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Tectonic Evolution of the Adirondack Mountains and Grenville Orogen Inliers within the USA

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SUMMARY
Recent investigations in geochronology and tectonics provide important new insights into the evolution of the Grenville Orogen in North America. Here, we summarize results of this research in the USA and focus upon ca. 1.4–0.98 Ga occurrences extending from the Adirondack Mountains to the southern Appalachians and Texas. Recent geochronology (mainly by U/Pb SHRIMP) establishes that these widely separated regions experienced similar tectonomagmatic events, i.e., the Elzevirian (ca. 1.25–1.22 Ga), Shawinigan (ca. 1.2–1.14 Ga), and Grenvillian (ca. 1.09–0.98 Ga) orogenies and associated plate interactions. Notwithstanding these commonalities, Nd model ages and Pb isotopic mapping has revealed important differences that are best explained by the existence of contrasting compositions of deep crustal reservoirs beneath the Adirondacks and the southern Appalachians. The isotopic compositions for the Adirondacks lie on the same Pb–Pb array as those for the Grenville Province, the Granite-Rhyolite Province and the Grenvillian inliers of Texas suggesting that they all developed on Laurentian crust. On the other hand, data from the southern Appalachians are similar to those of the Sunsas Terrane in Brazil and suggest that Amazonian crust with these Pb–Pb characteristics was thrust onto eastern Laurentia during its Grenvillian collision with Amazonia and subsequently transferred to the latter during the late Neoproterozoic breakup of the supercontinent, Rodinia, and the formation of the Iapetus Ocean. The ca. 1.3–1.0 Ga Grenville Orogen is also exposed in the Llano Uplift of Texas and in small inliers in west Texas and northeast Mexico. The Llano Uplift contains evidence for a major collision with a southern continent at ca. 1.15–1.12 Ga (Kalahari Craton?), magmatic arcs, and back-arc and foreland basins, all of which are reviewed.

The Grenvillian Orogeny is considered to be the culminating tectonic event that terminated approximately 500 m.y. of continental margin growth along southeastern Laurentia by accretion, continental margin arc magmatism, and metamorphism. Accordingly, we briefly review the tectonic and magmatic histories of these Paleoproterozoic and Mesoproterozoic pre-Grenvillian orogens, i.e., Penokean, Yavapai, and Mazatzal as well as the Granite-Rhyolite Province and discuss their ~5000 km transcontinental span.

SOMMAIRE
Des recherches récentes en géochronologie et en tectonique révèlent d'importants faits nouveaux sur l'évolution de l'orogénie de Grenville en Amérique du Nord. Nous présentons ici un sommaire des résultats de cet effort de recherche aux USA en mettant l'accent sur les indices datés entre env. 1,4 et 0,98 Ga, à partir des monts Adirondack jusqu'au sud des Appalaches et au Texas. Des données géochronologiques récentes (par microsonde SHRIMP principalement) indiquent que les roches de ces régions très éloignées les unes des autres ont subies l'effet d'épisodes tectonomagmatiques similaires, par exemple, aux orogenèses de l'Elzévirien (env. 1.25–1.22 Ga), de Shawinigan (env. 1.2–1.14 Ga), et du Grenvillien (env. 1.09–0.98 Ga), ainsi que des interactions des plaques associées. Malgré ces points communs, la chronologie Nd et la cartographie isotopique Pb a révélé des différences importantes qui s'expliquent plus aisément par des compositions contrastées des réservoirs profonds de croûte sous les Adirondacks et le sud des Appalaches. Les compositions isotopiques des Adirondacks sont de la même gamme Pb-Pb que

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ceux de la Province de Grenville, de la Province Granite-rhyolite et des boutonnières grenvilliennes du Texas, suggérant qu'ils se sont tous développées sur la croûte des Laurentides. Par ailleurs, les données des Appalaches du sud sont semblables à celles du terrane de Sunsas au Brésil, ce qui incite à penser que la croûte amazonienne, avec de telles caractéristiques Pb-Pb, a été poussée sur la portion est de Laurentia lors de sa collision grenvillienne avec l'Amazonie puis laissée à cette dernière au cours de la rupture du supercontinent Rodinia vers la fin du Néoprotérozoïque, avec la formation de l'océan Iapetus. L'orogène de Grenville (1,3 à 1,0 Ga env.) est également exposé dans le soulèvement de Llano au Texas et dans de petites boutonnières dans l'ouest du Texas et le nord du Mexique. Le soulèvement de Llano montre des indices d'une collision majeure avec un continent au sud, entre env. 1,15 et 1,12 Ga (craton de Kalahari?), des zones d'arcs magmatiques, d'arrière-arc et de bassin d'avant-pays, chacun étant présenté ci-dessous.

L'orogenèse de Grenville est considéré comme l'événement tectonique culminant qui marqué la fin d'une période d'environ 500 ma d'accroissement de la marge continentale le long de la bordure sud-est de la Laurentie, par accrétion, magmatisme d'arc de marge continentale, et métamorphisme. C'est pourquoi, nous passons brièvement en revue l'histoire tectonique et magmatique de ces orogènes pré-grenvilliennes paléoprotérozoïques et mésoprotérozoïques, pénokéenne, de Yavapai, et de Mazatzal ainsi que la Province de Granite-rhyolite, et discutons de son étendue sur env. 5 000 km.

INTRODUCTION

The Adirondack Mountains constitute the southernmost contiguous portion of the Mesoproterozoic Grenville Province (Fig. 1) and, as such, are well situated to make geologic connections with Grenvillian inliers in the Appalachian Mountains to the southeast and with those in the Midcontinent to the southwest. A summary chronological chart of major Mesoproterozoic tectonic events in the Adirondacks and the Appalachians is presented in Figure 2, in which it can be seen that evidence for many events of the same age are present in several locations pointing to a shared tectonic evolution (McLelland et al. 2010a). Similar timing of events is also noted between the Adirondacks and the Mesoproterozoic inliers of Texas. The shared evolution of these terranes is summarized in this paper along with new developments of the past several years.

Isotope geochemistry and geochronology have played major roles in extending our understanding of the entire Grenville Orogen, including the Adirondacks where they have clarified a geological history that had remained obscure for decades. The earliest systematic U–Pb zircon dating studies were due to L.T. Silver (Silver 1969) who used the Adirondacks as a laboratory in which to advance his pioneering research in multi-grain U–Pb zircon dating. Subsequent multi-grain U–Pb zircon dating by McLelland et al. (1988) and McLelland and Chiarenzelli (1990) extended Silver's results and, for the first time, established a coherent chronology and sequence of events in the Adirondack Mountains. The results demonstrated that the region was affected by three major orogenic events: the Elzevirian Orogeny (1.25–1.22 Ga), the Shawinigan Orogeny (ca. 1.16–1.14 Ga), and the Ottawan Orogeny (ca. 1.09–1.03 Ga) as well as the late- to post-orogenic anorthosite–mangerite–charnockite–granite (AMCG) suite at ca. 1.15 Ga. This framework provided boundary conditions enabling the unraveling of Adirondack tectonomagmatic history and placing the region into a self-consistent plate tectonic overview that we present here. More recently, McLelland and co-workers (McLelland et al. 2001, 2002, 2004; Heumann et al. 2006; Bickford et al. 2010; Chiarenzelli et al. 2010, 2011) undertook the first dating of Adirondack zircon by U–Pb SHRIMP2 techniques and this has vastly improved understanding of the detailed geochronology of events in the region. Both SHRIMP2 and thermal ionization mass spectrometry (TIMS) ages are presented in Table 1 where the results of each can be compared. Similar SHRIMP2 zircon geochronology has been applied to the Grenvillian inliers of the Appalachians by Tollo et al. (2006, 2010) and Aleinikoff et al. (2004, 2008) and references therein. At about the same time, application of a range of other isotopic studies, e.g. Sm/Nd crustal dating, oxygen isotopes, carbon isotopes, $^{40}Ar/^{39}Ar$ isotope geochemistry, Hf in zircon, and whole rock Pb/Pb investigations greatly expanded the database, while modern geothermometry and geobarometry enabled a deeper understanding of processes and events involved in the evolution of the Adirondacks as well as the Grenvillian inliers of the Appalachians and Texas. References to these studies, together with appropriate citations, are made in the text itself. Prior to this, we briefly summarize the pre-Grenvillian Proterozoic history of a long-lived series of continental margin arcs along southeastern Laurentia, i.e., the Paleoproterozoic Penokean, Yavapai, and Mazatzal orogens, together with the Mesoproterozoic Granite-Rhyolite Province. Tectonomagmatic activity along these arcs set the stage for the culminating Grenvillian Orogeny that resulted in the creation of the Rodinian supercontinent.

REGIONAL SETTING OF THE GRENVILLE OROGEN WITHIN THE USA

The Grenville Orogen (Fig. 1) represents the youngest of a series of Paleoproterozoic to Mesoproterozoic crustal additions to the southeastern Laurentian margin. From oldest to youngest, on the basis of Nd model ages (T_{DM}), these include: the Penokean (ca. 2.0–1.8 Ga), Yavapai (ca. 1.8–1.7 Ga), and Mazatzal (ca. 1.87–1.65 Ga) provinces or orogens, and the Granite-Rhyolite Province (ca. 1.487–1.37 Ga). Together, these terranes have been interpreted as long-lived island and continental margin arcs that were the site of accretion and juvenile plutonism that resulted in ~600 million years of crustal additions to Laurentia and culminated with the 1.3–0.98 Ga Elzevirian, Shawinigan and Grenvillian orogenies (Karlstrom et al. 2001; Whitmeyer and Karlstrom 2007, and references therein). Rocks of the Penokean, Yavapai, and Mazatzal provinces are generally tectonized by multiple deformational events and are commonly referred to as orogens or orogenic belts. The interpretation of these arcs

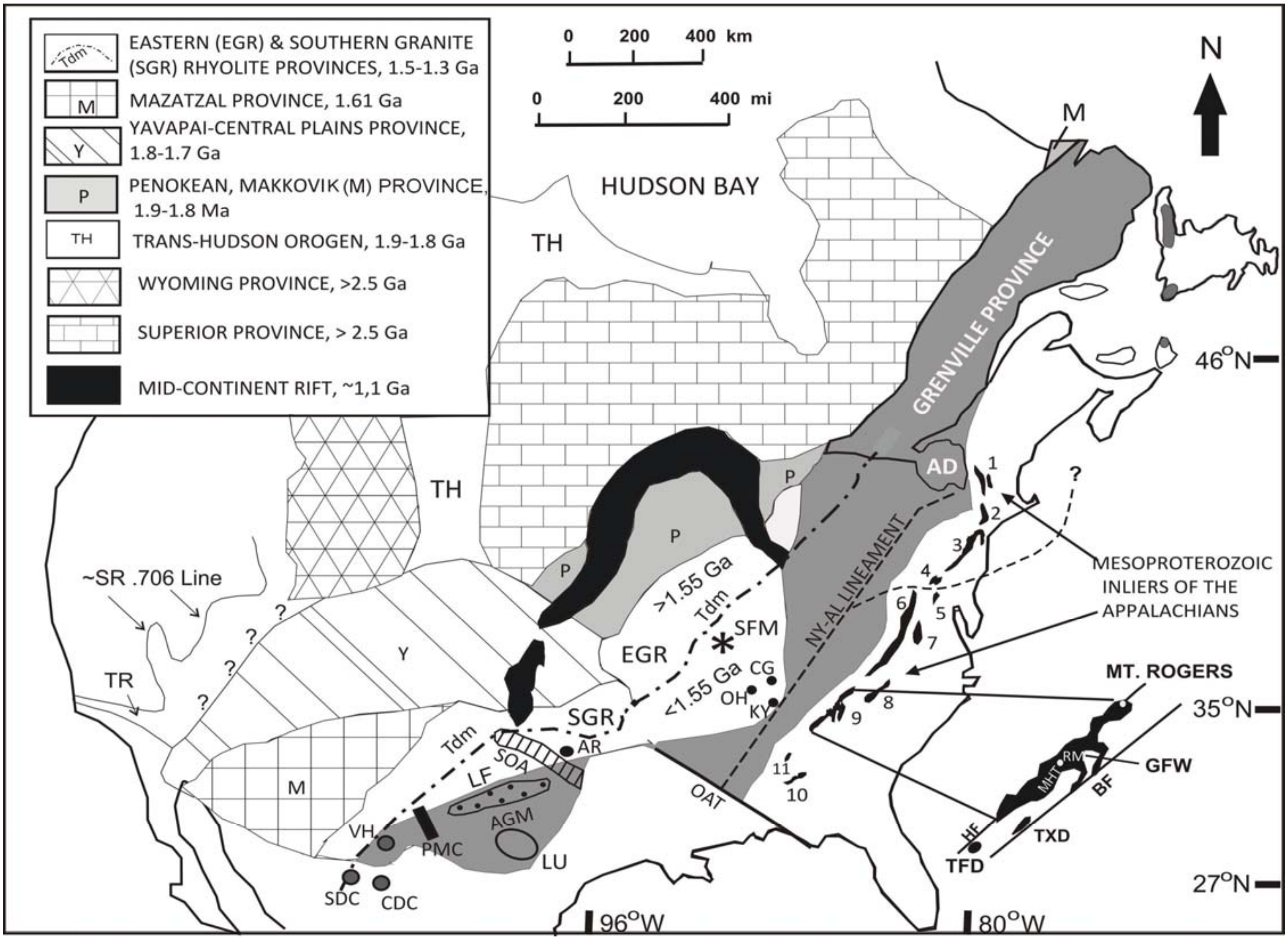

Figure 1. Generalized map depicting major tectonic and geochronological subdivisions in the USA. The Grenville Province is shown in medium gray and its exposed portions are indicated by heavy outlines. **Abbreviations**: AD = Adirondack Mountains, AGM = Abilene gravity minimum, AR = Arbuckle Mountains, BF = Brevard Fault, CDC = Cerro Del Carrizalillo, CG = Crab Orchard drill core, EGR = Eastern Granite-Rhyolite Province, GFW = Grandfather Mt. Window, HF = Hayesville Fault, KY = Kentucky drill core, LF = Llano Front, LU = Llano Uplift, MHT = Mars Hill Terrane, OAT = Oklahoma-Alabama Transform, OH = Orchard Hill drill core, PMC = Pecos Mafic Complex, RM = Roan Mt., SDC = Sierra Del Cuervo, SFM = St. Francois Mts., SGR = Southern Granite-Rhyolite Province, SOA = Southern Oklahoma Aulocogen, TFD = Tallulah Falls Dome, TXD = Toxaway Dome, VH =Van Horn. **Numbers:** 1 = Mount Holly complex and Chester-Athens Dome, 2 = Berkshire Mountains, 3 = Hudson-New Jersey Highlands, 4 = Honey Brook Uplands, 5 = Baltimore Gneiss domes, 6 = Shenandoah Massif, 7 = Goochland Terrane, 8 = Sauratown Mountains, 9 = French Broad Massif, 10 = Pine Mountain Uplift, 11 = Corbin Hill.

as accretionary is not universally accepted. In particular, parts of the Yavapai Province have been interpreted by Hill and Bickford (2001), Bickford and Hill (2007), and Bickford et al. (2008) to consist of older Penokean–Trans-Hudson crust that was remelted during extension.

In our summary, we have relied heavily on detailed studies by Karlstrom and Humphreys (1998), Karlstrom et al. (2001), and an extensive review by Whitmeyer and Karlstrom (2007), as well as references given therein. We have excluded the Mojave Province, or Mojavia, situated west of the Yavapai Province from our discussion, because it has recently been interpreted by Nelson et al. (2011) to be underlain by Yavapai crust overlain by a thick layer of Archean metasedimentary debris derived from the Wyoming Craton (Fig. 1). Yavapai-age plutons ascending through this metasedimentary cover experienced Sm–Nd and Pb-isotope contamination that make their crustal ages appear to be older than they actually are. Figure 1 shows the boundary of the Yavapai Province provided by Karlstrom et al. (2001), but question marks have been inserted to acknowledge the alternative interpretation that the Yavapai Province could extend all the way to Death Valley and on through the Transverse Range of California and be bounded on the west by the $^{87}Sr/^{86}Sr$ = 0.706 and the $^{208}Pb/^{206}Pb$ lines (Fig. 1) that mark the western edge of Precambrian crust (Wooden et al. 1998).

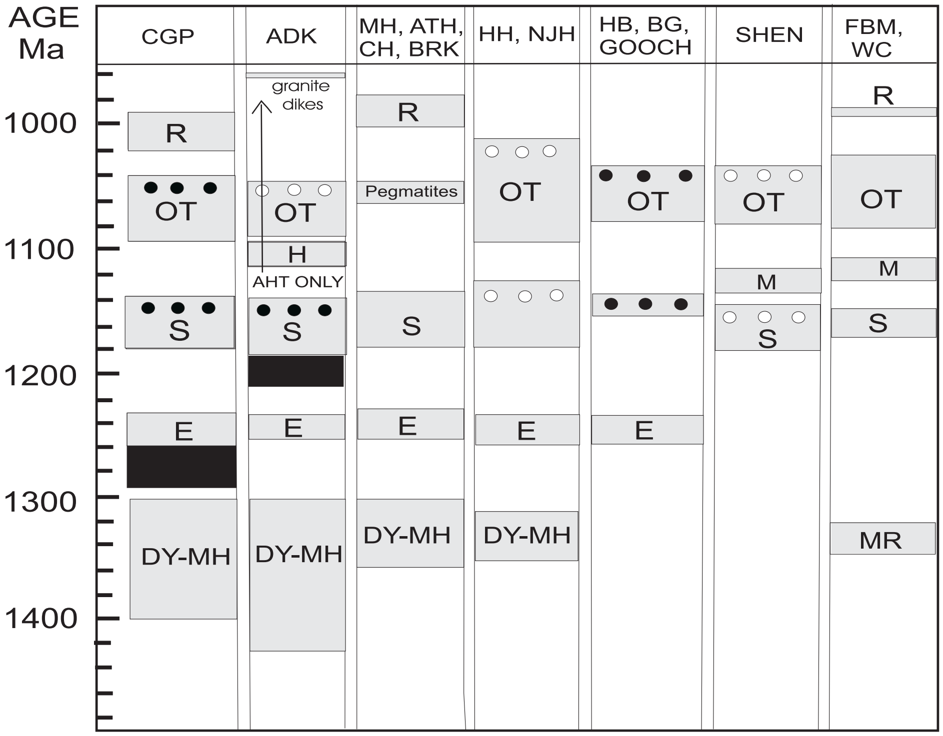

Figure 2. Chart summarizing major Mesoproterozoic (ca. 1.5–0.9 Ga) tectonic and magmatic events in eastern Laurentia. **Gray Rectangles:** 1) Orogenies with the following labels: R = Rigolet, OT = Ottawan, S = Shawinigan, and E = Elzevirian. 2) Major igneous events: H= Hawkeye Granite, M = Mitchell Granite, MR = Mount Rogers. **Circles:** White circles represent late- to post-tectonic AMCG suites, whereas black circles represent regions with only MCG magmatism. **Black Rectangles:** represent pre-orogenic arc magmatism in the Elzevirian (E) and Shawinigan (S) orogenies. **Abbreviations:** ADK = Adirondack Mts., AHT = Adirondack Highlands Terrane, ATH = Athens Dome, BRK = Berkshire Mountains, CGP = Canadian Grenville Province, CH = Chester Dome, FBM = French Broad, HH = Hudson Highlands, MH = Mount Holly complex, NJH = New Jersey Highlands, HB = Honey Brook Uplands, BG = Baltimore Gneiss domes, GOOCH = Goochland Terrane, H = Hawkeye Granite, SHEN = Shenandoah Massif, WC = Wolf Creek. Data for this time scale is summarized with references in the text of this article and in McLelland et al. 2010a. (After McLelland et al. 2010a).

Penokean Province

The Penokean Province (Fig. 1) is underlain by 1.89–1.80 Ga Paleoproterozoic crust (Van Schmus 1980) with Sm–Nd T_{DM} of ca. 2.0 Ga (Barovich et al. 1989; Holm et al. 2005), and records the transition from a passive to an active continental margin at ca. 2.4–2.23 Ga. It consists dominantly of deformed, metamorphosed volcanic and plutonic calcalkaline arc rocks referred to as the Wisconsin Magmatic Terrane and was accreted to Laurentia at ca. 1.89–1.83 Ga (Sims and Carter 1996). Subduction is interpreted to have been to the south, since there are no signs of coeval arc magmatism along the continental margin; however the arc rocks were eventually thrust over Laurentia, probably along the Niagara Fault (Sims and Carter 1996). Several Archean tracts occur within the Penokean Province and are probably exotic fragments. Rocks of similar age and character occur in the Makkovik Orogen at the northeastern terminus of the Grenville Province (Fig. 1). Dickin and McNutt (1989) described a wide belt of 2.09-1.72 Ga calcalkaline granitic gneiss in the eastern Grenville Province that they interpreted as a possible extension of the Penokean arc (Dickin 2000); however, the age could be the result of magma contamination by underlying Archean crust (cf. DeWolf and Mezger 1994).

Yavapai Province

The next major volcanic and plutonic terrane accreted to Laurentia was the large and complex Yavapai Province with a crustal T_{DM} age of 2.0–1.8 Ga, slightly older than the 1.8–1.7 Ga juvenile calcalkaline granite–greenstone belts, including pillow basalts, tonalite and granite plutons, and massive sulphide deposits that dominate the terrane and have been interpreted as island arc complexes (Karlstrom et al. 2000; Whitmeyer and Karlstrom 2007). Note, however, that one of us (MEB) has called attention to the bimodality of Yavapai rocks, the presence of ca. 1.85–1.88 Ga xenocrystic zircons, ca. 1.85–1.90 Ga Nd model ages, and ca. 1.85–1.90 Hf model ages, to argue that much of the Yavapai Province is in fact reworked Penokean and Trans-Hudson crust. This argument is strengthened by the presence of the ca. 1.84 Ga Elves Chasm Terrane in the Grand Canyon (Hawkins et al. 1996). The northern margin of the terrane is marked by the subvertical 1.78–1.75 Ga Cheyenne belt shear zone that lies near the southern terminus of the greenschist facies Wyoming Craton and can be geophysically tracked eastward to its contact with the Penokean Orogen. The Yavapai Province basement is so deformed and metamorphosed that it is currently difficult to resolve plate-tectonic details. Some workers (e.g. Karlstrom and Bowring 1988; Tyson et al. 2002; Jessup et al. 2006) have interpreted geophysical data to indicate a number of accretionary subduction zones, analogous to the present day Banda arc. These workers (c.f., Whitmeyer and Karlstrom 2007) envisioned a picture of almost continuous Yavapai-wide subduction and contractional deformation from 1.78 and 1.68 Ga. with an orogenic peak at ca. 1.71–1.69 Ga. As noted above, one of us (MEB) believes the history of the Yavapai Province is more complex than this, but accepts that arc accretion was probably locally important. Metamorphic rocks exposed at the surface today commonly give evidence of protracted, mid-crustal metamorphism at ~350–450 MPa. Lateral temperature gradients of ~300° C in these rocks bear witness to the major role played by granitic plutons in advecting heat towards the surface. In southeastern

TABLE 1. SUMMARY OF ISOTOPIC AGES IN THE ADIRONDACKS AND GRENVILLIAN INLIERS OF THE APPALACHIANS

LOCALITY	COMPOSITION	AGE (Ma)	±	REFERENCE	T_{DM} (Ga)	REFERENCE	OROGENY
ADIRONDACK LOWLANDS							
Rossie-Antwerp suite	diorite-granodiorite	1205	18	1, 2			Shawinigan
Hermon Granite	granite-granodiorite	1182	8	3			Shawinigan
Hyde School Gneiss	granite, tonalite	1172s	11	4	1.33, av of 3	27	Shawinigan
Edwardsville-North Hammond	AMCG granite-syenite	1164	4	5			AMCG
Leucosomes in metapelites	granitic pegmatite	1180-1160 (S-3)	17	3			
ADIRONDACK HIGHLANDS							
Dysart-Mount Holly Suite	tonalite-granodiorite	1301 (t-4)	15	1	1.39, av of 3		Fragment 1.4-1.3 arc
Elzevirian pluton	charnockite	1250	15	1			Elzevirian
AMCG granitoid plutons	mangerite to granite	1158 (t-5, S-8)	5	1,6	1.22 av of 6	27	AMCG
AMCG anothosite suite	anorthosite to gabbro	1154 (S-12)	6	1.6	1.33	27	AMCG
Hawkeye suite	granite	1096 (m-7)	8	1	1.32	27	uncertain
Lyon Mountain Granite	A-type leucogranite	1050 (S-10)	10	6, 7	1.35	27	Late Ottawan
Lyon Mountain pegmatite	granitic pegmatite	1041 (I-6, S-9)	9	7, 8			Late Ottawan
Leucosomes in metapelites	granitic pegmatite	1161 (S-5)	8	9			Late Ottawan
monazites core, mantle, rim	leucosome and granite	1176, 1051, 1026	17,5,5	3, 30			Shawinigan to Late Ottawan
GREEN MOUNTAINS, VERMONT							
Dysart-Mount Holly Suite	tonalite, trondjhemite	1430-1330t	9	10	1.46	28	Fragment 1.4-1.3 arc
College Hill pluton	granite	1244-1220t	8	10	1.47	28	Elzevirian
Foliated Shawinigan granites	granite	1172 (S-1)	7	11			Shawinigan
Pegmatite in augen gneiss	granite	1036	6	11			Late Ottawan
Rims on zircons	NA	1060-1070 (S-4)		11			Ottawan
Cardinal Brook suite	rapakivi granite	ca. 1000		10			Rigolet
BERKSHIRE MASSIF, MASSACHUSETTS							
Tyringham granitic gneiss	granite, 75% of basement	1179	9	12	1.46	12	Shawinigan
Zircon cores	NA	1070-1050 (S)		12			Inherited from LMG
Alaskite sills and dikes		1004-997 (S)	10	12			Rigolet
HUDSON HIGHLANDS, NEW YORK							
Dysart-Mount Holly Suite	tonalite-trondjhemite	1336 (S-9)	9	13			Fragment 1.4-1.3 Ga arc
Camp Smith plutonic rock	aplite	1238 (S1)	7	13			Elzevirian
Storm King Shawinigan pluton	granite	1174(S-1)	8	13	1.46	28	Shawinigan
Canopus pluton	monzonite-diorite	1142 S-1)	8	13			AMCG
Brewster granite (AMCG?)	hornblende granite	1134 (S-1)	7	13			AMCG?
Danbury augen granite	microcline granite	1045 (S-1)	11	14			Late Ottawan
Gneiss and migmatite	biotite granite	1057-1048	12	13,14			Late Ottawan
Crystal Lake granite	granite	1058	14	15			Ottawan
NEW JERSEY HIGHLANDS							
Dysart Mt. Holly Suite	tonalite	1366-1282 (S)	13	16			
Plutonic gneiss	dacite-granodiorite	1254-1248 (S)	8	16			Fragment 1.4-1.3 arc
Byram, Lake Hopatcong plutons	A-type granite	1188-1182 (S)	11	16			Elzevirian
Mount Eve granite	A-type granite	1019	4	16			Shawinigan
monazite, zircon metamorphic	NA	1045-1024 (S)		16			Late Ottawn-Rigolet
BALTIMORE GNEISS DOMES							Late-post Ottawn
layered felsic gneiss	biotite-quratz-feldspar	1247 (S-8)	19	Alein et al 2004			Elzevirian
foliated biotite granite	biotite granite	1075 (S-9)	15				Ottawan
zircon overgrowths I		1220					Late Elzevian
zircon overgrowths II		1160					Shawinigan-AMCG
zircon overgrowths III		1020					Late Ottawan-Rigolet

TABLE 1 (cont.). SUMMARY OF ISOTOPIC AGES IN THE ADIRONDACKS AND GRENVILLIAN INLIERS OF THE APPALACHIANS

LOCALITY	COMPOSITION	AGE (Ma)	±	REFERENCE	TDM (Ga)	REFERENCE	OROGENY
SHENANDOAH MASSIF					1.62-1.37	23	
metagranitoids , Group 1	granite, monzonite,diorite	1183-1144 (S-12)	12	18	1.69 av of 8	21	Fragment 1.4-1.3 Ga arc
metagranitoids, Group 2	granite, monzonite,diorite	1143-1111 (S-3)	12	18	1.57 av of 2		Shawinigan-AMCG
metagranitoids, Group 3	granite, monzonitte,diorite	1078-1028 (S-14)	8	18	1.5 av of 11		AMCG-Hawkeye?
metamorphic ages	zircon overgrowths	1067-1020	12	18			Ottawan
Roseland pluton	anorthsite	ca 1045m		19			Ottawan
GOOCHLAND TERRANE							
State Farm Gneiss	granitic	1057-1015s		19	1.5-1.3	19	Ottawan
Montpelier anorthosite	anorthosite	1045s	10	20			Ottawan
FRENCH BROAD MASSIF					1.88-1.55	22, 29	
Mt. Rogers granblastic gneiss	tonalitic	1327 (S-1)	7	21			arc fragment?
West of Mars hill, gneiss	tonalitic	ca. 1380		22			arc fragment?
Mars Hill detrital zircons in	metasediments	1680-1000		18, 21			deposited after ca. 1.0 Ga
Cloudland, Carvers Gap gneiss							
Smoky Mountains	granite	1045-1020 (S)		23			Ottawan
Mt. Rogers, weakly foliated rock	granite	ca. 1060 (S		21			Ottawan
Grandfather Mt. window	granitic gneiss	ca. 1080		24			Ottawan
TALLULAH FALLS DOME							
Wiley gneiss	quartzofelspathic	1158 (S-1)	19	24	1.3-1.2	24	Shawinigan-AMCG
Augen gneiss	granitic	1129 (S-1)	23	24			Group II
Wolf Creek granitoid	granitic	1151-1149 (S-2)	14	24	1.6-1.3	24	Shawinigan-AMCG
TOXAWAY DOME							
orthogeiss	granitic	ca.1110		24	1.6-1.3	24	Group II
PINE MOUNTAIN WINDOW							
high grade gneiss	granitic	1063-1011	13	25	1.6-1.3	24	Ottawa.-Rigolet

S-SHRIMP, N-number of samples, s-single grain TIMS, m-multi grain TIMS. References: 1) McLelland et al, 1988, 2) Chiarenzelli et al., 2008; 3) Heumann et al, 2006; 4) Wastenets, et al., 2006; 5) Peck et al, 2004; 6) McLelland et al, 2004; 7) McLelland et al., 2001, Selleck et al., 2005; 8) Lupuluscu et al., 2010, McLelland and Selleck, 2010; 9) Bickford et al., 2008; 10)) Ratcliffe et al,1991; 11) Aleinikoff et al., 2011; 12) Karabinos et al., 2003, 13) Ratcliffe and Aleinikoff, 2008; 14) Walsh et al., 2004; 15) Aleinikoff et al., 2011; 16) Volkert et al., 2010; 17) Aleinikoff et al., 2004; 18) Southworth et al., 2010; 19) Owens and Tucker, 2003; 20) Aleinikoff et al., 2006; 21) Tollo et al., 2006, 2010, 2012; 22) Berquist, 2005 Fisher, 2010 ; 23) Southworth et al, 2010, Tollo et al, 2006, 2010, 2012, Aleinikoff et al, 2012; 24) Carrigan et al., 2003, 25) Heatherington et al., 2007; 26) Steltenpohl et al., 2004, 27) Daly and McLelland, 1991; McLelland et al., 1993; 28) McLelland et al., 1994, 29) Bream et al., 2004 30) Wong et al., 2012

California 1.71–1.68 Ma events are referred to as the Ivanpah Orogeny and in the mid-continent the term 'Central Plains Orogeny' has been used. These, and other local names, have been subsumed by the term Yavapai Orogeny (Karlstrom and Bowring 1988, and Karlstrom et al. 2001). Plutons of Yavapai or Mazatzal age (ca. 1.7 Ga) occur in the Killarney magmatic belt situated within the northwestern corner of the Grenville Province (Davidson 1998; Rivers and Corrigan 2000).

Mazatzal Province

The formation of the Yavapai Province was followed by the assembly of the Mazatzal Province with 1.7–1.6 Ga rocks yielding T_{DM} = 1.8–1.6 Ga. The terrane includes juvenile 1.7–1.65 Ga oceanic arc assemblages, including greenstone belts and 1.66–1.65 Ga calcalkaline plutons consistent with continental margin back-arc affinities perhaps related to periods of slab rollback within an otherwise continuous contraction from 1.8–1.6 Ga. The Mazatzal Province has a complex, and apparently, transitional structural contact with the Yavapai Province and plutons of Mazatzal age occur well within the Yavapai (e.g. Bickford et al. 1989). This has been interpreted to be the result of collision along a south-dipping subduction zone in which the Yavapai Orogen margin of Laurentia was partially subducted beneath the Mazatzal Province at 1.68–1.65 Ga. When the subduction zone jammed, the contractional strain was accommodated by low angle back-thrusting away from the collisional zone in each block at ca. 1.65–1.60 Ga. The orogen extends eastward in the subsurface and reappears in the Grenville Province where rocks of Mazatzal age and character occur near Georgian Bay (Slagstad et al. 2009) on eastern Lake Huron (Fig. 3) and are spectacularly represented in the 800 km long, ca. 1.67–1.65 Ga juvenile (T_{DM} =1.71 Ga) Trans-Labrador Batholith emplaced by arc accretion and continental margin arc magmatism (Gower and Krogh 2002). To the south of the batholith, the very large Labradorian Province has a T_{DM} of

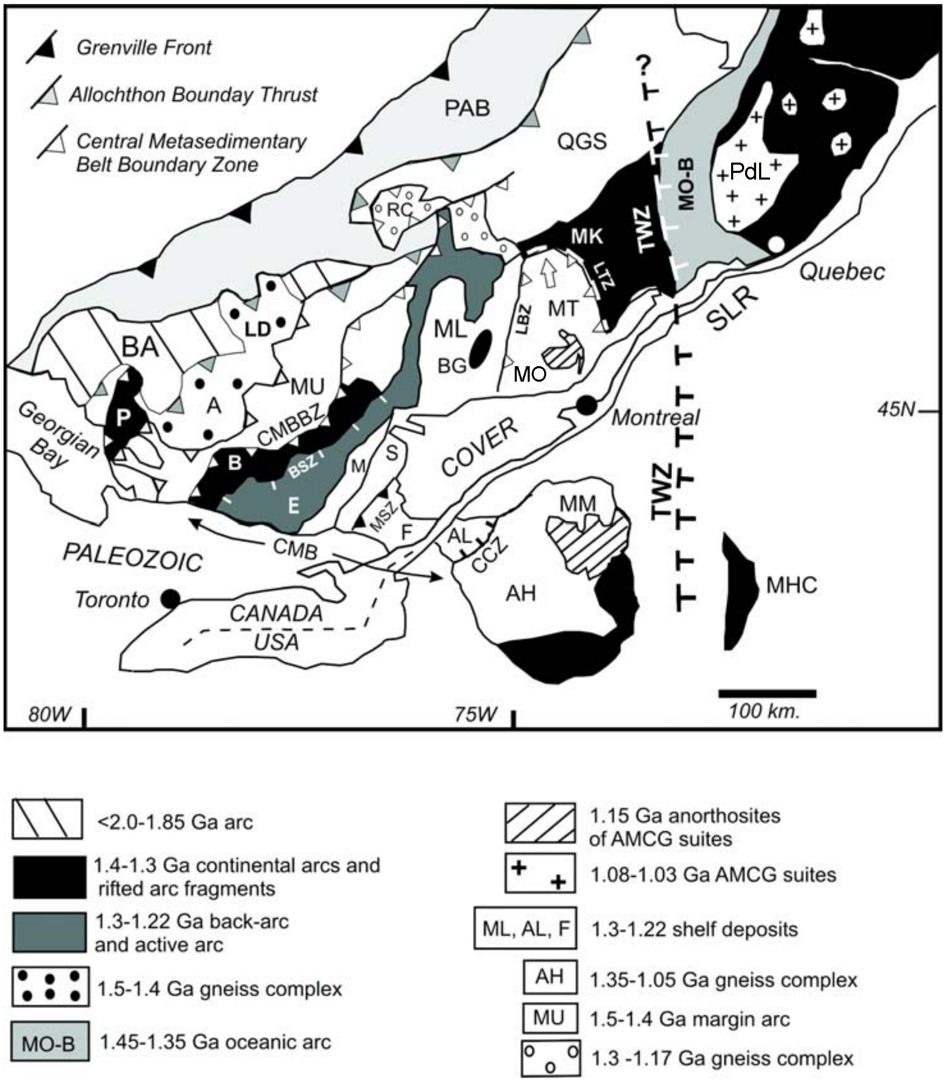

Figure 3. Map showing the southwestern segment of the Grenville Province plus the Adirondacks and Green Mountains. Black = 1.4–1.3 Ga margin arc and southeastern fragments, A, LD = Algonquin/Lac Dumoin, (1.5–1.4 Ga calcalkaline gneiss complex), AH =Adirondack Highlands, AL = Adirondack Lowlands, B = Bancroft Terrane, BA = Barillia (2.0–1.85 Ga arc), BSZ =- Bancroft Shear Zone, BG = Bondy Gneiss Dome, CCZ = Carthage-Colton Shear Zone, CMB = Central Metasedimentary Belt, CMBBZ = Central Metasedimentary Belt Boundary Zone, E = Elzevir Terrane, F = Frontenac Terrane, LBZ = Labelle Shear Zone, LTZ = Lac Taureau Shear Zone, M = Mazinaw Terrane, MHC = Mount Holly complex, MK = Mékanic Terrane, ML = Mont Laurier Terrane, MM = Marcy Anorthosite Massif, MO = Morin Anorthosite, MO-B = Montauban-La Bostonnaiss oceanic arc (1.45–1.35 Ga), MT = Morin Terrane, MU = Muskoka Domain (1.5–1.4 Ga margin arc), MSZ = Maberly Shear Zone, P = Parry Sound Domain, PAB = Parautochthonous Belt, PdL = Parc des Laurentides AMCG Suite, QGS = Quebec gneiss segment, RC = Reservoir Cabonga Terrane, S = Sharbot Lake Terrane, SLR = St. Lawrence River, TWZ = Tawachiche shear zone. (Modified from Hanmer et al. 2000).

~1.7 Ga (Dickin 2000).

Granite-Rhyolite Province and A-type Mesoproterozoic Granitic Magmatism in the Midcontinent

Situated between the Mazatzal and Grenville orogens, the Granite-Rhyolite Province (Fig. 1) of the mid-continent is known mainly from exposures in the St. Francois Mountains (SFM) of Missouri and the eastern Arbuckle Mountains of Oklahoma. In addition, a large number of drill holes have penetrated the province's Precambrian basement and have been dated by Bickford and Van Schmus (1985). On the basis of this dating, and extensive research in the St. Francois and Arbuckle mountains, two major subprovinces can be identified, the Southern Granite Rhyolite (SGR) Subprovince (Fig. 1) and the Eastern Granite-Rhyolite (EGR) Subprovince (Fig. 1; Van Schmus et al. 1993a, b). The EGR is characterized by average crystallization ages of ca. 1.47 Ga and the SGR by average crystallization ages of ca. 1.37 Ga. Basement rocks in both subprovinces are dominated by epizonal granite plutons and coeval rhyolite with very minor basalt and gabbro indicative of limited bimodality. In the St. Francois Mountains the exposed 1.47 Ga basement consists of undeformed ignimbrite, caldera complexes, and shallow granitic plutons. Exposures of the 1.38–1.37 Ga SGR occur mostly in the eastern Arbuckle Mountains (Fig. 1 [AR]), where granodiorite, granite, and granitic gneiss have yielded crystallization ages of ca. 1.39–1.37 Ga. Local subsurface samples yield crystallization ages of ca. 1.4–1.34 Ga that are close to the average age of 1.37 Ga in the SGR.

Sm–Nd T_{DM} ages for the basement beneath the EGR and the SGR have been obtained by Van Schmus et al. (1993a, b) and Rohs and Van Schmus (2007). The results define a dividing line between rocks to the northwest with T_{DM} >1.55 Ga and those to the south with T_{DM}<1.55 Ga (Fig. 1). Van Schmus et al. (1993a, b) interpreted this line as demarcating the southern terminus of Paleoproterozoic crust and suggested that it is a candidate for a suture between the ca. 1.55 Ga Laurentian margin and another accreted arc to the southeast. T_{DM} values for the St. Francois Mountain granite plutons are close to their crystallization ages providing a strong argument for derivation via melting of juvenile, calcalkaline crust shortly after its accretion (Van Schmus et al. 1993a, b; Menuge et al. 2002; Rohs and Van Schmus 2007; Slagstad et al. 2009). The T_{DM} values for the samples from the Arbuckle Mountains, which lie south of the T_{DM} line, are ca. 1.45–1.54 Ga, i.e., basically the same as those from the St. Francois Mountains indicating that the two regions are underlain by crust of the same age. Although crystallization ages for samples from the Arbuckle Mountains are ca. 1.39–1.37 Ga, it is plausible that renewed magmatism at ca. 1.4–1.33 Ga gave rise to the granitic rocks of the low T_{DM} portion of the SGR. This is strengthened by the presence of a second, minor granitic episode in the SFM, which is coeval with magmatism in the Arbuckle Mountains (Bickford and Mose 1975; Thomas et al. 1984; Rohs and Van Schmus 2007).

It has been argued that the Granite-Rhyolite subprovinces are the result of the development of a continental margin arc with northwest polarity and with suturing along the T_{DM} 1.55 Ga line (Van Schmus et al. 1993a, b; Rivers and Corrigan 2000; Menuge et al. 2002; Rohs and Van Schmus 2007; Slagstad et al. 2009). The arc is well exposed in the Grenville Province where evidence for ca. 1.5–1.35 Ga granitic magmatism spans the province from Georgian Bay (Fig. 3) to its eastern terminus in Labrador and is informally known as the Britt-Pinware belt (Rivers and Corrigan 2000). An accreted outboard arc (1.44–1.35 Ga), known as the Montauban-La Bostonnais Terrane (Fig. 3), occurs near the eastern margin of the Morin Terrane. As pointed out by Rivers (1997, 2008) and Rivers and Corrigan (2000), the Britt-Pinware belt represents a continental margin, Andean-type arc with northwest polarity and southward growth. Associated high-grade metamorphism, known as the Pinwarian Orogeny provides evidence for a regionally extensive orogenic event. The arc can be projected along the strike of subsurface geophysical trends (Fig. 1) into the eastern margin of the Granite-Rhyolite and Llano provinces. In the latter case, the Montauban-La Bostonaiss arc (Fig. 3) and the Coal Creek arc, located at the southeast margin of the Llano Uplift (Fig. 1), are similar in age and type (Rivers and Corrigan 2000). These correspondences strengthen the case for a continental margin arc origin for the Granite-Rhyolite Province. Rivers and Corrigan (2000) and Slagstad et al. (2009) have presented a plate tectonic model for the 500 km long, SW-NE trending Britt-Pinware belt continental margin arc. The width of the arc is about 500 km along a SE-NW line with northwest polarity. The leading edge includes the Muskoka domain (Fig. 3) that straddles the folded extension of the T_{DM} 1.55 Ga line that was subsequently thrust northwest over the continental margin. The Muskoka domain is underlain by large quantities of calcalkaline 'gray' dioritic to granodioritic orthogneiss with crystallization ages of ca. 1.45 Ga and T_{DM} of ca. 1.55–1.6 Ga typical of the southeast Laurentian continental margin arcs. The arc experienced alternating pulses of contraction and extension with the latter resulting in back-arc basins and basaltic underplating due to periods of rollback, slab breakoff, or delamination of lithosphere resulting in ascent of asthenosphere to the base of the crust. Within the back-arc basins, partial melting of gray gneiss produced large granitic plutons, many with A-type geochemistry, as well as minor anorthosite and gabbro. The Grenville Province plutons are coeval with, and intrude rocks of similar age and composition to those in the Granite-Rhyolite Province. They present a compelling case for an arc-related origin that included periods of slab rollback, delamination, back arc basins, and underplating by mafic magmas causing melting of older fertile lower crust.

A complication arising from this interpretation is the occurrence of 1.45–1.37 Ga A-type plutons that intrude Paleoproterozoic crust as far west as eastern California (e.g. Goodge and Veervort 2006). Because of the similarity of ages and chemistry of these rocks with those of the Granite-Rhyolite Subprovinces, it is widely assumed that they once also had a cover of coeval and chemically similar rhyolite. Accordingly, the causal mechanism of the Granite-Rhyolite Province might have extended throughout most of the western part of Laurentia. Goodge and Veervort (2006) presented a compelling model for widespread A-type magmatism based on Hf-in-zircon research. They have observed that from ca. 2.0–1.6 Ga in southern Laurentia "*prolific crustal growth assembled a large volume of new lithosphere in a geologically brief period of time.*" This fertile crust underwent post-orogenic conductive heating due to blanketing of mantle heat flow as well as heat advected by mafic magma ponded at the crust-mantle interface. Melting of the lower crust produced A-type silicic magmas that intruded to higher levels and regional extension ensued. The ductility of the deep crust as well as density differences inhibited ascent of the mafic magmas, which are minor components of the region. Here we couple this late magmatic extensional activity with the early marginal arc history described in the prior paragraph. Accretion at the Laurentian margin helped to trigger widespread late- to post-orogenic delamination, extension, and A-type magmatism in the hinterland (Goodge and Veervort 2006). Kay et al. (1998) have described similar timing and events for the vast Late Paleozoic to Jurassic granite-rhyolite terrane in South America. This resolution has the added advantage of removing the somewhat illusory distinction between orogenic and anorogenic magmatism.

GEOLOGY OF THE ADIRONDACK MOUNTAINS

Figures 4 and 5 present generalized geologic maps of the Adirondacks that include U/Pb SHRIMP2 ages of the principal igneous units (ca. 1.35–1.05 Ga). Both this section, and the following one, should be compared to age data in Table 1. The region is divided into the Adirondack Highlands Terrane (AHT; Fig. 4) and Adirondack Lowlands Terrane (ALT; Fig. 4) separated by the 1–10 km-wide Carthage-Colton Shear Zone (Fig. 4 [CCZ]) that dips ~45°NW and exhibits down-dip oblique normal offset at ca. 1050 Ma but also contains evidence of earlier, ca. 1.6 Ga eastward thrusting (Johnson et al. 2004; Selleck et al. 2005; Baird et al. 2008; Baird and Shrady 2011). The AHT is underlain principally by orthogneiss that is relatively resistant to erosion, while the Lowlands are underlain principally by metasedimentary rocks, notably marble, that are easily eroded thus accounting for the topographic differences between the two terranes.

The oldest rocks in the Adirondacks are a suite of 1.35–1.25 Ga tonalitic and granitic plutons (McLelland and Chiarenzelli 1990) that

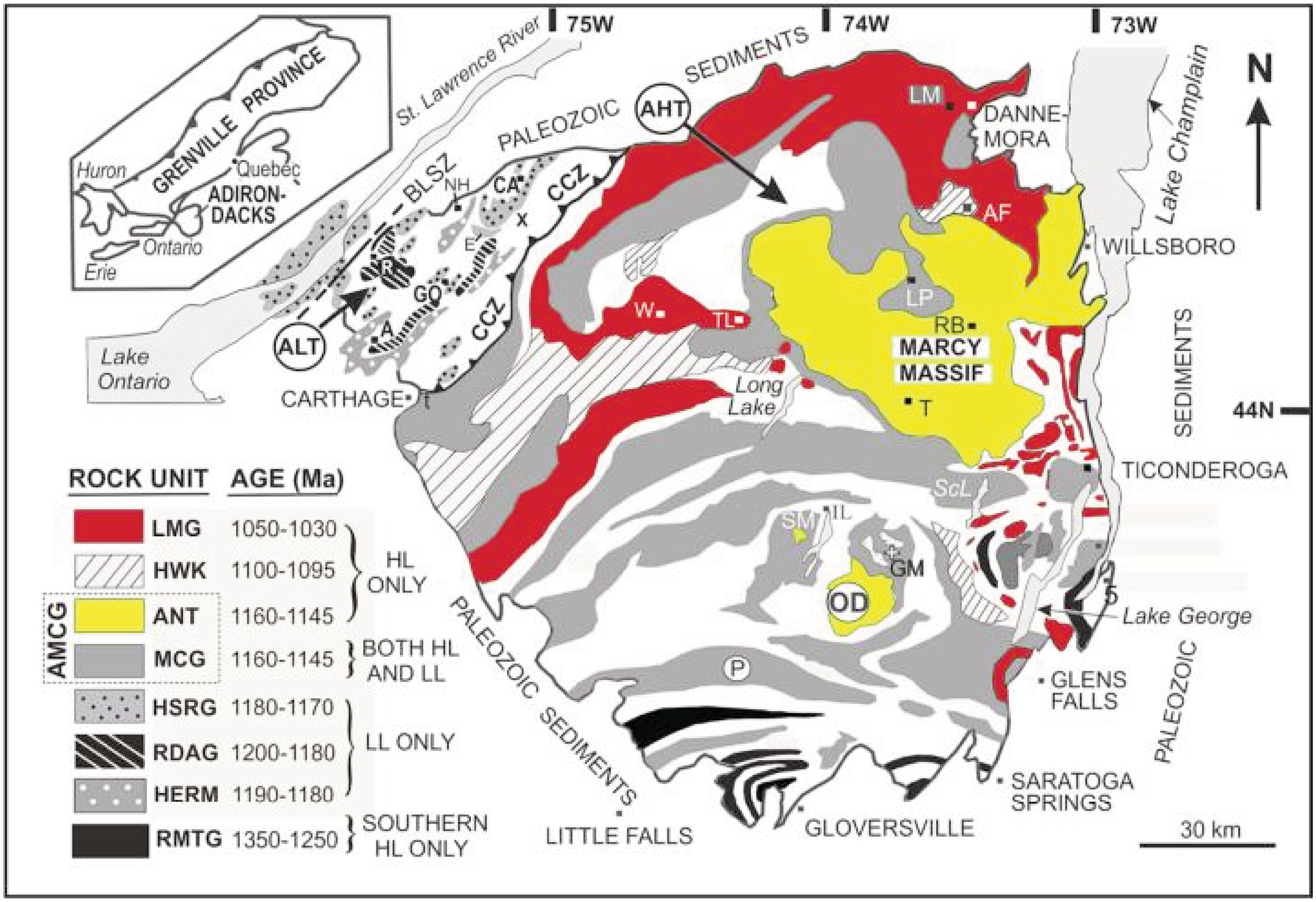

Figure 4. Generalized geological/geochronological map of the Adirondacks Highlands Terrane (AHT) and Adirondack Lowlands Terrane (ALT). Units designated by patterns and initials consist of igneous rocks dated by U–Pb zircon geochronology with ages indicated in the legend. Units present only in the AHT (HL only) are: ANT = anorthosite, HWK = Hawkeye Granite, LMG = Lyon Mountain Granite. Present in the southern AHT only (southern HL only) are: RMTG = Royal Mountain Tonalite and Granodiorite. Units present in the ALT only (LL only) are: HSRG = Hyde School Gneiss and Rockport Granite, RDAG = Rossie Diorite and Antwerp Granodiorite, HERM = Hermon Granite. All representatives of the AMCG suite (anorthosite-mangerite-charnockite-granite) are present in the AHT, but only the MCG portion (mangerite-charnockite-granite) is present in the ALT. Unpatterned areas consist of metasedimentary rocks, glacial cover, and undivided units. The Canada Lake Isocline is represented by the bent-finger pattern northeast of Gloversville. A = Antwerp, AF = Ausable Forks, BLSZ – Black Lake Shear Zone, CA = Canton, CCZ = Carthage-Colton Shear Zone, GO = Gouverneur, GM = Gore Mountain, IL = Indian Lake, LM = Lyon Mountain, LP = Lake Placid, NH = North Hammond, P= Piseco antiform, OD = Oregon Dome, R = Rossie, RB = Roaring Brook, ScL = Schroon Lake, SM = Snowy Mountain Dome, T = Tahawus, TL = Tupper Lake, W = Wanakena, X = ophiolite complex. E = town of Eddy. (After McLelland et al. 2010a).

occur in the southern and eastern AHT (Fig. 4). However, this suite is not intrusive into the Adirondacks but is interpreted to have been rifted from the 1.4–1.3 Ga Laurentian margin arc at ca. 1.3 Ga (Hanmer et al. 2000) and is discussed in a later section. Otherwise, metasedimentary rocks are the oldest units in both Adirondack terranes with depositional ages bracketed by detrital zircon in migmatitic metapelites and by cross-cutting relationships. In both terranes the detrital zircon analyses fall into the interval 1.3–1.22 Ga (Heumann et al. 2006; Bickford et al. 2008; McLelland et al. 2010a). The youngest detrital zircon age reported for the Irving Pond quartzite in the southernmost AHT as well as the Swede Mountain quartzite in the southeastern AHT (Silver 1969) is 1.3 Ga (Peck et al. 2010). Both quartzite units contain 2.7 Ga detrital zircon grains, and these are absent from any of the metapelite units. We suggest that the quartzite units were deposited near, or on, the Laurentian margin shortly after ca. 1.3 Ga. In contrast, the metapelite units are thought to have been deposited well off-shore from Laurentia and shielded from Archean zircon sources by the intervening Central Metasedimentary Belt (CMB) arc (McLelland et al. 2010a; Peck et al. 2010). The metapelite units of the AHT and ALT are similar in appearance, lithology, and chemistry, and it is tempting to interpret them as a single sedimentary horizon. However,

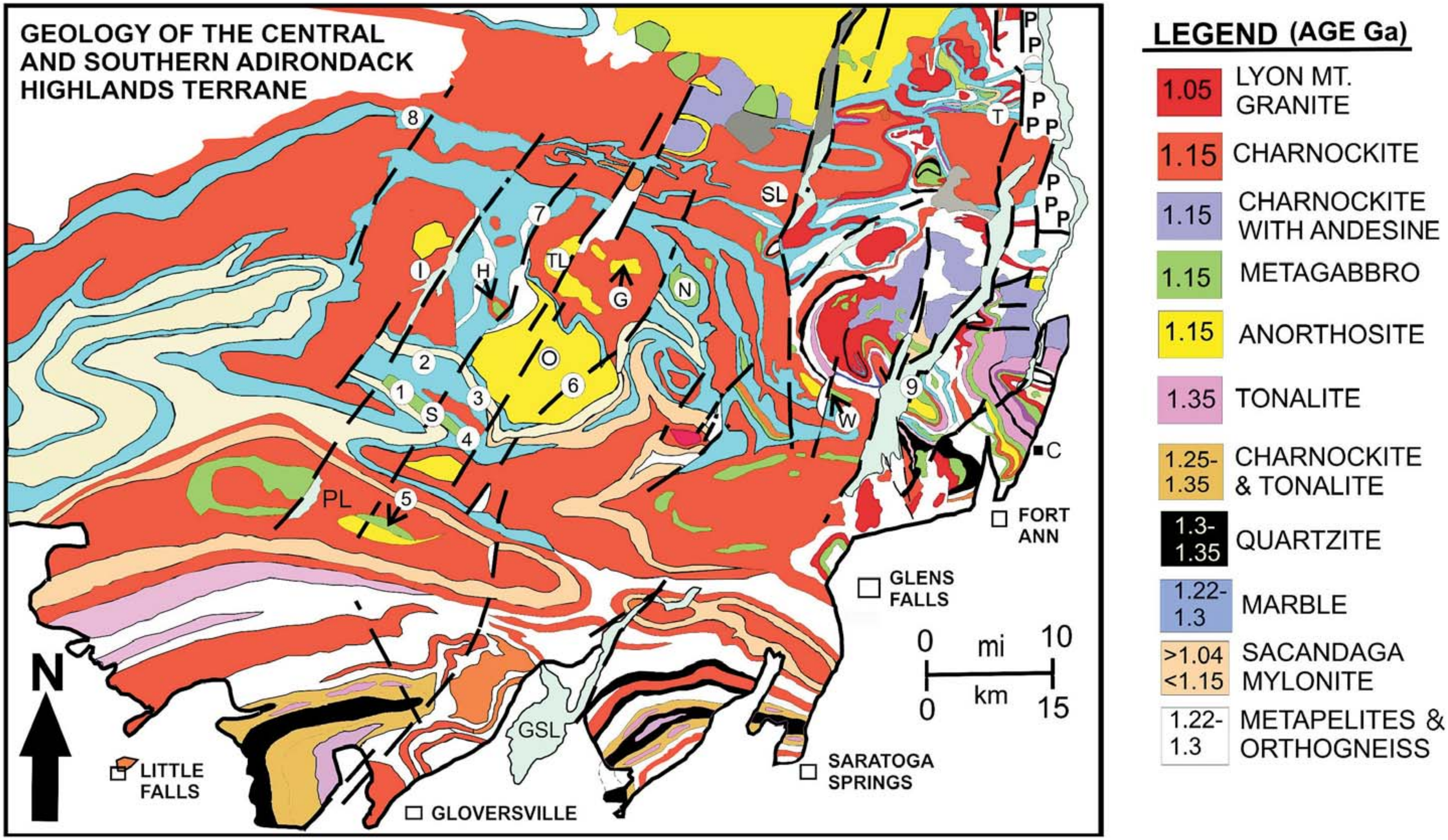

Figure 5. Geologic map of the southern and central Adirondacks. Ages (Ga) of units are shown in legend. Major faults are shown as dashed black lines. Localities discussed in text are shown by white circles and identified by letters. C = Comstock, G = Gore Mountain, GSL = Great Sacandaga Lake, H = Humphrey Mountain, I = Indian Lake, N = North Creek, O = Oregon Dome, P = Paleozoic inliers in the Adirondacks and Paleozoic outcrops abutting the northeastern corner of the figure, PL = Piseco Lake, TL = Thirteenth Lake and Ruby Mountain, S = Speculator, SL = Schroon Lake, T - Ticonderoga, W = Warrensburg. Numbers locate unnamed localities where small Gore Mountain-type occurrences are found. (Modified after McLelland and Selleck 2011).

tectonic evidence, discussed below, suggests that they were deposited at the same time but on opposite flanks of a wide back-arc basin (McLelland et al. 1993, 1994, 1996, 2010a; Chiarenzelli et al. 2010). Carbonate rocks, now metamorphosed to marble, were deposited on the shallow flanks of these basins and are evaporite-bearing. One of these, the Balmat stromatolitic marble (also referred to as the Upper Marble), hosts sphalerite SEDEX deposits, and contains detrital zircon ranging in age from 1.28 Ga to 1.22 Ga with the younger age fixing the maximum age of deposition.

The oldest igneous rocks intruded into the Adirondacks occur in the ALT and consist of calcalkaline diorites and granitoid bodies referred to as the Antwerp-Rossie Suite dated at ca. 1.2–1.17 Ga by U/Pb SHRIMP (McLelland et al. 2001; Chiarenzelli, et al. 2010). These arc-type plutons are widespread in the ALT (Fig. 4) and crosscut all Lowlands metasedimentary units thus fixing their minimum age. They were closely followed by the calcalkaline Hermon Granite Gneiss emplaced at ca. 1.18–1.17 Ga), and this, in turn, was followed by granite and tonalite assigned to the syntectonic ca. 1.172 Ga Hyde School Gneiss (Fig. 4). The ca. 1.172 Ga Rockport Granite that outcrops along the St. Lawrence River is correlated with the Hyde School Gneiss but does not include tonalite and is thought to have been intruded at a somewhat higher level (Wasteneys et al. 1999). Two minimally deformed plutons of ca. 1.16–1.15 Ga ferroan syenite (Fig. 4) have been dated in the western ALT (Fig. 4, Edwardsville, E and Canton, C) and have been correlated with AMCG rocks in the AHT (McLelland et al. 1988). Peck et al. (2011, 2013) have shown that the geochemical properties of the Edwardsville pluton link its source rocks to the Frontenac Terrane, which may comprise the underlying deep crust in the westernmost ALT. Note that none of the ca. 1.2–1.17 Ga plutons of the ALT occur within the AHT suggesting that they were separate terranes until ca. 1.16 Ga.

In contrast to the ALT, the AHT consists primarily of orthogneiss dominated by the ca. 1.15 Ga anorthosite-mangerite-charnockite-granite (AMCG) suite (Figs. 4, 5). Hf isotopic concentrations of zircon have established that Adirondack igneous rocks of the AMCG suite were derived from enriched mantle or crustal sources (Bickford et al. 2010). The less voluminous ca. 1.1 Ga Hawkeye Granite occurs at several localities in the AHT (Fig. 4). The youngest plutonic unit in the AHT, and one of considerable geologic importance, is the ca. 1.05 Ga Lyon Mountain Granite that rims much of the AHT periphery (Fig. 4).

The ALT shows little, if any, metamorphic effects related to the ca. 1.09–1.03 Ma Ottawan orogenic phase (Fig. 2) of the ca. 1.09–0.98 Ga Grenvillian Orogeny (Rivers 2008 2012). Hornblende $^{40}Ar/^{39}Ar$ cooling ages as old as 1.1–1.05 Ga demonstrate that the terrane did not experience temperatures exceeding ~500° C during the Ottawan Orogeny (Streepey et al. 2001; Dahl et al. 2004). Titanite ages as old as 1.16 Ga lead to a similar conclusion. Accordingly, upper amphibolite facies assemblages in the ALT must be the result of Shawinigan metamorphism, which caused widespread anatexis in metapelitic rocks. U /Pb zircon dating by SHRIMP2 has fixed the time of anatexis at 1.18–1.165 Ga. coeval with regional deformation and emplacement of Hermon Granodiorite and Hyde School Gneiss. High grade Shawinigan metamorphism affected the entire AHT resulting in assemblages above the second sillimanite isograd and caused widespread anatexis in metapelite (Heumann et al. 2006; Bickford et al. 2008; McLelland et al. 2010a). To a large extent, Shawinigan effects in the AHT are overprinted by the intense granulite facies Ottawan Orogeny that produced temperatures of ~750°–850°C and pressures of ~6–9 MPa in the AHT (Bohlen et al. 1985; Kitchen and Valley 1995; Darling et al. 2004; Storm and Spear 2005; among others) and reset titanite ages to ca. 1.03 Ga and hornblende $^{40}Ar/^{39}Ar$ ages to ca. 0.98 Ga to the southeast of the Carthage-Colton shear zone (Mezger et al. 1991, 1992; Streepey et al. 2001; Heumann et al. 2006).

Both the AHT and ALT are dominated by several fold sets, the earliest of which (F1) comprises intrafolial isoclines of Shawinigan age (Heumann et al. 2006). In the ALT, the earliest map-scale folds are northeast-trending isoclines (F2) with axial planes overturned to the southeast and commonly refolded along sub-parallel northeast axes (F3). The F2 and F3 folds of the ALT strongly deformed 1.18–1.16 Ga plutons but are crosscut by ca. 1.15 Ga granitoid bodies hence must be of Shawinigan age (McLelland et al. 2010 a, b). Upright and open to tight late northwest- and north-northeast-trending folds (F4, F5) produced a variety of fold interference patterns but little penetrative fabric. The age of the F4 and F5 folds is uncertain, but they may be the result of extensional collapse at ca. 1.05–1.03 Ga (Rivers, pers. comm. 2013). Northeast-trending shear zones disrupted the fold complex into panels but did not alter their internal tectonostratigraphy (Chiarenzelli et al. 2011). The absence of Ottawan deformation in the ALT is consistent with the undeformed state of the ca. 1.16 Ga Kingston dikes (Davidson 1998) of the Frontenac Terrane (Fig. 5) that lies directly west of the Black Lake Shear Zone (Fig. 4).

Within the AHT, the earliest map-scale folds are very large, gently plunging, recumbent isoclines (F2) whose axes trend east–west in the southern and central region and northeast–southwest in the northwest AHT (Figs. 4, 5). The ca. 1.15 Ga AMCG suite and the ca. 1.1 Ga Hawkeye Granite are penetratively deformed and folded by F2 deformation; hence F2 must be of Ottawan age. In contrast, Ottawan F2 isoclines and fabrics are largely absent from the ca. 1.05 –1.04 Ga Lyon Mountain Granite; hence, the granite must postdate the major compressional phase of the Ottawan Orogeny (ca. 1.09–1.05 Ga). All of these fabrics and folds are crosscut by ca. 1.04–1.03 Ga pegmatite dikes providing a minimum age to the time of fabric and fold formation. Extremely large, upright F3 folds strike east–west across the AHT for ~200 km and refolded F2 isoclines form 'bent index-finger' outcrop patterns (Figs. 4, 5, southern Highlands). Equally large, upright F4 folds with NNE axes result in dome and basin patterns where they intersect F3 folds, e.g. Piseco Lake anticline (Fig.5 [PL]).

The preceding brief descriptions of the AHT and ALT reflect important similarities and differences in their tectonic evolution, and these warrant explanation. This is expanded upon in the following section and plate tectonic models are presented that have broad implications for Mesoproterozoic North America.

REGIONAL ASPECTS OF THE GEOLOGIC HISTORY OF THE ADIRONDACK MOUNTAINS

Ca. 1.3 Ga Rifting of the ca. 1.4–1.3 Ga Continental Margin Arc and Opening of Two Back Arc Basins

As noted previously, the oldest rocks in the Adirondacks are 1.4–1.3 Ga juvenile tonalite and granodiorite (McLelland and Chiarenzelli 1990; Daly and McLelland 1991) exposed in the southern and eastern AHT (Fig. 2). The distribution of units of similar age and chemistry in the southwest Grenville Province is depicted in Figure 3, in which their area of outcrop is shown in black (Hanmer et al. 2000). This region contains the remnants of an extensive southeast-facing continental margin arc (Hanmer et al. 2000; Rivers and Corrigan 2000; Karlstrom et al. 2001; Rivers 2008; Rivers et al. 2012), which arose as a southeastern successor to an earlier (ca. 1.5–1.45 Ga) Andean arc that extended eastward into Labrador and is informally known as the Britt-Pinware granitoid belt (Rivers and Corrigan 2000). McEachern and van Breemen (1993) and Hanmer et al. (2000) proposed that the southeastern part of the 1.4–1.3 Ga arc was rifted from Laurentia along a northeast-trending fault zone in the vicinity of the Bancroft Terrane (Figs. 3, 6A, B). Rifting was accompanied by intrusions of ca. 1.29–1.25 Ga gabbro and nepheline syenite (Lumbers et al. 1990; Pehrsson et al. 1996). On the basis of the distribution of ca. 1.4–1.3 Ga continental margin rocks, it is inferred that the arc was split by intra-arc rifting with the northwestern remnants remaining in today's Bancroft Terrane where they comprise the Dysart granitoid suite (Easton 1992). To the southeast, rifted arc fragments were transferred eastward in a widening marginal basin (Figs. 6A, B, 7A) underlain by oceanic crust as indicated by the presence of younger volcanic and sedimentary rocks in the Central Metasedimentary Belt (CMB). Dickin and McNutt (2007) and Dickin et al. (2010) used Nd isotopes to identify domains in the CMB that are underlain by older basement that they correlated with the rifted arc, and which may have served as nuclei for Elzevirian island arcs during the closing stages of the marginal basin(s) that evolved and amalgamated from ca. 1.29 to 1.22 Ga (Fig. 7A). McLelland et al. (1996, 2010a) and Chiarenzelli et al. (2011) proposed that two back-arc basins were formed by the rifting of the continental-margin arc (Figs. 6A, B, 7A), i.e., the Central Metasedimentary Belt

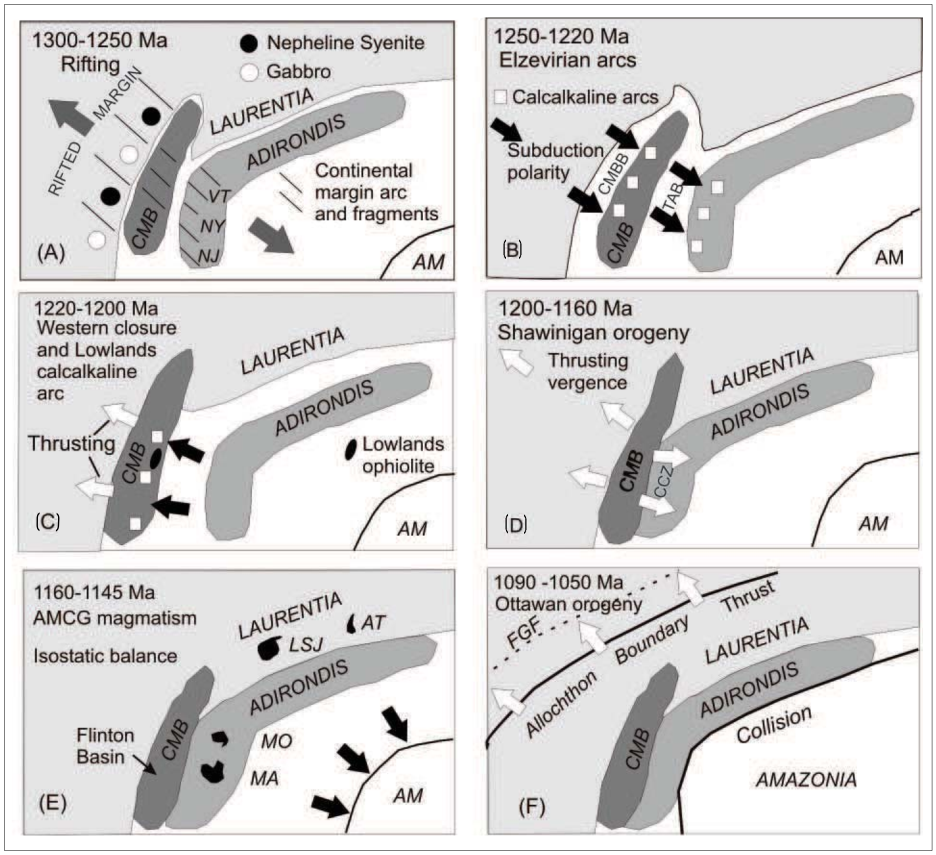

Figure 6. Schematic panel diagram summarizing the distribution and interaction of various segments of northeastern Laurentia during the interval 1.3-1.05 Ga encompassing the rifting, opening and closing of the Central Metasedimentary Belt back-arc basin (CMBB), Trans-Adirondack back-arc basin (TAB), and the Ottawan collision with Amazonia. Note that prior to ca. 1.3 Ga subduction had been to the northwest beneath the Laurentian margin. Blocky black arrows indicate polarity of subduction. Different shades of gray identify important terranes and arcs. Blocky white arrows represent extension. The crustal block labeled Adirondis is based, in part, on the model proposed by Gower (1996) for a large E–W crustal fragment rifted from Laurentia at ca. 1.4–1.3 Ga and reattached by collision at ca. 1.2–1.0 Ga. We have amended Gower's Adirondis by adding a N–S continuation in order to include Vermont (VT), New York (NY), and New Jersey (NJ) where rifted fragments of the Dysart-Mount Holly suite occur. Note that Amazonia is inferred to remain south of the Adirondis region until ca. 1.09 Ga, but its collision with the Laurentian margin farther to the south is inferred to have influenced pre-Ottawan tectonics in the Central Metasedimentary Belt (CMB) during the Shawinigan Orogeny. The Pyrites ophiolite complex is represented by the small black region in the CMB. Abbreviations: AM = Amazonia, AMCG = anorthosite-mangerite-charnockite-granite suite, AT = Atikonak River Anorthosite, CCZ = Carthage-Colton Zone, FGF = future Grenville Front, LSJ = Lac St. Jean Anorthosite, MA = Marcy anorthosite, MO- Morin anorthosite. (After McLelland et al. 2010a).

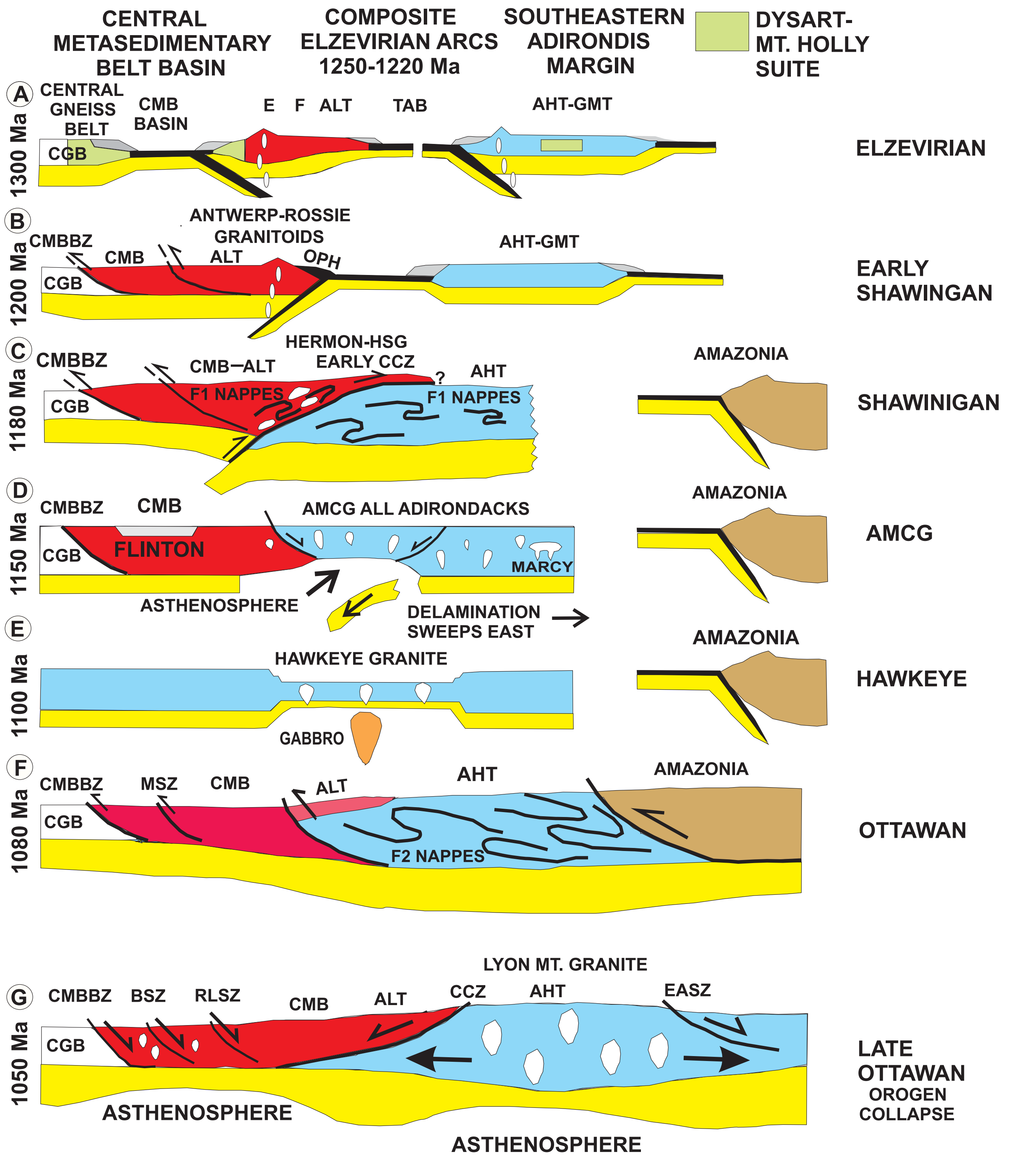

Figure 7. Plate tectonic models showing proposed tectonic evolution along a line from the Adirondack Mountains to the Central Metasedimentary Belt Boundary Zone (CMBBZ). The green areas schematically represent the Dysart-Mount Holly suite. **Abbreviations**: AHT =Adirondack Highlands Terrane, AHT-GMT = Adirondack Highlands-Green Mountains Terrane, ALT = Adirondack Lowlands Terrane, AMCG = anorthosite-monzonite-charnockite-granite suite, BSZ = Bancroft shear zone, CCZ = Carthage-Colton Shear Zone, CGB = Central Gneiss Belt, CMB = Central Metasedimentary Belt, E = Elzevir Terrane, EASZ = Eastern Adirondack shear zone, F = Frontenac Terrane, HSG = Hyde School Gneiss , MSZ = Maberly Shear Zone, OPH = Pyrite Ophiolite Complex, RLSZ = Robertson Lake Shear Zone, TAB = Trans-Adirondack basin. (Modified after McLelland et al. 2010a).

basin (CMBB) and Trans-Adirondack basin (TAB). The eastern margin of the TAB consisted of the AHT-Green Mountains (i.e., Mount Holly) Terrane (GMT) that contains its own rifted fragments of the 1.4–1.3 Ga continental-margin arc. During closure of the CMBB and TAB, two magmatic island arcs formed: the CMB or Composite Arc belt (CAB) to the west and the AHT-GMT arc to the east. The latter formed along the western margin of Adirondis (Figs. 6A, B, 7A), a term originally introduced by Gower (1996) who used it to account for crust rifted from Laurentia at ca. 1.4–1.3 Ga and reattached by collision at ca.1.2–1.0 Ga. We have extended his original Adirondis to include a ~NE–SW prong on its western margin that includes the following terranes: Vermont (Mount Holly), AHT, and Hudson-New Jersey Highlands (Fig. 6A). Also included is the Mauricie Terrane located just east of the Morin Terrane (Fig. 6E [MO]). The reason for including these terranes is that all of them contain juvenile 1.4–1.3 Ga tonalite and granodiorite rifted from the Laurentian margin arc (McLelland and Chiarenzelli 1990; Karabinos and Aleinikoff 1990; Karabinos et al. 1999; Ratcliffe and Aleinikoff 2001, 2008; Volkert et al. 2010). However, this in no way implies that the bedrock geology of these regions extends eastward into Quebec or Labrador. The continental-margin arc fragments are referred to as the Dysart-Mount Holly suite (Rivers and Corrigan 2000). Figure 6A, B show the sequence of events described above in map format and Figure 7A shows them in plate tectonic cross sections. Rivers and Corrigan (2000) estimated that the overall width of the two back-arc basins was similar to that of the Sea of Japan. Volkert et al. (2010) have identified the Trans-Adirondack back-arc basin as far as southern New Jersey, and Aleinikoff et al. (2008) reported rocks of Elzevirian age as far south as the Baltimore Gneiss domes.

The ALT formed along the eastern, trailing margin of the CMB arc and was built primarily from shelf and rise sediments (Chiarenzelli et al. 2011) deposited along the arc's eastern margin (Figs. 6B, 7A) from ca. 1.3–1.22 Ga with the timing based on detrital zircon ages (Heumann et al. 2006). Most of the rise rocks (sandstones, pelites, and volcaniclastic rocks) were deposited on oceanic crust of the Trans-Adirondack basin. Upon closure of the basin at ca. 1.21 Ga., slices of the oceanic crust were obducted onto the ALT where they occur as the Pyrites ophiolite complex (Figs. 6C, 7B) described by Chiarenzelli et al. (2011).

Closure of the Backarc Basins and the Elzevirian Orogeny (ca. 1.25–1.22 Ga)

Within the western CMB, the oldest post-rifting rocks are tholeiite formed within primitive outboard arcs at ca. 1.285 Ga and then deformed and overlain by mafic volcanic and volcaniclastic rocks (Carr et al. 2000 and references therein). The entire package was intruded by ca. 1.27 Ga tonalite plutons (e.g. Elzevir Pluton) and scattered deformation was underway. Farther to the east, calcalkaline volcanic rocks together with carbonate rocks, quartz-rich clastic rocks, and volcaniclastic rocks formed from ca. 1.28–1.27 Ga and probably represent amalgamation of individual arcs into a mature arc system. By ca. 1.245–1.22 Ga widespread metamorphism and tectonism was followed by gabbroic and granitic stitching plutons that intruded the older supracrustal sequences with the age of magmatism younging eastward (Carr et al. 2000 and references therein).

Calcalkaline Elzevirian plutons dated at ca. 1.25–1.22 Ga are present within the AHT (McLelland et al. 2010a), the Mount Holly complex (Ratcliffe et al. 1991; Ratcliffe and Aleinikoff 2001), and Hudson Highlands (Ratcliffe and Aleinikoff 2008). In the Baltimore Gneiss domes calcalkaline granitoid plutons have been dated at ca. 1.25–1.24 Ga and fall within the Elzevirian Orogeny interval (Aleinikoff et al. 2004). These ages suggest that the back-arc basins, island arc accretion, and the Elzevirian orogeny extended at least this far south.

The Early Shawinigan Orogeny, 1.21–1.2 Ga

The Shawinigan orogeny was originally defined by Corrigan (1995), Rivers (1997), and Rivers and Corrigan (2000) on the basis of studies near the small town of that name in the Mauricie region of Quebec. Initially, Corrigan (1995) bracketed the tectonism between 1.19 and 1.16 Ga, but this interval was subsequently widened to 1.19–1.14 Ga. As discussed by McLelland et al. (2010 a, b), the lower end of this age range includes the ca. 1.155 Ga anorthosite-mangerite-charnockite-granite (AMCG) magmatism that post-dated the contractional phase of the Shawinigan orogeny. In addition, McLelland et al (2010 a, b) have argued that, in the Adirondacks, the onset of the Shawinigan Orogeny began at ca. 1.22 Ga, and similar ages have been proposed in Canada by Corriveau and Van Breemen (2000) and Wodicka et al. (2004). Accordingly, we break our discussion of Shawinigan events into early contractional, late- to post-contractional, and AMCG events (Fig. 2).

At ca. 1.22 Ga, arcs formed during closure of the CMB marginal basin when it collided with the Bancroft Terrane passive margin (Hanmer 1988; Hanmer and McEachern 1992) on the northwest side of the basin (Figs. 6C, 7B) and its underlying Laurentian basement (Central Gneiss Belt, CGB) forming the northwest-verging Central Metasedimentary Belt Boundary Zone (CMBBZ). The northwest-verging thrusts caused subduction to step out to the east (Fig. 7B) with a northwestern polarity beneath the Adirondack Lowlands Terrane (McLelland et al. 1996, 2010b). Peck et al. (2004) investigated $\delta^{18}O$ values in zircon from the Lowlands and Frontenac terranes and concluded that their elevated values (11–12‰) reflect oxygen input from hydrated oceanic crust compatible with northwestern polarity during the early Shawinigan Orogeny. It was at this time that slices of ophiolite were obducted onto the Lowlands terrane (Figs. 6C, 7B) as the Pyrites ophiolite complex (Chiarenzelli et al. 2011).

At ca. 1.21 Ga, calcalkaline arc magmatism was initiated in the ALT with emplacement of the Rossie Diorite and the Antwerp Granodiorite (Figs. 6C, 7B) above the northwest-dipping subduction zone (McLelland et al. 2010a; Chiarenzelli et al. 2010). The Antwerp Granodiorite crosscuts all metasedimentary units in the ALT thus providing a minimum age (>1.21 Ga) for the sedimentary sequence. Equivalents of the Rossie-Antwerp suite do not occur in the AHT, which is consistent with their having been a separate terrane at this time (Figs. 6C, 7B) as well as being on the opposite side of the subduction zone. A maximum age of ca. 1.3 Ga for the metasedimentary rocks is fixed by their oldest detrital zircon grains, and the absence of Archean zircon is consistent with deposition in a basin outboard of the Laurentian continent. Although the detrital zircon signature of the metasedimentary sequence in the AHT is somewhat more complex, similar metapelite deposited in the TAB at this time contain a detrital zircon suite (ca. 1.3–1.22 Ga) that fixes the maximum age of deposition, and the absence of Archean zircon indicates a location outboard of Laurentia. The minimum age is fixed by crosscutting ca. 1.16 Ga plutons of the AMCG suite.

Main Contractional Phase of the Shawinigan Orogeny, 1.2–1.16 Ga

By ca. 1.19 Ga early collision-related deformation and metamorphism in the ALT, as well as the AHT, was underway (Figs. 6D, 7C). In the ALT the event was accompanied by emplacement of syntectonic plutons of ca. 1.18 Ga inequigranular Hermon Granite (Heumann et al. 2006) and ca. 1.17 Ga Hyde School Gneiss consisting of approximately equal amounts of leucogranite and tonalite (McLelland et al. 1992; Wasteneys et al. 1999). On the Canadian side of the St. Lawrence River, the ca. 1.17 Ga Rockport Granite is interpreted to be a shallow equivalent of granitic Hyde School Gneiss. None of these Shawinigan igneous rocks are found in the AHT, consistent with the fact that the subduction zone had a westward polarity beneath the ALT, and indicating that full-scale collision probably did not take place until ca. 1.17–1.16 Ga (Figs. 6D, 7C). During collision, upper amphibolite-facies metamorphism in both terranes resulted in widespread anatexis of metapelitic rocks transforming them into migmatites with leucosomes complexly folded by Shawinigan deformation. Igneous zircon from leucosome in metapelite from both the Adirondack Highlands and Lowlands terranes has been dated at ca. 1.18 –1.16 Ga (Heumann et al. 2006).

During the main Shawinigan collision, the ALT was thrust eastward over the AHT for an unspecified distance (Figs. 6D, 7C). The thrusting took place along a suture corresponding roughly to the present day CCZ (Fig. 7C), and its eastward vergence is recorded by kinematic indicators in the ca. 1.164 Ga Diana Syenite Complex (McLelland et al. 2010a, Baird and Shrady 2011). Overthrusting of the ALT placed it into the domain of the Adirondack orogenic lid accounting for its preservation of Shawinigan titanite ages (Mezger et al. 1991; McLelland et al. 1996, 2010a), as well as hornblende $^{40}Ar/^{39}Ar$ ages indicating that Ottawan temperatures in the Lowlands did not exceed 500°C (Streepey et al. 2001). Similar arguments can be made for the CMB in general, one of two major examples of the Ottawan Orogenic Lid proposed by Rivers (2008). Ultimately, this lid was juxtaposed with the deep-to-middle crust during late Ottawan orogenic collapse (Rivers 2008, 2012). In the case of the western Adirondacks, the detachment fault accommodating the collapse was the northwest-dipping CCZ that juxtaposed the Shawinigan amphibolite facies assemblages of the ALT against the granulite facies assemblages of the AHT.

The large-scale F2 and F3 folds in the ALT developed during the Shawinigan Orogeny (Fig. 7C). The time of origin of the upright F4 and F5 folds is uncertain, but they may have formed when the ALT was part of the orogenic lid, as seems to be the case elsewhere in the Grenville Province (Rivers 2012). Within the AHT, evidence for widespread penetrative Shawinigan orogenesis and metamorphism is provided by deformed 1.18–1.16 Ga pegmatitic leucosome in metapelite identical to those in the Lowlands (Heumann et al. 2006; Bickford et al. 2008) and by strongly deformed, foliated xenoliths in ca. 1.15 Ga plutons (McLelland et al. 2010a). Heumann et al. (2006) employed EMPA Ultrachron dating of monazite in oriented thin sections from an isoclinally (F2) refolded isocline (F1) to demonstrate that early axial planar foliation (S1) formed at ca. 1.18 Ga (i.e., Shawinigan Orogeny), whereas the later (S2) axial planar foliation formed at ca. 1.05 Ga (i.e., Ottawan Orogeny). This result provides confidence in assigning a Shawinigan age to many minor F1 isoclines. It is worth noting that, prior to dating leucosome in metapelite, the full extent and nature of Shawinigan metamorphism in the AHT remained largely camouflaged by the intense Ottawan overprint. It is possible that similar considerations may help to explain the apparent paucity of Shawinigan ages in much of the eastern Grenville Province; however, we note that Wodicka et al. (2003) reported pluton ages of ca.1.18–1.17 Ga in the vicinity of the Havre St. Pierre anorthosite massif.

Post-Contractional AMCG Magmatism at the End of the Shawinigan Orogeny, ca. 1.16–1.4 Ga

The AHT is underlain largely by a voluminous AMCG suite that includes the large Marcy Anorthosite massif (Figs. 4, 7D). Extensive SHRIMP2 geochronology has provided evidence that the granitoid rocks, anorthosite, and associated olivine gabbro are coeval at 1154 ± 6 Ma (McLelland et al. 2004; Hamilton et al. 2004). AMCG suites of similar age are present in the Canadian Grenville Province (e.g. Morin, Lac St. Jean, Atikonak; Fig. 6E) as well as southern Norway. The observation that these suites were emplaced during the terminal stages of contractional orogeny provides an important boundary condition regarding their origin (Corrigan and Hanmer 1997; McLelland et al. 1996, 2010b). In as much as this stage is commonly characterized by extensional orogen collapse accompanied by leucogranitic magmatism, McLelland et al. (2010b) interpreted the emplacement of the AMCG suite to be the result of delamination of the orogenic root followed by ascent of asthenosphere to the base of the continental crust where it underwent depressurization-melting resulting in gabbroic melts that ponded at the crust–mantle interface due to density controls. As discussed by Emslie (1978) and Emslie et al. (1994), the ponded gabbroic melts precipitated olivine and pyroxene that sank back into the mantle and andesinelabradorite plagioclase that floated at these pressures creating a low density crystal mush. Advected heat, as well as heat of crystallization, led to widespread melting of the calcalkaline lower crust and the production of AMCG intrusions. In the case of the AHT at ca. 1.155 Ga, the crustal melting appears to have been largely anhydrous and produced orthopyroxene-bearing rocks. By contrast, similar late- to post-orogenic events at ca. 1.05 Ga were accompanied by large influxes of hydrothermal fluids that promoted crustal melting and generated leucogranite represented by the Lyon Mountain Granite in the AHT (Fig. 4). In either case, the large-scale anatexis of the crust weakened the orogen, which then underwent extensional collapse as AMCG plutons ascended to the mid crust (Selleck et al. 2005; McLelland et al. 2010a, b; McLelland and Selleck 2011).

It should be emphasized that the key to AMCG genesis is to bring asthenosphere to the base of the crust and that there exist a variety of ways to do this. Among these are mantle plumes, back-arc rifting, subduction rollback, ridge subduction and reactivation of crustal-scale shear zones. In the case of the Adirondacks, geochronology strongly favours the delamination model presented here.

The Hawkeye Granite Event, ca. 1.1 Ga

The Hawkeye Granite suite (Fig. 4) is the least voluminous plutonic suite in the AHT. Unlike the AMCG granitoid bodies it contains hornblende as the major mafic mineral and, in many places; Hawkeye Granite strongly crosscuts AMCG units. Six samples dated by multigrain TIMS methods (McLelland and Chiarenzelli 1990) yielded ages ranging from 1103 ± 15 to 1090 ± 7 Ma with a weighted average age of 1096 ± 6 Ma. These ages overlap with the major periods of magmatism in the Midcontinent Rift (MCR) given by Paces and Miller (1993) and terminate at approximately the same time as the onset of thrusting that shut off magmatism in the rift (Cannon 1994). We consider that this is not coincidental but, if a far-field cause and effect exists, it will take more research to establish it. In Figure 7E, the Hawkeye Granite is shown evolving via gabbro-induced heating in an extensional setting that is consistent with a far field link to the MCR; however, this represents more speculation than it does fact.

The Ottawan Phase of the Grenvillian Orogeny, 1.09–1.03 Ga

The ca. 1.1 Ga Hawkeye Granite contains penetrative foliation and lineation that must be due to deformation in the Ottawan Orogeny that was the final major deformational event in the AHT (Rivers 2008, McLelland et al. 2010a). This conclusion is supported by monazite dating that yields robust Ottawan ages but only weak and irregular Rigolet signatures (McLelland et al. 2004; Heumann et al. 2006). We conclude, therefore, that the onset of the Ottawan Orogeny postdated 1.1 Ga. On the basis of data from the Grenville Province in Canada, as well as the timing of thrusting in the MCR, we place the onset of the Ottawan orogenic phase at ca. 1.09 Ga in the AHT. The end of the Ottawan orogenic phase is bracketed by zircon crystallization ages of 1.04 Ga for undeformed pegmatite as well as monazite ages of ca. 1030 Ma (McLelland et al. 2010a; Lupulescu et al. 2011; McLelland and Selleck 2011; Wong et al. 2012).

With the possible exception of two imprecise multigrain zircon ages of ca. 1.08 and 1.07 Ga, no Ottawan plutons older than 1.05 Ga are recorded in the AHT (McLelland et al. 2010a). However, monazite ages, and evidence from the Grenville Province in Canada demonstrates that large-scale deformation had begun by ca. 1.09 Ga and the building of an extensive, 60–80 km thick orogenic plateau was underway (Figs. 6F, 7F). Ductile flow at the mid-crustal levels such as represented by the AHT resulted in large-scale recumbent F2 isoclines that span the width of the southern Adirondacks (Figs. 4, 5). Modeling indicates that such structures take tens of millions of years to develop (Jamieson and Beaumont 2011). Conversely, the F2 folding and associated penetrative deformation has little, or no, effect on the ca. 1.05 Ga Lyon Mountain Granite (Figs. 4, 5). This implies that F2 folding must have terminated by this time thus bracketing the F2 deformation into the interval ca. 1.09–1.05 Ga. Peak metamorphic mineral assemblages in these rocks record temperatures of 750°– 850°C and pressures of 6–9 MPa consistent with mid-crustal granulite-facies conditions (Bohlen et al. 1985; Florence et al. 1995; Kitchen and Valley 1995; Darling et al. 2004; Storm and Spear 2005). There has been less certainty about when these granulite-facies *P*, *T* conditions developed in the AHT, but robust evidence has recently been provided by mineral assemblages, coupled with zircon dating, in the famous Gore Mountain garnet mine which exposes the world's largest garnet crystals (average diameter ~18 cm, largest diameter ~1 m; McLelland and Selleck 2012).

Gore Mountain is situated in the central AHT immediately north of the Oregon dome anorthosite massif (Fig. 4[G] and Fig. 5). The deposits are exposed in an open pit mine in coarse almandine amphibolite that is 50 to 100m wide and extends E–W for approximately 1.5 km and 50–100m wide. The ore body is situated within ca. 1.155 Ga AMCG rocks consisting of a small body of anorthosite enclosed within a large charnockite pluton. A steep border fault of uncertain displacement along the southern margin of the deposit juxtaposes garnet amphibolite against charnockite to the south and is associated with injections of ca. 1.05 Ga pegmatites that are part of the Lyon Mountain Granite suite. Typical exposures (Fig. 8) display large garnets with coarse, black hornblende rims or shells set in a much finer, gray matrix of plagioclase, hornblende, and minor orthopyroxene. It is common for the garnets to be aligned (Fig. 8A) along directions that we interpret to be healed, ductile shears that are common in the mine (Goldblum and Hill 1992). This is supported by the occurrence of veins of garnet rimmed by black hornblende along the outer margin of the vein (Fig. 8F).

Gore Mountain megacrystic garnet crystals show only minimal zoning, which is restricted to their margins. Isotopic dating of the garnets has been accomplished by Lu/Hf (Connelly 2006) and Sm/Nd methods (Basu et al. 1989; Mezger et al. 1992). An average of these results yields a crystallization age of 1049 ± 5 Ma, which is within

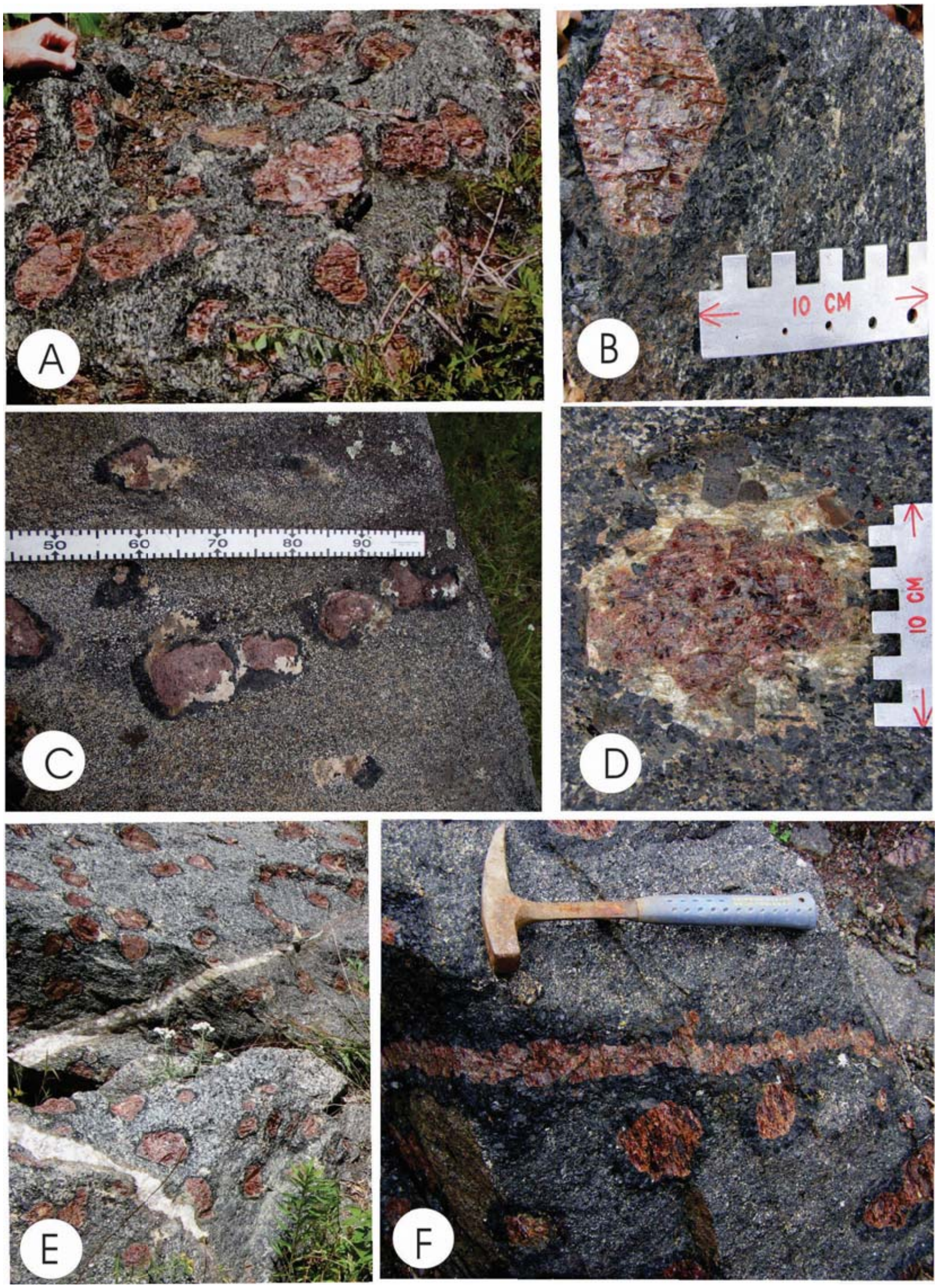

Figure 8. Typical exposures in the Gore Mountain open pit mine. A) Representative outcrop of Gore Mountain megagarnet amphibolite with 10-15 cm garnet crystals enclosed by rims of black hornblende set in a matrix of gray, finer grained plagioclase, hornblende, and subordinate orthopyroxene. Note the alignment of garnet megacrysts along diagonal from lower left to upper right. Scale is given by hand in upper left corner of photo. B) Idiomorphic crystal of garnet typical in the Gore Mountain occurrence. C) Aligned garnet grains with patches of white plagioclase containing bronze, euhedral crystals of orthopyroxene. The assemblage represents the reaction that is typomorphic of the transition from upper garnet amphibolite facies to granulite facies, i.e., Hbl + Grt → Pl + Opx ± Cpx + V. The boudinaged aspect of the garnet occurrences suggest the reaction was accompanied by extensional strain. D) Close-up of reaction in C) that has gone to near completion manifested by deep embayment of garnet and nearly complete consumption of hornblende. E) Dikes of ca. 1047 Ma pegmatite crosscutting ca. 1050 Ma megacrystic garnet amphibolite. F) Vein of euhedral garnet crystals bordered by rims of black hornblende suggesting that the assemblage formed by hydrothermal fluids moving along a nearly horizontal ductile shear zone. (Modified from McLelland and Selleck 2011).

error of the average SHRIMP2 age 1050 ± 10 Ma based on 11 samples of Lyon Mountain Granite exclusive of pegmatite (e.g. McLelland and Selleck 2011). The average of 8 SHRIMP2 U/Pb zircon ages obtained from late pegmatite intrusions associated with Lyon Mountain Granite is 1044 ± 7 Ma (McLelland and Selleck 2011). Monazite ages cited earlier indicate growth of rims at ca. 1050 Ma and virtually none younger than ca. 1036 Ma (Wong et al. 2012). Clearly a culmination in Ottawan igneous and metamorphic activity took place at ca. 1050–1035 Ma. Clarification of this culmination is provided by further examination and discussion of the Gore Mountain megagarnets as described below.

Figure 8A shows a typical view of aligned Gore Mountain garnets and their rims. Note, however, that Figure 8C, D show white patches of plagioclase (An_{40-60}) together with bronze orthopyroxene (En_{50-60}). The white patches embay into the garnet grains and their rims (McLelland and Selleck 2011). Figure 8D provides a close-up of a fully developed plagioclase and euhedral orthopyroxene rim that embays into the garnet and has consumed essentially the entire hornblende rim. Minor clinopyroxene is also a product but forms on remnant, or groundmass, hornblende. Clearly the garnet and hornblende have reacted to yield coexisting plagioclase and pyroxene as well as a fluid phase. This is a well-known reaction and has been extensively studied (de Waard 1965; Spear 1993, and references therein). It reflects passage from the upper almandine amphibolite facies (~750°C, 6–7 MPa) into the granulite facies at temperatures at, or slightly above, 800°C and pressures of 6–9 MPa as reported for Adirondack granulite-facies assemblages (Storm and Spear 2005). The reaction establishes a prograde, clockwise path for Ottawan metamorphism and fixes its inception as slightly post-1.05 Ga, given that the ca. 1.05 Ga megagarnet grains had already formed. EMPA Ultrachron dating of nearby monazite yields an average age of 1046 ± 14 Ma for thick mantles and 1026 ± 5 Ma for thin outer rims (Wong et al. 2012). There are no additional overgrowths on the monazite grains. These results demonstrate that peak metamorphism took place shortly after formation of the megagarnet and emplacement of ca. 1.05 Ga Lyon Mountain Granite and then ended rather abruptly. Our interpretation is that by ca. 1.05 Ga, the overthickened Ottawan lithosphere had delaminated and the ascent of asthenosphere to the base of the crust provided a thermal impulse that raised temperatures in the AHT to granulite-facies conditions. Simultaneously, the lower and mid-crust were weakened by the high temperatures and influx of fluids. Crustal melting produced the ferroan, A-type Lyon Mountain Granite that ascended as the weakened orogen underwent rapid collapse (Fig. 7G). The cool upper crust (i.e., ALT orogenic lid) was down-faulted into juxtaposition with the granulite-facies infrastructure preserved in the AHT. In the west, the major collapse took place along the Carthage-Colton Shear Zone (CCZ) at ca. 1.047 Ga and the Lyon Mountain Granite within the fault is both deformed by and crosscuts the shear zone (Selleck et al. 2005) documenting the contemporaneity of the emplacement of Lyon Mountain Granite with orogen collapse. Recently, Bonamici et al. (2011) used $\delta^{18}O$ zoning profiles in titanite to compute cooling rates in the CCZ, and their results showed that cooling took place at 6–60 times previous estimates with the best fit being a cooling rate of 30–50°C/m.y., a rate vastly in excess of earlier estimates of ~2°C/m.y. (Mezger et al. 1991; Streepey et al. 2001). It is inferred that the differences result from time-averaging of several rapid pulses of down-faulting and cooling followed by longer intervals of quiescence. The average curve through these punctuated events yields much slower cooling rates than revealed by the steep collapse intervals.

A record of orogen collapse is also preserved in the easternmost Adirondacks and exposed in road cuts near Comstock, NY (Fig. 5[C]). Here, foliation in strongly deformed ca. 1.155 Ga augen granite-gneiss dips to the east-southeast at ~30–40° and contains strong down-dip ribbon lineation (Wong et al. 2012). Kinematic indicators, including spectacular tails on alkali feldspar megacrysts, document a normal sense of fault displacement. EMPA Ultrachron dating of monazites establishes peak Ottawan metamorphism at ca. 1.05 Ga with a smaller pulse at ca. 1.03 Ga. Orientation of the monazite grains, and especially the tips of the grains, indicates down-to-the-east displacement at ca. 1.05–1.03 Ga. Together with the timing of displacement along the CCZ, this documents formation of a symmetrical gneiss dome or core complex (Fig. 7G) during the terminal collapse of the Ottawan Orogen (Wong et al. 2011, 2012; McLelland et al. 2012). The difference between the two areas is that hanging wall rocks are not exposed in the eastern AHT suggesting that a master collapse fault may lie buried beneath the Paleozoic cover to the east (McLelland et al. 2011; Wong et al. 2012). We suggest that this master fault is an extension of the Tawachiche Shear Zone (Corrigan and van Breemen 1997) whose along-strike projection passes just to the east of the Adirondacks in the Champlain Valley (Fig. 3 [TWZ]). This shear zone is similar in age to the eastern AHT shear zone and drops the 1.3–1.4 Ga Montauban-La Bostonnaiss island arc terrane down to the east against the Morin and Mékinac terranes (Fig. 3). McLelland et al. (2010a) have suggested that the Adirondack gneiss dome/core complex may extend northward through the Morin Terrane (see also Rivers et al. 2012).

TECTONIC EVOLUTION OF THE GRENVILLIAN INLIERS IN THE APPALACHIANS

When considering the Grenvillian inliers of the Appalachians, it is important to keep in mind that these basement rocks were part of the Laurentian margin that first underwent extension during the opening of Iapetus and the formation of a passive continental margin. This was followed by several major orogenies during which that margin was inverted during closure of the ocean basin and thrust westward for variable and unspecified distances. Accordingly, caution must be exercised when comparing the histories of the Mesoproterozoic massifs. As stated previously, reference to Table 1 will be useful in navigating the data presented below.

Oldest Rocks

We have already summarized occurrences of ca. 1.4–1.3 Ga rifted Laurentian margin arc fragments of the Dysart-Mount Holly suite in the Appalachian inliers from Vermont to New Jersey and ca. 1.25 Ma Elzevirian intrusions found as far south as the Baltimore Gneiss domes. Figure 1 shows the Grenvillian inliers in the Appalachians and Figure 2 summarizes their SHRIMP2 zircon ages and neodymium model ages (T_{DM}). Recently, Tollo et al. (2010) reported an age of ca. 1.327 Ga for granoblastic gneiss of intermediate composition (SiO_2 = 62%) in the Mt. Rogers area of the northern French Broad Blue Ridge massif. These rocks exhibit calcalkaline affinities on AFM diagrams, are magnesian, and plot in the volcanic arc field on Rb versus (Yb + Ta) discrimination diagrams. They are similar in age and chemistry to the Dysart-Mount Holly tonalite plutons of the AHT, Vermont, and southern New Jersey. This is the first recognition of possible candidates for the Dysart-Mount Holly suite this far south. If this possibility were borne out, it would strengthen ties between the Grenvillian inliers of the southern Appalachians and the Grenville Province itself. Further research will help to clarify the issue. In the Blue Ridge French Broad massif west of Mars Hill (Fig. 1), Berquist (2005) dated similar orthogneiss at ca. 1.38 Ga. In the context of the oldest rocks in the Grenvillian inliers, it is important to note that the 'ca. 1.8 Ga orthogneiss' reported from Roan Mountain in the Mars Hill Terrane (Carrigan et al. 2003) has been reinterpreted as a granulite-facies metasedimentary unit, i.e., Carvers Gap Granulite Gneiss and Cloudland Gneiss (Southworth et al. 2010; Tollo et al. 2010; Aleinikoff et al. 2012, 2013). Zircon in these units is clearly detrital in origin and ranges in age from 1.68 to 1.0 Ga indicating a maximum depositional age ca. 1.0 Ga. These rocks are part of a narrow belt of paragneiss deposited on Grenvillian basement from Virginia to North Carolina and metamorphosed shortly after ca. 1.0 Ga during the Rigolet phase of the Genvillian Orogeny (Aleinikoff et al. 2013). The lack of known ca. 1.68 Ga crust in southeast Laurentia suggests that zircon of this age may have been derived from an exotic source.

Shawinigan and AMCG Age Equivalents

Within the Mount Holly complex, Vermont, and nearby Athens and Chester domes, Ratcliffe and Aleinikoff (2001, 2008) dated a foliated granite at 1.172 Ga, and in Massachusetts 35% of the Berkshire Massif basement is underlain by 1.179 Ga (T_{DM} = 1.46 Ga) Tyringham granitic gneiss that intruded all other mapped units, which are generally similar to paragneiss units in AHT, Green Mountains, and Hudson Highlands, New York, (Karabinos et al. 2003; Ratcliffe and Aleinikoff 2008). In the Hudson Highlands, Ratcliffe and Aleinikoff (2008) obtained an age of 1.174 Ga for the widespread Storm King hornblende granite (T_{DM} = 1.46 Ga, Daly and McLelland 1991) that was deformed prior to intrusion by the ca. 1.14 and 1.13 Ga Canopus composite pluton (Aleinikoff 2008) composed of biotite monzonite and hypersthene-biotite diorite. The pluton contains dikes of ferrodiorite and ferrogabbro closely resembling late differentiates of the Marcy Anorthosite massif (McLelland et al. 1994) The Brewster, New York, hornblende granite is dated at ca. 1.13 Ga (Aleinikoff 2008). The Canopus and Brewster plutons crosscut earlier gneissic structures and isoclinal folds thus confirming the Shawinigan age of the structures.

The Byram-Hopatcong hornblende granite suite of the New Jersey Highlands has been dated at 1.176 Ga by Aleinikoff et al. (2007). Local, small layers of anorthositic affinity and the presence of charnockite, suggest that some AMCG magmatism occurred in the area (Volkert et al. 2010). There is clear evidence for Shawinigan deformation from the Green Mountains through the New Jersey Highlands (Ratcliffe and Aleinikoff 2008). In the latter area, Volkert et al. (2010) attributed the deformation to closure of the eastern arc (Losee arc) of the Trans-Adirondack back-arc basin against Laurentia. In their interpretation, this was followed by delamination-related intrusion of the Byram-Hopatcong suite A-type granite plutons into the deformed collision zone (Volkert et al. 2010).

Plutons of Shawinigan age (ca. 1.18–1.14 Ga) are well represented in the Shenandoah and French Broad Blue Ridge massifs (Fig. 1). Within the Shenandoah massif, there exists a range of ages from 1.183–1.030 Ga (Southworth et al. 2010) with a concentration of ages into two groups: ca. 1.18–1.14 Ga and 1.06–1.03 Ga. The older group is designated as Magmatic Interval I (Tollo et al. 2006, 2012), and the age overlaps with similar rocks in the Adirondacks, suggesting geologic connectivity between the Appalachian inliers and Shawinigan-age intrusions in the Adirondacks. Geochemically, the Magmatic Interval I suite in the Shenandoah Massif extends from granodiorite to granite and is subalkaline, tholeiitic, and transitional between peraluminous and metaluminous (Tollo et al. 2006). These characteristics are not unusual for rocks evolving in a continental margin suite, and almost all samples plot within the fields of collisional granite and volcanic-arc granites on a Rb versus (Y + Nb) Pearce discrimination diagram (Tollo et al. 2006). Most of the Group 1 rocks display A-type chemistry, which is interpreted as reflecting derivation by melting of deep crustal calcalkaline precursors (Menuge et al. 2002 and references therein). Granitoid rocks of the Adirondack AMCG suite also display A-type chemistry but are notably lower in SiO_2 than those of the Shenandoah massif and plot in the within-plate field of the Rb versus (Y + Nb) diagram. These differences may reflect differences in source compositions, extent of fractionation, etc.

The tectonic setting of Magmatic Interval I rocks remains somewhat enigmatic. Although their similarity in age to Shawinigan rocks in the Adirondacks suggests formation within a similar tectonic setting, there is currently little persuasive evidence favouring strong Shawinigan deformation/metamorphism in the Shenandoah Massif, although investigations do appear to support some orogenesis at ca.1.155–1.144 Ga (Tollo et al. 2006; Southworth et al. 2010).

Within Magmatic Interval 1 rocks in the Smoky Mountains at the southern end of the western French Broad massif (Fig. 1), Aleinikoff et al. (2007, 2012) have dated granitic leucosome in migmatites at ca. 1.194 Ga and gneissic granitoid rocks at 1.167 Ga both overlapping with Shawinigan metamorphism within Magmatic Group I in the AHT. At Mt. Rogers near the northern extremity of the French Broad massif, Tollo et al. (2006) have dated granitoid rocks at ca. 1.174–1.161 Ga. These plutons were intruded into hot (~750°C) upper amphibolite-facies crust at conditions reflecting regional Shawinigan metamorphism. Given these observations, we suggest that it is only a matter of time before metamorphism of Shawinigan age is identified in the Shenandoah Massif. Lacking from the Shawinigan age rocks of the Appalachians are equivalents of the strongly calcalkaline, subduction-related 1.21–1.17 Ga intrusions of the ALT (i.e., Antwerp Rossie suite, Hermon Granite, and Hyde School Gneiss), which may imply that, unlike the ALT, the Appalachian massifs were not situated above a subduction zone.

Other Interval I granitic rocks in the southern Appalachian Blue Ridge include the Wiley quartzofeldspathic augen gneiss of the Tallulah Falls Dome (Fig. 1) dated by SHRIMP at 1.158 Ga (Carrigan et al. 2003; Hatcher et al. 2004). Within the Toxaway Dome (Fig. 1) orthogneiss yield ages of 1.151 Ga and 1.149 Ga (Carrigan et al. 2003).

A major difference between the Magmatic Interval 1 granitoid rocks of the northern and southern Blue Ridge massifs and the AMCG suites of the Adirondacks is the absence of large masses of anorthosite from the former. Anorthosite is also absent from Shawinigan-age equivalents within the Grenvillian inliers of the New England and New Jersey Appalachians. Although small slivers of anorthosite have been reported in the Shenandoah Massif (Pettingill et al. 1984; Bartholomew and Lewis 1992), there is a notable absence of significant occurrences in the Blue Ridge massifs. This does not mean that the massifs are not related to contemporaneous rocks in the Adirondacks since some differences would be expected within any large suite of rocks. One rather extensive body of Adirondack-type anorthosite occurs within charnockitic gneiss in the Honey Brook Uplands inlier (Fig. 1) in Pennsylvania (Crawford and Hoersch 1984; Tarbert 2007). It has not been directly dated, but Pyle (2004) reported that monazite in adjacent charnockite constrains the anorthosite age to >1070 Ma. Sinha et al. (1996) analyzed the anorthosite for lead isotopes and reported that a plot of whole rock $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ forms a linear correlation equivalent to a $^{207}Pb/^{206}Pb$ age of ca. 1.132 Ga, which, given the uncertainties inherent in the method, is consistent with the 1.155 Ga age of Adirondack anorthosite. On a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot (Sinha and McLelland 1999) seven whole rock samples from Honey Brook plot very close to the Adirondack data (Fig. 9). It is possible that this anorthosite was emplaced at ca. 1.155 Ga, but SHRIMP II dating of zircon is required.

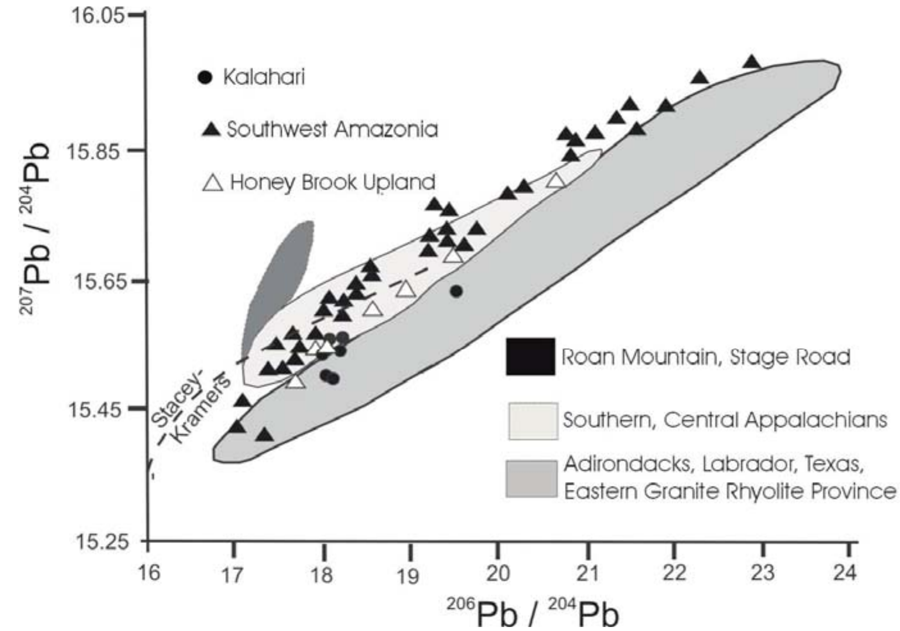

Figure 9. Plot of whole-rock Pb isotope ratios shows the Amazonian affinity of the southern and central Appalachians and the distinctly different, and strongly coherent, data for the Adirondacks, Llano, Labrador, and midcontinent areas. (After Sinha et al. 1996, Sinha and McLelland 1999, Lowey et al. 2003, McLelland et al. 2010a, and Fisher et al. 2011).

Ca. 1.13–1.11 Ga Magmatism

The Appalachian Blue Ridge massifs contain minor plutons of granitic composition (Magmatic Interval II; Tollo et al. 2006; Southworth et al. 2010) that are similar in age (i.e., 1.14–1.11 Ga) to the 1.12–1.1 Ga Hawkeye Granite of the Adirondacks. Although Magmatic Interval II (SHRIMP II ages) is significantly older than the Hawkeye Granite, the ages for the latter were obtained by multigrain techniques and are probably too young due to Ottawan overgrowths on the zircon grains. Six samples of Magmatic Interval II rocks have been dated by SHRIMP and are summarized by Southworth et al. (2010). The tectonic setting of the Group II granite plutons remains uncertain. Note that the Magmatic Group II suite was originally known as the Mitchell Granite (Tollo et al. 2006) and is so designated on Figure 2.

Ottawan Magmatism and Metamorphism

Ottawan orogenesis and magmatism are well represented in almost all of the Grenvillian inliers in the Appalachians. The only exceptions are the Mount Holly complex of the Green Mountains and the Berkshire Massif where evidence is more cryptic. With respect to the Mount Holly complex, evidence for Ottawan activity is: 1) an age of 1.036 Ga for migmatitic, pegmatitic augen gneiss (Ratcliffe and Aleinikoff 2001, 2008; Aleinikoff et al. 2011), 2) four SHRIMP ages of ca. 1.06-1.07 Ga zircon rims from older rocks (Ratcliffe et al. 2011), and 3) folding and metamorphism of ca. 1.149–1.119 Ga augen granite are interpreted to be the result of the Ottawan Orogeny at ca. 1.05 Ga. The scarcity of Ottawan ages in the Mount Holly complex suggests caution regarding interpretation of the extent of high-grade Ottawan metamorphism in the complex because of its Paleozoic overprint. On the other hand, as noted previously, the determination of 'old' $^{40}Ar/^{39}Ar$ ages suggest that it may form part of the orogenic lid. In the Berkshire Massif, the only evidence for Ottawan activity is the common occurrence of inherited ca. 1.07-1.05 Ga cores in the zircons of ca. 1.005 Ga alaskite sills (Karabinos et al. 2003). Although this is only indirect evidence for local Ottawan orogenesis, it does strongly imply the existence of ca. 1.05 Ga Lyon Mountain Granite source rocks at depth.

Within the Hudson Highlands, Walsh et al. (2004) obtained ages of 1.057–1.048 Ga for anatectic leucosome in migmatites, thus confirming Ottawan high grade metamorphism. Aleinikoff et al. (2012) have dated the Crystal Lake Granite at 1.058 Ga and a xenotime-monazite pod in paragneiss at 1.036 Ga. In addition, Walsh et al. (2004) dated deformed Danbury megacrystic granite at 1.046 Ga, an age equivalent to that of the chemically similar Lyon Mountain Granite of the AHT. In the New Jersey Highlands, undeformed trondhjemitic anatectite within the ca. 1.3 Ga Losee Tonalitic Suite have yielded an Ottawan age of 1.030 Ga (Volkert et al. 2010).

The State Farm Gneiss of the Goochland terrane (Fig. 1), has been dated by Sm–Nd (Owens and Samson 2004) at 1.046–1.023 Ga and at 1.057–1.013 Ga (Owens and Tucker 2003) using single grain zircon dating. Aleinikoff et al. (1996) also employed single grain zircon dating to obtain a crystallization age of 1.045 Ga for the coeval Montpelier Anorthosite. The anorthosite is similar in age and composition the CRUML-type (Chateau-Richer, St. Urbain, Matawa, Labrieville) AMCG suite of eastern Quebec (Owens et al. 1994). It is also similar to the ca. 1.045 Ga Roseland anorthosite of the northern Shenandoah Massif (Pettingill et al. 1984; Sinha et al. 1996; Owens and Samson 2004).

In the northern Shenandoah massif there exists ample evidence for Ottawan igneous activity and metamorphism. Ages for 12 dated samples range from 1.063 to 1029 Ga and compositions from orthopyroxene-bearing leucogranite to monzogranite. Together these lithologies represent Magmatic Interval III of Tollo et al. (2010) and Southworth et al. (2010). Metamorphic rims on these and older zircons fall into the age range of ca. 1.055 - .979 Ga, consistent with Ottawan metamorphism. According to Southworth et al. (2010), Ottawan deformation was less intense here than elsewhere in the Appalachians. In part, this may be the result of the late- to-post-tectonic emplacement of the Group III plutons, and this is also true in the Adirondacks where the late- to post-tectonic ca. 1.05 Ga Lyon Mountain Granite did not experience the early nappe-forming deformation that affected Shawinigan and older rocks. It is also the case for the ca. 1.16–1.15 Ga Parc des Laurentide Leucogranite (Fig. 3 [PdL]) in central Quebec (Corrigan and van Breemen 1996). Accordingly, we concur with Tollo et al. (2004) who interpreted the A-type leucogranitic Magmatic Interval III intrusions in the Shenandoah Massif to be compositionally and chronologically similar to Lyon Mountain Granite of the AHT and to have formed during ca. 1.05 Ga orogen collapse at the end of the Ottawan Orogeny.

Farther south in the Smoky Mountains of the French Broad Massif, weakly foliated granite bodies yielded ages of ca. 1.045–1.02 Ga, and in the Mt. Rogers area at the north end of the massif weakly foliated granite bodies yielded ages of ca. 1.06 Ga (Tollo et al. 2010). In the nearby Grandfather Mountain Window, the Blowing Rock Granitic Gneiss has been dated at ca. 1.08 Ga (Carrigan et al. 2003), and in the Pine Mountain Window high-grade gneiss yields ages of ca. 1.06–1.01 Ga (Steltenpohl et al. 2004).

All of the foregoing observations support the conclusion that the igneous and metamorphic history of the AHT is also present in the Grenvillian inliers of the northern and southern Appalachian massifs and that this represents Grenvillian connectivity throughout the region. The Shawinigan Orogeny in the Appalachians is interpreted to have resulted from the ca. 1.2 Ga collisions with Amazonia as it worked its way northward causing transpressional strain along the eastern Laurentian margin and by ca. 1.09–0.098 Ga made a direct, northwest verging collision with the Grenville Province (Tohver et al. 2002, 2004). In a related way, the Shawinigan closure of the CMB and TAB may have been due, in part, to a far-field effect related to the displacement of Amazonia along the eastern Laurentian margin (Figs. 6, 7). This is an attractive model; however, and not surprisingly, the final picture will be more complex. We discuss this in the following sections on Nd model ages and Pb-isotope arrays.

Rigolet Phase of the Grenvillian Orogeny

The ca. 1.01–0.98 Ga Rigolet phase that closed out the Grenvillian Orogeny is not observed in the ALT and is limited in the AHT to zircon overgrowths. A small granitic dike swarm dated at ca. 0.933 Ga (McLelland et al. 2001) in the southern AHT is too young to be part of the Rigolet phase but is noted here for completeness. Magmatism of Rigolet age is well represented in the Grenvillian inliers of the New England Appalachians. Ratcliffe and Aleinikoff (2001) dated the Cardinal Brook rapakivi granite suite of the Mount Holly complex and Chester and Athens domes at ca. 1.0 Ga, and Karabinos and Aleinikoff (1990) dated the granitic Bull Hill Gneiss at ca. 0.965 – 0.945 Ga. In the Berkshire Mountains, Karabinos et al. (2003) obtained ages of ca. 1.0 - 0.997 Ga for alaskite dikes and sills. In New Jersey the pristine, undeformed Mt. Eve Leucogranite yielded an age of 1.02 Ga (Drake et al. 1991; Gorring et al. 2004; Volkert et al. 2010) that is a borderline candidate for a Rigolet intrusion, although an argument for late-Ottawan intrusion could also be made. Within the Pine Mountain Uplift of the southern Appalachians high-grade granitic gneiss yielded an age of 1.011 Ga (Steltenpohl et al. 2004; Hetherington et al. 2006, 2007).

AGE OF SOURCE ROCKS FOR ADIRONDACK–APPALACHIAN MESOPROTEROZOIC MAGMATISM

Neodymium Model Ages

Neodymium model ages, T_{DM}, provide a powerful tool for ascertaining the time at which a given igneous rock, or its precursor, was extracted from the mantle. Perhaps not surprisingly, the igneous rocks of most large provinces yield the same T_{DM}, even if individual zircon crystallization ages differ (cf. Daly and McLelland 1991). In recent years, an increasingly broad database has been assembled demonstrating that terranes with disparate tectonic histories may exhibit similar neodymium model ages and, accordingly, were likely produced from the same mantle source. One of the most impressive associations extends the length of the Grenville Province from Labrador to the Adirondacks, the southeastern Granite-Rhyolite provinces, and the Grenvillian rocks of Texas. Along the ~5000 km length of this belt, the oldest granitoid plutons have zircon crystallization ages of ~1.45–1.35 Ga and T_{DM} ~1.55–1.4 Ga (Daly and McLelland 1991; McLelland et al. 1996; Menuge et al. 2002; Roller 2004; Dickin and McNutt 2007; Slagstad et al. 2009; Dickin et al. 2010; Fisher et al. 2010). Because the crystallization ages of the granitic plutons are within ~100 m.y. of their mantle extraction ages, they are considered to be juvenile implying an arc-related origin (e.g. Bowring et al. 1991). Accordingly, a southeast-facing continental margin arc setting has been proposed for the eastern margin of Laurentia from 1.48–1.35 Ga (Rivers and Corrigan 2000; Menuge et al. 2002). High-grade remnants of the actual arc are well exposed (Slagstad et al. 2009) in the Muskoka Domain (Fig. 3). As stated previously, this arc is characterized by T_{DM} ages <1.55 Ga. For orthogneiss within the Adirondacks, εNd versus age plots show that units with crystallization ages of ca. 1.155 Ga and ca. 1.05 Ga lie on the same Nd evolution trajectories as the oldest (ca. 1.35 Ga) juvenile tonalite of the Dysart-Mount Holly suite (Daly and McLelland 1991; McLelland et al. 1996).

In eastern Kentucky and central Tennessee, within ~250 km of the southern Appalachian Grenvillian inliers (Fig. 1), three drill holes (OH–DC and KY–PU, CO–DC) have encountered basement rocks, two of which have yielded U/Pb zircon crystallization ages of 1.38 Ga (OH) and 1.46 Ga (KY) (Van Schmus et al. 1993b; Fisher et al. 2010). In addition, the sample KY yielded a T_{DM} age of 1.45 Ga (Fisher et al. 2010) and a troctolite from a fourth nearby drill-core, CG, produced a T_{DM} of 1.38 Ga (Fisher et al. 2010). It was thought that these rocks comprised part of the Southern Granite-Rhyolite Province (crystallization ages = 1.4–1.34 Ga) or correlate with juvenile plutons intruded into parts of the Eastern Granite-Rhyolite Province (crystallization ages = 1.5–1.44 Ga). A question then arose regarding what relationship the rocks might have to the basement of the nearby Blue Ridge massifs. In order to address this issue, Fisher et al. (2010) determined Sm–Nd concentrations and T_{DM} values for 14 southern French Broad Massif samples and found only one value (1.43 Ga) below the 1.88–1.55 Ga range of the other 13. These T_{DM} ages, like others in the southern Appalachian inliers, are 400–500 m.y. older than their magmatic crystallization ages. In contrast, the T_{DM} age for drill-hole sample KY is 1.45 Ga and for CG is 1.38 Ga, i.e., normal ages for the Eastern Granite-Rhyolite Province, which lies in the subsurface within 250 miles of the French Broad Massif. On the basis of these results, it seems highly unlikely that the Eastern Granite-Rhyolite Province forms the basement for the southern Appalachian Grenvillian inliers.

Recent studies by Tollo et al. (2006) and Southworth et al. (2010) in the northern Shenandoah Massif have produced 11 T_{DM} ages ranging from 1.62 to 1.37 Ga, with 9 of the 11 model ages exceeding 1.49 Ga (average age of 1.51 Ga). The average age overlaps the range of the Eastern Granite-Rhyolite Province (1.55–1.43 Ga), but the diagnostic 1.5–1.4 Ga arc plutons of that province have not been recognized, making it unlikely that the Shenandoah Massif represents an extension of the Eastern Granite-Rhyolite Province.

It is possible that the Appalachian results are explicable on the basis of reworking of basement rocks, but the argument is painfully contorted and full of special pleading and speculation – especially given the proximity of the three drill-holes to the Grenvillian inliers of the southern Appalachians. A path through this confusion was provided by Tohver et al. (2004) and Loewy et al. (2003, 2004), who noted the striking similarities between neodymium model ages in the French Broad Massif and those in Amazonia. We discuss this in the next section.

Pb Isotope Arrays and Basement Mapping

Sinha et al. (1996) carried out a whole-rock Pb isotope investigation of the southern and central Appalachians, and Sinha and McLelland (1999) produced a comparable study for the Adirondack Mountains. The results are shown in Figure 9. Remarkably, the Pb–Pb arrays from the Grenvillian inliers in the southern Appalachians and Adirondacks data do not overlap. Instead, the Adirondacks plot in the same Pb–Pb space as those for samples from Labrador (Loewy et al. 2003, 2004), the Granite-Rhyolite Province (Van Schmus et al. 1993b), and the Llano and Van Horn uplifts of Texas (Roller 2004). In contrast, the Grenvillian inliers of the southern and central Appalachians form an array that overlaps with that of the Sunsas Orogen of southwest Amazonia (Tohver et al. 2004). This result implies that the Mesoproterozoic basement in the southern and central Appalachians is exotic to Laurentia and probably Amazonian in origin. It has been suggested that the Sunsas Orogen of western Brazil was overthrust onto Laurentia during collision from ca. 1.2–1.15 Ga and transferred to Laurentia during the Neoproterozoic breakup of the Rodinian supercontinent (Tohver et al. 2002, 2006; Loewy et al. 2003, 2004; McLelland et al. 2010a; Fisher et al. 2010). Supporting this model is a recent paleomagnetic pole for red beds in the Aguapei Group (D'Agrella-Filho et al. 2008) from which xenotime rims provide a well-constrained 1.15 Ga age for deposition. This result places the southwest Amazonian craton in proximity to the southeast margin of Laurentia at ca. 1.15 Ga and lends support to the ca. 1.2 Ga collision of Amazonia with Laurentia. The collision was transpressional and sinistral resulting in folding in Laurentia and strike-slip faulting in Amazonia (Tohver et al. 2004). We suggest that the Shawinigan Orogeny recorded in the Appalachian Grenvillian inliers resulted, in part, from the early phases of this collision, while the Grenvillian Orogeny was the product of a more head-on collision with the northeast-trending southern margin of Adirondis and the Grenville Province.

The inference of the presence of exotic crust in the southern and central Appalachians implies the existence of a cryptic suture between that region and the rest of Laurentia. This realization has re-awakened interest in the northeast-trending magnetic anomaly (Fig. 1) referred to as the New York–Alabama lineament (King and Zeitz 1978). The long-standing interpretation of this feature as an ancient suture is strengthened by the observation that it passes through a narrow tract between the drill holes in Kentucky and Tennessee that bear the isotopic signature of the Eastern Granite-Rhyolite Province and the Grenvillian inliers of the southern and central Appalachians with Amazonian isotopic signatures. The exact location is complicated by Paleozoic thrusting and restacking of the basement rocks. Notwithstanding this, the suture possibility remains viable and intuitively attractive.

THE GRENVILLE OROGEN IN TEXAS

Llano Uplift

The high-grade Mesoproterozoic core of the Grenville Orogen is exposed in the large (~9000 km^2) Llano Uplift of central Texas (Fig. 1). In addition, several small uplifts in west Texas and northeastern Mexico (Fig.1) expose mid-to low *P*, *T* assemblages in rocks where orogeny occurred during the late Mesoproterozoic to early Neoproterozoic. To the north, the Grenville Orogen is bounded by the Llano Front that represents the northern edge of Grenvillian deformation (Barnes et al. 1999; Rohs and Van Schmus 2007) and appears to coincide with the northern limit of the Abilene gravity anomaly, interpreted to reflect a granitic batholith. Near Van Horn (Fig. 1 [VH]), the front is exposed as a narrow (2–5 km.) fold and thrust belt north of the overriding Steeruwitz Thrust (Soegaard and Callahan 1994; Mosher 1998; Bickford et al. 2011).

The Llano Uplift is underlain by multiply deformed igneous and metamorphic rocks ranging in age from ca. 1.36–1.07 Ga including late- to post-kinematic granitic plutons with crystallization ages of ca. 1.12–1.07 Ga (Walker 1992; Mosher 1998; Mosher et al. 2008). A wide range of lithologies is represented including ophiolite and eclogite, and regional metamorphic grade was generally at upper amphibolite to granulite facies at ca. 1.15–1.12 Ga (Mosher 1998). Three major tectonic domains have been defined: from south to north and oldest to youngest they are the Coal Creek, Packsaddle, and Valley Spring domains that extend across the uplift (Mosher 1998). The principal lithic and tectonic subdivisions of the Llano Province are described below, and the account relies heavily on the research of Mosher (1998), Rohs and Van Schmus (2007), and Mosher et al. (2008).

Coal Creek Domain

The Coal Creek domain is underlain by dioritic to tonalitic plutons structurally overlain by thrust sheets of ophiolite consisting of serpentinized harzburgite. Together, the assemblage is interpreted as an ensimatic arc that was active from ca. 1.325 to 1.275 Ga (Roback 1996). Significantly, the domain exhibits an early magmatic and metamorphic history not present elsewhere in the Llano Uplift supporting the outboard origin of the arc. In addition, Pb and Nd isotopic values for the domain differ significantly from that elsewhere in the uplift, and at its northern extremity. The Coal Creek domain structurally overlies the younger Packsaddle Formation along the Sandy Creek ductile thrust zone (Roback 1996).

Packsaddle Domain

This polydeformed domain is dominated by metamorphosed shallow shelf and slope deposits (e.g. marble, quartzite) with intercalated igneous and volcaniclastic rocks (Mosher 1998, 2007). The supracrustal rocks record ~30 m.y. of deposition on an ancient continental shelf along the southern margin of Laurentia. Igneous layers within the sequence have yielded ages between ca. 1.25 and 1.24 Ga clearly post-dating Coal Creek magmatism. One sample near the Sandy Creek thrust yields a 1.274 Ga age, but this comes from a complex area near the tectonized contact zone with the Coal Creek domain.

Valley Spring Domain

The Valley Spring domain contains terrigenous clastic rocks, but is dominated by ca. 1.288–1.232 Ga granitic gneiss and rhyolitic sheets that may represent a continental-margin arc with subduction to the north beneath Laurentia. A single sample of the older granitic gneiss (basement?) has yielded an age of ca. 1.37 Ga. The Valley Spring domain is overthrust by the Packsaddle and Coal Creek domains and shows variable degrees of deformation that decrease in intensity away from the thrust contact. Rivers et al. (2012) have suggested that the Coal Creek arc may be a candidate for a southern extension of the Elzevirian CMB back-arc basin in the Grenville Province.

Orogenic Culmination in the Llano Uplift

On the basis of existing data, Mosher (1998) and Mosher et al. (2008) suggested that north-northeast transport and eclogite-facies metamorphism in the Llano Uplift was initiated at ca. 1.147–1.138 Ga in the west and 1.133–1.131 Ga in the east, where it continued until ca. 1.12 Ga. In order to account for these observations, Mosher (1998) and Mosher et al. (2008) invoked a shift in subduction polarity southward beneath the northern margin of a large, outboard southern continent with the accreted Coal Creek arc attached to its northern margin by ca. 1.25 Ga. The Llano–southern continent collision is inferred to have begun between 1.15 and 1.14 Ga and to have involved south-directed subduction of the leading margin of Laurentia producing eclogite, in addition to that formed at the base of the Coal Creek arc. The subduction also led to jamming of the subduction zone, which enhanced uplift, retrothrusting, and northeastward thrusting over the Laurentian margin (Mosher et al. 2008). Soegaard and Callahan (1994) termed these tectonic events the Llano Orogeny.

The identification of the southern continent remains elusive, but a likely candidate is the Kalahari Craton whose Pb–Pb array (Fig. 9) largely overlaps that of the Llano-Adirondack trend (Eglinton and Kerr 1989; Dalziel et al. 2000; Loewy et al. 2003, 2011; Roller 2004; Fisher 2010). Paleomagnetic poles derived by Dalziel (1992) and Weil et al. (1998) are consistent with this model. We conclude that orogenesis in the Llano Province began sometime between 1.15 and 1.14 Ga and may have been due to collision with the Kalahari Craton. Mosher (1998) and Mosher et al. (2008) have argued cogently that the eastern Laurentian collision with Amazonia (discussed in a previous section) could not have produced the approximately orthogonal coeval vergences that exist between the southern and central Appalachians and Llano Orogen nor can they explain the orthogonal divergence between the eastern Llano and West Texas vergences. Notwithstanding the foregoing, the case made for an Amazonian collision (Tohver et al. 2002) has its own merits, and should not be dismissed out of hand. The issue of the 'collision with a southern continent' deserves further research.

Late- to Post-Tectonic Magmatism

The Llano Uplift is noted for the intrusion (ca. 1.12 –1.07 Ga) of large ferroan, A-type granitic plutons. The older (ca. 1.12–1.16 Ga) intrusions are slightly deformed and are considered to be late-tectonic, but the younger, post-tectonic granite bodies (ca. 1.1–1.07 Ga) are circular, undeformed, and have low-pressure contact aureoles. The region shows evidence of extension at the time of the late plutonism. Mosher et al. (2008) accounted for these relationships by introducing slab-breakoff and delamination at ca. 1.1 –1.07 Ga. Removal of the dense lithosphere resulted in ascent of hot asthenosphere to the base of the crust, and these two factors led to buoyancy of the collisional orogen. Extensional, buoyant, and contractional collisional stresses coexisted for a period of time resulting in locally variable rifting and folding/faulting. During this period, influx of asthenospheric heat resulted in increasing melting of continental crust of intermediate composition to yield ferroan A-type granite. This weakened the lower and middle crust leading ultimately to orogen collapse and the emplacement of late- and post-tectonic 1.09–1.07 Ga granite plutons. Rivers et al. (2012) have suggested that this late extension may reflect the presence of an orogenic lid analogous to that in the Grenville Province.

West Texas and Northern Mexico

Small exposures of Mesoproterozoic rocks occur near Van Horn, Texas (Fig. 1 [VH]), and at Sierra Del Cuervo (Fig. 1 [SDC]) and Cerro Del Carrizalillo (Fig. 1 [CDC]) in Mexico. These provide additional insights into the late evolution of the Grenville orogen along Laurentia's southern margin. Among other things, the area contains the only preserved occurrence of a Grenvillian foreland sedimentary basin in North America, although remnants of such a feature may be preserved in Scotland (Krabbendam et al. 2012; Bonsor et al. 2012).

Near Van Horn (Fig. 1 [VH]) four 5–15 km long basement uplifts expose the gently south-dipping Steeruwitz Thrust that contains, in its footwall, the 1.38 to 1.33 Ga polydeformed (pre-thrust) upper greenschist to amphibolite facies bimodal metavolcanic and immature metasedimentary rocks of the Carrizo Mountain Group over polydeformed, but unmetamorphosed, sedimentary rocks to the north (Soegaard and Callahan 1994). The lowermost of the underlying units consists of stromatolitic, intertidal carbonate rocks of the Allamore Formation that contain thin rhyolitic flows and welded ash-flow tuffs dated at ca. 1.255 Ga and providing the time of deposition (Jon McLelland 1996; Bickford et al. 2000). This unit is unconformably overlain by the Tumbledown Formation consisting of sandstone with rhyolitic clasts and large carbonate blocks derived from the Allamore Formation. Both the rhyolitic clasts and a rhyolitic felsic tuff at the top of the formation yielded an age of ca. 1.243 Ga dating the time of deposition. Geochemistry of the bimodal suite and mafic volcanic rocks suggests that the Tumbledown Formation accumulated in an intracontinental rift or a marginal back-arc basin. Unconformably above the Tumbledown Formation is the Hazel Formation (~2500 m) consisting of boulder conglomerates and sandstones derived principally from the underlying Allamore and Tumbledown Formations. In addition, unmetamorphosed rhyolite and granite boulders and clasts of unknown provenance are also present and dated at ca. 1.13–1.12 Ga (Roths 1993). Soegaard and Callahan (1993) interpreted the agglomeratic Hazel Formation as formed in a prograding series of coalescing alluvial fans and sand dunes receiving very immature debris from a rapidly rising tectonic welt to the south. Tectonic transport of the thrust sheets composed of Allamore and Tumbledown Formations over the Hazel Formation resulted in the northwest-directed displacement of the entire package. The uppermost thrust sheet in the tectonic package consists of Carrizo Mountain Group units transported on the Steeruwitz Thrust, which has been interpreted as the culminating tectonic event in the Van Horn area (Bickford et al. 2000). However, the possibility must be reserved that the foreland thrust belt was produced by out-of-sequence faulting, during which the Steeruwitz thrust preceded the underlying thrusts in the sedimentary package (Grimes and Copeland 2004).

$^{40}Ar/^{39}Ar$ dating of hornblende and muscovite within a mylonite zone related to the Steeruwitz Thrust yielded ages of 1.04 Ga and 1.03 Ga, respectively, thus dating late movements on the fault (Jon McLelland 1996; Bickford et al. 2000). Grimes and Copeland (2004) produced $^{40}Ar/^{39}Ar$ ages of ca. 1.05–0.99 Ga for hornblende and muscovite in the Carrizo and Van Horn Mountains. Collectively, these ages bracket the Hazel Orogeny interpreted as a transpressive event that displaced units to the north-northwest (Soegaard and Callahan 1994). Mosher (1998) and Mosher et al. (2008) considered the Hazel Orogeny to be a late stage, western extension of the Llano Orogeny, but the age gap of ~90 m.y. suggests that it is better correlated with the 1.01–0.98 Ga Rigolet Orogeny that also involves low-grade foreland folding and thrusting. Five kilometers to the north of the Steeruwitz Thrust, the Allamore and Tumbledown Formations are undeformed and flat-lying. They are reexposed to the west in the undeformed Franklin Mountains north of El Paso where they occur as large roof pendants in the ca. 1.12 Ga alkaline Red Bluff Granites (Shannon and Barnes 1991; Bickford et al. 2000).

The degree of ductile deformation and thermal metamorphism of the Carrizo Mountain Group increases toward the south reflecting basin inversion causing stacking of thrust sheets from increasing depth. The immature nature of the sediment in the group favours their deposition in a continental rift basin (Rudnick 1983; Jon McLelland 1996; Bickford et al. 2000). After replotting the data of Rudnick (1983) on immobile trace element discrimination diagrams of Pearce and Cann (1973) and Pearce et al. (1984), Roths (1993) proposed that the Carrizo Mountain Group accumulated in a rift setting, consistent with the composition of dominantly feldspathic, micaceous metasandstone units in the central and southern Carizzo Mountains.

Until recently, the existence of a continental margin arc had not been demonstrated in the area. However, the required arc is now thought to be represented by exposures at Sierra Del Cuervo (Fig. 1 [SDC]), Mexico (Blount 1993) that consist of metagabbro (ca. 1.333 Ga), granite gneiss (1.274 Ga), metatonalite, and metadiorite all of which are metamorphosed to amphibolite facies. Geochemical signatures in these rocks indicate that they are similar to those in magmas generated at the base of an overthickened continental or island arc (Gill 1981). Crosscutting trondhjemitic dikes have been dated at 1.08 Ga (Blount 1993). Approximately 100 km to the east, the Cerro Del Carrazilillo (Fig. 1) Mesoproterozoic uplift consists of polydeformed and mutually crosscutting trondhjemite, granite, and tonalite produced during orogenesis. The existence of these two Mexican exposures provides compelling support for an early (1.4–1.3 Ga) back-arc rift basin along the southern Laurentian margin from Llano to Van Horn and is consistent with the culminating Llano Orogeny caused by collision of the southern continent at ca. 1.15–1.17 Ga. In contrast, collision with Amazonia at this time fails to satisfy the directions of Mesoproterozoic tectonic transport in Texas. In fact, the observation that in west Texas tectonic transport is to the north-northwest while in the east it is to the north-northeast suggests an indenter-type collision (Mosher 1998) that Amazonia would not be able to provide from its position along the eastern margin of Laurentia.

It should be noted, that one of us (MEB; Bickford et al. 2000) has suggested that the shallow-water depositional characteristics of the Allamore Formation, the generally low metamorphic grade of all the West Texas 'Grenvillian' rocks, and the bimodal nature of the volcanic rock assemblages, indicate deposition within rift basins. Further, the occurrence of such features as ca. 1.17 Ga alkaline syenite at Pajarito Mountain in New Mexico (Kelley 1968), the 1.1 Ga Apache Group (Silver 1978; Wrucke 1989, 1993), and the Unkar Group (Elston 1993; Larson et al. 1994) in Arizona, and the ca. 1.08 Ga Pahrump Group rocks in the Death Valley region of southern California (Lanphere et al. 1964; Heaman and Grotzinger 1992; Wright and Prave 1993), all of which have been interpreted as deposited in rift basins, led Bickford et al. (2000) to propose that a major transcurrent fault system extended across southern Laurentia that began ca. 1.12 Ga and persisted until about 1.08 Ga. It is possible that the continental arc model proposed above could be consistent with the formation of a major transcurrent fault system if the arc–continent collision were transpressional in nature.

It can now be stated with some confidence that the Grenville Orogen along the southern margin of Laurentia has been reasonably well defined and extends Mesoproterozoic continental margin arcs and Ottawan continental collisions at least as far southwest as the Trans-Pecos regions of Texas and northeastern Mexico, i.e., a distance exceeding 5000 km, and rivaling the dimensions of the Himalaya–Alps orogenic belt.

SUMMARY

Recent zircon U/Pb SHRIMP2 geochronology, together with other isotope geochemical research, have provided a much improved, and more complete, understanding of the evolution of the Grenville Orogen in North America. This review has focused on the Grenville Orogen in the USA and has also presented a brief summary of the long-lived Paleoproterozoic to Mesoproterozoic continental margin arcs that now underlie the midcontinent. These arcs were followed by the formation of the Grenville Orogen whose major tectonic, metamorphic, and magmatic evolution is summarized below.

1. The earliest events in the tectonomagmatic history of the Adirondacks took place during the interval 1.3–1.25 Ga when two back-arc basins were formed by rifting of a 1.4–1.3 Ga continental margin arc in what is now southwestern Ontario. The rifted fragments served as nuclei for the CMB and TAB that evolved into outboard arcs and are preserved in the AHT and Grenvillian inliers in Vermont, the Hudson Highlands, New Jersey Highlands and as far south as the Baltimore Gneiss domes. Recent work by Tollo et al. (2012) has demonstrated that rocks of similar age and chemistry occur near the northern margin of the southern Blue Ridge Massif and may represent a southernmost occurrence of the rifted continental-margin arc. This possibility warrants further research. In the Llano Uplift, as well as in West Texas, northward subduction resulted in continental margin magmatism, rifting, and formation of back-arc basins at ca. 1.4–1.3 Ga (Mosher 1998).
2. Closure of the Grenville Province back-arc basins at ca. 1.25–1.22 Ga resulted in the Elzevirian Orogeny and calcalkaline magmatism as the arcs amalgamated. By ca. 1.2 Ga, the western basin (CMB) closed out, and the arc collided with eastern Laurentia along the present Central Metasedimentary Belt Boundary Zone giving rise to an early phase of the Shawinigan Orogeny. This caused subduction to step out to the east and flip to a northwest polarity beneath the ALT that then experienced calcalkaline arc magmatism from ca.

1.2–1.19 Ga. The Pyrites ophiolite complex was obducted onto the ALT at this time. Elzevirian magmatism has been identified in the Grenvillian inliers of Vermont, New York, and New Jersey. Farther south, in the Baltimore Gneiss domes granitoid plutons have been dated at ca. 1.2–1.24 Ga (Aleinikoff et al. 2004), an age range that coincides with the Elzevirian Orogeny. In the Llano Uplift and West Texas, back arc basins closed out during this interval as the southern continent approached the Laurentian margin.

3. Closure of the eastern basin (TAB) resulted in collision of the AHT western margin of Adirondis with the ALT at the eastern margin of the CMB. This initiated the major collisional phase of the Shawinigan Orogeny (ca. 1.19–1.17 Ga) that caused upper amphibolite-facies metamorphism and anatexis in both the ALT and AHT. The ca. 1.18 Ga Hermon Granite Gneiss was intruded early in the collision and the syntectonic Hyde School Gneiss and the Rockport granite were intruded at ca. 1.72 Ga. During the collision, the ALT was thrust over the AHT for an unspecified distance and formed an upper crustal orogenic lid. Following the cessation of major contraction, the AMCG suite was emplaced as stitching plutons into both the AHT and ALT. Rocks of 1.19–1.17 Ga age are uncommon in the Mount Holly complex but are widespread throughout the other Grenvillian inliers of the Appalachians emphasizing the connectivity within the belt. One major exception is the absence of anorthosite massifs, although a coarse ca. 1.13 Ga anorthosite in the Honeybrook Uplands is a good candidate but requires accurate zircon dating. In the Llano Uplift, the collision with the southern continent took place from ca. 1.15–1.07 Ga while in West Texas it was closer to 1.12–1.03 Ga.
4. At ca 1.1–1.098 Ga, the Hawkeye Granite was intruded into the AHT. A possible correlative in the Appalachian inliers is the ca. 1.12 Ga Mitchell Granite, but the sample base is small and the crystallization ages are significantly older than the Hawkeye Granite. The Hawkeye Granite zircon ages were determined by multigrain analysis and need to be dated by SHRIMP methods.
5. Collision of Amazonia with northeast Laurentia resulted in the ca. 1.09–1.03 Ga Ottawan phase of the Grenvillian Orogeny and produced granulite-facies metamorphism and large fold nappes in the AHT but did not exceed ~500°C in the ALT orogenic lid. Geochronology and thermobarometry demonstrate that the *P-T-t* path was clockwise and that granulite-facies conditions did not ensue until shortly after ca. 1.05 Ga. At that time anatexis of the middle crust resulted in production of the Lyon Mountain Granite that advected heat towards the surface. The thermally weakened, ductile middle crust could no longer support the broad orogenic plateau and the orogen underwent extensional collapse. The collapse has been documented along the normal displacement, west-dipping Carthage-Colton Shear Zone that separates the AHT and the ALT (orogenic lid) and has been dated at ca. 1.047 Ga. A similar, but east-dipping, normal-displacement, shear zone in the eastern ALT has been dated at ca. 1.05–1.035 Ga. The Ottawan Orogeny took place throughout the Grenville inliers of the Appalachians where it has been dated at ca. 1.08–1.05 Ga, coeval with its age in the AHT. High-silica, ferroan leucogranite commonly occur late in the orogeny and is not generally penetratively deformed. Similar late- to post-orogenic granitic magmatism is present in the Llano Uplift, where ferroan leucogranite was emplaced from ca. 1.12–1.07 Ga. The older members of the group exhibit evidence of weak deformation, whereas the later plutons are totally undeformed and form circular intrusions with low-pressure contact aureoles. Both these, and the Adirondack leucogranite, have been attributed to delamination of lithosphere. In the Llano Uplift, continental collision with a southern continent is analogous to the ca. 1.2 Ga events of the eastern Grenville Orogen involving Amazonia but occurred from ca. 1.15–1.12 Ga.
6. Rigolet tectonomagmatism is restricted to overgrowths on zircon and monazite in the Adirondacks and southern Appalachian Grenvillian inliers but late dikes and a few small plutons do occur in the New England inliers. In West Texas, the Hazel Orogeny appears to have taken place at ca. 1.03–1.0 Ga and is transitional from late Ottawan to early Rigolet. The development of a low-grade foreland fold and thrust belt is similar to the formation of the Grenville Front during the Rigolet Orogeny.

The major tectonomagmatic features of the Adirondacks, summarized above, can be traced into parts of the Canadian Grenville Province, the Grenvillian inliers of the Appalachians, and the Llano Orogen. Precise geochronology and isotope geochemistry continue to establish a common tectonic history for much of this region but also reveal important differences in such crucial matters as the origin of deep crustal reservoirs, i.e., Nd and Pb isotopic compositions and the proposed transfer of Amazonian crust to the southern Appalachians as well as possible differences in potential colliders (i.e., Amazonia vs. Kalahari). Notwithstanding these differences, the transcontinental continuity of tectonic and magmatic history is remarkable. During ~500 Ma of Proterozoic earth history a series of transcontinental marginal arcs existed across most of North America and resulted in enormous growth of Laurentia. In addition, the Proterozoic provinces discussed in this paper can be followed into Scandinavia, Australia, and Antarctica as described by Karlstrom et al. (2001), among others. The end result was the formation of the supercontinent Rodinia regarding which the Grenville Orogen has provided, and continues to provide, significant information.

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