Geoscience Canada
Journal of the Geological Association of Canada
Journal de l'Association Géologique du Canada

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Volume 40, numéro 4, 2013

URI : https://id.erudit.org/iderudit/1021068ar

Aller au sommaire du numéro

Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

Découvrir la revue

Citer cet article

Hibbard, J. & Karabinos, P. (2013). Disparate Paths in the Geologic Evolution of the Northern and Southern Appalachians: A Case for Inherited Contrasting Crustal/Lithospheric Substrates. *Geoscience Canada*, *40*(4), 303–317.

HAROLD WILLIAMS SERIES

Disparate Paths in the Geologic Evolution of the Northern and Southern Appalachians: A Case for Inherited Contrasting Crustal/Lithospheric Substrates

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SUMMARY

Modern understanding of the tectonic evolution of the Appalachian orogen allows for recognition of most of the first-order lithotectonic elements and events of the mountain belt. Comparison of these features and events along the length of the orogen indicates that the northern and southern segments display distinct first-order differences. Contrasts between these segments existed from the onset of the Appalachian cycle. It has been recognized that Mesoproterozoic basement rock types south of approximately Pennsylvania are different from those to the north and more recently it has been shown that basement rocks in each area display distinct Nd and Pb isotopic signatures. Also, an early, ca. 770–680 Ma, Cryogenian stage of rifting is recorded in the southern Appalachians, but is not documented in the northern part of the orogen. During the Paleozoic Appalachian cycle, the accretion of peri-Gondwanan terranes was partitioned; Carolinia and Suwannee are confined to the southern Appalachians, and Ganderia, Avalonia, and Meguma to the northern Appalachians. Consequential to this partitioning, associated magmatism and some of the attendant tectonism is asymmetrically distributed between the two segments of the orogen. The terminal Appalachian collisional event, the Carboniferous Alleghanian orogeny, is distinctly different in the two segments of the orogen. The volumes of Alleghanian magmatic rocks in the northern and southern Appalachians are distributed asymmetrically and Carboniferous tectonic styles contrast sharply between the two regions. In addition, there is a modern first-order topographic change in the foreland of the orogeny. The southern foreland is characterized by a continuous, elevated plateau, whereas north of the New York promontory, foreland topography is more varied.

Throughout the Appalachian cycle, all of these varied first-order changes occur in the vicinity of the New York promontory, suggesting that the promontory represents an enduring, fundamental boundary in the orogen. The nature and duration of differences between the northern and southern segments of the orogen indicate that this boundary was not an extrinsic ephemeral feature, such as a plate triple junction or hot spot. Rather, we suggest that an intrinsic difference in the Laurentian crustal/lithospheric(?) substrate present from the outset of the Appalachian cycle, as reflected by contrasts in the Mesoproterozoic basement in each segment, could be the root cause of these significant contrasts.

SOMMAIRE

L'état actuel des connaissances sur l'évolution tectonique de l'orogène appalachien nous permet de reconnaître la plupart des éléments et des événements lithotectoniques de premier niveau de la chaîne de montagnes. La comparaison de ces caractéristiques et événements tout au long de l'orogène permet de distinguer des différences de premier ordre entre les segments nord et sud. Des contrastes entre ces segments ont existé depuis le début des Appalaches. Il a été reconnu que les roches de type socle du Mésoprotérozoïque à partir du sud de la Pennsylvanie environ, diffèrent de celles au nord, et plus récemment, il a été démontré que les roches de socle dans chacun de ces segments ont des signatures isotopiques Nd et Pb distinctes. En outre, un début de phase

Geoscience Canada, v. 40, http://dx.doi.org/10.12789/geocanj.2013.40.021

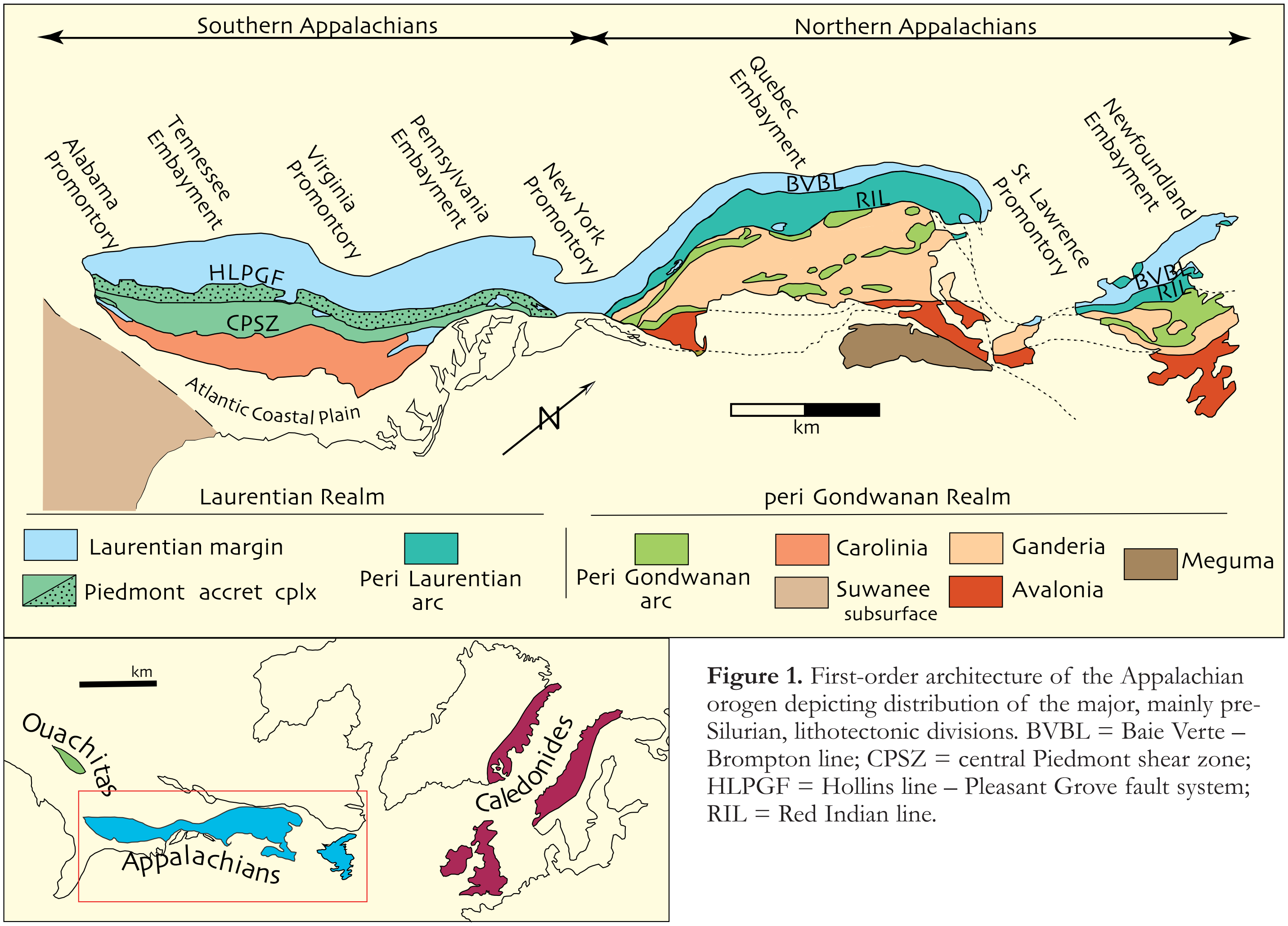

Figure 1. First-order architecture of the Appalachian orogen depicting distribution of the major, mainly pre-Silurian, lithotectonic divisions. BVBL = Baie Verte – Brompton line; CPSZ = central Piedmont shear zone; HLPGF = Hollins line – Pleasant Grove fault system; RIL = Red Indian line.

de distension au Cryogénien (770-680 Ma env.) est présent dans le segment sud des Appalaches, mais n'est pas documenté dans le segment nord de l'orogène. Durant le cycle paléozoïque des Appalaches, l'accrétion des terranes péri-Gondwana a été partagé; les terranes de Carolinia et de Suwannee sont confinés au segment sud des Appalaches, alors que ceux de Ganderia, d'Avalonie, et de Meguma sont confinés au segment nord des Appalaches. Conséquence de cette répartition, le magmatisme associé ainsi qu'une partie du diastrophisme relié sont répartis de manière asymétrique entre les deux segments de l'orogène. La phase terminale de collision des Appalaches, l'orogenèse Carbonifère alléghanienne, est nettement différente dans les deux segments de l'orogène. Les volumes des roches magmatiques alléghaniennes dans les Appalaches septentrionales et méridionales sont répartis de manière asymétrique et les styles tectoniques carbonifères contrastent fortement entre ces deux régions. En outre, on observe une différence topographique de premier ordre dans l'état actuel de l'avant-pays de l'orogenèse. Le segment sud de l'avant-pays est caractérisé par un plateau élevé continu, alors qu'au nord du promontoire de New York, la topographie d'avant-pays est plus diversifiée.

Tout du long du cycle des Appalaches, tous ces changements variés de premier ordre existent au pourtour du promontoire de New York, ce qui permet de penser que le promontoire représente une frontière déterminante durable dans l'orogène. La nature et la persistance de ces différences entre les segments nord et sud de l'orogène indiquent que cette limite n'était pas une caractéristique éphémère extrinsèque, comme une jonction triple de plaque ou un point chaud. Nous suggérons plutôt qu'une différence intrinsèque dans la croûte/substrat lithosphérique(?) laurentien existait dès le début du cycle des Appalaches, comme en témoignent les contrastes dans le socle mésoprotérozoïque dans chaque segment, et pourrait être la cause de ces contrastes significatifs.

INTRODUCTION

The Ouachita–Appalachian–Caledonide orogenic system is a Paleozoic collisional belt that snakes its way across two continents, from southern North America along its eastern seaboard, and across the Atlantic to the British Isles and Scandinavia (Fig. 1).

Three distinct segments of the system are delineated by two major bends; one separates the Ouachitas from the Appalachians at the Alabama promontory, and the other is an inferred bend, necessary to connect the Appalachians to the Caledonides prior to opening of the Atlantic Ocean

(Haworth 1981; Fig. 1). Each segment of the system has a distinct, first-order, Paleozoic collisional history; the Ouachitas were ultimately involved in the late Paleozoic amalgamation of Laurentia and South America (e.g. Pindell 1985), the Appalachians culminated with the late Paleozoic collision of Laurentia and Africa (e.g. Wilson 1966), and a large portion of the Caledonides record the middle Paleozoic collision of Laurentia and Baltica (e.g. Phillips et al. 1976). However, there are also major geological differences that roughly bisect the relatively linear central segment, the Appalachians, and the cause of these differences cannot readily be attributed to a distinct change in the first-order collisional components. The nature and possible cause of these differences are more subtle and form the focus of this contribution.

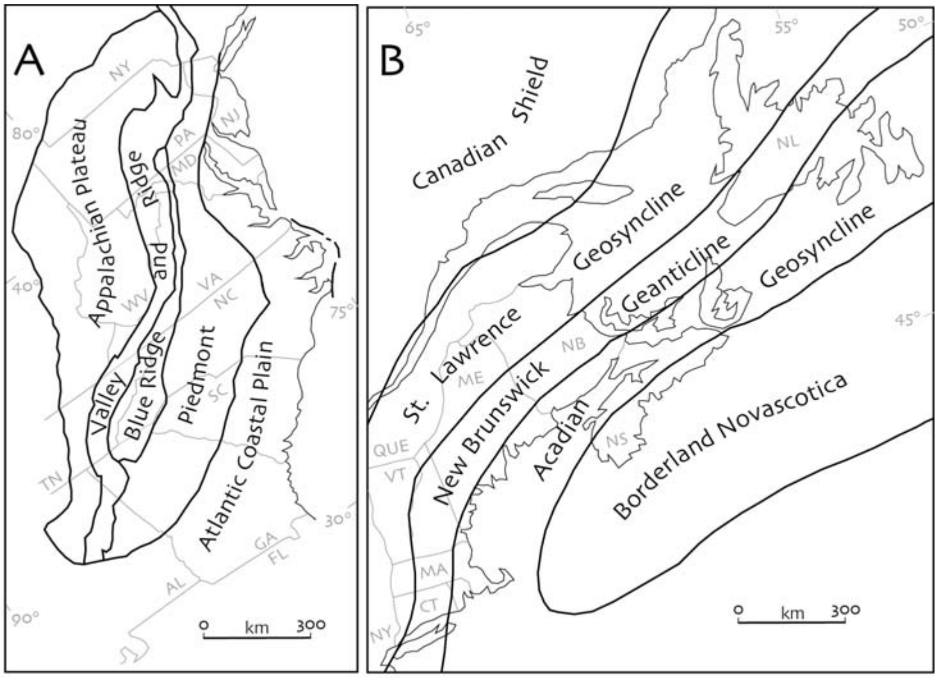

Figure 2. Mid-20th century subdivisions of the A. southern, and B. northern, Appalachians, adapted from Rodgers (1970) and Schuchert and Dunbar (1934), respectively.

Traditionally, the basis for lithotectonic subdivision of the Appalachians was different for its two main segments, the northern and the southern Appalachians (sensu Hibbard et al. 2007a; Fig. 2). The classical geological divisions of the southern Appalachians resulted from a commonality of rocks, structures, and physiography, encompassing such divisions as the Plateau, Valley and Ridge, Blue Ridge, and Piedmont provinces (e.g. King 1955; Rodgers 1970). In contrast, subdivision of the northern Appalachians was based on large-scale structures of geanticlines and geosynclines (e.g. Schuchert and Dunbar 1934) that conceptually evolved into anticlinoria and synclinoria (e.g. Rodgers 1970). Although more uniform, comprehensive zonal, terrane, and realm subdivisions of the entire orogen have been employed by subsequent researchers (Williams 1978; Williams and Hatcher 1982, 1983; Hibbard et al. 2006), the contrast inherent with the older subdivision systems has subliminally lingered. Because this dichotomy has never been directly addressed, many Appalachian geologists have a hazy, ill-defined, perception that the two segments of the orogen might have distinct lithotectonic histories.

Certainly, it has been recognized that the imprint of the Carboniferous Alleghanian orogeny created an obvious contrast between the northern and southern Appalachians (e.g. Karabinos 1997; Hibbard 2004; Hibbard et al. 2010). However, it is only during the last decade that our level of understanding of the tectonic evolution of the Appalachian orogen has become sufficient to allow us to recognize that this contrast is only the 'tip of the iceberg'. In this essay, we demonstrate that the hazy perception of distinct geologic evolutionary paths for each segment reflects a combination of multiple first-order contrasts in the geology of the northern and southern Appalachians. Highlighting the contrasts between the two segments leads to the recognition of an intriguing pattern; most major changes in the orogen are at the latitude of the New York promontory (Fig. 1), suggesting that it marks a fundamental boundary. It persisted as an important tectonic divide for at least 900 million years, indicating that it was not an ephemeral geologic feature but rather an enduring, likely crustal- or lithosphere(?)-scale, contrast.

In this essay, the New York promontory (Fig. 1) is taken to be the divide between the northern and the southern Appalachians (Hibbard et al. 2007a). In addition, we use the time scale of Walker et al. (2012) throughout.

LAYOUT OF THE OROGEN

The Appalachian orogen is composed of two major lithotectonic divisions, the Laurentian and the peri-Gondwanan realms (Fig. 1), both of which acquired their defining geologic character mainly before the Late Ordovician. The Laurentian realm (Laurentian Appalachians of Rankin 1994) encompasses essentially all of the rocks deposited either on, or in the oceanic domain adjacent to, ancient eastern North America and forms the western flank of the entire orogen. Locally, structural windows of Laurentian rocks are scattered among the more easterly accreted terranes (Fig. 1). In contrast, components of the peri-Gondwanan realm along the southeastern flank of the orogen formed proximal to Gondwana and thus they are exotic with respect to Laurentian elements.

The history of events that are responsible for the juxtaposition of Laurentian and peri-Gondwanan elements spans the time frame between the Neoproterozoic supercontinent of Rodinia and the Paleozoic–Mesozoic supercontinent of Pangea, which we term here the Appalachian cycle (Fig.

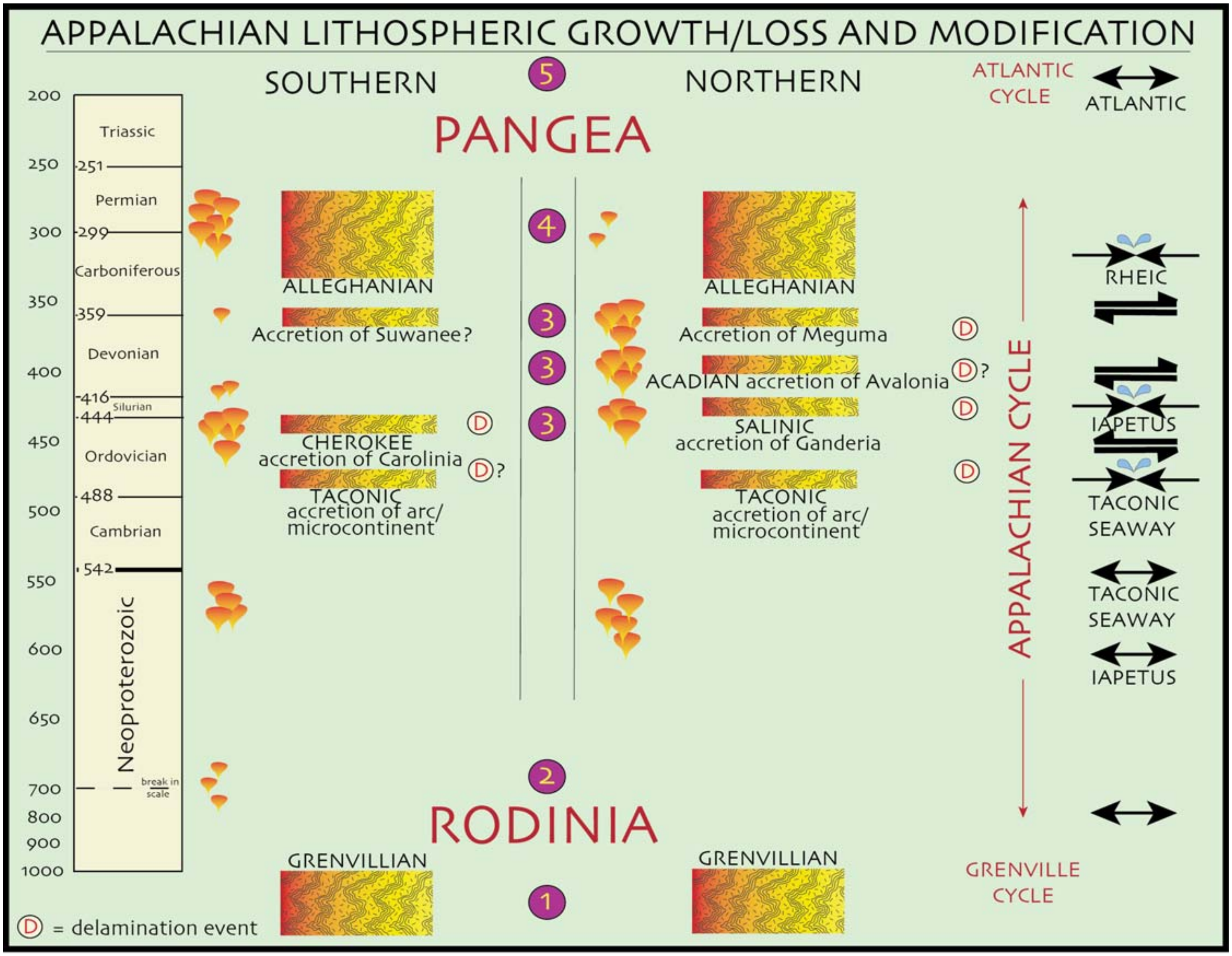

Figure 3. Timeline of the Appalachian cycle, showing major episodes of lithospheric growth, modification, and loss; encircled numbers correspond to descriptions cited in text. Patterned boxes = times of major tectonothermal events, balloons = qualitative representation of volume of magmatism, diverging black arrows = rift events, converging black arrows = ocean closure events, opposing black arrows = sense of dominant strike slip component of plate motion.

3). Most of these events record magmatic arc and microcontinent accretion to the eastern Laurentian margin; the culminating Alleghanian orogeny is broadly accepted as the final collision of Laurentia and Gondwana and the formation of Pangea.

Although some aspects of the first-order history of events depicted in Figure 3 are controversial, this chart serves as a useful starting point for our analysis; other reasonable sequences of events are not sufficiently different to alter the principal results of this study.

At the narrowest part of the orogen, the New York promontory, the Atlantic coastal plain cover cuts across the orogen as far west as the Laurentian realm, effectively forming a divide between northern and southern segments of the peri-Gondwanan realm (Fig. 1). This lack of contiguity between a large portion of the segments exacerbates the problem of comparing first-order components and evolutionary paths.

CONTRASTS IN EVOLUTION OF THE OROGEN

Along-strike first-order differences in the evolution of the orogen started prior to the Appalachian cycle and persist to the present (Fig. 3, encircled numbers). In this section, we describe the clearly documented major differences between the northern and southern segments of the orogen, starting with the oldest and proceeding to the youngest.

Pre- to Early Appalachian Cycle

Grenville basement (Fig. 3, # 1): Grenville basement exposures in the Appalachian orogen represent but a small sampling of the much more extensive Grenville province, which forms the eastern and southern margins of the North American shield and crops out from beneath platformal cover in southeastern Canada, the Adirondacks of New York, and the Llano uplift of Texas (Fig. 4). Rankin et al. (1993) first recognized contrasts between Grenville basement rock asso-

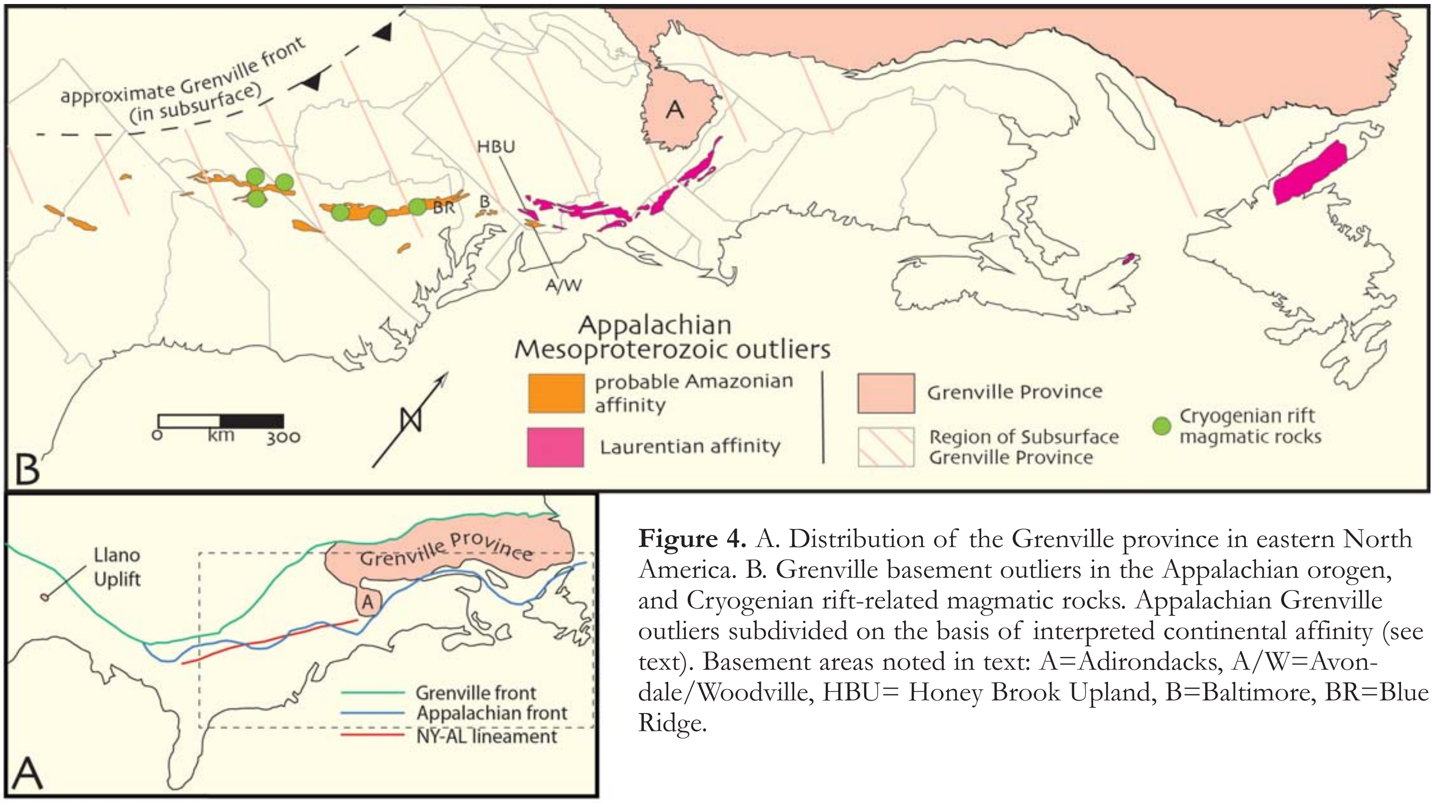

Figure 4. A. Distribution of the Grenville province in eastern North America. B. Grenville basement outliers in the Appalachian orogen, and Cryogenian rift-related magmatic rocks. Appalachian Grenville outliers subdivided on the basis of interpreted continental affinity (see text). Basement areas noted in text: A=Adirondacks, A/W=Avondale/Woodville, HBU= Honey Brook Upland, B=Baltimore, BR=Blue Ridge.

ciations in the Appalachians. The boundary between these contrasting Appalachian basement rocks is inferred to lie between the Honey Brook Upland on the north and the Avondale/Woodville, as well as the Baltimore and Blue Ridge, basement rocks to the south (Fig. 4). Rankin et al. (1993) noted that the southern Appalachian basement massifs, unlike the northern Appalachian massifs, are dominated by orthogneiss. Also, they made direct ties between the northern Appalachian basement massifs and the Grenville province in terms of composition, rock associations, age, and timing of tectonism. In contrast, southern Appalachian basement massifs are broadly similar to, but cannot be directly correlated with, rocks of the Grenville province (Rankin et al. 1993).

More recently, Nd and Pb isotopic data have been used to further distinguish the southern Appalachian Grenville rocks from those of the northern Appalachians and the Llano uplift (e.g. Sinha et al. 1996; Sinha and McLelland 1999; Loewy et al. 2003; Tohver et al. 2004; Fisher et al. 2010; McLelland et al. 2010). Pb isotope data for southern Appalachian basement rocks indicate that they have a distinctly higher time-integrated U/Pb ratio than rocks from the Grenville province in the Adirondacks and Labrador and other northern Appalachian basement massifs (Sinha et al. 1996; Sinha and McLelland 1999; Loewy et al. 2003; McLelland et al. 2010; Fisher et al. 2010). The boundary between these isotopic provinces appears to lie immediately east and south of the Honey Brook Upland (e.g. McLelland et al. 2010; Fig. 4). The distinct Pb isotopic signatures of the two regions imply either a lateral change in the U/Pb ratio of a single source region or that the two regions formed distinct isotopic terranes that were subsequently juxtaposed. Available Nd model ages suggest that southern Appalachian basement massifs have a more evolved heritage than northern Appalachian Grenville outliers and the adjacent Grenville province (Tohver et al. 2004; McLelland et al. 2010; Fisher et al. 2010). The distinct Pb and Nd isotopic signatures of the southern Appalachian Grenville rocks are a close match to those of time equivalent rocks in the Rondonian–Sunsas orogen of Amazonia; this similarity has led to the interpretation that the southern Appalachian basement massifs collectively represent Amazonian crust that collided with Laurentia at ca. 1.2–1.0 Ga and was left behind following the opening of Iapetus at the outset of the Appalachian cycle (Loewy et al. 2003; Tohver et al. 2004; McClelland et al. 2010; Fisher et al. 2010).

Appalachian Mesoproterozoic outliers are generally viewed as the structurally telescoped outer edge of Grenvillian rocks along the eastern Laurentian continental margin. Thus it appears that Mesoproterozoic Rondonian–Sunsas (Amazonian) lithosphere accreted during the Grenville cycle was the foundation for the southern Appalachians, south of approximately the Honey Brook Upland whereas the northern segment formed above Laurentian lithosphere. Some researchers have speculated that the western boundary of this exotic southern Appalachian Grenville block may extend in the subsurface to the New York–Alabama lineament (Fig. 4) and south along the lineament to the Alabama promontory (McLelland et al. 2010– their fig. 9; Fisher et al. 2010 – their fig. 9). If so, this scenario clearly requires a cross-strike basement discontinuity along the south side of the New York promontory, implying that the New York–Alabama lineament would have different significance north and south of such a discontinuity. Likewise, the southern edge of this Amazonian basement block is unclear, but must be located east of the Llano uplift, where Grenville basement is of Laurentian isotopic affinity (e.g. Loewy et al. 2003; Fisher et al. 2010).

Early southern Appalachian rifting (Fig. 3, # 2): The onset of the Appalachian cycle is marked by the breakup of the supercontinent Rodinia and formation of the eastern Laurentian margin. Neoproterozoic breakup was likely multistage (e.g. Cawood et al. 2001; McCausland et al. 2011) with two major pulses of Neoproterozoic, rift-related magmatism in eastern Laurentia: an older, Cryogenian phase spanning from ca. 770 to 680 Ma and a younger, mainly Ediacaran, phase ranging from ca. 620 to 530 Ma (e.g. Su et al. 1994; Aleinikoff et al. 1995; McCausland et al. 2007). The younger rift phase is responsible for the shape of the New York promontory, as well as the other promontories and embayments along the Iapetan rifted margin of eastern Laurentia (e.g. Thomas 1977). However, the older pulse is of interest here; it is defined by alkaline to peralkaline felsic and tholeiitic mafic magmatic rocks that Rankin (1970) assigned to the Crossnore plutonic-volcanic group (later termed the Crossnore Complex). In contrast to the widespread younger phase, the Cryogenian phase magmatic rocks are confined to the southern Appalachians; more specifically, this phase is associated with Grenville basement rocks in the region between the Tennessee and Pennsylvania embayments (Figs. 2, 4). In light of the apparent lithologic and isotopic differences between the northern and southern Grenville inliers, it appears that the Cryogenian phase of rift magmatism is confined to Grenville basement of Amazonian affinity in the southern Appalachians.

Syn-Appalachian Cycle Accretion of Peri-Gondwanan Elements

Following the two early contrasts within the orogen outlined above, the next major documented divergence in the evolution of the northern and southern Appalachians involves the Paleozoic accretion of the peri-Gondwanan realm elements of Carolinia, Ganderia, Avalonia, Meguma, and Suwannee to the Laurentian margin (Fig. 1; Fig. 3, #3). It is particularly striking that these elements are, at present, confined to regions on either side of the New York promontory; Carolinia and Suwannee are limited to the southern Appalachians and Ganderia, Avalonia, and Meguma to the northern orogen.

This odd partitioning of the peri-Gondwanan terranes to either side of the New York promontory could 1) reflect the original pattern of accretion, 2) arise from post-accretion processes such as either strike-slip tectonics or removal of portions of terranes during continental rifting and opening of the Atlantic, 3) be an artifact of current exposure, as Avalonia and Meguma are covered by younger strata in Long Island Sound, or 4) have resulted from any combination of 1 to 3. In the following descriptions of these crustal blocks, we will make the case that the apparent partitioning of these terranes was largely inherited from the original pattern of accretion.

Carolinia and Ganderia: Ganderia can be traced from the type locale in Newfoundland south to southern New England where it terminates on the north side of the New York promontory (Fig. 1); Carolinia extends from central Virginia south to Georgia (Fig. 1). Historic doctrine mandates that Carolinia represents the southern Appalachian equivalent of Avalonia (e.g. Rodgers 1972; Williams and Hatcher 1983). However, on the basis of respective geologic histories, it has been shown that Carolinia most closely resembles Ganderia within the Appalachian peri-Gondwanan realm (Hibbard et al. 2007a, b). Yet, first-order differences between Carolinia and Ganderia allow clear distinction between them. Most significant is the difference in Nd isotopic signatures within the Appalachian peri-Gondwanan realm. Carolinia has the most juvenile signature of all elements in the realm, whereas Ganderia is the most evolved. These isotopic signatures appear to reflect the nature of basement of these blocks, where Carolinia probably formed in an oceanic arc setting and Ganderia was likely constructed on some form of continental crust (Hibbard et al. 2007b).

The timing of accretion of these two elements is similar, although Carolinia appears to have accreted first, initiating the Late Ordovician southern Appalachian Cherokee orogeny (Hibbard et al. 2010, 2012), whereas Ganderia was accreted in the Early Silurian during the northern Appalachian Salinic orogeny (van Staal et al. 2008). The effects of the Cherokee orogeny inboard of Carolinia are confined to the southern Appalachians (e.g. Hibbard et al. 2010); likewise, the Salinic orogeny is a northern Appalachian event (e.g. van Staal et al. 2008). The areal limitation of tectonic imprints of the Cherokee and Salinic events to the south and north, respectively, strongly supports the idea that the modern spatial partitioning of Carolinia and Ganderia is mainly a reflection of their pattern of accretion.

Avalonia and the Acadian orogeny: Accretion of the microcontinent of Avalonia has generally been viewed as the cause of the Late Silurian–Middle Devonian Acadian orogeny (e.g. Bird and Dewey 1970; van Staal et al. 2009). The southern termination of documented Avalonian rocks lies on the northern side of the New York promontory (Figs. 1, 5). Thus, Avalonia appears to be confined to the northern Appalachians, with no currently recognized equivalent block in the southern Appalachians (Hibbard et al. 2007b).

This contrast between the northern and southern segments of the orogen is enhanced by the distribution of Acadian tectonothermal events. Specifically, the latest Silurian–Middle Devonian deformational/metamorphic/magmatic imprint is largely confined to the northern Appalachians. The Acadian tectonothermal event is, for the most part, absent in the southern Appalachians (e.g. Rodgers 1970; Hibbard et al. 2010) with the exception of minor plutonism. Although Late Silurian—Middle Devonian magmatic rocks are scattered along the length of the orogen, the volume of Acadian magmatism is asymmetrically distributed in the two segments of the orogen and the nature of magmatism in each segment appears to be distinct (Figs. 5, 6). In the northern Appalachians, Acadian magmatism (Fig. 5) is widespread, volumetrically significant, and has been attributed mainly to the combined effects of the establishment of flat slab subduction beneath Laurentia (Murphy et al. 1999) and subsequent slab break-off (van Staal et al. 2009). In contrast, Late Silurian–Early Devonian magmatism in the southern Appalachians is volumetrically meager relative to that of the northern orogen (Fig. 6). Southern Appalachian magmatic rocks are limited to mildly alkaline gabbro–syenite and leucogranite plutonism that is confined to Carolinia. The tectonic setting of these rocks is ambiguous (McSween and Harvey 1997), but the mildly alkaline nature and very limited volume collectively suggest that they are not subduction-related.

The apparent confinement of both Avalonia and its associated Acadian tectonothermal imprint to the northern Appalachians implies that its present exposed distribution reflects the pattern of accretion and underscores the role of the New York promontory as a fundamental boundary in the orogen.

Meguma and Suwannee: Meguma extends from Nova Scotia south to southern New England and apparently terminates on the north side of the New York promontory (Figs. 1, 7); Suwannee resides only in the subsurface along the southern corner of the Alabama promontory (Fig. 1). In the northern Appalachians, the accretion of Meguma to Laurentia has been interpreted as at least part of the cause of Late Devonian–Early Mississippian tectonism and magmatism (e.g. van Staal et al. 2009; White and Barr 2012). In New England, intense metamorphism and ductile deformation at this time has been termed the 'Neo-Acadian' orogeny (Robinson et al. 1998). However, the accretion of Meguma to Laurentia appears to be distinct from the Acadian docking of Avalonia and not a renewal of this collision (e.g. van Staal et al. 2009; Hibbard et al. 2010); consequently, because the time span of the event mainly encompasses the Fammenian, we prefer to use the more neutral, informal term 'Fammenian event' here, until a more appropriate term is suggested by those actively

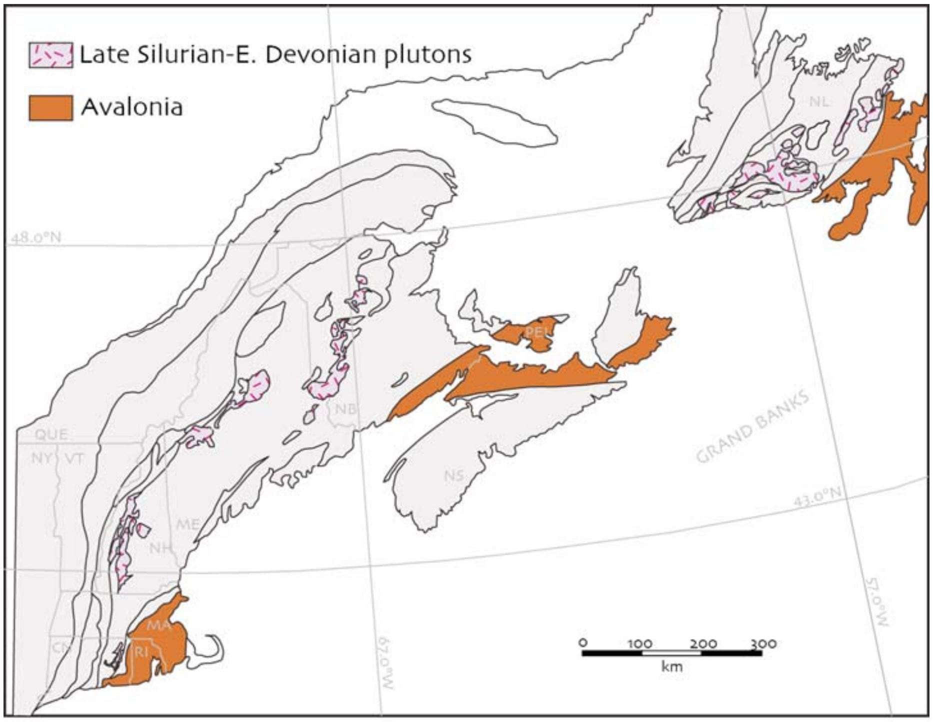

Figure 5. Distribution of Acadian elements in the northern Appalachians (from Hibbard et al. 2006). Note that the present southern termination of documented Avalonian rocks lies just on the north side of the New York promontory.

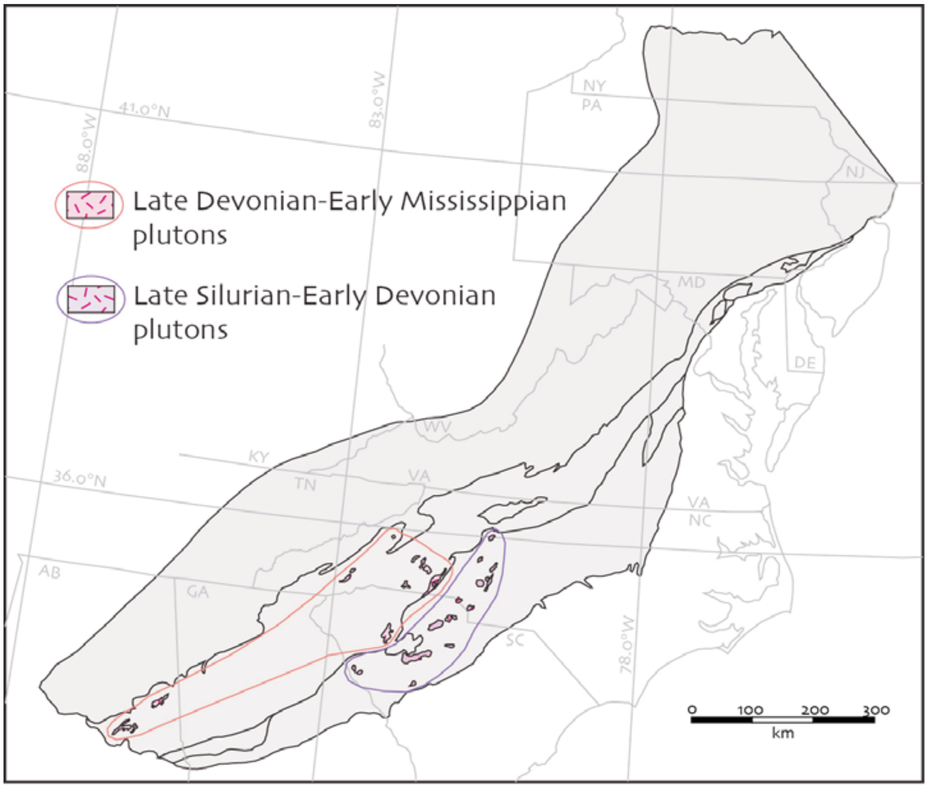

Figure 6. Middle Paleozoic plutonic rocks of the southern Appalachians subdivided by age, latest Silurian–Early Devonian and Late Devonian–Early Mississippian (from Hibbard et al. 2006). Note the distinct asymmetry in volume with respect to equivalent age plutons in the northern Appalachians, depicted in Figures 5 and 7.

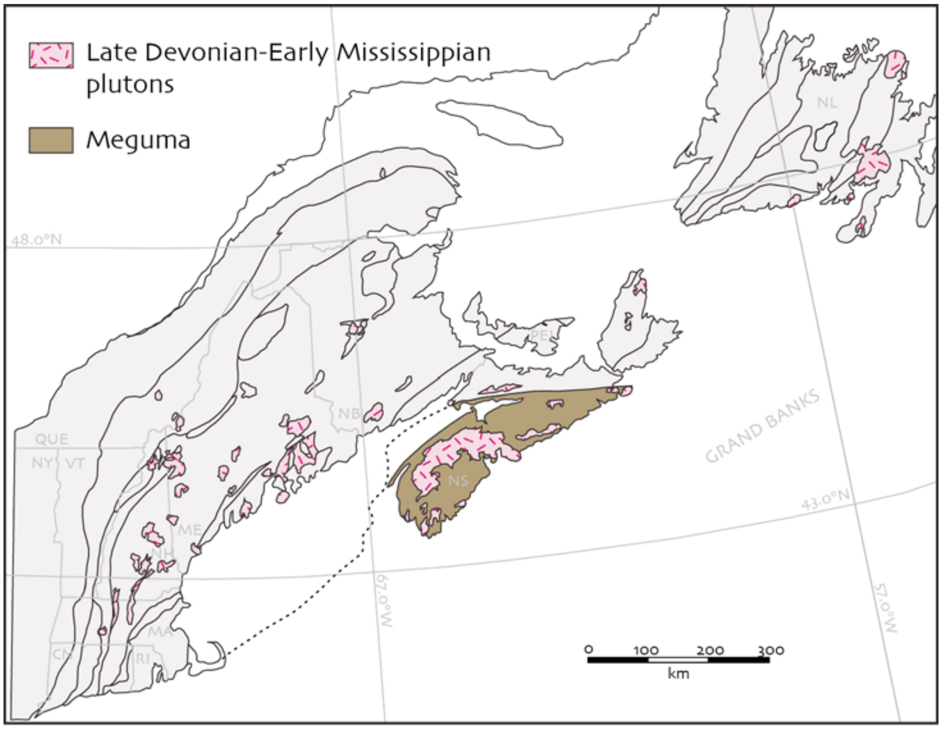

Figure 7. Distribution of Late Devonian–Early Mississippian, 'Fammenian event' magmatism and of the peri-Gondwanan block of Meguma (from Hibbard et al. 2006). Note that the southern termination of Meguma, like that of Avalonia, lies on the north flank of the New York promontory.

researching this topic.

A Fammenian event is also recorded in the southern Appalachians where it is manifest mainly as high-grade metamorphism and intense ductile deformation focused in the hinterland of the orogen during the time span ca. 375–345 Ma (e.g. Dennis and Wright 1997; Merschat et al. 2005). Suwannee also records a ca. 375–345 Ma thermal event (Scholle 1979; Dallmeyer 1991); on the basis of more inboard portions of the orogen and Suwannee sharing this Late Devonian–Early Mississippian thermal event, it has been speculated that the Fammenian event resulted, in part, from the accretion of Suwannee (Hibbard et al. 2010; Pollock et al. 2012). This interpretation requires that Suwannee was later translated along the southern Appalachian margin to its present position south of the Alabama promontory.

Late Devonian–Early Mississippian plutonism associated with the Fammenian event occurs in both segments of the orogen, but its volume is asymmetrically distributed (Figs. 6, 7). Magmatism of this age in the northern orogen is dominated by voluminous granitoid and subordinate bimodal plutonism that is distributed across the orogen from the Laurentian realm through all of the components of the peri-Gondwanan realm (Fig. 7). The origin of Fammenian event magmatism in the northern Appalachians is ambiguous and is likely related to more than a single tectonic environment (e.g. Moran et al. 2007; Hibbard et al. 2010). In the southern Appalachians, magmatism associated with this event is characteristically low volume and confined to the hinterland of the orogen in the Tennessee embayment and the Alabama promontory (Fig. 6). These plutons range in age from ca. 380 to 355 Ma and they have been interpreted to represent anatectic granite plutons, related to melting of host metaclastic rocks (Mapes 2002; Swanson 2008; Schwartz et al. 2011; Ingram et al. 2011).

Although the origin of magmatism in both the northern and southern segments of the orogen is ambiguous, the striking difference in the volume of magmatic rocks constitutes a fundamental difference between the two segments of the orogen. The coincidence of robust magmatism and the distribution of Meguma in the northern Appalachians suggest that Meguma was originally limited to that segment of the orogen. The meager magmatic signature in the southern Appalachians implies that if Suwannee was accreted at the same time as Meguma, different mechanisms of accretion operated between the northern and southern Appalachians at that time.

Summary of the distribution of peri-Gondwanan elements: The restriction of Carolinia and Suwannee to the southern Appalachians and Ganderia, Avalonia, and Meguma to the northern Appalachians is indeed odd. Documented occurrences of Avalonia terminate southward in the vicinity of the New York promontory; Meguma is interpreted to extend in the subsurface as far south as Cape Cod (Hutchinson et al. 1988). In addition, potential field patterns associated with both crustal blocks terminate southward in the vicinity of the promontory (Haworth et al. 1980; Zietz et al. 1980, Costain et al. 1989). These observations suggest that neither block extends south of the promontory. The distribution of tectonism and magmatism associated with the accretion of peri-Gondwanan elements closely mimics their present distribution. Collectively, these observations are most compatible with the idea that the present distribution of peri-Gondwanan terranes is largely the result of accretion processes, rather than post-accretion processes.

Late-syn Appalachian Cycle

Alleghanian contrasts (Fig. 3, #4): The terminal Appalachian event, the Alleghanian orogeny (ca. 340–260 Ma) involved the closure of the Rheic Ocean (e.g. Nance and Linneman 2008) and the collision of eastern Laurentia with western Gondwana (e.g. Hatcher 2002). The Alleghanian orogeny created some of the most obvious contrasts in the northern and southern segments of the Appalachians with respect to depositional systems, style of deformation, and magmatism.

North of the New York promontory, syntectonic deposition of clastic sediments occurred in the Narragansett and Maritimes transtensional basins (e.g. van de Poll et al. 1995)

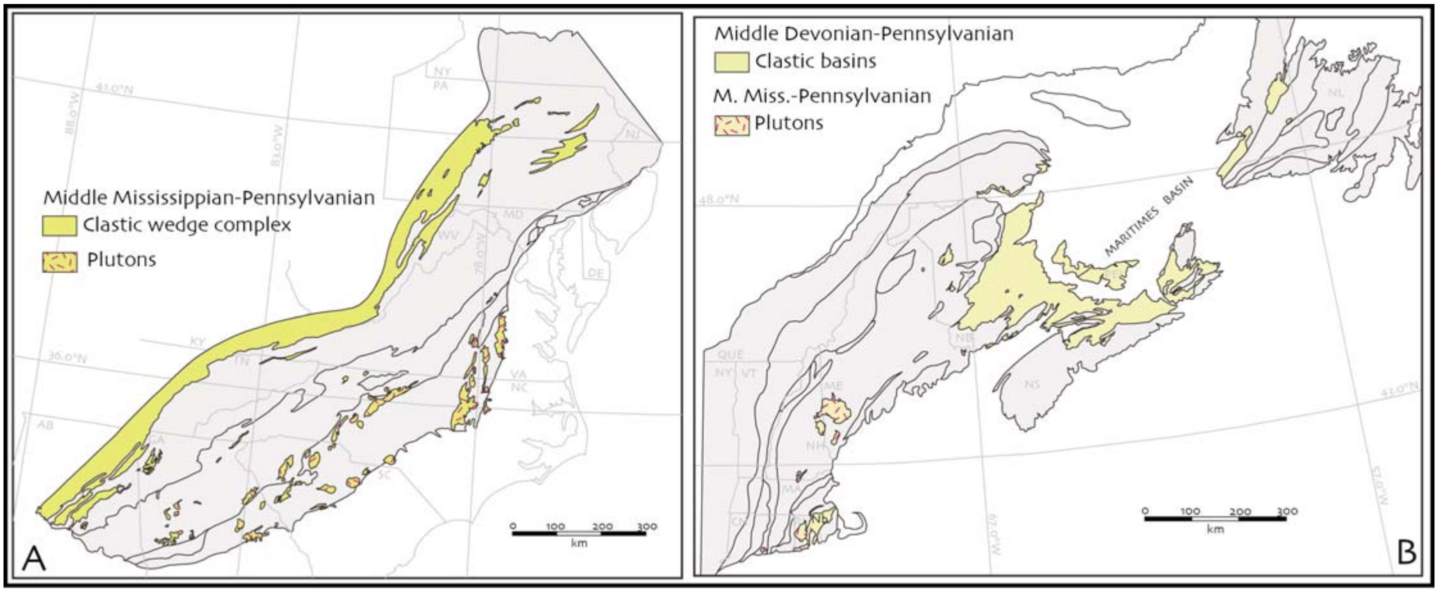

Figure 8. Distribution of Alleghanian depositional and magmatic systems in A. the southern Appalachians and B. the northern Appalachians (from Hibbard et al. 2006). Note the striking difference in the location of depocentres with respect to position in the orogen and the strong asymmetry in the distribution of Alleghanian plutonic rocks between the northern and southern segments of the orogen.

within a system of dextral strike-slip faults across the hinterland of the orogen (Figure 8B). The oldest strata in the basins are Middle Devonian, although this early phase is only sparsely preserved (e.g. Dunning et al. 2002). It is unclear if the basins evolved mainly within a continental rift regime and/or in an overall dextral strike-slip setting (van de Poll et al. 1995). In stark contrast to northern basins, syn-Alleghanian deposition in the southern Appalachians took the form of a northwestward prograding complex of clastic wedges in flexural foreland basins limited to the northwest flank of the orogen. Deposition here started later, in the Middle Mississippian (Fig. 8A) (e.g. Thomas 1977), than in the northern Appalachians.

The distinct depositional systems described above are intimately associated with contrasting styles of regional deformation in the two segments of the orogen. To the north, the Narragansett and Maritimes basins evolved along an anastomosing system of faults that record mainly a dextral component of shear (van de Poll et al. 1995) from the Middle Devonian until the Permian. The bounding faults of these transtensional basins are linked to a system of orogen-parallel dextral strike-slip faults in the southern Appalachians (e.g. Gates et al. 1986). In contradistinction to the tectonic setting of the northern basins, the southern Appalachian clastic wedge complex evolved in a dominantly shortening regime in which the crystalline Blue Ridge–Piedmont thrust sheet was emplaced onto the foreland with a cumulative shortening of greater than 400 km (Hatcher 2002). This extensive late Paleozoic thrust system extends from the Alabama promontory northward to the New York promontory; a narrow projection of the system may continue north of the New York promontory into the Hudson Valley fold-thrust belt, although the age of thrusting here is equivocal (Marshak 1986; Marshak et al. 2009). As in the northern Appalachians, a dextral component of shear was involved in this event (e.g. Hatcher 2002).

Alleghanian plutonism is largely confined to the southern Appalachian segment; only a few plutons extend into the northern Appalachians. This pattern of distribution is opposite that of both Acadian and Late Devonian–Early Mississippian magmatism, wherein magmatism was concentrated in the northern orogen. The Alleghanian plutonism is spatially distinct from the southern clastic wedge complex (Fig. 8A), as it is in the more central and easterly portions of the orogen. The Alleghanian plutonic rocks are dominated by granite and granodiorite, with minor gabbro, ranging in age from ca. 335 Ma to 270 Ma (e.g. Speer et al. 1994; Foster et al. 2012). The suite shows no apparent spatial trends with respect to either composition or age. The tectonic setting of these plutons is ambiguous, although Foster et al. (2012) concluded that they may reflect either or both the loci of Alleghanian crustal thickening or orogenic collapse during transcurrent faulting.

Post Appalachian Cycle

Modern topography (Fig. 3, #5): The modern topography of the Appalachian foreland is clearly related to processes that post-date the bedrock evolution of the Appalachians; nonetheless, there is a distinct contrast in foreland topography between the northern and southern segments, the origin of which has not been directly addressed. In particular, south of the New York promontory, the foreland is continuously elevated west of, and along the length of, the adjacent foreland fold thrust belt of the orogen, forming the Appalachian plateau province (e.g. Rodgers 1970; Fig. 9). The southeastern edge of the plateau is abrupt, generally forming an escarpment on the order of hundreds of

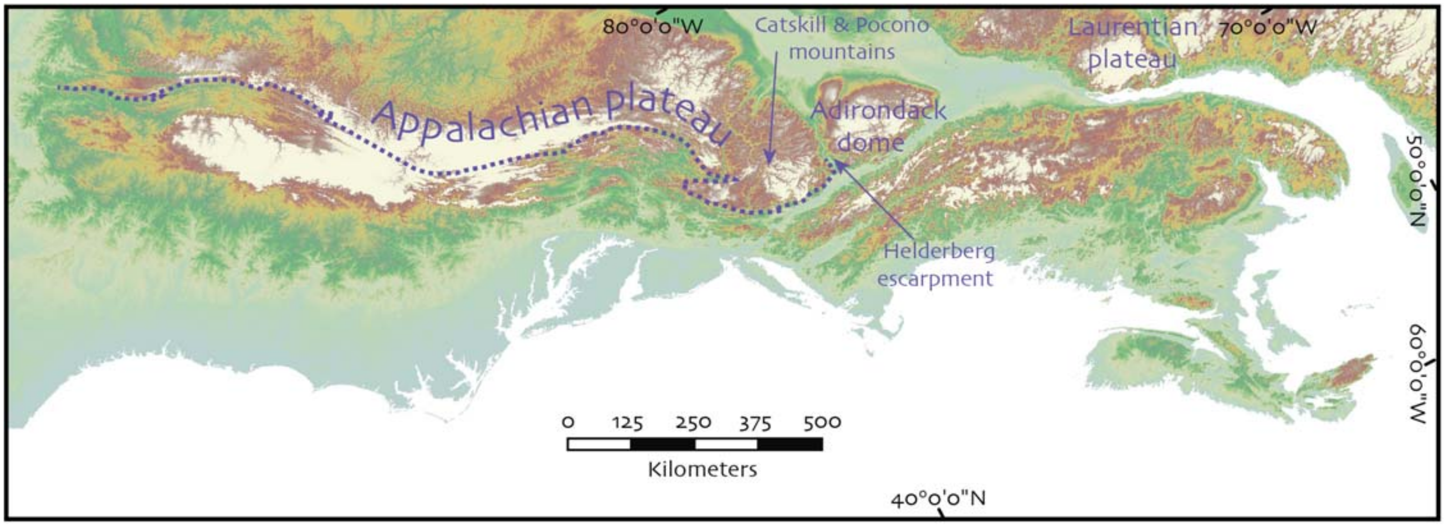

Figure 9. Digital elevation map depicting the contrasts in Appalachian foreland topography and major features referred to in text; light yellow enclosed areas include all elevations > 600 m.

metres above that part of the Valley and Ridge province along its southeastern border. The upland of the plateau province ranges from a true plateau (e.g. Cumberland Plateau, Allegheny Plateau) to areas that are highly dissected and in some places, mountainous (e.g. Cumberland Mountains, Allegheny Mountains), particularly along the southeast margin of the province. The plateau province appears to be the result of a protracted post-Appalachian, Mesozoic–Cenozoic exhumation history, although the origin of its elevation relative to the neighbouring Valley and Ridge remains unclear (e.g. Prowell and Christopher 2000; Reed 2003; Littlefield 2010).

The topography of the plateau drops off at the Helderberg escarpment on the north side of the New York promontory (Fig. 9). Immediately north of the escarpment, the Appalachian foreland is topographically punctuated by the anomalous Adirondack dome. This dome exposes a large area of Precambrian Grenville province rocks that apparently is undergoing active uplift at present (Isachsen 1975). North of the Adirondacks, foreland topography is subdued in the St. Lawrence Valley and the Gulf of St. Lawrence (Fig. 9).

DISCUSSION

The historic perception that the northern and southern Appalachians are distinct has lingered subliminally into the 21st century. Recent advances in understanding the geologic development of each segment of the orogen support the notion of disparate evolutionary paths for them. This distinction between segments is now grounded in multiple first-order observations that are varied in nature, including 1) distinct Grenville substrates, 2) apparently different tectonic regimes in the Cryogenian, 3) north–south partitioning of peri-Gondwanan accreted blocks and associated magmatism and tectonism, 4) distinct styles of Alleghanian deposition, tectonism, and magmatism, and 5) different topographic expressions of their respective forelands.

Recognizing these north–south contrasts with respect to mechanical behaviour, magmatism, and vertical motion, the question at hand is what mechanism(s) can account for them? The source of this first-order segmentation of the orogen could be either extrinsic, i.e. related to the geometry and nature of the plate(s) interacting with Laurentia, or intrinsic, i.e. associated with heterogeneities within the Laurentian margin, or could involve a component of both. The following three observations are important in sorting out extrinsic from intrinsic origins:

- the geologic contrast between the different segments of the orogen started before the Appalachian cycle and persists for ca. 1 billion years, up to the modern topographic expression of the Appalachian foreland.
- all of these changes appear at the same latitude in the orogen, in the vicinity of the New York promontory.
- the contrasts are varied in nature (different substrates, different tectonic environments, partitioning of accreted terranes and associated tectonism, and magmatism, modern topographic expression).

Thus, the underlying cause of the contrasts between the northern and southern Appalachians must have predated and endured for a longer time than the entire Appalachian cycle, remained focused at the latitude of the New York promontory, and effected a diverse array of significant geological differences. It is difficult to envisage an extrinsic mechanism, such as plate geometry, triple junctions, or hot spots on the outboard plate from Laurentia that could bring about the variety of changes over the duration of the Appalachian cycle and remain centred on the New York promontory. These mechanisms tend to be dynamic and ephemeral on the time scale of the Appalachian cycle. It would be highly fortuitous if, for example, either a plate triple junction or a hot spot continually occupied, or reoccupied, the same position outboard of the New York promontory. Rather, we strongly suspect that these observations ultimately require an intrinsic, persistent heterogeneity in either the crust or the lithosphere of the Laurentian margin at the New York promontory. Consequently, we suggest that the promontory marks the site of a change in the crustal/ lithospheric substrate to the orogen, as reflected by contrasts in the Mesoproterozoic basement in each segment.

As outlined above, on the basis of Nd and Pb isotopic characteristics, Mesoproterozoic basement outliers of the southern Appalachians have been interpreted to be derived from an older, more evolved, Amazonian source than from the more juvenile, Mesoproterozoic basement of the northern Appalachians. It is likely that this basement contrast between the two segments of the orogen reflects significantly different rheological architectures for these contrasting lithospheric substrates at the outset of the Appalachian cycle. Thus, where they conjoined along strike in the vicinity of the New York promontory, this thermal–mechanical contrast of crust/ lithosphere formed a first-order heterogeneity within the orogen. This heterogeneity in basement strengths could well have been responsible for the siting and formation of the New York promontory during Iapetan rifting (Thomas 1977).

Simple thermo-mechanical models support the idea that pre-existing rheological heterogeneities can result in strain variations in collisional mountain belts (e.g. Vauchez et al. 1998; Sobolev and Babeyko 2005). For example, Sobolev and Babeyko (2005) mathematically modeled variations in the initial rheological architecture of the continental plate in the central and southern Andes. Their models show that the thickness of continental crust is an important factor in determining the intensity of tectonic shortening. In light of such models, it is conceivable that initial differences in the Mesoproterozoic lithospheric substrate and crustal thickness between the northern and southern Appalachians were major factors in the tectonothermal evolution of these two segments; such a situation could help to account for the large discrepancy in Alleghanian shortening between the northern and southern Appalachians. Disparate crustal/lithospheric substrates may well have led to other independent evolutionary paths for the northern and southern Appalachians. Unfortunately, such factors as crustal thickness, the rheological architecture, geothermal gradient, magmatic fertility, and state of coupling between crust and lithospheric mantle of the Mesoproterozoic substrates are virtually unconstrained in the Appalachian orogen, and thus we are left with open-ended speculation as to how other specific variations we outline above – mechanical, magmatic, and vertical motion – could be generated with the orogen.

Once initiated, the heterogeneity introduced by two different crustal, if not lithospheric, substrates would be self-sustaining, for even under the same tectonic conditions, one segment would respond differently than the other perpetuating first-order contrasts. Also, mechanical heterogeneity at the New York promontory could influence the dynamic evolution of Appalachian plate boundaries. For example, if the southern terminus of Avalonia was marked by a southwest-migrating (present coordinates) plate triple junction between Laurentia, Avalonia, and a Rheic Ocean plate, mechanical contrasts at the New York promontory could impede the migration of that triple junction.

In considering recent foreland topography, it is possible that the contrast from the Appalachian plateau in the south to the St. Lawrence lowlands in the north is the result of the distribution of resistant Devonian–Carboniferous foreland sandstone units. However, it is intriguing to wonder if an inherited change in crustal/lithospheric thickness at the New York promontory, modified by Appalachian tectonism, could also add a component to this topographic contrast and somehow be responsible for the active doming of the Adirondacks immediately adjacent to the juncture of the north–south geomorphic contrast. Some manifestation of inherited thickness changes could conceivably perturb modern asthenospheric flow and cause localized upwelling on the north side of the promontory, in the Adirondack region. Clearly, such a speculative scenario can only be tested with data that are unavailable at this time.

The boundary between Laurentian and Amazonian basement in eastern North America originated as a crustal-scale, if not lithosphere-scale, fault zone that formed during late Mesoproterozoic accretion of southern Appalachian Mesoproterozoic basement. During the ensuing billion or so years of Appalachian and Atlantic cycles, this contact was inevitably modified by rift, collisional, and strike-slip events. How the modern boundary is manifest at different lithospheric depths is open to speculation, although considering the potential for tectonic modification during the Appalachian cycle, it is likely that what may have begun as a relatively narrow feature is now a wider, more irregular, and possibly segmented zone. If the contrast between the northern and southern Appalachians is linked to a Mesoproterozoic suture, as we speculate, it is important to delineate the full extent of this boundary, both to the west and south.

This Appalachian example of how heterogeneity of the continental lithosphere might control orogenic evolution has bearing on how we view the rheology of continental lithosphere. Thomas (2006) made a strong case for structural inheritance of Appalachian promontories and embayments back to at least the Mesoproterozoic, as well as for inheritance from the promontory and embayments through Appalachian–Ouachita shortening and Atlantic–Gulf rifting. Likewise, we call upon similar inheritance of lithospheric/crustal substrate to explain variations in the geological evolution of the northern and southern Appalachians. Considering the complex history of Appalachian orogenesis involving multiple times of mantle rejuvenation during rift episodes (at least 3: Cryogenian, Neoproterozoic–Cambrian, Triassic) and multiple hypothesized slab break-off and delamination events (Fig. 3) (e.g. Whalen et al. 2006), it appears that the rheological memory of structures being inherited is stored in the crust. This deduction is in accord with ideas that the strength of the lithosphere, i.e. the part that controls mechanical behaviour, resides in the crust (e.g. Maggi et al. 2000; Jackson 2002).

ACKNOWLEDGEMENTS

JH is grateful to Hank Williams for providing a guiding hand in his career path; Hank's 'laissez faire' style of advising allowed the young student to learn Appalachian geology ‘on the job’. JH acknowledges funding from the National Science Foundation (EAR-0228908 and EAR-9814273) for partial support of this study. We especially thank Bill Thomas for insightful and constructive feedback on early drafts of the manuscript. In addition, we have benefited from discussions with Sandra Barr, Brendan Murphy, Doug Rankin, Cees van Staal, and, of course, Hank Williams. Sandra Barr and Peter Cawood are thanked for constructive journal reviews and comments that improved the manuscript. Thanks to Sean Gallen for constructing the digital elevation map that formed the basis for Figure 9.

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Received April 2013
Accepted as revised September 2013