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Diachronous supracrustal extension in an intraplate setting and the origin of the Connecticut Valley–Gaspé and Merrimack troughs, northern Appalachians

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Abstract – In the Appalachians of mainland Canada and New England, Silurian/Early Devonian rocks are preserved in the Connecticut Valley–Gaspé and Merrimack troughs, and rest unconformably or in fault contact with older rocks belonging to Laurentia and to Gander/Avalon, respectively. The Silurian/Early Devonian rocks consist of marine clastic deposits with subordinate carbonates, lava flows and terrestrial deposits. The origin of these sedimentary basins is still poorly understood. Metamorphic ages and structures in the Laurentian margin, major unconformities and syn-sedimentary normal faulting in both troughs argue for significant crustal extension during deposition. The Connecticut Valley–Gaspé and Merrimack troughs are separated by inliers of pre-Ordovician to Ordovician rocks which we interpret as Silurian basement highs that would have been buried in Devonian times to form a composite sedimentary basin. Volcanic rocks are widely distributed in time and space in both basins, and are mostly subalkaline within-plate tholeiites, which is consistent with a tectonic setting involving crustal extension rather than with subduction. Granitic plutons are abundant in the Merrimack trough and attest to high temperatures at mid-crustal levels. It is suggested that crustal extension was responsible for the formation of both basins and that heating of the lower crust in the Merrimack trough during the Silurian was the result of synorogenic collapse likely triggered by delamination at the Laurentia–Medial New England boundary. Delamination of the subducted slab and the upwelling of the asthenosphere would have caused (1) isostatic uplift and formation of basement highs, (2) magmatism in the lower crust and regional-scale contact metamorphism in the upper crust, and (3) collapse of metamorphic terranes and the formation of subsiding sedimentary basins.

Keywords: Appalachians, tectonism, delamination, synorogenic extension.

1. Introduction

In mainland Canada and New England, sedimentary and volcanic rocks of Silurian and Devonian age represent approximately 50% of surface exposure and cover a minimal length of *c*. 1000 km of the Appalachian Belt (Figs 1, 2). Since the application of plate tectonic concepts to the Northern Appalachians, controversies have existed regarding the interpretation of these sedimentary basins. Different tectonic scenarios have been suggested (Fig. 3): (1) transpressive or transtensional rift basins (e.g. Keppie & Dostal, 1994; Bourque, Brisebois & Malo, 1995), (2) foreland basins overlying two subduction zones plunging in opposite directions (Bradley, 1983), and (3) foredeep and foreland basins associated with backarc extension and lithosphere delamination along NW-dipping (e.g. van Staal & de Roo, 1995; Moench & Aleinikoff, 2002), or (4) SE-dipping subduction zones (e.g. Robinson *et al*. 1998).

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This contribution re-examines available data on the palaeogeography and the magmatic, metamorphic and structural evolution of Silurian–Devonian deposits of mainland Canada and New England (Fig. 1). It is suggested herein that major characteristics of these basins, as well as the structural and metamorphic features of their basement rocks, are best explained as the result of crustal extension. Deep crustal and mantle processes that triggered the extension are difficult to ascertain, but we favour supracrustal extensional collapse due to late-stage delamination of the lithospheric mantle in a SE-dipping (present coordinates) subduction zone.

2. Geological setting

Silurian and Devonian rocks occur in two major sedimentary basins, here referred to as the Connecticut Valley–Gaspé and the Merrimack troughs (Bradley, 1983). These sedimentary basins are bordered and separated by inliers of Proterozoic and/or Cambrian–Ordovician basement rocks (Figs 1, 2). The troughs occur on both sides of Zen's (1983) Taconian suture

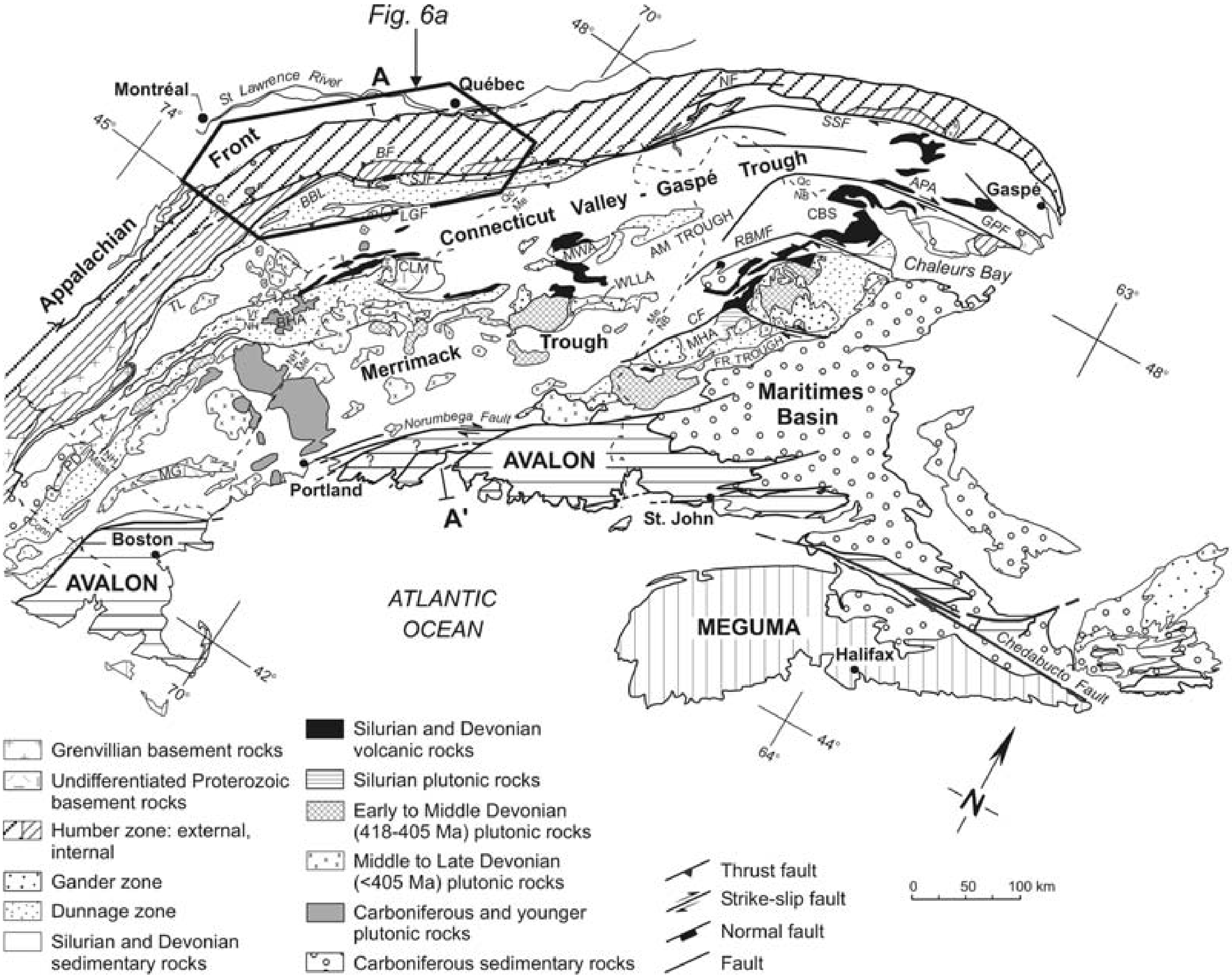

Figure 1. Simplified geological map of the Northern Appalachians of mainland Canada and New England showing the major lithotectonic elements of the region. Modified from Williams (1978). The major Silurian/Devonian sedimentary basins are the Connecticut Valley–Gaspé, Merrimack, Aroostook–Matapédia (AM) and Fredericton (Fr.) troughs. Basement rocks: CLM – Chain Lake Massif; MG – Massabesic Gneiss; PD – Pelham Dome. Major anticlinoria and synclinoria: APA – Aroostook–Percé anticlinorium; CBS – Chaleurs Bay synclinorium; BHA – Bronson Hill Anticline; MHA – Miramichi Highlands Anticline; MWA – Munsungun–Winterville Anticline; WLLA – Weeksboro–Lunksoos Lake Anticline. Major faults: *BBL* – Baie Verte–Brompton Line; *BF* – Bennett fault; *SJF* – Saint-Joseph fault; *LGF* – La Guadeloupe fault; *TL* – Taconic Line; *NF* – Neigette fault; *SSF* – Shickshock-Sud fault; *GPF* – Grand Pabos fault; *RBMF* – Rocky Brook–Millstream fault; *CF* – Catamaran fault. A–A′ – location of the structural profile of Figure 2. State boundaries: Conn – Connecticut; Mass – Massachussets; Me – Maine; NB – New Brunswick; NH – New Hamshire; Qc – Québec; Vt – Vermont. Note that the boundary between Medial New England (Gander zone) and Composite Avalon is approximate (see question marks); see text for discussion.

zone, suggesting that they were formed on different basements (Fig. 2). In the Gaspé Peninsula and New Brunswick, this Taconian suture is overlain by younger deposits or affected by faulting, and both troughs form a composite basin (Fig. 1). The Connecticut Valley–Gaspé and Merrimack troughs are characterized by contrasting tectonic and metamorphic histories attributed to the Acadian orogeny. On the basis of different *P/T* paths, metamorphic conditions and ages, Armstrong, Tracy & Hames (1992) have separated the New England Acadian orogen into Western and Eastern belts (Fig. 2), roughly corresponding to the Connecticut Valley–Gaspé and Merrimack troughs, respectively. The following descriptions are restricted to Silurian–Devonian rock units located west of the Norumbega fault zone (Figs 1, 2), a wide (> 25 km) zone of dextral transcurrent faulting of Late Devonian to Early Carboniferous age (Swanson, 1992; West & Hubbard, 1997) that defines the eastern boundary of the Merrimack trough in eastern Maine.

The Connecticut Valley–Gaspé trough varies from ∼10 to ∼70 km wide (Fig. 1). It lies between allochthonous rocks of the Humber and Dunnage zones (Williams, 1979) to the northwest, and the Bronson Hill/Boundary Mountains anticlinoria and correlative structures to the southeast. The northwestern contact with older rocks is commonly faulted, but outliers of Silurian/Devonian rocks resting on

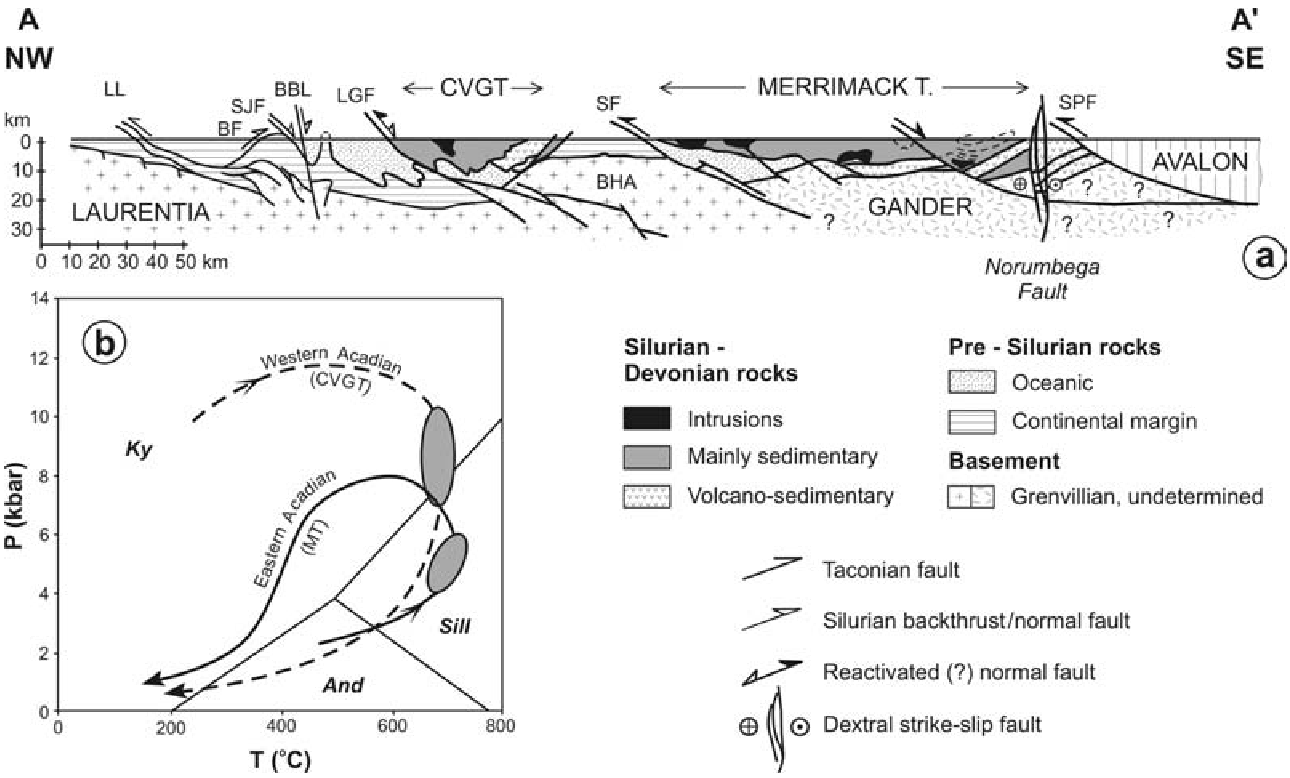

Figure 2. (a) Interpretative structural profile A–A′; see Figure 1 for location. Basement rock geometry extrapolated from seismic data of Stewart *et al*. (1993). Modified from Pinet & Tremblay (1995) and Stewart *et al*. (1993). LL – Logan's Line; SF – Squirtgun fault; SPF – Sennebec Pond fault, which is interpreted as the Medial New England–Composite Avalon boundary in coastal Maine (West & Hubbard, 1997). Other symbols as in Figure 1. See text for discussion. (b) *P–T* diagram showing postulated typical *P–T* trajectories for the Western and Eastern Acadian belts as defined by Armstrong, Tracy & Hames (1992). The patterned ovals indicate the approximate part of each trajectory at which peak *P–T* conditions were recorded. From Armstrong *et al*. (1992). CVGT – Connecticut Valley–Gaspé trough; MT – Merrimack trough; Ky – kyanite; And – andalusite; Sill – sillimanite.

Cambrian–Ordovician strata are locally found to the north of major faults (Fig. 1). The trough includes siliciclastic rocks, limestones, felsic to mafic volcanic rocks, and intrusive rocks. According to Bourque, Brisebois & Malo (1995), it comprises four principal sedimentary assemblages in the Gaspé Peninsula (Fig. 4): (1) Upper Ordovician–lowermost Silurian deep water siliciclastics and carbonates, (2) Silurian–lowermost Devonian shallow to deep water shelf facies, (3) Lower Devonian mixed siliciclastic and carbonate deep shelf and basin facies, and (4) Lower to Middle Devonian nearshore to terrestrial facies. The stratigraphy of the trough is less well known in southern Québec and New England but is considered to be correlative with the uppermost Silurian and Lower Devonian sequences of the Gaspé Peninsula (Bourque, Brisebois & Malo, 1995). The age of regional Barrovian (high temperature–high pressure; HT–HP, Fig. 2) metamorphism has been istopically dated at 395–375 Ma (Armstrong, Tracy & Hames, 1992; Tremblay, Ruffet & Castonguay, 2000). Regional deformation includes an early generation of NW-verging folds superposed by SE-verging backfolds (Hatch & Stanley, 1988) and by post-metamorphic domes, the two latter structures being only locally developed in southern Québec (Tremblay, Ruffet & Castonguay, 2000). In the Gaspé Peninsula and New Brunswick, both the Connecticut Valley–Gaspé and the Merrimack troughs were affected by regional anchi- to low-grade metamorphism (Hesse & Dalton, 1991) that post-dated Middle Devonian (Eifelian) rocks (Bourque, Malo & Kirkwood, 2000; Malo, 2001).

The Merrimack trough occupies much of east-central New England (Fig. 1). Basement rocks have been attributed to the Medial New England terrane (Robinson *et al*. 1998; Tucker, Osberg & Berry, 2001), which includes rock units of the Dunnage and Gander zones as defined by van Staal *et al*. (1998). The Merrimack trough comprises rock sequences of the Central Maine basin of Tucker, Osberg & Berry (2001), the Central Maine–Matapedia trough of Moench & Aleinikoff (2002), and the Aroostook–Percé anticlinorium and Chaleurs Bay synclinorium in northwestern New Brunswick (Bourque, Brisebois & Malo, 1995). In central New Brunswick, the Merrimack trough merges into the Fredericton and the Aroostook–Matapedia troughs of Bradley (1983) on both sides of the Miramichi Highlands inlier (Fig. 1). The Merrimack trough consists of a thick sequence of Silurian turbidites overlain by Devonian pelites and greywackes (Fig. 4). It includes Upper Silurian and

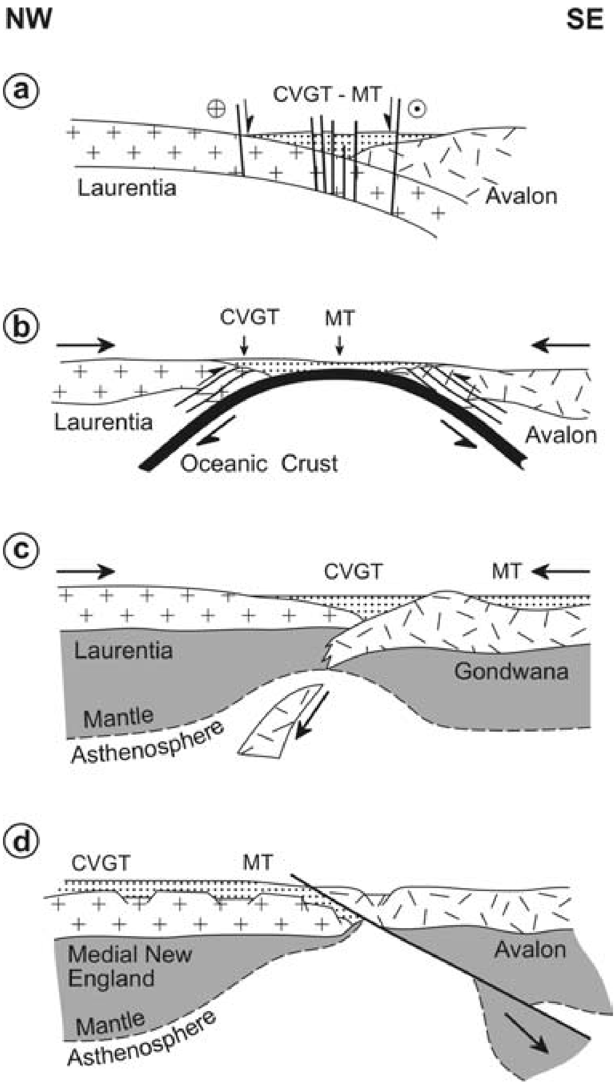

Figure 3. Sketches of existing tectonic models for the formation of the Connecticut Valley–Gaspé (CVGT) and Merrimack (MT) trough sedimentary basins. (a) Strike-slip basins model of Keppie & Dostal (1994) for New Brunswick and the Gaspé Peninsula. (b) Molluca Sea-type model of Bradley (1983) for Central Maine and southern Québec. (c) Syn-collisional delamination related to a NW-dipping subduction zone as suggested by van Staal & de Roo (1995) for New Brunswick and the Gaspé Peninsula. (d) Delamination of a subducted Medial New England terrane as suggested by Robinson *et al*. (1998) for New England. See text for discussion.

Lower Devonian volcanic rocks (Fig. 1) known as the Tobique and the Pisquataquis volcanic belts (Dostal, Wilson & Keppie, 1989). Age constraints for regional deformation and metamorphism are less firm than in the Connecticut Valley–Gaspé trough (Fig. 1). The regional high temperature–low pressure (HT–LP) metamorphism and related deformation are older than in the Connecticut Valley–Gaspé trough. Metamorphism varies from amphibolite-grade (locally granulite) in central and southern New England, to greenschist and sub-greenschist grade in northern Maine, New Brunswick and the Gaspé Peninsula. Isotopic ages and structural relationships suggest that metamorphism and deformation have been coeval with the emplacement of abundant granitic plutons that spans the interval *c*. 420–408 Ma (Eusden & Lyons, 1993; van Staal & de Roo, 1995; Solar *et al*. 1998; Bradley *et al*. 2000; Tucker, Osberg & Berry, 2001). An anticlockwise *P–T* path (Fig. 2) has been interpreted as evidence for regional-scale 'contact' metamorphism caused by heat input from voluminous plutonism in the lower crust. The HT–LP metamorphic assemblages are overprinted by a younger (*c*. 400 to 380 Ma) thermal event (Tucker, Osberg & Berry, 2001), which is considered here as correlative to regional metamorphism in the Connecticut Valley–Gaspé trough.

3. Evidence for extensional collapse and Silurian delamination

An understanding of the tectonic regime that prevailed in Silurian times must rely on the following geological parameters: (1) the character of faulting (extensional or compressional) during sedimentation (1 and 2 on Fig. 5), (2) the relationships between basements and overlying Silurian/Early Devonian basins (3 on Fig. 5), (3) the palaeo-geographic setting(s) that can be inferred from stratigraphic and sedimentological characteristics of the deposits (4 on Fig. 5), (4) the extent and composition of syn-sedimentary volcanism and plutonism, and its space–time variations (5 and 6 on Fig. 5), and (5) the relationships, if any, between the Silurian/Early Devonian sedimentary and magmatic record and 'proximal' subduction processes.

In the following section, we present and discuss various sets of metamorphic, structural, lithological and palaeogeographic data that are consistent with the predominance of crustal extension during the formation of major sedimentary basins in mainland Canada and New England in Silurian and Early Devonian times.

3.a. Structures of Cambrian–Ordovician basement rocks

The age and kinematics of basement structures in metamorphic rocks exposed in inliers, or at the periphery of the Connecticut Valley–Gaspé and the Merrimack troughs, represent key elements in determining the nature of tectonism that prevailed in Silurian and Devonian times.

3.a.1. Structural relationships at the Laurentian margin of the Connecticut Valley–Gaspé trough

Metamorphic rocks of the internal Humber zone fringe the northwestern boundary of the Connecticut Valley–Gaspé trough from New England to the Gaspé Peninsula (Fig. 1). In New England, isotopic ages from the Humber zone vary from Ordovician through Devonian. Silurian cooling ages have been locally

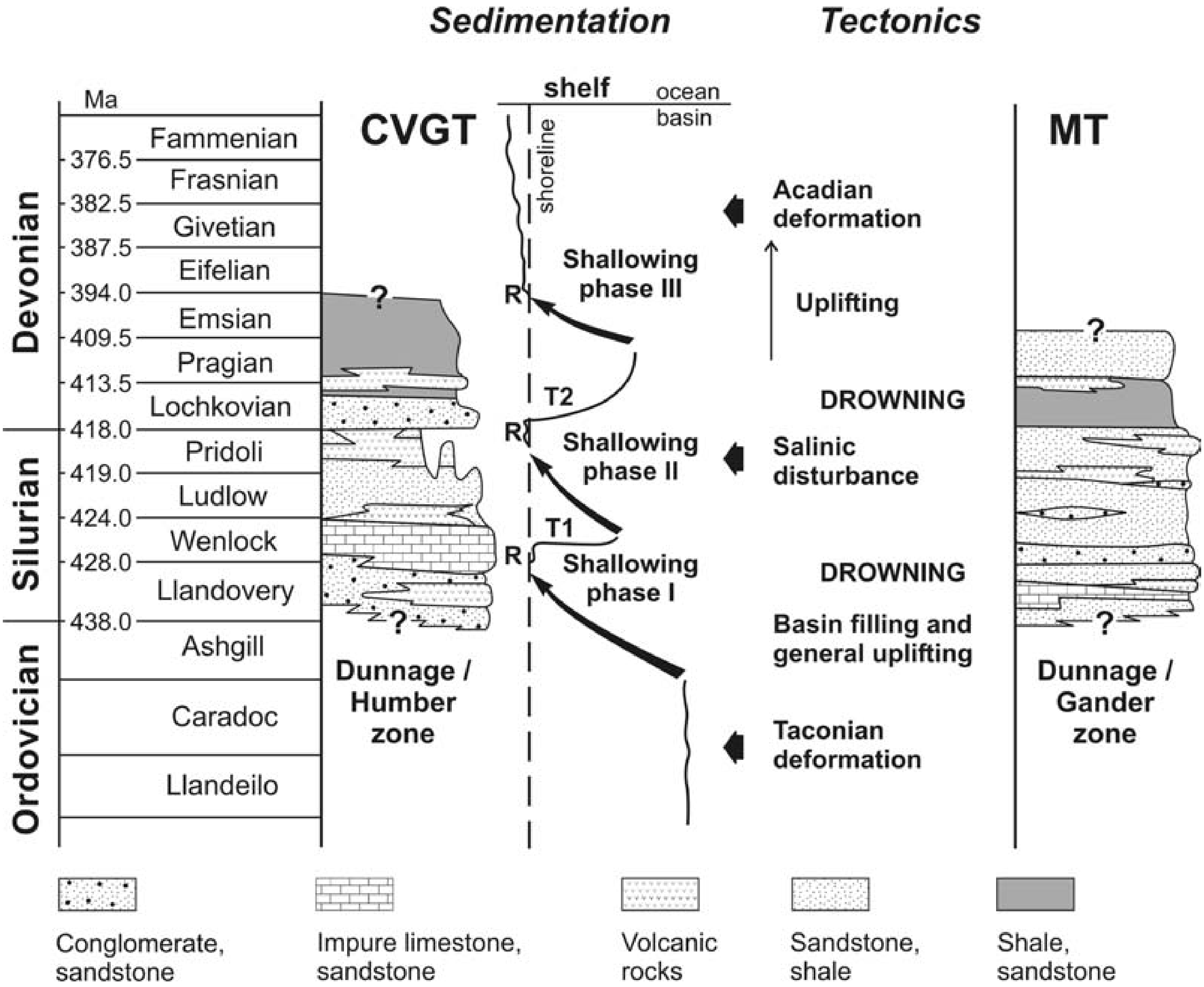

Figure 4. Simplified stratigraphic columns for the Connecticut Valley–Gaspé (CVGT) and the Merrimack (MT) troughs. Note that discontinuous volcanic rock units occur at various stratigraphic levels within both sequences. R – regression; T – transgression. Absolute ages for the Silurian and the Devonian are those suggested by Tucker *et al*. (1998). Modified from Bourque, Brisebois & Malo (1995).

found and attributed to delayed cooling after Taconian peak metamorphism (Laird, Lanphere & Albee, 1984; Sutter, Ratcliffe & Musaka, 1985) or to argon loss during the Acadian orogeny (Spear & Harrison, 1989; Rickard, 1991). In southern Québec, ^{40}Ar/^{39}Ar data show the coexistence of Middle Ordovician and Late Silurian/Early Devonian ages (Castonguay *et al*. 2001), the latter being attributed to structures related to the formation of the Connecticut Valley–Gaspé trough (Tremblay & Castonguay, 2002).

The structural characteristics of the internal Humber zone have been summarized by Tremblay & Castonguay (2002) in southern Québec (Figs 6, 7) and will not be discussed further. In terms of metamorphism, amphibole and mica ^{40}Ar/^{39}Ar ages from the internal zone vary between 431 and 411 Ma. High-temperature steps of Ordovician age (462–460 Ma) from amphiboles of the Arthabasca Amphibolite (Castonguay *et al*. 2001) attest to the fact that Taconian metamorphism is only locally preserved and, more importantly, that there is no protracted cooling from Ordovician to Silurian times and that both periods correspond to geochronologically (and kinematically) unlinked thermal events (Tremblay & Castonguay, 2002). To the southeast, the internal Humber zone is bounded by the St-Joseph fault (Pinet, Tremblay & Sosson, 1996) and the Baie Verte–Brompton line (BBL; Williams & St-Julien, 1982), which form a composite E-dipping normal fault system that extends for at least 200 km. In the hangingwall of the St-Joseph–BBL fault system (Fig. 7), metamorphic rocks locally exposed through Acadian anticlinal inliers have yielded Middle Ordovician ^{40}Ar/^{39}Ar muscovite ages (469–461 Ma; Castonguay *et al*. 2001) that show no evidence of a Silurian thermal overprint and are consistent with the high-temperature step ages from the Arthabasca Amphibolite. Middle Ordovician ages are attributed to Taconian metamorphism and are

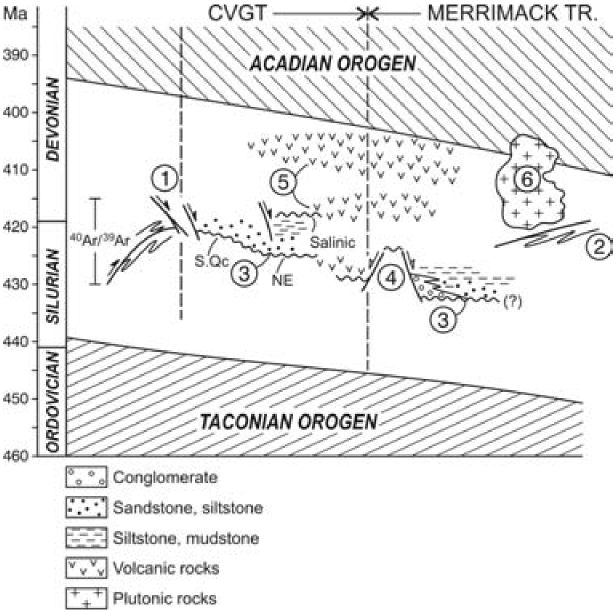

Figure 5. Schematic diagram illustrating key geological parameters that are used in this paper to constrain the tectonic regime that prevailed in the study area in Silurian and Early Devonian times. 1 – Structures of basement rocks and structural relationships at the western boundary of the Connecticut Valley–Gaspé trough; 2 – Structural relationships at the eastern boundary of the Merrimack trough; 3 – Silurian unconformities; 4 – Palaeogeography of Silurian/Early Devonian deposits; 5 and 6 – Silurian/Early Devonian volcanism and plutonism. See text for discussion. CVGT – Connecticut Valley–Gaspé trough; S.Qc – southern Québec; NE – New England.

consistent with the inferred age of progressive deformation of the Laurentian margin (*c.* 490–445 Ma: Stanley & Ratcliffe, 1985; Tremblay & Castonguay, 2002). Tremblay & Castonguay (2002) suggested that the Silurian–Early Devonian ages and associated hinterland-directed deformation (that is, backthrusts and normal faults) provide structural mechanisms and timing limitations that are compatible with the exhumation of the Laurentian margin and the Pridolian onset of sedimentation in the Connecticut Valley–Gaspé trough (Figs 6, 7).

Structural relationships on both sides of the St-Joseph–BBL fault system of southern Québec can be extrapolated southward and northward. Southward (in western New England), the St-Joseph–BBL fault system correlates with the Burgess Branch fault zone (Kim *et al.* 1999; Castonguay & Tremblay, 2003), a composite normal fault zone that separates metamorphic rock of the Green Mountain slice to the west (correlative to the internal Humber zone of southern Québec) against lower-grade units to the east (Kim *et al.* 1999). Northward (in northwestern Maine), the St-Joseph–BBL fault system merges into normal faults mapped at the boundary between the Connecticut Valley–Gaspé trough to the southeast and pre-Silurian rock sequences to the northwest (e.g. Osberg, Hussey & Boone, 1985). This suggests that, from western New England to northwestern Maine, there is an extensive set of Late Silurian to Early Devonian normal faults that extend for more than 400 km. In Gaspé Peninsula, the Shickshock-Sud fault (Fig. 1), which marks the northern boundary of the Connecticut Valley–Gaspé trough, is interpreted as a complex structure that records successive events of reverse and normal motion (Sacks *et al.* 2004). The fault separates amphibolite-grade metamorphic rocks of the Humber zone to the north and very low-grade rocks of the Connecticut Valley–Gaspé trough to the south, suggesting that it likely belongs to the same set of structures as the St-Joseph–BBL fault system.

3.a.2. Structural relationships at the Avalon margin of the Merrimack trough

The structural evolution of the Merrimack trough has been described by, among others, Tucker, Osberg & Berry (2001) and West, Beal & Grover (2003) in Maine, Eusden & Lyons (1993) in New Hampshire, and van Staal & de Roo (1995) in New Brunswick.

Tucker, Osberg & Berry (2001) proposed a detailed structural and metamorphic evolution for the Merrimack trough. Briefly, structures preserved in the Liberty–Orrington thrust sheet, inferred to be an E-verging thrust intruded by the 418 Ma Lincoln shonkinite, suggest that it was emplaced over the Fredericton trough at *c.* 420 Ma. They also described W-verging thrusts that affect Lower Devonian rocks and are cross-cut by intrusions dated at *c.* 404 Ma. Both these E- and W-verging thrust sheets were then deformed by regional upright isoclinal folds. These folds, in turn, are cross-cut by granitic rocks dated at 408 Ma, which constrain the regional folding event to the interval 418–408 Ma (Tucker, Osberg & Berry, 2001). These regional folds were then affected by younger folds that deform dykes dated at 399 Ma and are overprinted by static metamorphism dated at *c.* 380 Ma (Tucker, Osberg & Berry, 2001). In New Hampshire, D_1 deformation (which is part of a complex D_1 to D_4 deformational history) is characterized by E-facing F_1 folds related to thrust faults and nappes correlative to those (such as the Liberty–Orrington thrust sheet) in Maine (Eusden & Lyons, 1993). These thrust faults are presumably floored by a basal décollement that separates the Silurian sequence and the pre-Silurian 'basement', and to which are attributed flat seismic reflectors at depths of 2 to 10 km (Stewart *et al.* 1986; Stewart *et al.* 1993). Although this basal décollement has been interpreted as a W-verging D_1 thrust, Eusden & Lyons (1993) stressed that it could equally represent a major E-verging structure. In New Brunswick, van Staal & de Roo (1995) described similar E- and NE-verging F_1 folds and thrusts. They stressed that deformation and metamorphism in the Fredericton trough occurred before and during

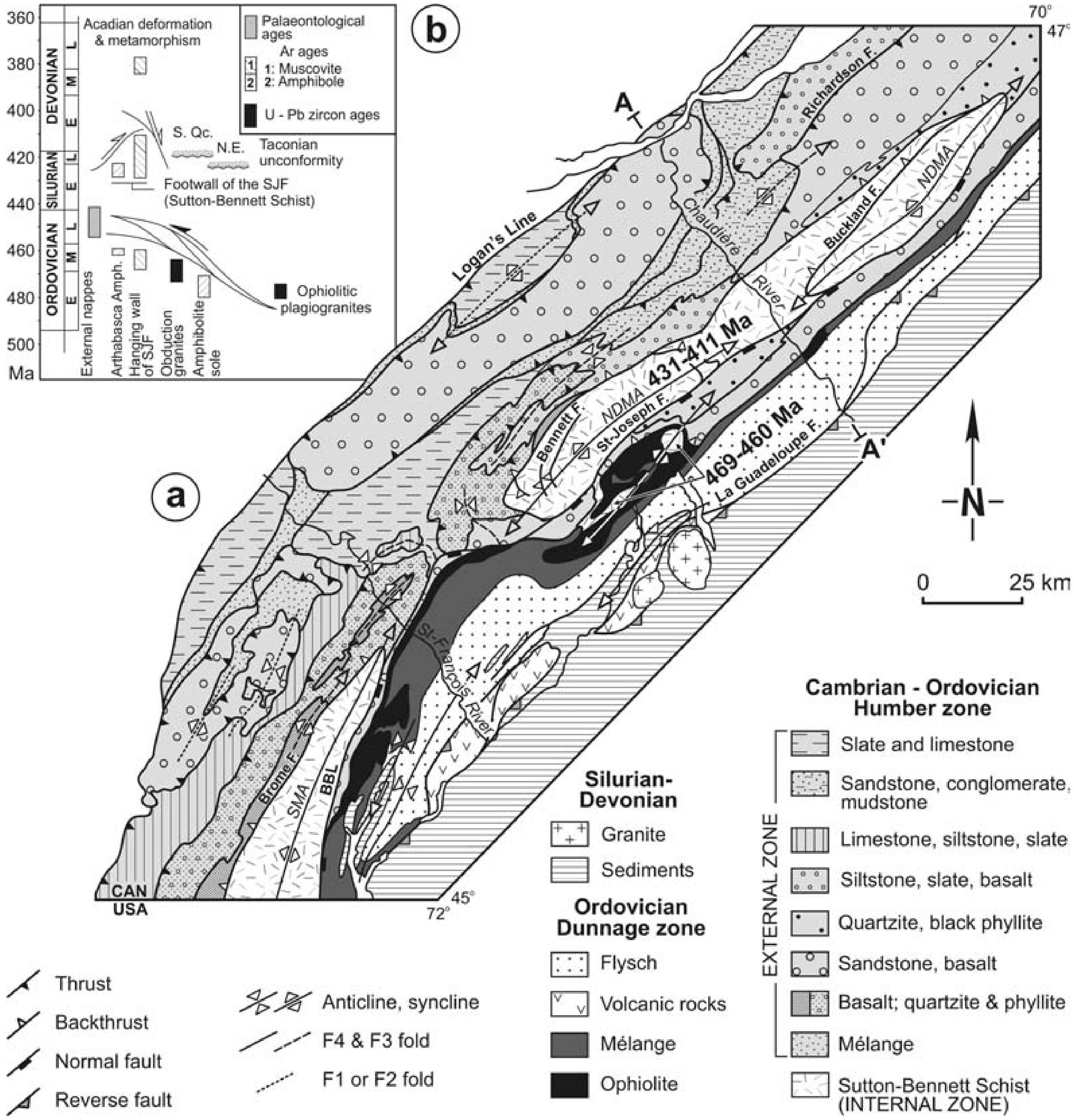

Figure 6. (a) Geological map of the southern Québec Appalachians showing the distribution of Ordovician and Silurian/Early Devonian $^{40}Ar/^{39}Ar$ ages for the internal Humber zone on both sides of the Saint-Joseph fault. (b) Diagram illustrating the various geochronological data available in this region. SMA – Sutton Mountains anticlinorium; NDMA – Notre-Dame Mountains anticlinorium; BBL – Baie Verte-Brompton Line; SJF – Saint-Joseph fault; S.Qc. – southern Québec; N.E. – New England. A–A′ – location of the structural profile of Figure 7. See text for details and Figure 1 for location.

the intrusion of Ludlovian granites and gabbros at *c.* 420 Ma, and that the trough represents a foreland basin developed during the NW-dipping subduction recorded by the Brunswick subduction complex.

3.b. Silurian unconformities

Unconformities and/or disconformities are widely distributed in both the Connecticut Valley–Gaspé and the Merrimack troughs. Silurian unconformities are prominent at the southeastern and northwestern margins of the Connecticut Valley–Gaspé trough and within antiformal inliers in both basins (Pavlides, Boucot & Skidmore, 1968; Osberg *et al.* 1989; Bourque, Malo & Kirkwood, 2000). Silurian rocks bevel across pre-Silurian stratigraphic sections locally cutting down to rocks of Precambrian age. Silurian rocks lie with much less angular discordance on rocks of the Dunnage zone than they do on those of the Humber zone; indeed, the parallelism between

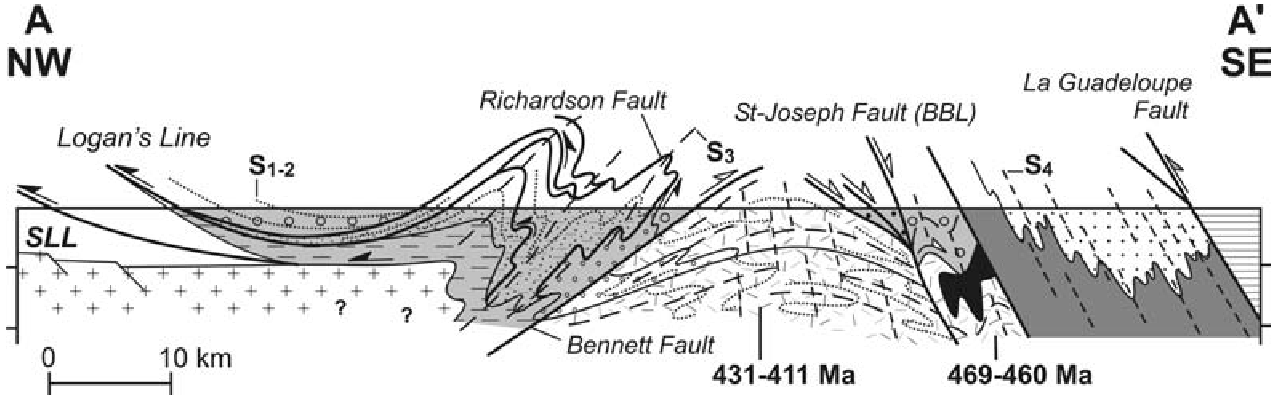

Figure 7. Structural profile of the southern Québec Appalachians illustrating the geometry and kinematics of regional polyphased deformation. The orientation of S_{1-2}, S_3 and S_4 tectonic fabrics as defined by Tremblay & Pinet (1994) are schematically shown. See Figure 6 for legend and location.

Dunnage rocks and the Silurian sections of both troughs is locally striking (e.g. Tremblay, Malo & St-Julien, 1995 for southern Québec; Tucker, Osberg & Berry, 2001 for central Maine). The sedimentary hiatus between Ordovician and Silurian strata is of variable extent. Sedimentation is almost continuous from the Ordovician into the Silurian at several localities in the Gaspé Peninsula, New Brunswick and northern Maine. Early Silurian deposits are lacking in southern Québec where Late Silurian (Pridolian) rocks overlie Upper Ordovician rocks (Boucot & Drapeau, 1968; Bourque, Brisebois & Malo, 1995; Tremblay, Malo & St-Julien, 1995). In the Gaspé Peninsula, a few outliers of Silurian to Lower Devonian rocks rest unconformably on rocks of the Humber Zone, and disconformably on those of the Dunnage Zone (Bourque, Brisebois & Malo, 1995).

Along the eastern border of the Connecticut Valley–Gaspé trough in New England, a widely exposed unconformity is overlain by the Clough Quartzite and by shallow-marine calcareous rocks (Robinson *et al.* 1998). The unconformity is locally angular but evidence for intense pre-Silurian deformation is limited. In eastern New England, Early Silurian unconformities are exposed along the Bronson Hill anticlinorium and other antiformal inliers such as the Munsungun–Winterville, Weeksboro–Lunksoos Lake, Miramichi and Massabesic (Figs 1, 2; Ludman, Hopeck & Brock, 1993; Robinson *et al.* 1998). Contact relationships are better exposed in the Gaspé Peninsula and New Brunswick, where the base of the Merrimack trough is exposed in the Aroostook–Percé anticlinorium. The sequence includes Upper Ordovician to lowermost Silurian deposits overlying rocks of the Humber and Dunnage zones (Bourque, Brisebois & Malo, 1995). The upper part of the Merrimack trough in the Gaspé Peninsula is in faulted contact with the Miramichi inlier but unconformities are locally preserved (Fyffe & Noble, 1985).

Contact relationships between the Connecticut Valley–Gaspé and Merrimack troughs and their basements suggest that erosion alone cannot have accounted for the exhumation of pre-Silurian rocks, and that extensional faulting probably played a significant role, at least during the Late Silurian–Early Devonian interval. In southern Québec and western New England, the occurrence of Late Silurian unconformities requires the older rocks to have been at the surface between *c*. 426 and 418 Ma.

3.c. Palaeogeography of Silurian/Early Devonian deposits

The Connecticut Valley–Gaspé and Merrimack troughs represent two major depocentres. The Silurian section of both basins is well exposed in several localities but the Devonian section is best exposed in the Gaspé Peninsula and New Brunswick. Within the Merrimack trough, smaller-scale depocentres have been interpreted in northern Maine (Ludman, Hopeck & Brock, 1993), between the Munsungun–Winterville, Weeksboro–Lunksoos Lake and Miramichi inliers (Fig. 1). Facies distribution and thickness variations have been documented by Osberg *et al.* (1989) and Robinson *et al.* (1998) in central and southern New England, by Ludman, Hopeck & Brock (1993) in northern Maine, and by Bourque, Brisebois & Malo (1995) in the Gaspé Peninsula. Stratigraphic and sedimentological data suggest that basement rocks formed topographic highs during sedimentation (Fig. 8), and that deposition occured in broad, graben-like basins separated by horst-like features during Silurian times (e.g. Robinson *et al.* 1998; Bourque, Malo & Kirkwood, 2000; Tucker, Osberg & Berry, 2001). Such an interpretation, if correct, requires extensional tectonism rather than compression. Basement inliers are less abundant in the Devonian section of both troughs, which is consistent with the burial of basement highs and the formation of a composite sedimentary basin (Fig. 8).

In the Connecticut Valley–Gaspé trough of New England and southern Québec, conglomerates, associated with sandstone and limestone, are predominant toward the base of Pridolian deposits (Boucot &

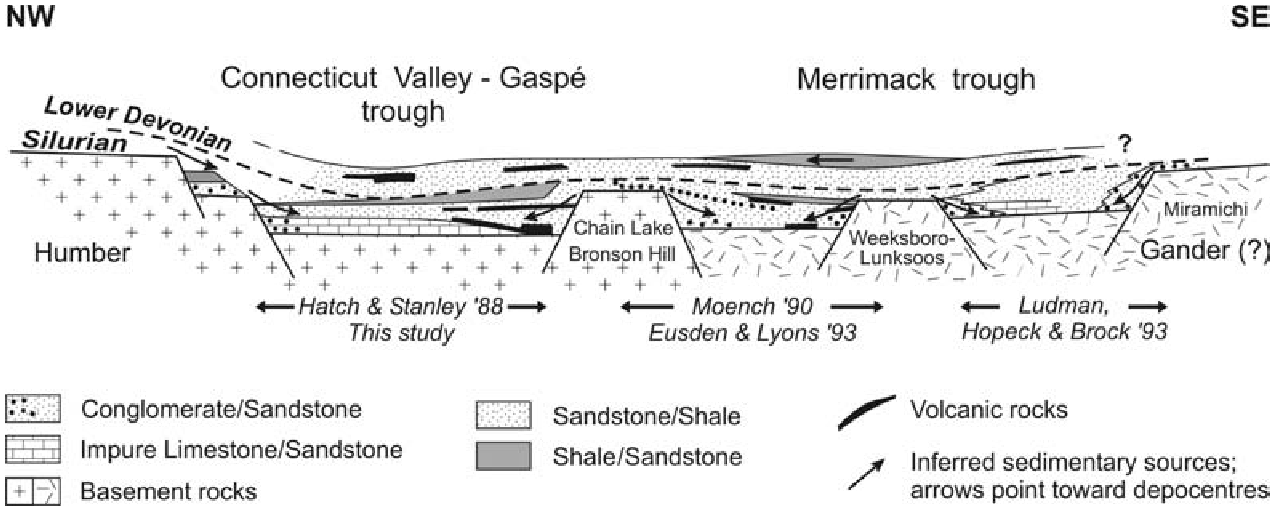

Figure 8. Schematic composite stratigraphic section across the Connecticut Valley–Gaspé and Merrimack troughs showing the distribution of lithological facies and the location of inferred topographic highs. Note that conglomeratic and coarse-grained facies occur close to basement outliers whereas fine-grained facies thickens toward the axis of depocentres. The broken line indicates the approximate location of the Silurian–Devonian boundary. See text for discussion.

Drapeau, 1968; Lavoie & Bourque, 1992). These rocks grade into impure limestone overlain by shale-sandstone turbidites and wackes toward the axis of the basin. The section exposed along the eastern margin of the Connecticut Valley–Gaspé trough is in many respects similar to the western edge of the Merrimack trough and, moreover, shelf facies of the Connecticut Valley–Gaspé trough interfinger eastward into the deeper water detrital section of the Merrimack trough (Osberg *et al*. 1989).

In the Merrimack trough of northern Maine, Lower Silurian conglomeratic facies are common adjacent to basement inliers, and thin toward the axis of basins by lateral grading into turbiditic wackes (Osberg *et al*. 1989). The overall sequence has been interpreted as a transition from proximal to distal facies, with the conglomeratic facies representing debris flows or slump deposits formed by faulting along basin margins (Ludman, Hopeck & Brock, 1993). Actual faults, however, have not been recognized to date but would have been active in Silurian times. Facies distribution shows an overall symmetry in regard to basement inliers (Fig. 8; Ludman, Hopeck & Brock, 1993). A similar transition from complex basin-margin facies passing eastward into distal facies has also been described in southern Maine and New Hampshire where it suggests the presence of a palaeo-topographic high centred on the Bronson Hill anticlinorium (Osberg *et al*. 1989; Robinson *et al*. 1998; Moench & Aleinikoff, 2002).

In the Gaspé Peninsula, the western margin of the Connecticut Valley–Gaspé trough is characterized by Silurian shelf and terrestrial deposits that are laterally equivalent to deep-basin shales and wackes (Bourque, Brisebois & Malo, 1995). In Ludlovian/Pridolian times, a period of erosion and inferred normal faulting, referred to as the Salinic Disturbance (Boucot, 1962), marks the deposition of terrestrial redbeds and conglomerates along uplifted areas and of fine-grained siliciclastic rocks in the adjacent marine basin (Fig. 4; Bourque, Brisebois & Malo, 1995). The Devonian is characterized by the drowning of the platform and by the westward progression of deltaic deposits associated with a progressive shallowing of the marine basin until the establishment of shallow-water carbonate sedimentation followed by or coeval with estuarine and fluviatile sediments (Fig. 4). The Salinic (or Salinian) Disturbance is dated as late Ludlow–early Pridoli, and represents an erosional disconformity that in places cuts deep into the underlying Silurian and Ordovician rocks (Fig. 4). In the Gaspé Peninsula, palaeo-topography related to syn-sedimentary faulting and erosion controlled the development of Late Silurian and Early Devonian facies, as shown by (1) sedimentary thickness variations and facies distribution on both sides of syn-sedimentary faults (Bourque, Malo & Kirkwood, 2000), (2) seismic sections supporting block faulting (Roksandic & Granger, 1981; St-Julien & Bourque, 1990), and (3) the close correspondance between syn-sedimentary faults and the location of conglomeratic facies and of a 1000 km long reef tract recognized from the Gaspé Peninsula to southern Québec (Bourque, Malo & Kirkwood, 2000). In the Gaspé Peninsula, as much as 1500 metres of uplift has been documented. The Salinic Disturbance supports the view that sedimentation within the Connecticut Valley–Gaspé trough took place during syn-depositional normal faulting.

3.d. Silurian/Early Devonian volcanism

Volcanic rocks occur at various stratigraphic levels within the Connecticut Valley–Gaspé and Merrimack troughs (Fig. 4), largely in the Piscataquis and Tobique Volcanic Belts (Dostal, Wilson & Keppie, 1989;

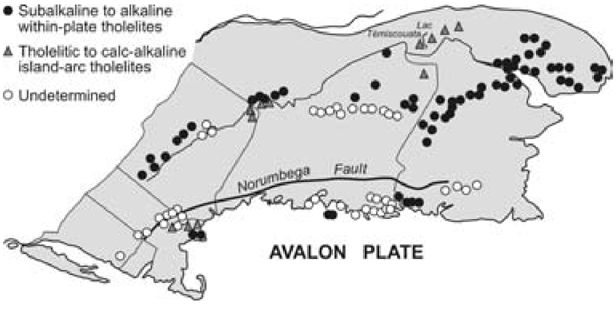

Figure 9. Distribution and chemical composition of post-Ordovician volcanic rocks in the Connecticut Valley–Gaspé and Merrimack troughs. Note that the vast majority of the studied volcanic sequences represent transitional to alkaline, within-plate tholeiites. See text for discussion.

Keppie & Dostal, 1994). The volcanic rocks occur at three major time intervals, late Early Silurian (Llandovery–Ludlow), latest Silurian to Early Devonian (late Pridoli–Lochkovian), and late Early Devonian (Emsian). Granitic plutons interpreted to be coeval with volcanism are abundant in the Merrimack trough (Fig. 1).

In the Connecticut Valley–Gaspé trough (Fig. 9), Early Silurian mafic volcanic rocks occur in the western part of the Gaspé Peninsula (Fig. 1, David & Gariépy, 1990) and Maine (Osberg, Hussey & Boone, 1985; Slack *et al*. 1999), in southern Québec (S. Chevé, unpub. Ph.D. thesis, Univ. Montréal, 1990; C. Desjardins, unpub. M.Sc. thesis, Univ. Laval, 1994) and New Hampshire (Moench, 1990), and possibly in southern Vermont (Osberg *et al*. 1989). On the basis of geochemical characteristics, David & Gariépy (1990) and Slack *et al*. (1999) interpreted these rocks as calc-alkalic volcanic rocks related to arc volcanism. The volcanic sequence of northwestern Maine is characterized by alkalic basaltic affinities (Schwartz & Hon, 1983). Volcanic rocks of southern Québec and correlatives are tholeiitic basalts with enriched mid-oceanic ridge basalt (MORB)-like geochemical affinity (C. Desjardins, unpub. M.Sc. thesis, Univ. Laval, 1994), whereas the southern Vermont volcanic sequence shows coexisting ocean-floor tholeiitic and alkaline trends (Hepburn, 1984).

Because of their similar lithologies and geochemical trends, Pridolian–Lochkovian and Emsian volcanic rocks of the Connecticut Valley–Gaspé trough are considered as a single group, making up the northern segment of the Tobique Volcanic Belt of Dostal, Wilson & Keppie (1989). These volcanic rocks occur mainly in the Gaspé Peninsula (Laurent & Bélanger, 1984), in southern Québec and in Maine (C. Desjardins, unpub. M.Sc. thesis, Univ. Laval, 1994; R. G. Marvinney, unpub. Ph.D. thesis, Syracuse Univ., 1986). Geochemical data indicate the coexistence of tholeiitic and alkaline trends (Fig. 9) that are attributed to within-plate volcanism (Laurent & Bélanger, 1984; Dostal, Wilson & Keppie, 1989; C. Desjardins, unpub. M.Sc. thesis, Univ. Laval, 1994).

In the Merrimack trough, volcanic rocks occur mostly in the Piscataquis Volcanic Belt of northern Maine (Osberg *et al*. 1989). The Piscataquis volcanics flank the western margin of the Munsungun–Winterville inlier (Fig. 1) and are laterally equivalent to volcanic rocks of the same age in the Gaspé Peninsula and New Brunswick. As in the Gaspé Peninsula, the Piscataquis volcanics occur at two stratigraphic levels, Pridolian-to-Lochkovian and Pragian-to-Emsian. Few chemical investigations have been made on these rocks; Sargent & Hon (1981) and Hon, Acheson & Schulman (1981) reported major element chemistry indicating calc-alkalic trends and trace element abundances (Sr, Rare Earth Elements) suggesting a derivation from partial melting of crustal sources. The geochemistry of correlative rocks in New Brunswick and the Gaspé Peninsula, which represent the southern segment of the Tobique Volcanic Belt, has been extensively studied (Laurent & Bélanger, 1984; Dostal, Wilson & Keppie, 1989); most models suggest that these rocks erupted in an intraplate environment (Fig. 9).

In summary, volcanic rocks with MORB, island-arc (IAT) or calc-alkaline affinity occur in the Connecticut Valley–Gaspé and Merrimack troughs (Fig. 8), but are restricted to the Early Silurian. In contrast, Late Silurian to Early Devonian volcanic rocks are transitional to alkaline with a distinctive within-plate geochemical affinity (Fig. 9). We suggest, therefore, that the Connecticut Valley–Gaspé and Merrimack troughs are characterized by two different volcanic cycles. The first cycle consists of Early Silurian calc-alkaline lavas, and the second is represented by Late Silurian to Early Devonian, transitional to alkaline rock types, the latter sequence being consistent with the predominance of intraplate extension during formation.

4. Origin of the Connecticut Valley–Gaspé and the Merrimack troughs

The Connecticut Valley–Gaspé and Merrimack troughs share so many lithological, sedimentological and palaeogeographic similarities that their formation can be reasonably attributed to the same geodynamic process. In the following section, we propose a model that may reconcile most of the various tectonic interpretations of the Silurian–Devonian evolution of Laurentia, Medial New England and Composite Avalon recently proposed for mainland Canada and New England (e.g. Bradley *et al*. 2000; Robinson *et al*. 1998; Tucker, Osberg & Berry, 2001; Moench & Aleinikoff, 2002).

In the area of Figure 1, there are three terranes of Proterozoic to Late Ordovician rocks, Laurentia, Medial New England and Composite Avalon, which are separated by two sutures. In mainland Canada and New England, it is assumed that the western part of Medial

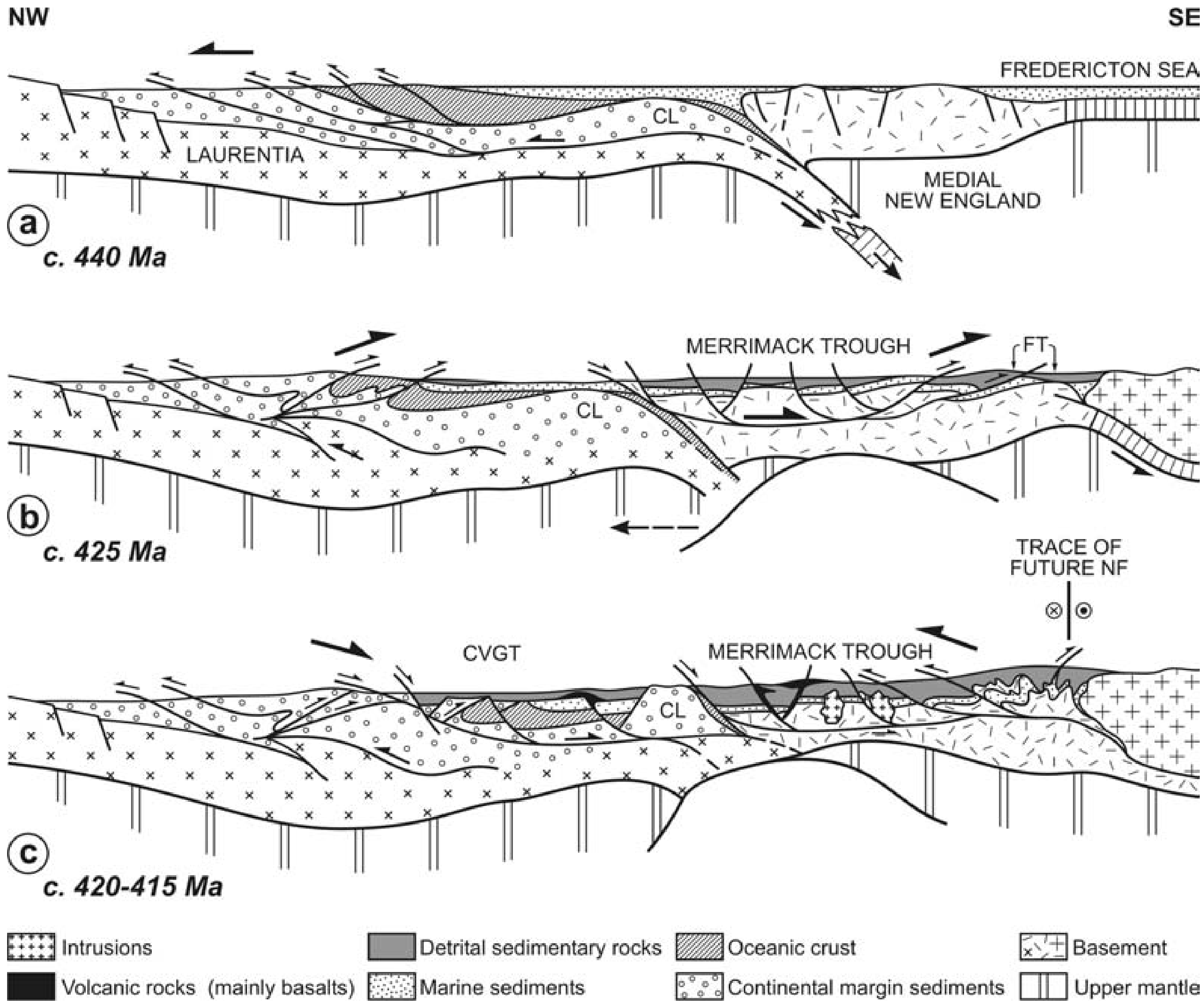

Figure 10. Schematic model for the tectonic evolution of the Appalachians of mainland Canada and New England in Silurian and Early Devonian times. (a) Inferred geometry of Laurentia and Medial New England at the end of the Taconian orogeny. (b) Uplift of asthenospheric material following delamination and formation of the Merrimack trough. (c) West-migrating crustal extension and formation of the Connecticut Valley–Gaspé trough. CVGT – Connecticut Valley–Gaspé trough; FT – Fredericton trough; CL – Chain Lakes Massif; NF – Norumbega fault.

New England had collided with Laurentia during the Taconian orogeny (e.g. Robinson *et al*. 1998; van Staal *et al*. 1998). Structural and metamorphic characteristics of the Laurentian margin, as well as the current disposition of ophiolites, mélanges, arc volcanics and flysch deposits, suggest that plate convergence was accommodated by a subduction zone dipping away from Laurentia (Osberg, 1978; Stanley & Ratcliffe, 1985; Pinet & Tremblay, 1995; Robinson *et al*. 1998; Moench & Aleinikoff, 2002). Following previous interpretations (Zen, 1983; Robinson *et al*. 1998; van Staal *et al*. 1998), we consider the Chain Lakes Massif (Fig. 1) to be a piece of Laurentia, although it is not clear if it has been always attached to Laurentia (e.g. Pinet & Tremblay, 1995), or rifted away in Early Cambrian times to form a microcontinental massif that collided with Laurentia during the Taconian orogeny (e.g. Waldron & van Staal, 2001).

There is no consensus regarding the location of the contact between Medial New England and Composite Avalon in mainland Canada and New England. However, most models agree about the inferred SE-dipping (present coordinates) subduction of Medial New England below Composite Avalon during Late Silurian and Early Devonian times (Robinson *et al*. 1998; Bradley *et al*. 2000; Tucker, Osberg & Berry, 2001). The Coastal Volcanic Belt of eastern Maine (Fig. 1) is interpreted to be the remnant of arc volcanism developed over Composite Avalon during the subduction of Medial New England.

4.a. Silurian delamination and upper crustal extension

We propose a model (Fig. 10) capable of explaining the Silurian uplift of the Laurentian and Medial

New England crust, the formation and evolution of Silurian–Devonian sedimentary basins, and the nature of volcanism in the Connecticut Valley–Gaspé and Merrimack troughs. The model requires a transition from shortening to extension of the crust at *c*. 440 Ma. Key features for the timing of this transition are as follows. (1) The upper age limit for Taconian deformation in the external Humber zone (Laurentian margin) can be fixed at *c*. 445–440 Ma (Hames *et al*. 1991; Ratcliffe, Hames & Stanley, 1998; Tremblay & Castonguay, 2002). (2) In the hinterland of the Laurentian margin (internal Humber Zone), Ordovician $^{40}Ar/^{39}Ar$ metamorphic ages (*c*. 470 to 460 Ma) coexist with younger $^{40}Ar/^{39}Ar$ ages of *c*. 430 to 415 Ma, which are associated with east (hinterland)-directed deformation and normal faulting that record the exhumation of the Taconian metamorphic wedge. Normal-fault fabrics (which are predominant along the eastern boundary of the internal Humber zone) cross-cut the backthrust structures and yield an average value of *c*. 420–415 Ma (see Castonguay *et al*. 2001). Isotopic age data from the Laurentian margin therefore suggest an average time lag of $\sim$ 20 Myr between the end of foreland-directed motion (*c*. 440 Ma) and the onset of extension (*c*. 420 Ma). (3) In the Merrimack trough, there is evidence for compressive E-directed deformation and metamorphism older than *c*. 420 Ma, suggesting that extension along the Laurentian margin was more or less coeval with, or slightly younger than, compression in the easternmost part of the Merrimack trough. (4) In the Connecticut Valley–Gaspé trough, isotopic age constraints for regional metamorphism and deformation are nowhere older than *c*. 395 Ma, suggesting that extension was the dominant process for $\sim$ 30 Myr in that part of the orogen.

Figure 10a shows the inferred geometry of Laurentia and Medial New England at the end of the Taconian orogeny (*c*. 440 Ma). After the docking of the Laurentian margin and Medial New England (Fig. 10a), detachment of the oceanic lithosphere from the continental lithosphere occurred when the thickened continental margin of the Laurentian plate entered the subduction zone. Following delamination, the 'hot' asthenosphere rose into the opening wedge (Fig. 10b), which induced isostatic rebound and localized uplifts of basement rocks as indicated by the emersion of post-Taconian highlands and the inferred horst-and-graben geometry of sedimentary basins during Silurian times. The associated collapse of crustal material resulted in extension and formation of the core of the Merrimack trough, and coeval E-directed thrusting at the Medial New England–Composite Avalon boundary (as documented in the Fredericton trough and eastern part of the Merrimack trough). We suggest that extensional collapse and thrusting were accommodated at depth by a major detachment fault corresponding to the 'basal décollement' of Eusden & Lyons (1993). The Merrimack trough is interpreted to be a sedimentary basin developed over the sutured Laurentia and Medial New England, whereas the Fredericton trough (and correlative terranes) represents a foredeep basin that underwent a period of folding and E-directed thrusting (Fig. 10b). Meanwhile, the Laurentian margin was subjected to E-directed deformation and associated metamorphism related to backthrusting folds and shear zones.

Lithospheric delamination at the boundary between Laurentia and Medial New England allowed hot asthenospheric mantle to well up, thereby adding heat to the lower crust. The result was that high grades of metamorphism at low pressure were attained in the Merrimack trough, and that during Late Silurian to Early Devonian times (425–415 Ma), sufficient heat had been transfered into the crust to cause partial melting and within-plate magmatism recorded by extensive and widespread volcanic rocks and granitic intrusions. At *c*. 415–410 Ma, stress associated with plate convergence between Medial New England and Composite Avalon became predominant, and ascending magmas were trapped in the crust as synorogenic granitic plutons (Fig. 10c). Following models suggested by Robinson *et al*. (1998), Tucker, Osberg & Berry (2001) and Moench & Aleinikoff (2002), we show that crustal extension and the formation of the Merrimack trough was coeval with subduction of oceanic crust (Fig. 10a, b; that is, the 'Fredericton Sea' of Moench & Aleinikoff, 2002) under Composite Avalon, accounting for the formation of the Coastal Volcanic Belt.

Stratigraphic data indicate that Silurian deposits are thicker and slightly older in the Merrimack trough than they are in the Connecticut Valley–Gaspé trough. An accumulation of at least 2–3 km of Silurian (pre-420 Ma) sediments has been documented in central Maine (e.g. Osberg *et al*. 1989), whereas Silurian sedimentation did not start before *c*. 426 Ma and *c*. 419 Ma in western New England and southern Québec, respectively. This suggests that crustal extension and basin formation over the Taconian hinterland likely progressed from east to west. The amount of crustal thinning following delamination is a complicated function that depends on, amongst other things, how the lithosphere was shortened before delamination, and how much material was delaminated and in which direction relative to the plate forces driving collision (e.g. Nelson, 1992). We suggest that delamination shifted west relative to the suture between Medial New England and Laurentia (compare Fig. 10b and c), and progressively moved to a position that enhanced (1) the uplift of peri-Laurentian terranes (such as the Chain Lake), (2) the exhumation of metamorphic rocks of the Laurentian margin by normal faults, and (3) the formation of the Connecticut Valley–Gaspé trough (Fig. 10c). Structures and $^{40}Ar/^{39}Ar$ age data from the Laurentian margin indicate that extension was accommodated by E-dipping normal faults (Tremblay & Castonguay, 2002), and that the exhumation of the

Laurentian margin possibly started as early as 425–420 Ma (Castonguay *et al*. 2001).

Data from central and eastern Maine indicate that by 415–410 Ma, collision between Medial New England and Composite Avalon was progressing westward (Fig. 10c), and was associated with NW-vergent folds and shear zones. This continued plate convergence and related compressional forces developed W-directed thrust sheets, recumbent folds and upright overtightened folds in New England (e.g. Tucker, Osberg & Berry, 2001) that progressively migrated northwestward toward the Acadian orogenic front in southern Québec and western New England (e.g. Bradley *et al*. 2000; Robinson *et al*. 1998), and overprinted (and reactivated) earlier structures related to crustal extension.

5. Discussion and conclusion

The origin of the Connecticut Valley–Gaspé and Merrimack sedimentary basins as proposed above for the Northern Appalachians is comparable, in terms of the inferred geodynamic setting, to Neogene synorogenic extensional basins of the Mediterranean Sea (e.g. Jolivet & Facenna, 2000) and the Eastern Carpathians (e.g. Gîrbacea & Frisch, 1998). The opening of the Mediterranean Sea occurred during the last 30 Myr (Dewey, 1988; Platt & Vissers, 1989; Guegen, Doglioni & Fernandez, 1998; Jolivet & Facenna, 2000). It originated on sites of earlier Late Cretaceous to Early Miocene crustal thickening and has been proposed as typical examples of extensional sedimentary troughs developed in an overall convergent setting. The basins form pericontinental troughs that extend for hundreds of kilometres, some of them (e.g. the Algerian and Provençal basins) being floored by oceanic crust. The Alboran Sea and Valencia basins, for instance, rest on extended and thinned continental crust which represent the remains of orogenic domains that crop out on land in the internal zones of the Betic and Rif orogens of southern Spain and Morocco (e.g. Platt & Vissers, 1989). These Mediterranean basins are broken up by horst and graben structures that form basement highs separating different depocentres. Basement highs are parallel to magnetic anomalies indicating the presence of mafic volcanic and intrusive rocks. In the Valencia trough, Marti *et al*. (1992) have shown that these volcanic rocks form two well-differentiated sequences, an Early to Middle Miocene volcanic cycle (24–18 Ma) represented by calc-alkaline andesitic and silicic pyroclastic rocks, and a Late Miocene–Recent (<10 Ma) cycle of poorly differentiated alkaline basaltic rocks. These chemical variations are mirrored by the geodynamic evolution of the region where two stages can be identified: a first stage (contemporaneous with calc-alkaline volcanism) in which the basin developed during a waning episode of arc volcanism, and a second stage (contemporaneous with alkaline volcanism) dominated by extensional tectonics. Extensional detachments and normal faults identified in basement rocks in the Betic orogen and within the Mediterranean basins have been interpreted as genetically related to crustal extension (Garcia-Duenas, Balanya & Martinez-Martinez, 1992; Vegas, 1992; Marti *et al*. 1992; Morley, 1993; Azanon, Crespo-Blanc & Garcia-Duenas, 1997; Guegen, Doglioni & Fernandez, 1998).

Geodynamic hypotheses for basin formation in the Mediterranean region include mantle diapirism combined with gravity tectonics, tectonic expulsion of microplates (Taponnier, 1977; Vegas, 1992), diachronous subduction rollback, backarc extension and extensional collapse (Dewey, 1988; Morley, 1993; Guegen, Doglioni & Fernandez, 1998; Jolivet & Facenna, 2000), and complete or partial removal of subcrustal lithosphere by delamination (Platt & Vissers, 1989; Docherty & Banda, 1995; Seber *et al*. 1996). Considering that the inception of extension over the entire Mediterranean region was broadly contemporaneous, Jolivet & Facenna (2000) argued that the principal cause should be a change in the geodynamics at the same scale, that is, a reduction in the compressional stresses between the African and Eurasian plates and an increase in the velocity of slab retreat and/or delamination. Both mechanisms would cause the thermally induced uplift of basement rocks and provide the necessary boundary conditions for extensional collapse of pre-existing orogenic domains and the formation of major sedimentary basins.

In summary, we conclude that extensional basins of the Mediterranean Sea share several basic similarities with Silurian–Early Devonian basins of the Northern Appalachians. (1) They form elongated troughs hundreds of kilometres in length at the periphery of continents that have undergone orogenic shortening. (2) They show an internal geometry characterized by basement uplifts buried during sedimentation. (3) Extension-related structures are preserved as synsedimentary faults or as detachments and normal faults in basement rocks within the adjacent continents. (4) Volcanism occurs at various stratigraphic levels and is characterized by coexisting calc-alkaline and alkaline trends. (5) Anomalous heat flow is inferred. (6) Basin development occurred in a timeframe of 10 to 20 Myr following crustal shortening. We suggest, therefore, that these basins were the result of a similar geodynamic setting that involved crustal extension triggered by delamination and/or subduction retreat and synorogenic collapse. Considering the continuing plate convergence between Africa and Eurasia, we predict that, in the future, Africa will collide with Europe, closing the Mediterranean Sea and forming a continental collision mountain belt similar to that of the Acadian orogeny in the Northern Appalachians.

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