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The Grenville Orogenic Cycle (ca. 1350–1000 Ma): an Adirondack perspective

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Abstract

The Adirondack Mountains are characterized by three major events that took place during the interval ca. 1350–1000 Ma. The earliest of these is the arc-related Elzevirian Orogeny (ca. 1350–1185 Ma) during which substantial volumes of juvenile calc-alkaline crust were added to the Adirondacks as well as to the northwest segment of the Central Metasedimentary Belt. Data from the southwestern United States as well as from Ireland and Baltica indicate that Elzevirian magmatism and orogeny were of global dimensions. Within the southwestern sector of the Grenville Province, the Elzevirian Orogeny culminated at ca. 1185 Ma when accretion of all outboard terranes was completed. Compressional orogeny related to this convergence resulted in overthickened crust and lithosphere which subsequently delaminated giving rise to orogen collapse and AMCG magmatism that swept southeastward from the Frontenac Terrane into the Adirondack Highlands during the interval ca. 1180–1130 Ma. Localized compressional events within neighboring parts of the Grenville Province emphasize the continued existence of contraction during this interval, although crustal extension caused local in sedimentary basins in which were deposited the Flinton and the St. Boniface Groups.

The Adirondacks have not yet provided any record of events within the interval ca. 1125–1100 Ma, although there is evidence of contraction elsewhere in the southwestern Grenville Province at that time. At 1100–1090 Ma the northern Adirondack Highlands were invaded by mildly A-type hornblende granites (Hawkeye suite) that are interpreted to be the result of local crustal thinning contemporaneous with rifting and mafic magmatism taking place in the Midcontinent rift. Immediately following, at ca. 1090 Ma, the global-scale continental collision of the Ottawan Orogeny was initiated. Strong convergence, deformation, and metamorphism continued to at least ca. 1070 Ma, and rocks older than this are profoundly affected by this event. During the waning stages of the Ottawan Orogeny, overthickened crust and lithosphere delaminated and the orogen underwent collapse. Large extensional faults such as the Carthage–Colton–Labelle shear zone developed and rapidly exhumed granulite facies rocks in the mobile core of the orogen which centers on the Adirondack–Morin terranes and extends southeastward into the New York–New Jersey Highlands. Extensional faulting along the Carthage–Colton mylonite zone dropped the amphibolite facies Lowlands down to the west and into juxtaposition with granulite facies rocks of the Highlands. U–Pb cooling ages from garnet, monazite, and titanite exhibit a sufficiently broad spectrum to accommodate an initial rapid rate of rebound-related cooling followed by a slower, erosion-controlled cooling history.

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During delamination, late- to post-tectonic granites of the Lyon Mt. Gneiss (ca. 1070–1045 Ma) were emplaced. The youngest member of this suite is an undeformed fayalite granite dated at ca. 1045 Ma which crosscuts all older rocks and fabric. High-potassium, post-tectonic granites of similar age are common in other parts of the southwestern Grenville Province.

Renewed contraction and metamorphism at ca. 1030 Ma demonstrate that the Ottawan Orogen was still experiencing convergence well after the peak of orogeny. However, most of the manifestations involve reactivation of older thrust faults, including the Grenville Front Tectonic Zone. The intrusion of small bodies of anorthosite at ca. 1015 Ma (i.e., Labrieville) provide further evidence for the emplacement of these rocks within collisional orogens, albeit in their collapsing phase.

Keywords: anorthosite; collisional tectonics; delamination; exhumation tectonics; orogeny; granitoid; zircons

1. Introduction

As a consequence of large size, complicated structural framework, high metamorphic grade, and inaccessibility, the Grenville Province (Fig. 1) has remained poorly understood until recent times. Stockwell (1964) summarized K–Ar dates from across the region and concluded that essentially the entire Province had experienced thermal metamorphism at 950 ± 150 Ma; an age that came to be associated

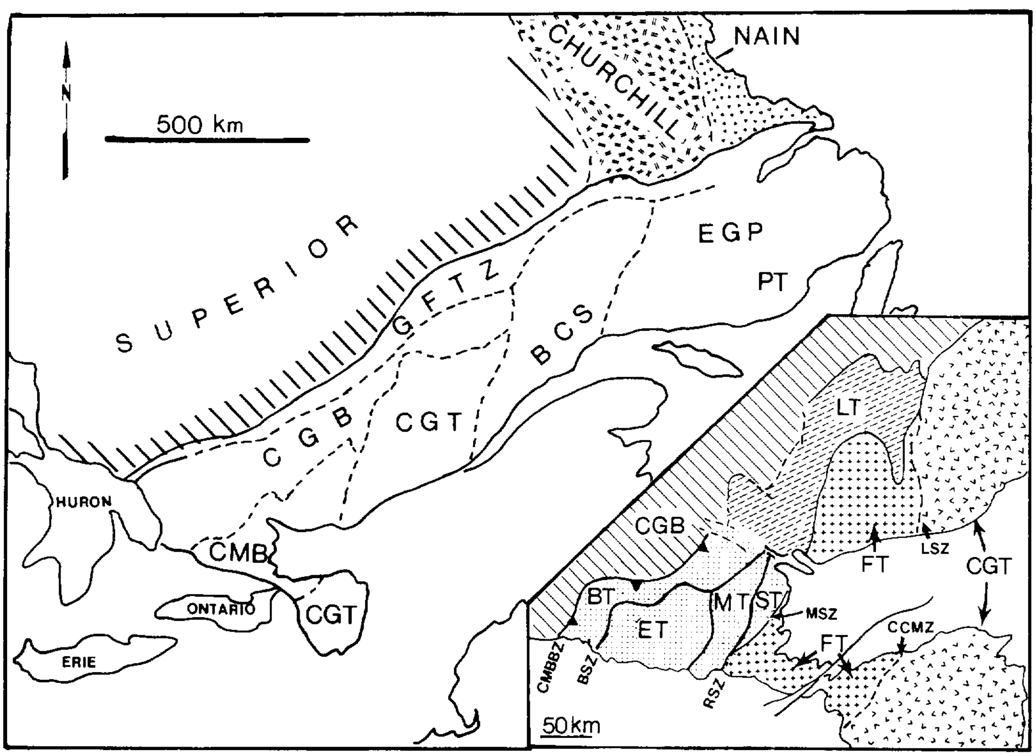


Fig. 1. Subdivisions of the Grenville Province according to Wynne-Edwards. Inset shows terranes of the Central Metasedimentary Belt (CMB) and shear zones as given by Easton (1994). *BCS* = Baie Comeau Segment; *BT* = Bancroft Terrane; *CCMZ* = Carthage–Colton Mylonite Zone; *CMBBZ* = Central Metasedimentary Belt Boundary Zone; *CGB* = Central Gneiss Belt; *CGT* = Central Granulite Terrane; *EGP* = Eastern Grenville Province; *ET* = Elzevir Terrane; *FT* = Frontenac Terrane; *GFTZ* = Grenville Front Tectonic Zone; *LSZ* = Labelle Shear Zone; *LT* = Mont Laurier Terrane; *MSZ* = Maberly Shear Zone; *PT* = Pinware Terrane; *RSZ* = Robertson Lake Zone.

with the vague and ill-defined 'Grenville Orogeny'. During the 1980s, detailed field studies coupled with modern geochronology began to reveal a protracted and complicated tectonic history that extended back to ca. 1700 Ma and involved several distinct orogenic events (cf. Moore, 1986; Scharer et al., 1986; Gower et al., 1990; Davidson, 1995). Two of the most important of these orogenic events were recognized in the Central Metasedimentary Belt (CMB, Fig. 1) by Moore and Thompson (1980) who designated them as the Elzevirian Orogeny (ca. 1300–1200 Ma) and the Ottawan Orogeny (ca. 1100–1000 Ma), respectively. Together, these two pulses constitute the Grenville Orogenic Cycle in the same sense that the Taconian, Acadian, etc., constitute the Appalachian Orogenic Cycle. Where currently employed, the term 'Grenville Orogeny' is used synonymously with the Ottawan Orogeny (cf. Rivers, 1995), but it is advisable to utilize the more clearly defined terminology of Moore and Thompson (1980) to which we adhere in this paper.

The Grenville Orogenic Cycle was preceded by older dynamothermal and magmatic events that extend back to the Labradorian Orogeny (ca. 1680–1650 Ma) in the eastern portion of the Province and may include extensions of Penokean and post-Penokean (ca. 1800–1700 Ma) rocks in western Ontario (Gower et al., 1990; Rivers, 1995). The existence of orogenic and magmatic activity in the Grenville Province at 1800–1600 Ma indicates that crustal growth and accretion represented by the Yavapai (ca. 1800–1700 Ma) and Mazatzal (ca. 1700–1600 Ma) Orogenies in the southwest also occurred along northeast Laurentia, although not necessarily in the same orogens (Hoffman, 1988, 1989). Between 1600 and 1400 Ma the Grenville Province was affected by granitoid intrusion and metamorphism at a number of centers summarized by Moore (1986), Gower et al. (1990), and Rivers (1995). These events still remain relatively obscure, and their discussion is beyond the scope of this paper; the interested reader is referred to the literature cited above.

As shown in Fig. 1, the Adirondack Mts. represent a southern extension of the Grenville Province to which they are connected via the Frontenac Arch. The Adirondacks are divisible into the rugged Highlands terrane dominated by orthogneisses and the topographically subdued Lowlands that are underlain principally by easily eroded metasediments, notably marbles (Fig. 2). Separating the Highlands and Lowlands is a high-strain zone of variable width (e.g., 1–10 km) referred to as the Carthage–Colton mylonite zone (CCMZ) that is occupied along most of its length by the Diana Complex consisting of

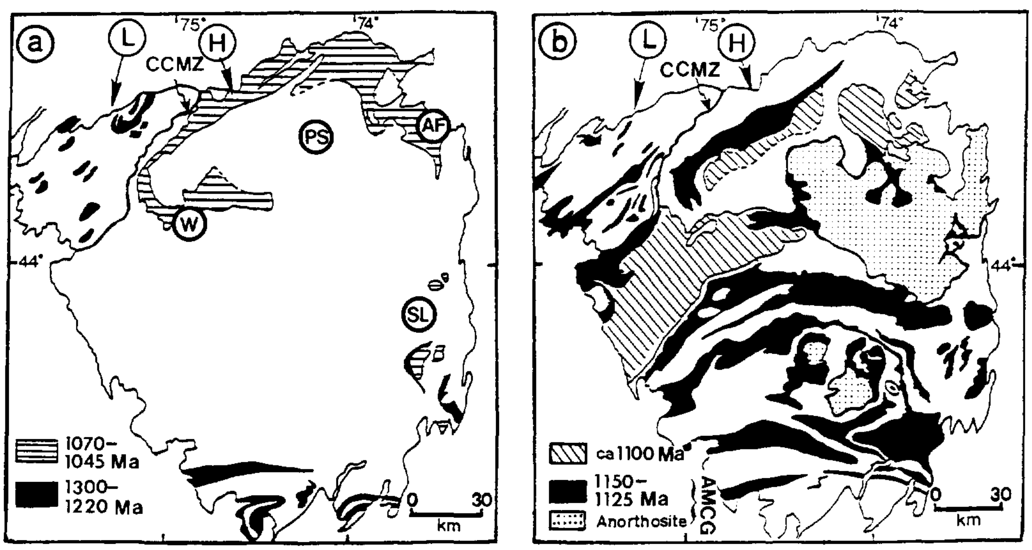


Fig. 2. Geochronological and lithologic subdivisions of the Adirondack Mountains. Age relationships shown in legends for (a) and (b). *AF* = Ausable Forks; *PS* = Paul Smith's; *SL* = Schroon Lake; *W* = Wanakena. *L* = Lowlands; *H* = Highlands; *CCMZ* = Carthage–Colton Mylonite Zone. After Chiarenzelli and McLelland (1991).

pyroxene-bearing granitoids (Geraghty et al., 1981). The CCMZ appears to extend into Canada as the Labelle shear zone, and, as shown in Fig. 1, the combined shear zones form the boundary between the Central Metasedimentary Belt (CMB) on the west and the Central Granulite Terrane (CGT) on the east. The Adirondack Highlands are part, therefore, of the CGT whereas the Lowlands belong to the Frontenac Terrane of the CMB. As noted by Buddington (1939) and discussed by several other workers (e.g., Bohlen et al., 1985; Valley et al., 1990; Kitchen and Valley, 1995), the Lowlands exhibit assemblages characteristic of upper amphibolite facies metamorphism whereas the Highlands comprise classic a granulite facies terrane (Buddington, 1939; deWaard, 1965). Both regions are characterized by intense, polydeformational folding accompanied by the development of strong penetrative fabrics including down-dip ribbon lineations of the sort commonly associated with ductile strain (McLelland and Isachsen, 1986). Although deformation and the widespread presence of orthogneiss preclude the establishment of stratigraphies in the region, it is clear that many of the lithic types and packages of the Adirondacks (e.g., anorthosite, marble–quartzite sequences) bear a close resemblance to rocks occurring north the St. Lawrence River in Canada and provide strong evidence for geologic continuity throughout the region.

The complicated structural framework and high metamorphic grade of the Adirondacks make it exceedingly difficult to establish geologic history from map patterns and petrologic relationships alone. As a consequence, very little progress could be made in reconstructing the tectonic evolution of the region until quantitative constraints were brought to bear on processes and events recorded in the rocks. To this end, thermobarometry and oxygen isotope studies (Bohlen et al., 1985; Valley et al., 1990) have provided important quantitative measures of metamorphic, igneous, and fluid processes. However, the ultimate key to unravelling Adirondack geologic history has been through the utilization of geochronology, as summarized below.

Although several Rb–Sr isochron studies were undertaken in the Adirondacks (e.g., Heath and Fairbairn, 1969), it was immediately evident that the high metamorphic temperatures of the area precluded the acquisition of unequivocal emplacement ages via this technique. Accordingly, Silver (1969) undertook a landmark investigation of U–Pb zircon ages in both the Highlands and Lowlands. These early results inevitably suffered from the fact that zircon dating was still in its infancy, but, nonetheless, they yielded data suggesting that some Adirondack charnockites were emplaced at ca. 1120 Ma and that metamorphic zircons formed in massif anorthosite at ca. 1050 Ma. These results, although limited in scope, remain in basic agreement with what is known today.

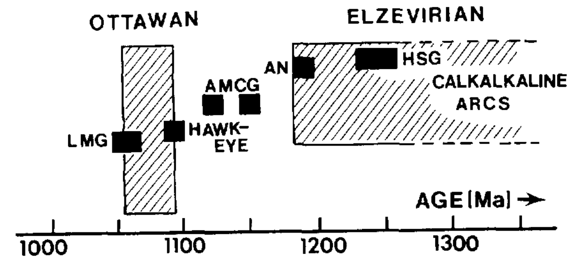


Fig. 3. Timing of principle igneous and metamorphic events in the Adirondack Mountains. *AMCG* = anorthosite–mangerite–charnockite–granite suite; *AN* = Antwerp granitoid and Rossie diorite; *HSG* = Hyde School Gneiss; *LMG* = Lyon Mt. Gneiss.

In 1985, McLelland and Chiarenzelli initiated a major program of U–Pb zircon dating in the Adirondacks. Over three dozen ages were determined (McLelland et al., 1988b; McLelland and Chiarenzelli, 1990a,b; Chiarenzelli and McLelland, 1991), and the results have provided the basis for unravelling the tectonic evolution of the region (Fig. 3). Although these data were obtained prior to the development of techniques for the analysis of single grains of zircons, they are internally consistent across the region and are believed to provide ages that correspond closely to the time of emplacement. Ongoing high-precision, single-zircon studies have corroborated this conclusion (McLelland and McLelland, 1995, 1996). The purpose of this paper is to summarize the results of these zircon studies and to provide a tectonic synthesis that satisfactorily accounts for both the geochronology and the field relationships of the region.

2. Chronology of major events within the Adirondack Mountains

The most significant intrusive and metamorphic events in Adirondack geologic history are summarized in Fig. 2, where Adirondack lithologies have been broken out on the basis of age. In the following discussion, we first present data regarding characteristics and emplacement ages of different suites of igneous rocks and follow this with a discussion of major metamorphic events. The high degree of correlation between the chemistry of rock suites and their age provides strong evidence that the zircon chronology has yielded correct results even in areas of granulite facies metamorphism (Chiarenzelli and McLelland, 1993). The order of the following discussion proceeds from the oldest (ca. 1350 Ma) to the youngest (ca. 1000 Ma) events, and relevant observations concerning events in the Proterozoic cores of the adjacent Appalachians are included under the several headings.

2.1. Summary of major igneous events in the Adirondack Mts.

2.1.1. ca. 1300 Ma calc-alkaline suite of the Adirondack Highlands

Within the Adirondacks, highly deformed, ca. 1300 Ma, rocks of calc-alkaline affinity (McLelland and Chiarenzelli, 1990b) have been recognized only within the southern and eastern Highlands (Fig. 2a). The most distinctive member of the suite is a pyroxene–hornblende tonalite which invariably contains disrupted, centimeter- to meter-scale amphibolitic layers that commonly exhibit mutually crosscutting relationships with the tonalite and are interpreted as coeval basaltic dikes. In addition to the tonalitic rocks, granodiorites and granites (now charnockites) are common in the suite and can represent as much as 50% of the lithic package. Although all of these rocks are highly metamorphosed, their anhydrous nature and quartzo-feldspathic composition have resulted in the preservation of original mineralogy and even original texture. Although chemical data from the tonalites do not discriminate between an island arc or continental margin setting, the presence of a substantial volume of granodiorites and granites, as well as the relative scarcity of mafic rocks, suggests that the arc foundation contained significant quantities of continental crust.

The age of the tonalitic suite ranges from 1330 Ma to 1307 Ma (McLelland and Chiarenzelli, 1990b), and therefore these rocks are somewhat younger than the 1350–1300 Ma ages reported by Ratcliffe et al. (1991) for similar tonalites in the Mt. Holly Complex of the adjacent Green Mts. of Vermont lying to the east of the Adirondacks. The chemistry of the Mt. Holly suite suggests that it evolved in an Andean-type collisional margin (Ratcliffe et al., 1991). Metasediments in the Mt. Holly Complex bear strong similarities to those in the eastern Adirondacks and suggest early continuity between the two regions. Within the Adirondacks some of these metasediments are crosscut by ca. 1300 Ma tonalites indicating an early depositional age. Within the New Jersey Highlands, the Lossee Fm. (Volkert, 1993) exhibits chemical characteristics similar to the tonalitic rocks of the Adirondacks and Green Mts. and, although undated, it is thought to belong to the ca. 1300 Ma suite.

Sm–Nd isotopic investigations (Daly and McLelland, 1991; Daly et al., 1992) reveals T_{DM} ages of ca. 1350–1450 Ma and $\epsilon_{Nd} = +3$ to $+5$ for tonalites of the Adirondacks and Green Mts. The T_{DM} ages are only slightly older than the emplacement ages of these rocks and demonstrate that they represent juvenile crustal additions to the Grenvillian Orogen. This stands in contrast to prior models (e.g., Wynne-Edwards, 1972; Dewey and Burke, 1973) which portrayed the orogen as comprising reworked Archean and early Proterozoic crust. The addition of substantial juvenile crust at ca. 1400–1300 Ma is consistent with the existence of a collisional arc at that time.

2.1.2. ca. 1240 Ma Charnockites of the Highlands

Pre-1150 Ma charnockitic rocks are known only from the southern Highlands (Fig. 2a) where the extensive Canada Lake charnockite yields an upper intercept age of 1243 ± 51 Ma and megacrystic charnockitic rocks of the Tomantown Pluton have a minimum Pb–Pb age of 1184 Ma (Chiarenzelli and McLelland, 1991). Within the Mt. Holly Complex of the Green Mts., Ratcliffe et al. (1991) have dated the College Hill granite at 1244±8 Ma. Compositionally, it is similar to both the Canada Lake charnockite and the Tomantown Pluton.

2.1.3. ca. 1230 Ma Hyde School Gneiss of the Adirondack Lowlands

Fourteen domical plutons (Fig. 2a) consisting of pink alaskite and grey tonalite (referred to as

Hyde School Gneiss—Buddington, 1939) together with lesser amounts of granodiorite occur scattered throughout the Adirondack Lowlands. The plutons are characterized by the presence of disrupted, dike-like sheets of amphibolite that generally account for 10–25% of areal exposure. Originally Buddington (1939) interpreted these plutons as intrusives (i.e., phacoliths), but subsequently they were reinterpreted as metamorphosed dacitic to rhyolitic ash-flow tuffs by Carl and Van Diver (1975). Recently, McLelland et al. (1992) have provided a range of petrologic and field evidence supporting an intrusive origin, and graphite–calcite geothermometry (Kitchen and Valley, 1995) indicates anomalously high temperatures near one pluton as would be expected from contact metamorphism.

The chemistry of Hyde School Gneiss is bimodal and exhibits calc-alkaline signatures (McLelland and Chiarenzelli, 1990b) suggesting a tectonic link to the older Highland tonalites summarized above. The ca. 1240 Ma granites of the Highlands or the Green Mts. may represent distant manifestations of the Hyde School magmatic event.

Sm–Nd investigations in the Adirondack Lowlands (McLelland et al., 1993) yield T_{DM} ages of ca. 1350 Ma ($\epsilon_{Nd} \approx +4$) which correspond to tonalitic Hyde School Gneiss representing juvenile crust. Daly and McLelland (1994) have demonstrated that most Lowland metasediments are characterized by T_{DM} of ca. 1500 ($\epsilon_{Nd} \approx 3$) and these rocks could also have participated in the generation of Hyde School Gneiss, particularly the alaskitic facies.

2.1.4. ca. 1185 Ma Antwerp granitoid and Rossie diorite of the Lowlands

Scattered occurrences of these small bodies are found within the Lowlands. The more abundant Antwerp granitoid consists dominantly of granodiorite and both it, and the Rossie diorite exhibit strong depletions in HREE (Carl et al., 1990), suggesting a deep, garnet-bearing source. The very regular outcrop trend of the Antwerp granitoid suggests fault-controlled emplacement. U–Pb zircon (McLelland et al., 1993) and Rb–Sr whole-rock isochron techniques (Carl et al., 1990) have yielded Antwerp granitoid ages of 1183 ± 7 Ma and 1197 ± 53 Ma, respectively. A Rb–Sr determination for Rossie diorite yielded an age of 1160 ± 42 Ma (Carl et al., 1990). To date, lithic equivalents of the Antwerp granitoid and Rossie diorite have not been recognized outside of the Adirondack Lowlands.

2.1.5. ca. 1150–1125 Ma, Anorthosite–charnockite–mangerite–granite (AMCG) suite

The voluminous AMCG suite of highly deformed and metamorphosed rocks underlies most of the Adirondack Mts. (Fig. 2b) and comprises a group that has long been of interest to petrologists. AMCG granitoids consist of mildly alkaline, iron-enriched types characteristic of the rapakivi suite, and anorthositic members consist of large plutons dominated by pyroxene and intermediate (AN_{45-50}) plagioclase typical of Proterozoic massif anorthosite (Emslie, 1978, 1985; McLelland, 1991; Ashwal, 1993). Within the Adirondacks, the largest body of anorthosite is the Marcy massif (70 × 50 × 7 km) which underlies the entirety of the northeastern region of high peaks. As observed by Silver (1969), and corroborated by McLelland and Chiarenzelli (1990a), the Marcy massif contains metamorphic zircons whose age of ca. 1050 Ma dates the time of peak granulite facies metamorphism. This conclusion is consistent with the equant, multi-faceted ('soccer ball') morphology of these zircon grains, as well as their low uranium content. Besides the metamorphic zircons, a small volume of baddelyite from the anorthosite gives a minimum age of 1087 Ma, and the air-abraded cores of zoned zircons yield a minimum age of 1113 Ma, both results pointing towards a still older emplacement age for the anorthosite (McLelland and Chiarenzelli, 1990a). In order to constrain this emplacement age, McLelland and Chiarenzelli (1990a) dated granitoids that both crosscut, and are crosscut by, anorthositic rocks of the Marcy massif. These yielded ages between 1134 ± 4 Ma and 1125 ± 10 Ma, respectively, and demonstrate that the anorthosite and granitoids are coeval at ca. 1130 Ma, and that they constitute a bimodal magmatic suite.

Although the anorthosites and granitoids of the AMCG suite are coeval, most workers agree that they are not comagmatic (e.g., Emslie, 1978, 1985; McLelland, 1991; Ashwal, 1993). The anorthositic rocks are best accounted for as gabbro-derived, variably contaminated (Valley et al., 1995) melts from the upper mantle, whereas the granitoids are thought to be derived from deep crustal sources. It is further argued that the entire suite arose as a consequence of ponding of gabbroic magma at the crust–mantle interface due to density contrasts (Barker et al., 1975; Emslie, 1978, 1985; McLelland, 1994). Gravity settling of olivine and aluminous pyroxenes from the ponded magmas drove residual melts to high-alumina compositions, and flotation of andesine and sodic labradorite resulted in the accumulation of a plagioclase-rich crystal mush of progressively decreasing density (Longhi and Ashwal, 1985). Magmatic heat and the heat of crystallization from these processes eventually raised the lower crust to solidus temperatures and granitoid melts were produced. Ultimately, the plagioclase-rich crystal mushes and the granitoid magmas ascended and, after interaction with surrounding crust, were emplaced as AMCG complexes which then underwent low-pressure differentiation discussed by McLelland et al. (1994). Note that the anhydrous nature of these complexes precludes their evolution in a water-enriched environment such as above a downgoing slab. In addition, they cannot evolve in zones of strong rifting, since this would lead to rapid tapping-off of gabbroic magma prior to the evolution of plagioclase crystal mushes. Finally, as shown by Fram and Longhi (1992) and Green (1969), the characteristically intermediate plagioclase of Proterozoic massif anorthosite is due to a pressure effect that depresses anorthite content by approximately one mol percent per kilobar increase of pressure in gabbroic magmas.

Recent U–Pb zircon investigations by Carl and Sinha (1992) have demonstrated that the widespread Hermon granite gneiss of the Lowlands was emplaced at 1149 ± 2 Ma and, therefore, is a member of the AMCG suite. In addition, McLelland et al. (1993) report ca. 1150 Ma syenites and granites with AMCG characteristics from the northern part of the Lowlands. Interestingly, rocks of AMCG age have not yet been recognized in the Green Mts. of Vermont, but granitoids of appropriate composition and age (e.g., ca. 1134 Ma Storm King granite (Grauch and Aleinikoff, 1985) are well represented in the Hudson Highlands of southeastern New York and their equivalents in New Jersey.

McLelland et al. (1994) have argued that olivine gabbros spatially associated with the anorthosite massifs should be included within the AMCG suite and represent tapped-off samples of parental gabbros otherwise ponded at depth. One xenolith-bearing example of these gabbros will be further discussed in another section and has been dated at 1144 ± 7 Ma. Another, which crosscuts the ca. 1130 Ma Marcy anorthosite, has yielded a baddelyite minimum age of 1109 Ma (McLelland and Chiarenzelli, 1990a). These ages are consistent with, and support, the proposal that the olivine gabbros are coeval with the massif anorthosite.

Sm–Nd results of Daly and McLelland (1991) show that AMCG granitoids may be derived from the ca. 1300 Ma tonalitic suite and its granitic components. In addition to this, Daly and McLelland (1994) show that the dominant T_{DM} age for Adirondack metasediments is ca. 1500 Ma ($\epsilon_{Nd} \approx +3$) which is permissive of these rocks serving a substantial parental role, a conclusion also indicated by the $\delta^{18}O$ investigations of Valley et al. (1995).

2.1.6. ca. 1100–1090 Ma The Hawkeye granitic suite of the Highlands

Within the diagonally ruled regions of Fig. 2b there occur several poorly defined tracts of pink, mildly A-type hornblende granite that yield U–Pb zircon ages of 1100–1190 Ma. These rocks are herein referred to as the Hawkeye granite suite after a typical occurrence in the northern Highlands (Postel, 1952). In part, the Hawkeye granite suite corresponds to Buddington and Leonard's (1962) hornblende granite which demonstrably crosscuts ca. 1130 Ma charnockites west of the Marcy anorthosite massif and which yields a U–Pb zircon age of 1098 ± 4 Ma (Chiarenzelli and McLelland, 1991). Elsewhere it is difficult to distinguish between Hawkeye and AMCG granitic rocks, and geochronology indicates that Buddington and Leonard's (1962) mapping did not always separate these types correctly. This is not surprising given the similar lithologies and intimate field association of the Hawkeye and AMCG suites.

It is critical to note that the Hawkeye granitic suite is strongly deformed and appears to have participated in most, if not all, of the intense orogenic events that deformed the AMCG suite into large ductile fold nappes (McLelland and Isachsen, 1986). Thus, as shown on the geologic map of Buddington and Leonard (1962), ca. 1100 Ma hornblende granitic gneiss is folded into the Stark isocline (Fig. 2b) along with ca. 1145 Ma rocks of the AMCG suite. Elsewhere, the Hawkeye suite exhibits planar and linear fabrics as penetrative and as intense as those exhibited by the AMCG suite. Buddington and Leonard (1962) suggest that Hawkeye suite rocks are locally less 'granulated' than AMCG counterparts and, hence, that a period of deformation intervened between the emplacement of each suite. However, the examples given are too qualitative and local to be convincing, and the probability remains that the AMCG and Hawkeye suites experienced the same degree of deformation and metamorphism. This is a crucial point, because it greatly constrains the onset of the Ottawan Orogeny to be described in the next section.

2.1.7. ca. 1080 Ma Mangerite of the northern Highlands

A single dated exposure of this unit has been recognized in the northernmost Highlands (PS, Fig. 2a). The importance of the rock rests in its well developed and steeply dipping foliation. A good penetrative fabric and lineation is also present in the unit and demonstrates that deformation continued after its emplacement. From available exposures it appears that the fabric is somewhat less intense than in older rocks such as the AMCG or Hawkeye suites. Garnets are also observed and are indicative of high metamorphic grade.

2.1.8. ca. 1070–1040 Ma Lyon Mt. Gneiss of the Highlands

Postel (1952) provided an extensive description of the alaskitic Lyon Mt. Gneiss from the type locality in the northeastern Highlands, and Whitney and Olmsted (1988) have discussed its geochemistry. As shown in Fig. 2a, Lyon Mt. Gneiss occurs throughout the Adirondack Highlands, and exposures are characterized by pink leucogranite with medium-grained, aplitic texture. Commonly, magnetite is the sole dark mineral, but green calcic pyroxene and hornblende occur locally. Although layering is ubiquitous, it is generally defined by compositional or modal differences, and it is common (but not invariable) for Lyon Mt. Gneiss to exhibit little, if any, internal penetrative fabric such as flattened or elongated quartz grains. Compositionally, Lyon Mt. Gneiss consists of several distinctive facies, the most voluminous of which is a quartz–microperthite gneiss that plots within the low-temperature trough of the normative system Ab–Or–Qu (Whitney and Olmsted, 1988). In addition, both high-soda (quartz–albite) and high-potash (quartz–microcline) variants exist and commonly accompany low-titanium iron oxide deposits of Kiruna-type that are associated with Lyon Mt. Gneiss (Foose and McLelland, 1995). The quartz–albite facies has drawn special attention because these rocks plot near to, or even along, the quartz–albite leg of the modal or normative system Ab–Or–Qu (Whitney and Olmsted, 1988) and, therefore, are not easily accounted for by common igneous processes. Based largely on this observation, Whitney and Olmsted (1988) proposed that Lyon Mt. Gneiss consists of ash-flow tuffs that, locally, were hydrothermally altered to analcite-bearing units that subsequently were metamorphosed into the present alaskitic facies including the enigmatic quartz–albite rock. This metavolcanic model has some attractive aspects and was proposed earlier by McLelland (1986) who also noted the widespread compositional layering in Lyon Mt. Gneiss. However, zircon ages obtained by McLelland et al. (1988b) and Chiarenzelli and McLelland (1991) preclude the metavolcanic hypothesis. This is because the zircons yield ages of ca. 1070–1040 Ma, and it can be shown that during that interval the entire Adirondack Highlands were undergoing high-grade metamorphism at approximately 25 km. Moreover, Lyon Mt. zircons exhibit elongate, doubly terminated habits and contain good examples of fine-scale, oscillatory zoning, both features being characteristic of igneous rather than metamorphic or hydrothermal origins. In addition, the widespread absence of penetrative fabric in Lyon Mt. Gneiss is wholly inconsistent with a pre-metamorphic origin, and good candidates for xenoliths exist at many localities. Accordingly, Chiarenzelli and McLelland (1991) and Foose and McLelland (1995) have concluded that Lyon Mt. Gneiss consists of alaskitic and related granitoids intruded into the Adirondack Highlands during late to post-tectonic magmatism accompanying the Ottawan Orogeny (see below). The layering present in the suite is interpreted to be the result of sheeted intrusions or as due to the effects of synorogenic magmatism.

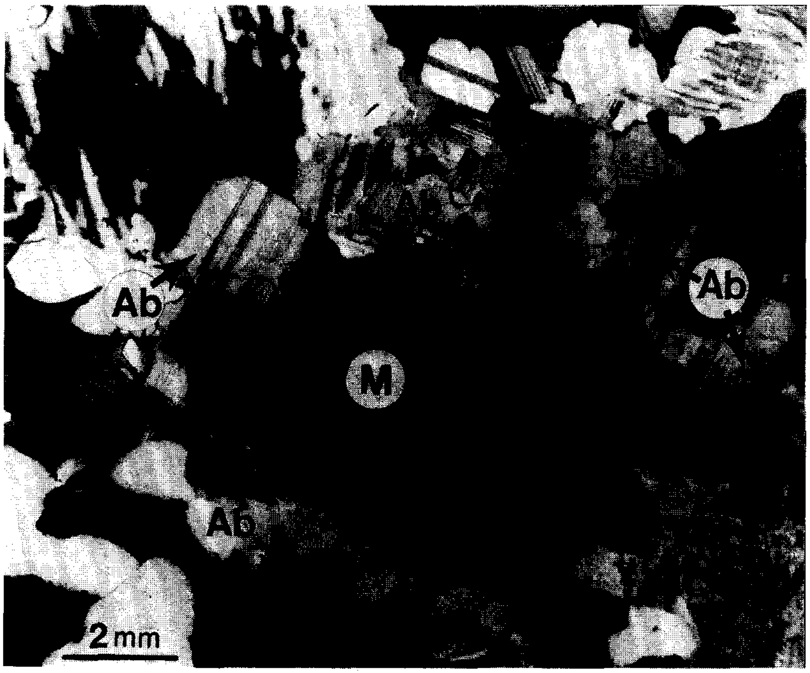


Fig. 4. Photomicrograph under crossed-polarized light showing albite (*Ab*) replacing a crosshatched grain of microcline (*M*). In the upper left and upper right corners smaller microcline cores (grey) are being replaced by albite (white).

It is noteworthy that Lyon Mt. Gneiss is almost everywhere accompanied by the intrusion of pegmatites and quartz veins. These reflect the presence of fluids in these rocks during the late stages of their crystallization. The same fluids are considered responsible for the deposition of the low-Ti iron oxide deposits most of which appear to be of hydrothermal origin (Foose and McLelland, 1995). In addition, hydrothermal fluids are considered to have been the agents for sodium and potassium metasomatism which are demonstrable in these rocks (Fig. 4) and which are characteristic of Kiruna-type iron-oxide deposits (Hitzman et al., 1992). It is possible that some of the albite in the quartz–albite units formed metasomatically from these fluids; however, the vast majority of these rocks exhibit coarse, igneous-looking textures, and they are best interpreted as facies of highly evolved, pegmatitic magmas in which such extreme mineralogies are commonly developed (London, 1990). Indeed, cross-cutting quartz–albite pegmatites are common in Lyon Mt. Gneiss and provide firm evidence for melts of this composition.

2.2. *Summary of major orogenic events in the Adirondack Mts.*

2.2.1. *Elzevirian Orogeny in the Adirondack Mts.*

Intense overprinting by the younger Ottawan Orogeny makes it difficult to identify fabric and mineral assemblages that are unequivocally Elzevirian in origin. Most of the evidence for this orogeny rests with the widespread occurrence of ca. 1300 Ma calc-alkaline rocks referred to above and with the presumed association of these lithologies with collisional margins and the accretion of offshore terranes. Locally, however, evidence for Elzevirian deformation and metamorphism exists both within the Elzevir Terrane (Lumbers et al., 1990) and the Adirondack Highlands. In the latter area, there appears to be preservation of both Elzevirian deformational fabric and mineral assemblages within a large xenolith of garnet–sillimanite–quartz–K-feldspar gneiss enclosed within a gabbro (McLelland et al., 1988a). As shown in Fig. 5, the gabbro transects a strong sillimanite-bearing foliation in the xenolith and even cuts across a large garnet. U–Pb zircon yields an age of 1144 ± 7 Ma for the gabbro (McLelland and

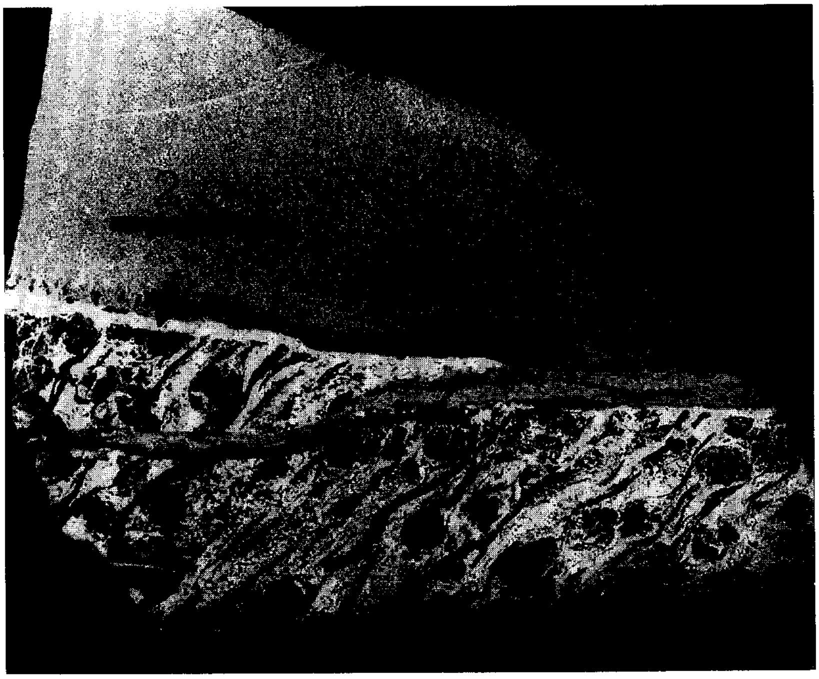


Fig. 5. Gabbro (grey) dated at 1144 ± 7 Ma (McLelland and Chiarenzelli, 1990a,b) crosscutting strong metamorphic fabric and mineralogy in garnet–sillimanite gneiss. Dark ribbons are rich in quartz and sillimanite. White areas consist of quartz and feldspar. Garnets are dark and rounded. Arrow points to a large garnet truncated at the contact. White layer at contact consists of anatectic granite. From McLelland et al. (1988a,b).

Chiarenzelli, 1990a), and the xenolith must predate this. Since there exists no evidence for metamorphic or igneous events older than 1350 Ma in the region, and since the only pre-1144 Ma orogeny is defined as the Elzevirian, it is reasonable to assign the metamorphism of the xenolith to this event. Strongly foliated garnet–sillimanite–quartz–K-feldspar gneiss, identical to that in the xenolith, is common throughout the eastern Adirondack Highlands where it is referred to as Hague Gneiss. It is probable that much of the high-grade assemblages and strong ductile fabrics in these rocks date from the Elzevirian Orogeny but are currently indistinguishable from equally high-grade and ductile Ottawan features unless fortuitously transected by a datable intrusion.

J. Aleinikoff (pers. commun., 1992) has air-abraded 1307±2 Ma zircons belonging to a Highland tonalite and captured the dust from the abraded metamorphic rims. The dust was then dated and yielded a minimum Pb–Pb age of 1226 Ma. Due to the limited nature of these data, this date must be treated with caution. Nonetheless, the age falls into an interval (ca. 1350–1220) corresponding to the emplacement ages of the calc-alkaline rocks associated with the collisional margins of the Elzevirian Orogeny and may date some of the metamorphism associated with that event. The ca. 1185 Ma magmatic ages of the Antwerp–Rossie suites represent the late magmatic events of the Elzevirian and coincide with the 1190–1180 Ma age given by McEachern and van Breemen (1993) for collision of the Central Metasedimentary Belt with the Central Gneiss Belt (Fig. 1). We take this age to mark the final accretion of Elzevirian arcs and hence the termination of the Elzevirian Orogeny.

2.2.2. ca. 1090–1030 Ma, The Ottawan Orogeny in the Adirondack Mts.

This extremely intense dynamothermal event has had profound effects in the Adirondack Highlands where granulite facies conditions ($P \approx$ 7–8 kbar, $T \approx$ 700–800°C) resulted in high-grade assemblages (Bohlen et al., 1985; Valley et al., 1990), and exceptionally large ductile fold nappes that are present throughout the entire region. Ottawan effects are somewhat less clear within the Lowlands and are discussed later in this section.

It is difficult to fix the precise time of onset for the Ottawan Orogeny in the Highlands. Given that AMCG rocks as young as ca. 1125 Ma are thoroughly affected by Ottawan deformation and metamorphism, it must post-date this suite. As remarked previously, similar structures and assemblages are also found within the ca. 1100–1090 Ma Hawkeye suite and, therefore, the peak of Ottawan effects must be younger than 1090 Ma. However, it is possible, though considered to be unlikely, that some of the earliest pulses of Ottawan contraction were initiated prior to 1100 Ma, and a pre-1090 Ma onset cannot be ruled out.

Clearly, Ottawan deformation and metamorphism were still ongoing at ca. 1080 Ma when pyroxene quartz syenite (see Sect. 2.1.7) rocks of the northern Highlands were deformed and metamorphosed. Peak metamorphic temperatures are reflected by the growth of metamorphic zircon in gabbro and anorthosite at ca. 1050 Ma (McLelland and Chiarenzelli, 1990a) and garnet in metapelite at ca. 1064 Ma (Mezger et al., 1991). Note, however, that Mezger et al. (1991) also report Highland garnet ages of 1154 ± 11, 1027 ± 4, and 1013 ± 4 Ma. It therefore appears that: (a) older garnets survived continued high temperatures of the Ottawan Orogeny; and (b) at least locally, these temperatures extended down to 1013 Ma. Monazite ages of 1033 ± 1 Ma (Mezger et al., 1991, 1993) and 1142 ± 2 Ma (Barrero, pers. commun., 1991) have been reported in the Highlands and, as with the garnets, indicate both survival of older ages and the continuation of temperatures of approximately 650–700°C (Parrish, 1990) to ca. 1030 Ma. Titanite ages within the Highlands fall in the range ca. 1030–990 Ma and indicate that temperatures of 500–600°C continued through this time interval. Based upon all of this evidence, we conclude that peak Ottawan temperatures of ~800°C were present throughout the Highlands at ca. 1050 Ma and were locally present down to ca. 1013 Ma. Accordingly, we fix the end of peak regional Ottawan metamorphism at ca. 1050–1040 Ma and regard this as the termination of the prograde, contractional phase of this major orogenic event.

The dates summarized above constrain the contractional phase of the Ottawan Orogeny to between ca. 1090 Ma and ca. 1040 Ma, the possibility of a slightly older starting date being reserved. Beginning as early as ca. 1070 Ma, and continuing until ca. 1045 Ma, granitic magmas of the Lyon Mt. Gneiss suite were emplaced within the Ottawan Orogen. At current levels of exposure, mineral assemblages within country rocks indicate metamorphic pressures corresponding to 20–25 km depth of burial. Since the present-day M-discontinuity lies some 40 km beneath the surface, it appears that the Ottawan crust attained thicknesses on the order of 60 km. It seems likely, therefore, that the Lyon Mt. suite of granitoids consists of deep crustal melts of the late- to post-tectonic variety (Turner et al., 1992). This is consistent with their mildly A-type chemistry and with the suggestion of bimodality indicated locally by their association with layers of amphibolite.

There is no clear-cut evidence for Ottawan metamorphism within the Adirondack Lowlands where sphene ages range between 1156 Ma and 1100 Ma while garnets and monazites yield ages of ca. 1160–1150 Ma (McLelland et al., 1988b; Mezger et al., 1991, 1992). These ages correspond to AMCG magmatism, and contact effects along the Diana quartz syenite contact demonstrate that this 1155 ± 4 Ma pluton was responsible for garnet, monazite, and sphene ages of 1168–1129 Ma in adjacent metapelites (Powers and Bohlen, 1985; Mezger et al., 1991, 1992). These results indicate that the Lowlands have not experienced titanite closure temperatures of ~500–650°C since AMCG magmatism at ca. 1150–1130 Ma. Notwithstanding these temperature constraints, the strong penetrative fabrics and isoclinal folding affecting the 1149 ± 26 Ma Hermon granite gneiss (Carl and Sinha, 1992; Buddington, 1939) suggest that rocks of the Lowlands experienced Ottawan deformation.

Zircon dating within the Green Mts. of Vermont has not yet yielded ages between the 960 Ma post-tectonic Stamford granite and the ca. 1244 Ma College Hill granite nor have any monazite or titanite age determinations been made. As a consequence, the nature and extent of the Ottawan Orogeny has not yet been quantitatively constrained in that region, although it appears to have been intense. However to the south, in the Hudson Highlands, the ca. 1134 Ma Storm King granite (Drake et al., 1991a) is representative of the AMCG suite, and the synto late-tectonic Canada Hill granite, dated at ca. 1040 Ma (Grauch and Aleinikoff, 1985), provide manifestations of Ottawan activity. Farther south in the Reading Prong of New Jersey Highlands, the Byram and Lake Hopatcong synkinematic to postkinematic suites are lithically similar to Lyon Mt. Gneiss (including their association with low-Ti magnetite deposits) and yield discordant U–Pb zircon ages of 1122 ± 53 Ma and 1088 ± 41 Ma (Drake et al., 1991a). The nearby, and unequivocally post-tectonic, Mt. Eve Granite has been precisely dated at 1019.8 ± 3.7 Ma (Drake et al., 1991b) and sets a lower limit for the Ottawan Orogeny in the New Jersey Highlands. Based upon this evidence, Drake et al. (1991a) have bracketed the Ottawan Orogeny within the Reading Prong at 1090–1020 Ma, in close agreement with the results presented in this paper.

3. Summary of characteristics of the Grenville Orogenic Cycle within the Central Metasedimentary Belt (CMB) of Ontario and the Central Granulite Terrane (CGT) of Quebec

Lumbers et al. (1990) report, that, within the Bancroft Terrane (Fig. 1), an early trondhjemitic to tonalitic suite of intrusive plutons (Dysart suite) yields U–Pb zircon ages of ca. 1350–1370 Ma similar to the ca. 1350 Ma age obtained by van Breemen and Hanmer (1986) for the Redstone tonalite within the thrust-faulted CMB boundary zone (CMBBZ, Fig. 1). Throughout the rest of the CMB, except for the Frontenac Terrane, these older, intrusive lithologies are followed by the ca. 1290 Ma granitoids of the Anstruther Complex (Burr and Carr, 1994) and the ca. 1290–1275 Ma Tudor metavolcanics principally of tholeiitic composition but containing rhyolitic and dacitic members (Silver and Lumbers, 1966; Davis and Bartlett, 1988). Possible pre-Tudor mafic and ultramafic rocks of the Queensborough Complex may represent an early ophiolitic suite (Chappell, 1978; Smith and Harris, 1996). Above the Tudor suite there occurs a thick sequence of calc-alkaline metavolcanics and associated metasediments intruded by diorites and tonalitic to trondhjemitic members of the 1280–1270 Ma Elzevir plutonic suite and by alaskites of the Metheun suite dated at 1250–1240 Ma (Heaman et al., 1986; van Breemen et al., 1986; Davis and Bartlett, 1988; van Breemen and Davidson, 1988; Lumbers et al., 1990). Also gabbroic rocks of the Lavant suite, which is best represented in the Sharbot Lake Terrane, have been dated at ca. 1240–1225 Ma (Lumbers et al., 1990; Corfu and Easton, 1995). Geochemical signatures of the igneous rocks suggest an island-arc environment (Brown et al., 1975; Condie and Moore, 1977) or a back-arc basin (Holm et al., 1985; Smith and Holm, 1987). It is possible that both environments existed during this interval. In any event, the calc-alkaline nature of the magmatism documents the existence of a collisional margin in large tracts of CMB from ca. 1350 Ma to ca. 1240 Ma. This scenario resembles the Adirondack region with the early tonalite–trondhjemite suite corresponding to the ca. 1350–1300 Ma tonalitic suite of the Highlands and Green Mts. and the late tonalite–trondhjemite and alaskite suites corresponding to ca. 1240 Ma charnockites as well as on the Hyde School Gneiss of the Lowlands. In addition, tonalitic rocks of ca. 1300 Ma age have recently been recognized in the St. Mauricie region (Fig. 6) east of the Morin anorthosite massif (Corrigan et al., 1994). Note, however, that no magmatism of this age has yet been reported within the Canadian sector of the Frontenac Terrane.

Hanmer and McEachern (1992) and Burr and Carr (1994) have utilized field relationships and U–Pb zircon dating to demonstrate that thrusting occurred along the CMBBZ at ca. 1185–1175 Ma and associated titanite ages of 1125 Ma and 1152 Ma confirm high-temperature events at that time. These ages correspond to ca. 1160 Ma ages for thrusting and synkinematic magmatism in the adjacent CGB (van Breemen et al., 1986) thus indicating regional contractional deformation at that time. Hanmer and McEachern (1992) conclude that by ca. 1185 Ma the CMB and CGB had already come into tectonic contact and the intervening volcanic marine basin had closed out. The ca. 1185 Ma Antwerp granitoid and Rossie diorite of the Adirondack Lowlands further suggest that the entire region had assembled into a single edifice by ca. 1180 Ma.

As noted by van Breemen and Hanmer (1986) and Hanmer and McEachern (1992) thrust faults in the CMBBZ were reactivated at ca. 1080–1050 Ma as indicated by U–Pb zircon ages on synkinematic granites as well as by dated monazites and titanites in shear zones. Metamorphic ages of

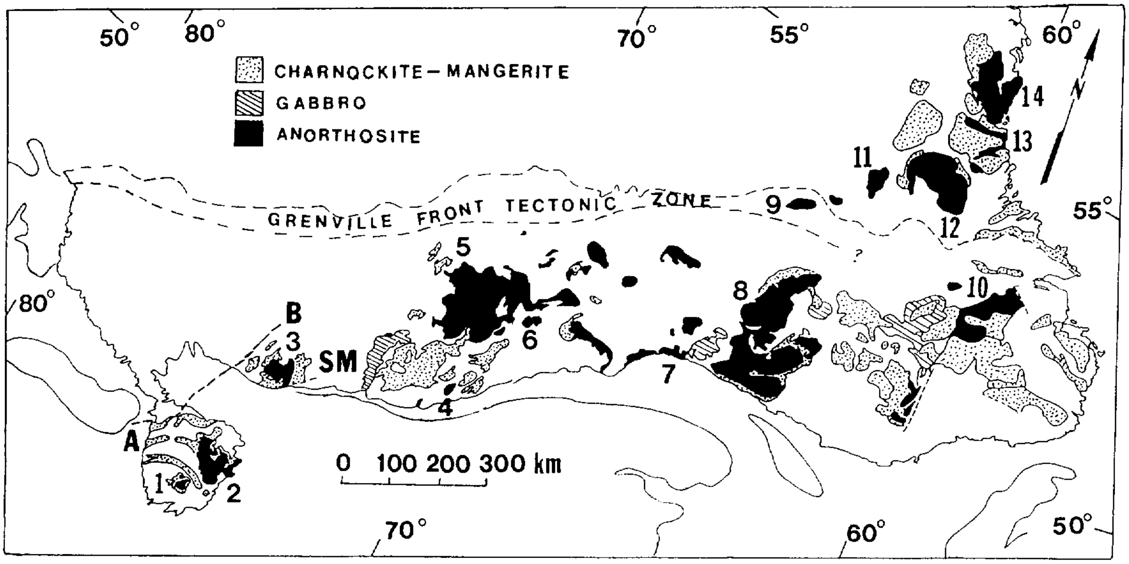


Fig. 6. Generalized map of anorthositic massifs within the Grenville Province and adjacent Labrador. The dashed line, *A–B*, separates terranes with anorthosite massifs on the east from ones lacking them on the west and corresponds to the Carthage–Colton–Labelle shear zone. *1* = Snowy Mt. and Oregon domes (ca. 1130 Ma); *2* = Marcy massif (ca. 1135 Ma); *3* = Morin anorthosite and Lac Croche Complex (1160 ± 7 Ma); *4* = St. Urbain anorthosite (ca. 1070 Ma); *5* = Lac St. Jean Complex (ca. 1150 Ma); *6* = Labrieville anorthosite (ca. 1015 Ma); *7, 8* = Havre St. Pierre Complex (1126 ± 7 Ma) including the Pentecote (1365 ± 7 Ma) anorthosite; *9* = Shabagamo intrusives; *10* = Mealy Mts. anorthosite (1646 ± 2 Ma); *11, 12* = Harp Lake anorthosite (ca. 1450 Ma); *13* = Flowers River Complex (ca. 1260 Ma); *14* = Nain Complex (ca. 1295 Ma) including Kiglapait intrusive (1305 ± 5 Ma). *SM* = St. Mauricie region. After McLelland (1989).

1080–1030 Ma in the CGB (van Breemen et al., 1986) demonstrate that Ottawan-related dynamothermal metamorphism extended well to the west of the CMB. However, scattered throughout the Frontenac and Elzevir (except for Mazinaw and Sharbot Lake) terranes are undeformed plutons of monzonitic to dioritic composition together with potassic granite (i.e., the Skootamata suite) dated by U–Pb zircon methods at 1090–1075 Ma (Corriveau et al., 1990; Lumbers et al., 1990; Marcantonio et al., 1990). The lack of deformation in these plutons, reflects either competency differences or indicates that Ottawan contraction was transmitted across the Grenville Orogen in such a manner that, several large tracts escaped internal deformation. Also Corrigan et al. (1994) describe undeformed granitoid plutons dated at ca. 1080 Ma in the St. Mauricie region (Fig. 6). In contrast to the undeformed nature of all of these granites, there is evidence of strong deformation and high-grade metamorphism affecting the Flinton Group in the Mazinaw Terrane (Fig. 1) at ca. 1030 Ma (Corfu and Easton, 1995) so that continued, localized closure of the Ottawan Orogen must have extended to times well after the emplacement of the ca. 1090–1075 Ma granitoids. Evidently some crustal blocks responded rigidly to Ottawan contraction whereas others yielded ductily. Within the Adirondack Highlands intrusive rocks within the time interval ca. 1080–1045 Ma show variable degrees of deformation with the younger examples (i.e., Lyon Mt. Gneiss) falling into the late- to post-tectonic category. Clearly, the timing of deformational and igneous events varied somewhat across the region, and the explanation of these differences awaits further investigation and synthesis.

By ca. 1045–1020 Ma compressional tectonics in the Ottawan Orogen gave way to extensional collapse, and shallow normal faults dropped crustal slabs down to the east along the CMBBZ (van der Pluijm and Carlson, 1989). In the St. Mauricie region, Corrigan et al. (1994) report low-angle, ductile normal faulting with down-to-the-east displacement beginning at ca. 1090 Ma and continuing to ca. 1050 Ma. Finally, titanite ages for the Sharbot Lake and

Frontenac terranes have been reported at 1175–1150 Ma while in the Elzevir and Mazinaw terranes they fall into the range 1060–1000 Ma (Mezger et al., 1993; van der Pluijm et al., 1994). These results support structural interpretations of late (ca. 1020 Ma) extensional displacement on the east-dipping Robertson Lake mylonite zone (Fig. 1) separating the Mazinaw and Sharbot Lake terranes (Davidson and Easton, 1994; Busch and van der Pluijm, 1996).

It is important to stress that igneous rocks older than ca. 1180 Ma have not been recognized in the Frontenac Terrane, thus reflecting a fundamental difference from other CMB terranes bordering it to the northeast and southeast. In addition, the uniformly high-granulite facies grade (ca. 1175–1150 Ma) in the Frontenac Terrane does not decrease westward towards lower grades (Reinhardt et al., 1973), but ends abruptly along the easterly dipping Maberly shear zone (Fig. 1) which forms the boundary between the Frontenac and Sharbot Lake terranes. This, plus the distinctive metasediments (mainly block tectonic marble and quartzite) of the Frontenac Terrane, strongly suggest that the Maberly shear zone represents an important tectonic boundary with an oblique thrust sense to the northwest (Davidson and Ketchum, 1993; Hildebrand and Easton, 1995). Within the Frontenac Terrane of Canada there is widespread occurrence of rocks compositionally similar to the AMCG granitoids of the Adirondacks that yield U–Pb zircon ages of 1180–1172 Ma (van Breemen and Davidson, 1988; Marcantonio et al., 1990). This suite includes the Rockport granite that is abundantly developed along the St. Lawrence River in Ontario and New York. Interestingly, this suite of rocks does not extend west of the Maberly shear zone or the Rideau fault and has not yet been recognized in the western CMB.

As indicated previously, the ca. 1080 Ma or ca. 1060 Ma plutonic suites in the Frontenac Terrane are relatively undeformed. This is consistent with titanite (Mezger et al., 1991, 1993) and hornblende $^{40}Ar/^{39}Ar$ ages (Cosca, 1989) that demonstrate that the Frontenac Terrane has remained below ~600°C since ca. 1175–1150 Ma and below ~400°C since ca. 1125–1108 Ma. These ages are similar to those obtained in the Adirondack Lowland sector of the Frontenac Terrane (Mezger et al., 1992, 1993) and demonstrate that the entire terrane did not experience the elevated Ottawan temperatures that characterize the Adirondack Highlands and contiguous CGT.

A crucial aspect of CMB geology is the presence of several rift-related sedimentary basins in the southwest Grenville Province. The largest to these is represented by the Flinton Group of the Elzevir Terrane (Moore and Thompson, 1980), and its maximum age of deposition is ca. 1150 Ma as constrained by detrital zircons of that age (Sager-Kinsman and Parrish, 1993). Since the Flinton Group was metamorphosed at ca. 1030 Ma, it must be older than this, and, in addition, the absence from it of ca. 1100–1090 Ma zircons from nearby plutons implies that it was deposited prior to this time (Corfu and Easton, 1995). Similarly, the St. Boniface Group in the St. Mauricie region of Quebec has recently been recognized by Corrigan et al. (1994) who have dated detrital zircons at 1180 Ma and crosscutting AMCG granitoids at ca. 1150 Ma. The presence of these basins demonstrates that extension was occurring across a broad tract of the southwestern Grenville Province during the interval ca. 1180–1100 Ma.

The last significant magmatic event in the CMB was the emplacement and fenitization, carbonatites and alkali granites which are bracketed between 1070 and 1040 Ma. These may be further manifestations of collapse of the Ottawan Orogen in that region at that time.

4. Plate tectonic synthesis

Within the Adirondacks there appear to be three major tectono-magmatic events that require plate-scale explanations, i.e., the Elzevirian and Ottawan Orogenies and emplacement of the AMCG suite. These are discussed separately below. In view of the preceding discussion, models and interpretations of these events have important implications for adjacent sections of the Grenville Province within Canada and the Appalachian Mts. Windley (1989) has presented a somewhat similar synthesis but necessarily without benefit of the more recent geochronology incorporated herein.

4.1. Elzevirian Orogeny

As demonstrated by AFM diagrams and other tectonic discrimination diagrams the ca. 1350–1300

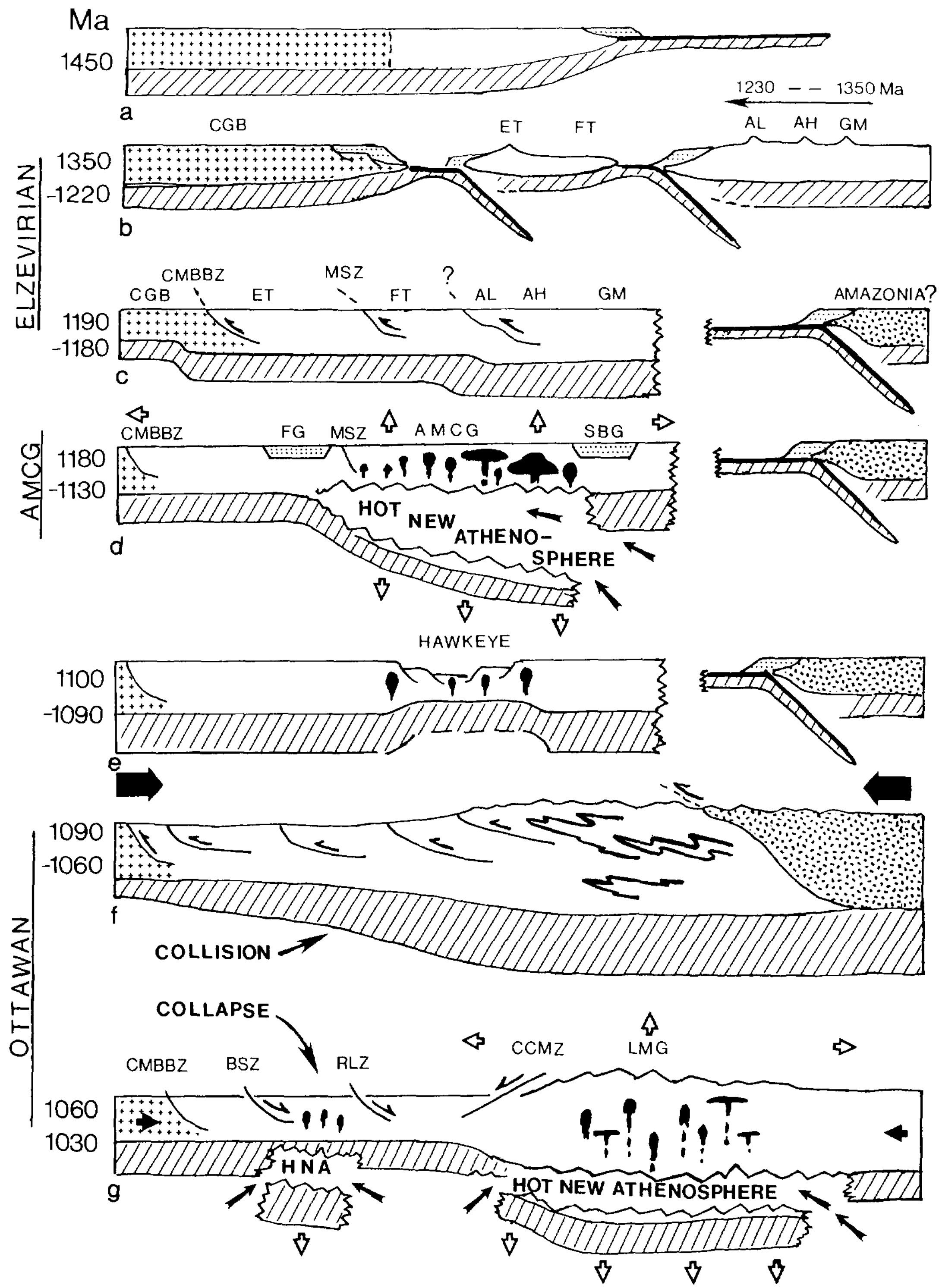
Ma tonalitic suites of the Adirondack Highlands and the Green Mts. correspond closely to normal calc-alkaline andesites of the western Americas, Aleutians, Japan, etc. (Brown, 1982; McLelland and Chiarenzelli, 1990b). While the chemical characteristics of the rocks indicate their evolution at a collisional margin, the analyses do not clearly discriminate between island-arc or Andean-type arc settings. The width of the Adirondack–Green Mt. arc is uncertain, but it must have spanned at least 400–500 km from the Adirondack Lowlands through the proto-Green Mts. (which would later be transported several tens of kilometers to the west by Paleozoic collisions). The physical continuity between the Highlands and Lowlands is consistent with Sm/Nd studies of these areas (McLelland et al., 1993) as well as by the lack of any apparent suture between them. A representation of this arc is shown in Fig. 7b which also indicates magmatism moving from east to west during the interval ca. 1350–1220 Ma as dictated by decreasing emplacement ages from the Green Mts. to the Adirondack Lowlands (Daly et al., 1992). The sweep of magmatism to the west may be accomplished either by physical growth of the plate margin, or by lessening depth of the subducting plate, or both.

The nature of the basement crust in the Adirondack–Green Mt. arc is problematic. To date, no igneous rocks predating ca. 1350 Ma have been recognized, and no unequivocally older basement is reflected in Sm–Nd data (Daly and McLelland, 1991; McLelland et al., 1993), although Marcantonio et al. (1990) report the possibility of older basement signatures in Sm–Nd results for the Frontenac Terrane. In addition, no significant tracts of mafic rock exist that might represent ancient seafloor or ensimatic arc material, although examples of such rocks have been described in the CMB (Smith and Harris, 1996) and the St. Mauricie region (Corrigan et al., 1994). However, tonalitic rocks dated at ca. 1300–1330 Ma in the Adirondack Highlands crosscut shelf-type metasediments including thick quartzites. Since these rocks must have been deposited on a substantial substrate, it is postulated that the Adirondack–Green Mt. block is underlain by unspecified amounts of sialic crust that predates ca. 1350 Ma tonalites. In order to minimize effects upon Sm–Nd data, it is necessary that this crust not be much older than 1350 Ma. A reasonable candidate for such crust is the ca. 1500–1450 Ma material within the CGB. As shown in Fig. 7a, newly formed 1500–1450 Ma continental crust of eastern Laurentia formed an integral unit just prior to the Elzevirian Orogeny. This basement and its sedimentary cover, were rifted into several blocks between 1450 Ma and 1350 Ma and postulated to have formed a significant fraction of basement material for the CMB–Frontenac block and the Adirondack–Green Mt. block. The presence of ca. 1450 Ma continental crust in the Adirondack–Green Mt. block is consistent with the large volume of high-silica granitoids emplaced into the region during the 1350–1220 Ma interval and with the observed increase of the granitic component with time.

To the west of the Adirondack–Green Mt. block lay the type Elzevirian arc (Fig. 7b) interpreted by Brown et al. (1975) as an ensimatic island arc but reinterpreted by Smith and Holm (1987) and Holm et al. (1985) as a back-arc or marginal basin. Although the issue remains unresolved, the island-arc model is consistent with possible sea floor slices reported by Brown et al. (1975) and Smith and Harris (1996) and is adopted here. As before, we postulate a ca. 1450 Ma sialic basement for at least part of the Elzevirian arc.

As shown in Fig. 7b the Frontenac Terrane is treated as the trailing, eastern edge of the Elzevirian arc. Since the Frontenac Terrane exhibits no evidence of ca. 1350–1220 Ma magmatic or tectonic activity, it is necessary to distance it as far as possible from Elzevirian activity. It is possible that the original distance between the terranes has been telescoped by subsequent orogeny. This would be consistent with thrusting along the Maberly shear zone which currently juxtaposes Frontenac Terrane granulite facies assemblages against lower-grade rocks to the northwest (Davidson and Easton, 1994; Corfu and Easton, 1995). Alternatively, the Frontenac Terrane may have been tectonically emplaced by strike-slip faulting at a later date (Mezger et al., 1993; Easton, 1994), but there exists no evidence to support this. Accordingly, the model shown in Fig. 7b is provisionally adopted with the understanding that the Frontenac–Elzevir crustal block has been significantly shortened by contractional orogeny.

The calc-alkaline Elzevirian arc system extended over global-scale distances. Thus ca. 1350–1250 Ma



Ma
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GM
AMAZONIA?
1190
-1180
c
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FG
MSZ
AMCG
SBG
AMCG
1180
-1130
HOT NEW ATHENO-SPHERE
d
HAWKEYE
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e
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f
COLLISION
OTTAWAN
COLLAPSE
CMBBZ
BSZ
RLZ
CCMZ
LMG
1060
1030
HNA
HOT NEW ATHENOSPHERE
g

calc-alkaline arc assemblages have been identified in the Llano uplift of Texas (Walker, 1992; Roback, 1994), in the Carrizo Mts. of west Texas (Soegaard, 1993; McLelland et al., 1995; M.E. Bickford, pers. commun., 1995), in Baltica (Gower et al., 1990), and in the Proterozoic of Ireland (Daly et al., 1994). Patchett and Ruiz (1989) have summarized Sm–Nd data from many of these areas and show that a large quantity of juvenile crust formed along the eastern and southeastern margin of Laurentia at ca. 1300 Ma further demonstrating that the Elzevirian Orogeny was a major event of plate tectonic scale.

In the Adirondack region, the Elzevirian Orogeny appears to terminate with the emplacement of the calc-alkaline Antwerp granitoid and Rossie diorite at ca. 1185 Ma (Fig. 7c). As indicated previously, this coincides with the time given by Hanmer and McEachern (1992) for the docking of the western CMB against the CGB which resulted in extremely high-strain and northwest-directed thrusting along the CMBBZ (Hanmer, 1988) and within the adjacent Bancroft Terrane.

4.2. AMCG magmatism

By ca. 1160 Ma the ocean basin between the Adirondack–Green Mt. and Elzevir Frontenac terranes appears to have closed. A related suture has not yet been recognized, although it is possible that such a feature once existed along the St. Lawrence River but has been obliterated by the 1172 Ma Rockport granite. Closure of the Elzevirian ocean basins must have resulted in widespread deformation and metamorphism, examples of which are clearly developed in the CMBBZ and the garnet–sillimanite xenolith (Fig. 5) described previously for the Adirondack Highlands. This regional contraction resulted in thickening of the continental crust and lithosphere throughout the orogen (Fig. 7c). Once the terranes were accreted, subduction zones were no longer present in the immediate area and, if operative, lay far to the east of the Green Mts. A consequent relaxation of contractional strain took place across the entire belt. This resulted in a situation ideally suited for delamination of upper mantle lithosphere and lower crust (Dewey, 1988; Sacks and Secor, 1990; Nelson, 1992; Kusky, 1993), and this began to take place on a regional scale (Fig. 7d). Delamination resulted in crustal rebound and extensional displacements as well as the influx of fresh, hot asthenosphere into the delaminated zone. Heating of the lower crust culminated in the production of felsic plutons the earliest of which were emplaced into the Frontenac Terrane as the monzonitic to syenitic Gananoque suite (Marcantonio et al., 1990) which is compositionally similar to AMCG granitoids of the Adirondacks. Following its onset at ca. 1180 Ma, the delamination-related magmatism swept southeast towards the Adirondacks and resulted in the granitic to monzonitic Rockport granite (ca. 1170 Ma) along the St. Lawrence River. This was followed in the Lowlands by the ca. 1150 Ma Hermon granite. Throughout the entire belt titanite ages fall within the interval 1175–1130 Ma and indicate that the thermal metamorphism is coeval with the ca. 1180–1150 Ma AMCG-type magmatism (Mezger et al., 1992). It is probable that these plutons added thermal energy to a crust already heated by the Elzevirian Orogeny and resulted in granulite facies assemblages that occur in the Canadian sector of the Frontenac Terrane (Corfu and Easton, 1995). The absence of substantial deformation from much of the Gananoque suite demonstrates that these plutons were emplaced under relatively quiescent conditions and that, in Canada, they remained relatively undeformed thereafter. A notable exception to this generalization exists along, and within, the Maberly shear zone where ca. 1170 Ma rocks are deformed by ductile shearing (Davidson and Easton, 1994). This localized deformation did not continue for long, since ca. 1150 Ma granites in proximity to the Maberly shear zone are undeformed.

Within the Lowlands the ca. 1150 Ma (Carl and Sinha, 1992) Hermon granite and coeval monzonitic

Fig. 7. Schematic NW–SE plate tectonic reconstruction for the Grenville Orogenic Cycle in the Adirondack Mountains and contiguous Grenville Province. Diagonal ruling = lithosphere; small dots = sediments; crosses = ~1450 Ma gneisses of the Central Gneiss Belt; unpatterned = crust of the Adirondack–Central Metasedimentary Belt region possibly including ~1450 Ma basement; random dashes = eastern colliding mass, possibly Amazonian; black = oceanic crust. *FG* = Flinton Group (Mazinaw Terrane); *SBG* = St. Boniface Group (St. Mauricie region). Other abbreviations as in Fig. 1. Note that neither horizontal nor vertical dimensions are to scale.

rocks reflect voluminous AMCG magmatism. In contrast to Highland AMCG-types, which are generally orthopyroxene bearing and relatively low in silica, the Lowland rocks are dominated by hornblende granite with SiO_2 contents on the order of 70%. It is possible that the higher water content of these granites reflects emplacement at shallower crustal levels than Highland equivalents. Their relationship to the Highland AMCG suite will be further discussed in a later section that considers the Ottawan Orogeny.

The AMCG suite of the Adirondack Highlands constitutes one of the classic examples of this globally important rock suite. The great volume of Adirondack AMCG magmas (Fig. 2b) reflects the input of substantial thermal energy into the lower crust and upper mantle. Delamination of an overthickened orogen (Fig. 7d) represents an attractive mechanism for providing the requisite energy in the form of hot, fresh asthenosphere which rises to the base of the newly exposed crust. Depressuration melting of the asthenosphere yields gabbroic magma which ponds and fractionates to yield plagioclase-rich crystal mushes and to cause deep crustal melting in the manner previously described (see also Turner et al., 1992; Kusky, 1993). As indicated in Fig. 7d, delamination is minimal in the southeastern Frontenac Terrane and increases in intensity into the Adirondack region where it terminates west of the Green Mts. This configuration is consistent with the observed distribution and volume of AMCG plutonism in the region. Delamination of both lower crust and lithosphere (Fig. 7d) is proposed in order to maximize crustal heating and to ensure ponding of tholeiitic magmas at pressures ($\leq$ 12 MPa) within the stability fields of olivine and plagioclase; this being a requirement for the generation of relatively silicic crystal mushes rich in intermediate plagioclase (McLelland, 1994).

AMCG magmatism represents a major event throughout the eastern Grenville Province. As shown in Fig. 6, recent U–Pb zircon dating has yielded ages for a number of Grenvillian anorthosite massifs and their related granitoids (Emslie and Hunt, 1990; Higgins and van Breemen, 1992; Martignole et al., 1993; Owens et al., 1994). Although these ages range from ca. 1650 Ma (Mealy Mts.) to 1018 Ma (Labrieville), the 1160–1130 Ma suite comprising the Lac St. Jean–Morin–Marcy massifs is particularly striking and emphasizes the great volumes of magma involved during this time interval (McLelland, 1989). Clearly a major, regional process must be associated with such an extensive magmatic terrane. Delamination subsequent to the terminal Elzevirian Orogeny (ca. 1150 Ma) is a process capable of providing crustal access to abundant mafic magma in a post-collisional tectonic setting and, therefore, to the generation of the AMCG suite. Many investigators (e.g., Emslie, 1978, 1985; Anderson, 1983; McLelland, 1991) have proposed that AMCG magmatism is of anorogenic derivation. These arguments were based on the absence of synchronous deformation, the anhydrous nature of the suite, and the need for a quiescent environment to ensure ponding and protracted fractionation. However, the delamination mechanism described here is capable of the same constraints and represents a more actualistic setting than does vaguely defined anorogenic magmatism. Furthermore, the geochronology presented above demonstrates that Grenvillian AMCG suites were emplaced into an orogen consisting of just-accreted magmatic arcs near a plate margin. Indeed, contractional motions, though diminished, continued within the orogen during AMCG emplacement, e.g., ca 1150–1120 Ma high-grade metamorphism and thrusting in the CGB (van Breemen et al., 1986; van Breemen and Hanmer, 1986) and ca. 1160 Ma ductile thrusting on the Maberly shear zone (Davidson and Easton, 1994). While the origin of these contractional strains remains uncertain they are not consistent with anorogenic magmatism as a regional mechanism. By the same token, the ca. 1015 Ma Labrieville anorthosite was clearly emplaced into the waning Ottawan Orogen during its waning stages (Owens et al., 1994) and cannot properly be considered as anorogenic but, instead, is quite consistent with the delamination mechanism proposed here.

4.3. Ottawan Orogeny

Within the Adirondacks there exists an absence of dated rocks spanning the interval ca. 1125–1100 Ma. The same dearth of information pervades much of the southwestern Grenville Province except for portions of the CGB where granulite facies nappe emplacement took place between 1130 and 1100 Ma and in the CMBBZ where renewed thrusting occurred at approximately the same time (van Breemen et al., 1986; Hanmer et al., 1994). In addition, Corrigan et al. (1994) cite the existence of northwest-directed thrusting in the St. Mauricie belt at ca. 1150–1090 Ma. These somewhat disparate results may reflect the diachronous onset of the Ottawan Orogeny along an irregular plate margin; however, the issue remains conjectural and in need of clarification.

The first clearly identifiable, post-AMCG magmatic event within the Adirondacks is the emplacement of the ca. 1100–1090 Ma mildly A-type Hawkeye suite in the northern Highlands. Currently no constraints exist on the tectonic framework into which these granites were emplaced. They could equally well be due to the onset of Ottawan compression or they could be related to extension as suggested by Mezger et al. (1992). What is especially noteworthy about the Hawkeye suite is that its emplacement age is almost exactly coeval with peak magmatism in the Midcontinent rift system (Paces and Miller, 1993; Cannon, 1994). Based upon this coincidence, it is here proposed that the Hawkeye suite resulted from lower crustal melting due to a mild, far-field echo in the Adirondacks of continental-scale extension in the Midcontinent (Fig. 7e). The absence of the Hawkeye suite outside of the Adirondack Highlands may reflect localized rifting due to greater weakening of this region by AMCG magmatism and related delamination. Presumably Hawkeye magmatism, and postulated extension, weakened the Highland terrane even further and must have raised its temperatures above those of the surrounding region. If so, these events prepared a hot, weak crust and lithosphere for the impending Ottawan Orogeny.

The Adirondack Highlands contain one of the world's classic granulite facies terranes which, together with associated intense deformation, can be directly attributed to the Ottawan Orogeny (Fig. 7f). The fact that Hawkeye suite rocks are thoroughly affected by this event constrains peak Ottawan activity to ages younger than ca. 1090 Ma. Strong deformation of ca. 1080 Ma pyroxene quartz syenite further constrains the onset of orogeny. Note that northwest-directed thrusting is observed to close out the Midcontinent rift system at ca. 1080–1060 Ma and this is thought to represent a far field effect of the Ottawan Orogeny (Cannon, 1994). As previously discussed, ca. 1045 Ma fayalite granites post-date the orogenic peak and establish its minimum age, at least locally. During the ca. 1090–1045 Ma orogenic interval the Highlands attained a double crustal thickness which must also have been accompanied by thickening of the lithosphere. Doubling of crustal thickness is best accounted for by: (1) magmatic underplating at an Andean-type margin; or (2) the collision of large-scale continental blocks, as in the Himalayas. Since the Adirondacks, and contiguous Grenville Province, contain few, if any, examples of Ottawan age Andean-type magmatism, it seems likely that the causative collision was of the Himalayan variety (Fig. 7f). For the same reason, the subduction zone is placed beneath the continental block outboard of Laurentia, and is given a southeasterly polarity. To date, no candidate for a suture (or exotic eastern continent) have been located, and it is assumed that the entirety of the Grenville Province consists of material accreted to Laurentia by, at least 1090 Ma. The outboard collider has not yet been identified, but the Amazonian Shield appears to be a good candidate (Hoffman, 1988, 1989, 1991). The foregoing sequence of rift-related heating followed by loading due to collision leads to a counter-clockwise *P–T–t* path. Detailed thermobarometry has led Bohlen (1987) and Spear and Markusen (1995) to propose this type of path, including a period of near-isobaric cooling. Based upon investigations of fluid inclusions, Lamb et al. (1991) concluded that a counter-clockwise path was consistent with the data and likely to have taken place. We concur and further suggest that isobaric cooling was followed by rapid depressurization as described below.

Beginning at ca. 1070 Ma, and continuing to at least 1045 Ma, the Highlands were invaded by large volumes of Lyon Mt. granite including fayalite granite referred to above. As discussed previously, and as pointed out by Foose and McLelland (1995), Lyon Mt. Gneiss is best accounted for as a late- to post-tectonic suite of high-silica, A-type plutons (Whitney and Olmsted, 1988). Rocks very similar to these have been attributed by Turner et al. (1992) and Kusky (1993) to crustal melting within a rapidly rebounding, overthickened orogen that has just undergone delamination. This model is well suited for the

Ottawan Orogen in the Adirondacks where crustal thicknesses on the order of 60 km had developed by ca. 1070–1040 Ma and must have been accompanied by overthickened lithosphere (Fig. 7f). Delamination of the dense lithospheric keel, plus or minus, some of the crust (Fig. 7g), would result in: (1) the influx of hot, new asthenosphere to heat the lower crust (England and Houseman, 1989; Houseman et al., 1981); and (2) the sudden dominance of buoyancy forces which would cause rapid crustal uplift and depressurization melting (Kay and Kay, 1993). As a consequence, plutons of crustally derived, A-type granites would ascend and be emplaced as Lyon Mt. Gneiss. Because contractional forces still existed within the orogen, Lyon Mt. Gneiss would range from synkinematic to postkinematic in its relationship with the country rocks. Eventual interaction with either meteoric or magmatic water led to the development of pegmatites, quartz veins, hydrothermal iron oxide deposits, and alkali metasomatism within Lyon Mt. Gneiss plutons (Foose and McLelland, 1995).

The rapid, late Ottawan uplift proposed here is consistent with conclusions by Florence and Spear (1995) based upon garnet zoning. Among the important consequences of this uplift is the inevitable extensional collapse that would be experienced by the core of the orogen (Dewey, 1988; Nelson, 1992). As in the case of the present-day orogens, such as the Himalayas, uplift and collapse would be accompanied by low-angle, extensional faults that would rapidly exhume deep, high-grade rocks and juxtapose them against lower grade hanging wall units. It is proposed that this juxtaposition took place along the Carthage–Colton mylonite zone which is interpreted to be a late extensional, collapse fault within the Ottawan Orogen (Foose and McLelland, 1995; Geraghty et al., 1981; Isachsen and Geraghty, 1986). Along this northwest-dipping zone, amphibolite facies rocks of the Lowlands are displaced down to the northwest so that they are juxtaposed against the granulite facies Highlands to the southeast (Fig. 7g). Although insufficient data currently exist to accurately constrain the offset along this zone, the monazite and titanite dating of Mezger et al. (1992) are consistent with the model. Within the Lowlands these ages are in the range ca. 1150–1130 Ma while immediately across the Carthage–Colton zone to the Highland ages do not exceed ca. 1030 Ma. The implication is that, prior to ca. 1045 Ma, a significant portion of the Lowlands sat on top of the Highlands and, although they were involved in Ottawan deformation, they did not experience Ottawan temperatures in excess of 500–600°C. Therefore the Lowland block preserved 1150–1130 Ma titanite and monazite ages related to AMCG emplacement. Within this structurally higher block, AMCG magmatism was dominated by Hermon granite rather than the hotter, drier mangerites and charnockites that were being emplaced into the deeper Highlands crust. Implicit in this model is the possibility that the Hyde School Gneiss of the Lowlands is a shallower equivalent of ca. 1240 Ma granites within the Highlands. While this possibility is recognized, the configuration of Fig. 7b is retained because it is improbable that the entirety of the present-day Lowlands has been displaced from above the present-day Highlands. Titanite ages of 1098 Ma within the CCMZ (Mezger et al., 1992) are believed to be related to emplacement of the Hawkeye granitic suite in the region. Finally, we note that it has often been observed that the Labelle shear zone (Figs. 1 and 6) of Quebec represents a northern extension of the Carthage–Colton mylonite zone (cf. Baer, 1976; McLelland and Isachsen, 1986; Rivers, 1995). This suggests that the combined high-strain zones represent a large zone of extensional collapse that exhumes granulite facies rocks of the Central Granulite Terrane from deep within the Ottawan Orogen. In addition, Corrigan et al. (1994) have recognized a similar, but eastward-facing, extensional detachment in the St. Mauricie region east of the Morin Complex (Fig. 6).

Apparently at odds with the foregoing model of rapid extensional collapse is the conclusion by Mezger et al. (1992) that, beginning at ca. 1050 Ma ($\sim$750°C), the Adirondack Highlands underwent a slow, time-integrated cooling of $\sim$1.5°C/m.y. for about 150 m.y. In contrast, the exhumation model would require initial cooling rates of an order of magnitude higher. A possible resolution to this apparent discrepancy lies in the small number of data points, and the spread in results, reported by Mezger et al. (1991) (p. 424), who take care to point out that their data may not be extensive enough to detect rapid pulses of uplift. For example, only four garnet ages are reported from the Highlands (e.g., 1154, 1064, 1026, and 1013 Ma) and the last three of these provide a 50-m.y. window for the onset of cooling from regional metamorphic temperatures of 750°C. Two titanite ages and one monazite age cluster around 1030 Ma and a third titanite yields 991 Ma. Mezger et al. (1991) choose to pass curves through these data by assigning the 1064 Ma age to their starting temperature of 750°C. However, the growth of this 1064 Ma garnet does not necessarily coincide with the onset of uplift and cooling. If an initial age of ca. 1050 Ma is chosen instead (based on metamorphic zircon ages and Lyon Mt. Gneiss), then the initial rate of cooling jumps to 7.5°C/m.y. When additional uncertainties in ages and closure temperatures are taken into account, it becomes possible to generate cooling rates as high as 10–15°/m.y. For a temperature gradient of 30°C/km, this corresponds to uplift rates of ~2 mm/yr, similar to those currently observed in the Himalayas (Zeitler, 1985; Hubbard et al., 1991), and which could result in 20 km of uplift in 10 m.y. Kinetic modelling studies of garnet zoning (Florence and Spear, 1995) suggest late, rapid uplift in the southern Adirondacks and are consistent with the model proposed here.

Within the Grenville Province of Ontario and Quebec, the Ottawan Orogeny appears to be less intense and more localized than in the Adirondacks (Easton, 1994; Corfu and Easton, 1995; Hanmer et al., 1994). In addition, some important differences in timing exist such as locally older (ca. 1120–1090 Ma) ages for the orogeny (cf. Corrigan et al., 1994; Hanmer et al., 1994). Importantly, there are large tracts of the CMB and CGB where no regional or granulite-grade metamorphic signatures have been recognized and where post-1160 Ma plutons (Frontenac Terrane) and ca. 1090–1065 Ma plutons (Skootamatta suite) are undeformed and titanite ages are in the range 1172–1108 Ma (van der Pluijm et al., 1994). These observations reflect the restriction of the high-grade, ductile facies of the Ottawan Orogeny to the Adirondacks, parts of the Mazinaw Terrane (Corfu and Easton, 1995), and possibly also the Morin Terrane of the CGT. On the other hand, the occurrence of 1090–1065 Ma Skootamatta suite plutons within portions of the CMB demonstrates that Ottawan-age plutonism extended to the west of the Adirondacks. As suggested in Fig. 7g, Skootamatta-related magmatism is interpreted here as the result of localized delamination beneath the CMB, although Corriveau et al. (1990) have interpreted the suite to have been emplaced above a subduction zone. Moreover, there exists evidence of local high-grade metamorphism of late Ottawan age, i.e., ca. 1035 Ma metamorphism of Flinton sediments in the central Mazinaw Terrane (Corfu and Easton, 1995) and ca. 1060 Ma metamorphism and granitic intrusion associated with renewed thrusting in the CMBBZ (McEachern and van Breemen, 1993; Burr and Carr, 1994). This Ottawan orogenic activity certainly caused crustal thickening by stacking of thrust sheets and resulted in elevated P, T conditions as reflected by ca. 1060–1000 Ma titanite and monazite ages in the Bancroft and Elzevir terranes and as proposed by Corfu and Easton (1995) in the Mazinaw Terrane. However, the low greenschist facies grade of the Hastings metamorphic low in the Elzevir Terrane attests to widespread P, T conditions that were well below those of the Adirondack Highlands. These differences can be attributed to two factors that may be related: (1) to the west of the Adirondack Highlands the Ottawan Orogeny was characterized by relatively brittle deformation localized along discrete shear zones and thrust sheets; and (2) the demonstrated ca. 1030–1020 Ma extensional collapse of the CMB along southeasterly dipping normal faults such as the Bancroft and Robertson Lake shear zones (Fig. 7g) (van der Pluijm and Carlson, 1989; Carlson et al., 1990; van der Pluijm et al., 1994). As a consequence of extensional collapse much of the western CMB comprises upper crustal material that was never exposed to more elevated P, T conditions that are recorded in the higher-grade, tectonically exhumed CGB to the west. This situation is similar to that already described for the Adirondack Lowlands and Highlands. Given their lower temperatures, the downdropped terranes would be expected to be characterized by somewhat less ductile deformation patterns, as is the case. Notwithstanding this, the absence of high-grade Ottawan metamorphism in the Frontenac Terrane, the discrete thrust-style tectonics along the CMBBZ, and the localized ca. 1035 Ma metamorphism of the Flinton Group all suggest that, during the Ottawan Orogeny regionally high-grade, ductile deformation did not extend westward much beyond the Adirondack Highlands. In contrast, the regionally developed anatectic Canada Hill granite (ca. 1040 Ma (Grauch and Aleinikoff,

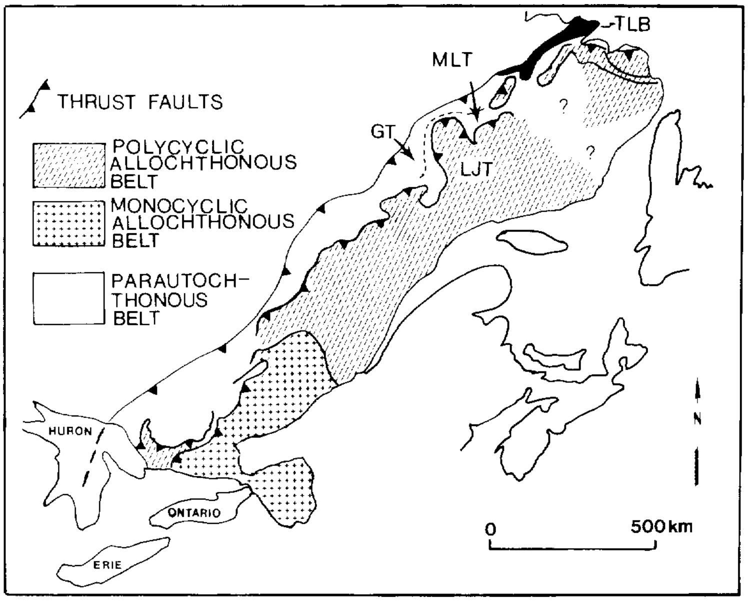

Fig. 8. Tectonic subdivisions of the Grenville Province according to Rivers et al. (1989). *GT* = Gagnon Terrane; *LJT* = Lac Joseph Terrane; *MLT* = Molson Lake Terrane; *TLB* = Trans-Labrador batholith.

1985)) in the Hudson Highlands, demonstrates that ductile, high-grade Ottawan effects existed southeast of the Adirondacks. A likely explanation of this configuration is that the mobile core of the Grenville Orogen lies to the southeast of the Province and the Adirondack Highlands represent its northwestern edge.

The unmetamorphosed and undeformed status of ca. 1045 Ma fayalite granite in the Adirondack Highlands signals an end to regional high-grade metamorphism and contractional strain by that time. However, the 1026–1013 Ma garnet ages of Mezger et al. (1992) indicate that localized high-temperature events may have continued to take place and ca. 1035 Ma dynamothermal in the Flinton Group (Corfu and Easton, 1995) suggest that contractional forces were still capable of causing localized, discrete tectonism. To the northeast, in Quebec, quiescent emplacement of the Labrieville and St. Urbain anorthosites (Owens et al., 1994) and the St. Ambroise A-type granitoids at ca. 1020 Ma are interpreted as late delamination-related events in the waning stages of the Ottawan Orogeny. However, the final contractional pulses of the Ottawan Orogeny did not occur until ca. 1000–980 Ma when the ca. 1630 Ma Lac Joseph terrane (Fig. 8) was emplaced over the Molson Lake terrane during which the latter underwent metamorphism up to eclogite facies grade (Connelly and Heaman, 1993). As shown in Fig. 8, the Lac St. Joseph–Molson Lake–Gagnon Terrane complex is typical of the allochthonous–parautochthonous terrane subdivision applied to the Grenville Province by Rivers et al. (1989). Although it is likely that some of the terrane boundary faults in Fig. 8 are reactivated older structures, it is certain that they accommodated substantial thrust displacement at ca. 1000–980 Ma. Similarly, renewed NW-directed shearing and faulting have been documented along the Grenville Front Tectonic Zone at ca. 1000–980 Ma (Krogh, 1989; Childe et al., 1992; Haggart et al., 1993) and Bethune and Dudas (1990) have shown that Sudbury dikes within the zone developed garnet and orthopyroxene assemblages at ca. 1032–985 Ma. These observations suggest that as the Ottawan Orogeny closed out, convergence was accommodated along localized, discrete, and perhaps rejuvenated shear zones that became progressively younger toward the northwest. This progression of thrusting towards the foreland is consistent with thrusting in modern orogens such as the Himalaya. To the southeast in the Green Mts. of Vermont (Ratcliffe et al., 1991) and in the Pinware Terrane (Fig. 8) of eastern Labrador

(Gower et al., 1991) granitoid magmatism continued to 960 Ma and records the final thermal events in the now fully assembled Ottawan Orogen. On an even grander scale, penecontemporaneous orogenies are found within the Proterozoic of west Texas where the Hazel Orogeny has been dated at ca. 1100 Ma (Soegaard, 1993) and the late Sveconorwegian Orogeny of the Baltic region now dated at 1090–980 Ma (Hansen et al., 1989; Daly et al., 1983). Like the Elzevirian Orogeny, the Ottawan took place on a global scale and probably culminated in the formation of the late Proterozoic supercontinent of Rodinia (Hoffman, 1991; Moores, 1991; Dalziel, 1991).

5. Summary

The Grenville Orogenic Cycle is fully developed within the Adirondacks with both Elzevirian and Ottawan elements well represented. In addition, voluminous AMCG magmas were emplaced at ca. 1150–1130 Ma corresponding to similar unites in the Grenville Province to the northeast.

The ca. 1350–1180 Ma Elzevirian Orogeny appears to have been arc-related with final closure taking place at ca. 1185 Ma throughout the southwestern Grenville Province. Shortly after closure, AMCG magmatism began in the Frontenac Terrane and then moved southeastward into the Adirondack Highlands. This magmatism is attributed to delamination of overthickened Elzevirian crust and lithosphere. The presence of local contractional strain during this interval suggests that AMCG magmatism was taking place in a collapsing, delaminating orogen that was undergoing relative extension. This is further indicated by the development of sedimentary basins such as those hosting Flinton and St. Boniface groups. This magmatism continued southward into the Hudson and New Jersey Highlands.

From ca. 1100–1090 Ma the northern Adirondack Highlands experienced intrusion by mildly A-type hornblende granites attributed to localized crustal thinning contemporaneous with rifting in the midcontinent. This was followed immediately by continental-scale collision responsible for deformation and metamorphism of all rocks older than 1080 Ma. Late- to post-tectonic Lyon Mt. Gneiss was intruded at ca. 1070–1045 Ma and is attributed to crustal melting during delamination, orogen collapse, and rapid rebound. Undeformed fayalite granites dated at ca. 1045 Ma appear to mark the end of a regional contraction, although localized compression and metamorphism continued until ca. 1035 Ma, both in the Adirondacks and in the Flinton Group farther west. As the Ottawan Orogen collapsed, large extensional faults developed and dropped lower-grade packages of crust, such as the Adirondack Lowlands, down into juxtaposition against high-grade rocks. The Carthage–Colton–Labelle shear zone represents a major example of this class of faults and exhumes granulite facies rocks in the core of the orogen, most of which may extend southeast of the Adirondack region.

By 1000 Ma the Ottawan Orogeny was largely played out but continued convergence from the southeast resulted in significant northwest-directed fault movement that activated the large allochthons of the eastern Grenville Province and ultimately caused late (ca. 980 Ma) movements along the Grenville Front Tectonic Zone.

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