middle amphibolite to high-temperature granulite facies; Carmichael et al. 1978; Davidson et al. 1990), rendering stratigraphic analysis and correlation from place to place extremely difficult, if not impossible, at all but local scale.

The Grenville Supergroup's original basement has not been recognised. The contact with older rocks of the central belt to the northwest is entirely tectonic, and lies within a broad, shallowly southeast-dipping ductile shear zone. This zone, at upper amphibolite facies, involves both the supergroup and the footwall gneisses of the central belt. Thrust-displacement sense has been documented along this zone in Ontario, but to the north, in Quebec, displacement appears to be oblique (Hanmer & Ciesielski 1984). Martignole & Pouget (1993; in press), however, document thrust tectonics in the Cabonga allochthon in western Quebec (Fig. 4). The marginal Bancroft and Cabonga terranes are characterised by marble tectonite, syenitic gneiss, and minor pelite and quartzite, as well as thrust slices of various kinds of metaplutonic rock (Hanmer & McEachern 1992). Thin units of nepheline-bearing gneiss associated with marble have usually been interpreted either to have had alkaline igneous protoliths or to have resulted from nephelinisation of pre-existing rocks (see Miller & Lenz 1993), but ultimate derivation from an evaporite-bearing sedimentary succession (Appleyard 1974; Haynes 1986) is not out of the question.

The Elzevir terrane (Brock & Moore 1983; Davidson 1986), southeast of the Bancroft terrane (Fig. 4), has recently been accorded superterrane status and divided into a number of smaller units (Easton 1992). Elzevir is characterised by volcanic rocks, predominantly mafic (including pillowed basalts), ranging in composition from tholeiitic to calc-alkaline (Condie & Moore 1977; Harnois & Moore 1991), and dated between 1.29 and 1.25 Ga (Davis & Bartlett 1988; Lumbers et al. 1990). They are associated with calc-alkaline plutons ranging from gabbro through tonalite to monzogranite, dated between 1.27 and 1.23 Ga. The volcanic rocks are interlayered with marble, which in less-deformed areas can be seen to have been derived from carbonate silt rhythmites, perhaps suggestive of a shelf-slope environment. Discontinuous units of fine, pyritic, siliciclastic sediments have been interpreted as submarine fans associated with local felsic volcanic sources (Easton 1986). Shallower water conditions are indicated, either locally or at certain stages, by stromatolitic dolomite marble and cross-bedded sandstone. The chemistry of the volcanic rocks suggest a palaeoenvironment of a convergent volcanic arc and a back-arc basin on stretched sialic crust (Condie &

Moore 1977; Holm et al. 1986; Harnois & Moore 1991). However, plutons of nepheline syenite and peralkaline granite, dated at ~1.24 Ga, seem out of place in this type of environment.

An apparently restricted part of the Elzevir superterrane (Mazinaw terrane; Easton 1992) includes an unconformably overlying succession of conglomerate, quartz sandstone, argillaceous sediment and carbonate (including an olistostromal facies), together constituting the Flinton Group (Moore & Thompson 1980). This group was deposited after folding of the underlying Grenville Supergroup, and after emplacement of the 1.27–1.23 Ga plutons. Detrital zircons from lower quartzose units indicate a maximum age of 1.15 Ga for sedimentation (Sager-Kinsman & Parrish 1993). The Flinton Group is preserved only in narrow synclines and was metamorphosed, along with underlying supracrustal and plutonic rocks, at ~1.03 Ga (Corfu & Easton 1994). This metamorphism (Ottawan orogeny as opposed to earlier Elzevirian orogeny, but both part of the Grenvillian orogenic cycle of Moore & Thompson 1980) is not known to be associated with plutonism of any kind. U–Pb titanite (Mezger et al. 1993) and $^{40}Ar/^{39}Ar$ amphibole cooling ages (Cosca et al. 1992) are consistent with relatively rapid uplift following this event. However, the southeasternmost part of the Elzevir superterrane (Sharbot Lake terrane) appears to have cooled several tens of million years earlier; this belt is separated from the Mazinaw terrane by the southeast-dipping Robertson Lake mylonite zone (Fig. 4), which records early ductile and later brittle deformation at low metamorphic grade and exhibits extensional kinematics. The age of regional metamorphism in the Sharbot Lake terrane is not known, but this terrane does not appear to record the 1.03 Ga amphibolite-facies metamorphism of underlying the Mazinaw terrane, as ~1.07 Ga plutons within it are neither deformed nor metamorphosed. Evidently, rocks that had cooled earlier at higher crustal level have been brought into juxtaposition with deeper level rocks.

A different geologic history is told by the neighbouring Frontenac terrane to the southeast, which also applies to most of Wynne-Edwards' (1972) 'Mont Laurier basin' in Quebec to the north. Here, the predominant supracrustal assemblage is pelite–quartzite–marble and lacks volcanic rocks. The boundary with the Elzevir superterrane is a high-strain thrust zone (Maberly shear zone), inclined to the southeast, along which granulite-facies rocks in the hanging wall contrast sharply with upper greenschist to lower amphibolite facies rock in parts of the Sharbot Lake terrane footwall. Meta-ultramafic to anorthositic rocks and monzonitic orthogneiss lenses reside in the immediate hanging wall. The monzonitic rocks are similar to less-deformed plutonic rocks farther southeast, which have been dated at ~1.17 Ma (van Breemen & Davidson 1988b; Marcantonio et al. 1990); similar ages have been obtained from monzonitic and charnockitic plutons to the north in Quebec (O. van Breemen, pers. comm. 1993). This plutonic suite ranges from noritic gabbro through pyroxene monzonite to leucogranite, and is chemically distinct from the older calc-alkaline suite in the Elzevir superterrane. Northwest-trending, undeformed olivine diabase dykes (Kingston swarm) cut these plutons in the southeast of the Frontenac terrane; they have been dated at 1160 Ma (U–Pb baddeleyite ages; S. Kamo, S. Pehrsson, pers. comm 1993).

Regional metamorphic mineral assemblages in the Frontenac terrane, uniformly at granulite grade, record higher pressure in the northwest (orthopyroxene–sillimanite assemblages, >7 kbar) than in the southeast (orthopyroxene–garnet–cordierite, <7 kbar). Metamorphism appears to pre-date the 1.17 Ga plutonic rocks; U–Pb ages of titanite in calc-silicate rocks record cooling through its blocking temperature between 1178 and 1157 Ma (Mezger et al. 1993), spanning this plutonism, with hornblende $^{40}Ar/^{39}Ar$ ages being somewhat younger (~1115 Ma; Cosca et al. 1992). The youngest plutons (~1075 Ma; Marcantonio et al. 1990) thus post-date regional cooling. There is no evidence for magmatism of Elzevirian age in the Frontenac terrane in Ontario. An older age (1415 Ma; McLelland et al. 1988) obtained for one granite that intrudes quartzite and is itself cut by 1.17 Ga granite dykes, is in conflict with single detrital zircon ages obtained from the quartzite (youngest 1306 Ma; Sager-Kinsman & Parrish 1993), and may be an artifact of inherited zircon.

Just south of the International Boundary, the Black Lake lineament, parallel to the St. Lawrence River, appears to separate rock associations typical of the Frontenac terrane from carbonate–pelite-dominated supracrustal rocks in the New York Lowlands terrane, and is associated with a southeastward drop in metamorphic grade. Diabase dykes of the Kingston swarm have not been observed in the New York Lowlands terrane. Leucogranites record ages between 1230 and 1285 Ma (McLelland & Chiarenzelli 1990), but U–Pb titanite cooling ages are similar to those in the Frontenac terrane (Mezger et al. 1993). Similarly, granodiorite orthogneiss in Quebec along the east side of the Central Metasedimentary Belt is dated at 1285 Ma (Machado et al. 1991). Along the southeast boundary of the New York Lowlands terrane, an apparently younger, unnamed succession of mainly carbonate rocks, including stromatolitic marble and hosting stratiform zinc deposits, occupies what may be a recumbent nappe, derived from the southeast and overriding more highly deformed metasedimentary rocks (Gouverneur marble, Popple Hill gneiss).

The Elzevir and Frontenac terranes in Ontario and their counterparts in Quebec are stitched by a potassic plutonic suite, comprising stocks of undeformed syenite and granite, dated at ~1.08 Ga (Corriveau et al. 1990). This suite has not been identified in the New York Lowlands terrane, nor in the Adirondack Highlands and Morin terranes to the east (Fig. 4); neither does it penetrate the northwestern boundary thrust zone in the central polycyclic zone. It is, however, coeval with younger components of Grenvillian AMCG plutonic suites farther east (dealt with in the next section).

The Adirondack Highlands and Morin terranes (presumably linked beneath Palaeozoic cover) contain highly deformed marble, pelitic and arenitic gneiss, and leucocratic gneiss possibly derived from felsic volcanic rocks. These host an early suite of tonalitic intrusions (1.35–1.30 Ga), superseded by massive intrusions of anorthosite and charnockitic granitoids, dated between 1.17 and 1.12 Ga (McLelland et al. 1988; Emslie & Hunt 1990; Chiarenzelli & McLelland 1993). Younger ages obtained from the AMCG suite and other plutonic rocks in the Adirondack Highlands terrane have been interpreted as the result of thermal disturbance of zircon U–Pb systematics (Chiarenzelli & McLelland 1993). Regional metamorphism is everywhere at medium-pressure granulite facies (≤8 kbar; Bohlen et al. 1985). Absolute age of metamorphism is uncertain, but mineral cooling ages in the Adirondacks are around 1.03 Ga (Mezger et al. 1991), at least 100 m.y. younger than in New York Lowlands and Frontenac terranes to the northwest, but coeval with most of the Elzevir terrane. The Adirondack Highlands and New York Lowlands terranes are separated by the Carthage–Colton mylonite zone, characterised by early ductile fabric, inclined to the northwest, and later brittle fabric, more steeply inclined, both indicating top-side-down displacement to the northwest (Heyn 1990). The brittle phase may reflect late extensional collapse off the Adirondack Highland core, but the early ductile phase could equally well represent nappe emplacement originating from the southeast. The equivalent boundary in Quebec (Labelle shear zone west of the Morin terrane; Indares & Martignole 1990a) is a steep ductile shear zone with shallow southeast-plunging stretching lineation; its kinematic significance is equivocal at present.

## Plutonic rocks

Plutonic rocks within the Grenville Province are divisible into three main groups with respect to time:

(1) integral plutonic components of pre-Grenvillian orogens, i.e. deformed Archaean granitoids in the parautochthonous belt, and Palaeoproterozoic suites, including 1.65 Ga Labradorian suites in the northeast part of the province and ~1.7 Ga age-equivalents of Yavapai and Mazatzal granites in the southwest;

(2) early Mesoproterozoic suites (1.5–1.35 Ga) within both the northwestwern parautochthonous and central polycyclic belts;

(3) Grenvillian suites (~1.3–0.95 Ga) concentrated predominantly in the southeastern part of the province.

Plutonic rocks of the first group are not related to the development of the Grenville orogen, and are not considered further. Those of the second group, however, may possibly presage the Grenvillian orogeny (cf. Windley 1989, 1993), and their distribution and ages are therefore summarised along with those of Grenvillian plutonic rocks in Figure 5.

The plutonic rocks of the second group have been described briefly in preceding sections. In summary, early Mesoproterozoic metaplutonic rocks in the parautochthonous and polycyclic belts in Ontario (Fig. 3) are coeval with 'anorogenic' igneous activity in the granite–rhyolite terranes of the United States midcontinent (Fig. 2), and may in part be their deformed and metamorphosed correlatives. Granitoid rocks of similar age occur in the Pinware terrane at the other end of the province, but have not yet been identified in the intervening region where the only dated igneous rocks in this age group are the calc-alkaline rocks of the St. Maurice terrane and the somewhat younger AMCG Pentecôte suite. Anorthositic rocks dated at ~1.35 Ga are also present in the Parry Sound domain and in the footwall of the Cabonga allochthon (Fig. 4), but are not associated with charnockite or granite and appear to have a more primitive chemistry (more calcic and magnesian) than anorthosite typical of AMCG suites.

## *Grenvillian igneous suites*

The presently known distribution of Grenvillian plutonic rocks is shown in Figure 6. With the exception of scattered occurrences in the range 1.31–1.24 Ga near the Grenville

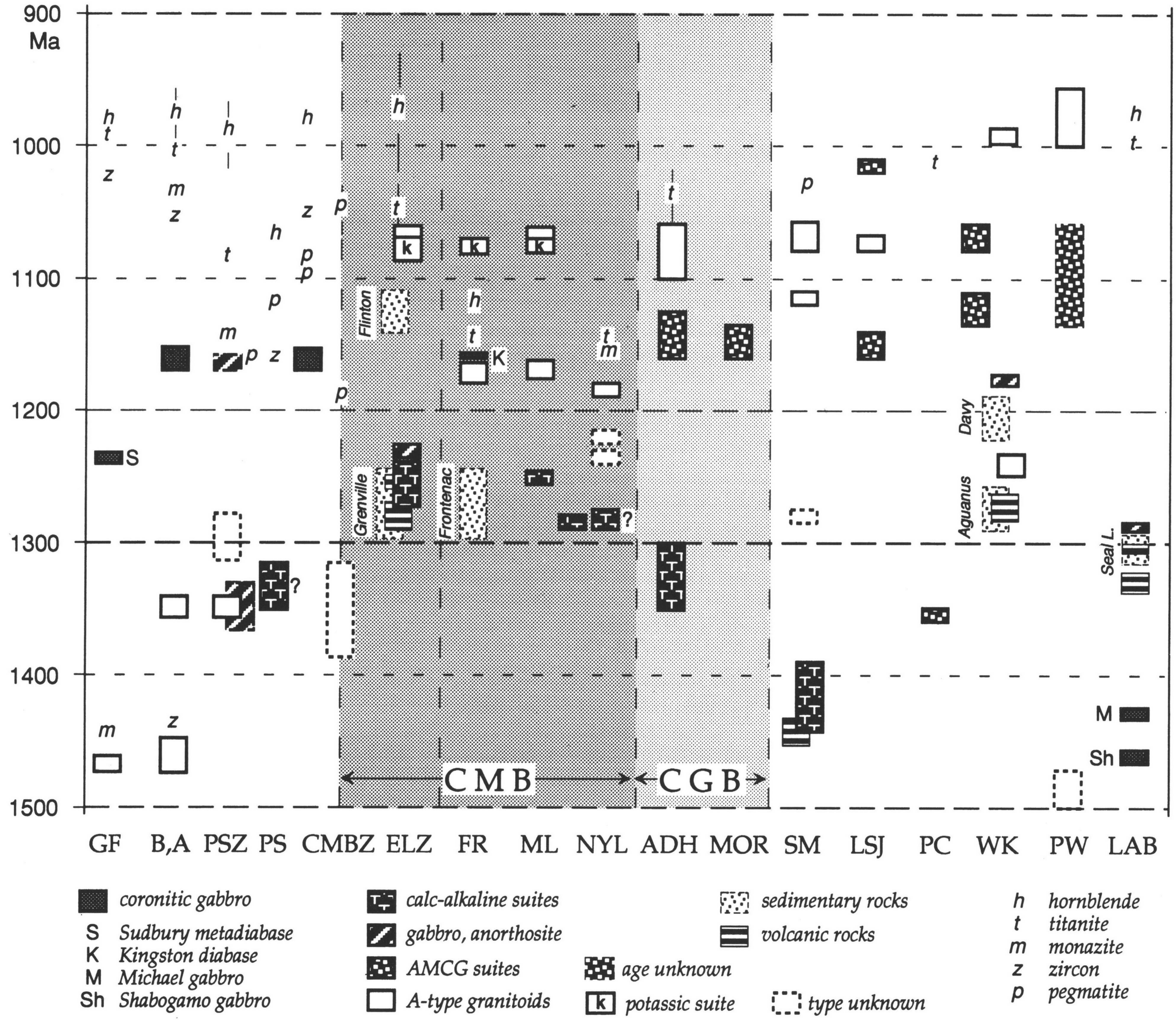


**Figure 5. Age and distribution of post-1.5 Ga plutonic rocks within the Grenville Province. Columns are ordered from southwest to northeast and comprise GF—southwest Grenville Front, B,A—Britt, Algonquin domains, PSZ—Parry Sound thrust zone, PS—Parry Sound domain, CMBZ—Central Metasedimentary Belt boundary thrust zone, ELZ—Elzevir terrane, FR—Frontenac, ML—Mont Laurier, NYL—New York Lowlands, ADH—Adirondack Highlands, MOR—Morin, SM—St. Maurice, LSJ—Lac St. Jean area, PC—Pentecôte, WK—Wakeham terrane, PW—Pinware terrane, and LAB—Grenville Front region in Labrador. CMB and CGB are Central Metasedimentary Belt and Central Granulite Terrane of Wynne-Edwards (1972). Age ranges are shown for the principal, named Grenvillian supracrustal units; metasedimentary rocks similar in age to or somewhat older that the Grenville Supergroup are present in the other CMB and CGB terranes. Ages of metamorphism (*z, m*) and cooling (*t, h*) are U-Pb ages except hornblende, which is $^{40}Ar/^{39}Ar$. Zircon ages obtained from syn-deformation pegmatites are shown by *p*.**

Front, they are restricted to the southeastern half of the province, and span the whole range (~1.3–0.95 Ga) accorded to the Grenvillian orogenic cycle. It is becoming apparent, however, that 1.3 Ga may not be an appropriate older age limit for 'Grenvillian' activity, that there may be a time gap of ~50 m.y. between early calc-alkaline igneous activity (>1.23 Ga) and younger anorthosite–mangerite–charnockite–granite (AMCG) suite plutons (<1.18 Ga), and that AMCG and A-type granite–syenite magmatism is volumetrically the most important. Within any one area, igneous rocks usually display episodic intrusion without temporal overlap of different types, and certain types are restricted to specific parts of the province.

Several of the Grenvillian igneous suites have been mentioned in the context of the Wakeham and Grenville supergroups. Calc-alkaline plutonic rocks (tonalite, trondhjemite and granodiorite) are present in the area underlain by the Grenville Supergroup in the southwest part of the province, where they are associated with volcanic rocks; this igneous activity spanned ~60 m.y., from 1.29–1.23 Ga, perhaps in two pulses (Easton 1992). Somewhat earlier calc-alkaline plutonic rocks (1.35–1.30 Ga) occur in the Adirondack Highlands of New York (McLelland & Chiarenzelli 1990) and in basement windows in the nearby northern Appalachians (Ratcliffe et al. 1991), raising the possibility that arc magmatism began earlier east of the Elzevir superterrane. The relationship between this and the even earlier calc-alkaline St. Maurice arc (1.45–1.39 Ga) farther northeast is not known, but it is tempting to postulate a westward-younging progression of successive arcs.

Of particular interest is the fact that volcanic rocks (rhyolite and tuff with subordinate tholeiitic basalt) and associated high-level granite plutons (1.27–1.24 Ga) of the Wakeham Supergroup in eastern Quebec, although coeval with Elzevirian calc-alkaline activity, are fundamentally different in character, being of continental rift type. A similar setting is reflected by peralkaline igneous rocks of the Letitia Lake Group and the overlying red-bed and basalt succession of the Seal Lake Group adjacent to the Grenville Front to the north (Fig. 3). Northeastern and southwestern parts of the Grenvillian Province thus record different tectonic environments early in the Grenvillian orogenic cycle; how far removed from one another they may have been at the time, however, is conjectural.

By far the most voluminous Grenvillian plutonism, that of the AMCG suite, gave rise to the well-known anorthosite–charnockite massifs in the central and eastern parts of the province (Fig. 6), as well as numerous, smaller satellite plutons. Known ages range between 1.16 and 1.01 Ga (Emslie & Hunt 1990; Doig 1990; Higgins & van Breemen 1992; van Breemen & Higgins 1993; Owens et al. 1994; Corrigan et al. 1994b). Individual massifs appear to have restricted ranges of age within this lengthy period. In the Frontenac terrane (Fig. 4), which is apparently devoid of the calc-alkaline magmatism of the Elzevir superterrane, A-type monzonite, syenite and granite plutons (Lumbers et al. 1990), dated between 1.18 and 1.16 Ga (van Breemen & Davidson 1988b; Marcantonio et

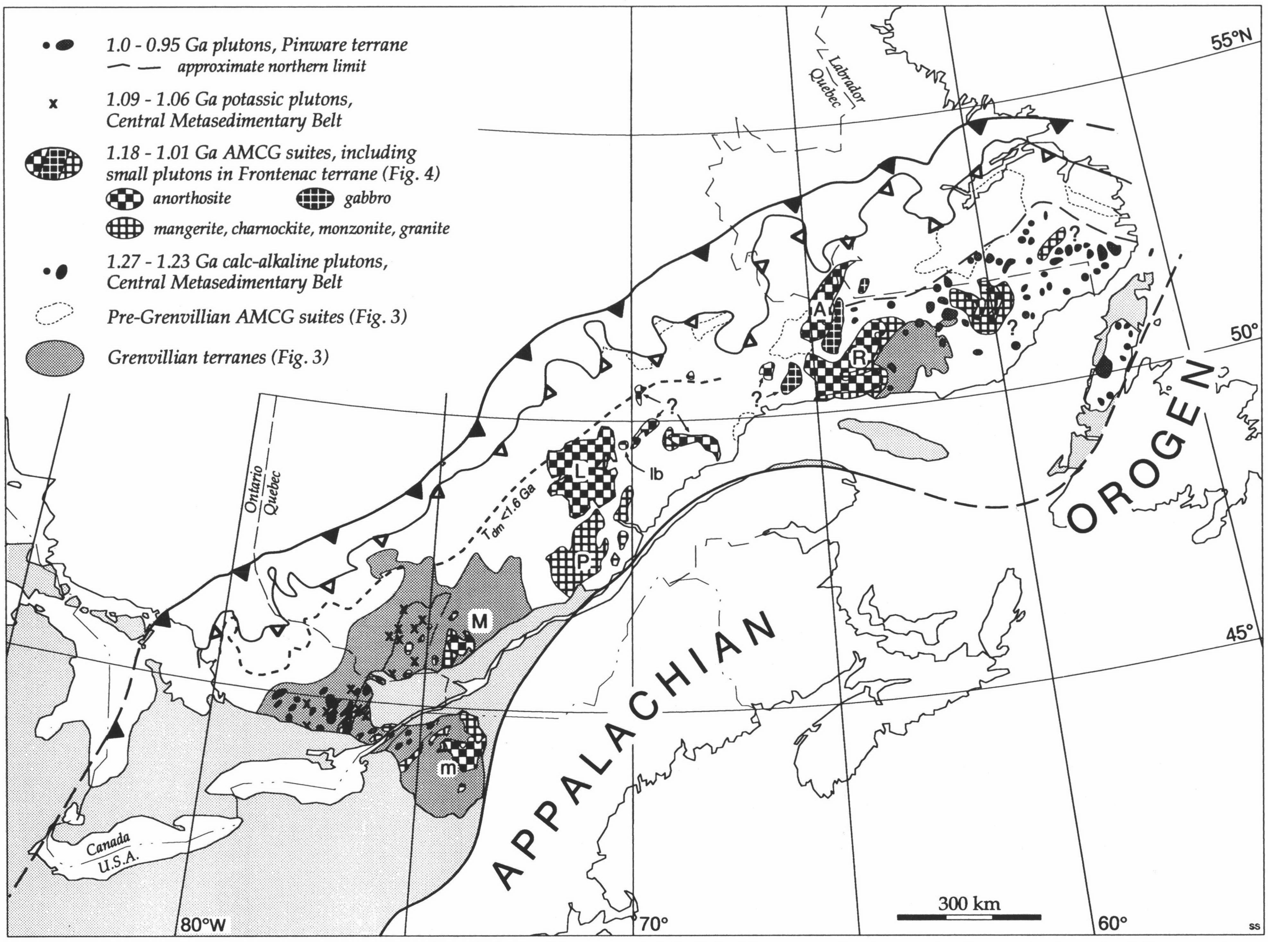


**Figure 6. Known distribution of plutonic rocks of Grenvillian age (<1.3 Ga). Many small plutons in the central part of the province have not been dated and are not shown. Northwest limit of <1.6 Ga Nd model ages is based on the work of Dickin & McNutt (1990) and Dickin & Higgins (1992). Dated AMCG suites are M—Morin (1160–1135 Ma), m—Marcy (1160–1125 Ma), L—Lac St. Jean (1160–1140 Ma, 1075 Ma), P—Parc des Laurentides (~1080 Ma), lb—Labrieville (1020–1010 Ma), A—Atikonak (1135–1110 Ma), and R—Romaine River (1080 Ma), Magpie River (1125 Ma, 1060 Ma) and Lac Allard; ? indicates undated AMCG suites which may be older (see Figure 3). Small monzonitic plutons in Frontenac terrane are between 1180 and 1160 Ma. (See text for references to geochronology.)**

al. 1990), are similar in age to AMCG suites in the Adirondack and Morin terranes, where older calc-alkaline rocks are again present. Monzonitic rocks of ~1.17 Ga age are also present in the Mont Laurier region of the Central Metasedimentary Belt in Quebec, but do not occur in the Elzevir superterrane in Ontario, with the possible exception of the Sharbot Lake terrane. However, small plutons of potassic syenite and granite with ages in the range 1.09–1.06 Ga (Corriveau et al. 1990) are present throughout the Central Metasedimentary Belt, though not in the central polycyclic belt to the northwest (Fig. 6).

Along the eastern side of the Wakeham terrane in the northeastern part of the province, the Davy Group is intruded by monzonite (1.08 Ga; Loveridge 1986) that is probably related to the neighbouring Havre St. Pierre AMCG complex, dated at ~1.06 Ga (van Breemen & Higgins 1993). An AMCG complex farther east in the Pinware terrane has not been dated. The Wakeham and Pinware terranes and the Long Range inlier in Newfoundland (Fig. 6) host numerous younger granite and syenite plutons dated between 1.01 and 0.95 Ga (Loveridge 1986; Gower et al. 1991; Owen & Erdmer 1990).

By way of contrast, igneous rocks of the time period 1.18–0.95 Ga are virtually absent from the central belt in Ontario and Quebec, the main exception being small amounts of coronitic olivine gabbro, which occurs almost invariably as small masses tectonically enclosed in ductile gneiss (Davidson 1991). Its crystallisation age is well established from primary baddeleyite at 1.17–1.15 Ga and it records metamorphism at 1.05 Ga (Davidson & van Breemen 1988; Heaman & LeCheminant 1993). Similar ages (~1.16 Ga) have been determined for zircon in meta-anorthosite and dykes of amphibolite in the footwall of the Parry Sound allochthon (Wodicka et al. 1994), ages that coincide closely with granulite-facies metamorphism in the allochthon and with syn-deformational pegmatite in the bounding shear zone (van Breemen et al. 1986). An earlier, isolated, deformed granite orthogneiss pluton dated at 1.24 Ga (Lumbers et al. 1991) occurs some 25 km south of the Grenville Front in Ontario, a region where otherwise the youngest plutonic rocks belong to the ~1.45 Ga suite. The only other dated igneous activity of comparable age in this area is that of intrusion of the 1235 Ma continental Sudbury diabase dyke swarm of the Southern and Superior provinces, deformed and metamorphosed in the parautochthonous belt (Dudàs et al. 1994).

With respect to the overall architecture of the Grenville Province, it is important to note that the limited number of Nd–Sm isotope studies made to date indicate relatively juvenile depleted mantle model ages for the calc-alkaline suite in the Adirondack Highlands (Daly & McLelland 1991), the AMCG suites (Ashwal & Wooden 1983; Emslie & Hegner 1993), and A-type and potassic suites in the Frontenac terrane (Marcantonio et al. 1990). $T_{dm}$s range between 1.55 and 1.20 Ga, in keeping with the fact that almost all of these igneous rocks lie southeast of the $T_{dm}$ <1.6 Ga line shown in Figure 6. The only exception known so far is the Atikonak massif ($T_{dm}$ >1.75 Ga; Emslie & Hegner 1993), which is the most northerly massif and known to lie within Labradorian crust.

In summary, calc-alkaline plutonic and associated volcanic rocks are spatially restricted to the central and southwest parts of the province, whereas AMCG and A-type plutons occur in the central and northeast parts, the two overlapping only in the central region. In terms of time, geochronology has shown that there is an apparent break of ~50 m.y. between the cessation of calc-alkaline igneous activity at ~1.23 Ga and the inception of AMCG and A-type plutonism at ~1.18 Ga. Earlier stages of the former overlapped AMCG and A-type plutonism in the range 1.47–1.34 Ga in other parts of the province, particularly if the St. Maurice arc is considered to have been the first manifestation of closure of a Grenvillian ocean. Grenvillian AMCG and A-type plutonism continued for ~230 m.y., a period equivalent in more familiar terms to the Mesozoic and Cainozoic eras combined; the span of time in any one area, however, may have been shorter, i.e. 1.18–1.06 Ga in the Frontenac and Mont Laurier regions of the Central Metasedimentary Belt, 1.13–1.0 Ga in eastern Quebec, extending to 0.95 Ga farther east. Although suggestive, the geochronological database is as yet insufficient to confirm whether there was a progressive younging eastward, or whether this igneous activity was episodic or relatively continuous.

It has been argued that the Grenvillian AMCG suites represent 'anorogenic' magmatism (McLelland 1986, 1989; Emslie & Hunt 1990). In terms of the Grenville Province as a whole, however, it is clear that metamorphism and contractional deformation occurred in some parts of the province at the same time as AMCG pluton emplacement in others, that the AMCG suites are themselves variously deformed and metamorphosed, and that contractional deformation (ductile thrusting) on major shear zones and along the Grenville Front continued within the period 1.05–1.0 Ga, after all but the youngest A-type plutons had been emplaced. The role of plutonic types in the overall development of the Grenville orogen will be addressed after the following summaries of metamorphism, deformation and post-Grenvillian events.

## Metamorphism

Grenvillian metamorphism has affected all parts of the province, but is not everywhere easy to distinguish from the effects of earlier metamorphisms. It is clear from geochronologic studies that older crystalline rocks were not necessarily overprinted to the extent that their earlier metamorphic history is obliterated. This is particularly true where Archaean rocks extend southeast of the Grenville Front (e.g. Indares & Martignole 1989, 1990b; Gariépy et al. 1990), and also in large parts of Labrador, where granulites are now known to have formed at ~1.65 Ga (e.g. Connelly & Heaman 1993). Moreover, surprises occur, such as the recent identification of 1.45 Ga metamorphism in the gneiss terranes of Ontario (Ketchum et al. 1994; Dudàs et al. 1994). It is for this reason, as well as the pre-Grenvillian ages of certain plutonic rocks, that much of the Grenville Province is termed polycyclic. In most of the regions where pre-Grenvillian metamorphism is recognised, however, Grenvillian metamorphism accompanying ductile deformation is pervasive.

An abrupt increase in grade is evident at the Grenville Front. This is due in part to uplift of lower levels of foreland rocks with pre-Grenvillian metamorphic assemblages within the adjacent parautochthon; for example, granulite-facies gneisses in the frontal hanging wall lie within 8 km of Huronian sedimentary rocks at greenschist grade in the neighbouring Southern Province, Ontario (Bethune & Davidson 1988). In places where previously low-grade or unmetamorphosed foreland rocks can be traced across the front, such as the Kaniapiskau Supergroup in western Labrador (Gagnon terrane in Fig. 3), upper amphibolite facies Grenvillian metamorphism is attained in the parautochthon within 30 km of the front (e.g. Rivers 1983; Rivers et al. 1993).

Metamorphic grade in the northwestern and central belts, manifested in gneiss and migmatite of both supracrustal and plutonic origin, is generally in upper amphibolite to granulite facies. Maximum palaeopressure estimates are relatively high, e.g. ~11 kbar in the Parry Sound region of Ontario (Anovitz & Essene 1990), ~8.5 kbar in the Adirondack Highlands of New York (Bohlen et al. 1985), ~10 kbar in western Quebec (Indares & Martignole 1990a) and in central Labrador (Arima et al. 1986). Evidence for eclogite-facies mineral assemblages, preserved in metamorphosed mafic igneous rocks akin to those in the Caledonian Western Gneiss Region of Norway (e.g. Griffin 1987), have been reported in Ontario (Grant 1989; Davidson 1990) and in the Molson Lake terrane in Labrador

(Indares 1993). These occurrences, for which pressure estimates are 14–16 kbar at ~750°C, are located in the lower parts of crust-scale thrust slices. This suggests that rocks buried tectonically to deep crustal level have been thrust, during a later stage of Grenvillian orogeny, to a level high enough for them to be exposed by subsequent erosional unroofing of the orogen, perhaps preceded by uplift associated with late Grenvillian extension. The same is likely true for some of the granulite terranes, particularly where they are thrust over amphibolite-facies rocks along low-angle ductile shear zones (e.g. Parry Sound domain and the Labradorian allochthons), coincident with inverted metamorphic gradients and changes in palaeopressure estimates (e.g. Tucillo et al. 1992).

The grade of Grenvillian metamorphism exposed in supracrustal rocks younger than ~1.3 Ga is varied. In Ontario, it is as low as upper greenschist facies in the central part of the Central Metasedimentary Belt (e.g. Carmichael et al. 1978; Davidson 1986). In the same area, relatively low-pressure granulite-facies rocks (7–5 kbar; Schau et al. 1986; Anovitz & Essene 1990) of the Frontenac terrane abut lower amphibolite-facies rocks of the Sharbot Lake terrane along a shear zone (Fig. 4), again indicating tectonic juxtaposition. In eastern Quebec, supracrustal rocks of the Wakeham Supergroup at greenschist grade lie structurally above migmatitic rocks, suggesting either an extensional tectonic or an unconformable relationship with older metamorphic rocks.

Grenvillian plutonic rocks are also metamorphosed, with the exception of the youngest ones. For example, although undoubted igneous charnockite is present in some AMCG complexes, many of the granitoid members of this suite are represented by well-foliated charnockitic orthogneiss carrying metamorphic orthopyroxene and garnet. Anorthosite and gabbro, although inherently resistant to deformation and recrystallisation, are in places reduced to gneiss containing upper amphibolite- to granulite-facies mineral assemblages. These rocks where undeformed, particularly troctolitic members, commonly exhibit coronas of metamorphic origin (cf. Davidson & van Breemen 1988).

Except for the rapid increase in metamorphic grade across the Grenville Front, there is no throughgoing zonal arrangement of metamorphic facies parallel to the orogen. Some grade changes within the interior reflect variations in tectonic level brought about by different amounts of uplift experienced by adjacent crustal segments. Others may be due to incomplete retrogression of granulite to amphibolite facies accompanying late-stage ductile Grenvillian deformation, explaining, for example, the occurrence of small areas of granulite-facies rocks in the central belt in Ontario and western Quebec, which is dominated by amphibolite-facies migmatitic gneiss (Davidson et al. 1990). Throughout most of the province, high-grade metamorphism occurred between ~1.06 and 1.02 Ga, followed by cooling to the argon closure temperature of hornblende by ~0.97 Ga (Fig. 5). Certain terranes, for example the Parry Sound, Frontenac and New York Lowlands terranes, experienced cooling at least 100 m.y. earlier (Cosca et al. 1991; Mezger et al. 1993). The significance of different T-time paths for adjacent crustal blocks in the southwest part of the province is discussed by van der Pluijm et al. (1994).

## Structural overview

As stated at the beginning of this review, the Grenville Front is a geophysically well-defined tectonic lineament represented at the surface by moderately to steeply south to southeast-dipping, thrust-sense faults and mylonite zones. This structural orientation is shared by much of the layering and foliation in the gneiss and granulite terranes of the northwest and central belts and by the bounding thrust zones between the two belts, although it is generally more shallowly inclined. Dip-parallel mineral stretching lineation is common. Northwest trends occur in eastern Labrador (Hawke River and southeastern Lake Melville terranes; Fig. 3) and in parts of western Quebec and Ontario, but in the latter are due to open folding about gently southeast-plunging axes of formerly southeasterly-inclined gneisses (e.g. Schwerdtner & van Berkel 1991). Domains with irregular structure, or with trends at a high angle to the prevalent northeast trend, are commonly found to be structurally discontinuous with surrounding domains, from which they are usually separated by narrow belts of well-layered gneiss. Formerly interpreted as paragneiss, these rocks are now recognised as ductile tectonites, equally likely to have developed from originally massive plutonic rocks by extreme attenuation as from layered supracrustal rocks (Davidson 1984a; Hanmer 1988). These ductile shear zones provide the basis for subdivision of the two belts into the lithotectonic domains or terranes outlined in preceding sections (see articles in Moore et al. 1986; Rivers et al. 1989). In some of these zones, features suggestive of severe flattening in S- and SL-tectonites point to a large component of pure shear. However, consistently oriented kinematic indicators in several shear zones imply a northwesterly directed sense of thrust displacement, although shear sense in others of similar oriention is extensional, with low-angle displacement toward the southeast (e.g. Culshaw et al. 1994).

Timing of displacement has been estimated for some of these shear zones by dating syntectonic pegmatites (Fig. 5). In the interior of the central belt in Ontario, thrust displacement took place along the western margin of the Parry Sound domain (Fig. 4) at around 1.16 Ga (van Breemen et al. 1986; Wodicka et al. 1994). Similar displacements occurred at ~1.10 Ga along the margins of the Seguin and Moon River thrust sheets (van Breemen & Davidson 1990) and at ~1.06 Ga farther east, suggesting large-scale (in terms of both time and space) out-of-sequence thrusting (break-back stacking of Nadeau & Hanmer 1992). Farther northwest, later extensional displacement occurred at ~1.03 Ga along the northwest boundary of the Shawanaga terrane (Fig. 4; Culshaw et al. 1994); this predates the last stages of thrusting along the Grenville Front to the northwest, estimated to have occurred at ~0.98 Ga (Haggart et al. 1993), only slightly older than cooling through the Ar closure temperature of amphibole farther southeast (~0.97 Ga; Culshaw et al. 1991; see Fig. 5). The timing of deformation in this part of the province is summarised by Jamieson et al. (1992). Timing is not so well constrained in other parts of the province. As stated earlier, the earliest amalgamation of terranes in the northeast part of the province may have been Labradorian (~1.6 Ga), but northward deep-crustal thrusting along both the Grenville Front, the boundary between the Gagnon and Molson Lake terranes, and the allochthon boundary thrust appears to have occurred late during the Grenvillian orogenic cycle (~0.99 Ga; Connelly & Heaman 1993; Connelly et al. 1993). In the central part of the province, the St. Maurice arc shows evidence of westerly directed thrust imbrication as early as 1.15 Ga, followed some 50 m.y. later by oblique sinistral shear (Corrigan et al. 1994b).

Turning to the Grenvillian supracrustal terranes of the southeastern belt, the northwest margin of the Central Metasedimentary Belt in Ontario (Fig. 4) is a broad ductile thrust stack inclined shallowly to the southeast (Hanmer & McEachern 1992), but in Quebec, except for the Cabonga allochthon, it is a zone of an oblique displacement (Hanmer & Ciesielski 1984). Terrane boundaries within the Central Metasedimentary Belt are also marked by high-strain zones (e.g. the thrust-sense Maberly shear zone and the extensional Robertson Lake mylonite zone; Fig. 4). Fold patterns within the various terranes differ from one another (e.g. interference folds vs linear fold belts), suggesting different histories. The southeastern boundary in New York State (Carthage–Colton mylonite zone) dips northwest and has top-side-down sense of shear to the northwest, whereas the equivalent boundary in Quebec (Labelle shear zone) is the locus of sinistral displacement. The other Grenvillian supracrustal terrane, the Wakeham terrane, is bounded on its northwest side by southeast-dipping extensional faults (Martignole et al. 1994), but to the southeast merges with high-grade gneisses.

Northwestward thrust displacement along the Central Metasedimentary Belt boundary zone (Fig. 4) began as early as ~1.19 Ga and was succeeded by a second period of thrusting between 1.08 and 1.06 Ga (McEachern & van Breemen 1993). High-grade ductile thrusting along the Maberly shear zone has not been dated directly, but post-dated emplacement of plutonic rocks of the ~1.17 Ga suite in overriding the Frontenac terrane. Southeastward extensional displacement along narrow zones of low-temperature mylonite developed in marble in the southeast of the Bancroft terrane has been dated at ~1.0 Ga, based on comparison with cooling curves in adjacent rocks (van der Pluijm & Carlson 1989). Similar displacement on the Robertson Lake mylonite zone, also occurring at relatively low temperature, may have been of comparable age; it appears to offset rocks with middle amphibolite assemblages dated at ~1.03 Ga (Corfu & Easton 1994).

Seismic reflection profiling of Grenvillian crystalline terranes has given another dimension to regional structural analysis. Several surveys have shown a wealth of moderately to shallowly inclined reflectors, in essence confirming cross-sections constructed from ground-based observations (e.g. Davidson 1984a; Rivers et al. 1989). Notable among these is a shipboard transect across the Grenville Front in Lake Huron (Green et al. 1988). This transect showed that the front and parallel structures above it penetrate the entire crust, shallowing slightly with depth and coinciding with minor depression of the crust–mantle boundary ('reflection Moho') at ~40 km depth. Transects on land within the orogen in Ontario have been equally fruitful in delineating crustal-scale thrust structure (White et al. 1994; Forsyth et al. 1994a 1994b), an example of which is shown in Figure 7. The most recent transects in western and eastern Quebec and across the Grenville Front along the Atlantic coast of Labrador await final processing.

In summary, the Grenville orogen in its type area, the southeastern Canadian Shield, can be envisaged as an imbricate stack of crustal-scale lenses inclined toward the south and southeast and riding on a basal, crust-penetrating thrust expressed at the surface by the Grenville Front. The stack was compiled largely by thrusting at deep to mid-crustal level with displacements of unknown, but perhaps large, magnitude during continued compression directed toward the Laurentian craton in the period 1.2–1.0 Ga, following closure of a postulated Grenvillian ocean. It was modified by extensional shearing and faulting late in its orogenic history ( Ga), coincident with the youngest stage of thrust-associated uplift along the Grenville Front.

## Post-Grenvillian events

Most parts of the Grenville Province record uplift and cooling between 1.0 and 0.9 Ga, the time of final assembly of an early Neoproterozoic supercontinent (Hoffman 1991; Windley 1993). Evidence for its subsequent break-up, leading to opening of the Iapetus Ocean and removal of the 'other side' of the Grenville orogen, is given by both sedimentary and igneous rocks associated with rift formation within and marginal to the province (Fig. 8). In Labrador, branching rifts are filled with terrestrial sediments of local derivation (Double Mer Formation), considered to be Eocambrian in age on the basis of palaeomagnetic comparison to 615 Ma diabase dykes of the Long Range swarm (Kamo et al. 1989; Murthy et al. 1992). Thin, undisturbed, sub-Cambrian terrestrial sediments associated with minor basalt occur on the eroded orogen opposite northern Newfoundland (Gower et al. 1994), and the Long Range inlier of Newfoundland is replete with northeast-trending diabase dykes. A number of late Neoproterozoic plutons lie along the St. Lawrence, notable among which is the large Sept Iles gabbro–anorthosite intrusion; this intrusion is at least 60 km in diameter, judging by the extent of its aeromagnetic and gravity anomaly beneath the St. Lawrence estuary, and has been dated, using Rb–Sr, at ~540 Ma (Higgins & Doig 1981) and by U–Pb zircon at 565 Ma (O. van Breemen,

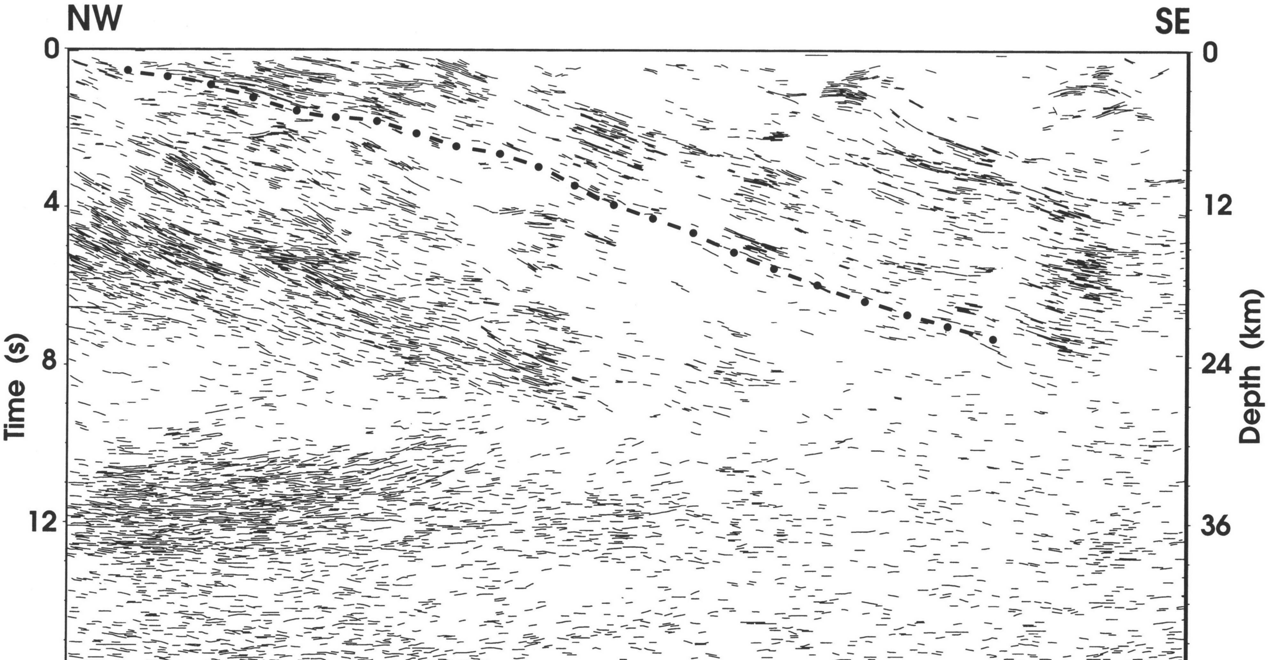


**Figure 7. Crustal structure beneath the northwestern part of the Grenville Supergroup: a seismic reflection transect in Ontario (White et al., 1994, Fig. 8). The broad band of shallowly southeast-dipping reflectors in the top part of the section is the boundary thrust zone of the Central Metasedimentary Belt (see Figure 4); the reflection Moho is at ~40 km.**

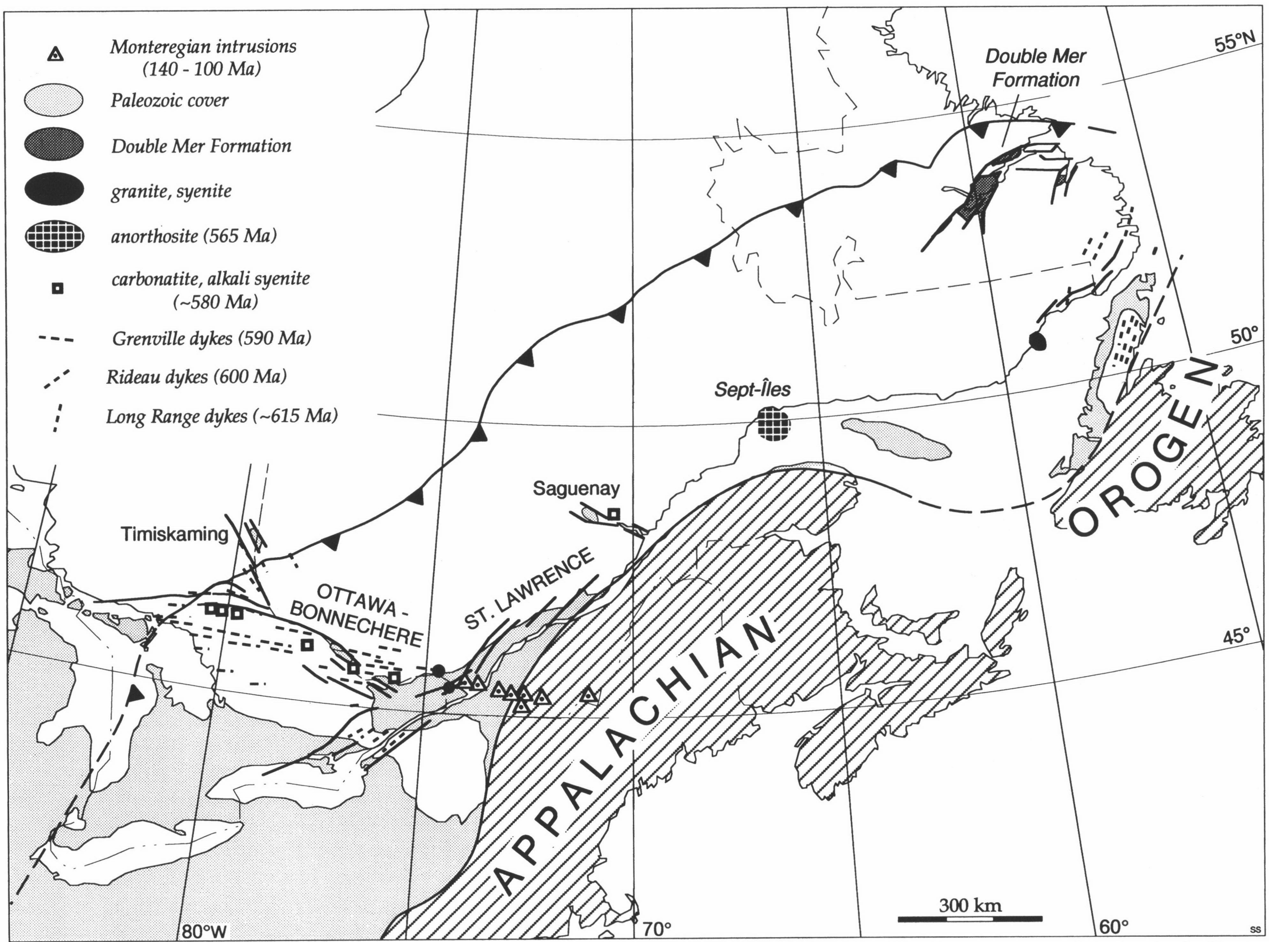


**Figure 8. Post-Grenvillian features of the Grenville Province (after Hoffman, 1989a, Fig. 47). Features are related principally to continental break-up at ~600 Ma (except Monteregian intrusions). Main rift faults are shown as solid lines, diabase dykes swarms are represented by short dashes.**

pers. comm. 1994). Rift faults along the St. Lawrence pass southwestward through the southern part of the Frontenac and New York Lowlands terranes, where northeast-trending diabase dykes (Rideau swarm; Fahrig & West 1986) and small occurrences of tilted conglomerate and sandstone are also present. Branches of the St. Lawrence rift system (Saguenay, Ottawa-Bonnechere, and Timiskaming graben) are associated with local alkaline igneous activity, including minor potassic volcanism and carbonatite intrusion, all Eocambrian in age. Tholeiitic diabase dykes of the Grenville swarm (Fahrig & West 1986), dated at 590 Ma (Kumarapeli et al. 1990) parallel the Ottawa–Bonnechere graben, extending over 500 km from near Montreal to beyond the Grenville Front in the Sudbury area.

As well as lack of evidence for rifting before about 600 Ma, there is also little evidence of appreciable topography at the time of early Palaeozoic sedimentation. Coarse detritus is not present in the basal part the Late Cambrian to Early Ordovician succession, which is represented by mature littoral sandstone succeeded by shallow marine carbonates. Reactivated faults of the rift system offset the Precambrian–Palaeozoic unconformity. Their renewed movement is likely related to Monteregian igneous activity (Cretaceous; Eby 1984), itself possibly linked to passage across a hot-spot (Sleep 1990).

## Concluding remarks

The early manifestations of Grenvillian orogeny (*sensu lato*) are recorded by the closure of what has been referred to as the Grenvillian ocean (Windley 1989, 1993), which may have been a wedge-shaped aulacogen closing to the north (but see Gower & Tucker 1994). This activity is recorded by the calc-alkaline volcanic and plutonic rocks (perhaps in a number of westward-younging arcs?), terminating with volcanism in the Elzevir superterrane at ~1.25 Ga and plutonism extending to ~1.23 Ga, considered to have been associated with southeast-directed subduction (Windley 1986). Thrust-sense ductile deformation at least as early as 1.19 Ga along the northwest boundary of the Central Metasedimentary Belt may record final closure and obduction of the arc rocks over older Mesoproterozoic crust (central belt) and perhaps its sedimentary cover (Bancroft terrane; Fig. 4). Continued northwest-directed compression may be represented by thrust-uplift at ≤1.16 Ga of the adjacent Frontenac block, which may have 'docked' during closure at ~1.2 Ga and thus be a terrane in the plate tectonic sense. Uplift and cooling of the Frontenac terrane began at this time (Mezger et al. 1993; Cosca et al. 1992), and detritus was shed northwestward onto exhumed arc rocks of the Elzevir superterrane (Flinton Group; Moore & Thompson 1980; Sager-Kinsman & Parrish 1993). The different terranes of the Central Metasedimentary Belt are apparently 'stitched' by small plutons of potassic syenite and granite (1.09–1.06 Ga; Fig. 5). Distribution of the youngest metamorphic event (≤1.03 Ga) recorded in parts of the Elzevir superterrane has been disrupted by extensional faulting.

Grenvillian AMCG and A-type plutonism, beginning at ~1.18 Ga, is all but restricted to the region east and northeast of the closed ocean basin (Figs 5 and 6). The lengthy period of perhaps episodic pluton emplacement (to 1.06 Ga in the Central Metasedimentary Belt, ~1.0 Ga in central Quebec, and 0.95 Ga farther northeast) overlapped continued ductile thrusting at least in the southwest part of the central belt

(1.16 to 1.05 Ga), and perhaps elsewhere in this belt (at present unconstrained by dating). Grenvillian metamorphism is dated in many places between 1.08 and 1.03 Ga, with some notable exceptions (earlier in the Parry Sound and Frontenac terranes, barely recorded in some of the Labradorian thrust sheets in the northeast part of the province).

Concerning application of the term 'anorogenic' to AMCG and A-type suites in general, a clear example of anorogenic setting is given by the well-known 1.45–1.3 Ga AMCG suites in Labrador north of the Grenville Front—they are neither deformed nor metamorphosed, and do not appear to be related to regional orogeny of any kind. In terms of petrochemistry, it is perhaps a logical extension to consider that virtually identical suites within the Grenville represent anorogenic magmatism (cf. McLelland 1989; Emslie & Hunt 1990). This may be true for such rocks of pre-Grenvillian age now incorporated into the Grenville orogen (cf. Windley 1989, 1993), which may thus be termed 'pre-orogenic' with respect to the Grenvillian orogenic cycle. In comparison, those younger than 1.18 Ga might be considered 'post-orogenic' with respect to closure of the Grenvillian ocean, represented by Elzevirian orogeny (≥1.23 Ga) in the southwest part of the province. Plutonism of this type closely following orogeny would correspond to 'anorogenic plutonism' following continental assembly of Windley (1993). However, in view of the evidence in the Grenville for continued compressive tectonics and high-grade metamorphism grossly coeval with AMCG and A-type plutonism, it must be asked whether these suites are really anorogenic (e.g. Corrigan et al. 1994b). Perhaps plutonic suites of 'anorogenic character' can be generated within the broad confines of a still-active orogen, following earlier tectonic crustal thickening and development of a thermal anomaly in the underlying asthenosphere. Resulting from this, addition to the middle and upper crust of magma derived through fractionation of mantle melts (gabbro, anorthosite) and melting in the lower crust (granitoid phases) (McLelland 1989; Emslie & Hunt 1990; Windley 1993; also see Hoffman 1989b) would follow the same course as for a strictly anorogenic environment (static thermal anomaly, mantle plume). If, however, compressional or transpressional orogenic forces, resulting from continued impingement of a continental block to the southeast, were still active during episodic plutonism or resumed shortly afterwards, thermal relaxation in the mid-crust, enhanced by heat from ascending plutons, would lead to metamorphism and softening with ductile deformation. The fact that many of the Grenvillian AMCG and A-type plutonic rocks are themselves deformed and metamorphosed (e.g. Martignole & Schrijver 1970), in contrast to the AMCG suites north of the front, may be the consequence of such a process. That parts or all of some Grenvillian complexes are not deformed may be explained by their inherent tectonic hardness, their age relative to deformation, or their localisation within slices bounded by ductile shear zones. In this regard, it is interesting that the 'anorogenic' setting widely accorded to Mesoproterozoic igneous rocks in the United States midcontinent is the subject of current dispute (cf. Nyman et al. 1994).

Many major questions about development of the Grenville Province remain unanswered. For example, if the province formed ultimately by continent–continent collision, and the calc-alkaline suites and Grenville Supergroup are all that remains of the intervening ocean, where is the suture between the two continental blocks? It cannot coincide with the $T_{dm}$ <1.6-Ga line shown in Figure 6, as this lies on the wrong side of the closed ocean basin. If the pre-Grenvillian crust containing the Grenvillian AMCG suites in the southeastern belt is all composed of reworked, but relatively young, Laurentian crust, as suggested by the model ages of these suites, then the whole of the Central Metasedimentary Belt may represent an enormous nappe structure rooted formerly southeast of the Adirondack Highlands (Davidson 1986; Hoffman 1992). Allowing this, a suture may lie in the northwestern Central Metasedimentary Belt, perhaps along the juncture between the Bancroft and Elzevir terranes (see Hanmer & McEachern 1992). The early interplay of these different crustal segments, particularly with respect to timing of displacement involving the terranes of the Central Metasedimentary Belt, remains to be worked out.

Two other aspects of Grenville geology deserve comment. One concerns the relationship between the mid-continental rift system (Fig. 2) and Grenvillian orogeny. The rift fill is exposed only in the Lake Superior region, the remainder being identified primarily on the basis of its gravity anomaly. It contains a thick fill of mainly basaltic flows, associated with mafic intrusions, that erupted during a 15 m.y. interval at ~1.10 Ga. Although occurring during the prolonged period of Grenvillian AMCG magmatism, the two do not coincide precisely; most AMCG ages are either older or younger than 1.10 Ga (see Fig. 5 and caption for Fig. 6). It does, however, coincide with a stage of thrusting within the central belt in Ontario (Moon River and Seguin terranes over the Parry Sound terrane; Fig. 4). Formation of the midcontinental rift (Gordon & Hempton 1986) and its partial closure (Cannon 1994) have been related to Grenvillian compression. Later displacement along the Grenville Front has apparently caused the southeast extension of the rift to be overridden, as its gravity anomaly dies out at the front. The volcanic fill has a thick detrital sediment cover, but it is curious that this sediment shows no evidence of a Grenvillian component.

This raises the second aspect, namely the lack of foreland basins adjacent to the front, and molasse-type deposits derived from what intuitively must have been a source of sediment, judging by the amount of uplift required by the steep metamorphic gradient parallel to the front. Related to this is the highly restricted development of fold-thrust deformation style in the frontal region. Steep, closely-spaced thrusts involving older foreland rocks are evident in some places, but only in Labrador is this style developed to any great extent, involving the Palaeoproterozoic Kaniapiskau Supergroup and, farther east, the Seal Lake Group. This scenario is attributed by Hoffman & Grotzinger (1993, following Beaumont et al. 1991) to the spatial relationship and orientation of the Grenville Province, during uplift and unroofing, to palaeolatitude and its control on prevailing wind direction, rainfall and erosion. The presence of a Grenvillian foreland thrust belt, however, has been interpreted from seismic data in the eastern U.S. midcontinent (Hauser 1993).

The prevalence of pre-Grenvillian anorogenic magmatism in two pulses (~1.7–1.6 Ga and 1.5–1.35 Ga), well documented in the Grenville Province and corresponding to igneous events beyond the front in the North American mid-continent and in Scandinavia, has been related to the final stages of assembly and subsequent break-up, respectively, of a supercontinent assembled at ~1.5 Ga (Windley 1993). Supercontinent break-up led to opening of the Grenvillian ocean. Subsequent to this, the Grenvillian orogenic cycle represents early closure of this ocean, continent–continent collision, and attendant crustal thickening during supercontinent reassembly. The latter was accompanied and followed by a long period of magmatism of 'anorogenic type' during gradual thermal relaxation, coeval on a gross scale with primarily northwestward translation and later gravitational collapse of thermally softened crust. Final cooling, bulk uplift and erosion occurred between 1.0 and 0.9 Ga. The Grenville Province remained quiescent until ~600 Ma, when break-up leading to opening of the Iapetus Ocean began. At this time it is likely that the 'other half' of the Grenville orogen, comprising the enigmatic southeastern continental mass, rifted away.

## The Musgrave Block—a brief comparison

The main similarities between the Grenville Province and the Musgrave Block lie in the nature and association of magmatism and metamorphism during the Grenvillian time span, imposed on pre-Grenvillian, Proterozoic crystalline crust (felsic and mafic gneisses). In this respect the Musgrave is comparable to the central belt of the Grenville Province. Introduction of mantle-derived gabbro and anorthosite (Giles Complex) into the mid-crust took place at about 1.08 Ga, and appears to have been of fairly short duration. Metamorphism was of relatively low-pressure type (Clarke et al. 1992). The possibility exists that the mafic–ultramafic plutonic activity was contemporaneous with mafic and A-type volcanic rocks at ~1.08 Ga (Tollu volcanics; Sun & Sheraton 1992; Sun et al. in press). This requires earlier Grenvillian plutonic and metamorphic rocks to have been unroofed by this time, at least in the western part of the Musgrave Block. Although granitoid rocks of similar age are present in the southeastern part of the Grenville Province, there is no evidence for coeval volcanism or sedimentation, this being a time of ductile deformation and high-grade metamorphism throughout much of the province. Also, unlike in the Musgrave Block, there is no equivalent to the latest Proterozoic to early Cambrian deformation and high-pressure metamorphism represented by the north-directed Woodroffe Thrust system (Clarke et al. 1993). Grenvillian basement is exposed in thrust slices within the neighbouring Appalachian orogen; the frontal thrusts of this orogen are directed toward the Grenville Province, and lie at high crustal level within Lower Palaeozoic cratonic cover.

If the continental reconstruction shown in Figure 1 is correct, the known belts of Grenvillian age in Australia are considerably narrower than in North America. The equivalent of the Grenville Front, identified in Antarctica by Storey et al. (1994), should lie on the southeast side of the Albany–Fraser belt and south of the Musgrave Block, passing north of the Gawler Craton.

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