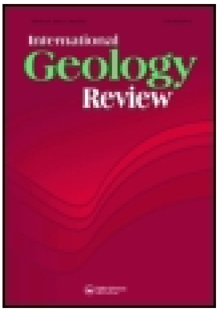

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J. Brendan Murphy [a] & J. Duncan Keppie [b]
[a] Saint Francis Xavier University
[b] Universidad Nacional Autonoma de Mexico
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The Acadian Orogeny in the Northern Appalachians

J. BRENDAN MURPHY[1]

Department of Earth Sciences, St. Francis Xavier University, Antigonish, Nova Scotia B2G 2W5, Canada

AND J. DUNCAN KEPPIE

Instituto de Geología, Universidad Nacional Autónoma de México, México D.F. 04510, México

Abstract

The Acadian orogeny, involving deposition of clastic wedges, deformation, metamorphism, magmatism, and exhumation, is limited in time to the Devonian, and in space to the northern mainland Appalachians. Conventional interpretations attribute it to collision between Laurentia and Avalon or Meguma terranes. However, advances in paleogeography indicate that the Avalon and Meguma terranes were accreted to Laurentia in the Late Ordovician and Early Silurian, which was synchronous with closure of the Iapetus Ocean. On the other hand, the Rheic Ocean remained open to the south. In this context, we propose that the Acadian orogeny developed on an Andean-type margin, and attribute it to flattening of the subduction zone as a consequence of collision of an oceanic plateau surrounding a plume. This model explains: (1) SE to NW diachronism in the onset of deformation throughout the Devonian; (2) the development of a ~400–380 Ma magmatic arc gap in Maritime Canada that was abruptly terminated in the Meguma terrane at ~380–370 Ma by (3) intrusion of voluminous felsic magmatism and plume-related lamprophyres as the plume thermally eroded the oceanic lithosphere, causing melting of the lower crust; (4) accompanying regional high-T, low-P metamorphism related to thermal anomalies above a plume; (5) emplacement of gold deposits and associated siderophile elements, possibly derived from fluid circulation above an ascending plume; and (6) rapid Late Devonian exhumation of ~10 km attributed to dynamic uplift over the plume. As the plume head migrated northward, the anomalously intense bimodal magmatism shifted into the Cobequid Highlands (Avalon terrane) at ~360 Ma, and then to the Magdalen Islands, where ~330 Ma plume-related magmatism occurred above a high-density, lower crustal lens interpreted as plume-derived underplated mafic rocks. Late Carboniferous formation of the Maritimes basin is attributed to cooling of this decapitated plume head.

Introduction

THE APPALACHIAN OROGEN extends for more than 3000 km from Newfoundland to Alabama along the eastern margin of North America, and pre-Mesozoic reconstructions imply former continuity and genetic linkages with the Caledonide and Variscan orogens of western Europe (Fig. 1). It is now generally accepted that the Appalachian-Caledonide-Variscan orogen represents the destruction of Paleozoic oceans such as the Iapetus and Rheic oceans, in which the accretion of suspect terranes to Laurentia-Baltica at various times during the Ordovician–Devonian was followed in the Permo-Carboniferous by terminal continental collision with Gondwana and the formation of Pangea (e.g., Williams, 1979; Keppie, 1985; van Staal et al., 1998 and references therein).

The destruction of these oceans is recorded by several episodes of orogenic activity that have generally been related to collision of various terranes with each other or with cratons (see Fig. 2). Thus, the earliest orogenic event, the Late Cambrian–Middle Ordovician Penobscotian ororeny, has been attributed to the amalgamation of composite terranes within the Iapetus Ocean (Keppie, 1993; Stewart et al., 1995). The early to mid-Ordovician Taconic orogeny is inferred to have been the result of collision between Laurentia and outboard oceanic arcs, backarcs, and oceanic terranes that originated in the Iapetus ocean and contain sparse Laurentian fauna (e.g., van Staal et al., 1998). The Late Ordovician–Silurian Salinic orogeny has been related to the accretion of the Gander, Avalon, Nashoba, and Carolina terranes to Laurentia during the closure of

[1]Corresponding author; email:bmurphy@stfx.ca

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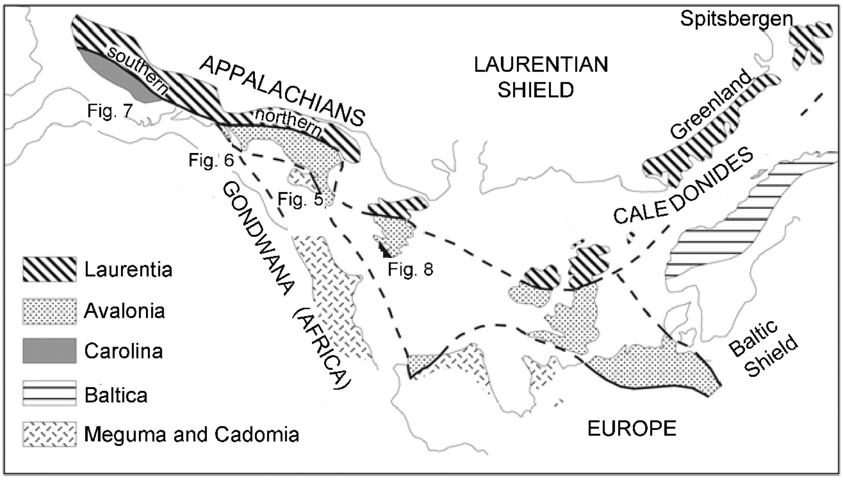

FIG. 1. Pre-Mesozoic reconstruction of the Appalachian-Caledonide-Variscan orogen, (from McKerrow et al., 2000). Locations of Figures 5 (Maritime Canada), 6 (New England) , 7 (Carolinas) , and 8 (Newfoundland) also are shown.

Iapetus (e.g., Keppie, 1985, 1993; van Staal et al., 1998; Hibbard et al., 2002). The Devonian Acadian orogeny has been attributed to collision of either Avalonia with Laurentia (Robinson et al., 1998) or to the accretion of the Meguma terrane (e.g., van Staal et al., 1998). There is general consensus that the last orogenic event, the Late Carboniferous–Permian Alleghenian orogeny, was due to terminal collision between Gondwana and Laurentia-Baltica that closed the Rheic Ocean and resulted in the formation of Pangea.

Although modern analogs record orogenic events due to collision of terranes, they also document widespread orogenic activity related to other mechanisms, such as flat-slab subduction and changes of the convergence rates and directions. Thus in the Andes, flat-slab subduction occurs in four geographically limited zones, two of which are related to collision of a mid-oceanic ridge with the trench (the Chile and Cocos ridges; Ramos and Alleman, 2001), one is inferred to result from subduction of an oceanic plateau (the Inca plateau; Gutscher, 2002), and one is genetically connected with subduction of a seamount chain (San Fernandez ridge; Ramos et al., 2002). In the Cordillera of western North America, the Late Cretaceous–Early Tertiary Laramide orogeny has been attributed to overriding of the Yellowstone hotspot (Murphy et al., 1998). These different mechanisms produce different geological records. Thus, ridge-trench collision is unique in producing a gap in the magmatic arc and slab windows that are associated with rift-related magmatism (Thorkelson and Taylor, 1989). Plume-trench collision also produces a magmatic-arc gap but is associated with a wide zone of deformation, and may be followed by extensive plume-related magmatism after the plume burns through the subducting slab and into the overlying lithosphere. Subduction of aseismic ridges and changes in the rate of convergence, although producing a magmatic-arc gap and a wide zone of deformation, are not associated with rift or plume magmatism. In the southwestern Pacific Ocean, Collins (2002) has related contractions (i.e., orogenic events) and extension to alternations of flat-slab and steep subduction that are restricted in both time and space. The difference between the southwestern and eastern Pacific may be related to different rates of convergence across the trench. However, in all of these cases, subduction is ongoing and its effects are restricted to a narrow zone, whereas flat-slab subduction is limited to short episodes with effects that have dimensions congruent with the along-strike width of the flat slab but a wide across-strike extent. In such cases, narrow and wide orogenic zones should alternate along any one active margin. This necessitates a close examination of the extent and duration of orogenic events in an orogen, rather than assuming that they may be correlated along the entire length of the orogen.

Flat-slab and convergence rate mechanisms for orogenic activity are probably more common in the

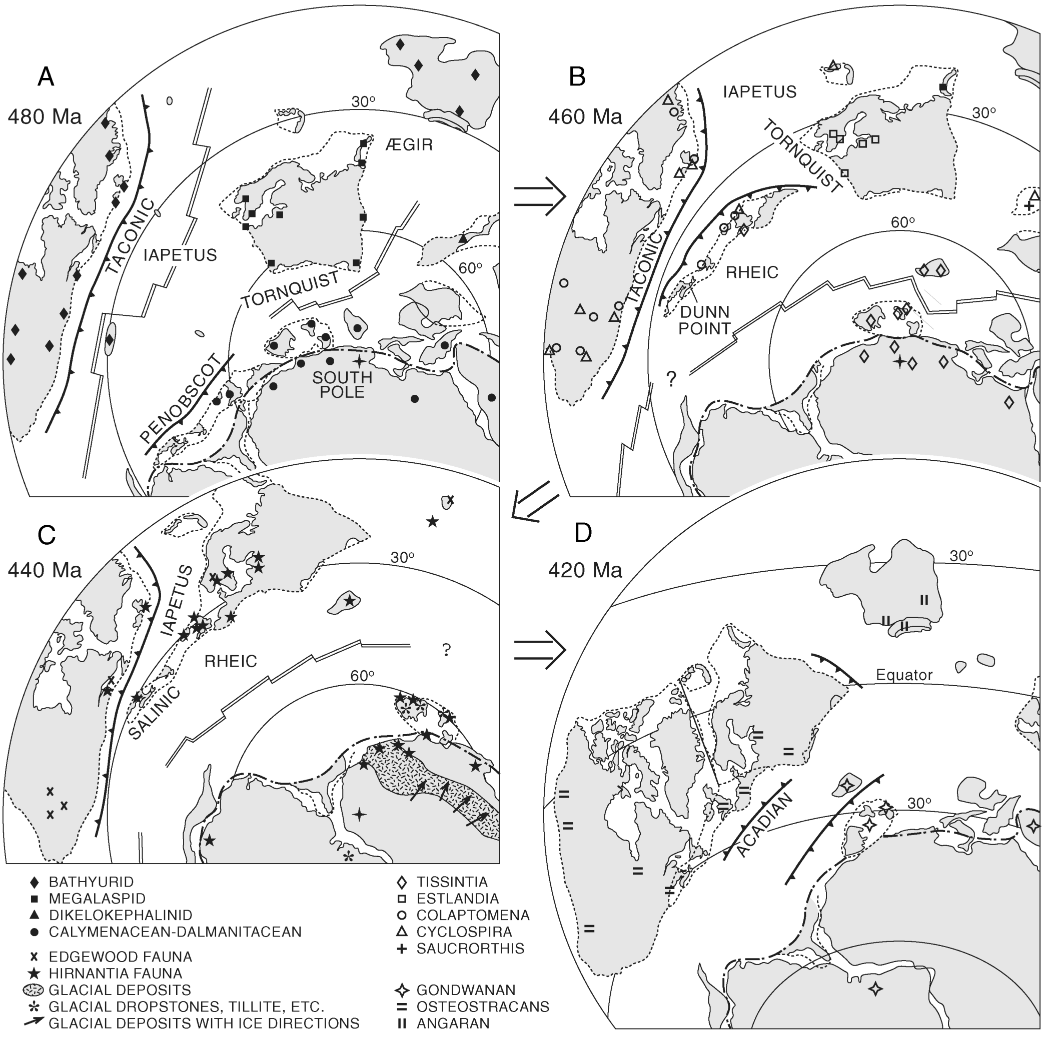

FIG. 2. Early Ordovician to Late Silurian paleogeographic reconstructions of the Circum-Atlantic region (based on Cocks and Torvik, 2002; Fortey and Cocks, 2003).

Appalachians than presently recognized. Murphy et al. (1999) and Keppie and Krogh (2000) proposed that the geological record of the Meguma and Avalon terranes in Maritime Canada during the Acadian orogeny is consistent with flat-slab subduction caused by subduction of an oceanic plateau and a related plume. This paper extends the implication of plume-trench collision as a mechanism for the Acadian orogeny to the northern Appalachians.

The mechanism deduced for the various orogenic events in the Appalachians is largely conditional upon inferred paleogeographic reconstructions. For example, the closure of ocean basins between terranes is generally related to collision orogenic events. Thus the closure of the Iapetus Ocean has been related to both the Ordovician–Silurian Salinic orogeny (e.g. Keppie, 1985, 1993; van Staal et al., 1998; Hibbard et al., 2002) and the Devonian Acadian orogeny (Robinson et al., 1998). Similarly the closure of the Rheic Ocean between the Meguma and Avalon terranes has been related to the Acadian orogeny (e.g., Schenk, 1997; van Staal et al., 1998), although some authors have suggested that the Meguma Group was deposited upon an Avalonian basement (Keppie and Dostal, 1991; Keppie et al., 1997; Murphy et al., 2004b). In view of these contrasting views, we first address the paleogeography just before the onset of the Acadian orogeny.

Silurian Paleogeography

The time of closure of the Iapetus Ocean between eastern Laurentia and Avalonia has been inferred to be either Late Ordovician–Early Silurian or Devonian; however, geological and geophysical data are accumulating in support of the former. Lithologic (O'Brien et al., 1983, 1996) and paleomagnetic data (Johnson and Van der Voo, 1986; Van der Voo, 1988) as well as faunal evidence (Pickering et al., 1988; Cocks and Fortey, 1990; Landing, 1996; Cocks and Torsvik, 2002; Fortey and Cocks, 2003) indicate that Avalonia was located along the periphery of Gondwana from the late Neoproterozoic to the Early Ordovician. Separation between Avalonia and Gondwana gradually increased during the Ordovician (Figs. 2A and 2B). Paleontological evidence supports faunal linkages of Avalonia with Baltica by the Late Ordovician (e.g., Williams et al., 1995; Fortey and Cocks, 2003). Recent geochemical and isotopic data from the ~1900 m Late Ordovician–Early Devonian sedimentary sequence of the Arisaig Group show that the clastic rocks contrast with the underlying Avalonian basement rocks, indicating that they were not derived from Avalonian basement (Murphy et al., 1996b, 2004a).

All sedimentary rocks are characterized by strongly negative ε_{Nd} (from –4.8 to –9.3) and T_{DM} ages >1.5 Ga, with an overall trend toward increasingly negative ε_{Nd} values from the base to the top of the group (Fig. 3). U-Pb detrital zircon data from Lower Silurian (Beechill Cove Formation), Middle Silurian (French River Formation), and Lower Devonian (Stonehouse Formation) strata of the Arisaig Group have similar zircon populations (Fig. 4). Some zircons are close to their respective depositional ages, suggesting that Arisaig basin formation may have been broadly coeval with active volcanism in the orogen. These rocks are also characterized by minor Ordovician and Cambrian zircons, significant populations of Neoproterozoic (550–700 Ma), Mesoproterozoic (0.95–1.3 Ga), Paleoproterozoic (2.0–2.2 Ga), and minor Archean zircons. A comparison between these data and the age of tectonothermal events in potential source areas (Fig. 4), together with regional geologic data, suggest that Arisaig Group strata were primarily derived from Baltica (Murphy et al., 2004a).

Paleomagnetic data indicate a 41°S ± 8° paleolatitude for the Avalon terrane in Nova Scotia (Dunn Point volcanics: Van der Voo and Johnson, 1985, recently dated at ~460 Ma; Hamilton and Murphy, 2004). Inasmuch as Laurentia lay at a paleolatitude of ~20°S between 460 and 440 Ma (e.g., MacNiocaill and Smethurst, 1994), this implies that Avalonia was located about 1700–2000 km south of the Laurentian margin at 460 Ma. Paleomagnetic data suggest that any paleolatitudinal separation between Avalonia and Laurentia had disappeared by the Early Silurian (Miller and Kent, 1988; Trench and Torsvik, 1992; Potts et al., 1993; MacNiocaill et al., 1997). This indicates a latitudinal convergence rate between Avalonia and Laurentia between 460 and 440 Ma of about 5.5 cm/yr (i.e., the destruction of the Iapetus Ocean). As Gondwana remained relatively stationary during this period (e.g., Torsvik et al., 1996), these data imply a northerly component of drift of Avalonia from Gondwana of about 8 cm/yr (development of the Rheic Ocean). Taken together, these data define the southern limit of Iapetus and the northern limit of the Rheic Ocean at 460 Ma. Thus these data indicate a connection between the death of the Iapetus Ocean and the Salinic orogeny, rather than with the Acadian orogeny.

In the southern and central Appalachians, paleomagnetic studies indicate minimal latitudinal separation between the Carolina terrane and Laurentia by ~455 Ma (Vick et al., 1987; Noel et al., 1988). According to Hibbard (2000), sinistral accretion of Carolina and related terranes to Laurentia began in the Middle to Late Ordovician and continued into the Early Silurian, as evidenced by $^{40}Ar/^{39}Ar$ cooling ages on micas that define the regional cleavage in the Carolina zone. Although paleomagnetic data indicate that Avalonia was at 41°S (Johnson and Van der Voo, 1990; Hamilton and Murphy, 2004) at ~460 Ma, suggesting a separation of ~2000 km, Hibbard et al. (in press) point out that because the current direct separation between sampled sites is ~1900 km, Carolina and Avalonia could represent the leading and trailing edges, respectively, of the same plate.

The Acadian orogeny has also been attributed to the collision of the Meguma and Avalona terranes and the closure of the Rheic Ocean. However, the original relationship between the Meguma and Avalon terranes is controversial (e.g., Keppie 1993; van Staal et al., 1998). Many authors have inferred

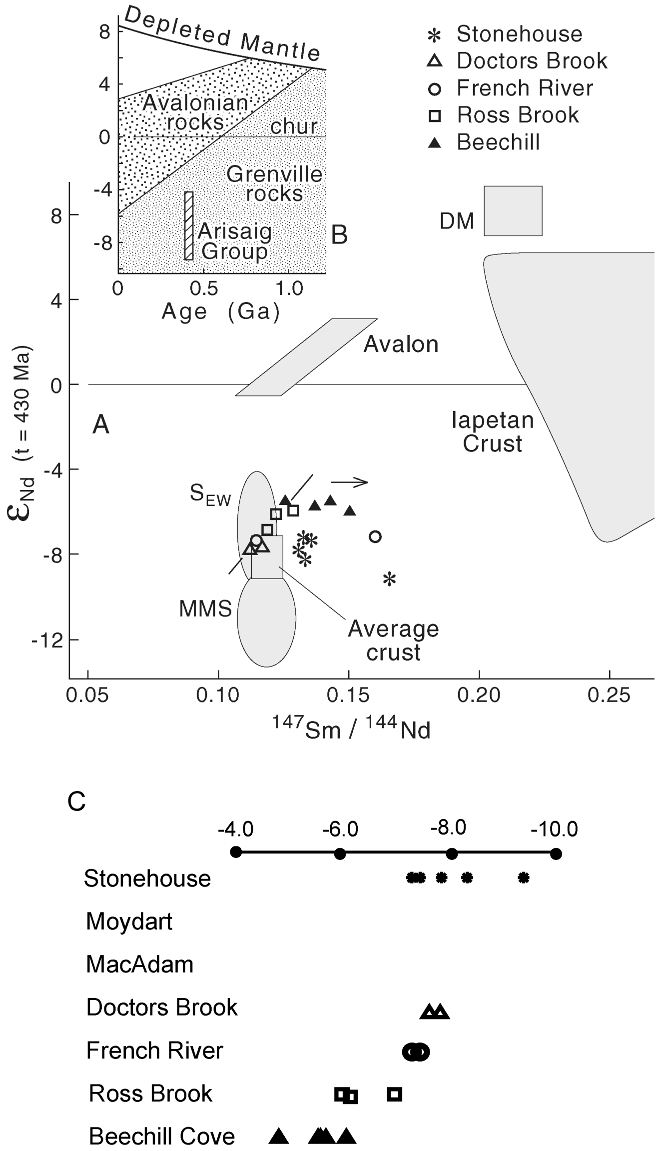

FIG. 3. A. $\varepsilon_{Nd}{}^{t}$ versus $^{147}Sm/^{144}Nd$ diagram (t = 430 Ma) comparing Sm-Nd isotopic data for the Arisaig Group with typical Sm-Nd isotopic compositions of Avalonian crust (Murphy and MacDonald, 1993; Murphy et al., 1996b). The Sm-Nd isotopic characteristics for the average upper crust are bracketed between modern global average river sediment ($^{147}Sm/^{144}Nd$ = 0.114; T_{DM} = 1.52 Ga; Goldstein and Jacobsen, 1988) and the average age of sedimentary mass (Miller et al., 1986). See also Thorogood (1990). Iapetan crust includes normal and depleted island arc tholeiites, and ophiolitic complexes in Newfoundland and Norway (Pedersen and Dunning, 1997; MacLachlan and Dunning, 1998). Silurian strata of England and Wales (S_{EW}) from Thorogood et al. (1990), and Meguma terrane metasedimentary rocks (MMS) from Clarke et al. (1997). B. $\varepsilon_{Nd}{}^{t}$ versus time (Ga) diagram (t = 430 Ma) comparing Sm-Nd isotopic data for the Arisaig Group with typical Sm-Nd isotopic compositions of Avalonian crust (Murphy et al., 1996b, 2000). Field for Grenville rocks after Patchett and Ruiz (1989), Dickin and McNutt (1989), Dickin et al. (1990), Daly and McLelland (1991), McLelland et al., (1993), Dickin (2000). C. Variation in $\varepsilon_{Nd}{}^{t}$ (t = 430 Ma) with stratigraphic height in the Arisaig Group. Beechill Cove Formation data from Murphy et al., 1996b.

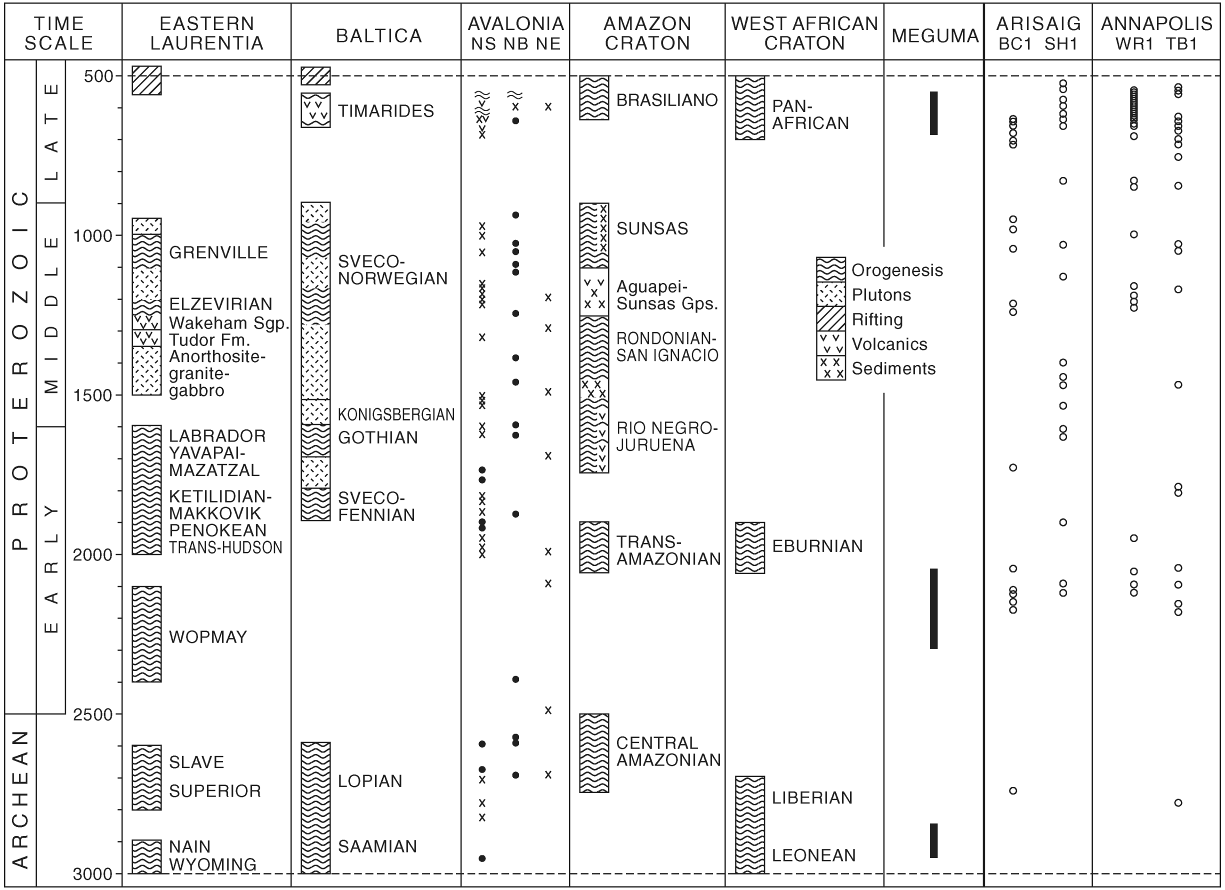

FIG. 4. Detrital zircon ages (open circles) from coeval uppermost Ordovician to Lower Devonian clastic sequences in the Avalon terrane (Arisaig Group) and Meguma terrane (Annapolis Valley), after Murphy et al. (2004b). In the Avalon terrane, BC-1 is from the Lower Silurian Beechill Cove Formation and SH-1 is from the Lower Devonian Stonehouse Formation. In the Meguma terrane, WR-1 is from the Upper Ordovician–Lower Silurian Whiterock Formation and TB-1 is from the Lower Devonian Torbrook Formation. These data are compared with detrital-zircon data from underlying uppermost Neoproterozoic–Lower Ordovician Meguma Group (Krogh and Keppie, 1990) and Neoproterozoic Avalonia (Keppie et al., 1998; Bevier et al., 1990). Symbols: x = concordant U-Pb zircon ages; filled circles = discordant $^{207}Pb/^{206}Pb$ ages. Also shown are tectonothermal events in Baltica (Gower et al., 1990; Roberts, 2003), eastern Laurentia (Cawood et al., 2001), Amazon craton (Sadowski and Bettencourt, 1996), northwest Africa (Rocci et al., 1991), and Gander (van Staal et al., 1996). Abbreviations: NS = Nova Scotia; NB = New Brunswick; NE = New England.

that the Meguma Group represents a Cambrian–Early Devonian passive margin bordering northwest Africa that was transferred to Laurentia during the Acadian orogeny (e.g., Schenk, 1997 and references therein). This was based primarily upon: (1) proposed stratigraphic correlations between the Cambro-Silurian strata in the Meguma terrane and coeval sequences in Morocco (Schenk, 1997); and (2) the Middle Devonian age of the Acadian orogeny, the oldest accretionary event recognized in the Meguma terrane. According to this model, the Avalon and Meguma terranes lay on the opposite sides of the Rheic Ocean, and were juxtaposed during the Acadian orogeny.

Alternatively, the Cambrian–Early Devonian strata of the Meguma terrane have been interpreted as a passive margin bordering the Avalon microcontinent, which would imply that the Meguma Group was deposited on Avalonian continental crust (e.g., Keppie et al., 2003 and references therein). This is based upon (1) the proposed correlation of the Upper Ordovician–Lower Devonian units in the Meguma terrane with coeval sequences in the rest of the Appalachians (Keppie and Krogh, 1999); and (2) the similarity of Nd-isotopic signatures in Late Ordovician–Early Silurian crustally derived igneous suites in the Meguma and Avalon terranes (Keppie et al., 1997). As the Silurian to Lower Devonian strata predate the Acadian orogeny, and no older deformational events are recorded, these data have been interpreted to indicate that the Meguma Group rested depositionally on Avalonian basement in the Cambro-Ordovician. In this interpretation, Avalonia and Meguma lay on the same (northern) flank of the Rheic Ocean, and together collided with Laurentia by the Early Silurian. Inasmuch as the Meguma is the most outboard terrane in the Appalachians, this latter model would imply that the eastern flank of the Appalachians would have resembled a modern Cordilleran or Andean margin.

U-Pb detrital zircon data from Ordovician and Lower Devonian clastic sedimentary rocks in the Meguma terrane (Fig. 4); (White Rock and Torbrook formations in the Annapolis Valley, respectively) are very similar to those from the Arisaig Group (Avalon terrane; Murphy et al., 2004b). In addition to abundant Cambrian–Late Neoproterozoic and Paleoproterozoic zircons, Late Ordovician–Early Devonian samples from the Meguma terrane have important Mesoproterozoic zircon populations (1.0–1.4 Ga) that are typical of Avalonia, and strongly suggest their contiguity by Late Ordovician–Early Silurian time. Because Avalonia had accreted to Laurentia-Baltica by the Late Ordovician, these data suggest that the Meguma terrane, like Avalonia, resided along the same (northern) margin of the Rheic Ocean at that time. That these terranes were juxtaposed throughout the Early Paleozoic and probably into the Neoproterozoic is also indicated by the absence of evidence for a Cambro-Ordovician accretionary event in both the Meguma and Avalonian stratigraphy, the lack of intervening suture zone ophiolitic units, and the similarity of Avalonian and Meguma basement Nd isotopic signatures in Paleozoic igneous suites (Keppie et al., 1998). In view of these recent data, the Acadian orogeny cannot be due to accretion of the Meguma and Avalon terranes.

Acadian Orogeny

The Acadian orogeny is named for Acadia, the old French name for the Maritime Provinces of Canada (Nova Scotia, New Brunswick, and Prince Edward Island). It is the term originally defined for the middle Paleozoic deformation event in the Appalachian orogen of Maritime Canada (including eastern Quebec). The term "Acadian" was introduced by Schuchert (1923) to explain Late Devonian deformation in the Chaleur Bay region of New Brunswick and Gaspé, Quebec. Several workers including Boucot et al. (1964) and Poole et al. (1970) showed that this deformation was regionally extensive in the northern Appalachians (Fig. 5). In Maritime Canada, the Acadian orogeny affected the entire width of the orogen, from the most outboard terrane (Meguma) to the Laurentian foreland. Donohoe and Pajari (1974) showed that the age of peak Acadian deformation became progressively younger northward from coastal Maine to Gaspé, varying from Gedinnian to post-Eifelian in age, a trend confirmed in a recent synthesis by Robinson et al. (1998).

The effects of the Acadian orogenic event are now widely interpreted to extend along the southeastern Laurentian margin from Pennsylvania to Newfoundland, and to correlative rocks in Western Europe (Bradley, 1989; Williams, 1979, 1993; Woodcock and Strachan, 2000) where Late Paleozoic deposits overlie, with angular unconformity, previously deformed Early Paleozoic sequences. This regional unconformity is commonly expressed by widespread Lower Devonian platformal carbonates overlying Taconic foredeep deposits, both

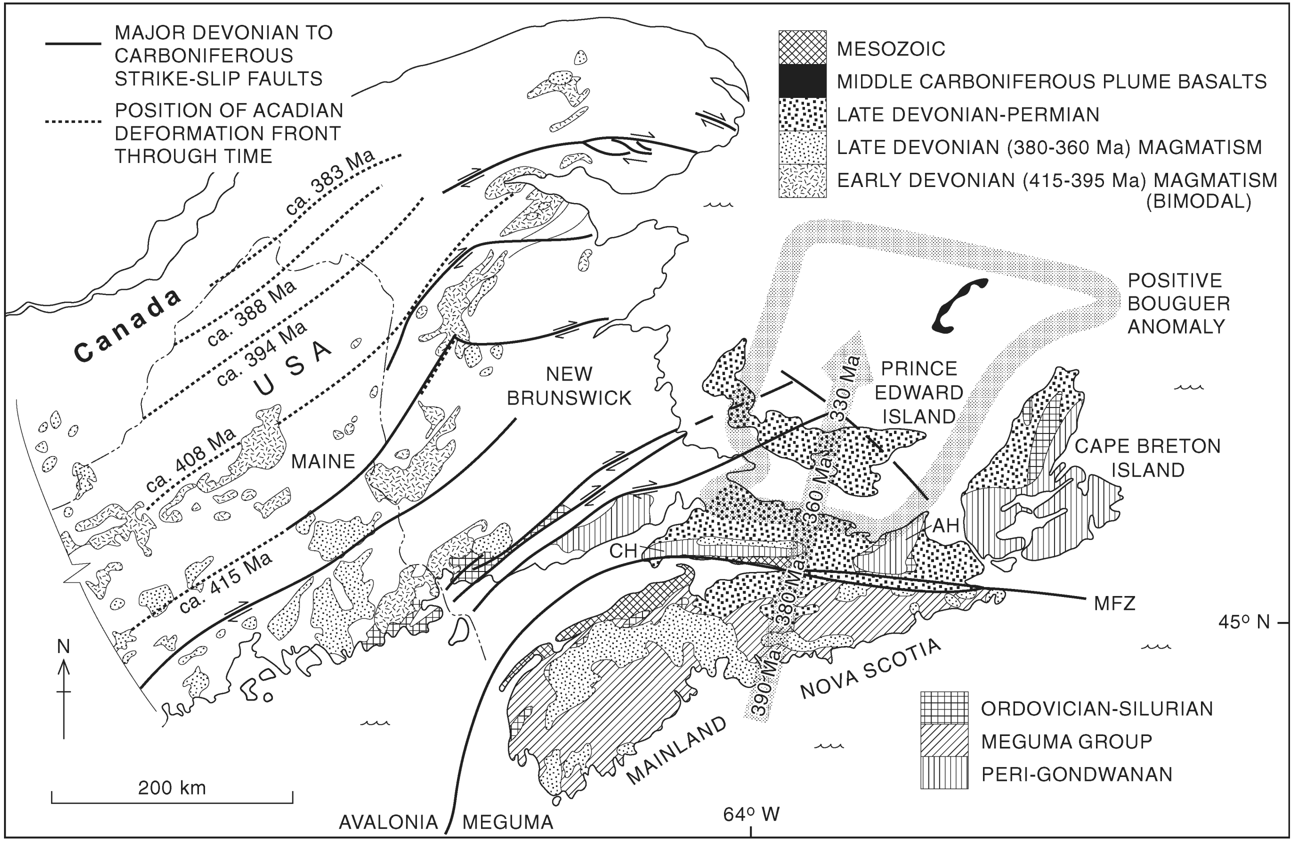

FIG. 5. Map of Appalachian orogen in Atlantic Canada and northern Maine showing Silurian–Devonian igneous rocks, the migration of Silurian–Devonian Acadian foredeep and deformation front through time (data from Robinson et al., 1998, extrapolated into New Brunswick), and Devonian–Carboniferous magmatism associated with plume activity (modified from Murphy and Keppie, 1998). Silurian arc magmatism and Early Devonian bimodal magmatism are associated with convergence of Avalonia and Meguma to Laurentia, and possibly related to resultant slab break-off (see van Staal et al., 1998). The proposed plume track from ca. 390 to 330 Ma is shown with a large arrow. The flat-slab model applies to the Acadian orogeny in Maritime Canada and adjacent Maine. Motions of upper and lower plates in a hotspot reference frame dictate that swell and plume would be overridden at different locations along the continental margin. Hence Late Devonian tectonism in New England may also be explained by this model.

traditionally recognized as clear demarcations between earlier Taconic and Acadian orogenic events. More recently, this demarcation has been related to a switch from sinistral-to dextral-dominated kinematics along major NE-trending faults (e.g., Keppie, 1993; Nance and Dallmeyer, 1993; Cawood et al., 1994; Anderson et al., 2001).

Meguma terrane

Stratigraphy. The Meguma terrane is exposed only in mainland Nova Scotia (Fig. 5), where it is separated from the Avalon terrane to the north by the Minas fault zone. The terrane is underlain by thick (~13 km) Cambrian–Ordovician turbidites (Schenk, 1997) of the Meguma Group containing a Gondwanan fauna (Pratt and Waldron, 1991) that are disconformably to conformably overlain by a 2.3 to 4.5 km thick Upper Ordovician to Lower Devonian sequence of bimodal volcanic rocks overlain by shallow-marine to continental clastic rocks with Rhenish-Bohemian fauna (Boucot, 1975). The Ordovician switch from turbidites to shallow marine deposits was accompanied by a change from a south-southwesterly to northwesterly source. Detrital zircons in the Goldenville Formation (lower unit of the Meguma Group) yielded ca. 3.0 Ga, 2.0 Ga, and 600 Ma ages and also indicate a Gondwanan (West African) source prior to separation from Gondwana (Krogh and Keppie, 1990). Near the base of the Upper Ordovician–Lower Devonian sequence, a rhyolitic tuff of the White Rock Formation yielded concordant U-Pb ages of ~440 Ma (Keppie and Krogh, 2000; MacDonald et al., 2002).

Structure. The earliest effects of the Acadian orogeny in the Meguma terrane began at ~415 Ma with regional metamorphism (predominantly greenschist-facies), polyphase deformation, and cleavage formation (Keppie and Dallmeyer, 1995) and continued to the Late Devonian (Hicks et al., 1999). On a regional scale, cleavage is axial planar to NE-trending shallowly plunging periclinal folds. Several studies propose that the onset of the Acadian orogeny at ~415 Ma was associated with oblique dextral convergence between the Meguma and Avalon terranes (Keppie and Dallmeyer, 1995). The current boundary between these terranes is defined by the E-W Minas fault zone (Fig. 5), along which several episodes of late Paleozoic dextral motion has occurred (e.g., Keppie, 1982; Murphy, 2003). Adjacent to this fault zone, regional folds are rotated clockwise, consistent with late Paleozoic dextral motion. Traced westward, this boundary swings into the NE-SW Bay of Fundy (Fig. 5). Seismic profiles in the Bay of Fundy show the major structure to be a SE-dipping Mesozoic listric normal fault inferred to be located along a late Paleozoic listric thrust zone (Keen et al., 1991). Coeval late Paleozoic (Alleghanian) deformation has been documented by Culshaw and Liesa (1997). The down-dip extension of the sole thrust either maintains its SE dip to the Moho or flattens at 15 km depth between the lower and upper crusts (Keen et al., 1991). The latter model implies that the Meguma terrane is allochthonous and that the Minas fault zone may be a lateral ramp (Keppie, 1993).

Magmatism. In the Meguma terrane, intrusion of widespread late syntectonic ~375–370 Ma granitoids and minor mafic dikes (Clarke et al., 1993, 1997) were accompanied by high T-low P metamorphism and shear zone deformation. Although these plutons clearly cross-cut early Acadian fabrics, studies by Benn et al. (1997) show that they crystallized during the latest stages of Acadian deformation and that their geometry is structurally controlled. Geophysical studies (e.g., Keen et al., 1991) show that the plutons have a broadly laccolithic geometry, and extend to depths of 5–10 km, with feeder zones extending to 25 km.

Exhumation. The earliest evidence of exhumation of Meguma terrane rocks is their occurrence as clasts in latest Devonian–Tournaisian Horton Group rocks (Martel et al., 1993), implying an uplift of between 6 and 10 km between ~370 and 360 Ma (e.g., Keppie and Dallmeyer, 1995; Jennex et al., 2000; Murphy, 2000; Murphy and Hamilton, 2000).

Avalon terrane in mainland Nova Scotia and New Brunswick

To the north of the Minas fault zone in mainland Nova Scotia, Avalonia (Fig. 5), the largest suspect terrane in the northern Appalachian orogen, occupies much of the southern flank of the Appalachians. Correlative rocks occur in Ireland, southern Britain, and adjacent parts of continental Europe, thereby providing a potential genetic linkage between orogenic events in Laurentia and Western Europe (e.g., McKerrow et al., 1991, 2000; Woodcock and Strachan, 2000).

Stratigraphy. Ordovician–Lower Devonian rocks in Avalonia of mainland Nova Scotia unconformably overlie older Neoproterozoic and Cambrian strata that contain typical Avalonian fauna (Landing and Murphy, 1991). Ordovician strata consist of ~460 Ma bimodal intracontinental volcanic rocks (Dunn

Point Formation) and interbedded red clastic sediments disconformably overlain by an 1800 m continuous stratigraphic sequence dominated by shallow-marine to continental, fossiliferous siliciclastic rocks (Arisaig Group and correlatives).

Waldron et al. (1996) interpreted the Silurian–Early Devonian subsidence history of the Arisaig Group as an initial phase of rapid subsidence and extension (30% to 60%) in the Early Llandovery, followed by thermal relaxation and slower subsidence rates in the Wenlockian and Ludlow. Vastly increased subsidence rates and accommodation space in the Pridoli (as represented by the Stonehouse Formation) was attributed to loading of the Avalonian margin due to interaction with a neighboring terrane (Waldron et al., 1996), probably the Meguma terrane.

The Arisaig Group is unconformably overlain by Middle Devonian interbedded basalts and continental rocks, and this unconformity is widely interpreted to represent the local manifestation of the Acadian orogeny.

Structure. In the Fredericton trough, the earliest Acadian deformation consists of upright, isoclinal folds with a low-grade cleavage deformed Llandovery-Gedinnian rocks before intrusion of granitoid plutons at 406 ± 7 Ma.

Magmatism. In the Cobequid Highlands of mainland Nova Scotia, Middle to Late Devonian (~360 Ma) magmatism is particularly voluminous, and is represented by bimodal volcanic and plutonic rocks (Doig et al., 1996; Piper et al., 1993).

In southern New Brunswick, the Kingston Complex (e.g., Currie, 1987) or terrane (Barr et al., 2002), is considered to be either part of Avalonia (e.g., Keppie and Dostal, 1991) or Ganderia (Barr et al., 2002). It consists of arc-related metavolcanic and metasedimentary rocks intruded by Early Silurian granite plutons and mafic dikes. The intrusive age of the mafic dikes in uncertain, but $^{40}Ar/^{39}Ar$ analyses on igneous hornblende are interpreted as a ~415 Ma cooling age (Nance and Dallmeyer, 1993). Magmatism in the Kingston Complex has been genetically related to the compositionally similar Late Silurian coastal Maine Complex.

The geochemistry of ~430–422 Ma Avalonian granitoids is typical of subduction, but a younger event (~396–367 Ma) has more mafic components and more juvenile signatures, which have been attributed to crustal delamination by Whalen et al. (1994). Silurian–Early Devonian arc-related plutonic and volcanic rocks switch off at the same time as deformation was occurring in the Central Maine Basin.

Siluro-Devonian geology in central and southern New Brunswick (north of the Kingston Complex) is dominated by relatively low grade volcanic and sedimentary rocks occurring in anticlinoria, which are affected by widespread plutonism and deformation, separated by basins that preserve a relatively continuous stratigraphic record. Deformation was accompanied by regional dextral shear (e.g., Nance and Dallmeyer, 1993; Schreckengost and Nance, 1996). Voluminous Siluro-Devonian granitoid rocks (Whalen et al., 1996) have metaluminous to slightly peraluminous, within-plate chemistry. Silurian plutons have complex histories that may involve input of a juvenile component, whereas Devonian granitoids represent partial melting of hybridized Avalonian crust. Whalen et al. (1996) attribute this magmatism to collision and lithosphere delamination accompanying and following the accretion of Avalonia to Laurentia.

Central and Northern Cape Breton Island

Important Early Silurian (~435 Ma) arc-related magmatism, metamorphism, followed by collisional orogeny in central and northern Cape Breton (Barr and Raeside, 1989; Keppie et al., 1991; see Fig. 5) may be correlative with similar-aged events in the La Poile Group of Newfoundland (e.g., Chandler et al., 1987; Dunning et al., 1990 ; O'Brien et al., 1991; Barr et al., 1998), which are attributed to the Salinic orogeny. According to Lin et al. (1994), these events collectively represented subduction followed by promontory-promontory collision between Laurentia and Avalonia during the Silurian.

Central and northern New Brunswick and neighboring Maine

Much of central and northern New Brunswick and neighboring Maine (Figs. 5 and 6) is underlain by Gondwana-derived Cambrian–Lower Ordovician strata of the Gander terrane (van Staal et al., 1998), which is unconformably overlain by a widespread Middle Ordovician volcano-sedimentary sequence interpreted as an ensialic rifted arc (van Staal, 1994) that oversteps the boundary with the Exploits subzone to the north and Avalonia to the south (Williams and Piasecki, 1990; van Staal et al., 1996) and contains peri-Gondwanan (Celtic) fauna (Neuman and Harper, 1992). Complex Late Ordovician–Silurian deformation is related to sinsistral oblique convergence and collision of peri-Gondwanan

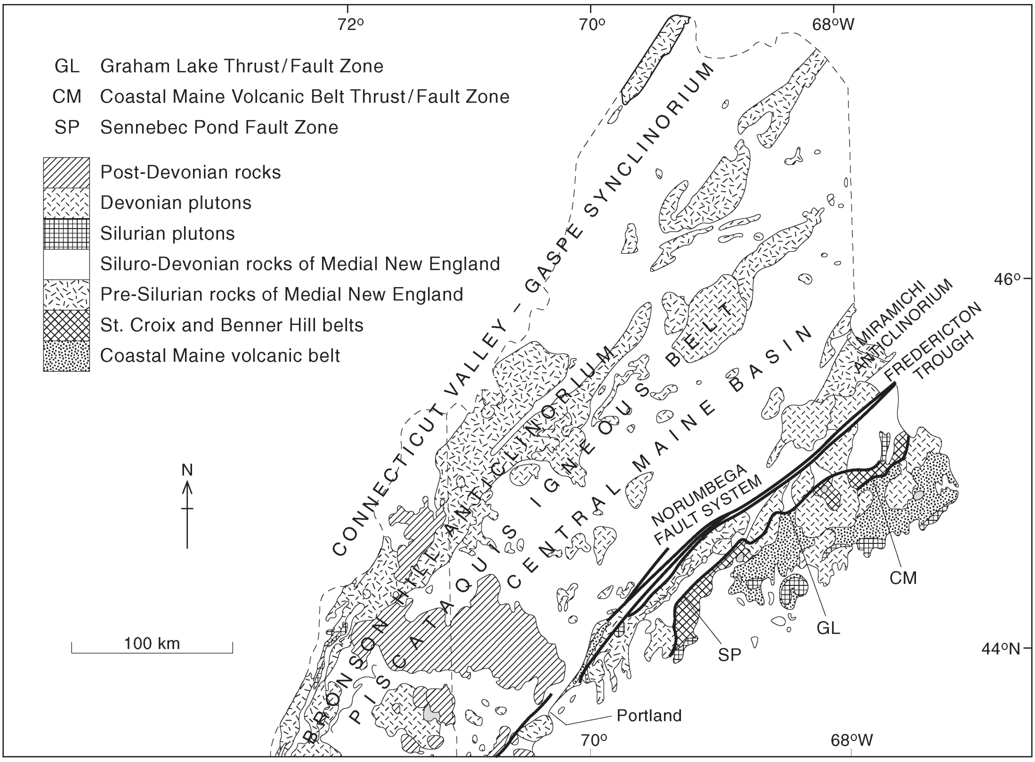

FIG. 6. Geology of northern New England (modified from Robinson et al., 1998; Tucker et al., 2001). Abbreviations: CM, GL, and SP = Coastal Maine, Graham Lake, and Sennebec Pond fault zones, respectively.

terranes against the Laurentian margin (van Staal et al., 1990). According to van Staal and de Roo (1995), several short-lived episodes of arc accretion, slab roll-back and breakup, and rapid exhumation of blueschist-facies metamorphic rocks are attributed to post-collisional extension.

A prominent feature of this region is the Silurian–Lower Devonian Tobique-Piscataquis magmatic belt and correlatives, which have been variously interpreted to represent arc (Rankin, 1968; Bradley, 1983; Thirlwall, 1988) or post-collisional magmatism (Arth and Ayuso, 1997; Ayuso and Arth, 1997) related to the closure of the Iapetus Ocean. Alternatively, they have been interpreted as intra-plate continental tholeiites intruded in an extensional environment (Dostal et al., 1989; Hon et al., 1992).

Foreland clastic wedge

In the Appalachian foreland of Quebec, Silurian–Lower Devonian sedimentary facies in the Gaspé Belt south of the Québec reentrant and the St. Lawrence promontory preserves evidence of significant syn-depositional tectonism, attributed by Malo et al. (1995) to along-strike Acadian structural variations as a consequence of collision along an irregular margin and by Bourque et al. (2000) to the Salinic "disturbance" beginning in late Llandoverian time and continuing into the Early Devonian. Llandoverian–Wenlockian regression is attributed to post-Taconian successor basin filling that culminated with extensive carbonate platform development. This was followed by extensional tectonics that produced shelf faulting and block tilting, on top of which block reefs and reef complexes developed and extended along the Gaspé-Témiscouata shelf. Early Devonian rapid subsidence in the Québec reentrant area was coeval with uplift in the St. Lawrence promontory, attributed to loading of the Laurentian margin associated with the further thrusting of Avalon and Meguma terranes over Laurentia. Lower to Middle Devonian clastic wedge deposits of the eastern Gaspé Peninsula record a gradual displacement of source areas from the southeast to the southwest.

Equivalent clastic wedge deposits in western New York state and Pennsylvania are the Middle–Upper Devonian clastic wedge (Quinlan and Beaumont, 1984) that thins to less than 30 m near Alabama (Hatcher, 1989), where subsidence curves in Middle Paleozoic strata show no effect of loading the Appalachian margin (Thomas and Whiting, 1995). The Catskill clastic wedge is widely interpreted to reflect this loading of the Laurentian margin and a westerly migrating foredeep and clastic wedge ahead of an advancing Acadian orogenic front (Bradley, 1989). Some of the source rocks for the Catskill delta deposits may have been located in the New York promontory in southern New England, where the Siluro-Devonian recumbent folds and high-grade metamorphism was followed by rapid uplift, and removal of 20 km of crust. Stewart et al. (1995) and Bradley (1989) attributed the Siluro-Devonian tectonothermal activity and westerly migration of the Catskill foredeep to the Acadian orogeny.

Post-Acadian structures in the Gaspé Peninsula affected rocks that are as young as Namurian, and such transpressive deformation, more than 1000 km away from areas of peak coeval Alleghanian metamorphism in the southeastern United States, is attributed by Jutras et al. (2003) to the far-field effects of rigid indenters during terminal continental collision. Middle-Late Devonian bimodal igneous rocks followed by Middle Carboniferous mafic rocks with plume-related geochemical signatures (Bedard, 1986) are consistent with intracontinental wrench syn-to-post Acadian tectonic regime.

In central Maine (Fig. 6), shallow-marine Silurian strata gave way to Lower Devonian deeper-water flysch deposits. The Central Maine Basin preserves a record of continuous Late Ordovician–Early Devonian deep-marine sedimentation (Berry and Osberg, 1989), with the lower strata derived from the west, and younger strata from the east. This basin has been interpreted as either a vestige of ocean between Avalonia and Laurentia (Bradley, 1989), or a post-collisional basin intracontinental regime (e.g., Hon et al., 1992).

Southern and Central Appalachians

Effects of the Acadian orogeny in the southern and central Appalachians (Fig. 7) are limited to: (1) a shear zone within the Carolina zone; (2) in the Blue Ridge province of western North Carolina, a phase of Devonian dextral strike-slip tectonics is partitioned into narrow shear zones where it is superimposed on earlier high-pressure Ordovician deformation (Willard and Adams, 1994); and (3) an upper Paleozoic ductile shear zone that defines the western limit of the Carolina zone may represent the latest stage in the movement of the zone against Laurentia. Late Devonian deformation in the central and southern Appalachians has been genetically linked with the Upper Devonian clastic wedge.

Newfoundland

The effects of the Acadian orogeny in Newfoundland are limited (Fig. 8). In central Newfoundland (Humber, Dunnage, and Gander zones), widespread Silurian (~435–415 Na) deformation, metamorphism, plutonism and exhumation are generally considered to be the climactic event following the Early Silurian, Salinic oblique sinistral collision of the Gander and Avalon terrane with Laurentia (Dunning et al., 1990; O'Brien et al., 1991; Williams, 1993; Cawood et al., 1994; Kerr, 1997; Schofield and D'Lemos, 2000) that occurred before onset of the Acadian orogeny. Devonian deformation in the Avalon terrane is limited to SE-vergent thrusting and folding adjacent to dextral faults (Keppie, 1993). An apparent hiatus in plutonism exists between the Silurian and the mid-Devonian. Devonian magmatism in Newfoundland occurs in isolated plutons in the Dunnage and Gander zones, but is most voluminous in the Avalon zone and adjacent to the Avalon-Gander boundary. The compositions of Devonian granites are also indicative of a post-collisional setting. Renewed plutonism was accompanied by a switch from sinistral kinematics of the Silurian to Devonian dextral kinematics (as exemplified by the Dover fault; Holdsworth, 1994) suggesting that the magmatism developed in response to wrench kinematics.

Summary

The data presented above indicates that the Acadian orogeny is limited in both time and space: it lasted from the Late Silurian to Late Devonian and is centered on the northern Appalachians. Outside this region, its effects are limited to strike-slip faults and sporadic magmatism. It appears to have spread diachronously from south to north with clastic wedges migrating northward and then westward, closely followed by the deformation front. In space it coincides with a gap in the magmatic arc that was

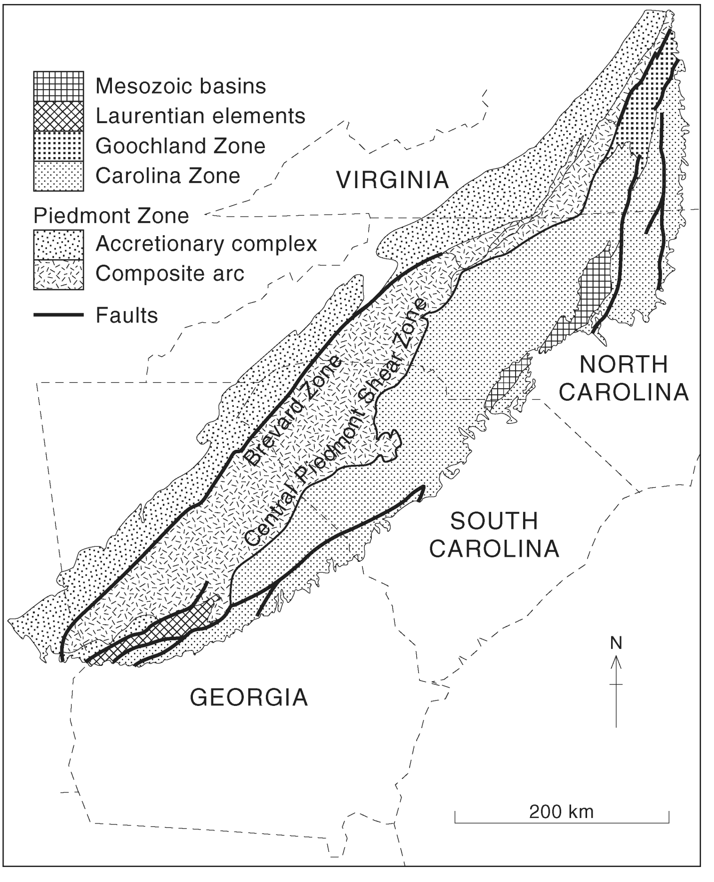

FIG. 7. Simplified geological map showing the general geology of the Southern Appalachians (after Hibbard et al., 2002; Hibbard, 2004).

subsequently interrupted by voluminous magmatism, some of which has a plume signature, and which also migrated from south to north.

Model for the Acadian Orogeny

The conclusion that the Avalon and Meguma terranes shared a common history during the Paleozoic has profound consequences for interpretation of the Acadian orogeny. Inasmuch as the Meguma is the most outboard terrane, this implies that all peri-Gondwanan terranes in the northern Appalachians were accreted prior to the mid-Silurian. The Late Silurian–Devonian Acadian orogeny, therefore, cannot be related to collision of the Meguma terrane with Avalonia or with the Laurentian margin. Instead, this scenario suggests that the Acadian orogeny occurred in a Cordilleran- or Andean-type setting.

Paleocontinental reconstructions imply continued convergence between Gondwana and Laurentia during the Late Silurian and Devonian, and consequently, subduction of the Rheic Ocean. However, over a wide region of Maritime Canada, voluminous magmatism ceased between ca. 395 and 380 Ma, and a period of relative magmatic quiescence occurred. During this period, the diachronous onset of deformation associated with the Acadian orogeny in the northern Appalachians migrated northwestward from Ludlovian in the southeast to Frasnian in the northwest (Fig. 3; Bradley, 1989; Keppie, 1993; Robinson et al., 1998), to extend across the entire width of the Appalachian orogen.

In the Meguma terrane, the period of magmatic quiescence was abruptly terminated by a voluminous ~380–370 Ma magmatic episode most dramatically represented by intrusion of the biggest

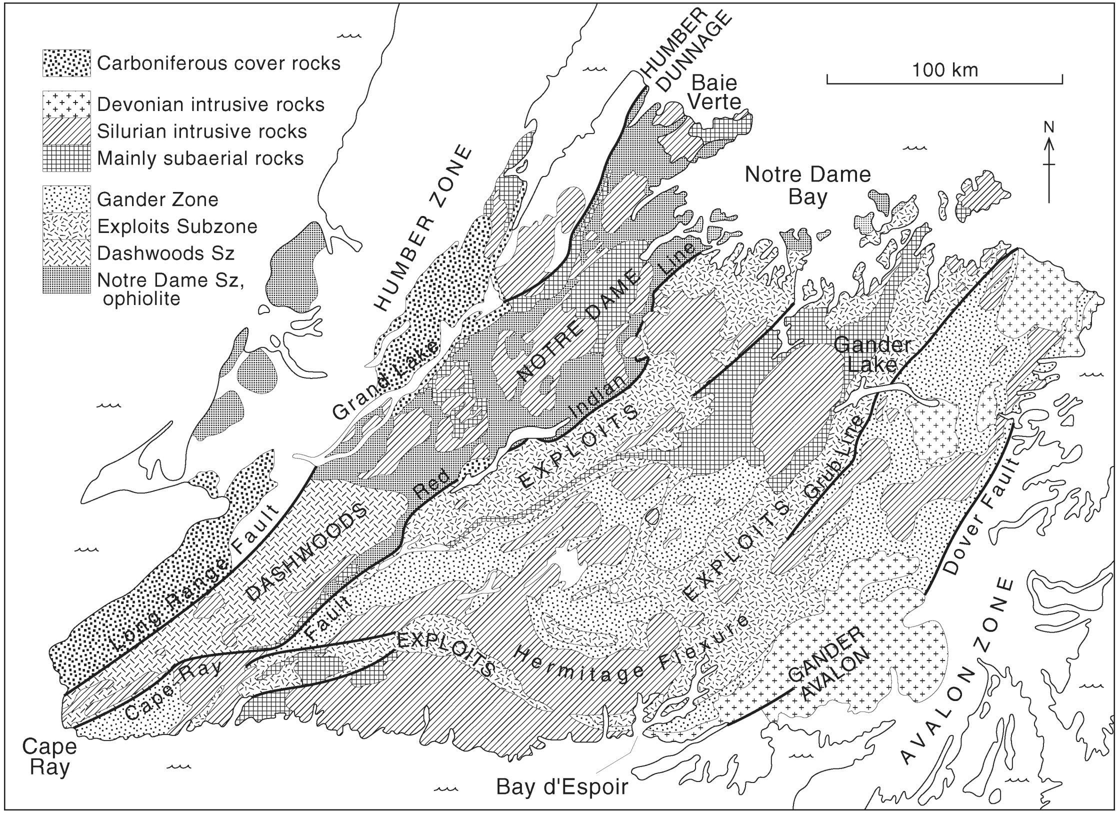

FIG. 8. Tectonostratigraphic subdivisions of central Newfoundland (after Williams and Piasecki, 1990; Williams, 1993). Age data for plutons compiled from Kerr (1997).

granitoid batholiths in the northern Appalachians and coeval lamprophyric dikes (e.g., Clarke et al., 1997). Coeval abundant gold and siderophile mineralization has an isotopic signature indicating a source within the lower crust and probably formed as a result of dehydration by mantle-derived magma and fluids (Kontak et al., 1990).

Magmatism in the Meguma terrane terminated abruptly by ~370 Ma. To the north, in the Cobequid Highlands on the Avalon terrane, voluminous ~360 Ma, bimodal magmatism commenced (Pe-Piper et al., 1989; Doig et al., 1996; Pe-Piper and Piper, 1998), with final emplacement of plutons at a shallow level, controlled by coeval dextral transpression along major E-W faults (Koukouvelas et al., 2002). Magmatism in the Cobequid Highlands terminated before ~355 Ma. Farther north, middle Carboniferous mafic rocks with plume-related geochemical signatures crop out around the periphery of the Maritimes basin and in the Magdalen Islands (Bedard, 1986). Although the Maritimes basin is poorly exposed, geophysical and borehole data indicate that ~3 km thick deposit of mainly terrestrial Carboniferous and Permian rocks. Beneath the Maritimes basin, seismic velocities of 7.2 m/s and a pronounced positive Bouguer anomaly are attributed to a 10–20 km thick Carboniferous underplating of mantle-derived magma (Marillier and Verhoef, 1989).

Murphy et al. (1999) and Keppie and Krogh (1999) proposed that the Silurian–Devonian Acadian orogeny in the type area was caused by flat-slab subduction, in a manner analogous to the modern Andes or the late Mesozoic–Cenozoic evolution of the southwestern United States (Fig. 9). This model provides a potential explanation for several anomalous aspects of the geology of the northern Appalachians that otherwise remain enigmatic. Following ~415 Ma convergence between the Avalon and Meguma terranes, the 395–380 Ma period of magmatic quiescence and the northwestward migration of the deformation front is attributed to the development of a flat slab beneath the Canadian Appalachians (Figs. 9A and 9B) and ensuing Laramide-style orogenic activity in which intermittent coupling between the subducted and overriding plates resulted in deformation that migrated to at least 600 km inboard of the continental margin. The flat-slab model is capable of explaining both the lack of 395–380 Ma arc magmatism associated with the convergence (a problem implicit in several previous models), and the diachronous migration of the deformation front and overstep sequences across the entire 500–800 km width of the orogen.

Flat-slab subduction has been attributed to several mechanisms: (1) far-field effects of terrane collision (Maxson and Tikoff, 1996); (2) overriding of an ocean plateau or dormant seamounts (e.g., Pilger, 1981; Gutchner et al., 2000); (3) subduction of young oceanic lithosphere (Gutscher, 2002) or a ridge (Yañez et al., 2002); (4) increased rates of convergence or changes in the direction of convergence (Ramos et al., 2002); or (5) overriding of a swell and an active plume (Murphy et al., 1999). All these mechanisms produce a migrating deformation front and temporarily switch off arc magmatism. However, only overriding of a plume would terminate a period of magmatic quiescence with voluminous magmatism with a linear, diachronous distribution, coupled with compositional changes from felsic- to mafic-dominated magmatism.

The Laramide orogeny is characterized by an almost complete absence of magmatism (the Paleocene magmatic gap), widespread deformation, and thick-skinned tectonics associated with basement uplifts located about 1500 km inboard of the continental margin. Most authors attribute these features to flat-slab subduction (e.g., Dickinson and Snyder, 1979; Liviccarri et al., 1981; Bird, 1988; Severinhaus and Atwater, 1990). However, origin of the flat slab is controversial, and not well constrained.

Recent geodynamic analysis of the modern flat-slab subduction zones has drawn attention to their spatial and temporal correlation with a subducting oceanic plateau (e.g., Gutscher et al., 2000; Yañez et al., 2002), suggesting a similar possibility for the Laramide orogeny. The Andean margin, for example, has several flat-slab segments, up to 500 km wide, that are each correlated with subduction of anomalously warm oceanic crust, represented by oceanic plateau (Gutscher et al., 2000). Murphy et al. (1998) speculated that the origin of flat-slab subduction in the western United States is due to the overriding by the continental margin of a mantle plume and related swell related to the ancestral Yellowstone hotspot. According to plate reconstructions, the ancestral Yellowstone hotspot would have collided with the margin at about 50 Ma. The model implies that the underlying plume would have been positioned beneath the Kula and/or Farallon oceanic plates prior to 55–50 Ma. Evidence for the existence of the plume in the oceanic realm is derived from Late Cretaceous basaltic terranes of the Coastal Ranges and from the Yukon Territory.

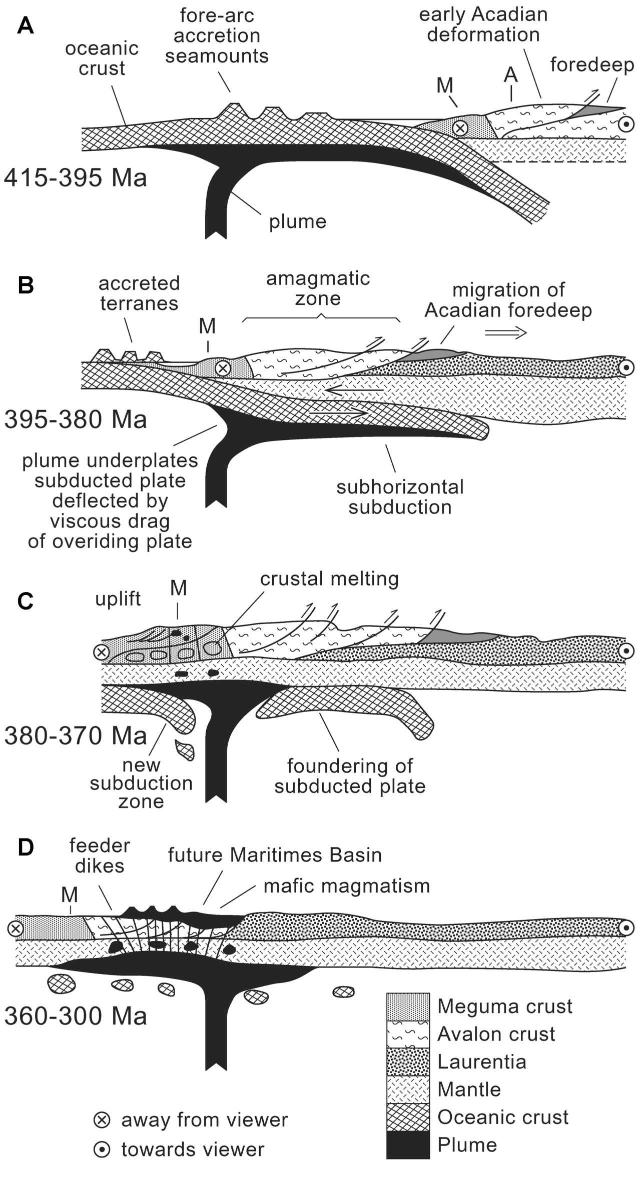

FIG. 9. Plate tectonic model for Acadian orogeny in the Maritime Appalachians. Cross-sections are coincident with the plume track in Figure 3. A. Between 415 and 395 Ma, plume resided beneath oceanic crust. Coeval magmatism and metamorphism (see Fig. 1) in Laurentia is interpreted to reflect telescoping of Avalonia (A) and Meguma (M) to Laurentia during which slab break-off may have occurred (van Staal et al., 1998). B. Between 395 and 380 Ma, the plume is overridden by the Laurentian margin, resulting in subhorizontal subduction and temporary cessation of magmatism and coeval migration of the Acadian foredeep and deformation front. C. Between 380 and 360 Ma, the plume head thermally erodes the subducted oceanic plate, causing intracrustal melting and minor mafic magmatism. D: Between 360 and 300 Ma, breakthrough of plume-related magmatism occurs. As the plume eventually dies, underplating by plume-derived magma results in the formation of a positive gravity anomaly and in the formation of the Maritimes basin. The region of flat-slab subduction may not extend to the central or southern Appalachians. Note that the process in which a continent overrides a plume and swell is considered diachronous, so that timing of events might be different in the northeastern United States.

Duncan (1982) and Wells et al. (1984) proposed that some basaltic provinces of the Coastal Ranges (such as the 60–50 Ma Crescent terrane) were seamounts generated by the Yellowstone hotspot that were accreted to western North America by the Eocene. In the Yukon Territory, the ca. 70 Ma Carmacks basaltic volcanics have plume-type geochemistry. Paleomagnetic data indicate that the Crescent and Carmacks basalts were both erupted at similar paleolatitudes to the Yellowstone hotspot (Johnston et al., 1996) although the Crescent volcanics underwent much less subsequent northward translation (Babcock et al., 1992).

The 395–380 Ma period of magmatic quiescence in Maritime Canada may be related to an incubation period in which the plume progessively assimilated or thermally eroded the overlying lithosphere (Fig. 9B), thereby exposing the continental lithosphere to the hot asthenosphere (Fig. 9C). The resulting melts led to an abrupt termination of magmatic quiescence and intrusion of voluminous ~380–370 Ma intracrustal granitoid rocks and lamprophyres of the Meguma terrane. Between 380 and 330 Ma, the site of magmatism moved northward to reside beneath the Maritimes basin by Visean times. The mafic component of the ~360 Ma magmatism in the Cobequid Highlands may represent melting of the lithospheric mantle above the plume. Visean-Westphalian mafic rocks around the Maritimes basin have plume-related geochemistry (Pe-Piper and Piper, 1998; Bedard, 1986) and are interpreted to reflect the penetration of the plume-derived magmas into the overlying continental crust (Fig. 9D).

Anomalously high heat flow associated with the plume provides a viable mechanism for regional-scale high-T, low-P metamorphism in the Meguma terrane that is broadly coeval with the intrusion of the plutons. In addition, current models for plumes involve ascent from the core-mantle boundary, a region thought to be anomalously rich in gold and siderophile elements (Brimhall, 1987), and the ascending plume may have transported these elements into the continental lithosphere (Rock and Groves, 1988). The ~20 m.y. interval between the overridding of the leading edge of the swell and its peak thermal effect provide a time window for circulating fluids to scavenge metals from the dehydrated lower crust.

The record of uplift and erosion within the Meguma and Avalon terranes can also be explained by the model. Overriding of the leading edge of the plume swell can account for the Early Devonian transition from shallow-marine to continental sedimentation recorded in both the Meguma and Avalon terranes. This change is synchronous with the earliest development of slaty cleavage in the southeastern Meguma terrane. The rapid exhumation of ~10 km in the Meguma terrane between 370 and 360 Ma (Keppie and Dallmeyer, 1995) and rapid uplift of the Cobequid Highlands at ~360 Ma (Ryan et al., 1987) may be the topographic expression of an overridden plume.

The high-density lens beneath the Maritimes basin (Marillier and Verhoef, 1989) may represent the beheaded plume, the cooling of which would induce sinking relative to surrounding uplifted areas. Such sinking could account for the geophysical anomalies and formation of the Maritimes basin (Fig. 9D). As the plume is considered stationary relative to the more mobile overlying lithosphere, there is no geophysical expression of plume activity in the Cobequid Highlands and the Meguma terrane.

The limited effects of the Acadian orogeny outside the northern mainland Appalachians may be a reflection of steepening of the subduction zone, resulting in a narrow active zone that may have become extensional rather than contractional, a factor that depends on the rate of convergence.

Discussion

In the Appalachians, several orogenic events have been recognized: Taconian, Penobscotian, Salinian, Acadian, and Alleghanian, and these have generally been correlated along the whole length of the orogen. Of these, the Salinian and Alleghenian orogenies have been interpreted as due to continent-continent collision, Laurentia-Avalonia and Laurentia-Gondwana, respectively. Thus their widespread distribution is to be expected. The Taconian and Penobscotian orogenies have been related to convergence in island arc settings, and if these island arcs have great length, their accretion to the margins may also be widespread.

The Acadian orogeny was initially interpreted to have resulted from continent-continent collision between Laurentia and Avalonia, or between the amalgamated Laurentia/Avalonia and Meguma/Africa. The former can now be discounted, inasmuch as data collected within the last 30 years indicate that Laurentia-Avalonia collision took place in the Late Ordovician–Silurian, i.e. before onset of the Acadian orogeny. On the other hand, recent detrital zircon data supports the contiguity of the Meguma and Avalon terranes during the Paleozoic, and imply that they accreted to Laurentia as a single microcontinent by the mid- to Late Silurian (~415 Ma). Hence, the collision of Avalonia or Meguma is unlikely to be the cause of the Late Devonian–Late Carboniferous tectonism and magmatism. The data support the hypothesis that the Meguma terrane is the passive margin on the southern margin of Avalonia, and that it formed along the northern (Laurentian) margin of the Rheic Ocean (Murphy et al., 2004b), which did not close until the Permo-Carboniferous.

This implies that the Acadian orogeny formed along an Andean-type margin, possibly by overriding a plume and its swell (Murphy et al., 1999; Keppie and Krogh, 1999). Arc-related magmatism and deformation related to crustal shortening occurred along most of the Andean margin. However, coeval orogeny related to flat-slab subduction, characterized by an absence of arc magmatism and deformation well inboard of the plate boundary, occurs in Peru and the Pampean, and appears to have been synchronous with changes in convergence rate and direction, and with thick-skinned tectonics related to intermittent coupling between the overridden oceanic lithosphere and the South American plate (Ramos et al., 2002). Similar variations in the dip of the subduction zone along the northern margin of the Rheic Ocean may account for the variation in the style of Acadian orogenesis from the southern Appalachians to Atlantic Canada.

Elsewhere in the circum-Pacific region, subduction-related orogenic activity appears to alternate between steeply and shallowly dipping subduction, a phenomenon called tectonic switching by Collins (2002). During periods of steep subduction, the overriding plate is generally subjected to extension, in which sedimentary basins may form, with convergent deformation limited to the trench area. An exception occurs if the convergence rate is high; then orogenic effects are more widespread. During periods of flat-slab subduction the overriding plate is subjected to convergence, causing medium- to high-grade metamorphism, polyphase deformation, and magmatism in the basins. According to Collins (2002), these tectonothermal events are often mistakenly ascribed to arc-continental collision, so tectonic switching may offer an alternative model that could resolve controversies about the timing and nature of "collisional" tectonics in the central and southern Appalachians.

Flattening of the Benioff zone is generally the result of collision of buoyant regions in the oceans such as seamounts, mid-oceanic ridges, young oceanic lithosphere, oceanic plateaus, island arc complexes, hot spots, etc. As these buoyant regions are of limited size, it follows that the associated orogenic events are limited in areal distribution. Furthermore, flattening of the subduction zone is gradual in producing diachronous orogenic effects that start at the trench and migrate inboard. On the other hand, if the flattening of the subduction zone is the result of increased convergence rates, the orogenic effects may have wider distribution.

Inasmuch as flat-slab subduction is a common feature of modern convergent margins, it should also be common in the geologic record. We believe that the Acadian orogeny in the northern mainland Appalachians may be the expression of such a process. The relative motion between the overriding plate and the plume implies that features such as the magmatic gap, plume-related magmatism, deformation fronts, and basin formation are separated in space as well as in time. As a result, these features may be difficult to recognize in ancient orogenic belts, especially where they are overprinted by polyphase deformation and dismembered by subsequent faulting. The presence of continental mafic rocks with plume-related chemistry is an important clue to the identification of such processes. Because even the strongest plumes have difficulty in penetrating continental lithosphere, the presence of plume-related volcanic rocks indicates that the plume and its related swell may have had a protracted earlier history.

Acknowledgments

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