Ophiolite obduction in the Quebec Appalachians, Canada — $^{40}Ar/^{39}Ar$ age constraints and evidence for syn-tectonic erosion and sedimentation[1,2,3]

Stéphane De Souza, Alain Tremblay, Gilles Ruffet, and Nicolas Pinet

Abstract: Detailed field work conducted in the Dunnage zone of the Quebec Appalachians, is herein combined with $^{40}Ar/^{39}Ar$ dating on a series of ophiolitic massifs, crosscutting granites, and associated metamorphic rocks occurring along the Baie Verte–Brompton line, the Taconian suture between Laurentia and Lower Paleozoic peri-Laurentian oceanic terranes. Studied massifs are the Lac-Brompton ophiolite and the Rivière-des-Plante Ultramafic Complex in southern Quebec, and the Nadeau Ophiolitic Mélange in the Gaspé Peninsula. Our work suggests that these massifs form remnants of eroded ophiolitic nappes, which are unconformably overlain by the Saint-Daniel and Rivière-Port-Daniel mélanges, and correlate with the Thetford-Mines and Mont-Albert ophiolitic complexes. Our $^{40}Ar/^{39}Ar$ data and compiled regional age constraints indicate that ophiolite obduction was diachronous along the strike of the orogen. The timing of obduction and mélange formation varies according to the irregular geometry of the Early Paleozoic Laurentian margin, with earlier collision occurring along, or at the margins of promontories. Obduction was initiated with the formation of infraophiolitic metamorphic soles between ca. 479 and 472 Ma in southern Quebec and the Nadeau Ophiolitic Mélange, and possibly as late as ca. 470–466 Ma for the Mont-Albert Complex. These sole rocks were later exhumed and translated onto the Laurentian margin with the overlying ophiolites between 475 and 460–457 Ma. The uplifting and erosion of the orogenic wedge during the waning stages of obduction, has resulted in the sedimentation of olistostromal mélanges and onlapping flysch units above the ophiolitic nappes, as well as foredeep flysch successions during the latest Arenig (?) to earliest Caradoc.

Résumé : Des études détaillées effectuées dans la zone de Dunnage des Appalaches du Québec sont combinées à de la géochronologie $^{40}Ar/^{39}Ar$ sur des roches granitiques et métamorphiques associées à des massifs ophiolitiques situés le long de la ligne Baie Verte–Brompton, la suture taconienne entre Laurentia et les terrains océaniques péri-laurentiens accrétés du Paléozoïque inférieur. Les massifs étudiés sont l'ophiolite du Lac-Brompton et le Complexe ultramafique de la Rivière-des-Plante dans le sud du Québec, ainsi que le Mélange ophiolitique de Nadeau dans la péninsule gaspésienne. Les données acquises suggèrent que ces massifs représentent des fragments de nappes ophiolitiques corrélables sur lesquelles reposent en discordance les mélanges de Saint-Daniel et de Rivière-Port-Daniel. Nos données $^{40}Ar/^{39}Ar$ et la compilation de données existantes, indiquent que l'obduction des ophiolites a été diachrone le long de l'orogène. La chronologie de l'obduction varie selon la géométrie de la marge laurentienne du Paléozoïque inférieur, avec une collision précoce au niveau des promontoires. L'obduction s'est initiée avec la formation des semelles métamorphiques infraophiolitiques entre ca. 479 et 472 Ma dans le sud du Québec et le Mélange ophiolitique de Nadeau, et probablement entre ca. 470–466 Ma pour le Complexe du Mont-Albert. Celles-ci ont ensuite été exhumées et transportées sur la marge laurentienne avec les roches ophiolitiques sus-jacentes entre 475 et 460–457 Ma. La surrection et l'érosion du prisme orogénique pendant les stades finaux d'obduction, ont engendré la sédimentation de mélanges olistostromaux et de flyschs sur les nappes ophiolitiques, ainsi que de successions flyschiques dans l'avant-pays, de l'Arenig tardif(?) jusqu'au Caradoc.

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S. De Souza and A. Tremblay. Département des Sciences de la Terre et de l'Atmosphère, Université du Québec, C.P. 8888, Montréal, QC H3C 3P8, Canada.
G. Ruffet. CNRS (CNRS/INSU) UMR 6118, and Université de Rennes 1, Géosciences Rennes, 35042 Rennes CEDEX, France.
N. Pinet. Geological Survey of Canada, 490 rue de la Couronne, Québec, QC G1K 9A9, Canada.

Corresponding author: S. De Souza (e-mail: de_souza.stephane@courrier.uqam.ca).

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Fig. 1. (*a*) Lithotectonic map of the Northern Appalachians of mainland Canada and New England showing embayment–promontory geometry of the region (modified from Tremblay and Pinet 2005). BBL, Baie Verte-Brompton line. (*b*) Generalized geological map of the southern Quebec Appalachians (modified from Schroetter et al. 2005). SMA, Sutton Mountains anticlinorium; NDMA, Notre-Dame Mountains anticlinorium; MOO, Mont-Orford ophiolite; LBO, Lac-Brompton ophiolite; AO, Asbestos ophiolite; TMO is the Thetford-Mines ophiolite; RPUC, Rivière-des-Plante Ultramafic Complex. See Fig. 1*a* for location.

Introduction

Ophiolitic complexes and mélanges occur discontinuously along the Baie Verte–Brompton line (Williams and St-Julien 1982), a narrow linear belt extending for 1500 km in the Canadian Appalachians, from southern Quebec to Newfoundland (Fig. 1*a*). Williams and St-Julien (1982) originally interpreted the Baie Verte–Brompton line as a steeply-dipping polyphase tectonic zone of ophiolite emplacement representing the surface expression of the Taconian suture zone between Laurentia and the bordering Iapetus Ocean. In Quebec, the Taconian Orogeny resulted from an Early to Middle Ordovician, Tethyan-type obduction event involving the emplacement of large nappes of suprasubduction zone oceanic lithosphere onto Laurentia (Pinet and Tremblay 1995; Tremblay and Castonguay 2002; Schroetter et al. 2005; Malo et al. 2008; Tremblay et al. 2009, 2011). The term "obduction", which generally refers to any type of ophiolite emplacement mechanism (e.g., Coleman 1971; Dewey 1976; Moores 1982; Searle and Stevens 1984; Searle et al. 1994; Gregory et al. 1998; Gray and Gregory 2003; Whattam 2009), is here used to describe the combination of processes by which an ophiolite is emplaced onto a continental margin, from the inception of subduction to its subaerial exposure as part of an orogenic belt (Gray et al. 2000; Wakabayashi and Dilek 2003; Tremblay et al. 2011).

At the orogen scale, Cambrian–Ordovician lithotectonic features of the Appalachians define embayments and promontories that are believed to be inherited from the cratonic break-up of Rodinia (Fig. 1*a*; Thomas 1977; Allen et al. 2010), and to have played an important role in the sedimentological and tectonic evolution of the Appalachians (Stockmal et al. 1987; van Staal et al. 1998; Malo et al. 1995; Tremblay et al. 2000). More specifically, the promontory–embayment geometry of the margin has been inferred to influence the distribution of the rift and passive margin sequences (Lavoie et al. 2003; Cousineau and Longuépée 2003), the formation, obduction, and preservation of the ophiolites (Cawood and Suhr 1992), the along-strike variations in the timing and structural style of both the Taconian and Acadian orogenies (Lavoie 1994; Tremblay et al. 2000; Sacks et al. 2004; Malo et al. 1992, 1995, 2008), and the Lower Paleozoic syn-tectonic sedimentation (Hiscott 1995).

Geochronological studies, mostly from the Thetford-Mines and Mont-Albert ophiolitic complexes (Figs. 1*b*, 2; Lux 1986; Dunning and Pedersen 1988; Whitehead et al. 1995, 2000; Pincivy et al. 2003; Malo et al. 2008; Tremblay et al. 2011), have provided significant isotopic age constraints for ophiolite formation and (or) obduction. However, little is known about the tectonic history and timing of obduction and mélange formation along the entire length of the Baie Verte–Brompton line in the Quebec Appalachians. In this contribution, we combine detailed field observations and new ^{40}Ar/^{39}Ar age data from granites, ophiolitic rocks, and infraophiolitic metamorphic rocks of the Lac-Brompton ophiolite and Rivière-des-Plante Ultramafic Complex in southern Quebec, and the Nadeau Ophiolitic Mélange in the Gaspé Peninsula (Figs. 1*b*, 2). These data are then synthesized with published geochronological constraints for ophiolitic complexes of the Quebec Appalachians to document orogenic processes related to ophiolite obduction, syn-tectonic sedimentation and mélange formation in the context of an irregular collision zone.

Geological setting

The Quebec Appalachians comprise three main lithotectonic assemblages: the Cambrian–Ordovician, Humber and Dunnage zones (Williams 1979), and the overlying Silurian–Devonian succession of the Gaspé Belt (Fig. 1; Bourque et al. 2000; Lavoie and Asselin 2004). The Humber and Dunnage zones were amalgamated during the Taconian Orogeny and represent the remnants of the Laurentian continental margin and the adjacent oceanic domain, respectively (Williams 1979; van Staal et al. 1998). In Quebec, penetrative Taconian deformation is essentially confined to the Humber zone, and has been attributed to the closure of the Iapetus Ocean and obduction of a large ophiolitic nappe, now preserved as the southern Quebec and Gaspé Peninsula ophiolites (Pinet and Tremblay 1995; Tremblay and Castonguay 2002; Malo et al. 2008).

Stratigraphy and structure of the Dunnage zone in the southern Quebec Appalachians

In the Quebec Appalachians, the Dunnage zone is best exposed in southern Quebec (Fig. 1*b*), where it consists of: (*i*) a series of well-preserved to dismembered ophiolite complexes, namely, from south to north, the Mont-Orford, Lac-Brompton, Asbestos, and Thetford-Mines ophiolites, and the Rivière-des-Plante Ultramafic Complex; (*ii*) the Saint-Daniel Mélange; (*iii*) the Magog Group; and (*iv*) the Ascot Complex (Fig. 2; Tremblay 1992). The ophiolite complexes of southern Quebec are all believed to represent remnants of a composite slab of suprasubduction zone oceanic lithosphere (Schroetter et al. 2005; De Souza et al. 2008; De Souza and Tremblay 2010). Oceanic plagiogranites from the Thetford-Mines ophiolite yielded U–Pb zircon ages of 478 +3/–2 and 480 ± 2 Ma (Whitehead et al. 2000). The Mont-Orford ophiolite is presumably older (U–Pb zircon age of 504 ± 3 Ma; David and Marquis 1994) and is believed to represent a magmatic arc basement that rifted to form the other complexes (De Souza et al. 2008). Mantle peridotites of the Thetford-Mines, Asbestos, Lac-Brompton, and Rivière-des-Plante complexes, are crosscut by a series of granitoids that are referred to as peridotite-hosted granites (Whitehead et al. 2000; De Souza et al. 2008; De Souza and Tremblay 2010; Tremblay et al. 2011). These granitic rocks were shown to be derived from the anatectic partial melting of Laurentian continental margin sedimentary rocks during ophiolite emplacement as a result of shear heating

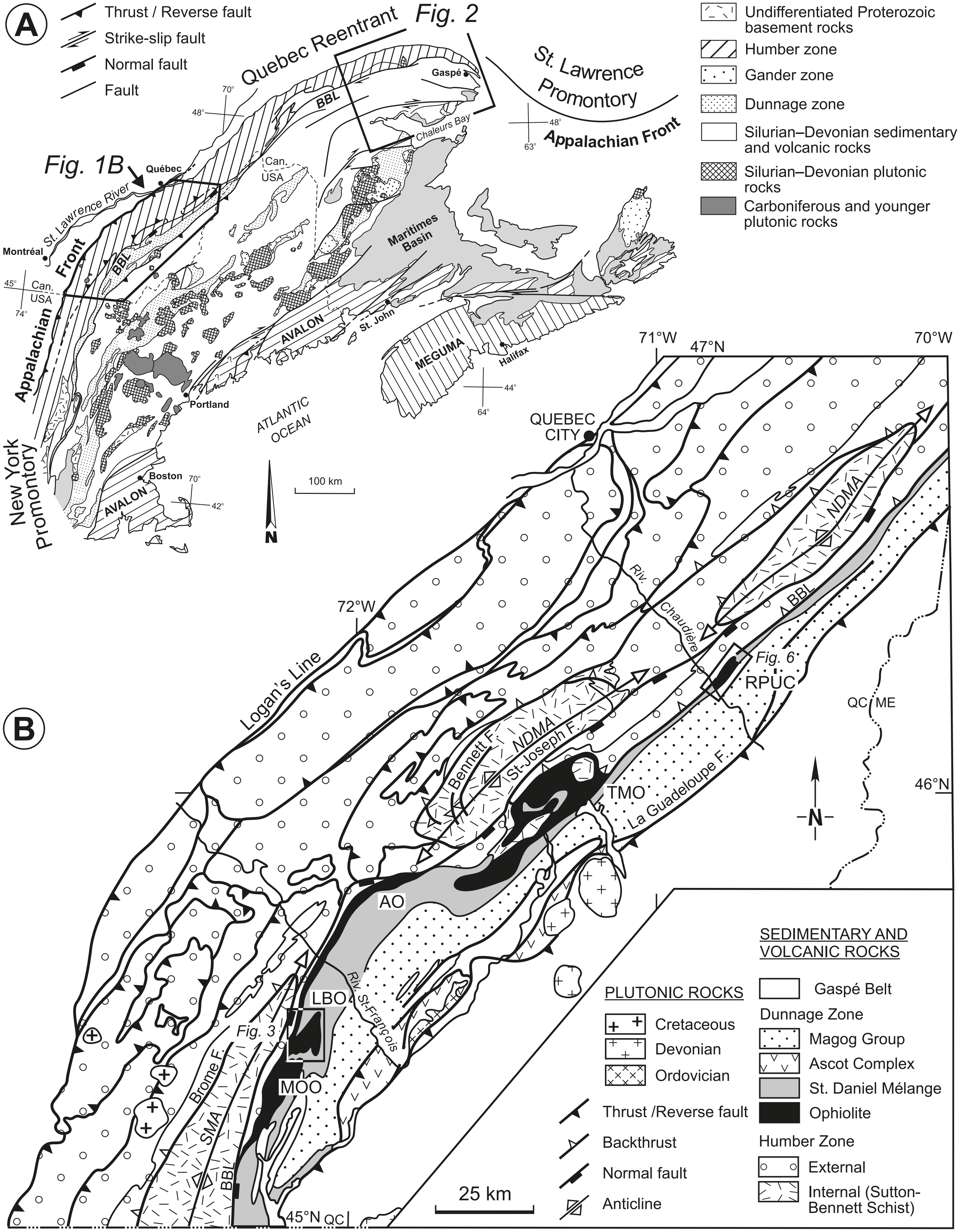
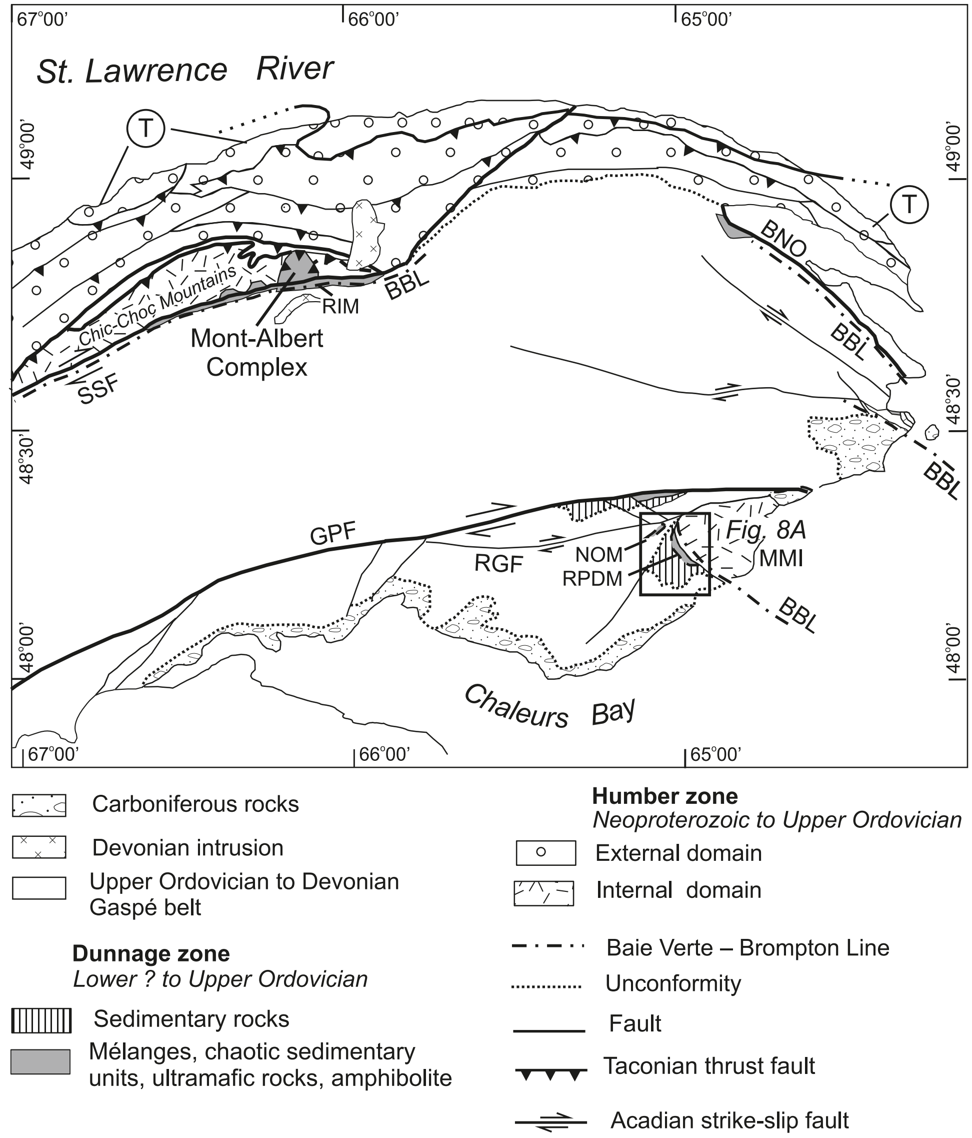

A
Thrust / Reverse fault
Strike-slip fault
Normal fault
Fault
Quebec Reentrant
Fig. 2
St. Lawrence Promontory
Appalachian Front
Undifferentiated Proterozoic basement rocks
Humber zone
Gander zone
Dunnage zone
Silurian–Devonian sedimentary and volcanic rocks
Silurian–Devonian plutonic rocks
Carboniferous and younger plutonic rocks
Gaspé
BBL
Chaleurs Bay
Fig. 1B
Québec
Can.
USA
St. Lawrence River
Montréal
Front
Appalachian
Maritimes Basin
AVALON
St. John
MEGUMA
Halifax
Portland
ATLANTIC OCEAN
New York Promontory
Boston
100 km
N
70°
48°
63°
45°
74°
44°
64°
42°
B
71°W
47°N
70°W
QUEBEC CITY
72°W
Logan's Line
Riv. Chaudière
NDMA
BBL
Fig. 6
RPUC
QC ME
Bennett F.
St-Joseph F.
TMO
La Guadeloupe F.
46°N
N
AO
LBO
Fig. 3
MOO
Riv. St-François
Brome F.
SMA
45°N
QC
VT
25 km
PLUTONIC ROCKS
Cretaceous
Devonian
Ordovician
Thrust /Reverse fault
Backthrust
Normal fault
Anticline
SEDIMENTARY AND VOLCANIC ROCKS
Gaspé Belt
Dunnage Zone
Magog Group
Ascot Complex
St. Daniel Mélange
Ophiolite
Humber Zone
External
Internal (Sutton-Bennett Schist)

Fig. 2. Generalized geological map of the Gaspé Peninsula modified from Malo et al. (2008). BBL, Baie Verte-Brompton line; BNOF, Bras Nord-Ouest fault; MMI, Maquereau-Mictaw inlier; GPF, Grand Pabos fault; NOM, Nadeau Ophiolitic Mélange; RGF, Rivière Garin fault; RPDM, Rivière-Port-Daniel Mélange; SSF, Shickshock Sud fault; T, Tectonic slices containing Tourelle, Deslandes, and Cloridome formations or other correlative units. The geology of New Brunswick is undifferentiated. See Fig. 1*a* for location.



and residual heat transfer from the ophiolite to the margin (Whitehead et al. 2000; Tremblay et al. 2011). In the Thetford-Mines area, these granitic rocks yielded U–Pb zircon ages of 470 +5/–3 Ma and 469 ± 4 Ma (Whitehead et al. 2000), and ^{40}Ar/^{39}Ar muscovite ages varying between ca. 466 and 460 Ma (Tremblay et al. 2011). A ^{40}Ar/^{39}Ar hornblende isochron age of 477 ± 5 Ma (Whitehead et al. 1995), for the infraophiolitic metamorphic sole of the Thetford-Mines ophiolite, was recently shown to be partly inherited from its basaltic protolith, and revised to a younger age of ca. 471 Ma (Tremblay et al. 2011).

Debris flows and conglomerates characterizing the base of the Saint-Daniel Mélange (Fig. 1*b*) form the lower part of a syn-collisional sedimentary basin unconformably overlying the ophiolitic basement and underlying metamorphic rocks (Schroetter et al. 2006; De Souza et al. 2008; Tremblay et al. 2009). The Magog Groups is a Caradoc (the Ordovician time scale of Sadler et al. (2009) is used throughout this article) flysch-dominated turbiditic succession that unconformably overlies the Saint-Daniel Mélange (Cousineau and St-Julien 1994; Schroetter et al. 2006), whereas the Ascot Complex is thought to represent the remnants of a Middle to Late Ordovician peri-Laurentian volcanic arc sequence (Fig. 1*b*; Tremblay et al. 1989; Tremblay 1992).

In southern Quebec, the Humber and Dunnage zones share a similar structural evolution (Schroetter et al. 2005). A Middle to Late Ordovician (471–456 Ma; Castonguay et al. 2001, 2007; Tremblay and Castonguay 2002; Tremblay et al. 2011) S_{1-2} schistosity is associated with ophiolite emplacement during the Taconian Orogeny, and is only developed in rocks of the Humber zone and the infraophiolitic metamorphic sole rocks (Tremblay and Castonguay 2002; Schroetter et al.

2005; Daoust 2007). Taconian deformation culminated with the emplacement of the Taconic allochthons between 460 and 445 Ma as part of a foreland-propagating thrust system (St-Julien and Hubert 1975; Sasseville et al. 2008). Two generations of post-obduction structures are recognized: (*i*) D_3 Silurian – Early Devonian SE-verging folds and faults that culminated with the formation of steep southeast-dipping normal faults, such as the St-Joseph fault, and (*ii*) D_4 Late Devonian NW-verging folds and reverse faults related to the Acadian Orogeny (Fig. 1*b*; Tremblay and Pinet 1994; Pinet et al. 1996; Castonguay et al. 2001, 2007; Tremblay and Castonguay 2002; Castonguay and Tremblay 2003; Schroetter et al. 2005).

Stratigraphy and structure of the Dunnage zone in the Gaspé Peninsula

In the Gaspé Peninsula (Fig. 2), Cambrian(?)–Ordovician ophiolitic rocks, mélanges, and sedimentary rocks assigned to the Dunnage zone occur in the Mont-Albert Complex, as a series of tectonic slivers along major faults and as structural inliers beneath the sedimentary cover of the Gaspé Belt (see Tremblay et al. 1995 for a review). The Mont-Albert Complex (Beaudin 1980) consists of mantle peridotites and of an infraophiolitic metamorphic sole (Gagnon and Jamieson 1986; Pincivy et al. 2003; Malo et al. 2008). As in southern Quebec, olistostromal breccias comprising ophiolitic rock fragments occur in the Gaspé Peninsula as part of the Rivière-Port-Daniel Mélange, which is associated with ultramafic rock slivers and delineates the Baie Verte–Brompton line in the Maquereau–Mictaw inlier (Fig. 2; De Brouker 1987). Williams and St-Julien (1982) have suggested, based on fragment and matrix petrography and stratigraphic relationships with adjacent pre-Silurian rock units, that the Rivière-Port-Daniel Mélange correlates with the Saint-Daniel Mélange, and that both were probably formed in similar stratigraphic settings. The Mictaw Group is a Llanvirn to Caradoc flysch-dominated turbiditic succession that unconformably overlies the Rivière-Port-Daniel Mélange (De Brouker 1987).

Taconian accretionnary events in the Gaspé Peninsula include the formation of high-grade metamorphic rocks, such as the metamorphic sole of the Mont-Albert Complex (Pincivy et al. 2003; Malo et al. 2008), and the emplacement of northwest-verging thrust sheets during ophiolite obduction (St-Julien and Hubert 1975; Malo et al. 2008). The metamorphic sole of the Mont-Albert Complex and the underlying metamorphic rocks of the Humber zone yielded $^{40}Ar/^{39}Ar$ amphibole and muscovite ages of ca. 465 to 457 Ma and 459 to 456 Ma, respectively, with evidence of a late increment at ca. 449 Ma in both of these assemblages (Lux 1986; Pincivy et al. 2003; Malo et al. 2008). These ages were interpreted to record the progressive transfer of deformation from the oceanic domain to the continental margin (Malo et al. 2008). In the Taconian foreland of the Gaspé Peninsula, synorogenic chromite-bearing flysch units provide evidence for ophiolite obduction and erosion, and the foundering of the Laurentian margin as early as the late Arenig – early Llanvirn (Fig. 2; Hiscott 1978, 1995). Acadian regional structures are related to a transpressional deformation regime and the development of dextral strike-slip faults and oblique folds (Malo and Béland 1989; Malo et al. 1992; Pinet et al. 2008; 2010). Palinspastic restoration of the pre-Acadian Cambrian–Ordovician features in the Gaspé Peninsula suggests that rocks of the Nadeau Ophiolitic Mélange and the Maquereau–Mictaw inlier were originally located ca. 120 km to the east of their current location, along the Baie Verte–Brompton line (Malo et al. 1992).

$^{40}Ar/^{39}Ar$ geochronological data

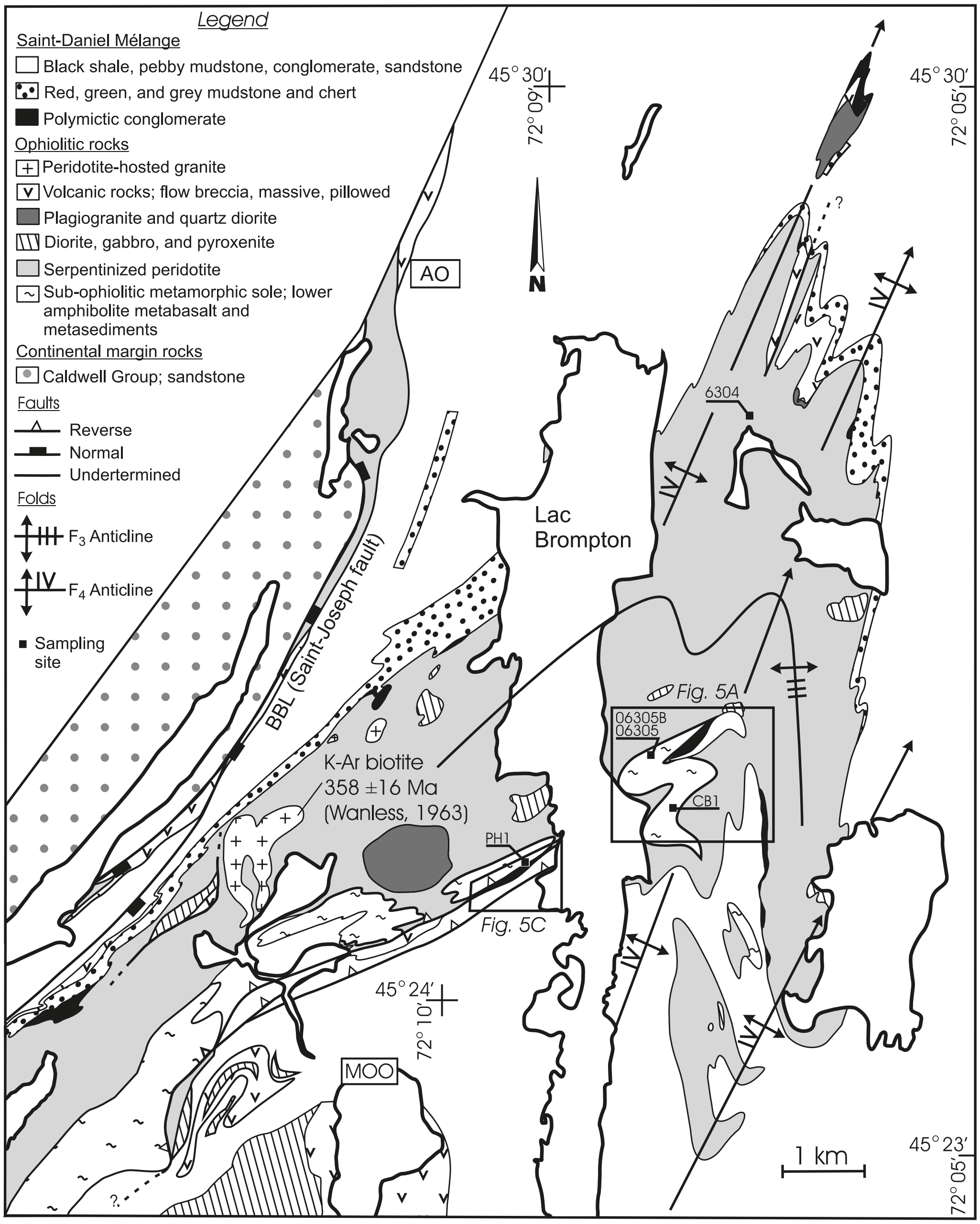
For the purpose of this study, a series of samples of igneous and metamorphic rocks collected in the Lac-Brompton ophiolite, the Rivière-des-Plante Ultramafic Complex, and the Nadeau Ophiolitic Mélange, was selected for white mica and amphibole laser step-heating $^{40}Ar/^{39}Ar$ analyses. Single grains of sericite, muscovite, and amphibole were separated from 0.25 to 0.5 mm fractions of crushed rock samples and handpicked using a binocular microscope. The sample preparation and analytical procedures for the laser step-heating measurements are detailed by Ruffet et al. (1991, 1995) and Castonguay et al. (2001, 2007), whereas the tectonic setting of the dated samples and analytic results are presented in the following sections.

The Lac-Brompton ophiolite

The Lac-Brompton ophiolite (De Souza et al. 2008) mostly consists of harzburgitic mantle peridotites with minor occurences of a discontinuous crustal unit preserved as pyroxenitic to gabbroic plutonic rocks and boninitic mafic volcanic rocks (Fig. 3). It has been correlated with both the Asbestos and Thetford-Mines ophiolites based on the geochemistry of volcanic rocks and dykes, ophiolite stratigraphy, and relationships with adjacent rock units (De Souza et al. 2008). The lowermost contact of the Lac-Brompton ophiolite is marked by a discontinuous unit of metavolcanic and metasedimentary rocks that have been collectively interpreted as the remnants of an infraophiolitic metamorphic sole (Fig. 3; Daoust 2007). The ophiolite and its metamorphic sole are both unconformably overlain by the Saint-Daniel Mélange, which consists of a basal unit made up of polymictic breccia and laminated chert–mudstone that is overlain by pebbly mudstone, black shale, and sandstone. The breccia unit mostly consists of ophiolite-derived mafic and ultramafic lithologies, granitoid and sedimentary rock fragments, but is also locally entirely made up of foliated sole-type metamorphic rock clasts, suggesting that the metamorphic sole was formed and then uplifted during or prior to the sedimentation of the Saint-Daniel Mélange.

The metamorphic sole itself is made up of amphibolites, phyllite, and mica schist (Daoust 2007). The metamorphic mineral assemblages are, in order of increasing metamorphic grade: (*i*) epidote + plagioclase + hornblende ± sphene ± chlorite; (*ii*) hornblende + epidote + plagioclase ± sphene; and (*iii*) hornblende + plagioclase ± sphene in the amphibolites, and muscovite + quartz + chlorite ± plagioclase ± garnet ± zoisite in the phyllites and mica schists. The amphibole compositions and the nature of mineral assemblages indicate maximum pressure and temperature conditions of 5–8 kbar (1 bar = 100 kPa) and 700 °C (Daoust 2007). The geochemical composition of the mafic protolith to the amphibolite corresponds to tholeiitic-transitional MORB (mid-ocean ridge)-like to alkali basalts, which have been interpreted as metamorphosed passive margin to continental rift-related

Fig. 3. Generalized geological map of the Lac-Brompton area showing the location of the samples used for $^{40}Ar/^{39}Ar$ analyses. MOO, Mont-Orford ophiolite; AO, Asbestos ophiolite; BBL, Baie Verte-Brompton line. Modified from De Souza et al. (2008). See Fig. 1*b* for location.



volcanic rocks. The dominant fabric in the metamorphic sole is a $S_{1–2}$ composite foliation marked by amphibole, plagioclase, epidote, and micaceous minerals, and that has been attributed to ophiolite obduction (Daoust 2007). This foliation is absent in the Saint-Daniel Mélange and is only developed in ultramafic rocks that are immediately adjacent to the metamorphic sole. The ophiolitic and metamorphic sole rocks, as well as the Saint-Daniel Mélange are, however, all affected by northwest- to northeast-trending F_3 folds and faults belonging to the D_3 phase of Tremblay and Pinet (1994), and Tremblay and Castonguay (2002). These are in turn overprinted by Acadian-related, upright and steeply-plunging F_4 folds (Fig. 3).

$^{40}Ar/^{39}Ar$ *results*

Published isotopic age constraints for the Lac-Brompton ophiolite and related metamorphic rocks are rare. A single K–Ar biotite age of 358 ± 16 Ma has been measured for a biotite- and muscovite-bearing granitoid crosscutting the mantle peridotites (Wanless 1963), which has been later interpreted as a crystallization age (St-Julien and Hubert 1975). However, De Souza et al. (2008) have shown that the dated rock is a peridotite-hosted granite similar to those of the Thetford-Mines ophiolite, suggesting that this Late Devonian age is related to thermal resetting during the Acadian Orogeny, or more simply to weathering.

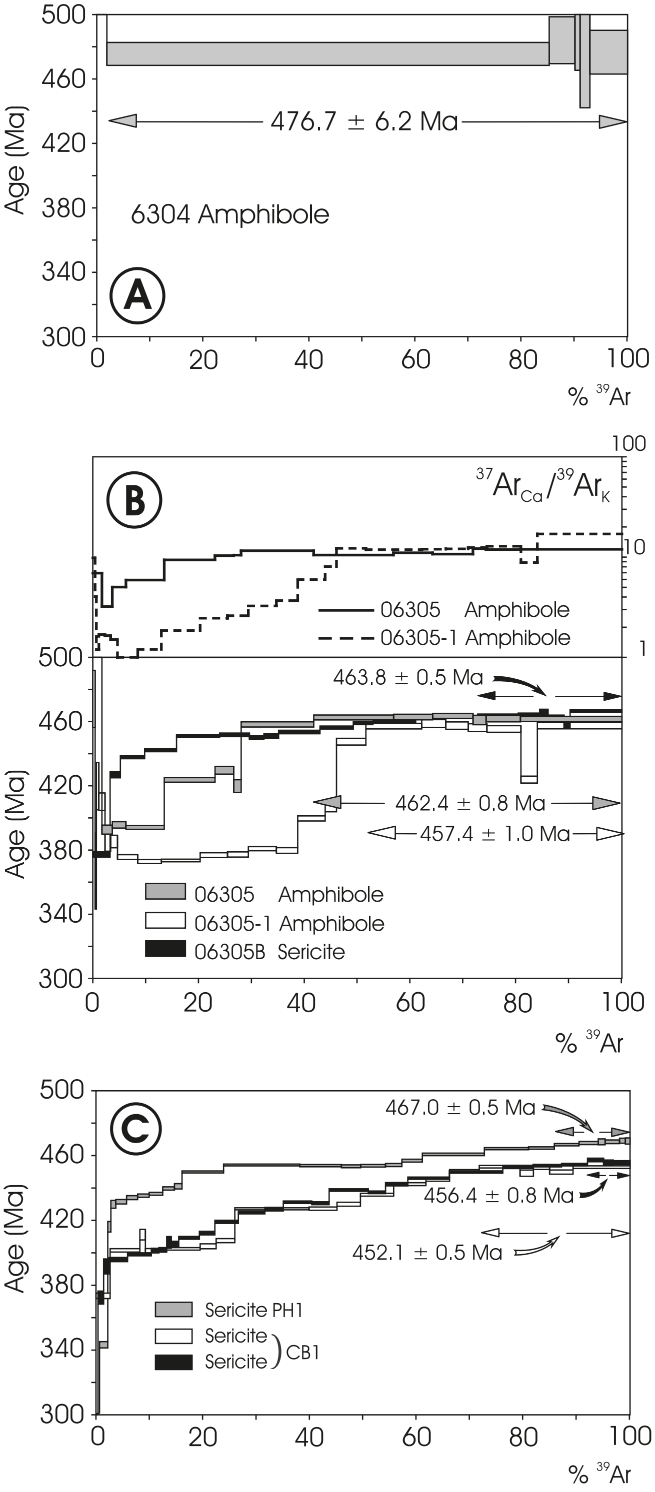
For this study, the analyzed samples of metamorphic and igneous rocks were collected in five different locations in the Lac-Brompton ophiolite (see Fig. 3). Amphibole sample 6304 was taken from a dyke of amphibolitized and coarse-grained pyroxenitic gabbro crosscutting the mantle. This gabbro is not foliated and is composed of magnesio-hornblende, zoisite, albite, and relict clinopyroxene, a mineral assemblage typical of oceanic hydrothermal metamorphism commonly developed in ophiolitic crustal rocks (Juteau and Maury 1999). The amphibole yielded a $^{40}Ar/^{39}Ar$ plateau age of 476.7 ± 6.2 Ma (Fig. 4*a*). The large error is correlative of the very high CaO/K$_2$O calculated ratios (ca. 130; $CaO/K_2O = 2.179 \times (^{37}Ar_{Ca}/^{39}Ar_K)$). There is no sign of a post-cooling disturbing event.

Four samples were collected from the metamorphic sole of the ophiolite. Samples 06305 and 06305B consist of amphibolite and mica schist, respectively, and were collected 70 m apart (Figs. 5*a*, 5*b*). The amphibolite sample is medium-grained and consists of brown to light green zoned amphibole, plagioclase and quartz. The mica schist sample shows a penetrative foliation marked by fine-grained muscovite (sericite), quartz, garnet, and chlorite. Both amphibole experiments from sample 06305 show variably staircase-shaped age spectra in the first 40%–50% of $^{39}Ar_K$ degassing, with a pseudo-plateau (24.7% of $^{39}Ar_K$) at ca. 375 Ma for the most disturbed one, which is also linked to the lowest measured $^{37}Ar_{Ca}/^{39}Ar_K$ ratios (Fig. 4*b*). The less disturbed amphibole experiment yields a high-temperature pseudo-plateau age at 462.4 ± 0.8 Ma supported by a flat $^{37}Ar_{Ca}/^{39}Ar_K$ segment with highest measured values. The most disturbed experiment yields a slightly younger pseudo-plateau age at 457.4 ± 1.0 Ma corresponding to a less regular $^{37}Ar_{Ca}/^{39}Ar_K$ segment, which could suggest a slight persistence of a disturbance in the high-temperature steps (Fig. 4*b*). These results are coherent with petrographic observation and microprobe analysis of the dated sample (Daoust 2007), which indicate that the amphiboles are zoned and characterized by Ca-poor and Ca-rich end members.

Sericite from sample 06305B also displays a staircase-shaped age spectrum, with low-temperature steps at 376.8 ± 1.6 Ma (Fig. 4*b*), whereas the high-temperature steps define a pseudo-plateau age at 463.8 ± 0.5 Ma, that is concordant with the amphibole age.

Samples PH1 and CB1 consist of mica schist similar to the one of sample 06305B. Sample PH1 was collected ca. 3 m beneath the unconformity marking the base of the Saint-Daniel Mélange (Figs. 5*c*, 5*d*). Both samples, PH1 and CB1. yield staircase-shaped age spectra, with an overprint that is much more pronounced for sample CB1 (Fig. 4*c*). Both experiments from sample CB1 yield reproducible age spectra that define high-temperature pseudo-plateau ages at 452.1 ± 0.5 Ma and 456.4 ± 0.8 Ma (Fig. 4*c*). On the other hand, sample PH1, with a less disturbed age spectrum, displays older high-temperature pseudo-plateau ages, up to 467.0 ± 0.5 Ma (Fig. 4*c*).

Fig. 4. $^{40}Ar/^{39}Ar$ age spectra for (*a*) amphibole of sample 6304; (*b*) amphibole and sericite from sample 06305 and 06305B, respectively; (*c*) sericite from samples PH1 and CB1. See Figs. 3 and 5 for location of sampling sites.



The Rivière-des-Plante Ultramafic Complex

The Rivière-des-Plante Ultramafic Complex (De Souza and Tremblay 2010) lies along the Baie Verte–Brompton line (Fig. 1). It is bounded on the northwest by a northwest-dipping D$_3$ backthrust fault, and is unconformably overlain by sedimentary rocks belonging to the Saint-Daniel Mélange to the southeast (Fig. 6). It comprises harzburgite, serpentinite, ophicalcite, gabbro, and granite, and has been interpreted as an eroded ophiolitic remnant comprising mantle peridotites that correlate with those of the Thetford-Mines ophiolite (De Souza and Tremblay 2010). The Rivière-des-Plante

Fig. 5. (*a*) Detailed geological map of the metamorphic sole of the Lac-Brompton ophiolite and Saint-Daniel Mélange (see Fig. 3 for location); (*b*) cross-section showing the location and tectono-stratigraphic setting of samples 06305, 06305B; (*c*) Detailed geological map of the Saint-Daniel Mélange and metamorphic sole of the Lac-Brompton ophiolite (see Fig. 3 for location); (*d*) cross-section showing the location and tectono-stratigraphic setting of sample PH1. Thick arrow indicates topping direction in the polymictic breccia. Common legend for Figs. 5*a*, 5*b*, 5*c*, and 5*d*.

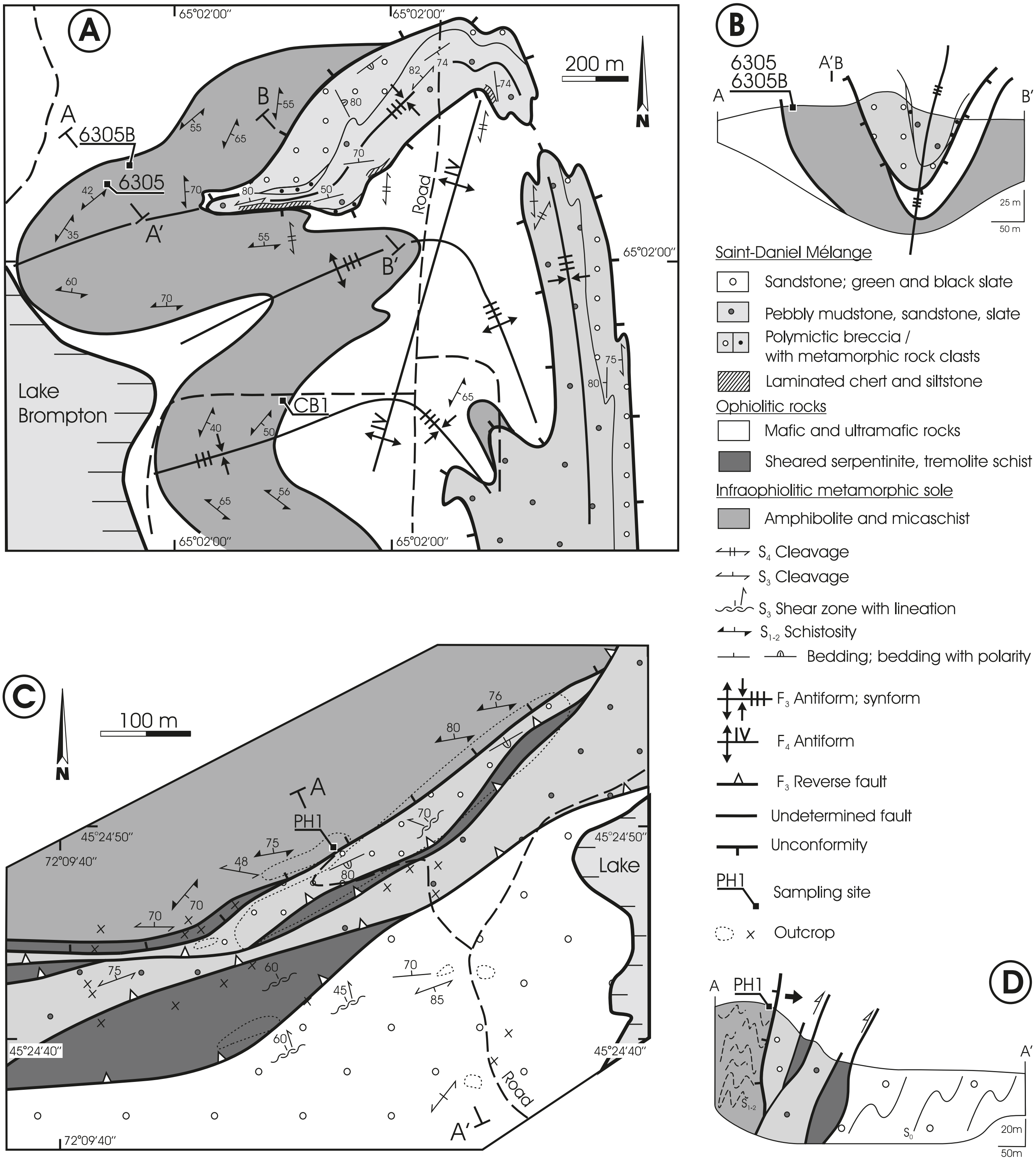
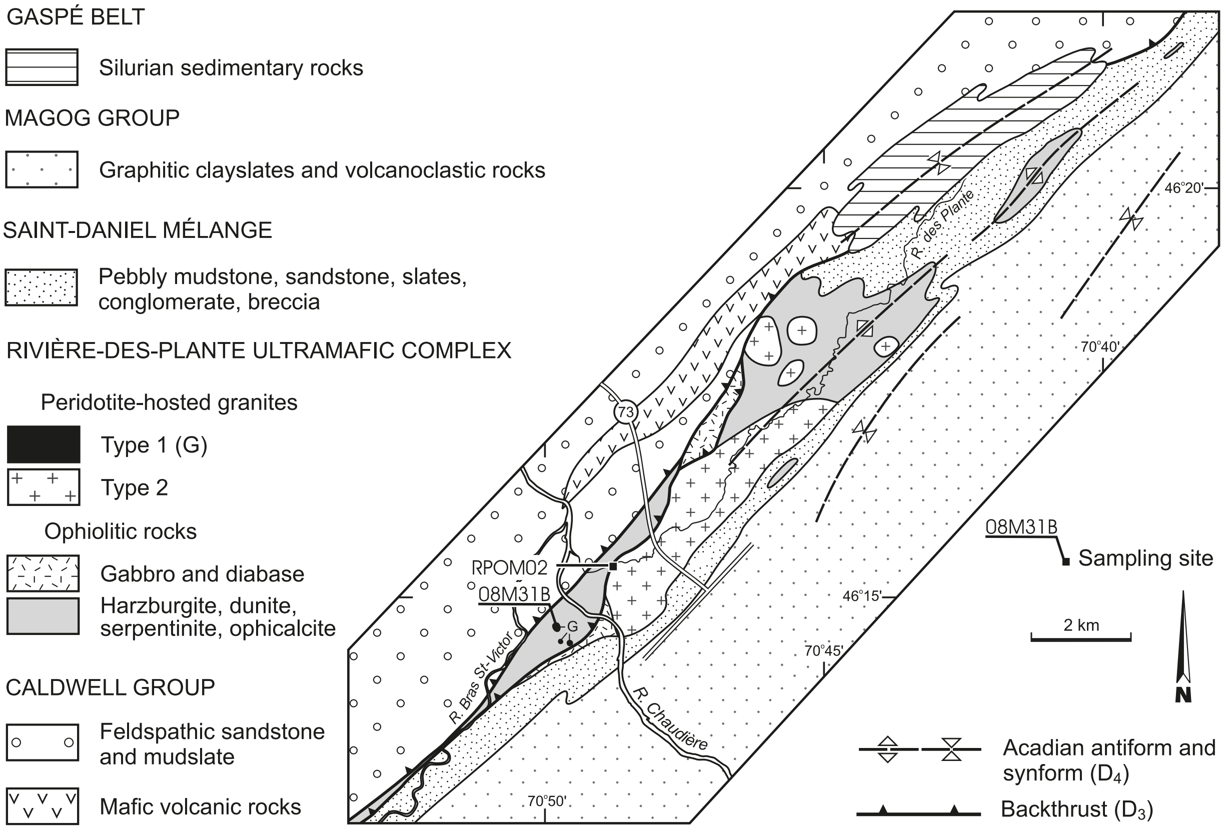


Fig. 6. Geological map of the Rivière-des-Plante Ultramafic Complex showing the location of samples RPOM02 and 08M31B (modified from De Souza and Tremblay 2010).



Ultramafic Complex is also characterized by the occurence of peraluminous granites that have been divided into two textural sub-types: xenolith-free type 1 and xenolith-bearing type 2 granites (De Souza and Tremblay 2010).

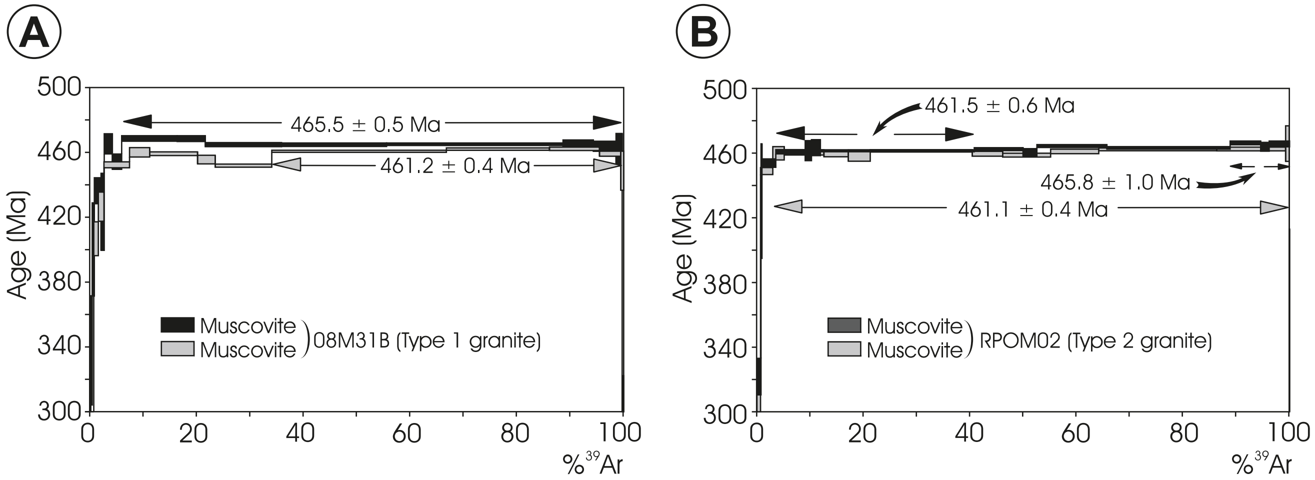
Type 1 granites occur as small intrusions (<100 m) in the southwestern part of the complex (Fig. 6), or as dykes and fault-bounded bodies less than 10 m wide. They are equigranular to porphyritic, medium- to coarse-grained, locally foliated, and often rodingitized along their margins. In thin section, these rocks are made up of euhedral to sub-euhedral plagioclase, quartz, K-feldspar, biotite, muscovite and minor zircon, apatite and oxides. Type 1 granites are peraluminous and have a normative composition of granite *sensu stricto*. Type 2 granites consist of randomly-oriented xenoliths dispersed in a medium-grained felsic matrix composed of K-feldspar, plagioclase, muscovite, reddish-brown biotite, zircon, and apatite. Chlorite and sericite aggregates are found as pseudomorphs after cordierite (Cousineau 1991; Trzcienski et al. 1992), and garnet has been locally observed. The xenoliths consist of subrounded-to-angular, schistose, and gneissic metasedimentary rocks and amphibolite. The mineralogical assemblages of the matrix and xenoliths suggest emplacement of these granitic rocks under low-pressure conditions (i.e., less than 3 kbar; Trzcienski et al. 1992). Type 2 granite is frequently foliated and locally deformed into a gneissic mylonitic facies (De Souza and Tremblay 2010). The sedimentary breccias marking the base of the Saint-Daniel Mélange are locally entirely made up of pebble- to boulder-size fragments of foliated to undeformed type 1 and type 2 granites, indicating that cooling and deformation of the granitic rocks must have preceded the sedimentation of the mélange.

$^{40}Ar/^{39}Ar$ results

The two analyzed samples that were collected in the Rivière-des-Plante Ultramafic Complex consist of a type 1 (sample 08M31B) and a mylonitic type 2 (RPOM02) granite (see Fig. 6 for location). Sample 08M31B is from an undeformed, coarse-grained porphyritic granite made up of quartz, sericitized plagioclase, K-feldspar, muscovite, and chloritized biotite. Muscovite forms randomly-oriented interstitial crystals with respect to feldspar and does not show evidence of dynamic recrystallization. The two analyzed muscovite grains from this sample yield distinct age spectra, a flat one with a plateau age at 465.5 ± 0.5 Ma, whereas the second one displays a slightly disturbed age spectrum with a high-temperature pseudo-plateau age at 461.2 ± 0.4 Ma (Fig. 7*a*).

Sample RPOM02 was collected at a site where the mylonitized facies of type 2 granite is best exposed and developed, and in fault contact with serpentinite. The sample shows a porphyroclastic mylonitic texture that is overprinted by a northwest-dipping cleavage genetically-related to SE-directed backthrusting (De Souza and Tremblay 2010). Two muscovite grains from sample RPOM02 were analyzed. One of them yields a staircase-shaped age spectrum that shows an increase in apparent ages from ca. 461.5 Ma in the low-tem-

Fig. 7. ^{40}Ar/^{39}Ar age spectra for muscovite from samples 08M31B and RPOM02 (see Fig. 6 for sample location).



perature steps, and to ca. 466 Ma (pseudo-plateau at 465.8 ± 1.0 Ma) in the high-temperature steps (Fig. 7*b*). The duplicated experiment displays a flat age spectrum with a plateau age at 461.1 ± 0.4 Ma, perfectly concordant with the low-temperature pseudo-plateau age (461.5 ± 0.6 Ma) of its alter ego (Fig. 7*b*).

The Nadeau Ophiolitic Mélange

The Nadeau Ophiolitic Mélange forms a 5 km-long and 700 m-wide lens-shaped inlier beneath the cover sequence of the Gaspé Belt, in the vicinity of the Maquerau–Mictaw inlier (Fig. 8; De Brouker 1987). It is made up of serpentinized peridotite, amphibolite, granitoid, mica schist, and quartzite. De Brouker (1987) interpreted the peridotite as sheared serpentinite forming the matrix of a mélange, but our mapping of the area rather suggests that the ultramafic rocks and granitoids form part of an ophiolitic massif that is underlain by sole-type amphibolite and mica schist (Figs. 8*a*, 8*b*, 8*c*). Peridotites of the Nadeau Ophiolitic Mélange consist of massive chromite-bearing dunite and harzburgite showing a high-temperature foliation typical of mantle rocks. The granitoids are massive or foliated, coarse- to fine-grained, and locally rodingitized at the contact with the host ultramafic rocks (De Brouker 1987). They have the modal composition of granite, granodiorite or tonalite, with varying amounts of muscovite and biotite. Their overall composition and petrographic characteristics suggest that they are peridotite-hosted granites similar to those crosscutting the mantle rocks of the Thetford-Mines ophiolite. Granitoids intrude the metamorphic sole rocks and the ultramafics; a critical relationship that is not documented in southern Quebec (Fig. 8*d*).

The antiformal culmination in which is exposed the Nadeau Ophiolitic Mélange is attributed to the Acadian Orogeny. It corresponds to northeast-trending folds in the Mictaw Group and Gaspé Belt (Fig. 8). The metamorphic fabric in the mica schist and amphibolite is interpreted as the result of Taconian, obduction-related metamorphism. A breccia unit located along the strike of, and bounding the Rivière-Port-Daniel Mélange, was previously interpreted as a tectonic breccia related to the Rivière-Port-Daniel fault (Williams and St-Julien 1982; De Brouker 1987). It consists of angular to rounded fragments of foliated metasandstone, granitic gneiss, and chloritic schist, and is interlayered with sedimentary rocks of the Mictaw Group (De Brouker 1987). These gradational contacts rather suggest that the breccia is of sedimentary origin and formed close to a topographic high including metamorphic rocks of the Maquereau Group. The breccia unit should thus be included in the Rivière-Port-Daniel Mélange, as illustrated in Fig. 8*a*. Moreover, the coexistence of ophiolitic and metasandstone fragments in the Rivière-Port-Daniel Mélange indicates that the source rocks consisted of both Humber and Dunnage zones lithologies.

^{40}Ar/^{39}Ar results

The samples that were collected in the Nadeau Ophiolitic Mélange for ^{40}Ar/^{39}Ar analysis consisted of coarse-grained muscovite-bearing granite (07AT99), mica schist (07AT100) and amphibolite (07AT98). The mica schist is intimately associated with the amphibolite, and consists of quartz, plagioclase, alkali feldspar, muscovite, biotite, chlorite, zircon, sphene, apatite, and garnet (De Brouker 1987). The two analyzed amphiboles from sample 07AT98 have yielded strongly disturbed and inconclusive age spectra (not shown). The muscovite from the mica schist, however, displays a perfect plateau age at 470.0 ± 0.4 Ma (Fig. 9*a*). The two analyzed muscovites from the granite provided slightly, but notably, distinct age spectra, a flat one with a plateau age at 475.1 ± 0.3 Ma (Fig. 9*a*), whereas the second one presents a subtle, but characteristic, saddle shape with low- and high-temperature apparent ages at ca. 474.5 Ma (mean at 474.5 ± 0.6 Ma) and a saddle minimum at 471.9 ± 0.7 Ma (Fig. 9*b*).

Interpretation and synthesis

A compilation of isotopic age data for peridotite-hosted granites, ophiolitic, and infraophiolitic metamorphic rocks, as well as biostratigraphic age constraints for the Magog and Mictaw groups is shown in Fig. 10, and will be used in the following sections to synthesize and discuss the ^{40}Ar/^{39}Ar data presented herein.

Ophiolitic gabbros

There are no U–Pb ages for the crustal sequence of the Lac-Brompton ophiolite, but valuable time constraints for its crystallization and cooling history can be inferred from our

Fig. 8. (*a*) Simplified geological map of the Maquereau–Mictaw inlier and Nadeau Ophiolitic Mélange (modified from De Brouker (1987)). (*b*) Geological map and (*c*) cross-section of the Nadeau Ophiolitic Mélange and adjacent rock units showing the location of samples 07AT98, 07AT99, and 07AT100 (geology from this study and compiled from De Brouker (1987)). (*d*) Photomontage showing the ultramafic rocks (UM), mica schist (M), amphibolite (AM), and peridotite-hosted granite (PHG) of the Nadeau Ophiolitic Mélange.

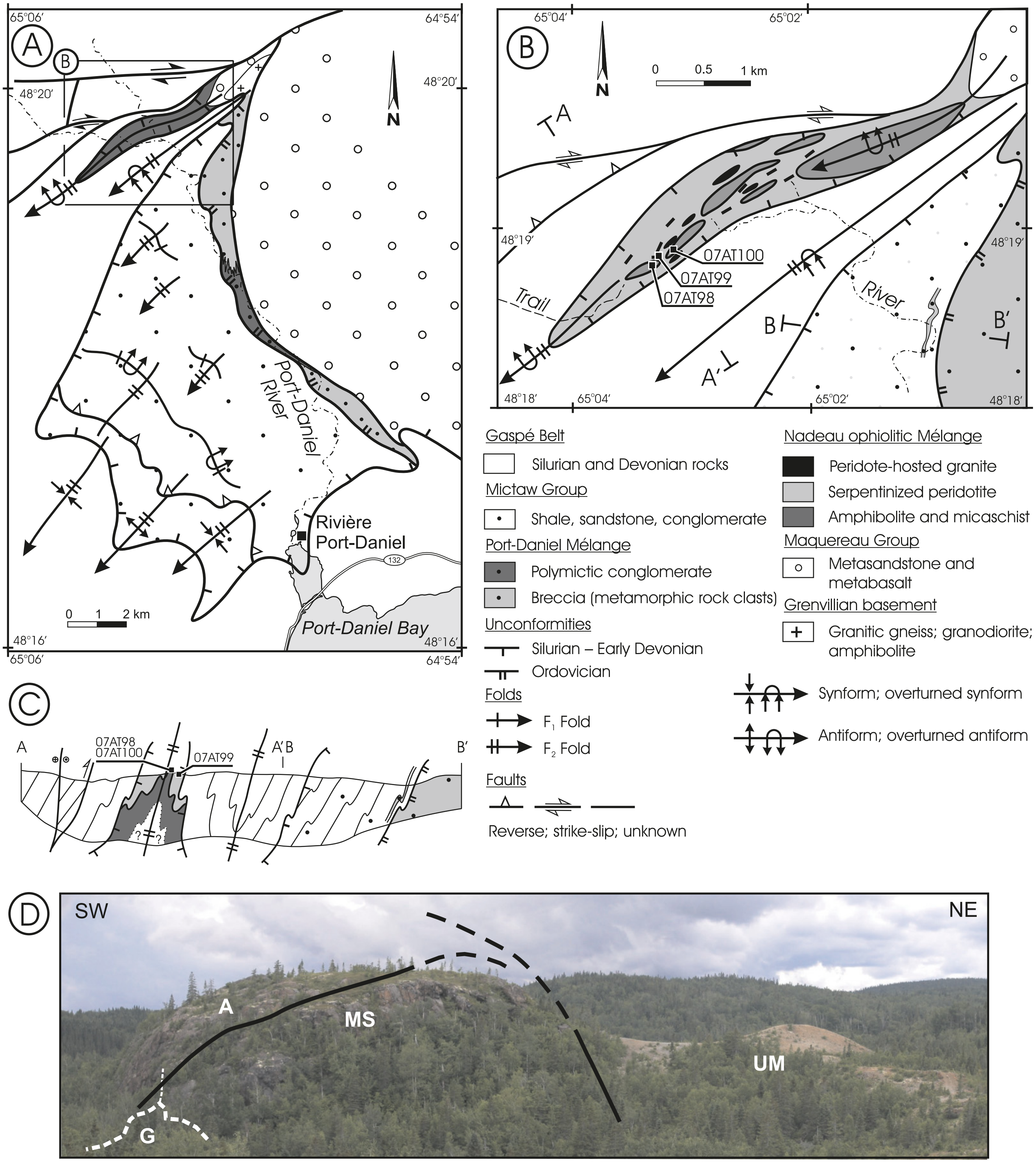
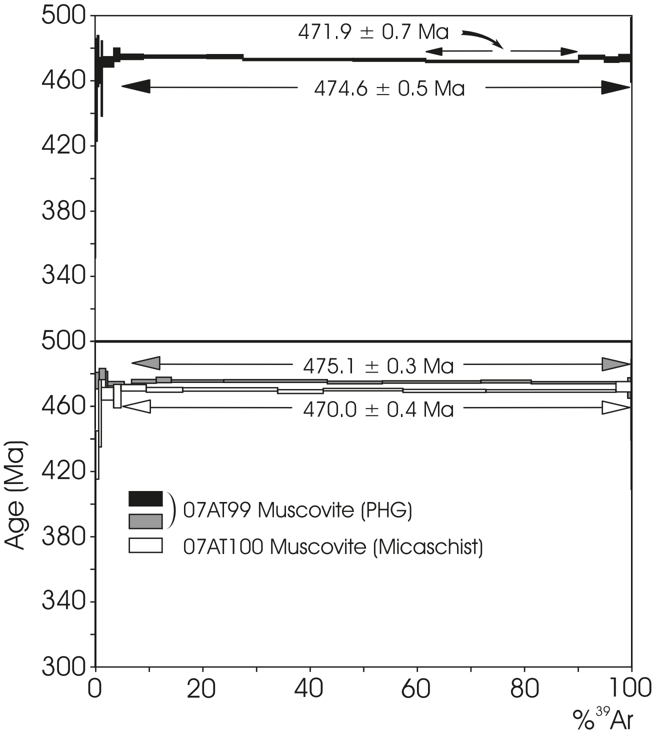


Fig. 9. ^{40}Ar/^{39}Ar age spectra for muscovite from samples 07AT99 and 07AT100.



^{40}Ar/^{39}Ar age data and correlation with the Thetford-Mines ophiolite. An amphibole plateau age of 476.7 ± 6.2 Ma for the ophiolitic gabbro (6304) provides the best minimum estimate for its formation. The Thetford-Mines and Lac-Brompton ophiolites have been interpreted as originating from the same oceanic slab (e.g., Schroetter et al. 2005; De Souza et al. 2008; Tremblay et al. 2009). Such an interpretation and correlation are supported by the concordance of our ca. 477 Ma amphibole age with the mean ^{40}Ar/^{39}Ar amphibole cooling age of 477.6 ± 3.5 Ma and U–Pb zircon crystallization age of 479.2 ± 1.6 Ma yielded by plagiogranites and gabbros of the Thetford-Mines ophiolite (Fig. 10; Tremblay et al. 2011; Whitehead et al. 2000). This suggests that both ophiolitic bodies share a similar cooling history and, therefore, formed more-or-less synchronously at ca. 479 Ma. However, the lack of plutonic facies in the ophiolitic complexes of the Gaspé Peninsula inhibits further correlations and comparisons with the cooling and crystallization history of the Mont-Albert Complex and Nadeau Ophiolitic Mélange.

Metamorphic sole rocks

Samples from the metamorphic sole of the Lac-Brompton ophiolite consistently yield amphibole and sericite age spectra showing evidence of thermal overprinting and (or) recrystallization. In spite of such overprint, these minerals still yield older increments with amphibole and sericite pseudo-plateau ages at ca. 463 Ma for samples 06305 and 06305B, and as old as ca. 467 Ma for micashist PH1. The slightly younger pseudo-plateau ages between ca. 452 and 457 Ma yielded by sericite and amphibole of samples CB1 and 06305, together with pseudo-plateau and low-temperature step ages at ca. 376 Ma calculated from samples 06305 and 06305B, indicates that such young ages are clearly related to an Acadian disturbance (Fig. 4*c*). Moreover, the ca. 4 Ma age discrepancy between the sericite pseudo-plateau ages of sample CB1 and the fact that they are younger than the inferred age of both the Magog Group and the Saint-Daniel Mélange (see below) suggest that, probably due to ^{40}Ar* loss, these ages represent minimum estimates. This is also consistent with the compositional zonation of the amphiboles and the persistence of variable ^{37}Ar$_{Ca}$/^{39}Ar$_K$ ratios into the high-temperature steps of experiment 06305–1 (Fig. 4*b*). The Ca-poor component observed in the low-temperature steps propably represents partial recrystallization of previously-formed Ca-rich amphibole. On the other hand, sericite samples PH1 and 06305B, and amphibole experiment 06305 display less disturbed age spectra with older high-temperature pseudo-plateau ages up to 467.0 ± 0.5 Ma (Fig. 4*c*). The latter sericite age represents the best estimate for the cooling of the metamorphic sole rocks below the closure temperature of muscovite. The correlation of a medium to high- temperature pseudo-plateau at 462.4 ± 0.8 Ma with a flat ^{37}Ar$_{Ca}$/^{39}Ar$_K$ segment for amphibole experiment 06305, and its concordance with the high-temperature sericite age of 463.8 ± 0.5 Ma for sample 06305B (Fig. 4*b*), indicate that the sole rocks were locally affected by an episode of thermal overprinting and (or) recrystallization at ca. 463 Ma. It can thus be suggested that the sole amphibolites and mica schists initially crystallized in Early (?) to Middle Ordovician times, were exhumed at or prior to ca. 467 Ma, and then transported over the Laurentian margin and locally metamorphosed at ca. 463 Ma.

The ^{40}Ar/^{39}Ar ages and the inferred series of events for the infraophiolitic metamorphic rocks of the Lac-Brompton ophiolite are consistent with the crystallization and cooling history of the metamorphic sole of the Thetford-mines ophiolite, as reported by Tremblay et al. (2011). The latter rocks yield ^{40}Ar/^{39}Ar ages of ca. 471 Ma on amphibole and of 466 Ma on muscovite, with evidence for recrystallization as young as ca. 460–457 Ma. Such ages have been interpreted as representing the successive cooling of the metamorphic sole below the closure temperature of amphibole and muscovite, respectively, and later recrystallization of the muscovites during continental thrusting of the ophiolite and uplifting of the collisionnal orogenic wedge (Tremblay et al. 2011).

The 470.0 ± 0.4 Ma muscovite plateau age from mica schists of the Nadeau Ophiolitic Mélange (07AT100), may result either from recrystallization or cooling below the closure temperature of muscovite, indicating that these metamorphic rocks were exhumed and thrusted onto the Laurentian margin with the overlying ophiolitic rocks as early as late Arenig. Data presented in this study for the Nadeau Ophiolitic Mélange are therefore significantly older than the available isotopic age constraints for the Mont-Albert Complex (Fig. 10), where the metamorphic sole rocks yield amphibole and muscovite cooling ages of ca. 465 to 459 Ma (Fig. 10; c.f., Malo et al. 2008).

Peridotite-hosted granites

Petrographic and ^{40}Ar/^{39}Ar data on muscovites from the peridotite-hosted granites of the Rivière-des-Plante Ultra-

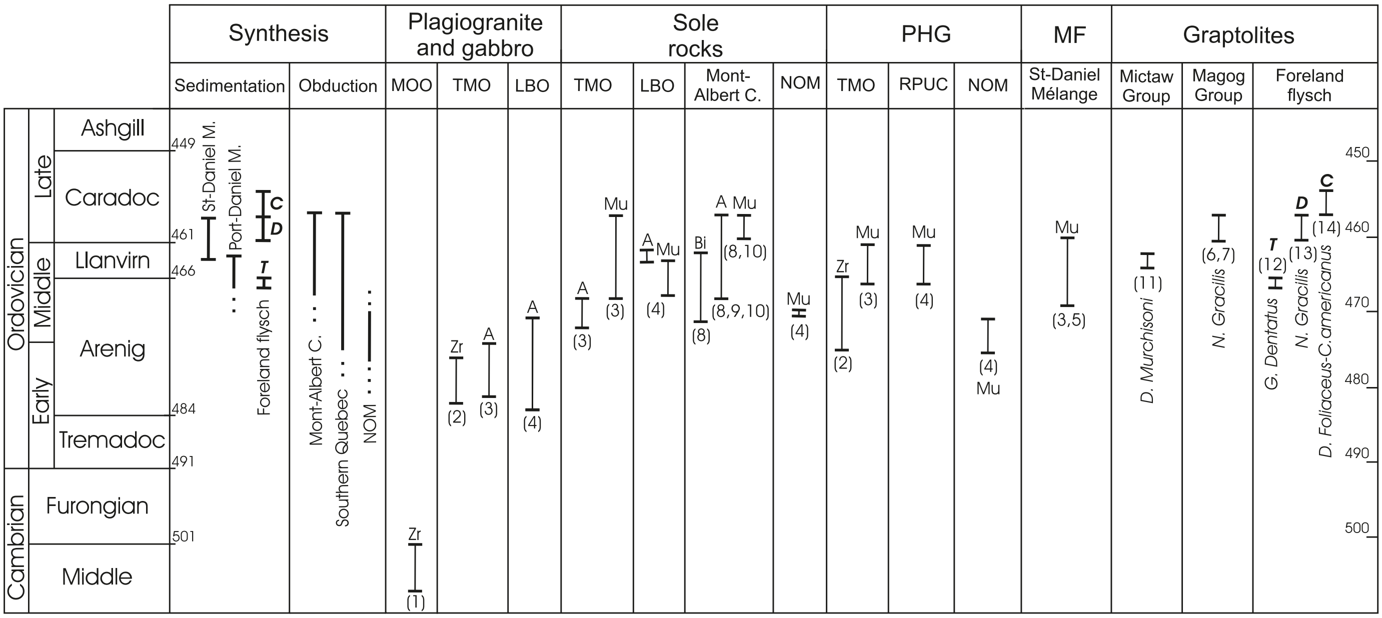


Fig. 10. Compilation and synthesis of U–Pb and $^{40}Ar/^{39}Ar$ isotopic age data for ophiolitic rocks, infraophiolitic metamorphic sole rocks, and peridotite-hosted granites of the southern Québec and Gaspé Peninsula Appalachians, as well as biostratigraphic age constraints for the Magog and Mictaw groups, and the Trourelle, Deslandes, and Cloridorme formations. Age intervals shown in this figure take into account the uncertainties related to the isotopic age data. LBO, Lac-Brompton ophiolite; MF, Metamorphic rock fragments; MOO, Mont-Orford ophiolite; NOM, Nadeau Ophiolitic Mélange; PHG, Peridotite-hoste granites; RPUC, Rivière-des-Plante Ultramafic Complex; TMO, Thetford-Mines ophiolite. Stratigraphic units: C, lower Cloridorme Formation; D, Deslandes Formation; T, Trourelle Formation; $^{40}Ar/^{39}Ar$ data: A, Amphibole; Mu, Muscovite; U–Pb data: Zr, Zircon. Data sources: (1) David and Marquis (1994); (2) Whitehead et al. (2000); (3) Tremblay et al. (2011); (4) this study; (5) Schroetter et al. (2006); (6) Riva (1974); (7) Cousineau (1990); (8) Malo et al. (2008); (9) Lux (1986); (10) Pincivy et al. (2003); (11) De Brouker (1987); (12) Hiscott (1978); (13) Riva (1968) and Bloechl (1996); (14) Prave et al. (2000). Time scale from Sadler et al. (2009) and Gradstein et al. (2004), and graptolite zones from Webby et al. (2004).

mafic Complex, and comparison with age data for those of the Thetford-Mines ophiolite (Fig. 10), clearly show that they have undergone a polyphase cooling and crystallization history. The 08M31B plateau age at 465.5 ± 0.5 Ma and the concordant RPOM02 high-temperature pseudo-plateau at 465.8 ± 1.0 Ma for undeformed type 1 and mylonitic type 2 granites, respectively, suggest that the Rivière-des-Plante granites cooled below the closure temperature of muscovite at ca. 466 Ma. In both cases, the age and spectra shape discrepancies of duplicated analyses and the staircase-shaped age spectrum of the first RPOM02 muscovite experiment, indicate that the studied samples record a heterogeneous disturbance at ca. 460 Ma, regardless of deformation. Although it remains to be confirmed, such a disturbance could be the result of heterogeneous fluid-rock interactions with partial to complete induced recrystallizations (Tartèse et al. 2011).

The age spectra yielded by the granitic rocks of the Rivière-des-Plante Ultramafic Complex are almost identical to those obtained for similar granitoids of the Thetford-Mines ophiolite, which suggest initial cooling of muscovite and later recrystallization at ca. 466 and 461 Ma, respectively (Tremblay et al. 2011). Such similarities in the $^{40}Ar/^{39}Ar$ ages, not only indicate a common cooling and crystallization history for these granitic rocks, but further support the inferred correlation of ophiolitic rocks and granitoids of both complexes. This, as well as the mean 469.5 ± 2.8 Ma U–Pb age yielded by peridotite-hosted granites of the Thetford-Mines ophiolite (Whitehead et al. 2000), suggests that granitic rocks of the Rivière-des-Plante Ultramafic Complex also initially crystallized at ca. 470 Ma.

However, muscovites from a peridotite-hosted granitoid of the Nadeau Ophiolitic Mélange yielded significantly older plateau, and high- to low-temperature step ages of ca. 475 Ma. The saddle-shaped age spectrum of the duplicate experiment of sample 07AT99 is evidence for a disturbance at or slightly after ca. 472 Ma. The partial re–neocrystallization of white micas can generate saddle-shaped age spectra that are the result of distinctive degassing patterns of initial–inherited and re–neocrystallized domains for a given crystal (e.g., Cheilletz et al. 1999; Alexandrov et al. 2002). According to these authors and in good agreement with plateau ages yielded by (*i*) duplicated muscovite experiment and (*ii*) mica schist muscovite from the metamorphic sole, the initial crystallization or cooling of the 07AT99 muscovite would have occurred at ca. 475 Ma or earlier, and it would have recorded a partial recrystallization history linked to deformation and (or) fluid circulation at or slightly later than ca. 472 Ma.

Our data and compiled U–Pb and $^{40}Ar/^{39}Ar$ age constraints for peridotite-hosted granites of southern Quebec and the Nadeau Ophiolitic Mélange highlight significant discrepancies in their crystallization and cooling history from one area to the other. Considering the nature of the dated mineral species and the isotopic dating methods that were used, it can be concluded that granitic rocks of the Nadeau Ophiolitic Mélange cooled below the closure temperature of muscovite ca.

10 Ma before those of southern Quebec and probably crystallized more than 3–5 Ma earlier (Fig. 10).

Discussion

As previously mentioned, the obduction of suprasubduction, Tethyan-type ophiolites, can be defined as a series of processes conducting to the final emplacement of oceanic lithosphere onto an adjacent continental margin. These are (*i*) intra-oceanic subduction and formation of an ophiolite and its metamorphic sole, (*ii*) exhumation of the metamorphic sole, (*iii*) thrusting of the ophiolitic nappe over the continental margin, and (*iv*) its subaerial exposure as part of an orogenic belt (Wakabayashi and Dilek 2003). Obduction sensu stricto can be considered as ending with the syncollisional uplift and erosion of the ophiolite and underlying metamorphic rocks (Tremblay et al. 2011). This can be accomplished once the ophiolitic nappe is being uplifted and transported passively on top of a foreland-propagating thrust system, as continental and (or) oceanic material is progressively underplated beneath it (Searle and Cox 1999; Bortolotti et al. 2005; Cloos et al. 2005; Schroetter et al. 2006; Tremblay et al. 2011). In this tectonic framework, the main issues that will be discussed in the following sections are the correlation of ophiolitic complexes along the Baie Verte-Brompton line, the chronology of events related to ophiolite obduction onto Laurentia, and the exhumation processes leading to mélange formation and termination of obduction.

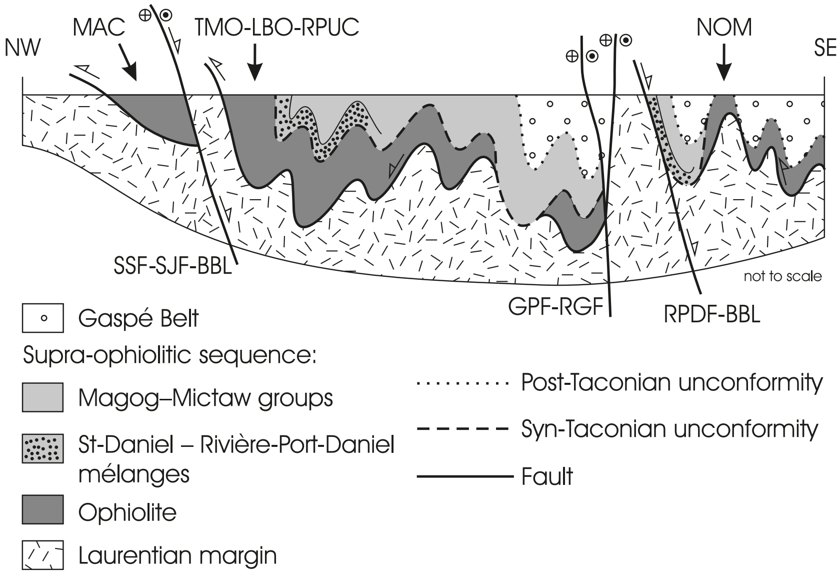
Obduction diachronism in the Quebec Appalachians

In the Quebec Appalachians, major ophiolitic complexes and serpentinite bodies marking the Baie Verte-Brompton line have been interpreted as more-or-less correlative fragments of obducted oceanic lithosphere formed in short-lived subduction-related pericontinental marginal basins (Fig. 11; Hébert and Bédard 2000; Huot et al. 2002; Schroetter et al. 2003; De Souza et al. 2008; Malo et al. 2008; Tremblay et al. 2009). The petrography, geochemical composition, and isotopic ages of infraophiolitic metamorphic rocks, all suggest that these are mostly derived from oceanic and (or) continental margin mafic igneous protoliths with minor amounts of interlayered sedimentary rocks (Clague et al. 1981; Feininger 1981; Gagnon and Jamieson 1986; De Brouker 1987; Daoust 2007). Since ^{40}Ar/^{39}Ar ages for metamorphic soles are considered as cooling ages, and that sole amphibolites cool rather rapidly below the closure temperature of amphibole, the ^{40}Ar/^{39}Ar amphigole ages for such metamorphic rocks are more probably 1 to 5 Ma younger than peak metamorphism (Hacker 1990, 1991; Hacker et al. 1996). The sole protoliths were likely overthrusted and metamorphosed during nascent stages of obduction, after the crystallization of the ophiolites between ca. 479 and 472 Ma in southern Quebec, and between ca. 470 and 466 Ma for the Mont-Albert Complex. These metamorphic sole rocks were then exhumed and successively cooled below the closure temperatures of amphibole and muscovite, from ca. 471 to 467–466 Ma in southern Quebec, and 465 Ma to 459 Ma in the Mont-Albert Complex. Although no ^{40}Ar/^{39}Ar amphibole age has been obtained for the Nadeau Ophiolitic Mélange, our ^{40}Ar/^{39}Ar ca. 470 Ma muscovite age of the micaschists (sample 07AT99) suggests that the sole amphibolite there was uplifted and cooled below the muscovite closure temperature 3–12 Ma earlier than in other infraophiolitic metamorphic rocks of the Quebec Appalachians.

A minimum age for underthrusting and anatectic melting of the Laurentian margin beneath the obducting ophiolites is provided by the mean 469.5 ± 2.8 Ma U–Pb zircon crystallization age of the peridotite-hosted granites belonging to the Thetford-Mines ophiolite (Whitehead et al. 2000), and the ca. 475 Ma ^{40}Ar/^{39}Ar muscovite cooling age we obtained for similar rocks of the Nadeau ophiolitic Mélange. As emphasized by Whitehead et al. (2000) and Tremblay et al. (2011), up to ca. 2 Ma of shear heating at the base of the ophiolite nappe may have been necessary to account for partial melting of continental margin siliciclastic rocks. This suggests that, in southern Quebec, underthrusting of the Laurentian margin would have been initiated at ca. 471 Ma or slightly earlier, at least 5 Ma prior to the cooling of the peridotite-hosted granites below the muscovite closure temperature at 465–466 Ma. By applying the same reasoning to the Nadeau Ophiolitic Mélange granitoids, it can be inferred that underthrusting and anatectic melting of the continental margin there was initiated well before 475 Ma, possibly earlier than ca. 480 Ma. Following their initial emplacement onto Laurentia, the ophiolitic nappes were actively translated over the margin at least until ca. 460–457 Ma in southern Quebec and in the Mont-Albert Complex, as suggested by ^{40}Ar/^{39}Ar muscovite and amphibole ages related to the latest increments of recrystallization and (or) cooling of the infraophiolitic metamorphic rocks from both areas (Fig. 10). By the latest Arenig – early Caradoc, active thrusting and shear deformation of the ophiolitic nappes was progressively transferred to lower thrust slices within the continental margin, whereas the uplifting of the ophiolites and underlying metamorphic sole rocks was more-or-less completed.

The U–Pb and ^{40}Ar/^{39}Ar geochronological constraints for ophiolitic complexes of the Quebec Dunnage zone, therefore suggest that orogenic processes leading to the Taconian obduction of ophiolitic nappes onto Laurentia have been diachronous along the strike of the orogenic belt. Unequivocal evidence for interactions between Laurentia and ophiolitic nappes between ca. 480 and 475 Ma in the Nadeau Ophiolitic Mélange, suggests that ophiolite emplacement was initiated earlier in the vicinity of the St-Lawrence promontory than in the central segment of the Quebec embayment. ^{40}Ar/^{39}Ar muscovite ages also indicate a significant ca. 3–10 Ma delay in the cooling history of the metamorphic soles and peridotite-hosted granites from both areas, and ca. 5 Ma between amphibole and muscovite ages for the sole rocks of the southern Quebec ophiolites and the Mont-Albert Complex. Such variations in the age data can be tentatively attributed to the inherited irregular geometry of the Laurentian margin that developed in Early Paleozoic times (Thomas 1977). Obduction-related deformation and metamorphism were likely older at the periphery of the Quebec embayment than in its central segment (Fig. 1*a*), where obduction was vanishing by ca. 460–457 Ma and lasted between approximately 10 to 22 Ma. Using a conservative convergence rate of 1 cm/a, it can be extrapolated that the Quebec ophiolites are therefore rooted at a minimum distance of 100 km to the southeast (present coordinates) of their current location.

Fig. 11. Composite and schematic interpretative section across the post-Acadian Laurentian margin of the Québec Appalachians showing the location and stratigraphic position of the various ophiolitic complexes, supra-ophiolitic sedimentary sequences and Gaspé Belt basin, as well as major structural features and unconformities. BBL, Baie Verte–Brompton line; GPF, Grand Pabos fault; LBO, Lac-Brompton ophiolite; MAC, Mont-Albert Complex; NOM, Nadeau Ophiolitic Mélange; RGF, Rivière Garin fault; RPDF, Rivière-Port-Daniel fault; RPUC, Rivière-des-Plante Ultramafic Complex; SJF, Saint-Joseph fault; SSF, Shickshock Sud fault; TMO, Thetford-Mines ophiolite.



Syn-Taconian exhumation and sedimentation in the Quebec Appalachians

Thrusting of ophiolites onto a continental margin ultimately leads to their exhumation and subaerial exposure, and to the formation of syncollisional sedimentary basin(s) and olistostromal mélanges derived from the erosion of the uplifted orogenic wedge (Gray et al. 2000; Bortolotti et al. 2005; Cloos et al. 2005; Tremblay et a. 2011). Examples of such sedimentary units are the Saint-Daniel and Rivière-Port-Daniel mélanges. Both are characterized by sedimentary breccias and conglomerates that comprise ophiolitic, metamorphic, and sedimentary rock fragments, and are interlayered with mudstone and chert (De Brouker 1987; Schroetter et al. 2006; De Souza et al. 2008; Tremblay et al. 2009). Metasedimentary rock fragments in the Saint-Daniel Mélange yielded $^{40}Ar/^{39}Ar$ muscovite ages varying between 467 and 463 Ma in the Thetford-Mines area (Fig. 10; Schroetter et al. 2006; Tremblay et al. 2011), suggesting rapid uplifting and recycling of the Taconian orogenic wedge. Graptolite-bearing slates and sandstones overlying the Saint-Daniel and Rivière-Port-Daniel mélanges, belong to the Llanvirn and early Caradoc Magog and Mictaw groups (Fig. 10; Riva 1974; De Brouker 1987; Cousineau 1990). The age of the Saint-Daniel Mélange can be therefore tightly bracketed in the 463–461 to 456 Ma interval, whereas a minimum age of ca. 462 Ma can be suggested for the Rivière-Port-Daniel Mélange (Fig. 10). Mélange formation and syncollisional basin development were thus initiated earlier in Gaspé Peninsula than in southern Quebec, which is consistent with the inferred diachronism in the exhumation history of both areas.

Further evidence for syn-obduction sedimentation is provided by comparing the isotopic age constraints presented herein with the stratigraphic record of the Appalachian foreland of the Gaspé Peninsula. There, the late Arenig – early Llanvirn Tourelle Formation (Fig. 10; Biron 1972), located ca. 35 km to the NE of the Mont-Albert Complex, is the oldest of a series of chromite- and mafic detritus-bearing flysch units (Figs. 1*a*, 2; Hiscott 1978, 1995). Paleocurrent and petrographic provenance data for the Tourelle Formation suggest that detritus were transported westward into a foredeep basin, away from the St. Lawrence promontory, and were derived from the erosion of a Grenville-type basement, variously-metamorphosed continental margin rocks and ophiolitic rocks (Hiscott 1978). The youngest ophiolite clast-bearing flysch units of the Gaspé Peninsula foreland are the Caradoc Deslandes Formation and the lower part of the Cloridorme Formation (Figs. 1*a*, 2; Prave et al. 2000). Again, this is consistent with the onset of ophiolite exhumation at 475–470 Ma in the vicinity of the St. Lawrence promontory, the final emplacement of the Mont-Albert Complex at 459–457 Ma, and with the obduction diachronism highlighted above (Fig. 10).

We believe that a similar suturing history took place along the entire length of the Quebec Appalachians. Obduction of the ophiolites onto the Laurentian margin occurred along northwest-directed and shallow-dipping thrust surfaces, thereby creating an almost flat-lying suture zone (Fig. 11). The syn-obduction uplift and erosion of an accretionnary ridge(s) made up of ophiolitic and metamorphic rocks conducted to the formation of olistostromal mélanges as a result of mass wasting on top of the advancing ophiolite nappe(s), and to the sedimentation of foredeep successions. Finally, the progressive deepening and stabilization of the basin during the waning stages of obduction, led to the deposition of thick onlapping flysch sequences represented by the Magog and Mictaw groups. As shown on Fig. 11, the existence of late- to post-Ordovician unconformities, the occurrence of Late Silurian – Early Devonian normal faults, as well as the superposed Acadian deformation (Tremblay and Pinet 2005; Malo et al. 2001, 2008) account for missing sections and additional structural complexities in the pre-Silurian stratigraphic record of the Quebec Appalachians.

Comparisons with northern New England and Newfoundland

Ophiolites, mafic-to-ultramafic complexes, arc-related rocks, and serpentinite slivers that occur in a structural setting similar to those of southern Quebec are also known along the strike of the Baie Verte–Brompton line (and correlative structures) in Newfoundland and New England (Church 1977; Doolan et al. 1982; Williams and St-Julien 1982; Karabinos et al. 1998; van Staal et al. 1998; Kim and Jacobi 2002; van Staal 2007). In the Baie-Verte Peninsula of western Newfoundland, for instance, Tremadocian ophiolitic rocks are overlain by the Flatwater Pond and Snooks Arm groups (Hibbard 1983; Bédard et al. 2000; Skulski et al. 2010), both representing correlative units of an ophiolite cover sequence to which has been attributed a maximum age of ca. 479 Ma (Skulski et al. 2010). The Flatwater Pond and Snooks Arm groups comprise abundant mafic and felsic volcanic rocks that overlie iron formations and conglomerates. Megabreccias and olistostromes marking the base of the Flatwater Pond Group comprise ophiolite-derived fragments and metamorphic rock clasts attributed to erosion of the metamorphosed Laurentian continental margin (Kidd 1974; Williams and St-Julien 1982; Skulski et al. 2010). West of the Baie Verte–Brompton line, Middle Cambrian to Tremadocian ophiolitic rocks belonging to the Bay of Islands Ophiolite and St-Anthony Complex (Williams and Smyth 1973; Karson and Dewey 1978; Suhr and Cawood 2001) are underlain by metamorphic sole amphibolites that yielded ^{40}Ar/^{39}Ar amphibole ages of 469 ± 5 and 489 ± 5 Ma, respectively (Dallmeyer and Williams 1975; Dallmeyer 1977; new decay constant), suggesting that obduction may have been initiated earlier in western Newfoundland than in Quebec, or that it overlaps in both areas. As for the Quebec Appalachians, stratigraphic relationships and age data from the Baie-Verte Peninsula indicate that mélange formation has been coeval with ophiolite obduction, although it was followed there by a much more voluminous amount of mafic volcanism (Bédard et al. 2000; Skulski et al. 2010) rather than Magog- or Mictaw-type flysch sedimentation.

In western New England, the tectonic units of the Baie Verte–Brompton line extend into the Rowe-Hawley belt, where arc-related and ophiolitic rocks are poorly-preserved as strongly dismembered amphibolite, peridotites and (or) serpentinite slivers, gneisses, and schists that were accreted to Laurentia during the Early to Middle Ordovician (Doolan et al. 1982; Stanley and Ratcliffe 1985; Kim and Jacobi 1996; Karabinos et al. 1998; Coish and Gardner 2004; Coish 2010). Moreover, the Saint-Daniel Mélange and the Magog Group are only locally present to totally absent from the geological record south of the Quebec–Vermont border. The lack of well-preserved ophiolites and related syncollisional deposits in western New England suggests that, in contrast to the Quebec and Newfoundland Appalachians, large-scale ophiolite obduction was probably of minor importance there during the Taconian Orogeny, such an hyposthesis being supported by a south-directed decrease in the Cr and Ni content of Ordovician foreland flysch units from the Canadian to the US Appalachians (Hiscott 1984).

Conclusion

Geological and ^{40}Ar/^{39}Ar geochronological data for the Lac-Brompton ophiolite, the Rivière-des-Plante Ultramafic Complex in southern Quebec, and the Nadeau Ophiolitic Mélange in the Gaspé Peninsula, suggest that they form, along with the Thetford-Mines and Mont-Albert ophiolitic complexes, eroded remnants of a composite ophiolitic slab. Ophiolite obduction was initiated with the formation of metamorphic sole rocks between ca. 479 and 472 Ma in southern Quebec and possibly as late as 470–466 Ma in the Mont-Albert Complex, shortly after the crystallization of the ophiolitic rocks. Underthrusting of the Laurentian margin beneath the obducting ophiolites was first initiated along the margin of the St. Lawrence promontory between ca. 480 and 475 Ma, earlier than in southern Quebec at 472–470 Ma. The progressive exhumation and continental thrusting of the ophiolites over the margin, between 471–457 Ma in southern Quebec and 465–457 Ma in the Mont-Albert Complex, has ultimately led to the uplift and unroofing of the orogenic wedge. This has resulted in the formation of the Saint-Daniel and Rivière-Port-Daniel mélanges as part of syncollisional sedimentary basins on top of the ophiolitic nappes, and foreland flysch successions between the latest Arenig (?) to early Caradoc. Diachronism in the tectono-sedimentary evolution along the strike of the Taconian Orogeny in the Quebec Appalachians may be likely attributed to the irregular geometry of the Early Paleozoic Laurentian margin. Also, lithotectonic variations along the Baie Verte–Brompton line, from western New England to western Newfoundland, highlight additional complexities in the Taconian obduction history that may also be the result of an irregular collision zone.

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