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TECTONIC EVOLUTION OF THE QUEBEC-MAINE APPALACHIANS: FROM OCEANIC SPREADING TO OBDUCTION AND COLLISION IN THE NORTHERN APPALACHIANS

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ABSTRACT. This paper is a review of lithostratigraphic and structural data from southern Québec and western Maine. The principal new assumption is that a significant part of Taconian deformations was related to the obduction of a large ophiolitic nappe now outcropping on both sides of the Connecticut Valley-Gaspé trough. This hypothesis is consistent with: (1) the correlation of the sedimentary covers of the southern Québec and western Maine ophiolites, (2) the fact that the Baie Verte-Brompton Line does not represent the root zone of ophiolitic rocks, and (3) the structural analysis, indicating that earliest deformations occurred only in the continental margin rocks. The important along-strike variations in ophiolite genesis and emplacement along the orogen are attributed to the initial geometry of the continental margin.

INTRODUCTION

In the northern Appalachians, two major deformational events of Paleozoic age are recognized: the Taconian (Middle to Late Ordovician) and the Acadian (Late Silurian to Middle Devonian) orogenies. The Taconian orogeny was interpreted as the result of a collision between the Laurentian continental margin and an island arc terrane formed over an east-facing subduction zone (Osberg, 1978; Stanley and Ratcliffe, 1985). The Acadian orogeny is considered to be the consequence of the accretion of terrane(s) from the east by either a renewed tectonic convergence (Osberg and others, 1989) or by polarity flip of a Taconian subduction zone (van Staal and others, 1990). However, two major problems in the tectonic investigation of mountain belts are to distinguish clearly the effects of superimposed deformations and to correlate them to sedimentary, metamorphic, and magmatic events. In southern Québec, continental and oceanic rock units of Cambro-Ordovician age can be used to investigate the earliest stages (Taconian) of the Appalachian orogen, whereas the final stages (Acadian) can be studied by the comparison of pre- and post-Taconian rocks at the scale of the orogen.

In this paper, we will review the lithostratigraphic and structural data from southern Québec and western Maine and propose a tectonic model involving the opening of oceanic basins and the obduction of a large ophiolitic nappe, followed by a continent-continent collision. We also discuss some controversial aspects of Appalachian tectonics, such as the distribution of Taconian and Acadian deformation and their geodynamic interpretation (Hatcher, 1989; Drake and others, 1989; Osberg and others, 1989), the extent of Appalachian "suspect terranes" (Williams and Hatcher, 1983; Zen, 1983), and the origin and correlation of various ophiolitic remnants (Boone and Boudette, 1989).

THE SOUTHERN QUEBEC AND WESTERN MAINE TRANSECT

In the Québec Appalachians, St-Julien and Hubert (1975) divided the Taconian orogen into an autochthonous domain to the northwest and external and internal domains to the southeast. They suggested that the deformation of continental margin deposits was Taconian-related and that the oceanic rocks recorded both Taconian and Acadian features. Williams and St-Julien (1982) identified the Baie Verte-Brompton Line (fig. 1, BBL) as a major fault boundary within the Cambro-Ordovician sequences of the Canadian Appalachians. The BBL was interpreted as a tectonic suture between continental rocks of the Laurentian margin to the northwest (Humber zone of Williams, 1979) and the ophiolites, arc volcanics, mélanges, and syn-orogenic deposits making up the Dunnage zone to the southeast. The interpretation of the BBL as a suture zone was mainly based on the present location of ophiolitic rocks along a narrow zone parallel to the line (figs 1 and 2). However, field data (Tremblay and Pinet, 1994) and seismic reflection studies (Spencer and others, 1989) suggest that the BBL is a shallow crustal feature and does not represent the root zone of the Iapetan oceanic crust.

East of the Dunnage zone, pre-Silurian rocks of the Chain Lakes massif have been interpreted either as high-grade, exotic basement rocks of Precambrian age (Boone and Boudette, 1989) or as coarse-grained sedimentary rocks belonging to the Laurentian margin (Trzcienski, Rodgers, and Guidotti, 1992). In western Maine, Cambro-Ordovician ophiolitic rocks of the Boil Mountain Complex (Boudette, 1982) overly in fault contact the Chain Lakes massif.

Stratigraphic and structural relationships within and between tectonostratigraphic units along the Québec-Maine transect are shown in the cross section of figure 3.

The southern Québec-western Maine transect exhibits some important features that can be used to unravel the tectonic evolution of the Appalachian orogen: (1) the continental margin deposits preserve a consistent paleogeographic succession, and the internal domain includes distal facies of the Laurentian margin; (2) the rocks of the oceanic assemblage (including ophiolites, their sedimentary covers, and subduction-related volcanics) are well preserved; (3) the presence of post-Taconian sedimentary rocks allows discrimination between Taconian and Acadian deformational features; and (4) a deep seismic profile from southern Québec to western Maine is available and can be used to constrain the geometry of basement rocks (St-Julien, Slivitzky, and Feininger, 1983; Spencer and others, 1989).

Basement Rocks

The western boundary of the Québec-Maine transect is the Grenville tectonic province over which rock units of the Humber zone were

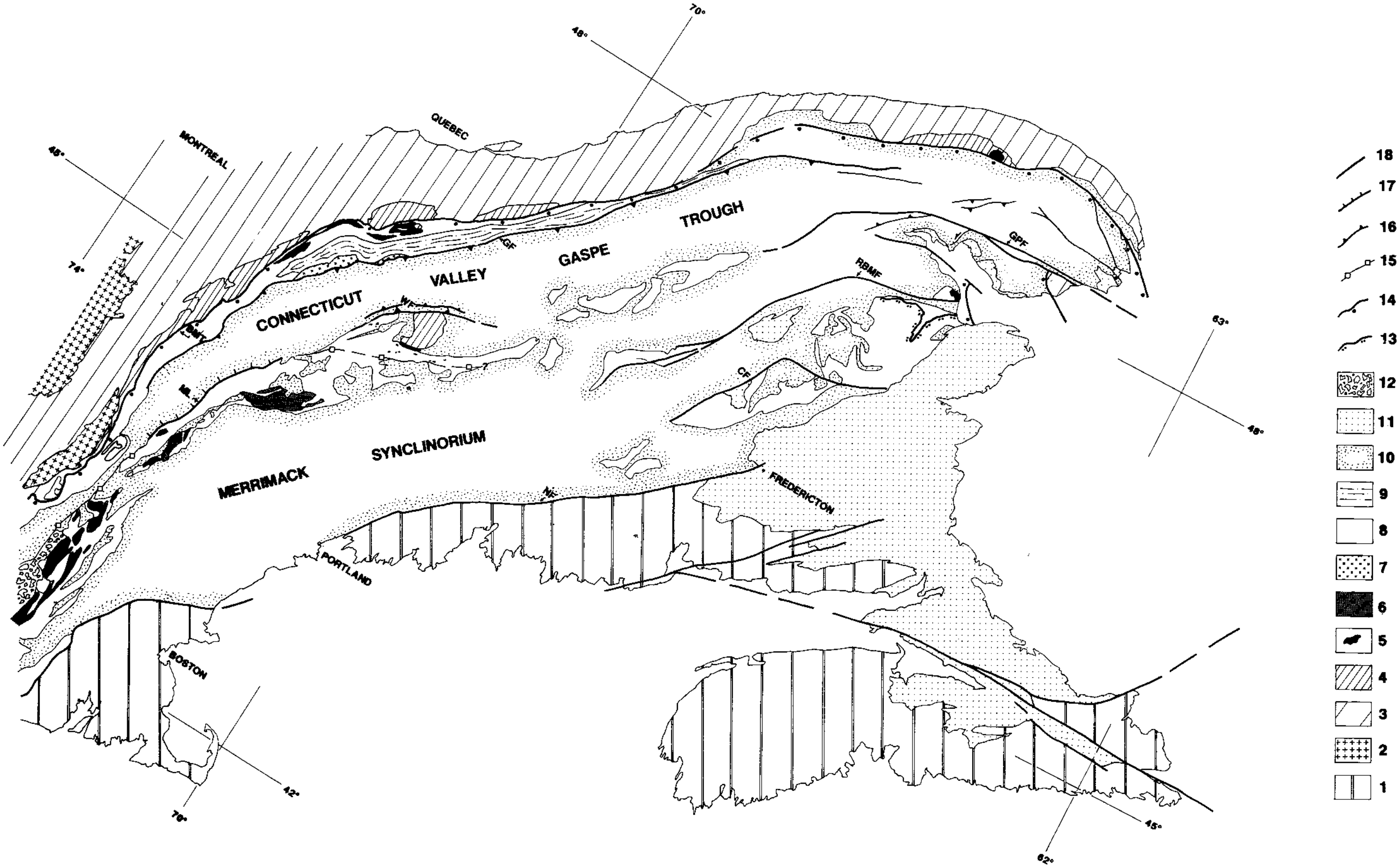

Fig. 1. Tectonic map of the Northern Appalachians showing the location of major lithotectonic units. Modified from Williams (1978). (1) Undiffenciated Avalon and Meguma zones, (2) Grenvillian basement rocks, (3) Humber zone rocks of the Taconian external zone, (4) Humber zone rocks of the Taconian internal zone (including the Chain Lakes massif), (5) ophiolites, (6) Bronson Hill arc rocks, (7) Ascot Complex, (8) mostly Cambro-Ordovician oceanic rocks (undifferenciated), (9) Magog group, (10) Silurian and Devonian rocks, (11) Carboniferous cover rocks, (12) Mesozoic rocks, (13) blueschist belt, (14) Baie verte-Brompton line, (15) inferred trace of autochtonous Laurentian margin, (16) thrust faults, (17) normal faults, (18) strike-slip faults. BMT: Boundary Mountain Thrust; CF: Catamaran Fault; GF: La Guadeloupe Fault; GPF: Grand Pabos Fault; ML: Monroe Line; NF: Norumbega-Fredericton Fault; RBMF: Rocky Brook-Millstream Fault, WF: Woburn Fault.

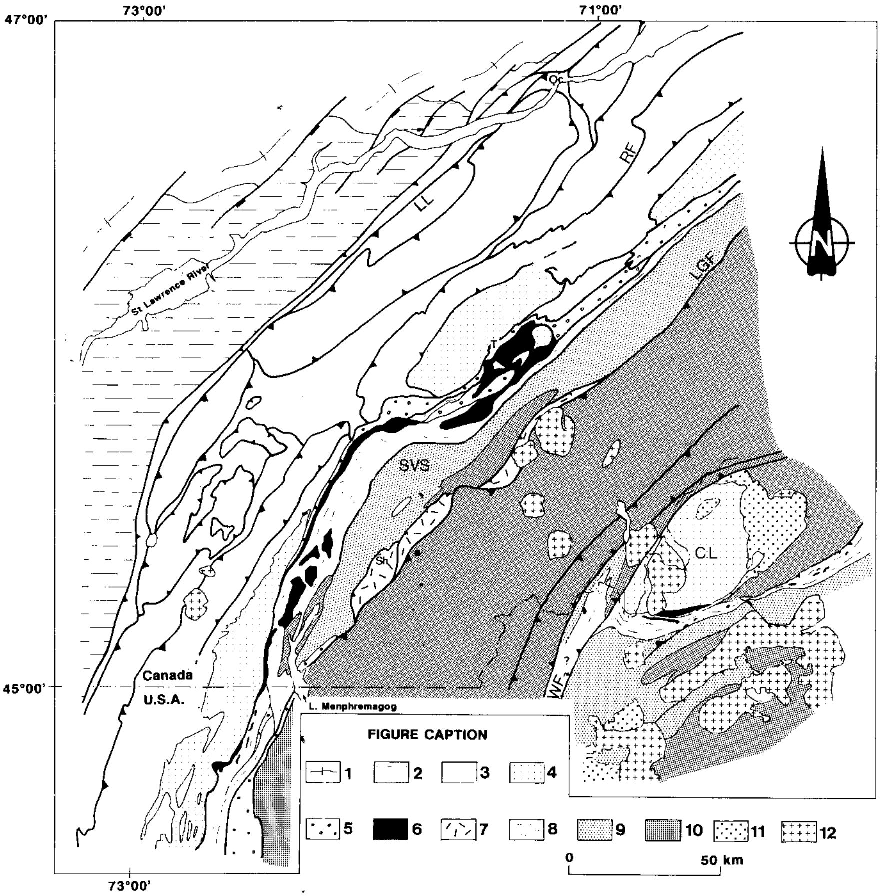

Fig. 2. Geological map of southern Québec, western Maine, and northern Vermont. Modified from St-Julien and Slivitsky (1985), Globensky (1987), Stanley and Ratcliffe (1985), and Boone, Boudette, and Moench (1970). (1) Grenvillian rocks, (2) Cambro-Ordovician rocks of the autochthonous domain, (3) fault-imbricated continental rocks of the external-internal Taconian zones, (4) Sutton-Bennett schists and metasedimentary rocks of the Chain Lakes massif, (5) Caldwell Group, Bunker Hill Sequence, and Moretown Formation, (6) Ophiolites of the Québec-Maine transect, (7) Ascot Complex, (8) St-Daniel and Hurricane Mountain mélanges, (9) Magog Group and Dead River Formation units and correlatives, (10) Silurian-Devonian rocks, (11) pre-Acadian intrusives (Attean pluton and correlatives), (12) syn- to post-Acadian intrusives. CL: Chain Lakes massif; LGF: La Guadeloupe Fault; LL: Logan's Line; RF: Richardson Fault; SVS: St-Victor Synclinorium; WF: Woburn Fault. Qc: Québec city; Sh: Sherbrooke; T: Thetford-Mines.

unconformably deposited. A nearly continuous basement reflector can be traced on seismic profile (fig. 3) from Grenville exposures to the northwest down to a point located beneath the Chain Lakes massif to the southeast (see Spencer and others, 1989). In Québec, a slice of Grenvillian rocks is exposed along the Richardson fault (Vallières, Hubert, and

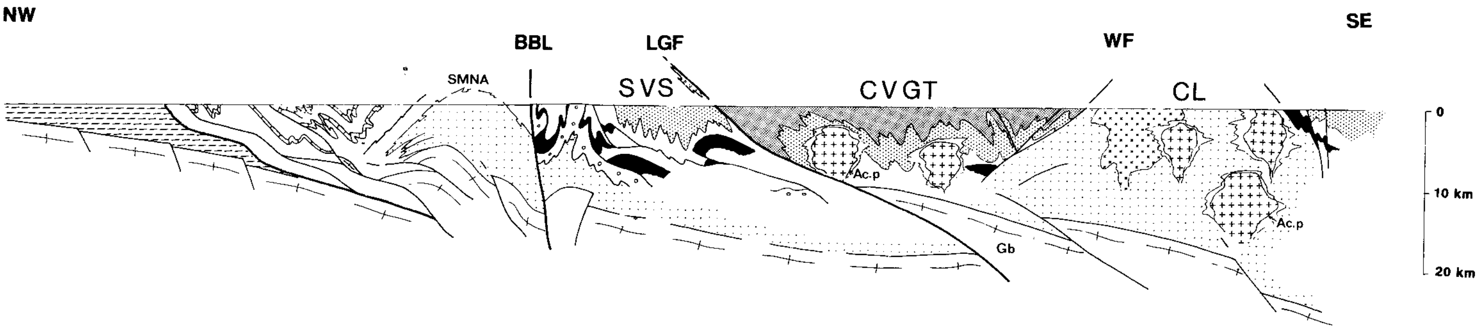

Fig. 3. Structural profile of the Québec-Maine transect. Note that some along-strike features have been grouped for clarity. Basement rocks geometry was extrapolated from seismic data of Spencer and others (1989). Same symbols as figure 2. BBL, Baie Verte-Brompton Line; CL, Chain Lakes; CVGT, Connecticut valley-Gaspé trough; LGF, La Guadeloupe Fault; SMNA, Sutton-Monts Notre Dame Anticlinorium; SVS, Saint Victor Synclinorium; WF, Woburn Fault.

Brooks, 1978), which marks the external-internal zones boundary of the Taconian orogen (St-Julien and Hubert, 1975).

Continental Margin Rocks of The Humber Zone

In southern Québec, autochthonous platformal and allochthonous slope and rise deposits of Cambro-Ordovician age occur between the Grenville basement to the northwest and the BBL to the southeast (figs. 2 and 3). West of Logan's Line (fig. 2), the continental rocks of the platformal domain are weakly deformed and weakly metamorphosed, whereas they are strongly folded and fault-imbricated in the external domain and are metamorphosed to upper greenschist grade in the internal domain (St-Julian and Hubert, 1975). Despite deformation and metamorphism, careful studies by a large number of workers allow utilization of the stratigraphic record to reconstruct the geodynamic evolution of the continental margin. The following points have been selected as key features (see figs 2 and 4):

1, The Postdam and Beekmantown groups (autochthonous domain) represent a passive margin sequence of Early Cambrian to lower Middle Ordovician age (Globensky, 1987; Lavoie, 1994). Distal rocks of equivalent age are found both in the external (Sillery Group and correlatives) and internal (Oak Hill Group) domains.

2, The Tibbit Hill Formation (Oak Hill Group) is a transitional to alkaline mafic volcanic sequence extruded during the rifting of Laurentia at about 554 Ma (Coish and others, 1985; Pintson, Kumarapelli, and Morency, 1985; Kumarapelli and others, 1989).

3, The Early Cambrian Cheshire Formation mainly composed of quartzite is interpreted as a rift-drift transition, whereas overlying rocks (Dunham and Sweestburg formations) record the progressive building of a continental shelf and slope system along a subsiding passive margin (Colpron, 1990).

4, The Sutton-Bennett schists (fig. 2) are believed to be metamorphosed and distal equivalents of the Oak Hill Group (St-Julien and Hubert, 1975). This is consistent with: (A) the absence of proximal facies (limestones, dolomites, coarse clastic rocks) within the metamorphic suite, and (B) the geochemistry of mafic schists of the Sutton Suite interpreted as continental tholeiites erupted trough a thinned continental crust (Colpron, 1990).

5, A well-developed unconformity of Middle Ordovician age at the top of the Beekmantown Group (fig. 4) was attributed to a migrating peripheral bulge associated with a Taconian plate convergence (Jacobi, 1981; Knight, James, and Lane, 1991; Lavoie, 1994).

6, In the autochthonous domain, rock units of upper Middle Ordovician to lower Late Ordovician age (Chazy, Black River, and Trenton groups) record the deepening of a foreland basin in a convergent margin setting (Globensky, 1987; Lavoie, 1994).

7, In the external zone of the Taconian orogen, the closure of the foreland basin is marked by the imbrication of nappes and associated

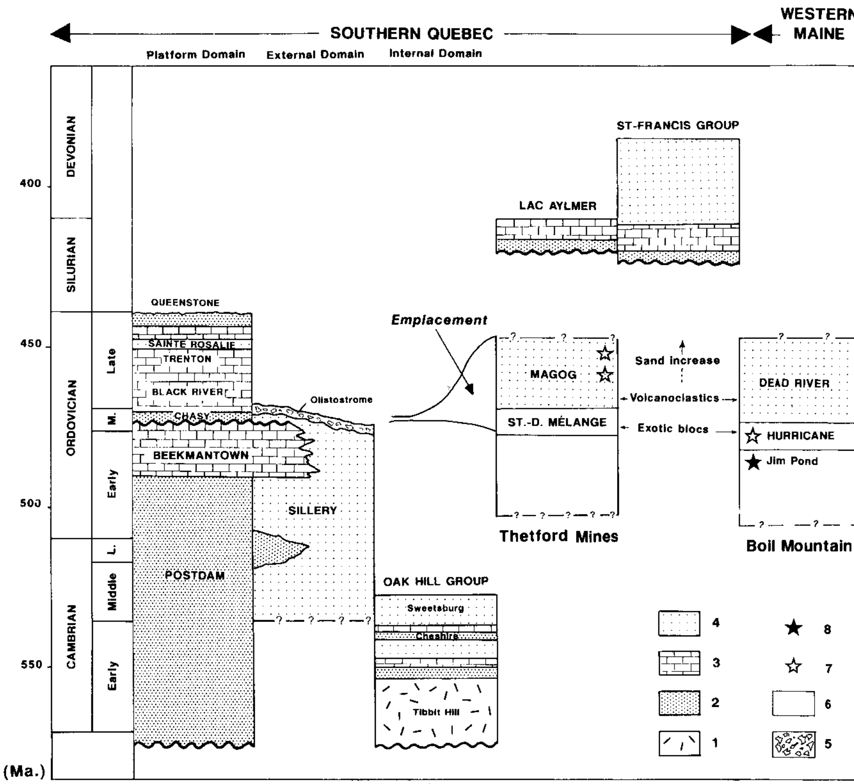

Fig. 4. Stratigraphic table for the southern Québec Appalachians: (1) volcanic rocks, (2) mostly clastic rocks, (3) mostly carbonates, (4) turbidites, (5) olistostromal deposits, (6) ophiolitic rocks, (7) paleontological data from sedimentary rocks overlying the Thetford-Mines and Boil Mountain complexes, (8) geochronological data from the Jim Pond Formation.

olistostromal deposits that vary from east to west between lower to upper Middle Ordovician age (St-Julien and Hubert, 1975). In the autochthonous domain, the emplacement of these nappes is recorded by argillites of the Middle to Late Ordovician Ste-Rosalie Formation (Globensky, 1987), whereas the overlying Queenston Group was interpreted as Taconian molasse deposits (Globensky, 1987).

The sedimentological significance of the Caldwell Group (fig. 2), the easternmost Cambrian (?) unit of the continental sequence (St-Julien and Hubert, 1975; Cousineau, 1990), remains problematical. Meter-thick beds of coarse-grained, quartz-rich sandstones are the most common lithology of the Caldwell Group, suggesting a proximal source, while the lack of limestone beds or clasts indicates that the Caldwell group was deposited either before the platform development or far from it. Finally,

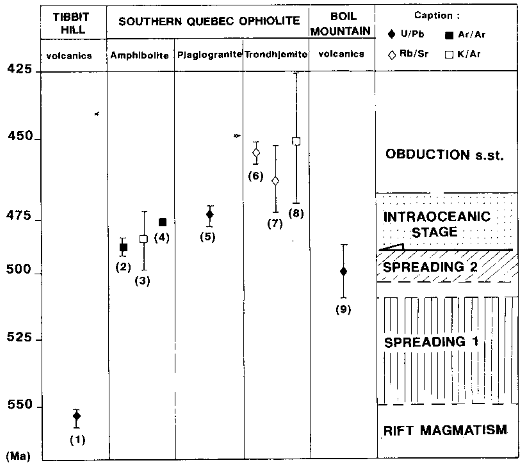

Fig. 5. Available geochronological data for the Québec-Maine transect and their geodynamic interpretation (see text). Data from (1) Kumarapelli and others (1989); (2) and (3) Clague, Rubin, and Brackett (1981); (4) Lux (1984); (5) Dunning, Krogh, and Petersen (1986); (6) Clague, Frankel, and Eaby (1985); (7) Poole (1980); (8) Laurent, Taner, and Bertrand (1985); (9) Aleinikoff and Moench (1985).

the interbedded mafic volcanics were shown to be rift-related (Gariepy, 1978). Accordingly, we here suggest that the Caldwell Group is a syn-rift sequence deposited in proximity to a distal topographic high belonging to the Laurentian margin.

Oceanic Rocks of The Dunnage Zone

Southern Québec ophiolites.—The southern Québec ophiolites (fig. 2) consist of three main bodies (Thetford-Mines, Asbestos, and Mount Orford) located along the BBL. They are overlain by the Saint-Daniel mélange and the Magog group. The origin and evolution of these ophiolites are constrained by the age of crystallization, the age of obduction, and the geochemical signature of associated volcanic rocks.

The ophiolitic volcanic rocks from the Thetford-Mines and Asbestos complexes include island-arc tholeiites and boninites suggesting a supra-subduction zone setting (Laurent and Hébert, 1989). Such an environment is consistent with the inferred setting for most Appalachian ophiolites (Cawood and Suhr, 1992) as well as world-wide orogenic belts (Harris, 1992).

A single U-Pb zircon age on a plagiogranite from the Thetford-Mines ophiolitic Complex (478 Ma, Dunning, Krogh, and Petersen, 1986) suggests that it was formed in Early Ordovician times. However, this is younger than ^{40}Ar-^{39}Ar ages from tectonic amphibolites found at the base of the ophiolite and interpreted as remnants of intraoceanic, obduction-related metamorphism (Clague, Rubin, and Brackett, 1981, 491 Ma;

Lux, 1984, 482 Ma). Such an inconsistency could be explained in two ways: either the age of amphibolites is incorrect (Lux, 1986), or the analyzed plagiogranite records off-axis magmatism that post-dated the main phase of ophiolite crystallization. A clear example of the latter case is found in the Oman ophiolite (Ernewein, Pflumio, and Whitechurch, 1988; Boudier, Ceuleneer, and Nicolas, 1988).

In the Thetford-Mines Complex, the lower tectonic peridotite is cross cut by felsic dikes and pods that intruded the oceanic crust during obduction, at approx 450 to 456 Ma (Laurent, Taner, and Bertrand, 1984; Clague, Frankel, and Eaby, 1985). This is both coeval and younger than the peak of metamorphism recorded in the overthrusted continental margin rocks (around 471-439 Ma, Laird, Lanphere, and Albee, 1984).

The Québec ophiolites appear to record a three-fold evolutionary sequence as suggested by Laurent, Taner, and Bertrand (1984): (1) formation of the oceanic crust by the opening of a marginal basin in Early Ordovician times; (2) intra-oceanic upthrusting of this crust soon afterward leading to the formation of the underlying amphibolitic sole; and (3) obduction of the oceanic crust over the continental margin. Available geochronological data and error ranges suggest that the time bracket between stages 2 and 3 varied between 26 and 41 Ma (fig. 4, see below).

Mélange and flysch units.—The St-Daniel mélange is an orogen-scale unit which, according to Williams and St-Julien (1982), stratigraphically overlies the ophiolites, although their mutual contact is commonly faulted. In fact, most contacts between ophiolitic sequences of southern Québec and surrounding rocks are faulted, and the St-Daniel mélange is found both below and above the ophiolitic rocks. The St-Daniel is an unfossiliferous unit characterized by a wide variety of blocks and slices of both oceanic and continental affinities in a black shale matrix. It has been interpreted as the remnant of an oceanic accretionary complex formed along an east-dipping subduction zone in Taconian times (Cousineau and St-Julien, 1992; Tremblay, 1992a). Although we agree in a strong tectonic control on the genesis of the St-Daniel mélange, we are not convinced that it originated from the disruption of trench-fill deposits rather than pelagic and hemipelagic ocean-floor sediments (see below).

The St-Daniel mélange is disconformably overlain by upper Middle Ordovician to Late Ordovician deposits of the Magog group (Cousineau, 1990; figs. 3 and 4). The Magog group is a 10 km-thick flysch sequence that crops out in the St-Victor synclinorium (fig. 2 and 3). Volcanoclastic rocks are common toward the base, but most of the Magog Group (>70 percent) consists of quartz- and lithoclast-rich turbidites recording the erosion of existing Taconian nappes (Cousineau, 1990). The occurrence of detrital chromite grains throughout the Magog Group implies that ultramafic rocks were being eroded and suggests that ophiolitic slices may already have been accreted to the continental margin at this time. Therefore, the Magog Group can be considered, at least in part, as syn-Taconian deposits.

Arc volcanics and plutonics.—In southern Québec, tectonic slivers of subduction-related volcanic rocks belonging to the Ascot Complex are found along the La Guadeloupe fault (fig. 2, Tremblay, 1992b). Mafic volcanics range from typical island-arc tholeiites to boninites (Tremblay, 1992a and b) and show compositional similarities with neighboring ophiolitic rocks. The geochemical characteristics (Tremblay, Hébert, and Bergeron, 1989) and abundant inherited zircons (David, Marquis, and Tremblay, 1993) found in the felsic volcanic rocks suggest a continental margin setting.

The scarcity of geochronological data from the Ascot Complex (only a preliminary U-Pb zircon age of 455-460 Ma, David, Marquis, and Tremblay, 1993) makes uncertain any direct comparison with the volcanics outcropping in the Bronson Hill anticlinorium of New England. The latter forms dome structures consisting of a core of gneisses of intrusive origin (Oliverian plutonic series; U-Pb ages on zircon varying between 454-442Ma; Tucker and Robinson, 1990) with an overlying cover sequence of volcanic rocks (Ammonoosuc volcanics; U-Pb age of 453 ± 2 Ma) and sulfidic black schists with subordinate volcanic rocks (Partridge Formation; U-Pb age of 449 +3/−2 Ma). These plutonic and volcanic rocks were interpreted as the products of a major Taconian-related volcanic arc (fig. 1; Zartman and Naylor, 1984; Stanley and Ratcliffe, 1985; Schumacher, 1988; Tucker and Robinson, 1990). The Bronson Hill and the Ascot Complex differ in the following ways: (1) the volume of arc-related rocks is much smaller in the Ascot Complex; (2) the Bronson Hill arc was built upon a continental basement (Zartman and Naylor, 1984; Tucker and Robinson, 1990), whereas it varied from oceanic to continental in the Ascot Complex. Although available U-Pb zircon ages are closely similar, the relationship between the Ascot Complex and the Bronson Hill is still debatable and could be interpreted either as two different magmatic arcs or as dismembered and accreted fragments of a single arc system (see discussion in Tucker and Robinson, 1990).

The Connecticut Valley-Gaspé Trough

The Connecticut Valley-Gaspé trough is in tectonic contact with older rock units of the Dunnage zone along the La Guadeloupe fault (figs. 2 and 3). It is made up of Silurian and Devonian sedimentary rocks belonging to the St-Francis Group and to the adjacent volcano-sedimentary Frontenac Formation to the southeast. In southern Québec, the age of rocks in the Connecticut Valley-Gaspé trough is constrained by the occurrence of Late Silurian (Pridolian) brachiopods at the base of the sequence (Lavoie and Bourque, 1993), as well as late Early Devonian fossil plants in its upper part (Hueber and others, 1990). In southern Québec there is no evidence for uncomformable relationships between Devonian and Silurian rocks (Salinic disturbance) as was shown to exist in the Gaspé Peninsula (Bourque, Brisebois, and Malo, 1991).

The Connecticut Valley-Gaspé trough was crosscut by intrusive granitic rocks that form the westernmost members of an extensive suite of Acadian plutons found in New England and the Maritime Provinces. These intrusive rocks have been dated between 362 and 384 Ma (Lowdon, 1960; Heizler, Lux, and Decker, 1988; Simonetti and Doig, 1990) and probably formed by partial melting of a thickened continental crust during the Acadian orogeny (Simonetti and Doig, 1990).

The Chain Lakes Massif and Overlying Ophiolitic Rocks

In eastern Québec and western Maine, the Chain Lakes massif consists mainly of coarse-grained, metamorphosed sedimentary rocks. Historically, it has been interpreted as belonging to the Cambro-Ordovician sequence of western Maine (Albee, 1961; Marleau, 1968). However, the Chain Lakes massif has since been re-interpreted as an "exotic terrane" of high-grade metamorphic rocks (Boone and Boudette, 1989 and references therein). Recently, Trzcienski, Rodgers, and Guidotti (1992) proposed an alternative hypothesis in which the Chain Lakes massif would represent an inlier of sedimentary rocks belonging to the Laurentian continental margin. These various hypothesis conflict on the following points: (1) U-Pb zircon ages of 1500 Ma or more reported by Naylor and others (1973); crystallization ages or inherited ages?; and (2) sillimanite-bearing metamorphic rocks (with rare occurrences of andalusite and garnet); regional or contact metamorphism? We believe that a choice between these hypothesis can be made by comparing the pre-Silurian oceanic sequences of western Maine and southern Québec.

In western Maine, the Chain Lakes massif is structurally overlain by an Early Paleozoic ophiolitic sequence (Boil Mountain Complex, Boudette, 1982) and associated Cambro-Ordovician cover rocks. A U-Pb zircon age of 500 ± 10 Ma from ophiolitic volcanics of the Boil Mountain Complex (Jim Pond Formation) indicates that it formed in Early Ordovician times (Aleinikoff and Moench, 1985). Geochemical data suggest that the ophiolite was formed in a subduction zone setting (Coish and Rogers, 1987). Overlying cover rocks consist of the Hurricane and the Dead River formations. The former is a mélange unit consisting mainly of a black shale/siltstone matrix with blocks of both endogeneous (feldspathic sandstones and wackes) and exotic lithologies (ophiolitic rocks). Based on the local occurrence of primitive sponges, a Cambrian to Early Ordovician age has been proposed for the Hurricane Formation (R. M. Fink, oral communication cited by Boone and Boudette, 1989). However, similar rocks cropping out in the Munsungun area (Chase Brook Formation) appear to be no older than upper Tremadocian (Neuman, 1967). The Dead River Formation disconformably overlies the Hurricane mélange. It is a volcanogenic flysch sequence that grades upward into a poorly-sorted meta-sandstone sequence.

The lithologies that overly the southern Québec ophiolites are very similar to rock units described above (fig. 4). The Hurricane and the St-Daniel mélanges are both dominated by black shales that contain blocks of diverse origin. Limited fossil evidence suggests that both units may be of Early Ordovician age (see fig. 4). The Dead River Formation and the Magog Group are also quite similar in terms of lithologies (mainly noncarbonaceous shales and sandstones), facies associations, and age controls (fig. 4). We believe that these units are correlative.

The correlation of oceanic units occurring on both sides of the Connecticut Valley-Gaspé trough implies that the Chain Lakes massif most likely represents an inlier of sediments belonging to the Laurentian margin, as was suggested by Trzcienski, Rodgers, and Guidotti (1992). Therefore, the root zone for the Québec-Maine ophiolites would be located to the east of the Chain Lakes massif as proposed by Zen (1983) who drew the "Taconian margin" of the Laurentian craton as extending from the Boil Mountain ophiolite to the south, up to the Caucomgomoc (western Maine) Complex and to the Elmtree Inlier (northern New Brunswick) to the north. The age range between the ophiolites of southern Québec and western Maine is in the order of 20 Ma or less depending on the significance of the 478 Ma age from the Thetford-Mines Complex (see above). Taking into account a present-day distance of 100 km between the southern Québec and western Maine ophiolites and a tectonic shortening in the order of 80 percent, 20 Ma corresponds to an oceanic spreading rate of 2.5 cm/yr, which is consistent with modern spreading of oceanic basin.

In the framework of this interpretation, well-defined seismic reflectors located under the St-Victor synclinorium and the Connecticut Valley-Gaspé (see St-Julien, Slivitzly, and Feininger, 1983) are interpreted as dismembered ophiolites structurally overlying the Grenvillian basement (fig. 3). The high-grade metamorphism characterizing the Chain Lakes massif could be attributed, at least partly, to the emplacement of a large ophiolitic nappe (see below). Blocks of Chain Lakes-like rocks found in mélanges of the Québec Appalachians (Cousineau, 1990; de Broucker, 1986; Boone and Boudette, 1989) would therefore be interpreted as tectonic slices of continental rocks that were caught up during obduction.

STRUCTURAL SYNTHESIS

In the Northern Appalachians, the generation and distribution of Taconian and Acadian deformations are still being debated (see Drake and others, 1989; Osberg and others, 1989 for reviews). On the basis of a regional structural characterization of pre- to post-Taconian rocks (Tremblay and Pinet, 1994), we wish to propose a relative chronology for the tectonic events in southern Québec and western Maine.

Acadian Deformation

The Acadian orogeny took place after the deposition of the Silurian-Devonian rocks of the Connecticut Valley-Gaspé trough. In southern Québec, the trough rocks record the effect of only one regional deformational event. Polyphased structures are, however, found locally along both the eastern and western boundaries of the trough and also in the vicinity of the Québec-Vermont border. The structure of trough rocks in southern Québec contrasts sharply with that of correlative units in New England, where at least three generations of Acadian folding have been described (Osberg and others, 1989). On the basis of similar strike and geometry and crosscutting relationships with superposed structures (Tremblay and Pinet, 1994), regional folds of the Connecticut Valley-Gaspé trough in southern Québec are believed to be correlative with the oldest generation of folds recognized in New England. The amount of tectonic shortening is believed to be approximately in the same range or greater than the one recently proposed for the trough rocks in the Gaspé peninsula (80 percent, Kirkwood, 1993). This type of structural style, characterized by tight upright folding, implies the existence of a décollement surface at depth. The weak pre-Silurian mélange units (inferred to underly the trough, see fig. 3) are the most probable level where simple shear-dominated deformation would have been concentrated.

The Connecticut Valley-Gaspé trough is fault-bounded. To the west, the La Guadeloupe fault (fig. 2) is a high-angle reverse fault characterized by the development of prominent down-dip stretching lineations in adjacent units (Tremblay and St Julien, 1990). On the seismic profile, it appears as a major tectonic boundary offsetting the Grenvillian basement for several kilometers (fig. 3; Spencer and others, 1989). However, the apparent tectonic inversion along the La Guadeloupe fault (youngest-over-older rocks) implies an earlier stage of pre-Acadian normal or strike-slip motions.

To the southeast, the Connecticut Valley-Gaspé trough is in faulted contact with the Chain Lakes massif along the Woburn fault, which appears as a steep northwest-dipping structure on the seismic profile (fig. 3; Spencer and others, 1989). The Woburn fault is correlative to the Thrasher Peak fault. Along the New Hampshire-Maine border, the Thrasher Peak fault is characterized by a dextral sense of shear (W. E. Trzcienski Jr, personal communication, 1993). In Québec, the overall southeastward vergence of associated folds (Lebel and Tremblay, 1993) suggests, however, that the Woburn fault bears a significant backthrust component.

In the Québec Appalachians, Acadian deformation has been recognized to the west of the Connecticut Valley-Gaspé trough as far as the Sutton-Notre-Dame Mountains anticlinorium (Tremblay and Pinet, 1994). However, the style and intensity of deformation vary from east to west. The Magog Group is characterized by a single phase of Acadian folding coaxial with structures observed in overlying post-Ordovician rocks (Tremblay and St-Julien, 1990; Cousineau and Tremblay, 1993). In the St-Daniel mélange and southern Québec ophiolites, Acadian folds are superimposed on older fabrics (Tremblay and Pinet, 1994). To the west of the BBL, the formation of a large-scale, northeast- and southwest-plunging antiformal fold that makes up the Sutton-Notre-Dame Mountains anticlinorium is believed to be related to Acadian deformation.

Taconian Deformation

In the Appalachian orogen, evidence for a Taconian deformational event consists of well-documented Taconian uncomformities (Pavlides, Boucot, and Skidmore, 1968) and thermochronologic data ranging from 475 to 445 Ma believed to represent metamorphic cooling ages (Drake and others, 1989; Amstrong, Tracy, and Hames, 1992).

In southern Québec, ophiolites and mélange rocks of the Dunnage zone were involved in large-scale, southeast-verging recumbent folds of late Taconian age superimposed over older northwest-verging folds and faults (St-Julien, 1987; Tremblay and Pinet, 1994). The structure of ophiolitic rocks is well-displayed in the Thetford-Mines area (fig. 2) where the oceanic mantle sequence, including the basal amphibolite, defines a large syncline that is cored by ophiolitic cumulates, gabbros, volcanic rocks, and overlying mélanges. The St-Daniel mélange commonly shows a prominent Taconian cleavage (Cousineau, 1990). However, most of the stratigraphical complexity of the mélange predated this fabric. The amalgamation of blocks of various nature took place as a near-solid slurry through deformation zones formed beneath ophiolitic nappes during their emplacement while pelagic sedimentation was still continuing. However, this was most probably coeval with the formation of olistostromal deposits both in the front and the back of stacked ophiolitic thrust sheets, thus accounting for both depositional and faulted contacts preserved in the St-Daniel mélange. Similar processes have been invoked to explain tectonic melanges associated with the Late Cretaceous emplacement of the Oman ophiolite (Lippard, Shelton, and Gass, 1986).

Slope and rise deposits belonging to the inner part of the Humber zone have suffered more deformation than adjacent oceanic rocks. The Sutton-Bennett schists are characterized by structures and fabrics recording polyphased folding and faulting (Colpron, 1990; Marquis, 1991). The early Taconian regional schistosity was associated with the formation of down-dip stretching lineations, isoclinal folds, and faults. As for the ophiolite and mélange rocks, these fabrics were affected by southeast-verging late Taconian recumbent folds and by upright Acadian folds (Tremblay and Pinet, 1994). The contact between continental and oceanic rocks (obduction contact) thus has been folded twice and does not correspond to the BBL.

West of the Sutton-Notre-Dame Mountains anticlinorium, the regional deformation was essentially Taconian-related. The external zone of the Taconian orogen is made up of nappes that overrode olistostromal deposits formed during their imbrication (St-Julien and Hubert, 1975). Along Logan's Line, a series of southeast-dipping thrust faults mark the limit with the autochtonous domain. These thrust faults involved the whole package of continental rocks and are connected at depth to a décollement at the top of the basement (fig. 3, St-Julien, Slivitzky, and Feininger, 1983).

RETRODEFORMATION OF THE QUEBEC-MAINE TRANSECT

In the following section, the structural profile of figure 3 will be retrodeformed by removing each deformational stage. Before doing so we must discuss the possibility of orogen-parallel motions (strike-slip) during both the Taconian and Acadian orogenies (Zen, 1983; Ferril and Thomas, 1988; Malo and others, 1992; among others).

The Baie Verte-Brompton Line is marked by several sub-vertical faults, commonly lined by serpentinized ultramafic rocks. In the Lake Memphremagog area (fig. 2), sub-horizontal stretching lineations were locally observed along the BBL. However, this contrasts strongly with the overall down-dip trend of stretching lineations developed in the Sutton-Benett schists. Therefore, we believe that the strike-slip components along this part of the Québec-Maine transect are limited to minor, late-stage motion.

East of the BBL, the La Guadeloupe fault is characterized by down-dip stretching lineations (Tremblay, St-Julien, and Labbé, 1989; Labbé and St-Julien, 1989), excluding the possibility of significant strike-slip motion in Acadian times. Along the Woburn fault, Trczienski, Rodgers, and Guidotti (1992) described nearly horizontal stretching lineations, raising the possibility of significant transcurrent motions and of a positive flower structure geometry along the eastern side of the Connecticut Valley-Gaspé trough. In summary, evidence for strike-slip motions along the Québec-Maine transect are nearly absent along the BBL and the La Guadeloupe Fault but could have been significant along the western side of the Chain Lakes massif.

The pre-Acadian reconstruction of the Québec-Maine transect (fig. 6B) has been obtained by: (1) unfolding the Connecticut Valley-Gaspé trough and most of the Magog group; (2) removing the effect of late folds in the ophiolitic sequences and adjacent Humber rocks (Sutton-Notre-Dame Mountains anticlinorium); (3) removing the inferred backtrusting component along the Woburn fault and the reverse motion along the La Guadeloupe fault; and (4) deleting the Middle Devonian plutonism.

On figure 6B, the western border of the Connecticut Valley-Gaspé trough is shown as a topographic high, which is consistent with sedimentological data from Lavoie and Bourque (1993) suggesting that post-Ordovician units of the area were deposited in different sedimentary basins lying on both sides of the Ascot Complex. To the east, the trough was bounded by the Chain Lakes massif as suggested by sedimentary sources located to the east for Siluro-Devonian rocks occurring near the Québec-Maine boundary and by western sedimentary sources for rocks lying along the western side of the Merrimack synclinorium (fig. 7; Hatch, Moench, and Lyons, 1983). Finally, the alkaline and transitional volcanic rocks of the Frontenac Formation (Chevé, 1990; Desjardins and others, 1993) are believed to be the southward extension of post-Taconian volcanic suites of the Gaspé Peninsula interpreted to be tensional or transtensional-related volcanic products (Laurent and Bélanger, 1984; Bédard, 1986).

NW
SE
A
B
C
D
BBL
LGF
WF
SMNA
Ac.p
Gb
0
10 km
20 km
LA
As
LL
SD
M
SF
vF
DR
H
(BBL)
OH
SM
Ql
LL
uM
Ap
Oph
C
Us
SB
RP
l.M
P

The late Taconian stage (lower Late Ordovician, fig. 6C) illustrates the association of both northwest- and southeast-verging structures along the Laurentian margin. The backfolding that affected both the oceanic and continental rocks is attributed to the tectonic wedging of basement rocks. This event was nearly coeval with the deposition of the upper part of the Magog Group as suggested by the existence of detrital components originating from a mixed continental-oceanic source (fig. 7; Cousineau, 1990). At the same time, the Taconian nappes were being imbricated in the external domain of the orogen and overrode upper Middle Ordovician olistostromal deposits (St-Julien and Hubert, 1975).

The early Taconian stage (Middle Ordovician, fig. 6D) was dominated by west-directed folding and faulting and corresponded to the emplacement of early nappes in the external domain. The regional structural features and metamorphism of the Sutton-Bennett schists were produced during this stage (fig. 7). The mostly ductile character of these fabrics is attributed to the tectonic stacking of nappes of both continental and oceanic lithologies (ophiolite emplacement). The oceanic crust remained relatively undeformed, except for tectonic slicing and mixing with the St-Daniel mélange. An eastern volcanogenic source prevailed during the deposition of the lower Magog Group (Cousineau, 1990), although the occurrence of sparse detrital chromite grains suggests the concomittent erosion of ophiolites.

Thrusting of the continental sequence during the early Taconian stage was "thin-skinned," and we suggest that basement rocks were not involved (fig. 6D). The age of olistostromal deposits of the external domain (see St-Julien and Hubert, 1975) shows that the stacking order of nappes progressed from the oceanic domain toward the continental foreland. In contrast, a west-to-east stacking order more likely prevailed during the latest Taconian stage (fig. 6C), as a consequence to the formation of basement duplexes.

Fig. 6. Retro-deformation of the Québec-Maine transect (see text for discussion and comments).

(A) *Present day cross section (I):* **Ac.p,** Acadian pluton; **Gb,** Grenvillian basement; **SSMA,** Sutton Mont-Notre-Dame Anticlinorium. Main faults: **BBL,** Baie Verte-Brompton Line; **LGF,** La Guadeloupe Fault; **WF,** Wobburn Fault.

(B) *Pre-Acadian stage (II):* **As,** Ascot complex; **DR,** Dead River Formation; **Gb,** Grenvillian basement; **H,** Hurricane Formation; **LA,** Lac Aylmer Formation; **LL,** Lac Lambton Formation; **M,** Magog group; **SD,** Saint Daniel mélange; **SF,** Saint Francis group; **vF,** volcanics of the Frontenac Formation. (**BBL**), proto-Baie Verte-Brompton Line.

(C) *Late Taconian stage (III):* **Ap,** Attean pluton; **DR,** Dead River Formation; **OH,** Oak Hill group and equivalents; **Ol,** Olistostrome; **SD,** Saint Daniel mélange; **SM,** Sainte Malachie basement sliver; **u.M,** upper Magog group. (**BBL**), proto-Baie Verte-Brompton Line; LL, Logan's Line.

(D) *Early Taconian stage (IV):* **As,** Ascot complex; **C,** Caldwell; **l.M,** lower Magog group; **Ol,** Olistostrome; **OH,** Oak Hill group and equivalents; **Oph,** Ophiolitic rocks; **P,** Platform deposits; **RP,** Rivière des Plantes ophiolitic slice; **SB,** Sutton-Benett schists; **SD,** Saint Daniel mélange; **Us,** Ultramafic sheet.

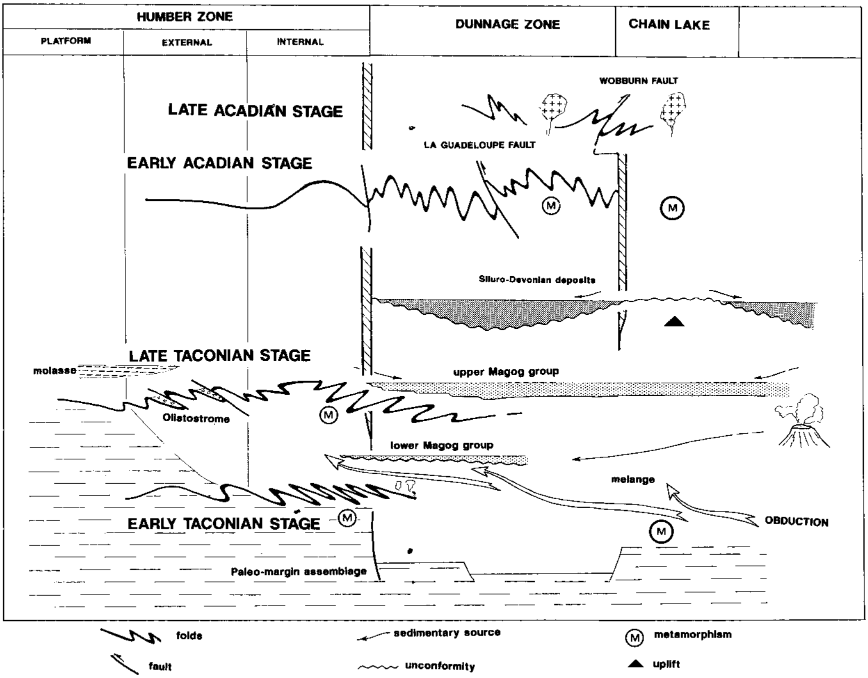

Fig. 7. Schematic synthesis of major tectonic events and associated metamorphic and sedimentological features for the Québec-Maine transect.

Implications for the Taconian Orogeny

In the New England Appalachians, the Taconian orogeny is generally believed to be the result of the convergence between the Laurentian margin and a volcanic arc to the east (Stanley and Ratcliffe, 1985, and references therein), the ophiolite emplacement being attributed to the accretion of subducted oceanic crust to the overriding plate. However, ophiolitic remnants formed in such fashion are generally small (1-3 km thick) and exhibit the same deformational history as the adjacent continental rocks (Le Pichon and others, 1987; Lallemand and others, 1989; Bernstein-Taylor and others, 1992a and b).

Based on examples from the Newfoundland Appalachians, Williams (1979) suggested that the obduction of large and thick (12 km; Karson, Collins and Casey, 1984) slabs of oceanic crust was associated with the Taconian orogeny. Obduction models involving the continental overthrusting of oceanic basement from the upper plate are classically exemplified by the Mesozoic Oman ophiolite (Coleman, 1981; Lippard, Shelton, and Gass, 1986; Goffé and others, 1988; Michard and others, 1989). In such models, the continental margin rocks are typically deformed earlier and more intensely than the overriding ophiolitic sequence.

In order to make a choice between these two tectonic models, it is necessary to discuss the intraoceanic history of accreted ophiolites, the origin of deformation in both the ophiolites and adjacent sedimentary rocks, and the timing of both metamorphism and arc magmatism.

In southern Québec, the emplacement of the oceanic crust is a two-stage mechanism implying an intraoceanic detachment followed by obduction onto the continental margin. For classical obduction examples (such as Oman), age data suggest several million years of intraoceanic travel of the ophiolitic nappe, even if Rb/Sr and K/Ar age data could significantly exaggerate the time range between ophiolite genesis and accretion to the continent (see Harris, 1992). In southern Québec, the structural analysis of both the continental margin rocks and the ophiolitic assemblages indicates that the earliest deformation of the margin rocks was almost synchronous with the emplacement of the overlying ophiolite. In New England, available thermochronological data suggest that part of the Taconian-related metamorphism predated the associated arc volcanism (Bronson Hill) and that models for a Taconian arc-continent collision require revision (Tucker and Robinson, 1990). An alternative hypothesis would be to consider the Taconian deformation and metamorphism of the Laurentian margin as the product of the obduction of oceanic crust that predated any collisional interaction with the volcanic arc.

In southern Québec, available geochronological and structural data are consistent with the obduction of a large ophiolitic nappe during the Taconian orogeny. The Chain Lakes massif is here considered to be sedimentary rocks belonging to a continental margin inlier that has suffered high grade metamorphism during ophiolite emplacement. This interpretation is in agreement with variations of the metamorphic grade within the Chain Lake massif (Trzcienski, Rodgers, and Guidotti, 1992); the eastern part of the massif being at higher grade than its western flank, which is consistent with the inferred polarity (east-over-west) of ophiolite emplacement. However, acurate metamorphic age determinations from the Chain Lakes massif will be a key criterion to test our model.

GEODYNAMIC SYNTHESIS OF THE QUEBEC APPALACHIANS

The inferred tectonic evolution and a palinspastic reconstruction of the Québec-Maine transect is shown on figure 8. Although it is not possible to define precisely the structural evolution of each unit, the model can be used to show the structural setting and the timing of Taconian and Acadian deformation and metamorphism.

In southern Québec, the Early Cambrian rift-drift transition (Cheshire Formation: Ch) can be used to approximate the onset of sea-floor spreading at 540 Ma (fig. 8A), which is consistent with data from Newfoundland (Williams and Hiscott, 1987). This was followed by the development of a carbonate platform and the deposition of slope and rise deposits along a subsiding passive continental margin (fig. 8B).

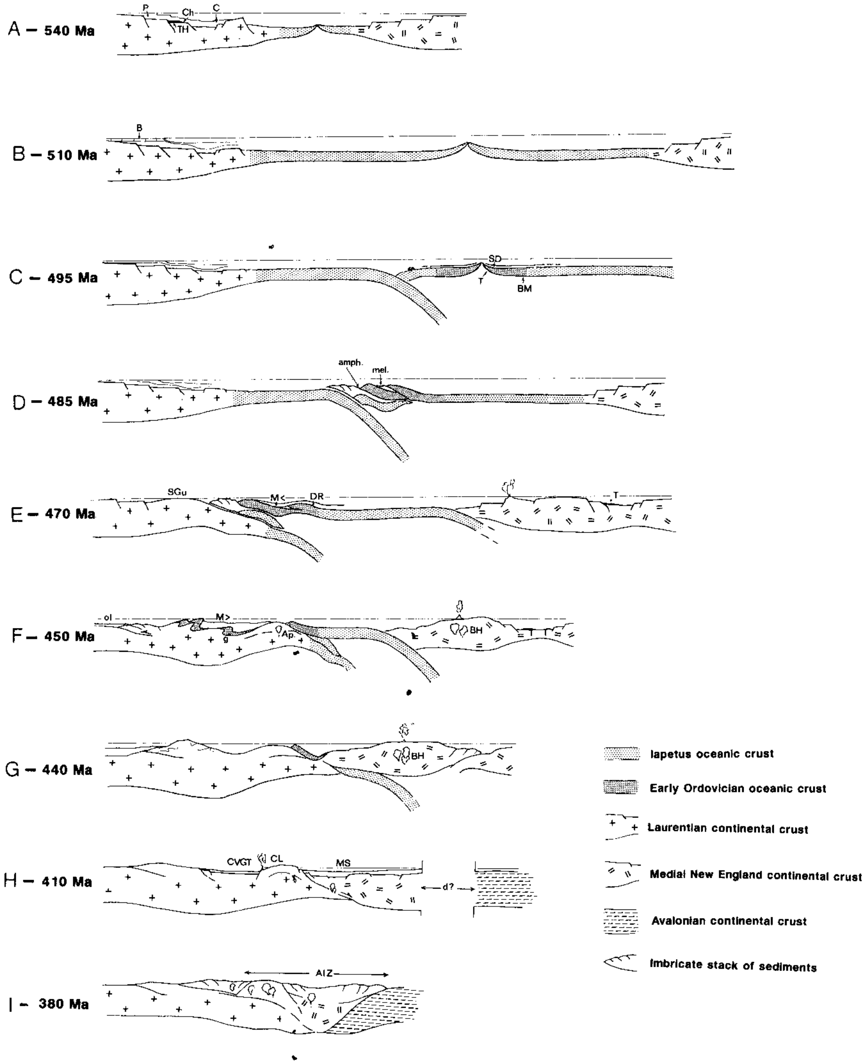

Fig. 8. Tectonic model for the geodynamic evolution of rock units lying along the Québec-Maine transect. (A) **540 Ma:** rift-drift transition along the Laurentian margin. The rifting is recorded by alkaline volcanism (Th: Tibbit Hill) and coarse-grained fluvial deposits (P: Postdam). Caldwell Group rocks (C) are attributed to distal sedimentary sources (horst?). The inferred rift-drift transition (Cheshire Formation, Ch) marks the initiation of sea-floor spreading and the formation of Iapetus *sensu stricto*. (B) **510 Ma:** Following the opening of a large oceanic basin, a platformal margin was established along the Laurentian margin (B, Beekmantown group). (C) **495 Ma:** Rifting of a marginal sea. The Thetford-Mines (T) and Boil Mountain (BM) ophiolites are interpreted as the record of this oceanic basin. The St-Daniel (SD) and Hurricane Mountain mélanges were deposited over the newly-formed oceanic crust. (D) **485 Ma:** Onset of the closure of the marginal sea leading to the formation of amphibolites (amph.) underlying the ophiolites and mélanges rocks (mel) overlying it. (E) **470 Ma:** Obduction of the oceanic crust onto the continental margin and associated peripheral bulge leading to the Saint Georges uncomformity (SGu). Lower units of the Magog Group (M <) and the Dead River Formation (DR) were deposited within open sea over the moving oceanic crust. Eastward, volcanic rocks (Tetagouche Group, see van Staal and others, 1990) recorded an extensional setting. (F) **450 Ma:** Late Taconian stage associated with the deposition of upper units of the Magog group (M >) and the coeval emplacement of most external nappes. Small-scale granitic intrusive (g) recorded the vanishing ophiolite obduction whereas late orogenic intrusives (Ap: Attean pluton) were emplaced in Taconian internides. (G) **440 Ma:** Docking of the Medial New England Terrane against the Laurentian margin leading to the cessation of arc volcanism along the Bronson Hill arc (BH). (H) **410 Ma:** Post-Taconian, intra-continental formation of sedimentary basins such as the Connecticut Valley-Gaspé trough (CVGT) and the Merrimack synclinorium (MS) that were separated by the Chain Lakes massif (CL). (I) **380 Ma:** The Acadian orogeny is attributed to the collision of the Taconian orogen with Avalonia. AIZ: Acadian internal zone.

Between 505 and 490 Ma, the onset of plate convergence led to the creation of new oceanic crust (marginal sea) in a supra-subduction zone environment (fig. 8C). This follows the broad line of the model proposed by Cawood and Suhr (1992) for the Newfoundland ophiolites. However, clear evidence for the geodynamic setting remain unknown, but two hypothesies can be proposed: a supra-subduction zone setting or an intraoceanic pull-apart setting related to bloc extrusion or to strike-slip sliver migration (see below). The geochemistry of the southern Québec ophiolite (Laurent and Hébert, 1989) suggests, as commonly noted in many ophiolites (Edelman, 1988), the involvement of a subduction zone, even if there is no evidence of arc-detritus in the sedimentary cover. The duration of spreading episodes shown in figure 8A to C are about 40 Ma for the Iapetus ocean *sensu stricto* (fig. 8A and B) and 10 Ma for the marginal basin (fig. 8C). Given a mean spreading rate of 2.5 cm/yr, this would lead to the formation of 1000 km- and 250 km-wide oceanic basins respectively.

Between 495 and 485 Ma (fig. 8D), intraoceanic obduction was initiated at the thermal boundary between the ancient and the newly-formed oceanic crusts, and amphibolite-grade metamorphic rocks were produced along the thrusting surface. At superficial levels, the disruption of sedimentary rocks overlying the oceanic crust led to the formation of most of the St-Daniel and Hurricane Mountain mélanges. The obduction of the oceanic crust (fig. 8E) caused the metamorphism of slope and rise rocks and the westward migration of the peripheral bulge across the continental margin. Continuing convergence led to the formation of basement duplexes (about 450 Ma) which induced backthrusting and backfolding of the internal Taconian zones (fig. 8F). Isostatic rebound of the tectonically thickened outer margin followed the ophiolite emplacement (see Lippard, Shelton, and Gass, 1986 for the Oman ophiolite) and induced the tectonic uplifting of the Boil Mountain and Chain Lakes massif (fig. 8H). The uplift of this area gave it a high potential energy for normal faulting and caused a sympathetic downward flexure farther to the west, which could have accounted for part of the deepening of the newly formed Connecticut Valley-Gaspé trough.

During the intraoceanic emplacement stage (fig. 8D), convergence was mainly accommodated by movement of the oceanic slab. Its emplacement onto the continental margin (fig. 8E and F) most probably implied the slowing down of the ophiolitic nappe, thus inducing the initiation of an eastward subduction zone along which was taken an increasing part of the tectonic convergence. The resulting magmatic arc (Bronson Hill) was developed over a continental crust in Late Ordovician time (454-442 Ma, Tucker and Robinson, 1990). The Bronson Hill arc is believed to be the principal source for volcanoclastic rocks lying at the base of the Magog/Dead River units, which were deposited in an open basin developed on the moving oceanic crust. However, the model does not exclude the possibility of backarc extension as a significant mechanism that could have led to the formation of small oceanic basins (that is, Iapetus II of van Staal and others, 1990). Younger ophiolitic rocks preserved in the

Fournier Group in northern New Brunswick may represent part of such marginal basins which were closed between 440 and 450 Ma (see van Staal and others, 1990).

In Late Silurian time, the Humber zone and its Grenvillian basement, the allochthonous Dunnage zone and the Medial New England basement of Osberg and others (1989) were already welded (fig. 8G). An extentional tectonic regime prevailed and induced the formation of both the Connecticut Valley-Gaspé trough and the Merrimack synclinorium (fig. 8H). The collision with an Avalonian continental masse contributed to superimposed metamorphism and deformation during the Acadian orogeny (fig. 8I).

DISCUSSION AND CONCLUSIONS

The variety of models proposed for ophiolite genesis and emplacement emphasizes the absence of concensus for the Appalachians. Ultramafic rocks occurring across the Québec-Vermont boundary are ideal areas to study along-strike variations of ophiolite structural setting. In southern Québec, well-preserved remnants of oceanic crust suggest the obduction of a large ophiolitic nappe in Taconian times. In Vermont, ophiolitic rocks are sparsely distributed, much smaller than in Québec, and probably represent oceanic crust slivered off from a subducting slab (Stanley and Ratcliffe, 1985; Stanley and others, 1984). Such along-strike variations could be attributed to the original geometry of the Laurentian margin, made up of promontories and reentrants (Thomas, 1983). During the Ordovician convergence, this geometry would have resulted in the opening of small oceanic basins in the reentrant either by crustal block extrusion or by trench roll-back (Cawood and Suhr, 1992; Edelman, 1988). The promontory/reentrant transition also corresponded to diachronicity of collisional events (Tremblay, 1992a).

In the Northern Appalachians, the existence of a Penobscotian orogeny was based on unconformities of Early Ordovician age found locally in northern Maine (Neuman, 1967; Boone and Boudette, 1989), which seem to be mostly coeval with the formation of ophiolites of the Québec-Maine transect (see fig. 8C). However, the existence of major dextral strike-slip faults in Maritime Canada (fig. 1; Malo and Béland, 1989, van Staal and Fyffe, 1991) suggests that the pre-Acadian location of these Penebscotian localities was originally located closer to the St. Lawrence promontory. The promontory probably acted as an indentor leading to lateral expulsion of crustal blocks (fig. 9) which were associated with local deformational events (for example, Penebscotian). As proposed by Cawood and Suhr (1992) and Jenner and others (1991), ophiolite generation took place in an intra-arc setting in Newfoundland. However, an intraoceanic setting seems more likely for the southern Québec and western Maine ophiolitic rocks, considering the absence of Early Ordovician magmatic arc in New England.

We believe that major Appalachian ophiolites originated in relatively small oceanic basins that formed in reentrants. The ophiolite genesis and

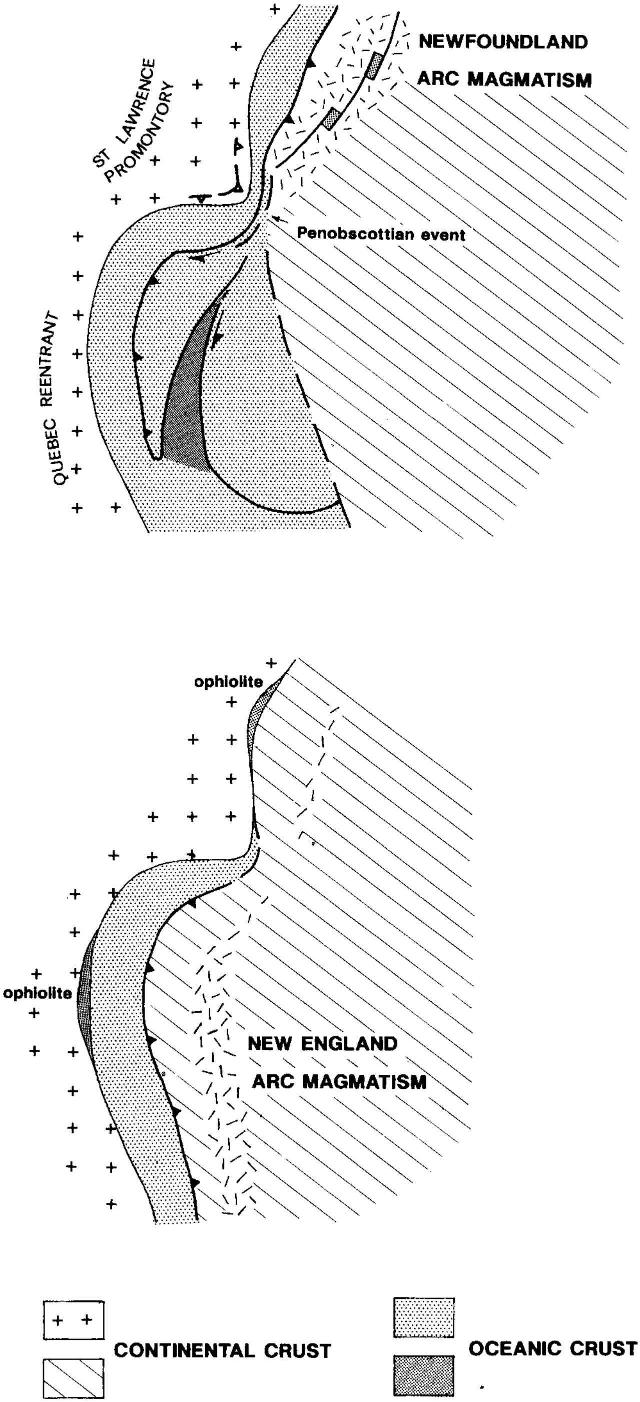

Fig. 9. Schematic plan view for the geodynamic evolution of the Northern Appalachians and the inferred consequences of the geometry of the Laurentian on the evolution of adjacent oceanic terranes (see text for discussion).

obduction both took place in a convergent setting. In the proposed model, ophiolites along the BBL do not represent a primary subduction suture but a polyphased tectonic boundary marking the leading edge of the obducted ocean floor. As suggested by Zen (1983), we believe that the oceanic root zone must be located east of the Chain Lakes massif.

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