

The Advocate ophiolite mantle, Baie Verte, Newfoundland: regional correlations and evidence for metasomatism¹

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Abstract: Mantle rocks of the Advocate ophiolite near Flatwater Pond (Baie Verte, Newfoundland) are dominated by harzburgite tectonites, which are extensively converted to listvenite along the Baie Verte Road fault and represent a potential gold exploration target. Most Advocate harzburgites have forsteritic olivine (Fo_{90.5} to Fo₉₃) and Cr-spinels, with Cr# (= 100Cr/(Cr + Al)) between 52 and 64 and Mg# (= 100Mg/(Mg + Fe²⁺)) between 56 and 68. These mineral chemical signatures, together with high whole-rock MgO (46%–48%), low Al₂O₃ (<1%), and TiO₂ (<0.003%), imply the Advocate harzburgites are refractory residues after ca. 25%–35% melting. Cr-spinel compositions of Advocate mantle rocks overlap with Cr-spinels from the mantle rocks of the Point Rouse and Betts Cove ophiolites, with Mg# higher than those of Bay of Islands or Thetford Mines mantle Cr-spinels. Although refractory in terms of major elements and mineral chemistry, Advocate harzburgites contain high La–Ce–Pr–Pb–Nd–Sm–Zr contents suggestive of pervasive metasomatism. Similar geochemical signatures occur in all ophiolitic mantle rocks from the Baie Verte Peninsula examined so far. The enrichments are not consistent with supra-subduction zone syn-melting metasomatism as observed in other Appalachian ophiolites. The apparent absence of visible metasomatic channels in most outcrops suggests that metasomatism occurred before obduction by diffuse percolation, but the nature and origin of the metasomatic agent remain speculative. The similarities of mineral and whole-rock geochemistry imply that all mantle rocks from Baie Verte ophiolites are correlative and may represent remnants of a single obducted slab.

Résumé : Les roches du manteau de l'ophiolite Advocate (Baie Verte, Terre-Neuve), à proximité du parc provincial de Flatwater Pond, sont dominées par des tectonites à harzburgite, lesquelles ont été en grande partie changées en listvenite le long de la faille de la route de Baie Verte; elles représentent une cible possible pour l'exploration de l'or. La plupart des harzburgites Advocate contiennent de l'olivine forstérite (Fo_{90.5} à Fo₉₃) et des spinelles chromifères où le rapport Cr (Cr# = 100Cr/(Cr + Al)) se situe entre 52 et 64 et le rapport Mg (Mg# = 100Mg/(Mg + Fe²⁺)) se situe entre 56 et 68. Ces signatures minérales-chimiques, avec des compositions élevées de MgO pour la roche entière (46–48 %), faibles en Al₂O₃ (<1 %) et en TiO₂ (<0,003 %) signifient que les harzburgites Advocate sont des résidus de réfractaires découlant d'une fusion de 25 à 35 %. Les compositions des spinelles chromifères des roches du manteau Advocate chevauchent celle des spinelles chromifères provenant des roches du manteau des ophiolites de Point Rouse et Betts Cove et ont les rapports Mg plus élevés que ceux des spinelles chromifères de Bay of Islands ou de Thetford Mines. Bien que réfractaires en termes d'éléments majeurs et de chimie des minéraux, les harzburgites Advocate contiennent des teneurs élevées de La–Ce–Pr–Pb–Nd–Sm–Zr, suggérant un métasomatisme perversif. Des signatures géochimiques similaires se retrouvent dans toutes les roches ophiolitiques du manteau de la péninsule de Baie Verte analysées à ce jour. Les enrichissements ne concordent pas avec le métasomatisme contemporain à la fusion dans la zone de supra-subduction tel qu'observé dans d'autres ophiolites des Appalaches. L'absence apparente de chenaux métasomatiques visibles dans la plupart des affleurements porte à croire que le métasomatisme s'est produit avant l'obduction par percolation diffuse, mais la nature et l'origine de l'agent métasomatique demeurent spéculatives. Les similitudes entre la géochimie des minéraux et de la roche entière signifient que toutes les roches du socle provenant des ophiolites de la Baie Verte sont corrélatives et peuvent représenter les lambeaux d'une dalle unique d'obduction.

[Traduit par la Rédaction]

Received 6 July 2009. Accepted 15 January 2010. Published on the NRC Research Press Web site at cjes.nrc.ca on 18 March 2010.

Paper handled by Associate Editor A. Polat.

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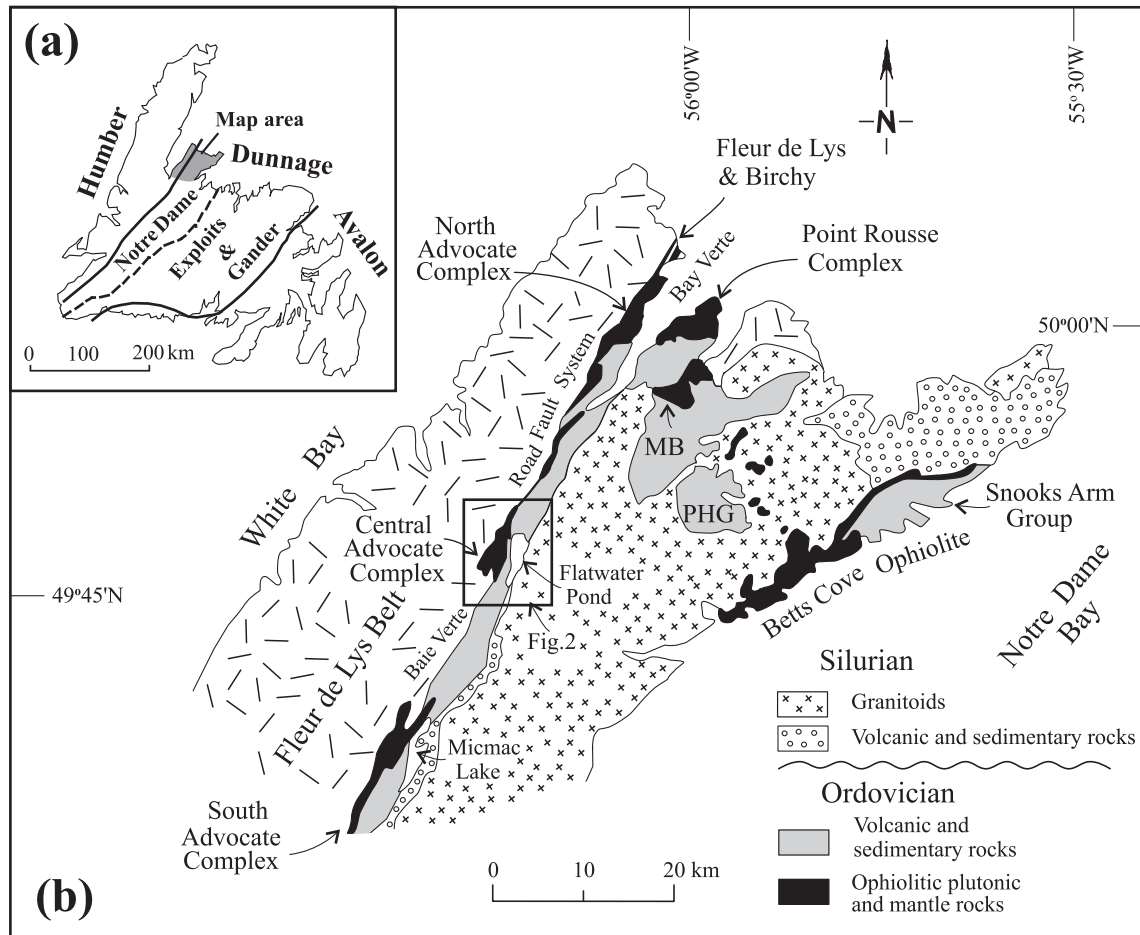
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Introduction

The Ordovician Taconian orogeny is associated with the accretion onto the Laurentian continental margin (i.e., the Humber Zone of Williams 1979) of oceanic and arc terranes (Notre Dame subzone of the Dunnage Zone). Notre Dame subzone ophiolites in Newfoundland occur as allochthons emplaced onto the continental margin rocks (e.g., Bay of Islands Complex, Casey et al. 1985; Cawood and Suhr 1992), as Dunnage Zone “basement” (e.g., Betts Cove ophiolite, Tremblay et al. 1997), and at the Humber–Dunnage Zone interface (e.g., Advocate ophiolite, Fig. 1; Hibbard 1983; van

Fig. 1. Sketch map showing location of study area, adapted from Bédard et al. (2000). Ophiolite complexes highlighted in black (MB, Ming's Bight). Ordovician volcanosedimentary assemblages are grey. Some of these, like the lower Packet Harbour Group (PHG), are boninitic and correlate with the Betts Cove ophiolite. Others are probably correlative with the Upper Snooks Arm Group and may be post-obduction sequences.



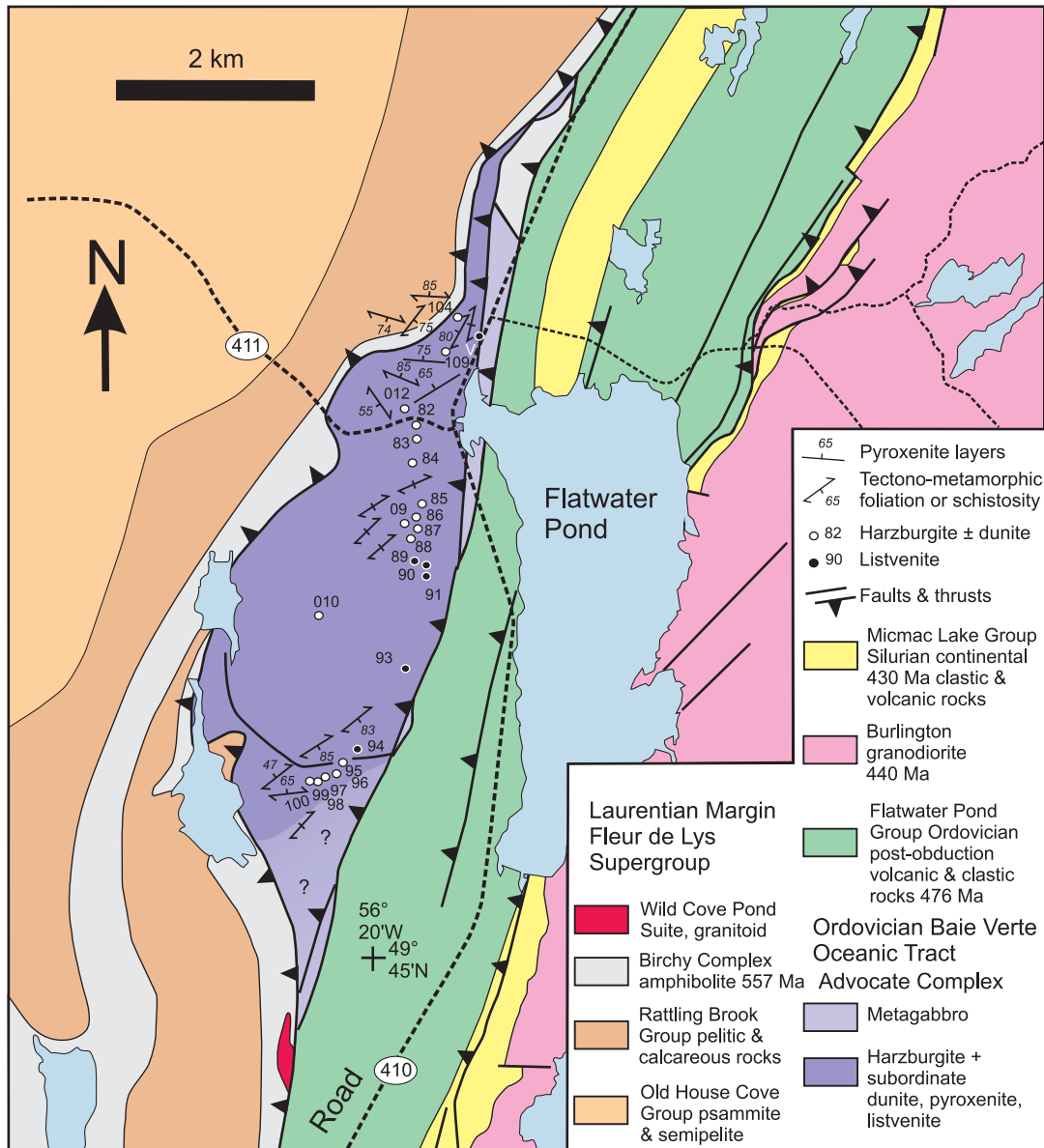
Staal et al. 1998). The disruption caused by the numerous tectonometamorphic–plutonic events that postdate ophiolite obduction in the Baie Verte Peninsula of Newfoundland (e.g., Jamieson 1986; Tremblay et al. 1997) makes it difficult to establish links among the different ophiolite occurrences.

The Betts Cove ophiolite outcrops on the eastern shore of the Baie Verte Peninsula (Fig. 1). It is capped by a thick sequence of volcanic and sedimentary rocks, with the lowermost lavas (and subjacent sheeted dykes and cumulate rocks) recording a fore-arc seafloor-spreading event (Bédard et al. 1997, 1998, 1999, 2000 and references therein). It is characterized by dykes, lavas, and cumulate rocks of boninitic affinity, which grade up into depleted-arc tholeiites (Mount Misery Formation, Lower Snooks Arm Group, Bédard et al. 2000). A gabbro from this sequence was dated at $488.6^{+3.1}_{-1.8}$ Ma (Dunning and Krogh 1985). An erosional unconformity bevels tilted blocks containing cumulates and lavas (Bédard et al. 2000), upon which the Upper Snooks Arm Group was deposited. The Upper Snooks Arm Group consists of alternating sequences of undepleted tholeiitic lavas with few signs of arc affinity (Bédard et al. 2000), epiclastic rocks eroded from the underlying strata (Balsam Bud

Cove Formation, Kessler and Bédard 2000), and a calc-alkaline basalt to rhyolite sequence with unambiguous arc signatures (Bobby Cove and Balsam Bud Cove formations, Bédard et al. 2000; Cousineau and Bédard 2000). A calc-alkaline rhyolite from the Balsam Bud Cove Formation of the Snooks Arm Group was dated at 467 Ma (Skulski et al. 2008).

Supracrustal volcanosedimentary packages occur elsewhere in the Baie Verte Peninsula, many as roof pendants in the Burlington granodiorite and Cape Brulé granite (Fig. 1). Skulski et al. (2008) have matched some of these packages (Packet Harbour Group, 487 Ma; Pointe Rousse Complex, 482 Ma; Fig. 1) with the Betts Cove section and suggested formal correlations. The Lower Packet Harbour Group (PHG on Fig. 1) contains boninitic lavas similar to those of the Betts Head Formation at Betts Cove and is coeval (Skulski et al. 2008), suggesting that the obducted slab was at least 15 km wide. Skulski et al. (2008) suggested that deposition of the Upper Snooks Arm Group postdates obduction of the ophiolites onto the Laurentian margin. If this is correct, then the distribution of these rocks cannot be used to correlate oceanic basement or delineate the size of the obducted slab.

Fig. 2. Detail map of area near Flatwater Pond where mantle rocks of the Central Advocate Complex outcrop. Map adapted from Hibbard (1983). The small white v is the virginite (listvenite) occurrence.

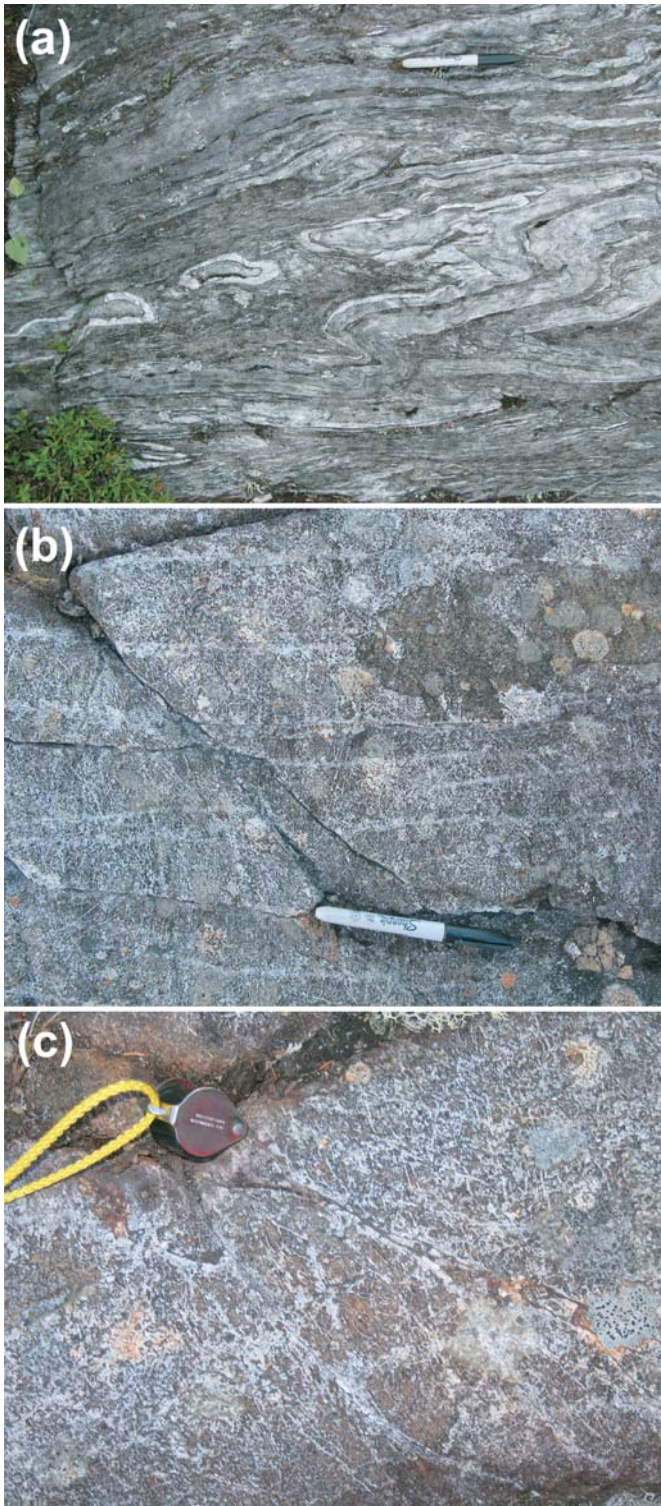


Mantle rocks represent another pre-obduction facies that could potentially be compared and correlated on a regional scale. Mantle rocks were not recognized during the Betts Cove mapping project, but subsequent unpublished work by the first author suggests that most of the meta-peridotitic rocks in the Red Cliff Pond to Long Pond areas (see Bédard et al. 2000) are mantle meta-harzburgites. Where these are not completely converted to talc–carbonate–magnetite schist, they are massive and appear unlayered, unlike the cumulate peridotites at Betts Cove, which are intricately interlayered with pyroxenites. Another difference is that relict Cr-spinel in the inferred Betts Cove mantle rocks are distinctly lower in Cr# ($100\text{Cr}/(\text{Cr} + \text{Al})$) and higher in Mg# ($100\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) in comparison with the cumulate rocks (see later in the text). A thick conglomerate caps the presumed mantle rocks at Betts Cove (south shore of Long Pond). Cr-spinels

in the sandstone matrix and in peridotite cobbles from this conglomerate have the same compositions as the more massive harzburgites beneath, and so the conglomerate is interpreted to represent erosion products from mantle rocks uncovered by pre-obduction extensional faults (oceanic core complex).

Obvious mantle rocks occur in the central massif of the Advocate complex, outcropping as a series of hills west of the Bay Verte Road near Flatwater Pond (Fig. 1). There are no data from the southern and northern massifs of the Advocate complex. Recent work by Escayola et al. (2009) on the listvenites of the Point Rousse ophiolite suggests they include metasomatized mantle rocks. Mantle rocks have been recognized elsewhere in Baie Verte at Ming's Bight, on Three Sisters Island (near Point Rousse) and in the Birchy – Fleur de Lys complex (Fig. 1). We present new data from

Fig. 3. Field photographs. (a) Complexly folded Fleur de Lys Supergroup metasedimentary rocks located <10 m from the contact with ophiolitic rocks to the northwest of station 109 (Fig. 2). (b, c) Advocate harzburgite partly replaced by talc–carbonate veins (station 91, Fig. 2). (a, b) Pen for scale; (c) handlens for scale.



the central massif of the Advocate complex and from other mantle relicts in the area that suggest that all are correlative, which implies obduction of a slab at least 30 km wide (southeast–northwest).

Rocks hosting the Advocate complex

The Advocate complex near Flatwater Pond is a fault-bounded sliver dominated by mantle harzburgite (Fig. 2). To the west are rocks of the Humber Zone, composed of (Hibbard 1983) a lower structural level of migmatites, eclogite, and gneiss (East Pond Metamorphic Suite); a cover sequence of metaclastic schist, marble, amphibolite, and greenschist (Fleur de Lys Supergroup, 558 ± 1 Ma, van Staal et al. 2008); and an intrusive granitoid suite (Wild Cove Pond Igneous Suite). Fleur de Lys rocks near the contact are intensely deformed (Fig. 3a). To the east of the Advocate ophiolite are rocks of the Dunnage Zone. There are a variety of isolated, fault-bounded gabbroic and peridotitic slivers that represent dismembered ophiolite fragments, possibly torn from the Advocate massif itself. Listvenites are locally prominent to the west of the Baie Verte Fault Zone (Figs. 3b, 3c, 4d). The volcanic and clastic rocks of the Flatwater Pond Group have been newly dated at 476 Ma (Skulski et al. 2008), contain inherited zircons of 500–2600 Ma age, and are time correlative with the Upper Snooks Arm Group. The abundance of inherited zircons was interpreted by Skulski et al. (2008) to indicate that these magmas sampled continental basement, implying that the Flatwater Pond and correlative Upper Snooks Arm groups might be post-obduction sequences.

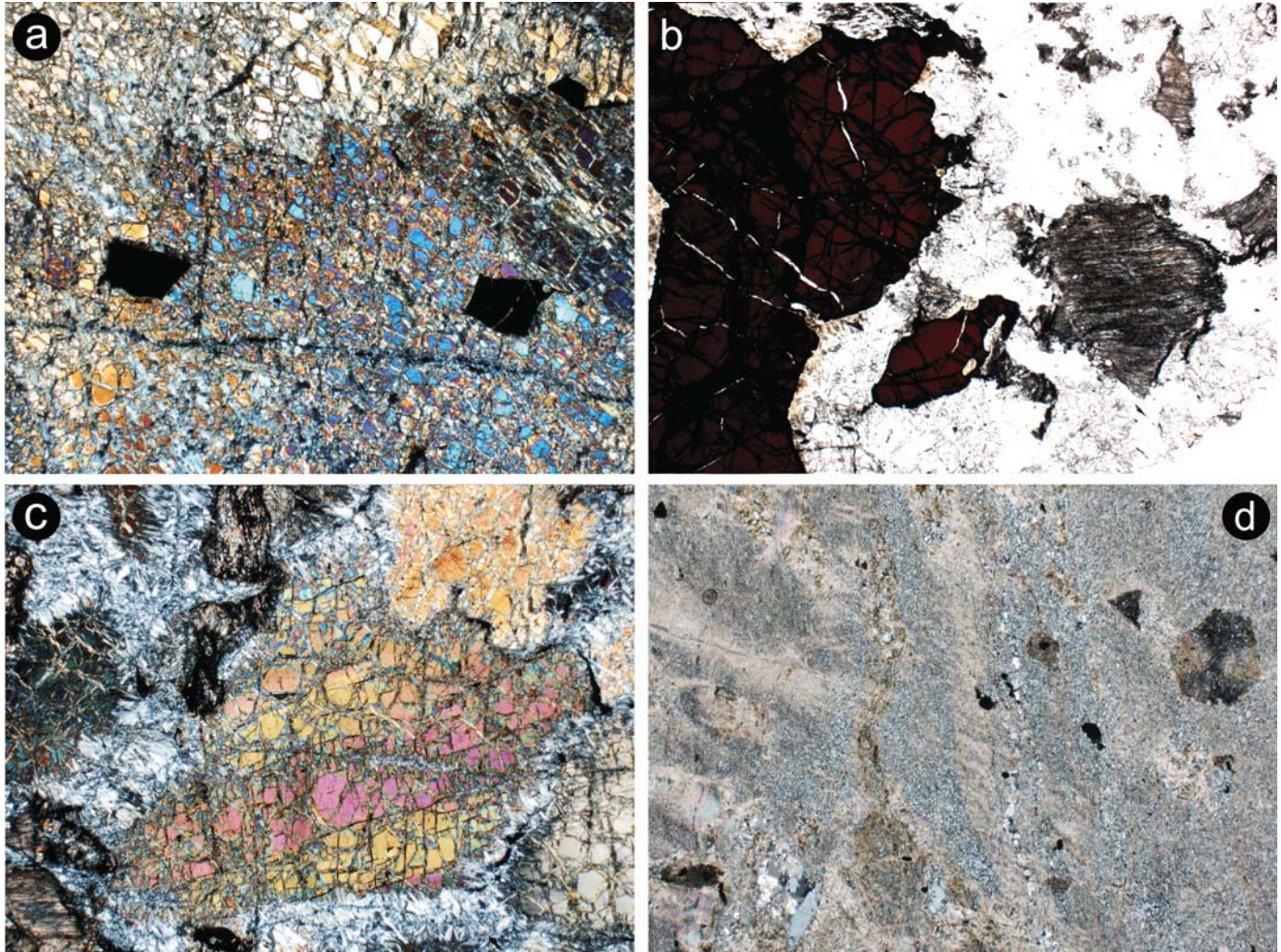
Ordovician rocks in the Baie Verte Peninsula were exposed to erosion to create a marked unconformity, upon which were deposited a variety of Silurian subaerial clastic rocks, tuffs, and lavas of the Cape St. John (427 Ma, Coyle 1990) and Micmac Lake groups. Ophiolitic rocks occur as substrates to the extrusive and sedimentary rocks, but also form enclaves and roof pendants in the coeval Burlington granodiorite (440–432 Ma, Cawood and Dunning 1993) and Cape Brulé granite (430 Ma, Cawood and Dunning 1993), which probably represent the source of the pyroclastic rocks.

The Advocate ophiolite near Flatwater Pond

The Central Advocate ophiolite massif is dominated by massive harzburgite, with subordinate dunite dykes and rare orthopyroxene-rich layers or veins. Most rocks have a penetrative, steeply dipping foliation striking northeast, defined by the preferential alignment of orthopyroxene porphyroclasts and chromite grains. Locally, east–west- and north–west-striking layers and fabrics are observed, either preserving pre-emplacment orientations or, in some cases, representing post-emplacment overprints. Rare dunite dykes are ca. 1 m wide, but have irregular contacts. Harzburgite contains ca. 20% orthopyroxene pseudomorphs (bastite), and ca. 1% chromite, commonly with holly-leaf shapes (<5 mm, Fig. 4b), and is surrounded by secondary magnetite and (or) ferrite-chromite rims (cf. Burkhard 1993). Fresh clinopyroxene or orthopyroxene was not observed in any of the samples collected. In contrast, almost every sample contains abundant fresh olivine, locally with preserved tilt-walls and subgrain boundaries (Fig. 4c) suggesting that they are mantle relicts. Dunites are dominated by medium- to coarse-grained anhedral olivine with euhedral Cr-spinel (Fig. 4a).

Listvenites are metasomatic rocks generated by carbonate–silica metasomatism of ultramafic precursors (e.g., Halls and Zhao 1995; Akbulu et al. 2006; Escayola et al.

Fig. 4. Photomicrographs of Advocate ophiolite rocks. Field of view of all photographs is ca. 5 mm. (a) Dunite, sample 84B, crossed nicols. Note the euhedral chromite grains. (b) Harzburgite, sample 85A, plane light. Dark patches are large anhedral chromites with holly-leaf shapes, and turbid pseudomorphs are after orthopyroxene porphyroclasts. Pale areas are olivine and serpentine. (c) Harzburgite, sample 86A, crossed nicols. Serpentinized material is pale grey. Note the large olivine with tilt walls in the lower center. (d) Felsic rock, sample 89B, crossed nicols. This rock yielded a granitic major element composition. Note the abundant sericite and quartz in the groundmass and the sector-zoned subhedral carbonate to the right.



2009) and are thought to be favourable gold exploration targets. There is a known occurrence of listvenite situated along the Baie Verte Road fault(s). It has the local name “virginite” because it is both beautiful and rare. The new mapping shows that a substantial part of the Advocate massif situated near the Baie Verte Road fault (stations 89 to 94) has been affected by this type of metasomatism, and may represent a gold exploration target. In outcrop, the metasomatized rocks weather white (Fig. 3) and locally (station 89) have a slabby appearance that could easily lead to misidentification as layered gabbros. Ubiquitous chromite and local antigorite relics demonstrate that most of these rocks were once peridotites, however. Transitional facies show intense talc–carbonate–quartz replacement of harzburgite (Figs. 3b, 3c). Published maps (Hibbard 1983) show a wedge of crustal gabbroic rocks in the southernmost part of the massif. However, stations (95 to 97) that should have intercepted these crustal rocks encountered only strongly bleached harzburgite. Consequently, the area underlain by

“crustal” rocks on Hibbard’s 1983 map (Fig. 1) has decreased and may not in fact exist.

The most strongly altered rock (sample 89B) has a broadly granitic chemical signature (see Table 3 in “Geochemistry” section). In thin section (Fig. 4d), the rock has a foliated porphyroclastic texture, with abundant quartz and sericite, and numerous euhedral carbonates that may be pseudomorphous after a primary igneous phase. It is not clear to what extent the anomalous geochemistry of this analysis reflects the listvenitization process and to what extent it reflects a prior lithological heterogeneity.

Mineral chemistry

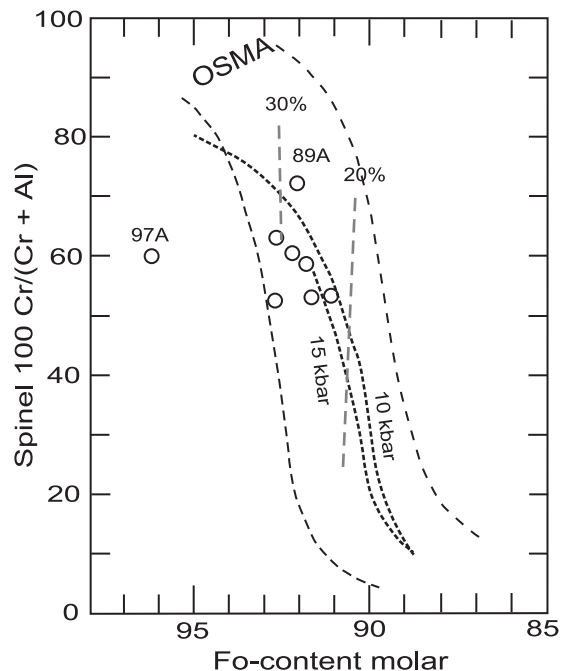
Most of the polished thin sections from the Advocate ophiolite itself were analyzed at Laval University (Québec City) on a Cameca Camebax 5-spectrometer electron microprobe. Analytical details can be found in the appendix to Bédard et al. (2007). Minerals in two rocks from the Advo-

Table 1. Advocate complex average olivines.

07SNBL	82A	84Bdun	86A	90A	85A	89A	97A	104A
<i>N</i>	6	6	6	6	6	6	5	6
SiO ₂	40.51	40.90	40.81	40.45	38.65	40.79	41.34	41.17
TiO ₂	0.002	<dl	<dl	<dl	<dl	0.0002	<dl	<dl
Al ₂ O ₃	0.007	0.004	0.001	0.068	0.003	0.003	0.027	0.002
Cr ₂ O ₃	0.030	0.005	0.008	0.004	0.004	0.004	0.099	0.009
FeO	8.06	7.15	8.00	6.78	7.22	7.68	3.80	8.73
MnO	0.18	0.09	0.12	0.12	0.10	0.10	0.77	0.14
MgO	49.65	50.55	50.20	46.95	47.87	50.05	53.44	50.14
CaO	0.05	0.02	0.05	0.04	0.05	0.04	0.02	0.05
NiO	0.41	0.38	0.39	0.35	0.34	0.38	0.08	0.43
Na ₂ O	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01
Total	98.90	99.11	99.58	94.78	94.26	99.06	99.58	100.68
Fo m	91.65	92.65	91.80	92.63	92.19	92.06	96.19	91.10

Note: <dl, less than detection level; Fo m, molar Fo-content; *N*, number of points analyzed.

Fig. 5. Spinel $100 \times \text{Cr}\# (= \text{Cr}/(\text{Cr} + \text{Al}))$ vs. olivine molar Fo-content. OSMA is the olivine–spinel mantle array from Arai (1994). Two melting curves with estimated percent melting at 10 and 15 kbar pressures (1 kbar = 100 MPa) are from Jaques and Green (1980). Harzburgite 97A has anomalously forsteritic olivine.



cate ophiolite (station 12) were analyzed at the Serveis Científicotècnics of the Universitat de Barcelona (Spain), using a WDS–CAMECA SX 50 instrument. Excitation voltage was 20 kV and beam current 15 nA, except for analyses of Cr-rich spinel for which a current of 20 nA was preferred. Most elements were measured with a counting time of 10 s, except for Ni, V, and Zn (30 s).

Olivine compositions for most Advocate harzburgites range from Fo_{90.5} to Fo₉₃ and NiO wt.% from 0.34 to 0.46 (Table 1), compositions typical of other Appalachian ophiolites like Thetford Mines or the Bay of Islands Complex. Olivine–chromite pairs fall along the olivine–spinel mantle array (OSMA) of Arai (1994, Fig. 5). The sole exception is

sample 97A, which has anomalously magnesian olivines (average (av) Fo_{96.2}) with low NiO contents (0.05–0.1 wt.%) and high MnO contents (av 0.77%). Sample 97A is intensely carbonated, and the olivine was probably recrystallized, losing Ni and Fe, and gaining Mg and Mn.

Chromites are mostly homogeneous, with little core-to-rim zoning (Table 2a). Cr-spinel in most Advocate mantle rocks shows a limited compositional range (Table 2b), with Cr# varying from ca. 52 to 64 and Mg# from ca. 56 to 68 (Fig. 6d). Comparison with experimental data suggests this range of compositions reflects melting degrees (*F*) of ca. 28%–35% (Figs. 5, 6d). Cr-spinels from a dunite (sample 84B) are not significantly different from harzburgite Cr-spinels. Samples 1, 2, and 89A have chromites with higher Cr# (70–80). Rims and overgrowths are typically enriched in the magnetite component or are Cr-rich ferrite-chromites (Burkhard 1993; Table 2c, Fig. 6d).

Relict chromites from the Pointe Rouse listvenites (Escayola et al. 2009) overlap the composition of Advocate chromites (Figs. 6c, 6d), scattering towards magnetites generated by listvenitization. Data from Betts Cove mantle rocks and their erosion products also overlap the Advocate chromite field, with similar Cr# and Mg# (Fig. 6c). Note that the Betts Cove lavas and cumulates have chromites with distinctly higher Cr#, approaching the composition of Pacific boninite chromite phenocrysts. In contrast, data from the mantle facies of the Bay of Islands and Thetford Mines ophiolites exhibit a wide compositional range in terms of Cr# and Mg# (Figs. 6a, 6b), with a coherent trend that is offset towards lower Mg# in comparison to data from the Baie Verte (Advocate, Betts Cove, Pointe Rouse) ophiolites (Figs. 6c, 6d).

Geochemistry

One set of rocks was analyzed by inductively coupled plasma – emission spectroscopy (ICP–ES) and ICP–MS (mass spectrometry) at the INRS (Institut National de la Recherche Scientifique) laboratories in Québec City, with methods and precision as described in the appendix to Dupuis et al. (2009). These are the analyses that were combined to generate the average and end-member Advocate

Fig. 6. Spinel $100\text{Cr}\#$ ($= \text{Cr}/(\text{Cr} + \text{Al})$) vs. $100\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ for Appalachian ophiolitic mantle chromites. (a) Data for the Bay of Islands Complex, including data from the North Arm Mountain massif (NAMM; Malpas 1976; Riccio 1976; Varfalvy 2000; and unpublished analyses from the first author); the Lewis Hills (Smith and Elthon 1988; Edwards 1991); and Table Mountain (Suhr 1991). Symbols represent averages for individual rocks. Three 700°C olivine–spinel isotherms are from Bédard (1997). (b) Data from the Thetford Mines massif, data from Pagé et al. (2008), for the Duck Lake Block (DLB) and Caribou Mountain Block (CMB). Symbols represent averages for individual rocks. The field for the Bay of Islands Complex (BOIC) is shown for comparison. Note the very similar distribution and range. TMO, Thetford Mines ophiolite. (c) Data from the Betts Cove ophiolite (Bédard et al. 2000 and unpublished analyses). Filled stars are averages from two massive harzburgites inferred to represent mantle. The open star is the average of detrital chromites from a boulder conglomerate resting on these massive harzburgites. The ∇ symbols are microphenocrysts from boninitic sheeted dykes and lavas. Most chromites in cumulate rocks occupy the indicated field, except for some of the most reequilibrated rims, marked as open diamonds. Data from listvenites of the Point Rousse ophiolite (Escayola et al. 2009) are also shown. Relict grains cluster with the Betts Cove data and scatter towards reequilibrated magnetite-rich compositions developed during metasomatism of a presumed mantle precursor. A 1200°C isotherm for Fo_{90} olivine–spinel equilibration is shown for comparison. Note that the Betts Cove and Point Rousse mantle chromites are displaced to higher Mg# compared with the Bay of Islands and Thetford Mines chromites. The boninite field is from Pagé et al. (2008). BC, Betts Cove; Ol, olivine. (d) Data from the Advocate ophiolite. Plus symbols are averages for individual rocks. Most cluster in a restricted field that exactly overlaps with Betts Cove mantle (BCM) and Pointe Rousse primary chromites (PR). Chromites from dunite sample 84B (small grey field) are not radically different from those of adjoining harzburgites. Secondary ferrit-chromites are marked as “f,” secondary magnetite as “m,” and altered rims as “r.” Chromites from harzburgite (Hz) sample 89A have higher Cr# but may not be primary. Chromite compositions of harzburgite 109A are bimodal, with a high-Cr# population (“x”) possibly partly reequilibrated. Harzburgite sample 98A contains only ferrit-chromites. The broken line is a partial melting curve from Hirose and Kawamoto (1995), with ticks representing extent of melting of primitive mantle.

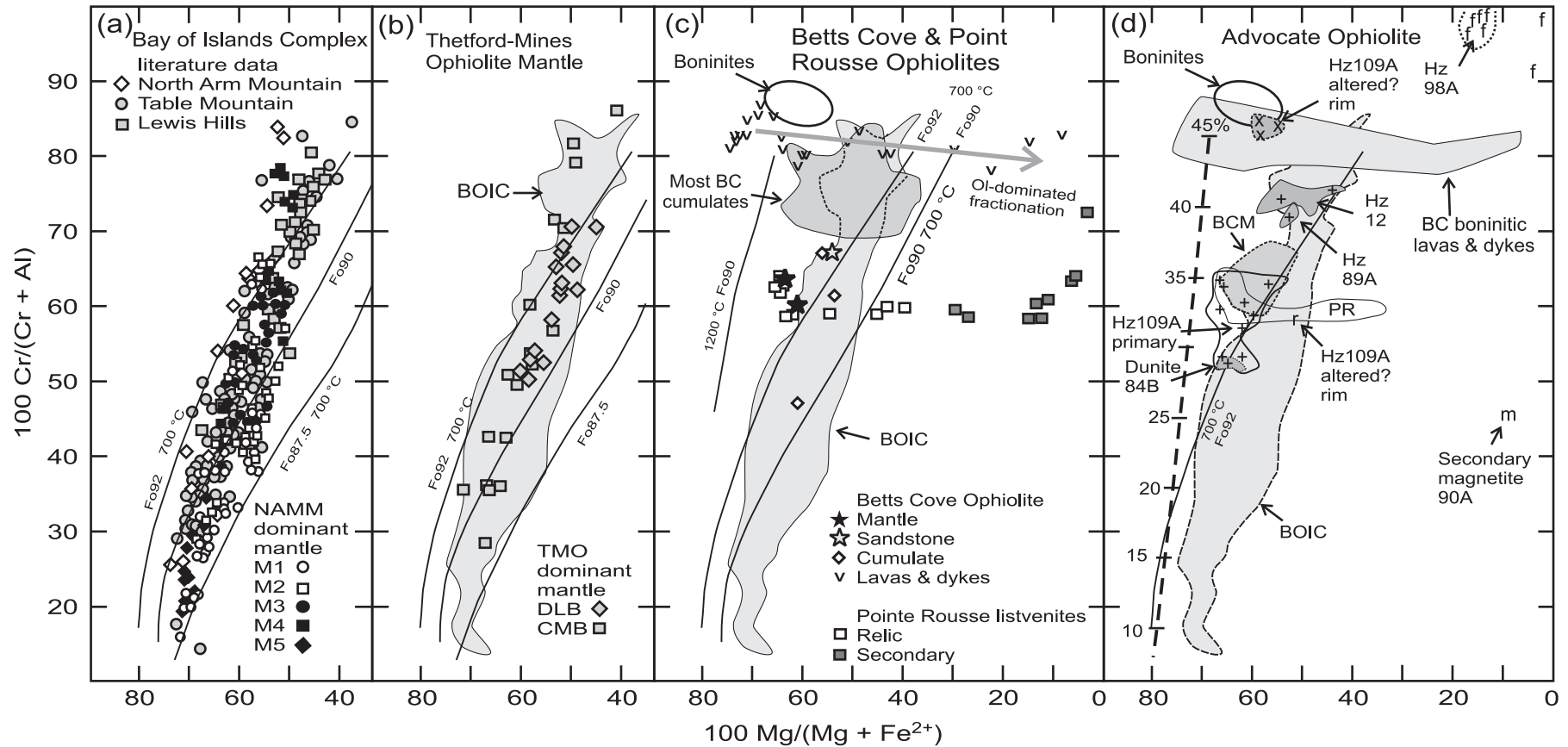


Table 2. Advocate complex spinels.

	Av	Std	Avcore	Avrim	Average values					
07SNBL	96A		96A	96A	82A	84B	85A	86A	89A	90A
<i>N</i>	10		5	5	6	6	6	6	2	5
SiO ₂	0.06	0.011	0.06	0.06	0.034	0.041	0.035	0.044	0.035	0.143
TiO ₂	0.002	0.005	0.001	0.003	0.002	0.010	0.001	0.005	0.004	<0.001
Al ₂ O ₃	20.24	0.330	20.26	20.21	25.78	26.40	21.51	22.65	14.15	19.46
Cr ₂ O ₃	50.63	0.475	50.53	50.73	43.71	43.37	49.19	48.04	54.83	49.23
V ₂ O ₃	0.27	0.03	0.26	0.27	0.23	0.26	0.25	0.28	0.36	0.30
Fe ₂ O ₃	1.58	0.341	1.66	1.50	2.06	1.77	1.55	1.06	2.05	2.77
FeO	13.33	0.574	13.15	13.51	13.54	14.05	14.81	15.66	17.46	16.55
NiO	0.11	0.067	0.13	0.09	0.09	0.12	0.09	0.09	0.19	0.07
MgO	14.22	0.217	14.24	14.20	14.61	14.47	13.28	13.02	10.90	12.17
CaO	0.001	0.003	0.002	0.001	0.001	0.002	<dl	0.002	<dl	0.004
MnO	<dl		<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl
CoO	0.21	0.302	0.26	0.15	0.14	0.11	0.35	0.21	0.01	0.20
Na ₂ O	0.02	0.01	0.02	0.02	0.006	0.015	0.007	0.007	0.007	0.009
Total	100.63		100.53	100.73	100.20	100.61	101.03	101.06	100.00	100.90
Si	0.013		0.013	0.013	0.008	0.010	0.009	0.011	0.009	0.036
Ti	0.000		0.000	0.001	0.000	0.002	0.000	0.001	0.001	0.000
Al	5.833		5.841	5.826	7.284	7.423	6.174	6.492	4.308	5.691
Cr	9.786		9.767	9.806	8.280	8.179	9.471	9.233	11.196	9.656
V	0.052		0.052	0.053	0.044	0.050	0.049	0.054	0.075	0.060
Fe ³⁺	0.291		0.306	0.276	0.372	0.318	0.285	0.194	0.400	0.518
Sum	15.977		15.979	15.975	15.989	15.982	15.988	15.985	15.987	15.960
Fe ²⁺	2.726		2.689	2.763	2.712	2.803	3.015	3.184	3.772	3.434
Ni	0.021		0.025	0.018	0.018	0.023	0.017	0.017	0.037	0.015
Mg	5.181		5.188	5.174	5.218	5.144	4.820	4.718	4.197	4.500
Mn	0		0	0	0	0	0	0	0	0
Ca	0.054		0.068	0.040	0.037	0.028	0.091	0.055	0.003	0.052
Co	0.041		0.051	0.030	0.027	0.021	0.068	0.041	0.003	0.039
Na	0.009		0.007	0.011	0.003	0.007	0.003	0.003	0.003	0.004
Sum	8.023		8.021	8.025	8.011	8.018	8.012	8.015	8.013	8.040
Cr#	62.65		62.58	62.73	53.20	52.42	60.54	58.72	72.22	62.92
Cr3#	61.51		61.38	61.64	51.96	51.38	59.45	58.00	70.40	60.86
Fe3#	1.83		1.92	1.74	2.33	2.00	1.79	1.22	2.51	3.26
Fe2#	34.47		34.13	34.80	34.20	35.27	38.48	40.29	47.33	43.28

Note: Av, average; Std, standard deviation; Avcore, average at core; Avrim, average at rim; *N*, number of points analyzed; AvFeC, average Fe-content;

mantle compositions. Data from the Bay of Islands and Thetford Mines ophiolites were generated at the same laboratory. A second set of samples was analyzed at Actlabs Canada. These data are less precise and are principally used for correlation purposes. Positive peaks for Zr–Hf–Ba in the Actlabs data are probably spurious.

Apart from the listvenites and a single quasi-granitic analysis (sample 89B), all analyzed samples are depleted harzburgites to dunitic harzburgite with high MgO contents (all major elements normalized volatile-free) of 46%–48% (Fig. 7), with low Al₂O₃ (<1%) and TiO₂ (<0.003%, Table 3). Most major elements fall along putative primitive mantle (PM) melting trends and indicate depletions corresponding to $F > 25\%$, except for CaO (Fig. 7a), which was probably perturbed during metamorphism. Transition metal abundances broadly resemble those of other Appalachian ophiolites (Fig. 8). Incompatible trace element variations are illustrated on PM-normalized diagrams (Fig. 9a, PM = primitive mantle = pyrolite of McDonough and Sun 1995). Note that the abundances of Rb and Cs determined at INRS

by ICP–MS are only semiquantitative. The normalized trace element profiles are coherent, with most Advocate mantle samples yielding fairly similar results. Heavy rare-earth element (HREE) profiles are flat, with abundances ca 0.02–0.09 × PM. There is a prominent positive Pb anomaly, and negative Nb and Ti anomalies. The profiles are fractionated, with light REE (LREE) ranging to ca 0.8 × PM. Sample 104A is more enriched than the others and was not included in the average. Although more enriched overall, sample 104A has the same shape (Fig. 9a). In comparison with other Appalachian ophiolites, the Advocate mantle is strongly enriched in medium REE (MREE) and LREE/HREE. Sample 89B yields results similar to a granite, except for low Na₂O contents (Table 3) and relatively high contents of MgO, Ni, and Cr.

Data from the Advocate ophiolitic mantle generated at Actlabs (Figs. 7, 8, 9b) are generally coherent with the INRS data, but noisier. Actlabs data for Ti, Sc, V, and Zn are not shown in Fig. 8 because the analyses did not plot coherently. Comparison of data from the Ming's Bight ophi-

				Core	Rim	Rim	AvFeC	AvFeC	Std
94A	97A	104A	109A	89A-11	89A-10	86A-7	104A	98A	
5	4	6	6					3	5
0.060	0.069	0.030	0.028	1.83	0.02	0.14	0.15	0.05	0.076
<0.001	0.001	0.007	0.008	<dl	<dl	<dl	0.012	0.015	0.017
19.69	21.99	25.88	23.10	10.1	0.04	0.05	5.12	0.47	0.241
51.09	48.36	43.98	45.85	41.2	5.77	0.77	40.54	35.59	1.401
0.28	0.24	0.26	0.28	0.21	0.05	0.06	0.20	0.13	0.029
1.80	1.75	1.33	1.85	13.3	63.8	68.2	23.49	32.84	1.826
12.97	13.04	14.99	14.72	24.8	30.5	30.2	12.21	26.38	0.373
0.10	0.13	0.10	0.09	0.08	0.08	0.39	0.26	0.39	0.121
14.33	14.44	13.74	13.33	6.93	0.37	0.64	9.27	2.61	0.209
0.006	0.003	0.002	0.006	0.002	<dl	0.016	<dl	<dl	<dl
<dl	<dl	<dl	<dl	<dl	<dl	0.028	4.95	<dl	
0.25	0.26	0.14	0.22	<dl	0.19	<dl	<dl	0.39	0.283
0.015	0.013	0.017	0.015	0.04	<dl	0.02	0.034	0.019	0.017
100.57	100.27	100.47	99.48	98.82	100.82	100.52	96.26	98.81	
0.015	0.017	0.007	0.007	0.502	0.006	0.042	0.044	0.016	
0.000	0.000	0.001	0.001	0	0	0	0.003	0.003	
5.685	6.300	7.330	6.683	3.254	0.014	0.018	1.713	0.165	
9.892	9.292	8.354	8.896	8.927	1.384	0.185	9.102	8.383	
0.055	0.048	0.050	0.055	0.046	0.013	0.014	0.045	0.030	
0.332	0.320	0.241	0.342	2.746	14.577	15.686	5.028	7.372	
15.978	15.977	15.984	15.985	15.475	15.994	15.944	15.935	15.970	
2.656	2.651	3.011	3.020	5.677	7.708	7.665	2.888	6.559	
0.020	0.025	0.020	0.019	0.017	0.019	0.095	0.059	0.093	
5.230	5.229	4.921	4.876	2.831	0.168	0.289	3.926	1.157	
0	0	0	0	0	0	0.007	1.191	0	
0.066	0.068	0.037	0.058	0	0.063	0	0	0.126	
0.049	0.051	0.027	0.043	0	0.047	0	0	0.094	
0.007	0.006	0.008	0.007	0.023	0	0.014	0.019	0.011	
8.022	8.023	8.016	8.015	8.525	8.006	8.056	8.065	8.030	
63.50	59.59	53.27	57.10	73.29	98.98	91.13	84.17	98.07	
62.18	58.39	52.46	55.87	59.80	8.66	1.16	57.45	52.66	
2.09	2.01	1.52	2.15	18.40	91.25	98.72	31.74	46.31	
33.68	33.64	37.96	38.25	66.73	97.87	96.36	42.37	85.00	

Cr# = 100Cr/(Cr + Al); Cr3# = 100Cr/(Cr + Al + Fe); Fe3# = 100Fe³⁺/(Cr + Al + Fe³⁺); Fe2# = 100Fe²⁺/(Mg + Fe³⁺).

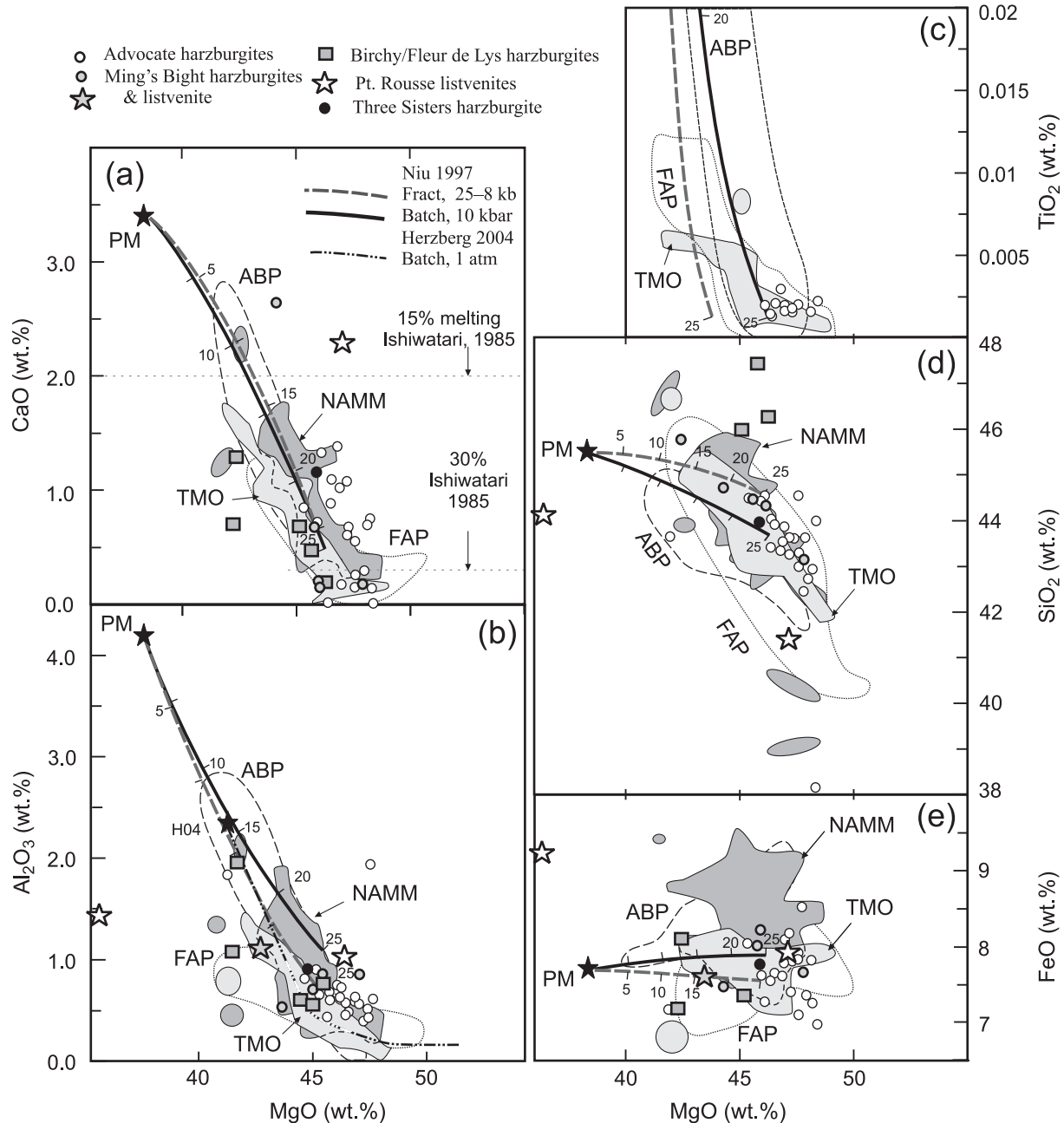
lite (Fig. 9c) and the Fleur de Lys and Birchy complexes (Fig. 9d) have profile shapes and abundances essentially indistinguishable from those of the Advocate ophiolitic mantle, and a formal correlation is proposed on this basis. Data from Point Rousse were collected to investigate the listvenitization process (Escayola et al. 2009). Sample 1A2 from this location (Fig. 10a) is indistinguishable from typical Advocate mantle, while sample 1A3 resembles the enriched facies of the Advocate suite (sample 104). This resemblance is consistent with a formal correlation between the Advocate and Point Rousse mantle rocks. The other rocks from the Point Rousse massif (samples 1B3 and 2A1) are more enriched, and it is not clear whether they represent a less depleted mantle facies or whether they are cumulate rocks. Irrespective of the protolith, all rocks from Point Rousse exhibit prominent positive Sr anomalies (Fig. 10a) and low Co and Ni (Fig. 8) signatures, which may be related to listvenitization. A fresher harzburgite from nearby Three Sisters Island is similar to the most depleted Point Rousse rock (sample 1A2, Fig. 10a), except for the lack of a positive Sr anomaly.

Discussion

Mantle rocks from the three massifs of the Baie Verte Peninsula examined here contain chromites with unusually high Mg#, only partly overlapping the data from chromites of mantle harzburgites from the Thetford Mines and Bay of Islands ophiolites (Fig. 6). This suggests that all three of the Baie Verte ophiolites for which data are available may represent the same mantle block, and supports a formal correlation of the Betts Cove, Pointe Rousse, and Advocate ophiolites. If correct, this implies that the obducted slab was at least 30 km wide (SE–NW). The high chromite Mg# and high olivine Fo-contents suggest that the Baie Verte mantle was unusually refractory. This hypothesis is supported by the distribution of whole-rock data on variation diagrams, with the Advocate data falling mostly on the extensions of mantle melting curves with $F > 25\%$.

The distribution of data on the spinel Cr# vs. Mg# diagram is controlled by several different processes. Increasing degrees of melting raise Cr# (Figs. 5, 6d), but subsequent

Fig. 7. Major element variations of Advocate mantle rocks (“o” symbols), compared with a variety of other mantle subtypes and melting curves. The curves are batch (equilibrium) and fractional melting curves from Niu and Hékinian(1997) and Herzberg (2004). Black stars are the initial starting compositions for Herzberg (2004, H04) and primitive mantle (PM), with sources and compositions as per Pagé et al. (2009). The abyssal and fore-arc peridotite fields (respectively, ABP and FAP) are from Pagé et al. (2009). The NAMM (North Arm Mountain Massif, Bay of Islands Complex) data are from Varfalvy (2000) and unpublished data from the first author. The TMO (Thetford Mines ophiolite) data are from Pagé et al. (2009). Most listvenites plot offscale at high CaO and low MgO. 1 kbar = 100 MPa. 1 atm = 101.325 kPa.



melt impregnation lowers Cr# (Pagé et al. 2008). However, decreases in Cr# can also be caused by reequilibration with pyroxene or by fractional crystallization of pyroxene and, to a lesser extent, chromite (Bédard and Hébert 1998). The microphenocrysts in Betts Cove boninite dykes and lavas range from high Mg# and Cr# similar to Pacific boninite phenocrysts, to lower Mg# values along an olivine + trace chromite fractionation path (Fig. 6c). Betts Cove cumulates are systematically offset towards lower Cr# in comparison with the

dyke data (Fig. 6c), probably as a result of loss of Cr to the abundant pyroxene in these rocks, coupled with Al-enrichment from the reaction of primocrysts with abundant trapped melt (20%–30%, Bédard et al. 2000). As discussed by Bédard and Hébert (1998), the low Mg# of most Cr-spinels in cumulate and mantle facies is probably the result of down-temperature reequilibration of Fe = Mg between olivine and chromite, with the stopping point reflecting a balance between the blocking temperature and the composition of the

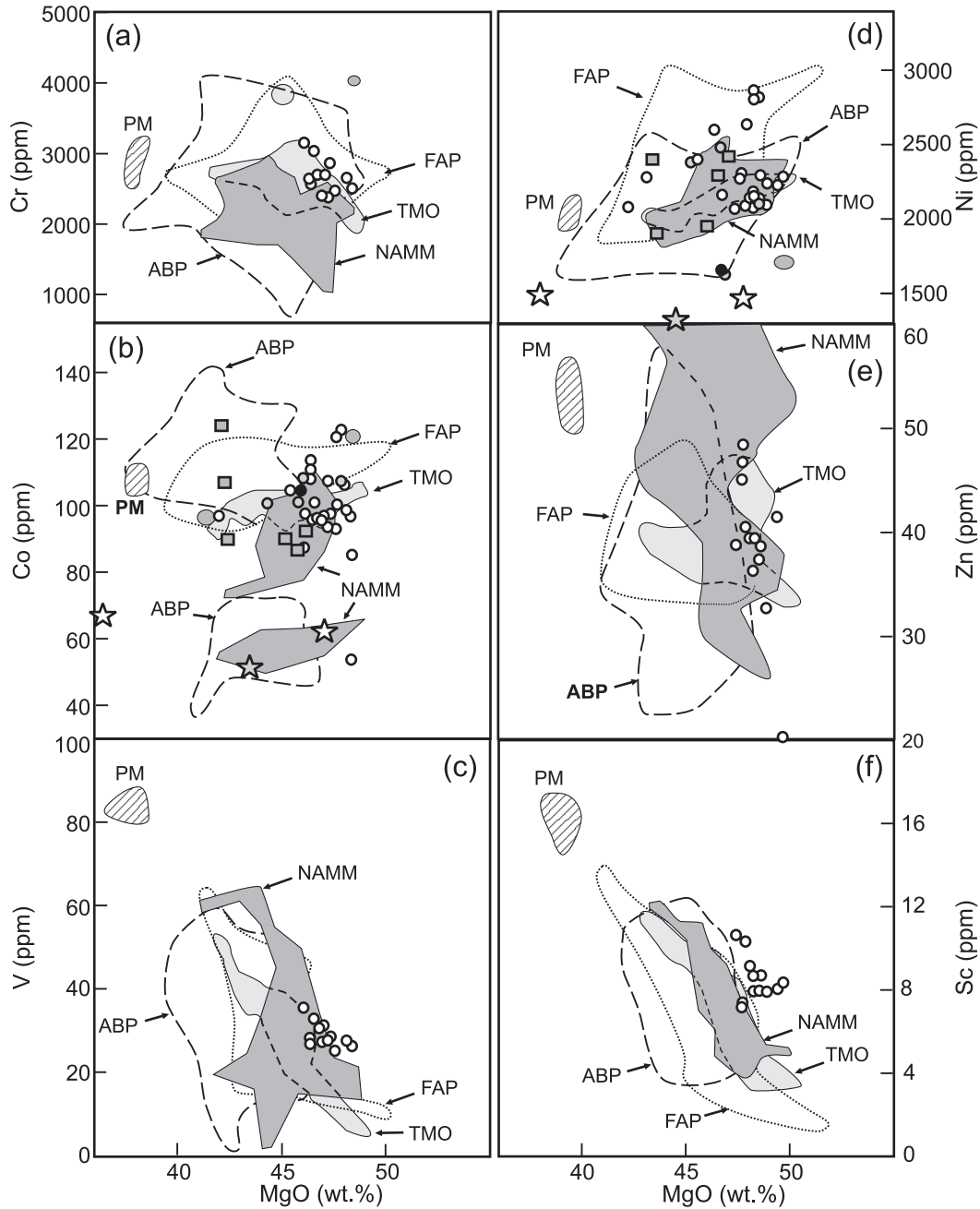
Table 3. Whole-rock analyses, Advocate complex.

	hz	hz	whz	whz	whz	whz	whz	whz	whz	whz	whz	whz	felsic
07SNBL	82A	86A	89B1	89B2	90A	94A	94Ad	96A	97A	98A	104A	109A	89B
Major elements (wt.%)													
SiO ₂	40.04	39.32	41.61	40.92	40.11	37.59	37.54	38.54	38.12	38.79	38.75	38.15	70.66
TiO ₂	0.0027	0.0014	0.0019	0.0019	0.0014	0.0012	0.0012	0.0017	0.0019	0.0017	0.0014	0.0016	0.261
Al ₂ O ₃	0.67	0.46	0.60	0.55	0.44	0.38	0.38	0.54	0.52	0.62	0.55	0.50	12.84
Fe ₂ O ₃ *	7.81	8.01	7.56	7.92	7.97	9.33	9.30	6.83	6.72	7.94	7.70	7.19	3.33
MnO	0.12	0.11	0.12	0.13	0.11	0.09	0.09	0.09	0.08	0.11	0.11	0.11	0.04
MgO	43.22	44.30	43.10	43.36	43.49	40.19	40.09	41.23	41.96	41.46	41.78	41.28	2.62
CaO	1.27	0.64	1.24	1.01	0.61	0.008	0.010	0.13	0.009	0.16	0.91	0.94	1.26
Na ₂ O	0.014	0.033	0.045	0.038	0.027	0.004	0.007	0.005	0.005	0.007	0.008	0.004	0.410
K ₂ O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	4.76
P ₂ O ₅	<0.03	<0.04	<0.04	<0.04	<0.05	<0.03	<0.03	<0.04	<0.03	<0.04	<0.04	<0.04	<0.05
LOI	8.6	9.3	7.9	7.9	8.4	14.5	14.5	14.4	14.1	13.1	11.8	13.2	3.3
S	<0.007	<0.008	<0.008	<0.007	<0.009	<0.007	<0.007	<0.007	<0.007	<0.008	<0.009	0.05	0.05
Total	101.79	102.21	102.14	101.83	101.13	102.04	101.88	101.79	101.55	102.15	101.62	101.41	99.53
Trace elements (ppm)													
Cs	0.111	0.114	0.053	0.064	0.076	0.066	0.112	0.078	<0.05	<0.05	0.110	<0.05	10.67
Rb	0.120	0.158	0.092	0.088	<0.06	<0.04	<0.05	<0.05	<0.05	<0.05	2.23	<0.05	186
Ba	<1.4	<1.5	<1.7	<1.4	<1.9	<1.3	1.5	<1.5	2	<1.6	<1.7	<1.5	659
Th	<0.2	<0.2	<0.2	<0.2	<0.2	<0.1	<0.2	<0.2	<0.2	<0.2	0.177	<0.2	14.0
U	<0.005	<0.005	0.006	<0.005	<0.006	<0.004	<0.005	<0.005	<0.005	<0.005	0.044	0.006	4.0
Nb	0.012	0.010	<0.005	0.016	<0.006	<0.004	0.031	<0.005	0.007	<0.005	0.547	0.012	25.4
Ta	<0.02	<0.02	<0.02	<0.02	<0.02	<0.01	<0.02	<0.02	<0.02	<0.02	0.023	<0.02	1.66
La	0.170	0.226	0.303	0.212	0.288	0.191	0.144	0.141	0.101	0.208	0.958	0.155	49.3
Ce	0.364	0.504	0.710	0.472	0.548	0.427	0.298	0.312	0.206	0.453	2.19	0.343	116.9
Pr	0.037	0.054	0.083	0.047	0.053	0.043	0.030	0.029	0.020	0.049	0.249	0.037	13.6
Pb	5.42	1.71	0.69	0.64	1.12	0.43	0.48	0.68	0.47	0.79	0.91	0.53	9.79
Sr	<1.4	<1.5	<1.7	<1.4	<1.9	<1.3	<1.3	<1.5	<1.4	<1.6	<1.7	2.2	82.5
Nd	0.157	0.211	0.328	0.200	0.240	0.180	0.109	0.124	0.087	0.210	0.953	0.158	52.4
Sm	0.029	0.043	0.071	0.032	0.035	0.041	0.023	0.027	<0.02	0.040	0.207	0.032	11.22
Zr	2.91	3.12	2.02	1.42	1.97	1.14	1.25	1.03	0.612	0.802	14.8	0.836	541
Hf	0.004	0.003	0.005	0.004	0.004	<0.002	0.005	<0.003	<0.003	<0.003	0.201	0.003	13.0
Eu	<0.009	0.016	<0.01	<0.01	<0.02	<0.008	<0.009	<0.009	<0.009	<0.01	0.034	<0.01	2.49
Gd	0.013	0.028	0.041	0.016	0.017	0.014	0.010	0.007	0.003	0.018	0.140	0.017	9.27
Tb	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.027	<0.02	1.78
Dy	0.019	0.027	0.050	0.029	0.026	0.030	0.015	0.018	0.009	0.027	0.162	0.025	10.13
Y	0.202	0.550	0.345	0.239	0.246	0.196	0.164	0.168	0.120	0.203	1.20	0.184	59.8
Ho	<0.005	<0.005	<0.005	<0.005	<0.006	<0.004	<0.005	<0.005	<0.005	<0.005	0.029	<0.005	2.12
Er	0.016	0.014	0.025	0.017	0.016	0.013	0.012	0.010	0.008	0.020	0.089	0.014	5.68
Tm	0.002	<0.003	0.004	0.003	<0.003	<0.002	<0.003	<0.003	<0.003	<0.003	0.014	<0.003	0.848
Yb	0.025	0.023	0.034	0.028	0.021	0.018	0.018	0.019	0.017	0.026	0.086	0.022	5.43
Lu	0.004	0.004	0.006	0.005	<0.003	0.003	0.003	0.002	0.004	0.005	0.015	0.004	0.866
Co	96	99	97	101	97	113	108	93	85	97	96	93	<18
Cr	2698	2636	3128	3027	2850	2610	2627	2471	2504	2693	2412	2393	104
Cu	<6.9	<7.6	<8.3	<7.2	9.7	<6.5	6.8	<7.3	<6.9	12.4	<8.6	<7.5	14.4
Ni	2130	2213	2055	2069	2274	2283	2257	2075	2266	2130	2158	2125	84
Sc	9.11	8.06	10.6	10.3	8.66	7.35	7.29	7.90	8.34	8.63	7.93	7.95	8.53
V	30	27	35	33	28	27	27	25	26	31	27	28	<18
Zn	39	41	39	40	39	45	48	32	20	39	36	37	86
Cd	<6.9	<7.6	<8.3	<7.2	<9.4	<6.5	<6.7	<7.3	<6.9	<7.9	<8.6	<7.5	<8.9
As	<83	<92	<100	<86	<113	<78	<80	<88	<82	<94	<103	106	<107

coexisting olivine (a near-infinite reservoir of Fe and Mg). Chromites in ophiolites commonly fall along ca. 700 °C isotherms, a few of which are illustrated in Fig. 6. The Baie Verte chromites fall on the high-temperature, high-Fo side of the Fo₉₂ – 700 °C isotherm, which is consistent with the presence in some of these rocks of olivines up to Fo₉₃. How-

ever, half of the Advocate rocks have average Fo < 92, and so blocking temperatures for this suite of rocks are probably slightly >700 °C.

The Advocate mantle harzburgites have normalized trace element profiles that are completely different from typical Thetford Mines or Bay of Islands mantle rocks, with signifi-

Fig. 8. Minor element variations of Advocate ophiolite mantle rocks and other Baie Verte mantle rocks. Same notes and sources as Fig. 7.

cant incompatible element enrichment. This enrichment seems at odds with the refractory nature that is implied by high whole-rock MgO and low Al_2O_3 and TiO_2 ($F > 25\%$); and by high chromite Cr# ($F = 28\text{--}35\%$). The incompatible element enrichment of Advocate harzburgites cannot be related to an initial source enrichment because melting processes deplete the incompatible elements very rapidly (Pagé et al. 2009).

The felsic rock analyzed at station 89B may represent an extreme metasomatic overprint, and it might best record the signature of the metasomatic agent that generated the anomalous Advocate trace element enrichment. To test the hypothesis that the observed geochemical spectrum of Advocate harzburgites represents metasomatism by a melt

similar to the composition of sample 89B, small proportions of this contaminant were added to the most depleted of the analyzed Advocate harzburgites (Fig. 10b). Admixture of just 0.15% of sample 89B to the depleted end member can generate trace element profiles similar to the average Advocate harzburgite, whereas the most enriched harzburgite (sample 104A) requires 1.3% (Fig. 10b). The fits are remarkably good for almost every element.

This begs the question of how the least enriched Advocate harzburgite was generated. Since there is no information on the pre-metasomatic composition of the Advocate harzburgite, we assumed for the sake of argument that it was similar to the Thetford Mines mantle (Fig. 9a). Because the HREE contents of average Thetford Mines mantle harzbur-

Fig. 9. Primitive mantle (PM)-normalized extended trace element plots. PM is the pyrolite composition of McDonough and Sun (1995). Sample locations and descriptions for the rocks analyzed at Actlabs will be published elsewhere. (a) Advocate harzburgites (INRS data) are dots with solid lines, whereas the “granitic” sample (89B) is shown as open boxes with a broken line. The field is for data from the North Arm Mountain Massif (NAMM) of the Bay of Islands Complex (sources as per Fig. 7), with the average Thetford Mines mantle (avTMOHz) from Pagé et al. (2009). DMM, depleted MORB (mid-ocean ridge basalt) mantle source, which is also the starting composition for the melt modeling. AAM is the average abyssal mantle from Niu (2004). (b) Advocate harzburgites (Actlabs data). The field shows the main group of Advocate rocks analyzed at INRS. (c) Mantle rocks from Ming’s Bight. Note the overall similarity to the Advocate data. (d) Mantle rocks from the Fleur de Lys Supergroup – Birchy Complex. Note the overall similarity to the Advocate data.

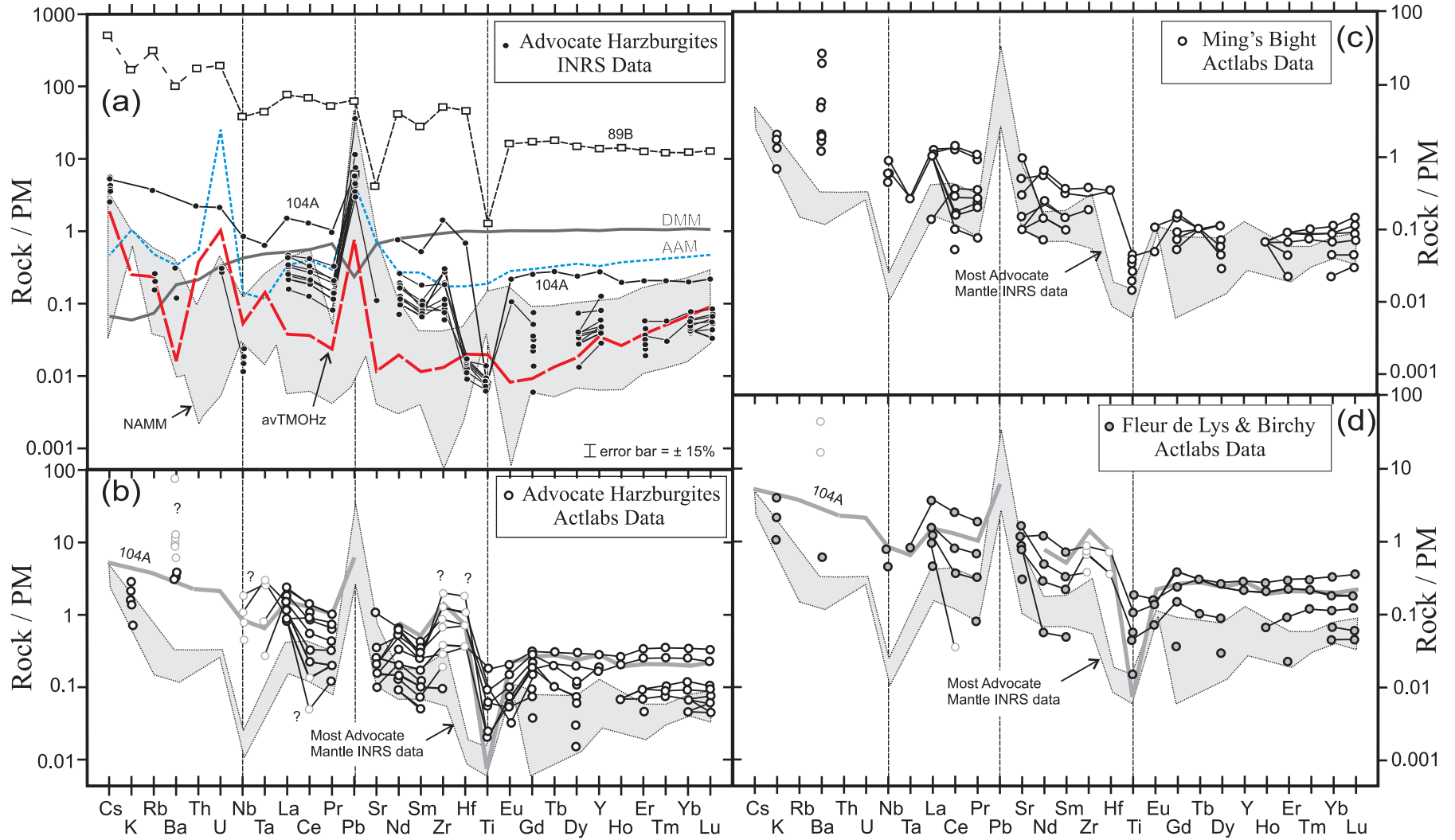
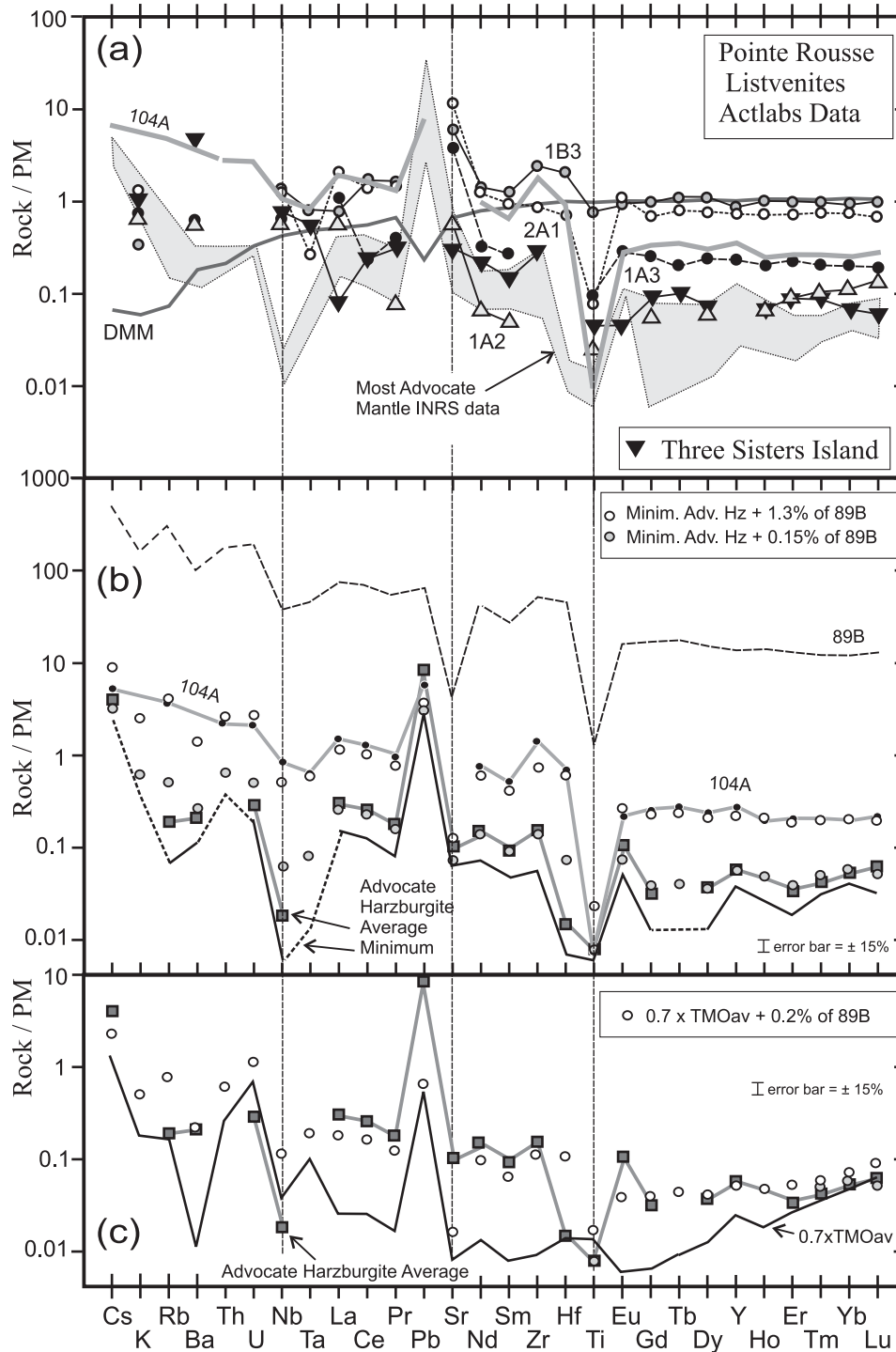


Fig. 10. (a) Possible mantle rocks from the Point Rousse ophiolite. Sample 1A2 resembles typical Advocate mantle, while 1A3 resembles enriched Advocate sample 104A. The enriched samples (1B3 and 2A1) are either undepleted mantle or cumulates. Note the ubiquitous +Sr anomalies, which are absent in the fresher harzburgite from nearby Three Sisters Island. (b) Mixing model between sample 89B and the most depleted Advocate harzburgite. Where elements were below the detection limit, values were either set to the detection limit or were simply interpolated (broken lines, Fig. 9b). The average Advocate mantle (filled boxes) excludes sample #104A. The grey and white circles are mixtures of 0.15% and 1.3% contaminant. (c) Mixing model between sample 89B and $0.7 \times$ average Thetford Mines ophiolite harzburgite (TMOav) from Pagé et al. (2009). The black boxes are the average Advocate harzburgite. DMM, depleted MORB mantle; Minim. Adv. HZ, minimum Advocate harzburgite; PM, primitive mantle.



gite are a little higher than the HREE contents of most Advocate harzburgites, the starting composition for the modeling was assumed to be equal to $0.7 \times$ the average Thetford

Mines value (Fig. 10c). This is consistent with the apparently more refractory nature of the Advocate mantle relative to the Thetford Mines mantle (e.g., Figs. 6–8). Mixing

calculations (Fig. 10c) suggest that addition of only 0.2% of a contaminant similar to sample 89B to the depleted Thetford Mines mantle source ($0.7 \times \text{TMO}$) can reproduce the trace element profiles of average Advocate mantle harzburgite. The mixing model slightly overestimates the HREE contents and underestimates LREE contents, but given the uncertainties in the starting compositions, the fit is remarkable. The excellent fit of these models (Figs. 10b, 10c) is consistent with the notion that the Advocate mantle records a metasomatic overprint on a protolith that was similar to a more “normal” Appalachian supra-subduction zone mantle, examples of which are well preserved in the Thetford Mines and Bay of Islands ophiolites.

What then is the origin and nature of this metasomatic agent? One possibility is that these signatures reflect pervasive listvenitization, and that sample 89B is simply a more pervasively listvenitized harzburgite. The formation of listvenite can be described as a three-stage metasomatic process acting on a serpentine-rich protolith:

- (1) carbonatization due to a reaction of serpentine + $\text{CO}_2 = 3 \text{ carbonate} + 2 \text{ quartz} + 2 \text{ H}_2\text{O}$;
- (2) silicification, either due to an external contribution of silica or as a result of silica released in reaction (1); and
- (3) mica formation during a reaction like $3 \text{ albite} + \text{K} + 2 \text{ H}_2 = \text{muscovite} + 6 \text{ quartz} + \text{Na}$.

The third stage would require an external source of K that could be linked to deuteric fluids associated with felsic intrusions (Plissart et al. 2009), or to seawater-derived fluids channeled along faults. The high K_2O (>4%) and low Na_2O (<0.5%) of sample 89B are consistent with stage 3 listvenite (and inconsistent with formation as an oceanic plagiogranite). However, strongly listvenitized rocks from Point Rouse show prominent positive Sr peaks (Fig. 10a) and are depleted in Ni and Co (Fig. 8), signatures that are noticeably absent in Advocate mantle rocks, including sample 89B (Figs. 8, 9). The geographically widespread nature of the enriched trace element signatures in Baie Verte harzburgites, the absence of characteristic listvenite-related positive Sr and negative Co–Ni anomalies in most Advocate harzburgites, together with the absence of obvious fluid channels on the outcrop scale, do not support a listvenitization origin for these problematic trace element enrichments.

Other possible metasomatic agents include (i) subduction-related fluids or melts; (ii) a partial melt of overridden continental margin sediments, as has been suggested for intramantle two-mica granites that occur in the Thetford Mines ophiolite (Clague et al. 1981; Whitehead et al. 2000); (iii) a later intrusion related to the Burlington – Cape Brulé pulse; or (iv) introduction of a fertile melt or fluid prior to obduction. We weigh these hypotheses in turn.

The geochemistry of the Thetford Mines mantle rocks was simulated by Pagé et al. (2009) as the result of synchronous melting + arc-related metasomatism. For Thetford Mines, reasonable solutions were obtained by Pagé et al. (2009) for critical or fractional melting scenarios involving very small proportions (ca. 2% of each melting increment) of an arc contaminant largely derived from subducted Grenvillian sediments, proportions which are in accord with models based on isotopic data. Very similar proportions and compositions of contaminants were calculated from the geo-

chemistry of Betts Cove boninites by Bédard (1999). However, it proved impossible to fit the average Advocate harzburgite with this type of forward model with a normal felsic or sedimentary contaminant (using the same DMM source composition as Pagé et al. (2009), with the same melting proportions, degree of melt retention during critical melting, and D (partition coefficient) values). To obtain a satisfactory fit would require an unrealistic contaminant with ca. 7000 ppm La.

The overall uniformity of the enrichment pattern on a multi-kilometre scale seems difficult to reconcile with a partial melt of overridden continental margin sediments, or a later intrusion related to the Burlington – Cape Brulé pulse, because one would expect a syn- to post-obduction metasomatic event to be spatially heterogeneous, with felsic dykes or veins apparent in outcrop. Because all Advocate harzburgites show these enrichments, even in outcrops where rocks are massive and lack obvious intrusions or channels, we infer that these geochemical signatures were introduced while the Advocate mantle rocks were still hot, allowing near-homogeneous metasomatism by diffuse percolation. In contrast, the extremely silica-rich sample 89B may reflect a more focussed case of mantle metasomatism, possibly related to an intra-mantle structure.

Because this anomalous Advocate-type geochemical signature appears to be widespread, but limited to the rocks of the Baie Verte Peninsula, we infer that the metasomatic agent was introduced into the mantle by a discrete event that characterizes the geologic history of this area. A speculative possibility is that the melts and (or) fluids were introduced into the mantle rocks prior to obduction as a result of failed continental subduction or delamination of a lower crustal block. Alternatively, the signature may represent a metasomatic overprint related to development of a successor arc.

Conclusions

Mantle rocks of the Advocate ophiolite (Baie Verte, Newfoundland) are dominated by harzburgite tectonites. These are extensively converted to listvenite close to the Baie Verte Road fault and represent a potential gold exploration target. Most Advocate harzburgites have forsteritic olivine ($\text{Fo}_{90.5}$ to Fo_{93}), and Cr-spinels with Cr# (= $100\text{Cr}/(\text{Cr} + \text{Al})$) between 52 and 64, and Mg# (= $100\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$) between 56 and 68. These mineral-chemical signatures, together with high whole-rock MgO (46%–48%) and low Al_2O_3 (<1%) and TiO_2 (<0.003%), imply the Advocate harzburgites are refractory residues after ca. 25%–35% melting. Cr-spinel compositions of Advocate mantle rocks overlap compositionally with Cr-spinels from the mantle rocks of the Point Rouse and Betts Cove ophiolites, with Mg# values higher than those of Bay of Islands or Thetford Mines mantle Cr-spinels. This suggests that the Baie Verte ophiolites are unusually refractory and correlative, and may represent remnants of a single obducted slab. Although refractory in terms of major elements and mineral chemistry, Advocate harzburgites contain high La–Ce–Pr–Pb–Nd–Sm–Zr contents suggestive of pervasive metasomatism. Similar signatures are widespread in other Baie Verte mantle rocks but are restricted to this geographic area. The enrichments are most

compatible with post-melting metasomatism, but the absence of visible metasomatic channels in most outcrops suggests that metasomatism occurred by diffuse percolation before obduction. The source of the contaminant is uncertain. It could have been introduced either by subduction of the Laurentian margin beneath a peri-continental oceanic basin or arc, by delamination of thickened continental or arc crust, or be related to successor arc magmatism.

Acknowledgements

Steven Hinchey, Tony Fowler, and Cees van Staal helped with the traverses and sampling. Neil Rogers, Tom Skulski, and Sébastien Castongay helped with the field and computer logistics. Marc Choquette helped with the microprobe analyses. Philippe Girard did the crushing and grinding; and Anissa Bensadoune and Julie Perreault performed the whole-rock analyses at INRS. The manuscript was significantly improved by reviews from Paul Robinson and Ali Polat. This paper represents work done through the TGI-3 program.

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