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Precambrian Evolution of the Avalon Terrane in the Northern Appalachians: A Review

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Article abstract

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Precambrian Evolution of the Avalon Terrane in the Northern Appalachians: A Review

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The Avalon terrane of the Northern Appalachians forms a distinctive tectonostratigraphic belt defined primarily by the presence of late Precambrian (circa 600 Ma) volcano-sedimentary and granitoid rocks overlain by Lower Paleozoic sequences containing Acado-Baltic fauna. Avalon terrane is exposed in eastern Newfoundland, Cape Breton Island and the northern Nova Scotian mainland, southern New Brunswick, coastal southeastern Maine, and southeastern New England.

The Precambrian evolution of Avalon terrane includes two major tectonothermal events that involved both continental and oceanic basement. Local oceanic mafic magmatism and regional metamorphism of a mid-Proterozoic (late Helikian?) carbonate-clastic platform and its gneissic continental basement may record an early Hadrynian (750-800 Ma) rifting or subduction event and local platform collapse. Late Hadrynian (580-630 Ma) calc-alkaline granitoid plutonism and widespread volcanism of tholeiitic, calc-alkaline and occasionally peralkaline affinities record a closure event that is interpreted to involve ensialic arc, oceanic interarc, and both extensional and transtensional continental back-arc settings. Closure terminated, perhaps through transform interactions, in the late Hadrynian Avalonian orogeny and was locally heralded by the development of flysch containing evidence of Vendian glaciation and followed by molasse-like successor basins. Latest Hadrynian volcanogenic redbeds and bimodal volcanism, associated with widespread back-arc transtension, may herald inception of the Iapetus ocean and platform re-establishment during the earliest Paleozoic.

Onset of overlapping, Atlantic-realm platform conditions in the Cambro- Ordovician was accompanied by minor, within-plate rift volcanism and is in places succeeded by late Ordovian-early Devonian bimodal volcanic rocks, shallow marine sediments and rare peralkaline plutons. Effects of a mid-Ordovician ("Taconian") tectonothermal event occur locally but are generally limited to major unconformities. Widespread early to mid-Devonian Acadian metamorphism and deformation may record the tectonic juxtapositioning of Avalon and Gander terranes and was accompanied by the emplacement into both terranes of locally voluminous Acadian granitoid plutons. However, portions of the Avalon terrane may have accreted earlier. Deposition of widespread Devono-Carboniferous, molasse-like sequences associated with bimodal tholeiitic to alkaline volcanics form an overlap sequence with the remainder of the Appalachian orogen, although the present position of the Avalon terrane with respect to the orogen is locally controlled by major Alleghanian faulting. Undeformed Triassic redbeds and mafic volcanic rocks herald initial rifting of the present Atlantic Ocean.

Dans les Appalaches septentrionales, la lanière d'Avalon forme une zone tectonostratigraphique distincte définie principalement par la présence de roches volcano-sédimentaires et granitoïdes tardi-précambriennes (circa 600 Ma) recouvertes par des séries paléozoïques inférieures qui renferment une faune acado-baltique. La lanière d'Avalon affleure dans l'est de Terre-Neuve, dans l'île du Cap-Breton, dans le nord de la péninsule de Nouvelle-Ecosse, au Nouveau-Brunswick méridional, sur la côte sud-est du Maine et dans le sud-est de la Nouvelle-Angleterre.

Deux épisodes tectonothermiques d'envergure ont affecté les socles continental et océanique et ainsi conditionné l'évolution précambrienne de la lanière d'Avalon. Un magmatisme océanique local et le métamorphisme régional d'une plate-forme à terrigènes et à carbonates du Protérozoïque moyen (tardi-Hélikien?), ainsi que de son socle

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gneissique continental, pourraient traduire une phase de rifting ou de subduction et d'effondrement local de celle-ci à l'éo-Hadrynien (750-800 Ma). Un plutonisme granitoïde calco-alcaline et un volcanisme largement répandu à caractères tholéiitique, calco-alcalin et, occasionellement, peralcalin tardi-hadryniens (580-630 Ma) concrétisent un épisode de serrage qui semble englober des régimes d'arc ensialique, d'inter arc océanique et des contextes d'arrière arc continental tant en extension qu'en transtension. Le serrage se conclut, peut-être par des jeux transformants, lors de l'orogénie avalonienne au tardi-Hadrynien et s'illustra localement par le développement de flyschs qui portent la trace d'une glaciation vendienne; après quoi s'implantèrent des bassins successeurs de type molassique. Au fini-Hadrynien, des grès roux volcanogéniques et un volcanisme bimodal, accompagnés d'une transtension largement répandue dans l'arrière arc, peuvent annoncer la naissance de l'océan Iapetus et le retour d'une plate-forme au tout début du Paléozoïque.

L'amorce de conditions de plate-formes du domaine atlantique qui s'empilèrent au Cambro-Ordovicien, s'accompagna d'un faible volcanisme de type rift intra plaque. Des volcanites bimodales, des sédiments marins d'eau peu profonde et de rares plutons peralcalins s'y greffèrent par endroits au tardi-Ordovicien ou à l'éo-Dévonien. On note localement les effets de l'épisode tectonothermique médio-ordovicien ("taconien") bien qu'ils se limitent pour une grande part à des discordances majeures. Le métamorphisme et la déformation acadiens très répandus, d'âge éo- à médio-dévonien, pourraient représenter l'accolement tectonique des lanières d'Avalon et de Gander; ils s'accompagnèrent par l'emplacement dans ces deux lanières de plutons granitoïdes acadiens localement volumineux. Par contre, des portions de la lanière d'Avalon pourraient s'être accrétées plus tôt. Au Dévono-Carbonifère, la déposition extensive d'assises de type molassique associées à des volcanites bimodales tholéiitiques à alcalines façonne une séquence de couverture sur le reste de l'orogène appalachien bien que la position actuelle de la lanière d'Avalon soit inféodée localement à de grands accidents alléghaniens. Des lits roux et des volcanites mafiques non-déformées du Trias annoncent l'ouverture de l'océan Atlantique actuel.

[Traduit par le journal]

INTRODUCTION

In Atlantic Canada and New England, the southeastern margin of much of the Northern Appalachian orogen forms part of a distinctive tectonostratigraphic belt traditionally termed the "Avalon Platform" (Kay and Colbert 1965; Williams 1969) or the "Avalon Zone" (Rodgers 1968, 1972; "Zone H" of Williams *et al*. 1972, 1974). Although generally less deformed than other belts within the Appalachian orogen, the Avalon zone is distinguished principally by the presence of late Proterozoic (Hadrynian) volcano-sedimentary sequences and co-genetic granitoid rocks of the circa 600 Ma Avalonian (Cadomian II) orogeny that are overlain by Lower Paleozoic, shallow-marine platformal successions bearing Acado-Baltic (Atlantic-realm) trilobite fauna (Skehan *et al*. 1978; O'Brien *et al*. 1983; Rast and Skehan 1983).

As defined by Williams (1978, 1979), the Avalon zone forms one of five tectonostratigraphic zones within the Northern Appalachian orogen (Fig. 1) distinguished on the basis of contrasts in their pre-Silurian evolution and interpreted in terms of the creation and destruction of a late Precambrian - early Paleozoic Iapetus Ocean. Thus the Humber zone records the development and destruction of the western miogeocline of Iapetus, whereas the Dunnage zone preserves vestiges of Iapetus and its island arc, remnant arc, and back-arc sequences. The Gander zone has been interpreted to contain elements of the eastern active margin of Iapetus (Kennedy 1976; Williams 1978, 1979; Coleman-Sadd 1980) but is defined largely on its structural and metamorphic style, closely resembles the Dunnage zone in age and lithology, and lacks proven Grenvillian basement, rift-related magmatism, and a passive margin history (Williams and Hatcher 1983). However, relationships of the more easterly Gander, Avalon and Meguma zones to the Iapetus cycle are uncertain as the zones are structurally uncoupled and show no demonstrable connection to the ancient North

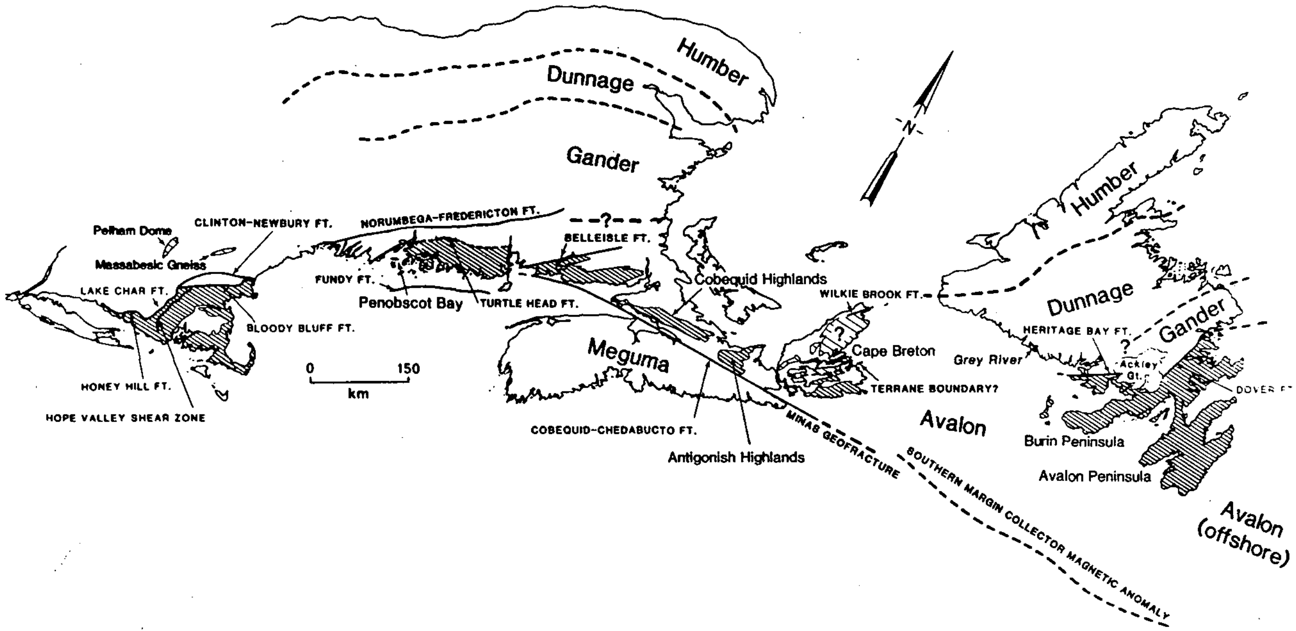

Fig. 1. Distribution of Precambrian Avalon terrane (broad-shaded where uncertain) and major terrane boundary faults in the Northern Appalachians (modified after Zen 1983). Zone boundaries from O'Brien *et al.* (1983) and Williams and Hatcher (1983); Collector Anomaly from Haworth and Lefort (1979); and Fundy Fault from Ballard and Uchupi (1975).

American miogeocline. More recent treatments of the Appalachian orogen have therefore viewed these, and other zones in the southern Appalachians and Europe, as a mosaic of suspect terranes (Keppie 1981; Williams and Hatcher 1982, 1983; Zen 1983; Keppie *et al.* 1985) that lie west of the eastern miogeoclinal margin of Iapetus preserved in the Scandinavian Caledonides, the Mauritanides of west Africa, and possibly Morocco (Williams 1984).

Within the Avalon terrane, wide variations in Proterozoic depositional settings and volcanic affinities suggest a composite terrane history during the Precambrian, the assembly of which may correspond to the late Precambrian Avalonian orogeny and must have occurred prior to the development of the widespread Cambro-Ordovician overlap sequence bearing distinctive Atlantic-realm fauna (Williams and Hatcher 1982, 1983). Cambro-Ordovician faunal contrasts (Cocks and Fortey 1982; Neuman 1984) and recently determined paleomagnetic discrepancies (Johnson and Van der Voo 1985; Van der Voo and Johnson 1985) suggest considerable separation of Avalon terrane from cratonic North America and place the Avalon terrane at high paleolatitudes in the Lower Paleozoic. However, paleomagnetic evidence for the position of the Avalon terrane with respect to North America remains inconclusive for much of the Paleozoic (Kent and Opdyke 1978, 1979; Spariosu and Kent 1983; Scotese *et al.* 1984) and the mechanism and timing of the accretion of Avalon terrane to the remainder of the Appalachian orogen remains debated. Similar Devonian plutonic histories and local sedimentary linkages in Newfoundland suggest docking of the Avalon and adjacent Gander terranes during the mid-Paleozoic (Williams and Hatcher 1982, 1983) although portions of the Avalon terrane may have accreted earlier (Robinson and Hall 1980; Keppie *et al.* 1985; Currie *et al.* 1986; Ludman 1986). The absence of linkages between the Avalon and Meguma terranes across the Minas Geofracture (Fig. 1), other than a Carboniferous overlap sequence, suggests docking of the Meguma terrane during the mid-to-late Paleozoic (Keppie 1982a; Williams and Hatcher 1982, 1983; Scotese *et al.* 1984; Spariosu *et al.* 1984). Kinematic and Ar/Ar geochronological analysis of ductile shear zones associated with this boundary (Keppie *et al.* 1985) suggests accretion of the Meguma zone involved dextral displacements during the mid-to-late Devonian (360-373±7 Ma, Dallmeyer and Keppie 1984).

DISTRIBUTION OF THE AVALON TERRANE

The Avalon terrane, whose type area is the Avalon Platform of Newfoundland (e.g. King 1980), is the largest Appalachian suspect terrane extending more or less continuously from offshore northeastern Newfoundland to southern New Brunswick, and discontinuously to southern Maine, southeastern New England and possibly the Carolinas (Williams 1978; Williams and Hatcher 1982, 1983). It may also form the basement to Florida (Smith 1982). However, the tectonostratigraphy of the Carolina terrane (Secor *et al.* 1983) may be sufficiently distinctive to warrant discontinuing the use of the term Avalon terrane in the southern Appalachians. Possible correlatives of the Avalon terrane occur outside the Appalachian orogen in the Caledonides of southern Britain (Rast *et al.* 1976), the Cadomian massifs of western and central Europe (Rast 1980), and the Pan-African belts of northwest Africa (Piqué 1981; O'Brien *et al.* 1983; Rast and Skehan 1983).

Within the Canadian Appalachians (Fig. 1), O'Brien *et al.* (1983) defined the Avalon terrane as occupying Newfoundland east of the Hermitage Bay and Dover faults (Blackwood and Kennedy 1975; Dallmeyer *et al.* 1981a), at least southeastern Cape Breton (Barr and Raeside 1986) and the Antigonish and Cobequid Highlands of Nova Scotia north of the Minas Geofracture (Keppie 1982a), and New Brunswick south of the Wheaton Brook and Belleisle faults (McCutcheon 1981; Currie 1984, 1986a). Avalon terrane is continuous westward in the offshore to the edge of the continental shelf (King *et al.* 1985) and is bound to the southeast by the Collector magnetic anomaly (Haworth and Lefort 1979; Williams and Hatcher 1982, 1983). Deep seismic reflection results have recently shown the Dover fault to be a major crustal suture separating lower crust of markedly different seismic character (Keen *et al.* 1986).

In southern Maine, the Avalon terrane occupies the Coastal Volcanic Belt south of the Turtle Head fault (Stewart and Wones 1974; Keppie *et al.* 1985) and possibly north of the offshore Fundy fault (Ballard and Uchupi 1975) which may separate the Avalon and Meguma terranes beneath the Triassic Fundy Basin. Avalon terrane also forms much of southeastern New England where it is bound to the north and west by the Bloody Bluff, Lake Char, and Honey Hill faults (Skehan and Murray 1980; Skehan 1983; Zen 1983; Zartman and Naylor 1984).

However, due largely to its composite Precambrian nature, considerable discrepancy exists in the usage of the term Avalon terrane and further subdivision is undoubtedly necessary. O'Hara and Gromet (1985) have recently identified two Avalonian terranes (Esmond-Dedham and Hope Valley) in southeastern New England that are separated by the Hope Valley shear zone and are distinguished by contrasting Paleozoic accretionary histories and late Precambrian plutonic rocks (e.g. Hermes and Zartman 1985). However, as the Hope Valley shear zone is an Alleghanian feature, the distinction between these terranes may largely reflect post-accretionary, Alleghanian reorganization. Gaudette and Olszewski (1986) have similarly suggested, on the basis of distinctive thermo-tectonic histories, that "Avalon" be restricted to the Avalon platforms of Newfoundland and Boston whereas inboard terranes, which show some similarities to "Avalon" and are bound to the north and west by the Lake Char - Campbell River-Nonesuch River-Norumbega fault system, should be grouped separately as the Hope Valley-Cape Breton terrane. However, such a subdivision ignores the distinction of Avalon terrane based on lowermost Paleozoic faunal criteria and the presence of late Precambrian volcano-plutonic suites.

Keppie *et al.* (1985) applied the term "Avalon composite terrane" to the product of late Precambrian (Avalonian) terrane amalgamation and suggest that, prior to this time, "Avalon" comprised numerous terranes that probably evolved separately. Thus the Avalon composite terrane includes the Avalon Peninsula terrane of Newfoundland, the Cape Breton and Cheticamp terranes of Cape Breton, the Antigonish and Cobequid terranes of mainland Nova Scotia, the Caledonia Highlands and Kingston terranes of southern New Brunswick, the Islesboro terrane (Coastal Volcanic belt) of southern Maine, and the Cape Cod and Boston terranes of southeastern New England. However, given present uncertainties in the detailed geology of these areas and their degree of Precambrian separation, such extensive subdivision may be premature. Northern portions of the Cape Breton terrane, for example, may contain correlatives of the Gander and Humber zones (Barr and Raeside 1986; Raeside and Barr 1986), whereas the Cradle Brook fault of southern New Brunswick may tectonostratigraphically subdivide the Caledonia Highlands terrane (McLeod 1986).

In an attempt to avoid confusion, Avalon terrane in the following summary is used in reference to the late Precambrian volcano-plutonic criteria and the early Paleozoic faunal distinctions and hence corresponds to the Avalon zone of O'Brien *et al.* (1983), the Avalonian terrain of Rast and Skehan (1983), and the Avalon composite terrane of Keppie *et al.* (1985).

AVALON TECTONOSTRATIGRAPHY IN THE NORTHERN APPALACHIANS

Details of Avalon lithostratigraphy and tectonics have been presented by numerous authors, most recently Piqué (1981), O'Brien *et al.* (1983), Rast and Skehan (1983), Skehan (1983), and Keppie *et al.* (1985). These are summarized and updated for the Northern Appalachians in the following review in order to provide a tectonostratigraphic framework within which more detailed geologic studies of individual segments of the Avalon terrane may be compared.

Precambrian Components

The earliest known components of the Avalon terrane are platformal quartzites and marbles of probable Middle Proterozoic (Helikian) age (Hofmann 1974) but uncertain tectonic significance, that are spatially associated with granodioritic and tonalitic gneisses considered to represent an earlier basement (Currie 1983) to the clastic-carbonate cover (Fig. 2). Candidates for basement include the Kelly Mountain complex of Cape Breton (Keppie 1979), the Mount Thom and Bass River (Great Village River gneiss) complexes in the Cobequid Highlands (Donohoe and Wallace 1985), and the Brookville gneiss of southern New Brunswick (Wardle 1978; Currie *et al.* 1981). Potential candidates may also include gneisses of the Grey River complex in southern Newfoundland (Smyth 1981), although more recent work suggests these may be early Paleozoic (S.J. O'Brien, pers. comm. 1986), and recently recognized gneisses in central Cape Breton (S.M. Barr, pers. comm. 1986). Platformal successions include the George River Group of Cape Breton (Milligan 1970), the Gamble Brook and Folly River schists (Bass River complex) of the Cobequid Highlands (Donohoe and Wallace 1985), and the Green Head Group of southern New Brunswick (Wardle 1978). Probably equivalent, medium-grade Precambrian carbonate and clastic rocks are reported (Stewart and Wones 1974; Osberg *et al.* 1985) from Penobscot Bay, Maine (Fig. 1), and may also include quartzites of the Westboro Formation in southeastern New England (Rast and Skehan 1983).

Upper Proterozoic (Hadrynian) components of Avalon (Figs. 2) include submarine basalts and mafic intrusive rocks of ophiolitic affinity (Strong *et al.* 1978) that are largely restricted to the Burin Group of southern

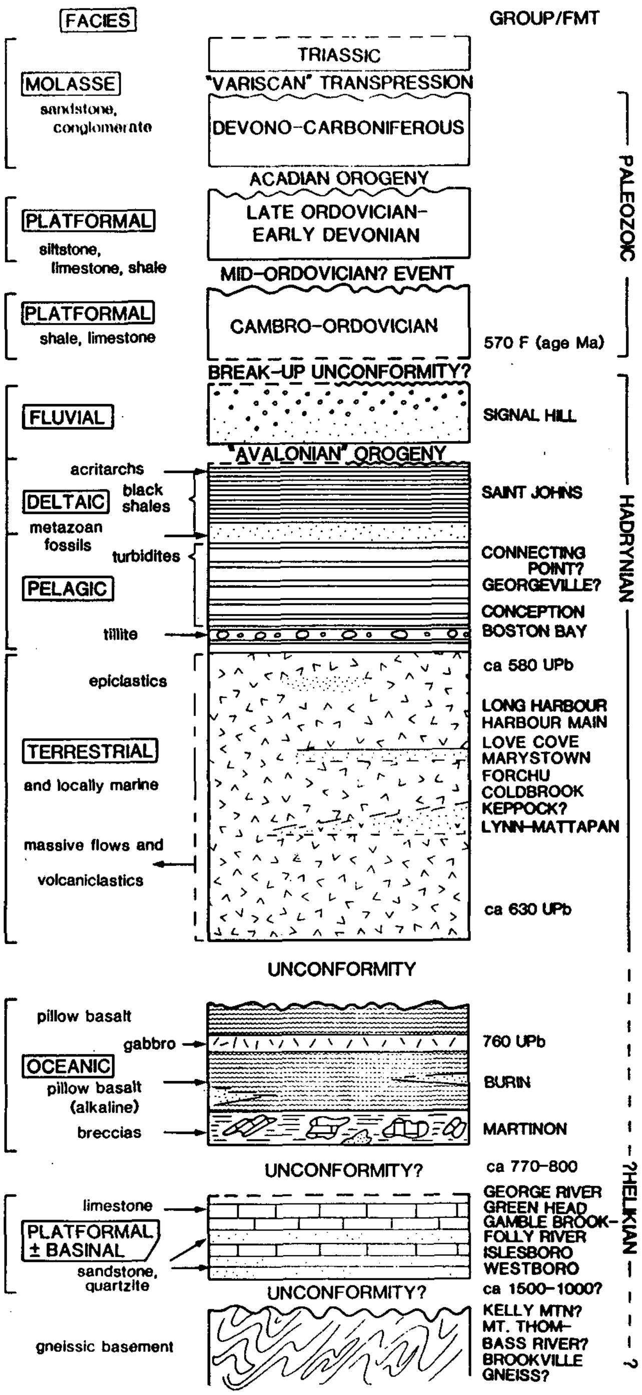

Fig. 2. Schematic composite section of the Avalon terrane in the Northern Appalachians showing facies development, tectonism and nomenclature (modified after O'Brien *et al*. 1983).

Newfoundland where their age, dated by an intrusive but probably comagmatic gabbro, is at least 762±2 Ma (U/Pb, Krogh *et al*. 1983). A gabbroic pegmatite in Boston has yielded a K/Ar age of 886±22 Ma (Zartman and Naylor 1984).

These and broadly similar Rb/Sr metamorphic ages obtained by Olszewski *et al*. (1981) and Gaudette *et al*. (1985) from the Kelly Mountain complex (701±66 Ma and 680-700 Ma respectively), by Olszewski and Gaudette (1982) from the Brookville gneiss (771± 55 Ma), and by Brookins (1976) from gneisses of the Penobscot Bay region (750±100 Ma), suggest that northwestern portions of the Avalon terrane underwent a period of regional metamorphism, deformation and, perhaps, ocean crust formation that is distinct from, and earlier than, the late Hadrynian Avalonian orogeny.

Late Hadrynian subaerial volcanic rocks occur throughout the Avalon terrane and show ages that cluster in the range 580-630 Ma (O'Brien *et al*. 1983; Rast and Skehan 1983). In Newfoundland, they occur in four distinct belts bound by Acadian faults (O'Brien *et al*. 1983) and include the calc-alkaline, bimodal basalt-rhyolite suite of the Connaigre Bay and Long Harbour Groups (O'Driscoll and Strong, 1979); the volcanic and volcaniclastic rocks, basalt flows, and rhyolitic pyroclastic rocks of the Marystown and and the 590±30 Ma (U/Pb, Dallmeyer *et al*. 1981b) Love Cove Groups; the bimodal, spilite-keratophyre succession of the enigmatic Bull Arm Formation (Hughes and Malpas 1971); and bimodal pyroclastic rocks, lavas and volcaniclastic rocks of the mildly alkalic to tholeiitic Harbour Main Group (Papezik 1970). The Marystown Group displays a three-stage, calc-alkaline/tholeiitic to mafic alkalic to dominantly felsic evolution, the lower part of which may correlate with the Connaigre Bay Group and the upper part with the Long Harbour Group (Strong *et al*. 1984). The Long Harbour Group is capped by peralkaline rhyolites that have been correlated with those of the Love Cove Group. The Harbour Main Group, which is intruded by the 607±11 Ma (Rb/Sr, McCartney *et al*. 1966) Holyrood granite, is dominated by metaluminous rhyolites and alkali basalts but outcrops occur in three belts of slightly differing ages (607 Ma, 622 Ma and 631 Ma; S.J. O'Brien, pers. comm. 1986). O'Brien *et al.* (1986) have proposed a three-stage, calc-alkaline/mildly tholeiitic to mildly alkaline to peralkaline magmatic evolution for the late Hadrynian volcanic rocks of Newfoundland, comparable to that of the Mesozoic-Cenozoic Basin and Range Province.

Late Hadrynian volcanic rocks in mainland Canada include felsic pyroclastic rocks, basalts, andesites and rhyolites with calc-alkaline, volcanic arc affinities in the Fourchu Group of Cape Breton (Keppie *et al.* 1979a, 1985); ignimbrites, felsic tuffs, andesites and basalts of the Keppoch Formation in the Antigonish Highlands (Murphy 1984); and felsic tuffs, volcanoclastic rocks and felsic to mafic flows of calc-alkaline chemistry (Rast *et al.* 1984) in the Coldbrook Group of southern New Brunswick (Giles and Ruitenberg 1977; Currie 1984). Late Hadrynian tholeiitic and ocean island basalts in the Georgeville Group, which overlies the Keppoch Formation (Murphy 1984), have been interpreted in terms of an interarc basin (Dostal *et al.* 1984). A diabase and bimodal, rhyolitic-dacitic dike complex (Rast 1979; Currie 1984), which locally intrudes the Coldbrook Group and shows tholeiitic to calc-alkaline affinities (Rast *et al.* 1984), has been attributed to the transtensional opening of the Iapetus Ocean (Rast 1979) and may be penecontemporaneous with the formation of the adjacent Pocologan mylonite zone in southern New Brunswick (Rast and Currie 1976; Rast and Dickson 1982).

In southeastern New England, felsic pyroclastic rocks, rhyolites, dacites and mafic flows of the bimodal Middlesex Fells and Lynn volcanic complexes are intruded by the co-genetic (Smith *et al.* 1985), 630±15 Ma Dedham granodiorite (K/Ar, Zartman and Naylor 1984) and may be equivalent to parts of the Coldbrook Group, from which Stukas (1977) obtained several ~630 Ma, Ar/Ar release spectra, and older portions of the subaerial volcanic succession in Newfoundland (Rast and Skehan 1983). Mafic members of the Middlesex Fells complex are transitional alkali olivine basalts (Durfee Cardoza *et al.* 1985). The younger, 602±3 Ma Mattapan volcanics (U/Pb, Kaye and Zartman 1980), which comprise ash flow tuffs, lahars, volcanic breccias and andesites, have been interpreted as the product of caldera collapse (Thompson 1985). Highly deformed and metamorphosed, late Hadrynian rhyolitic and mafic volcanic rocks may be represented in the Ellsworth Formation of southern Maine (Osberg *et al.* 1985; Stewart 1986).

Intrusive into the late Hadrynian volcanic rocks of Newfoundland, Nova Scotia, New Brunswick, New England and perhaps Maine is a suite of probably co-genetic, granitoid plutons with ages in the range 540-620 Ma (e.g. O'Brien *et al.* 1983; Skehan 1983; Zartman and Naylor 1984; Hermes and Zartman 1985). Compositions are commonly granitic, granodioritic and tonalitic but range to minor diorites and gabbros, and their chemistries are typically of calc-alkaline affinity (O'Driscoll and Strong 1979; Clarke *et al.* 1980; Skehan 1983; Hermes and Zartman 1985). The significance of these granitoid rocks remains uncertain, but the presence in some of a strong primary foliation, their absence as intrusions into Cambrian strata, and their chemical similarity to Cenozoic Cordilleran and Andean granitoids suggest that those yielding older ages may be syntectonic with respect to the late Precambrian Avalonian orogeny (O'Brien *et al.* 1983). If so, early Cambrian radiometric dates from some of these granitoid rocks may be anomolously young (Poole 1980). Polyphase deformation and greenschist to amphibolite facies metamorphism accompanied the Avalonian orogeny in Nova Scotia and Cape Breton (Keppie 1982b), and deformed late Precambrian volcanic clasts occur in basal Cambrian conglomerates in southern New Brunswick (McCutcheon *et al.* 1982). In Newfoundland, however, effects of the Avalonian event are largely restricted to the development of local unconformities (O'Brien *et al.* 1983), although cataclastic granitoid clasts occur in proximal fan facies of the late Precambrian Signal Hill Group (S.J. O'Brien, pers. comm. 1986).

In the Avalon Peninsula of Newfoundland, thick sequences of flyschoid and molasse-like sediments overlie the late Hadrynian volcanic rocks (Fig. 2) and are locally overlain by Cambrian strata (King 1980). Conformably and locally unconformably overlying the Harbour Main Group, the late Hadrynian Conception Group comprises a thick, flysch-like sequence dominated by marine, turbiditic volcaniclastics that carry well-preserved Ediacara fauna (Anderson and Misra 1968) and contains a distinctive tillite unit (Gaskiers Formation) near its base (Bruckner and Anderson 1971). The group may correlate with the dominantly argillaceous Connecting Point Group to the west (King 1980). The Conception Group is, in turn, conformably overlain by black shales and siltstones of the St. John's Group which are conformably succeeded by molasse-like redbeds of the Signal Hill Group. King (1980) has interpreted this succession as reflecting shoaling of a marine turbidite basin followed by southward delta progradation and the development of alluvial plain conditions. Basal orthoquartzites of the unconformably overlying Cambrian sequence represent the onset of marine shelf conditions.

With the exception of the Antigonish Highlands, where thick basinal shales and turbidites associated with intermittent oceanic-type volcanism dominate the Georgeville Group (Murphy 1984), extensive late Hadrynian sedimentation is not represented elsewhere within the Canadian Avalon terrane, nor is it present in the Burin Peninsula of Newfoundland. In Cape Breton and southern New Brunswick, late Hadrynian volcanic rocks are respectively succeeded by redbeds of the Morrison River (Weeks 1954) and Ratcliffe Brook (Hayes and Howell 1937) Formations, and then by Cambrian shales. However, recently identified "Eocambrian" feldspathic redbeds, felsic tuffs and basalts may disconformably separate the late Hadrynian Coldbrook and Cambro-Ordovician Saint John Groups in southern New Brunswick (Currie 1984, 1986a; Tanoli *et al.* 1985). Hadrynian to Ordovician interbedded feldspathic and manganiferous metasedimentary rocks are exposed in coastal southern Maine (Stewart 1986).

In southeastern New England, however, the Boston Basin contains extensive conglomerates, argillites and sandstones with occasional interbeds of tuffs (Billings 1976) and andesites of the Brighton volcanics (Durfee Cardoza *et al.* 1985). This thick succession, which constitutes the Boston Bay Group, nonconformably overlies the late Precambrian Dedham granodiorite, contains Vendian acritarchs and clasts of the Lynn and Mattapan volcanics (Skehan and Murray 1980, Skehan 1983), and, with the exception of the abundance of conglomerates, broadly resembles the Conception Group of Newfoundland. Like the Conception Group, the Boston Bay Group is overlain by Cambrian strata, contains a possible tillite (Squantum Member of the Roxbury Conglomerate), and has a late Precambrian volcano-plutonic provenance (Skehan 1983; Galli and Bailey 1986). Socci (1985) has suggested a glaciomarine origin for the Roxbury Conglomerate, while Socci and Smith (1985) have interpreted the Boston Bay Group in terms of debris flows and turbidites of a submarine fan system, as originally implied by Dott (1961). Galli and Bailey (1986) suggested a back-arc setting for the Boston Bay Group. Clastics and pillow basalts of the Blackstone Series in Rhode Island (Dreier and Mosher 1981) are of uncertain correlation but constitute an additional late Precambrian sedimentary sequence.

Cambro-Ordovician Overlap Sequences

Shallow-marine, platformal Cambro-Ordovician overlap sequences with distinctive Atlantic-realm fauna unconformably to disconformably overlie the late Hadrynian volcano-sedimentary successions of Newfoundland, Nova Scotia, New Brunswick and southeastern Massachusetts (O'Brien *et al.* 1983; Skehan 1983) and late Precambrian granitoid rocks in Rhode Island and southeastern Maine (Skehan 1983; Stewart 1986). Typically floored by Lower Cambrian (Tommotian) orthoquartzites, these sequences are dominated by shale, limestone, sandstone and oolitic ironstone in Newfoundland (O'Brien and King 1982), and Lower Cambrian to Arenig shale, sandstone and limestone in Cape Breton (Keppie 1982b) and in the Saint John Group of southern New Brunswick (Hayes and Howell 1937; Pickerill and Tanoli 1985). Cambrian to Lower Ordovician conglomerate, slate, quartzite, limestone and oolitic ironstone unconformably overlie the Georgeville Group in the Antigonish Highlands (Murphy *et al.* 1982; Murphy 1984; Keppie *et al.* 1985), whereas metamorphosed, late Proterozoic to Ordovician pelites and sandstones rest on sialic Precambrian rocks in the Coastal Volcanic Belt of Maine (Stewart 1986). Further north in Maine, quartzite, arenite and thick Ordovician sulfidic and carbonaceous shales of the Cambro-Ordovician Cookson and Penobscot Formations (Osberg *et al.* 1985) have been correlated with the Saint John Group (Ludman 1986), although their fauna may not be diagnostic of an Atlantic origin (Stewart 1986). In southeastern New England, Acado-Baltic trilobites are characteristic of the Lower Cambrian limestones and shales of the Weymouth and Hoppin Formations, and the Middle Cambrian shales and siltstones of the Braintree Argillite (Skehan and Murray 1980; Skehan 1983). Lower Cambrian lime mudstones and shales that resemble the Hoppin Formation and rest unconformably on late Precambrian turbidites have recently been identified in southeastern Rhode Island (Webster *et al.* 1986).

Minor but widespread bimodal volcanic rocks of early to middle Cambrian age accompany the Cambro-Ordovician successions of Newfoundland ((Greenough and Papezik 1985), Nova Scotia (Murphy *et al.* 1985), New Brunswick (Greenough *et al.* 1985), Maine (Stewart 1986) and possibly New England (Skehan 1983). Dominated by continental alkalic and less common tholeiitic basalts with compositions consistent with a within-plate setting, this episode of volcanism has been attributed both to mild tensional tectonics associated with the final stages of Iapetus rifting (Greenough and Papezik 1985, 1986), and to faulting within local pull-apart basins formed during the last, transpressional stages of the late Hadrynian Avalonian orogeny (Murphy *et al.* 1985).

Late Ordovician and Younger Evolution

Although a detailed summary of the late Ordovician and younger evolution of the Avalon terrane is beyond the scope of this paper, the tectonostratigraphy of the Avalon terrane continues with an extensive post-Ordovician record. Late Ordovician and Silurian rocks occur in the eastern Newfoundland offshore, mainland Nova Scotia and southern Maine but are absent in other areas of the Avalon terrane. A 4000 m thick sequence of Ordovician-Silurian marine shales is unconformably overlain by Devonian redbeds in the Newfoundland offshore (Durling *et al.* 1986). In the Antigonish Highlands, non-marine redbeds and late Ordovician-early Silurian bimodal volcanic rocks unconformably overlie late Cambrian-early Ordovician black shales and pass upwards through Silurian shallow marine sedimentary rocks containing shelly Atlantic fauna (Watkins and Boucot 1975) into early Devonian nonmarine clastics (e.g. Keppie 1980; 1982b). Similarly, in the Cobequid Highland, bimodal but predominantly felsic volcanic rocks and fossiliferous quartz wackes, siltstones and shales that span the Silurian overlie probable late Ordovician siltstones and tuffs, and are followed by early Devonian redbeds

(Donohoe and Wallace 1985). Thick, Lower Silurian to Lower Devonian bimodal volcanic and shallow marine sedimentary rocks bearing shelly Atlantic fauna also occur in southern Maine (Gates 1969; Brookins *et al.* 1973; Stewart 1986).

Although little concensus exists on the timing of assembly between the Avalon terrane and adjacent terranes and their docking with the margin of the Northern Appalachian orogen (e.g. Williams and Hatcher 1983; Zen 1983; Keppie *et al.* 1985), pre-Silurian accretion to more westerly terranes has been proposed by some for portions of the Avalon terrane in Canada (Keppie *et al.* 1985; Currie *et al.* 1986), Maine (Ludman 1986) and New England (Robinson and Hall 1980). Effects of the mid-to-late Ordovician Taconic orogeny, which are widely manifest in western portions of the Northern Appalachians (e.g. Stanley and Ratcliffe 1985), are absent within the Avalon terrane. However, evidence for broadly contemporaneous deformation and metamorphism exists locally. Major unconformities separate early Ordovician from early Silurian rocks in the Antigonish Highlands (Keppie *et al.* 1985) and southern Maine (Stewart 1986), and the late Precambrian from the early Silurian in the Cobequid Highlands (Donohoe and Wallace 1985). In the northern Antigonish Highlands, local polyphase folding and greenschist facies metamorphism occurred between the Arenig and latest Ordovician (Keppie 1982b, Keppie *et al.* 1985), while late Ordovician (470 Ma, Rb/Sr) pegmatitic sweats in the Brookville gneiss (Olszewski *et al.* 1980) may indicate locally elevated temperatures in southern New Brunswick (Currie *et al.* 1981; Nance 1982). Evidence for Ordovician deformation and metamorphism may also exist in the form of metamorphosed fragments in the Lower Silurian of southern Maine (Stewart and Wones 1974), in the presence of pre-Silurian deformation in the Cookson Formation (Ludman 1985) if its correlation with the Saint John Group (Ludman 1986) is upheld and, indirectly, in the single Ordovician faunal province envisaged for Maine by Neuman (1984). Bimodal, earliest Silurian volcanic rocks in mainland Nova Scotia (Boucot *et al.* 1974) and similar Silurian-Devonian volcanics in southern Maine (Brookins *et al.* 1973) show anorogenic, within-plate characteristics (Moench and Gates 1976; Gates 1978; Keppie *et al.* 1979b) but have been interpreted as reflecting thermal and mechanical readjustments of Avalonian crust following Ordovician deformation (Currie *et al.*, 1986). Ordovician and Silurian peralkaline plutons in southeastern New England (Zartman and Marvin 1971), such as the Quincy granite in the vicinity of Boston, are also anorogenic (Zartman and Naylor 1984).

During the early to mid-Devonian Acadian orogeny, the Avalon terrane was affected by widespread regional metamorphism and polyphase deformation (e.g. Bradley 1983; Rast 1983). Metamorphic grades are typically of greenschist facies or lower and peaked at 370-390 Ma in Newfoundland where they are interpreted as accompanying tectonic juxtapositioning of the Avalon and Gander terranes (Dallmeyer *et al.* 1983; O'Brien *et al.* 1983). Associated Acadian granitoid plutons consist of locally voluminous suites of largely post-tectonic granites and granodiorites that occur throughout the Avalon and adjacent terranes, although they have yet to be firmly demonstrated in southern New Brunswick (Currie 1986b). Ages for these plutons cluster in the interval 340-370 Ma (e.g. Brookins 1972; Clarke *et al.* 1980; Strong 1980; Donohoe and Barr 1981; Zartman and Naylor 1984; Hermes and Zartman 1985).

Following the Acadian orogeny, the tectonostratigraphy of the Avalon terrane is no longer unique, but is sedimentologically and plutonically linked to those of its bounding terranes (Williams and Hatcher 1982, 1983). In Newfoundland, Devonian conglomerates containing clasts derived from the adjacent Gander terrane unconformably overlie Upper Cambrian shales on the eastern side of the Hermitage Bay Fault (Williams 1971), while the 355 Ma (Rb/Sr, Bell *et al.* 1977) Ackley granite straddles the same terrane boundary (Fig. 1).

Similar Devonian and Carboniferous molasse-like facies of alluvial, fluvial and locally lacustrine and shallow marine origin occur throughout most of the Avalon terrane, and are accompanied by subordinate bimodal volcanic sequences of tholeiitic to strongly alkaline affinities in Newfoundland (O'Brien and King 1982), western Cape Breton (Blanchard *et al.* 1984), northern Nova Scotia (Keppie and Dostal 1980), the Magdalen Islands (Barr *et al.* 1985), possibly in southern New Brunswick (Strong *et al.* 1979) although the age of these has been questioned (Currie and Nance 1983), and southeastern Maine (Pickerill *et al.* 1978). In southeastern New England molasse-like sequences are largely Pennsylvanian in age (Lyons 1979) and devoid of volcanics (Skehan 1983).

Carboniferous redbeds in coastal southern New Brunswick are additionally involved in extensive late Paleozoic (Alleghanian/Variscan) thrusting and polyphase deformation (e.g. Rast and Grant 1973; Ruitenberg *et al.* 1973; Ruitenberg and McCutcheon 1982) that, elsewhere in Canada, are largely confined to the Minas Geofracture (Keppie 1982a; Donohoe and Wallace 1985). In Massachusetts and Rhode Island, Pennsylvanian sedimentary rocks are also affected by strong, polyphase deformation and metamorphism (Burks *et al.* 1981; Mosher and Rast 1986) and are intruded by the Permian Narragansett Pier granite (Hermes *et al.* 1981a, b). In both regions, late Paleozoic deformation appears to have involved an important component of transpression (Mosher 1983; Nance and Warner 1986) that was associated with the final tectonic juxtapositioning of the Avalon and Meguma terranes (e.g. Spariosu *et al.* 1984).

Carboniferous redbeds deposited within Alleghanian transtensional basins (e.g. Bradley 1982; Yeo and Ruixing 1986) are locally overlain unconformably by undeformed fluvial and alluvial sequences of Triassic age (Klein 1962). Triassic deposition occurred in response to initial rifting of the present Atlantic Ocean (e.g. Ballard and Uchupi 1975; Nadon and Middleton 1984) and was locally accompanied by the extensional reactivation of Alleghanian faults (Plint and Van de Poll 1984).

PRECAMBRIAN TECTONIC MODELS FOR THE AVALON TERRANE

Controlling factors for the late Precambrian evolution of the Avalon terrane remain largely equivocal due to uncertainties in regional correlation and local geologic development, coupled with the diverse geochemical signatures and scattered distribution of its Hadrynian igneous record. Earlier interpretations have consequently ranged from a pre-Iapetus, ensialic island arc (Rast *et al.* 1976) to an aborted Proterozoic rifting event, perhaps related to the opening of the Iapetus Ocean (Strong *et al.* 1978). More recent models advocate a genetic distinction between the development of Avalon terrane and that of Iapetus and point to the diversity in volcanic geochemistry as evidence of the composite nature of the Precambrian Avalon terrane, the accretion of which was largely complete prior to the inception of the Iapetus cycle.

Keppie (1982b) and Dostal *et al.* (1984), for example, have interpreted the late Precambrian development of the Avalon terrane of Nova Scotia in terms of a cratonic island arc (Cape Breton terrane), an interarc basin (Antigonish terrane, Murphy and Keppie 1985), and a remnant arc (Cobequid terrane) associated with the subduction of a major ocean lying to the southeast (Fig. 3). These terranes were assembled during the Avalonian orogeny to produce the Avalon composite terrane, and subsequently displaced by Devonian and

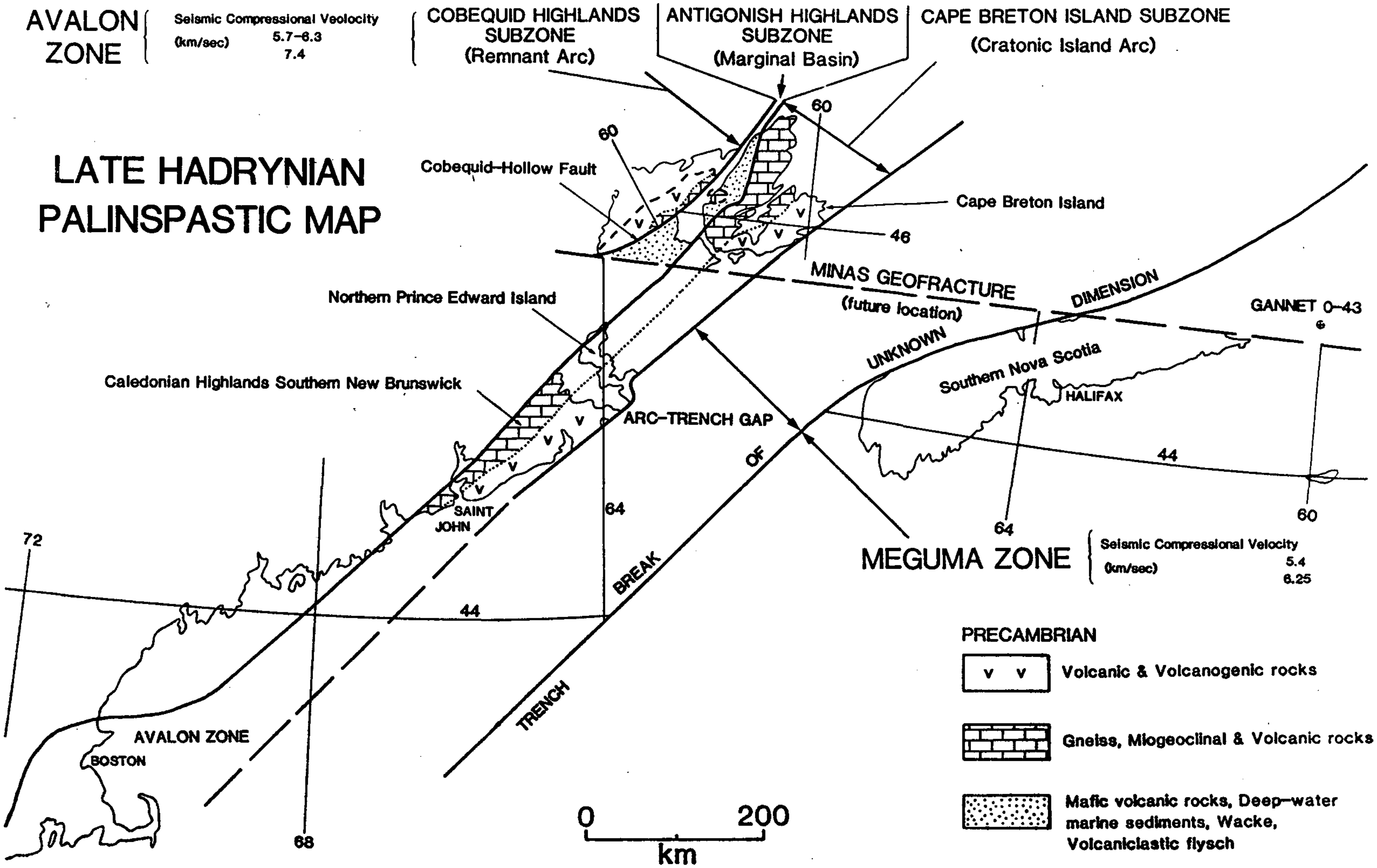

Fig. 3. Late Hadrynian palinspastic map for the Avalon and Meguma terranes in the Northern Appalachians as proposed by Keppie (1982b).

younger strike-slip movements on the Minas Geofracture. However, whether diversity in volcanic geochemistry that essentially reflects the spatial and temporal variation of volcanic regimes within a single arc complex is sufficient evidence to invoke separate suspect terranes is debatable and, with the possible exception of the Antigonish terrane (Murphy 1984), there is little evidence to suggest that processes of suspect terrane accretion occurred during the Avalonian orogeny.

Rast and Skehan (1983) have similarly suggested that the Avalon terrane originated as a microcontinental arc which was separated from North America by a back-arc basin and from West Africa by the late Precambrian Cadomian Ocean (Fig. 4a). They suggest that the arc developed as a volcanic carapace covering older sialic islands and ensimatic basins derived from fragmentation of an African supercontinent at 800-850 Ma. However, the processes by which this carapace developed are unclear in their model. Closure of this ocean and back-arc basin at 600-650 Ma (Fig. 4b) respectively produced the Cadomian (II) and Avalonian orogenies and accreted Avalon to the North American and West African cratons.

In contrast, O'Brien *et al.* (1983) employ the model of Kroner (1980) to propose a Pan-African origin for the Avalon terrane in Canada. In this model (Fig. 5), rifting of pre-Pan-African continental basement during

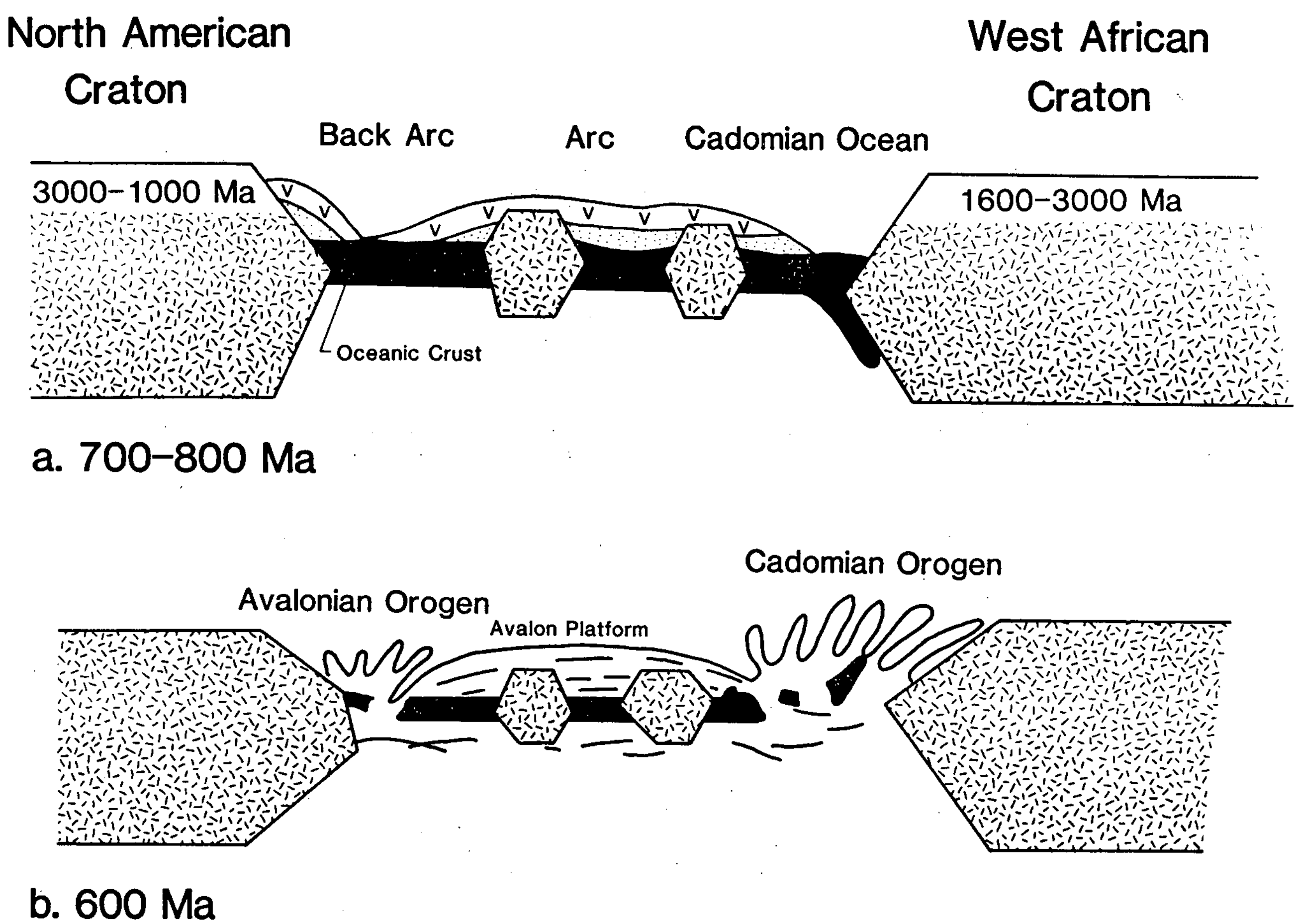

Fig. 4. Schematic cross sections from the North American (Laurentian) to the West African (Gondwanan) cratons proposed by Rast and Skehan (1983). (a) Section through Cadomian basins and microcontinent (ca. 700-800 Ma). (b) Section through Avalonian orogen, Avalon Platform and Cadomian orogen (ca. 600-650 Ma). No vertical scale implied.

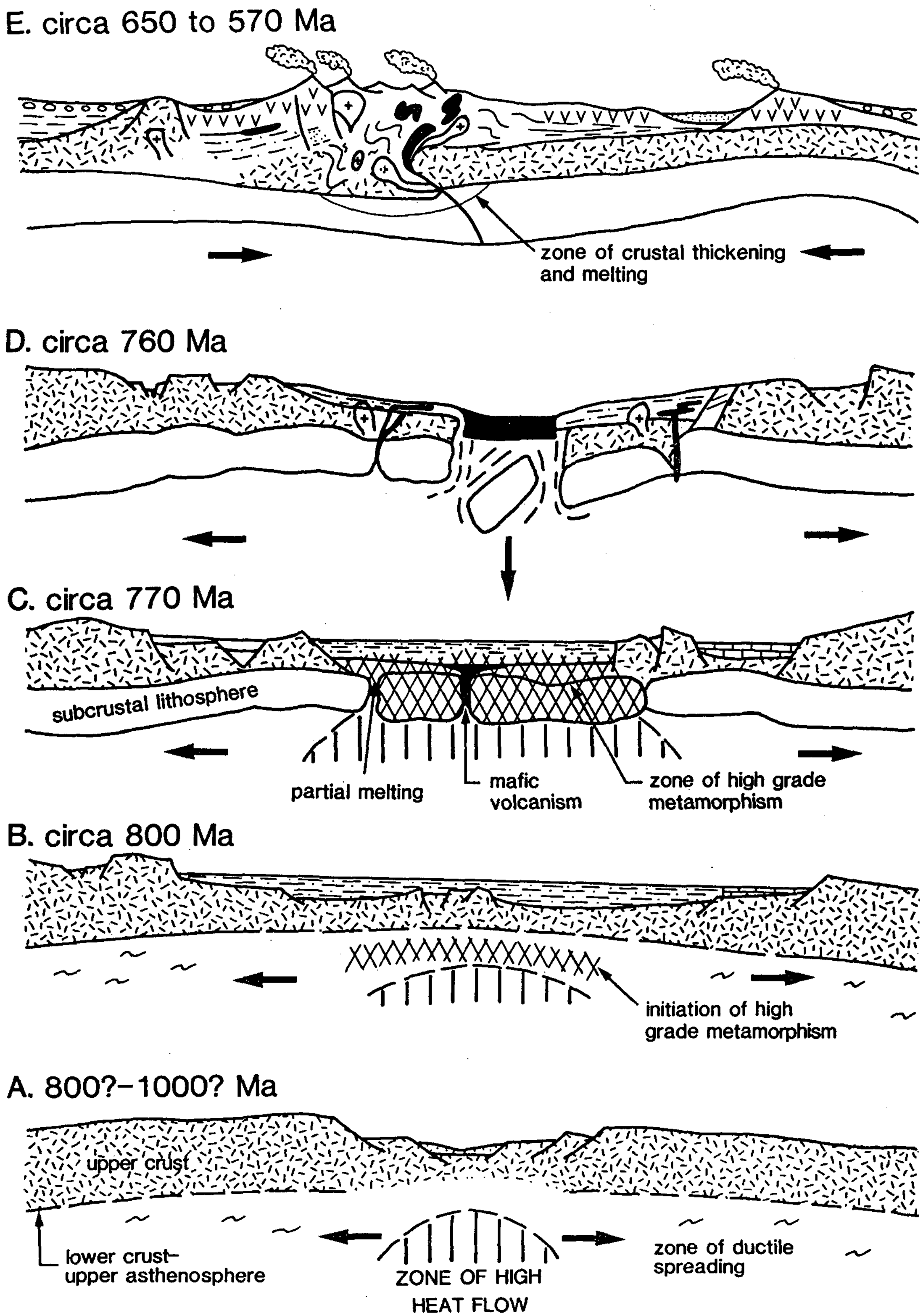

Fig. 5. Schematic cross sections illustrating major stages in the Precambrian development of the Avalon terrane in Canada as proposed by O'Brien *et al.* (1983).

the interval 800-1000 Ma initially produced ensialic basins (c.f. George River and Green Head Groups) that subsequently underwent partial melting and high-grade metamorphism during the period 750-800 Ma due to ductile spreading of the lower crust and local crustal separation (c.f. Burin Group). The closure of these basins is attributed to limited subduction and collision during the interval 570-650 Ma, and produced late Hadrynian volcanic assemblages (c.f. Marystown Group and equivalents) and Avalonian orogenesis that terminated with the intrusion of granitoids and marine-to-terrestrial clastic deposition (c.f. Conception/St. Johns/Signal Hill Groups). The diversity of deformational intensity and volcanic geochemistry is attributed to the degree of crustal separation and ocean crust formation and, hence, subsequent variations in the style and amount of subduction and collision.

However, while there is general concensus on the existence of a late Hadrynian magmatic arc complex within the Avalon terrane, the nature of the early Hadrynian event is less certain. The presence of similar carbonate slump-breccias in both the Martinon Formation (Wardle 1978), which may unconformably overlie the Green Head Group (Leavitt 1963; Currie 1984), and the Burin Group (Strong *et al.* 1978) suggests the early Hadrynian tectonothermal event coincided with the collapse of the Green Head carbonate platform (Currie 1986b). The age of the Green Head Group is uncertain, but the Helikian age assigned to it on the basis of the stromatolite *Archaeozoon acadiensis* (Hofmann 1974) would suggest that, by the early Hadrynian, the platform was already well established and, hence, unrelated to the early Hadrynian rifting event proposed by O'Brien *et al.* (1983). Given the limited record of this event, a case could then be made for the collapse and regional metamorphism of a pre-existing platform during an early Hadrynian subduction event, perhaps coinciding with older Rb/Sr ages (e.g. 750±80 Ma, Cormier 1969; 830±55 Ma, Stukas 1977) obtained from volcanic rocks of the Coldbrook Group. If so, the Burin Group, which rests on clastic rocks derived from a subaerial felsic volcanic terrane (Strong *et al.* 1978), could be reinterpreted as the product of a back-arc basin.

Furthermore, although the age of the basement of Avalon terrane remains controversial (e.g. Zen 1983), model age constraints on the protolith of the Brookville gneiss (Olszewski and Gaudette 1982) are not inconsistent with the development of the Green Head platform on Grenvillian basement, tempting correlation of the Green Head Group with Helikian platform carbonates of the Grenville belt (e.g. Baer 1967). Considerations such as these have led Currie (1986b) to propose a tectonostratigraphic history for the Avalon terrane involving the repeated break-up and rewelding of a North American continental edge.

Evidence for a late Hadrynian subduction event is more compelling and forms a common theme to recent models of the late Precambrian evolution of Avalon terrane. However, with respect to the present distribution of Avalon terrane within the Northern Appalachians, wide lateral and/or temporal variations must have existed within and, more importantly, behind the late Hadrynian magmatic arc complex. In Newfoundland (O'Brien *et al.* 1986), at least three episodes of volcanic activity that span an interval of 50 Ma are locally separated by periods of sedimentation and follow an evolutionary path similar to that of the Basin and Range Province. Early calc-alkaline granitoids and calc-alkaline to mildy tholeiitic basaltic and rhyolitic rocks are followed by epiclastic volcanism, rhyolites and mildly alkaline flood basalts and, finally, by peralkaline, bimodal volcanism and rare plutonism associated with terrestrial sedimentation in strike-slip basins. Development of a magmatic arc in Newfoundland would therefore appear to have been followed by continental back-arc transtension that, in turn, may have heralded the inception of the Iapetus ocean and the re-establishment of platformal conditions recorded in overlying Cambro-Ordovician succession.

A broadly similar pattern may also be recorded in the Boston Platform where calc-alkaline granitoid and co-genetic pyroclastic rocks (e.g. Dedham North Granodiorite-Lynn Volcanic Complex, Smith *et al.* 1985) and younger ash-flow volcanism (c.f. Mattapan Volcanic Complex, Thompson 1985) are succeeded by intermediate to mafic flows, tuffs and agglomerates (c.f. Brighton Volcanics, Durfee-Cardoza *et al.* 1985) that are associated with the development of the Boston Basin. Acritarchs, facies associations and broadly northward paleoflow within the overlying Boston Bay Group suggest a marine, back-arc extensional setting during the latest Hadrynian (A.D. Socci, pers. comm. 1986) that again yielded to platformal conditions recorded in the Early Cambrian Weymouth Formation.

In Nova Scotia, southern New Brunswick and coastal Maine the evolution of the magmatic arc remains uncertain as the precise age and correlation of late Precambrian volcanic rocks is unknown. Nevertheless, significant variations in the processes operating in the back-arc would appear to have occurred in mainland Nova Scotia and New Brunswick. In the northern Antigonish Highlands (Murphy *et al.* 1980, Murphy 1984; Murphy and Keppie 1985), for example, basal ocean-floor tholeiites and thick shales and turbidites of the late Hadrynian Georgeville Group, that are penecontemporaneous with continentally floored rhyolites, basaltic-andesites and basalts of the Keppoch Formation to the south, are interpreted as forming in a narrow, deep-water basin floored by oceanic crust. Thus back-arc processes within the Antigonish Highlands involved the generation of ocean crust that has been attributed (Keppie 1982b, Murphy and Keppie 1985; Fig. 3) to the development of an interarc basin between a cratonic island arc, recorded in volcanics of the Fourchu Group of Cape Breton (Keppie *et al.* 1979a), and a remnant arc represented by presumed older volcanics in the Cobequid Highlands (e.g. Donohoe and Wallace 1985). Furthermore, alkalic basaltic volcanism that occurs first in the Keppoch Formation and later in the Georgeville Group has been related to the influence of "hot-spot" magmatism on a southerly moving, interarc lithosphere. Alaskitic and appinitic plutonism and deformation within the Georgeville Group during the latest Hadrynian are taken to reflect closure of the interarc basin and are followed by Cambrian rocks interpreted as a rift-related succession (Murphy 1984).

In southern New Brunswick, in contrast, back-arc processes appear to have involved significant strike-slip movements and the penecontemporaneous development of a 2 km-wide mylonite zone (Rast and Dickson 1982) and a mafic to bimodal dike complex (Rast 1979; Currie 1984, 1986a). Mafic and felsic flows, tuffs, ignimbrites and intercalated sedimentary rocks of the Coldbrook Group are generally considered equivalent to the Fourchu Group of Cape Breton (e.g. Keppie *et al.* 1985) although they are likely to exceed 10 Km in thickness (Giles and Ruitenberg 1977) and their stratigraphy, age range and geochemical affinities are poorly known. Nevertheless, a magmatic arc setting for the Coldbrook Group, and the late Hadrynian and probably cogenetic granitoid plutons with which it is associated, seems likely. However, parallel and adjacent to the Belleisle fault, which here forms the northwestern boundary of the Avalon terrane, Coldbrook lithologies are affected by temporally and spatially associated zones of intense mylonitization and dike injection that are absent in the Cambro-Ordovician Saint John Group (Rast and Dickson 1982). The dike complex, which extends laterally for 200 km, consists of predominantly northeast-trending mafic dikes at its narrower southwestern end (Rast 1979) but forms a 5 km-wide zone of alternating, north-south mafic and rhyolitic dikes to the northeast (Currie 1984, 1986a). Mylonitization affects earlier but not later dikes and has been attributed to left-lateral shear (Rast and Dickson 1982) compatible with the obliquity of north-south dike orientations to the regional trend of the complex. In southern New Brunswick, therefore, the onset of Cambro-Ordovician platformal conditions, which were heralded within the magmatic arc by minor, latest Hadrynian bimodal volcanics and redbeds that may unconformably overlie the Coldbrook Group (Currie 1986a), was preceded by focused back-arc transtension.

The evolution of the late Hadrynian arc complexes thus followed quite separate paths within each of the areas in which the Avalon terrane is exposed. However, since the relative separation of these areas in the late Hadrynian is unknown, the variations in their evolution are not inconsistent with their development within a single subduction system as illustrated by the present complexity of the Indonesian region (Hamilton 1979). Interestingly, their is no evidence within the Avalon terrane that subduction was terminated through a major collisional event. In fact, deformation and metamorphism associated with the Avalonian orogeny are both mild and localized, being most intense in the Antigonish Highlands where their development has been linked to closure of the interarc basin (Murphy and Keppie 1985). Elsewhere, however, subduction was followed by back-arc rifting and shear suggesting that transform termination of oblique subduction, perhaps as a result of ridge-trench collision, was followed by back-arc relaxation and extension. Furthermore, in each of these areas, some form of back-arc extension heralded the onset of Cambro-Ordovician, Atlantic-realm platformal conditions that are widely attributed to the Lower Paleozoic location of the Avalon terrane near the southern margin of the Iapetus Ocean (e.g. Cooks and Fortey 1982; Neuman 1984). It would therefore appear that the locus of Iapetus rifting, at least on its southern margin, was initially provided by latest Hadrynian extension within the back-arc region of the late Precambrian Avalon terrane.

SUMMARY AND DISCUSSION

The Avalon terrane of the Northern Appalachians, which can be defined by the presence of late Precambrian volcano-sedimentary sequences and granitoid plutons and Lower Paleozoic Atlantic-realm platformal successions, forms a distinctive tectonostratigraphic belt that lies inboard of the Meguma terrane along much of the orogen's southeastern margin. The oldest known elements of the terrane are Helikian carbonates and mature clastic rocks that rest on gneissic continental basement and locally are overlain unconformably by slide breccias and turbidites interpreted to record collapse of the ensialic platform during an early Hadryian (ca. 750-800 Ma) tectonothermal event. Associated high-grade regional metamorphism and local ocean-floor tholeiitic magmatism affect the northwestern margin of the terrane and have been attributed to an abortive rifting event. However, the association is not inconsistent with an episode of subduction and back-arc spreading.

Voluminous late Hadrynian volcanic and associated granitoid rocks are the products of a magmatic arc system that appears to have involved a variety of back-arc processes including terrestrial and marine continental back-arc extension and transtension, and oceanic back-arc basin formation. Transform termination of oblique subduction coupled with local back-arc shortening is proposed for the late Hadrynian Avalonian orogeny. Latest Hadrynian bimodal volcanic rocks may herald the inception, within the former back-arc, of the Lower Paleozoic Iapetus Ocean recorded in Cambro-Ordovician platformal successions and local within-plate volcanism. Together, these form an overlap sequence, following a minor (break-up?) unconformity, to the Precambrian development of the Avalon terrane.

The Paleozoic evolution of Avalon terrane locally continues with latest Ordovician to early Devonian bimodal volcanism and shallow marine sedimentation that follows fragmentary evidence for a mid-Ordovician tectonothermal event and is followed by locally intense Acadian deformation, metamorphism and widespread plutonism. However, the significance of these events with respect to the Paleozoic accretionary history of the Avalon terrane remains uncertain. Widespread Devono-Carboniferous molasse and predominantly alkaline bimodal volcanic rocks form an overlap sequence with adjacent terranes and are locally affected by late Paleozoic deformation and metamorphism. Triassic redbeds and mafic volcanic rocks reflect the initial rifting of the present Atlantic Ocean.

Current tectonostratigraphic models for this complex evolutionary record have been strongly influenced by the recent proposition that much of the Northern Appalachians outboard of the North American miogeocline, rather than comprising a longitudinal system of zones, represents a mosaic of terranes with quite separate geologic histories. As a result, conventional tectonic models based on the overall bilateral symmetry of the belt that is implicit in the zonal scheme, although not without considerable merit, have proven to be over simplistic. Paradoxically, the broad regional correlations encouraged by zonal subdivisions permitted the construction of coherent tectonic models despite our rudimentary knowledge of their detailed geology. In contrast, successful terrane analysis requires a level of geologic sophistication beyond that currently available and, hence, the introduction of the terrane concept has temporarily compromised our understanding of the evolutionary history of the orogen. The interpretation of Avalon (and other terranes within the Appalachian orogen) is therefore at an exciting stage of disarray. In particular, our knowledge of the Precambrian tectonic, magmatic and stratigraphic evolution of the Avalon terrane, and the position and accretionary kinematics of Precambrian terrane boundaries that may exist within it, remain poorly understood, while the Paleozoic coherency and accretionary history of the terrane are poorly constrained. As a result, opinions diverge on what is and is not "Avalonian" although it is this author's view that the basic bipartite definition should hold.

Of the numerous additions to the geological data base needed to resolve these major uncertainties, precision radiometric ages and high-quality paleomagnetic data are essential for possible terrane identification within Avalon and the determination of their displacement histories; further igneous and isotopic geochemistry is needed for evidence of tectonic setting, magmatic evolution and basement signatures; extensive metamorphic and deformational analysis is required to provide detailed thermotectonic models; coupled sedimentological and structural studies are necessary to determine terrane tectonostratigraphy and the nature and location of source areas; refined paleontology is required to establish internal stratigraphies, the age of overlap sequences and evidence of faunal provinces; and both shallow and deep seismic reflection data would contribute valuable information concerning seismic stratigraphy, deep crustal structure, the nature of terrane boundaries, and the style of accretion. Much of this information is in the process of being collected since without doubt, the most valuable contribution of the terrane concept to date has been the revitalization of multidisciplinary bedrock mapping that is both rapidly expanding our knowledge of Avalon terrane and providing the data base needed for its eventual interpretation.

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