A lost arc–back-arc terrane of the Dunnage oceanic tract recorded in clasts from the Garin Formation and McCrea mélange in the Gaspé Appalachians of Québec

Céline Dupuis†
Michel Malo*
Institut National de la Recherche Scientifique, Eau, Terre et Environnement, 490 de la Couronne, Québec, Québec G1K 9A9, Canada

Jean Bédard§
Geological Survey of Canada–Québec, Earth Science Sector, 490 de la Couronne, Québec, Québec G1K 9A9, Canada

Bill Davis
Mike Villeneuve
Geological Survey of Canada–Ottawa, Earth Science Sector, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada

ABSTRACT

Upper Ordovician Garin conglomerates (base of the Gaspé belt, Québec Appalachians) contain three igneous clast populations. (1) Calc-alkaline intermediate-felsic rocks resemble Exploits (New Brunswick, Maine) and Notre Dame (Québec, Newfoundland) subzone lavas. Clasts (monzonite-rhyodacite) give U-Pb zircon ages between 465 and 466 Ma, precluding correlation with Exploits rocks. We suggest that the suite represents peri-Laurentian continental arc magmas coeval with the Red Indian Lake Group of Newfoundland. Correlation of lavas from a Gaspé well with the Popelogan arc implies that the Red Indian Line passes through southern Gaspé. (2) Mafic tholeiitic-to-alkaline clasts resemble New Brunswick and Maine (Exploits subzone) alkaline lavas. We interpret them as magmas associated with initiation of a back-arc basin, possibly on the Laurentian margin. (3) Mafic-intermediate tholeiitic to calc-alkaline clasts have an oceanic subduction component and correlate with Notre Dame subzone lavas (Québec, Newfoundland). They are interpreted as products of spreading and off-axis magmatism of a peri-Laurentian back-arc basin. We correlate McCrea mélange lavas to the calc-alkaline intermediate-felsic and mafic-intermediate suites and interpret them as samples of a Notre Dame subzone terrane coeval with the Red Indian Lake Group of Newfoundland during initiation of a successor arc–back-arc, a terrane which is no longer preserved in New Brunswick and Maine but that provides some evidence for possible extensions of Newfoundland's geology into the Gaspé Appalachians of Québec. A mid-ocean-ridge basalt–like intrusion in the McCrea mélange (Ar-Ar age: 471.2 ± 11.2 Ma) is coeval with peri-Laurentian ophiolites in Newfoundland and may record a back-arc opening event.

Keywords: igneous clasts, calc-alkaline, tholeiite, volcanism, back-arc basin, Dunnage zone, Gaspé Appalachians.

INTRODUCTION

The Gaspé Peninsula of Québec is one of the few parts of the Appalachian orogen where near-continuous post-Taconian sedimentation is preserved (the Gaspé belt). While this has led to a very good understanding of post–mid-Ordovician geological history, the relatively poor exposure of the basement hampers reconstruction of the accretion history. In this contribution, we attempt to clarify the events that immediately followed the Taconian orogenic pulse by: (1) providing new age data on a suite of mid-ocean-ridge basalt (MORB)–like intrusions (the Pabos Suite) that crosscut an accretionary mélange; and (2) investigating the provenance of clasts in the Garin Formation, the lowermost post-Taconian sedimentary unit. These data allow us to propose a revised geological scenario, using Newfoundland's geology as a template, for this part of the Québec Appalachian orogen during a critical age interval separating the last increments of the Taconian orogeny from the first sedimentation within the Gaspé belt successor basin.

Volcano-sedimentary rocks of the extensive Middle Paleozoic Gaspé belt unconformably overlie (or are in faulted contact with) Upper Neoproterozoic to Upper Ordovician rocks of the Humber and Dunnage zones (Figs. 1 and 2). The basal unit of the Gaspé belt is the Upper Ordovician Garin Formation (Fig. 2; Malo, 1988; Malo and Bourque, 1993), a turbiditic siliciclastic unit including conglomerates derived from a source region composed mainly of sedimentary and volcanic rocks (Ducharme, 1979; Vennat, 1979; Malo, 1988). Igneous clasts in the Garin conglomerates include extrusive and intrusive, mafic to felsic varieties. In the southern Gaspé Peninsula, the Garin Formation paraconformably overlies Llanvirnian sandstones of the Arsenault Formation and the McCrea mélange (Malo and Bourque, 1993) and marks a hiatus corresponding to five graptolite zones (~10 m.y.). In the Popelogan inlier of northwestern New Brunswick, the Balmoral Group of the Dunnage zone is overlain by the Grog Brook Group or the White Head Formation (Wilson et al., 2004), a hiatus of 2 to nearly 15 m.y., respectively (Fig. 3, column A). Thus, throughout this part of the Appalachians, there is an age gap separating accretion of terranes during the Taconian from the first deposition of strata in the Gaspé belt successor basin. Since rocks of the McCrea and Popelogan inliers are considered

†E-mail: celine.dupuis.1@ulaval.ca.
*E-mail: michel.malo@ete.inrs.ca.
§E-mail: Jean.Bedard@rncan.gc.ca.

GSA Bulletin; January/February 2009; v. 121; no. 1/2; p. 17–38; doi: 10.1130/B26251.1; 17 figures; Data Repository item 2008161.

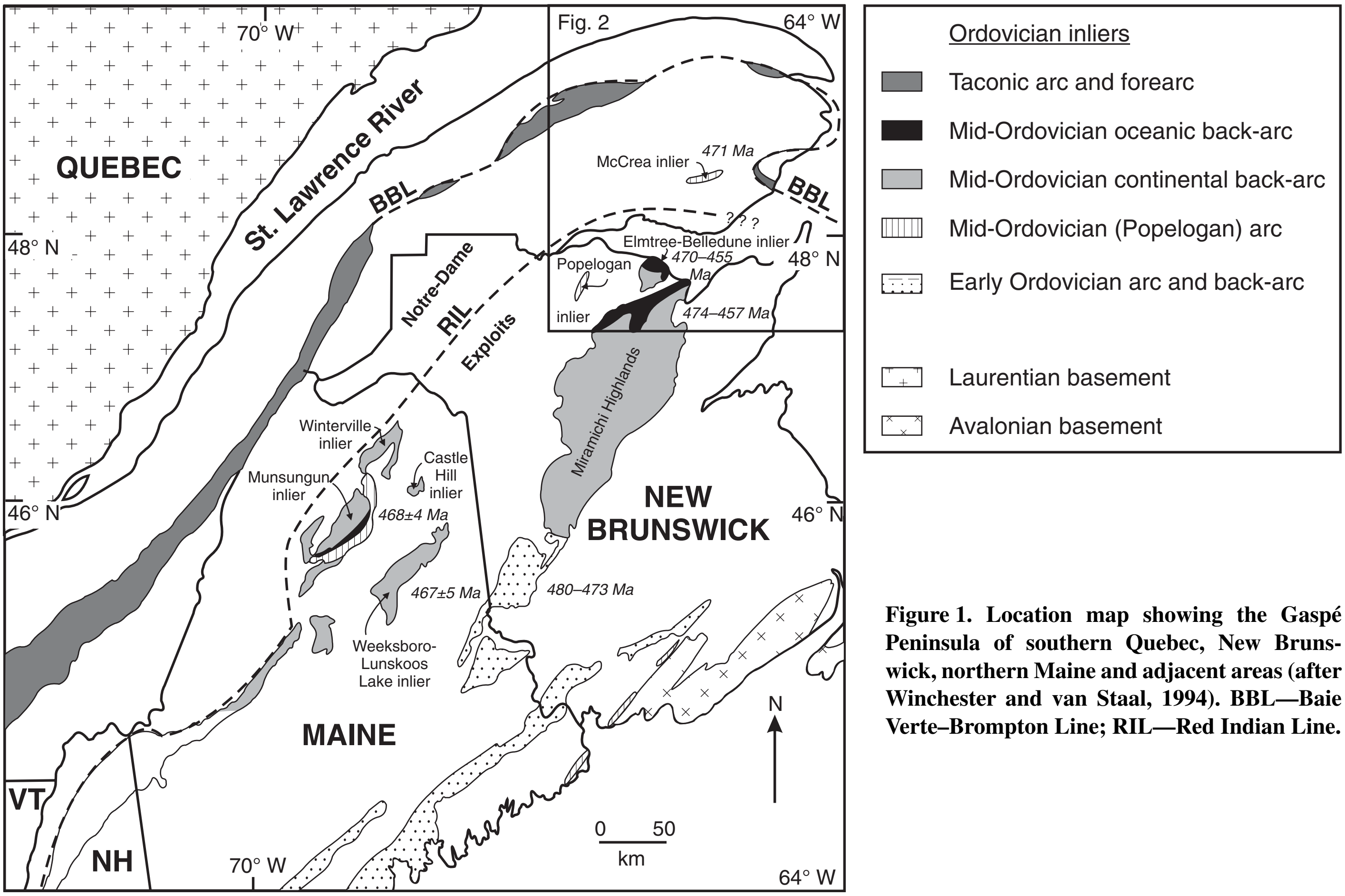


Figure 1. Location map showing the Gaspé Peninsula of southern Quebec, New Brunswick, northern Maine and adjacent areas (after Winchester and van Staal, 1994). BBL—Baie Verte–Brompton Line; RIL—Red Indian Line.

part of the oceanic Dunnage zone (see Williams, 1995), then clasts in the Garin Formation could include fragments of the Ordovician Iapetus oceanic domain, and so provide information about the events in adjoining terranes that are now buried beneath younger units. In this paper, we document the petrography and geochemistry of the igneous clasts from the Garin Formation and provide new geochronological data on some of them. These data allow us to correlate these rocks with putative source terranes. When combined with new age data from the underlying Dunnage zone rocks in the Gaspé Peninsula, we obtain improved constraints for tectonic models of the Dunnage oceanic tract during Ordovician (syn- to post-Taconian) time.

GEOLOGICAL SETTING

Tectonostratigraphy of the Gaspé Appalachians

The Canadian Appalachians in the Gaspé Peninsula consist of four tectonostratigraphic assemblages: (1) the Upper Neoproterozoic to Upper Ordovician Humber zone; (2) the Ordovician Dunnage zone; (3) the Upper Ordovician to Middle Devonian Gaspé belt; and (4) the Upper Devonian to Carboniferous Maritimes Basin (Fig. 2).

Rocks of the Humber zone consist of rift-related basalts, slope-and-rise deposits of the Laurentian passive margin (Lavoie et al., 2003), and synorogenic foreland basin turbidites (Prave et al., 2000). Regional deformation of the Humber zone is dominated by the Taconian orogeny, which records ophiolite obduction, collision of arc terranes, crustal thickening of the Laurentian margin, and the emplacement of northwest-verging thrust sheets (St-Julien and Hubert, 1975; De Broucker, 1987; Slivitzky et al., 1991; Pincivy et al., 2003). In Gaspé, the contact between the Humber and Dunnage zones is commonly marked by a series of partly dismembered ophiolites and associated mélanges (Malo et al., 1992a) called the Baie Verte–Brompton Line (Williams and St-Julien, 1982).

The Dunnage zone is composed of rocks derived from the Ordovician Iapetus Ocean. It is subdivided into the Notre Dame and Exploits subzones, which correspond to Iapetan terranes formed outboard of Laurentia and Gondwana, respectively. The Red Indian Line (Fig. 1), the tectonic contact between both subzones, was developed during Late Ordovician closure of the main tract of the Iapetus Ocean (van Staal et al., 1998), and it is regarded as the orogen's main suture zone. Near the Baie Verte–Brompton Line, the Dunnage zone in Gaspé is represented by inliers that contain tectonic and/or olistostromal mélanges and serpentinite bodies, which include (from the northwest to the southeast, Fig. 2): the Ruisseau Isabelle mélange, the Lady Step Complex, the Rivière Port-Daniel mélange, the Nadeau ophiolitic mélange, and the McCrea mélange. Some deformational features of the Dunnage zone are attributed to Taconian accretionary processes (De Broucker, 1987; Tremblay et al., 1995), but the major regional deformation event is the Acadian orogeny.

The Gaspé belt post-Taconian successor basin is divided into four broad temporal and lithological assemblages (Fig. 2; Bourque et al., 2000). From the base to the top, these are: (1) the uppermost Ordovician–lowermost Silurian deep-water, fine-grained carbonate-siliciclastic facies of the Matapédia Basin belonging to the Honorat Group (which has only one formation,

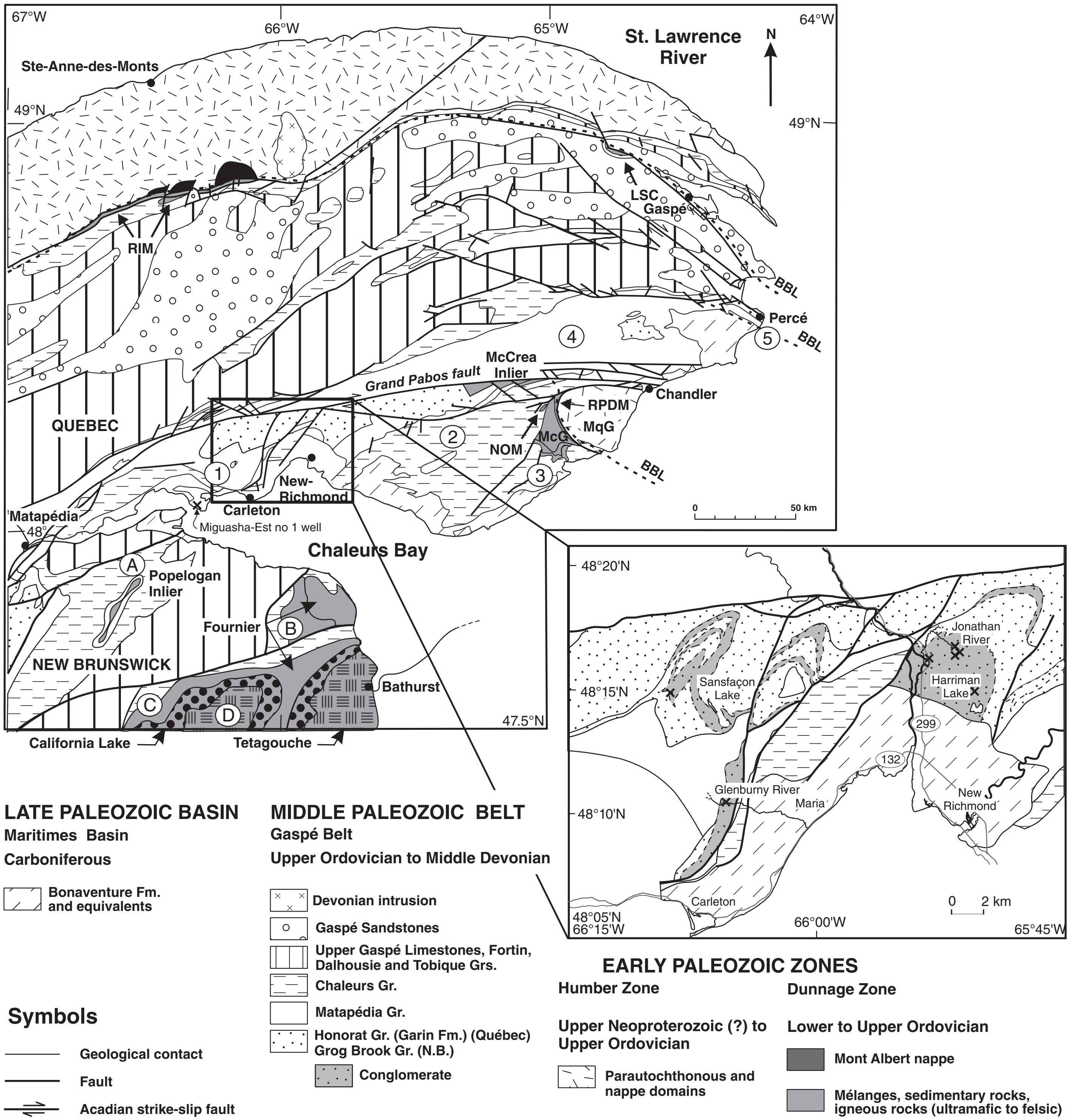


Figure 2. Generalized geology of Gaspé and northern central New Brunswick (modified after Malo, 2004; Gosselin, 1988 [inset]; van Staal et al., 2003; Wilson et al., 2004). Xs on inset map indicate sampling locations. BBL—Baie Verte–Brompton Line; LSC—Lady Step Complex; McG—Mictaw Group; MqG—Maquereau Group; NOM—Nadeau ophiolitic mélange; RPDM—Rivière Port-Daniel mélange. Numbers 1–5 and letters A–D correspond to locations of stratigraphic sections of Figure 3.

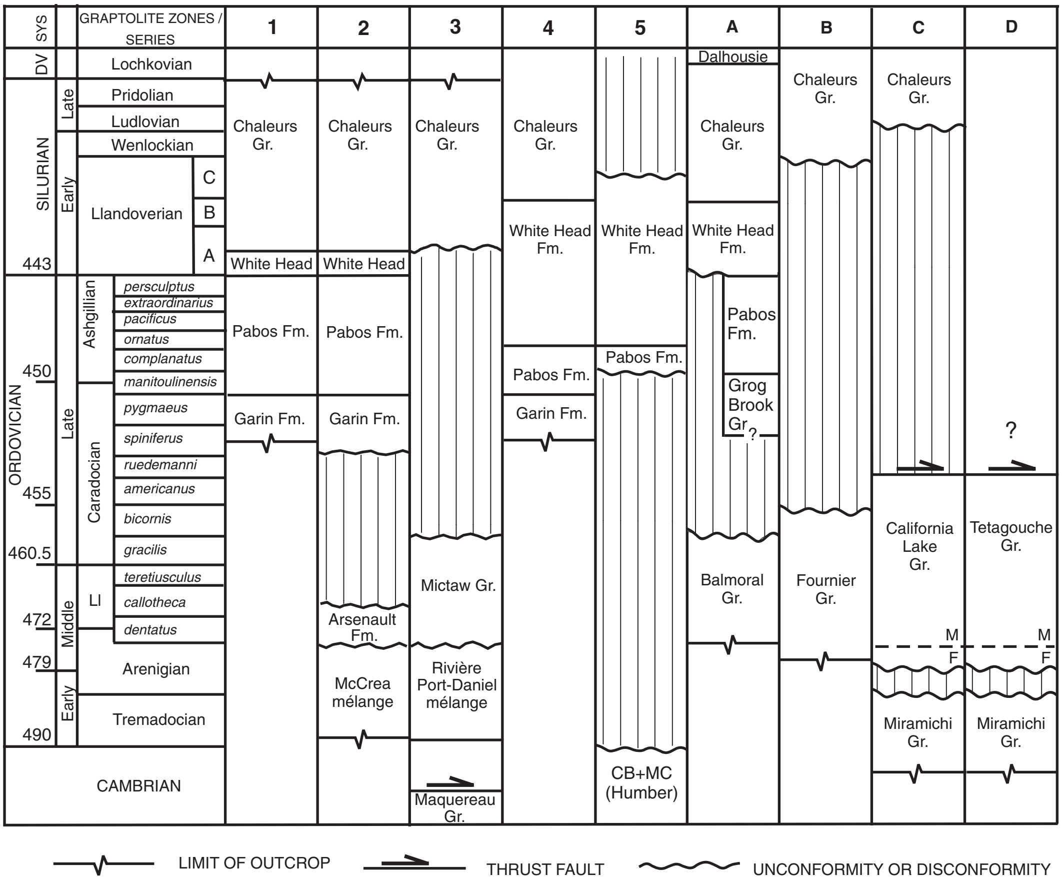


Figure 3. Biostratigraphical position and correlation of the rock units (modified from Malo, 2004; Wilson et al., 2004; van Staal et al., 2003). CB+MC—Corner of the Beach and Murphy Creek Formations; F—felsic rocks; Fm—Formation; Gr—Group; Ll—Llanvirnian; M—mafic rocks. Numbers and letters in column headings correspond to locations shown in Figure 2. Radiometric ages are from Webby et al. (2004).

the Garin Formation) and the Matapédia Group; (2) the Silurian–lowermost Devonian shallow- to deep-shelf facies of the Chaleurs Group; (3) the Lower Devonian mixed siliciclastic and carbonate fine-grained deep-shelf to basin facies of the Upper Gaspé Limestones and Fortin Groups; and (4) the Lower to Middle Devonian near-shore to terrestrial coarse-grained facies of the Gaspé Sandstones Group. The Gaspé belt was deformed mainly by the Acadian orogeny during the Middle Devonian, but it also shows structures related to the Salinic disturbance (Malo, 2001). Rocks have been affected by regional anchimetamorphism to low-grade burial metamorphism (Nowlan and Barnes, 1987; Chagnon, 1988; Hesse and Dalton, 1991).

The Matapédia Basin and Its Dunnage Zone Basement in Southern Gaspé Peninsula and Northern New Brunswick

The lowermost rocks of the Gaspé belt define the Matapédia Basin and outcrop mainly in the southern Gaspé Peninsula, northwestern New Brunswick, and northeastern Maine (Malo, 2004). In Gaspé and New Brunswick, the Matapédia Basin consists of the Garin Formation and the Grog Brook and Matapédia Groups, all of which unconformably overlie rocks of the Dunnage zone (Fig. 2). The Upper Ordovician Garin Formation is made up of terrigenous rocks, including black claystone, noncalcareous gray mudstone, greenish-gray siltstone, calcareous siltstone, calcareous quartz-wacke, lithic wacke, conglomerate, and silty dolomitic limestone (Malo, 1988; Malo and Bourque, 1993). Conglomerates contain volcanic, sedimentary, plutonic, ultramafic, and rare metamorphic clasts derived from a source region located to the south (Ducharme, 1979; Vennat, 1979; Malo, 1989). The Matapédia Group consists of a lower laminated calcareous mudstone unit (Pabos Formation), followed by a succession of calcareous rocks (White Head Formation) (Malo, 2004).

The Upper Ordovician Grog Brook Group in New Brunswick is the lithostratigraphic equivalent of the Garin Formation (Figs. 2 and 3). The Grog Brook Group consists of a thick series of mainly siliciclastic turbidites, sedimentary structures, and bed forms typical of deep-water facies (Wilson et al., 2004). Polymictic conglomerates of the Grog Brook Group contain rounded to angular clasts of unfoliated felsic and mafic volcanic rocks, fine-grained sedimentary rocks, chert, quartz, and feldspar in a mudstone or siltstone matrix (Wilson et al., 2004).

Upper Ordovician rocks of the Matapédia Basin in the Gaspé Peninsula unconformably overlie Dunnage zone rocks of peri-Laurentian affinity of the McCrea inlier (column 2, Fig. 3), whereas in two other inliers, the Maquereau-Mictaw inlier and the Nadeau ophiolitic mélange, the Dunnage zone basement is unconformably overlain by Silurian rocks of the Chaleurs Group (column 3, Fig. 3). The McCrea inlier (Fig. 2) consists of two lithostratigraphic units (column 2, Fig. 3): the McCrea mélange, and the forearc turbidites of the Arsenault Formation. The Maquereau-Mictaw inlier is a tectonic collage made up of Cambrian rift-related basalt, arkose, and slate of the Maquereau Group (Humber zone; Bédard and Wilson, 1997) juxtaposed against Dunnage zone rocks of the Rivière Port-Daniel mélange and the Mictaw Group (De Broucker, 1987). The Lower Ordovician McCrea and Rivière Port-Daniel mélanges are made up of tectonic slices and mappable blocks of serpentinite, listwaenite, granitic rocks, and basalt, and clasts of granitic gneiss, serpentinite, red slate, and calcareous siltstone embedded in a matrix of black shale and pebbly mudstone (De Broucker, 1987; Malo et al., 1992b). The Llanvirnian Arsenault Formation and the basal unit of the Mictaw Group (Neckwick Formation)

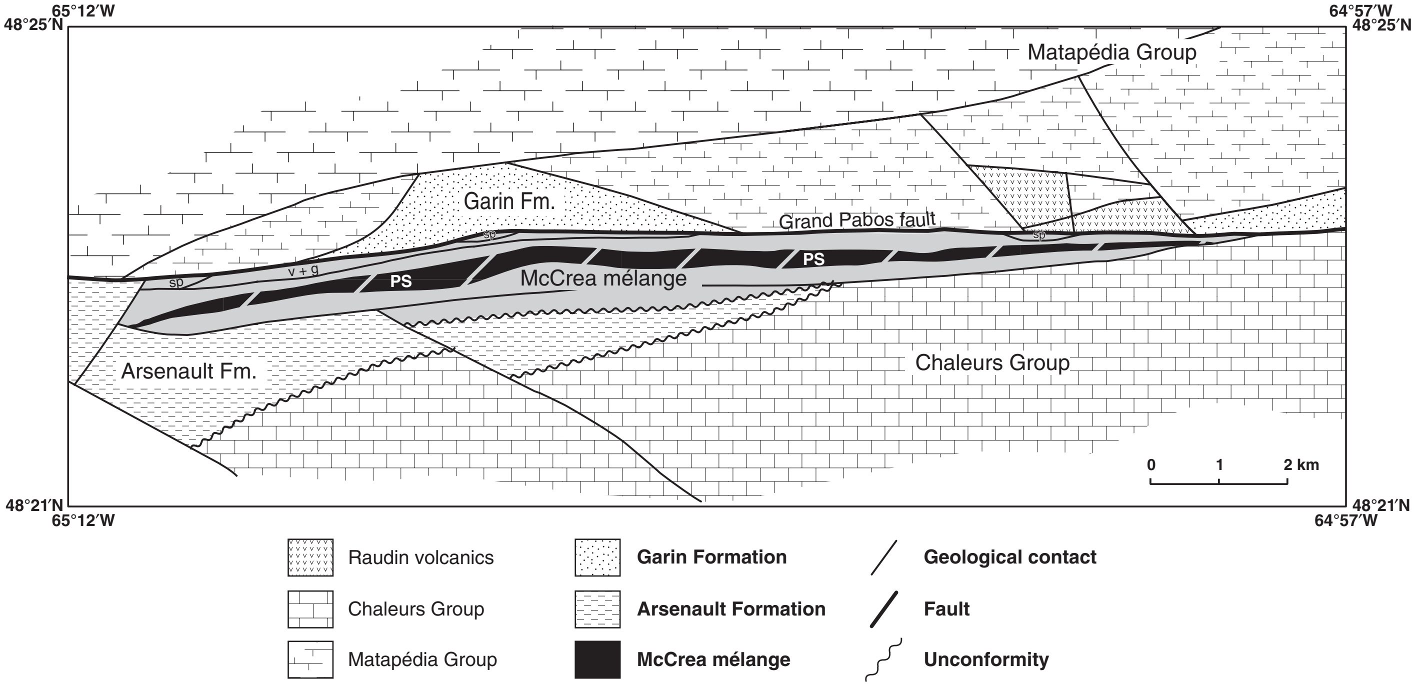


Figure 4. Geological map of the McCrea inlier south of the Grand Pabos fault (modified from Malo et al., 1992b). PS—Pabos Suite; sp—serpentinite; v + g—volcanic and granitic rocks.

(Malo and Bourque, 1993) are correlative and consist of turbiditic sandstones, shales, and minor tuffs. Detailed mapping of the McCrea inlier south of the Grand Pabos fault (Fig. 4) shows that the 15-km-long gabbronoritic sill of the MORB-like Pabos Suite is intruded into the pebbly mudstone of the McCrea mélange. In the Maquereau-Mictaw inlier, ferrogabbroic rocks that are potentially correlative with the Pabos Suite (Bédard, 1986) cut sedimentary rocks that might be part of the Rivière Port-Daniel mélange, although they are mapped as Neckwick Formation (De Broucker, 1987). The Nadeau ophiolitic mélange contains blocks of serpentinized peridotite, amphibolite, tuffaceous graywacke, quartzite, and granitic rocks embedded in a serpentinite matrix, as well as very large blocks of metagraywacke and amphibolite correlated with the Chain Lakes Massif (De Broucker, 1987; cf. Gerbi et al., 2006).

Upper Ordovician rocks of the Matapédia Basin also directly overlie Dunnage zone rocks of peri-Gondwanan affinity in the Popelogan inlier in New Brunswick (Figs. 2 and 3, column A). Ordovician magmatic rocks of the Exploits subzone record the formation of the Popelogan arc, its rifting, and the development of the Tetagouche-Exploits back-arc basin (van Staal et al., 1998, 2003). The Middle to lowermost Upper Ordovician Balmoral Group, exposed in the Popelogan inlier, consists of subduction-related picritic to andesitic rocks of the Goulette Brook Formation (Wilson, 2003) and overlying dark-gray shale and chert of the Popelogan Formation (Wilson et al., 2004). In contrast, in the Elmtree-Belludune inlier and Miramichi Highlands of New Brunswick, the Dunnage zone basement is directly overlain by Silurian rocks of the Chaleurs Group (Fig. 3, columns B–D). The Upper Arenig-Caradoc Fournier Group in the Elmtree-Belledune inlier and the northern Miramichi Highlands (Figs. 2 and 3, column B) is made up of tholeiitic to alkaline basalts and gabbro, with chert, shale, siltstone, and limestone (van Staal et al., 2003). The Middle Arenig to Caradoc Tetagouche and California Lake Groups of the northern Miramichi Highlands (Figs. 2 and 3, columns C–D) consist of rhyolitic to basaltic volcanic rocks with shale and siltstone (van Staal et al., 2003). Further south in the Miramichi Highlands, volcanic and sedimentary rocks of the Lower to Middle Arenig Meductic Group also represent remnants of the Popelogan arc (van Staal et al., 2003).

LOCALIZATION OF SAMPLES AND FIELD DESCRIPTIONS

The Pabos Suite sill occurs immediately to the south of the Grand Pabos fault (PS on Fig. 4). The sill is 150–200 m thick, strikes east-west, and is composed of fresh, hornblende-bearing olivine gabbronorite. The sill is described in Bédard (1985, 1986).

The McCrea mélange contains slivers of dark-gray to green and red, fine- to medium-grained and usually massive basaltic volcanic rocks associated with a fault breccia containing fragments of granitoids and granitic gneiss. The basalts contain phenocrysts of prismatic feldspar and secondary epidote, calcite, and hematite.

Conglomerates of the Garin Formation in the Gaspesian Chaleurs Bay area occur as massive beds (Fig. 2), 1–7 m thick (Simard, 1986; Gosselin, 1988), containing more than 85% igneous and sedimentary pebbles and cobbles, which range from 2 mm to 40 cm in diameter (average 6 cm). Igneous clasts range from gabbro, diabase, and basalt to monzonite, rhyolite, and quartz-feldspar porphyry. Sedimentary clasts are fine to pebbly sandstone, siltstone, mudstone, and chert.

We analyzed three volcanic rocks collected from the deepest geological formation encountered in the Miguasha-Est no. 1 well (Fig. 2). The surface geology consists of sedimentary rocks of the Carboniferous Bonaventure Group, but Paleozoic volcanic rocks were sampled between 1260 and 1430 m depth, below a major unconformity between sedimentary rocks assigned to basal units of the Chaleurs Groups and a sequence of dark-gray to reddish volcanic rocks assigned to the Balmoral Group (C. Morin, Hydro-Québec, 2006, personal commun.). If these volcanic rocks are indeed equivalents of the Balmoral Group, then they would represent samples of the buried Popelogan arc.

PETROGRAPHY OF GARIN CONGLOMERATE CLASTS

Of the 69 igneous rock clasts sampled, the 27 freshest and biggest samples were analyzed. Volcanic rocks range from rhyolite to basalt, while intrusive rocks range from monzonite to gabbro. All rocks have experienced low-grade metamorphism. Metamorphic phases include fibrous actinolite, magnetite, leucoxene (after ilmenite), chlorite, epidote, calcite, and quartz. Epidote, calcite, and quartz fill veins and amygdules.

All volcanic rocks are porphyritic, with prismatic plagioclase phenocrysts up to 1 cm long. Rhyolites also contain phenocrysts of prismatic alkali-feldspar, subrounded quartz, and euhedral to subhedral hornblende, whereas basalts have additional clinopyroxene phenocrysts. Monzonite and porphyritic latite have prismatic plagioclase, granophyric intergrowths of alkali-feldspar and quartz, subhedral to euhedral clinopyroxene, hornblende, biotite, and ilmenite. Fresh plagioclase, K-feldspar, clinopyroxene, and ilmenite occur in gabbro and diabase. Prismatic plagioclase and euhedral to subhedral clinopyroxene occur as phenocrysts in diabase, or form an ophitic texture.

WHOLE-ROCK CHEMISTRY

Clasts of the Garin Formation

Many elements are mobile under the low-grade metamorphic conditions that affected these rocks (e.g., Hart et al., 1974). Because of the probable mobility of alkalies, we classify the rocks on the basis of silica content and high field strength element (HFSE) ratios (Fig. 5). See Data Repository.[1] We divide the 27 analyzed clasts into three main suites: calc-alkaline intermediate-felsic, transitional-alkaline, and mafic-intermediate suites (Fig. 5). We also attribute paleotectonic affinities to these suites based on trace-element discrimination diagrams (e.g., Figs. 6 and 7; see reviews by Rollinson, 1993; Pearce, 1996). Note that petrographic characteristics do not systematically follow the geochemical class subdivision. The three suites have been further subdivided according to specific geochemical characteristics observed on primitive mantle–normalized extended trace-element patterns (Fig. 8).

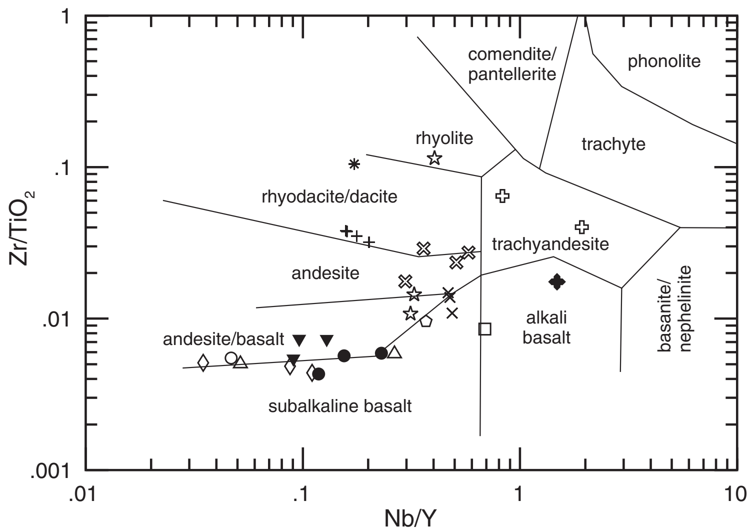
Calc-Alkaline Intermediate-Felsic Suite

Monzonitic and volcanic rocks of the calc-alkaline intermediate-felsic suite (13 samples) range in composition from calc-alkaline andesite to rhyolite (Fig. 5). Rocks of the suite show extensive geochemical variation on primitive mantle–normalized extended trace-element patterns (e.g., Yb ranges from less than 1 to more than 10 times the primitive mantle) and increasingly prominent negative P, Eu, and Ti anomalies as SiO_2 increases (Figs. 8A–8E).

Andesitic rocks, monzonites, and rhyolites all have clear calc-alkaline geochemical signatures characterized by strong light rare earth element (LREE) and U-Th enrichment and prominent negative Nb-Ta anomalies (Figs. 8A and 8C). However, variations in REE abundances, especially heavy (H) REEs, define two subgroups among these calc-alkaline rocks. Subgroup 1 is composed of the andesitic rocks GLEN-78 and GLEN-80A and rhyolite GLEN-52 and is enriched in HREE (Fig. 8A). Note that two andesites of the Miguasha-Est no. 1 well have multi-element patterns similar to those of the HREE-rich andesites of subgroup 1, while the rhyolite from this same well somewhat resembles HREE-rich rhyolite GLEN-52, but it has weaker negative Nb-Ta anomalies and slight positive Zr-Hf anomalies (Fig. 8B). Subgroup 2, composed of the monzonites and HREE-poor rhyolites, is more depleted in HREE than subgroup 1 and is more variable in LREE content (Fig. 8C). A trachyandesite (RLH-49A) has a broadly similar pattern to the subgroup 2 samples, except for prominent negative Zr-Hf anomalies, which are not observed in any other sample from the calc-alkaline intermediate-felsic suite (Fig. 8D). Three porphyritic rhyodacites/dacites are also broadly similar, but they have the lowest La/Yb ratios and show slight positive Zr-Hf anomalies (Fig. 8E). One HREE-poor monzonite (RJ-27) and one porphyritic rhyodacite/dacite (RLH-87) were dated by the U-Pb zircon method (see following).

On a tectonic discrimination diagram for silicic rocks, the HREE-poor rocks clearly plot in the field of volcanic arc–related felsic rocks, whereas the HREE-rich rocks, including the Miguasha volcanic rocks, overlap the fields of volcanic arc and within-plate felsic rocks (Fig. 6A). Note that we have also plotted intermediate rocks of the suite on this diagram for comparison purposes. The strong negative Nb-Ta anomalies, enrichment in LILE and LREE, and generally evolved

[1]GSA Data Repository Item 2008161, geochemical data, is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.



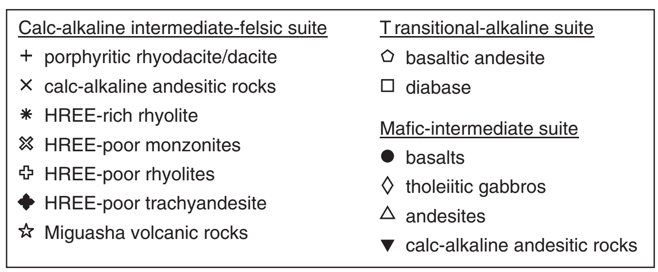


Figure 5. Zr/Ti versus Nb/Y classification diagram of Winchester and Floyd (1977).

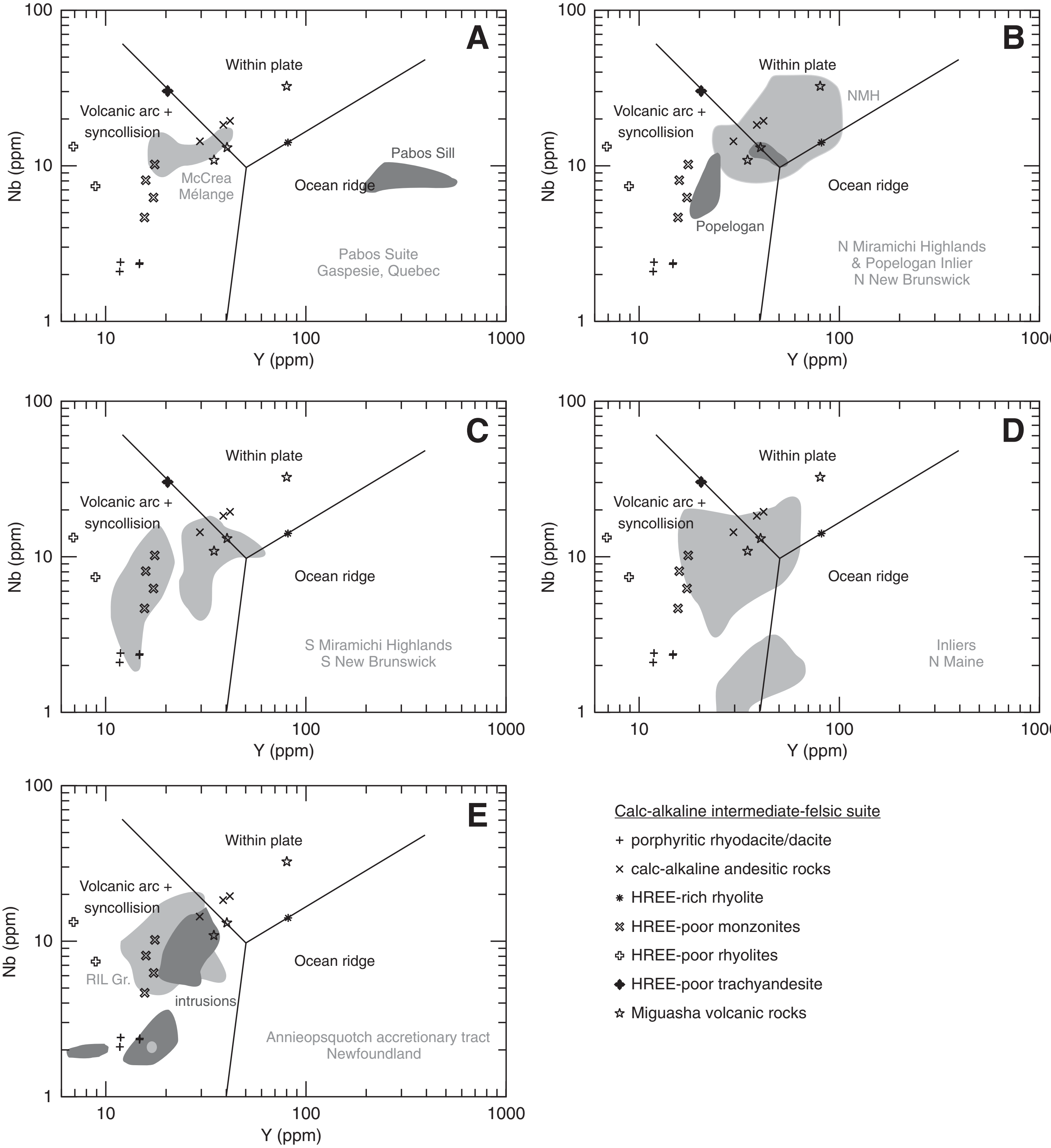


Figure 6. Nb-Y discrimination diagram for intermediate-felsic rocks (after Pearce et al., 1984). Gray fields represent rocks of the Exploits subzone from different regions of New Brunswick and northern Maine, as well as rocks of the Notre Dame subzone in the Gaspé Peninsula (Québec) and Newfoundland: (A) Pabos Suite and McCrea mélange, the Gaspé Peninsula, Québec (Malo et al., 1992b); (B) Tetagouche and California Lake Groups, in the northern Miramichi Highlands (light gray; van Staal et al., 1991; Rogers et al., 2003b), and Goulette Brook Formation in the Popelogan inlier (dark gray; Wilson, 2003), northern New Brunswick; (C) Meductic Group in the southern Miramichi Highlands, southern New Brunswick (Dostal, 1989; Fyffe, 2001); (D) Winterville Formation and Stacyville volcanics in the Winterville, Munsungun, Castle Hill, and Weeksboro-Lunksoos (W-L) inliers, northern Maine (Winchester and van Staal, 1994; Schulz and Ayuso, 2003); and (E) Red Indian Lake Group (RIL Gr.) (light gray) and Otter Pond complex intrusions (dark gray) in the Annieopsquotch accretionary tract, Newfoundland (Lissenberg et al., 2005b; Zagorevski et al., 2006).

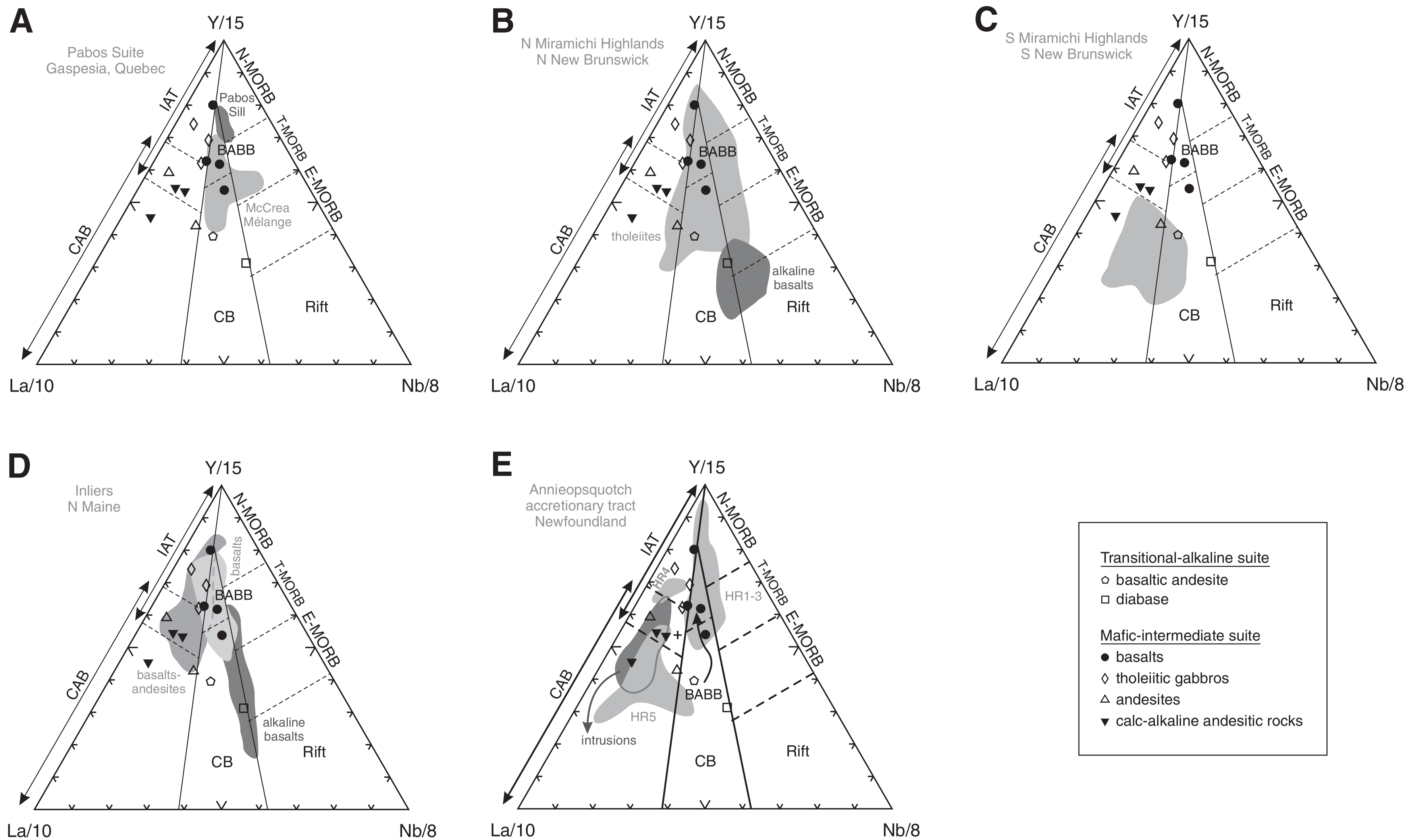


Figure 7. Classification of mafic-intermediate and tholeiitic-to-alkaline suite cobbles in the La-Y-Nb discrimination diagram of Cabanis and Lecolle (1989). Gray fields represent mafic to intermediate rocks of the Exploits subzone from different regions of New Brunswick and northern Maine, as well as rocks of the Notre Dame subzone in the Gaspé Peninsula (Quebec) and Newfoundland: (A) Pabos Suite (dark gray) and McCrea mélange (light gray), Gaspé Peninsula, Quebec (Bédard, 1986; Malo et al., 1992b); (B) Fournier, Tetagouche, and California Lake Groups in the northern Miramichi Highlands (van Staal et al., 1991; Winchester et al., 1992; Rogers et al., 2003b), northern New Brunswick; (C) Meductic Group in the southern Miramichi Highlands, southern New Brunswick (Dostal, 1989; Fyffe, 2001); (D) Winterville Formation and Stacyville volcanics in the Winterville, Munsungun, Castle Hill, and Weeksboro-Lunksoos (W-L) inliers, northern Maine (Winchester and van Staal, 1994; Schulz and Ayuso, 2003); and (E) Red Indian Lake Group (Harbour Round Formation [HR]) (light gray) and Otter Pond complex intrusions (dark gray) in the Annieopsquotch accretionary tract, Newfoundland (Lissenberg et al., 2005b; Zagorevski et al., 2006). Key: BABB—back-arc basin basalt; CAB—calc-alkaline basalt; CB—continental arc basalt; IAT—island-arc tholeiite; MORB—mid-ocean-ridge basalt (N-MORB—normal MORB, E-MORB—enriched MORB); OIB—ocean-island basalt.

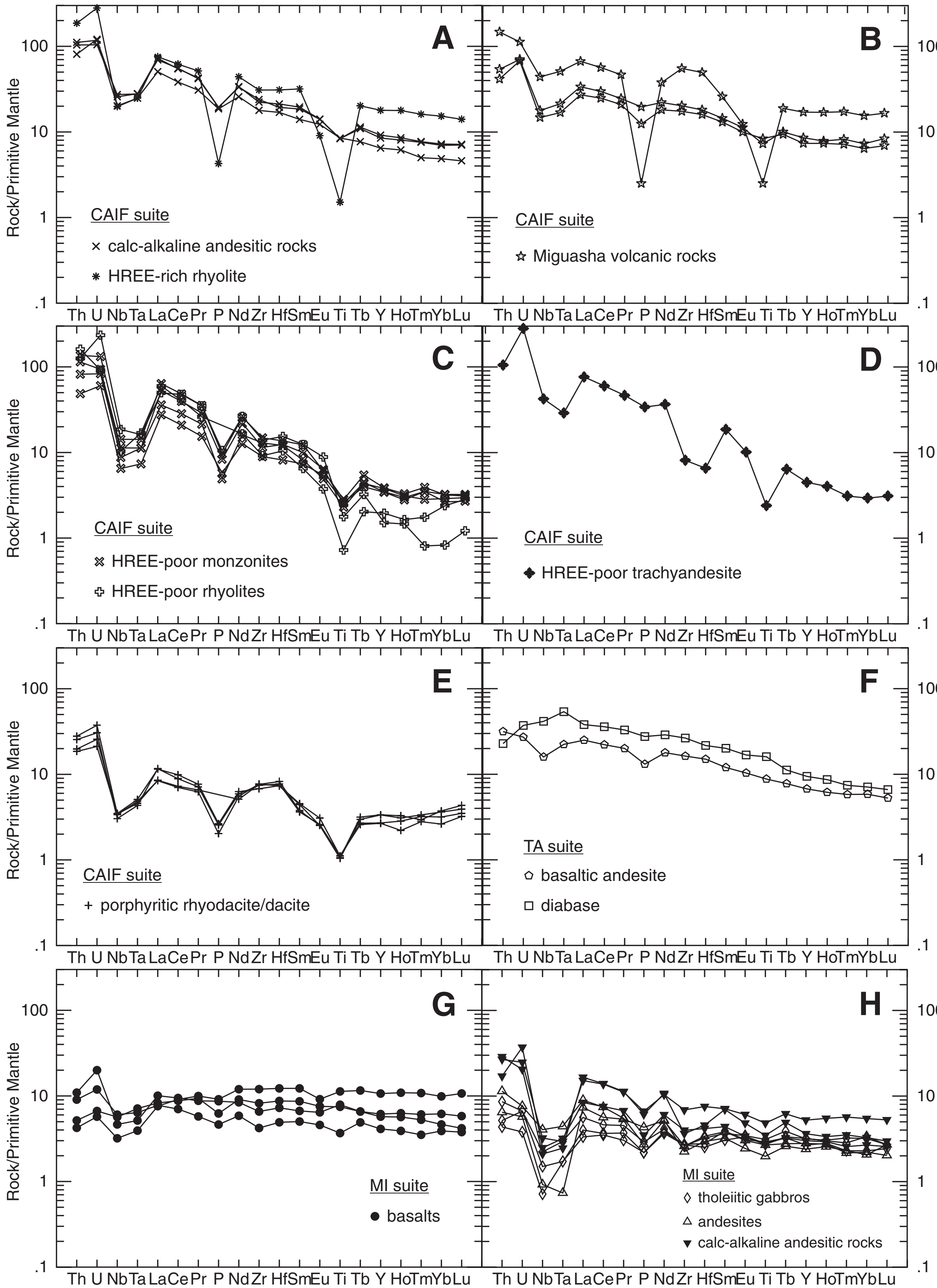


Figure 8. Multi-element patterns normalized to primitive mantle (PM) for the three Garin rock suites. Normalizing values in this and subsequent figures are from Sun and McDonough (1989). CAIF—calc-alkaline intermediate-felsic, TA—tholeiitic-to-alkaline suite, MI—mafic-intermediate.

nature of these rocks are typical of calc-alkaline continental magmas (Fig. 8).

Transitional-Alkaline Suite

The tholeiitic-to-alkaline rock suite (two samples) is composed of one diabase and one basaltic andesite, each of which has a slightly different geochemical signature (Fig. 5). On tectonic discrimination diagrams for basalts, rocks of the transitional-alkaline suite plot in the field for continental basalts, and the transitional-alkaline diabase RLH-34 plots close to the rift field (Fig. 7). Diabase RLH-34 has a LREE-enriched pattern and shows very slight positive Nb-Ta and Ti anomalies (Fig. 8F) characteristic of within-plate alkaline basalts (Pearce, 1996), and we infer derivation from an enriched mantle source. The lesser LREE enrichment and slight negative Nb-Ta anomalies of basaltic andesite RJ-24 suggest either a small contribution from a subduction component or minor crustal contamination (Fig. 8F). This rock can therefore be interpreted to represent either a transition between a within-plate source and a developing subduction zone, or contamination by continental crust.

Mafic-Intermediate Suite

Rocks of the mafic-intermediate suite (12 samples) range in composition from tholeiitic basalts and gabbros to andesitic rocks (Fig. 5). All rocks of the suite have oceanic signatures characterized by low REE and U-Th abundances (Figs. 8G–8H). However, variations on the slope of the multi-element patterns define two subgroups. Subgroup 1 is composed of the tholeiitic basalts that have flat to slightly HREE-depleted REE patterns (Fig. 8G). The slight negative Nb-Ta anomalies and slight enrichment in U-Th suggest the influence of an arc component or crustal contamination. Such geochemical signatures are characteristic of marginal basins (Pearce, 1996). On tectonic discrimination diagrams, these samples plot in or close to the field for back-arc basin basalts (Fig. 7).

Subgroup 2 is composed of tholeiitic gabbros and andesites. The tholeiitic gabbros have fairly flat REE patterns, but they are more depleted than the basalts of subgroup 1 (Fig. 8H). They have more pronounced negative Nb-Ta anomalies, slight negative Ti anomalies, and enrichment in U-Th, which together probably imply an important influence from an arc component. The andesites and calc-alkaline andesitic rocks have more enriched compositions and show progressive enrichment in the most incompatible LREE and U-Th (Fig. 8H), pronounced negative Nb-Ta anomalies, and distinct negative Ti anomalies. Subgroup 2 rocks plot in the adjacent and partially overlapping island-arc tholeiite and calc-alkaline basalt fields (Fig. 7). Such geochemical signatures and associations, ranging from tholeiitic to calc-alkaline, are characteristic of oceanic arcs (Pearce, 1996). The importance of the subduction component does not seem to be related to the degree of LREE enrichment.

Granitic and Mafic Rocks of the McCrea Mélange

Granitic rocks of the McCrea mélange overlap the fields of volcanic arc and within-plate felsic rocks on the tectonic discrimination diagram for silicic rocks, similar to subgroup 1 of the calc-alkaline intermediate-felsic suite (Fig. 8A). Mafic lavas of the McCrea mélange range from tholeiitic to calc-alkaline and have been interpreted as containing an oceanic subduction component (Malo et al., 1992b). On the tectonic discrimination diagram, McCrea basalts plot in the field for back-arc basin basalts, overlapping the fields for transitional MORB (T-MORB) and continental basalts (Fig. 7A). On this diagram, they are mostly similar to tholeiitic basalts of subgroup 1 of the mafic-intermediate suite. However, due to the analytical procedure available at that time, Nb values are not precise and may have been overestimated during analysis. Overall, basalts of the McCrea mélange show close resemblance to the mafic-intermediate suite clasts in the Garin Formation (see discussion on the comparison of Garin clasts with potential source terranes below) and may represent samples of the Garin Formation's source terrane.

AGE DATA

Hornblende from a gabbronorite sample from the Pabos Suite sill was dated using the ^{40}Ar-^{39}Ar method. Although it yields a reproducible plateau age of 489.4 ± 5.1 Ma when all steps that yield greater than 1% of ^{39}Ar gas released are included (Fig. 9A), a $^{40}Ar/^{39}Ar$ ratio of 619 ± 102 indicates the presence of excess ^{40}Ar (Fig. 9B). Correcting the data for this component yields a less precise, but younger age of 471.2 ± 11.2 Ma, which is interpreted to more accurately reflect the age of the suite. Our preference for the younger age is further supported by geological relationships, namely, the close spatial association between the McCrea mélange and the Llanvirnian Arsenault Formation (see discussion on the origin of the Pabos Suite).

Two clasts from conglomerates of the Garin Formation were dated using the U-Pb sensitive high-resolution ion microprobe (SHRIMP) II method on zircons. The HREE-poor monzonite sample RJ-27 yielded an age of 466.0 ± 4.7 Ma, while porphyritic rhyodacite/dacite RLH-87 gave an essentially identical age of 465.2 ± 4.9 Ma (Fig. 10).

DISCUSSION

Igneous clasts from conglomerates of the Garin Formation belong to three suites that represent at least three different tectonic environments. Here, we compare the geochemical signatures of these rocks with a series of suites from the peri-Gondwanan Exploits subzone, with igneous rocks of the peri-Laurentian Notre Dame subzone, and with other potential source rocks in order to better constrain their provenance. Before discussing the tectonic implications of these geochemical correlations, it is useful to summarize the tectonic evolution of the New Brunswick–northern Maine Exploits subzone, and that of the Newfoundland Notre Dame subzone (Fig. 11).

Tectonic Evolution of Ordovician Arcs in Iapetus

Exploits Subzone

The older parts of the calc-alkaline Popelogan arc formed in the early to middle Arenig (480–473 Ma) (Dostal, 1989; Winchester and van Staal, 1994; Fyffe, 2001; Schulz and Ayuso, 2003; Wilson, 2003; van Staal et al., 2003) (Figs. 1 and 11A). In the late Arenig to Caradoc (471–465 Ma), this continental margin arc rifted, and an ensialic back-arc basin opened up to eventually become a Japan Sea–type marginal basin floored by both oceanic crust and highly extended continental crust: the Tetagouche-Exploits back-arc basin (van Staal, 1987; van Staal et al., 1991, 2003; Rogers et al., 2003a). Llanvirnian tholeiites of the Tetagouche Group record rift volcanism through thinned continental crust followed by eruption of Caradocian alkaline basalts (van Staal et al., 1991) (Fig. 11B). Tholeiites of the Fournier Group (470–455 Ma) represent oceanic back-arc spreading and off-axis magmatism on the arc side of the Tetagouche-Exploits back-arc basin (van Staal et al., 1991, 2003; Winchester et al., 1992) (Fig. 11B).

Notre Dame Subzone

In contrast to the abundance of geochemical data on volcanic and intrusive rocks of the Exploits subzone in New Brunswick and Maine (van Staal, 1987; Dostal, 1989; van Staal et al., 1991, 2003; Winchester et al., 1992; Winchester and van Staal, 1994; Fyffe, 2001; Rogers et al., 2003b; Schulz and Ayuso, 2003; Wilson, 2003), there are few complete geochemical data sets on volcanic and intrusive rocks of the Notre Dame subzone in the Gaspé Peninsula. The latter mainly come from the McCrea inlier (Malo et al., 1992b) and the Pabos Suite (Bédard, 1986). For the purpose of comparison with volcanic terranes of the Notre Dame subzone, we use

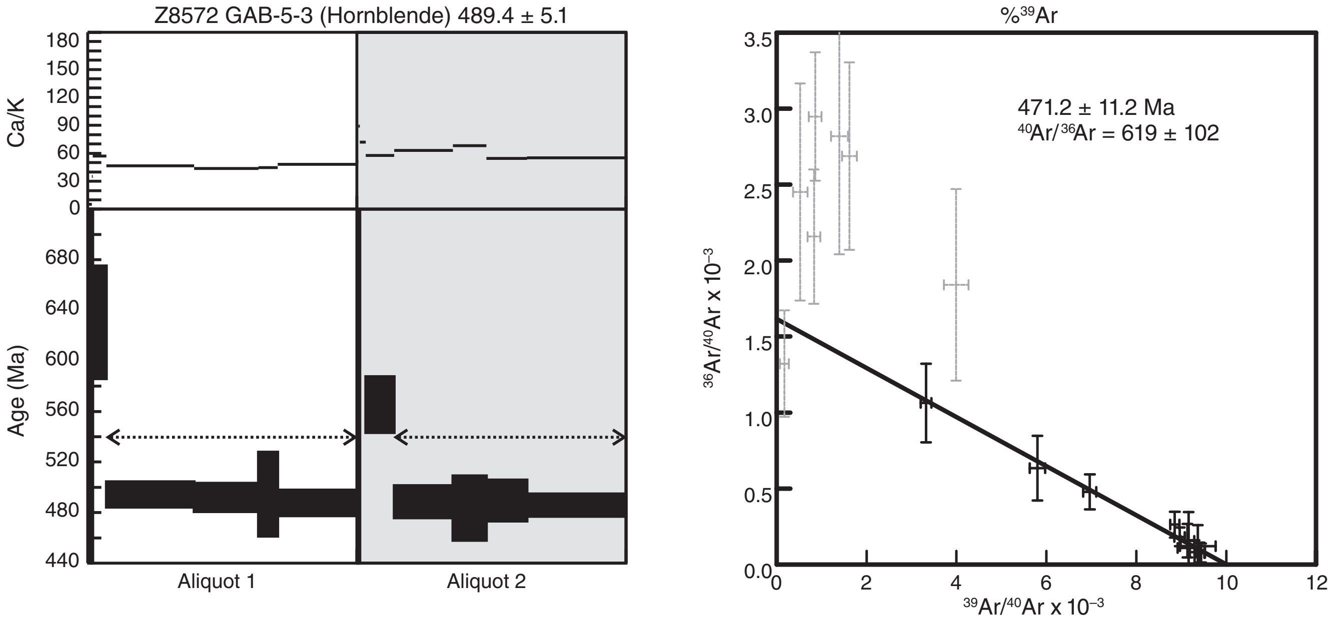


Figure 9. ^{39}Ar-^{40}Ar age data for hornblende from the gabbronorite of the Pabos Suite. (A) ^{39}Ar-^{40}Ar gas release plot. Steps included in plateau age are marked by dashed line terminated by arrowheads. (B) Inverse isochron plot indicating presence of excess ^{40}Ar. Steps containing less than 1% of ^{39}Ar released are grayed and not included in regression.

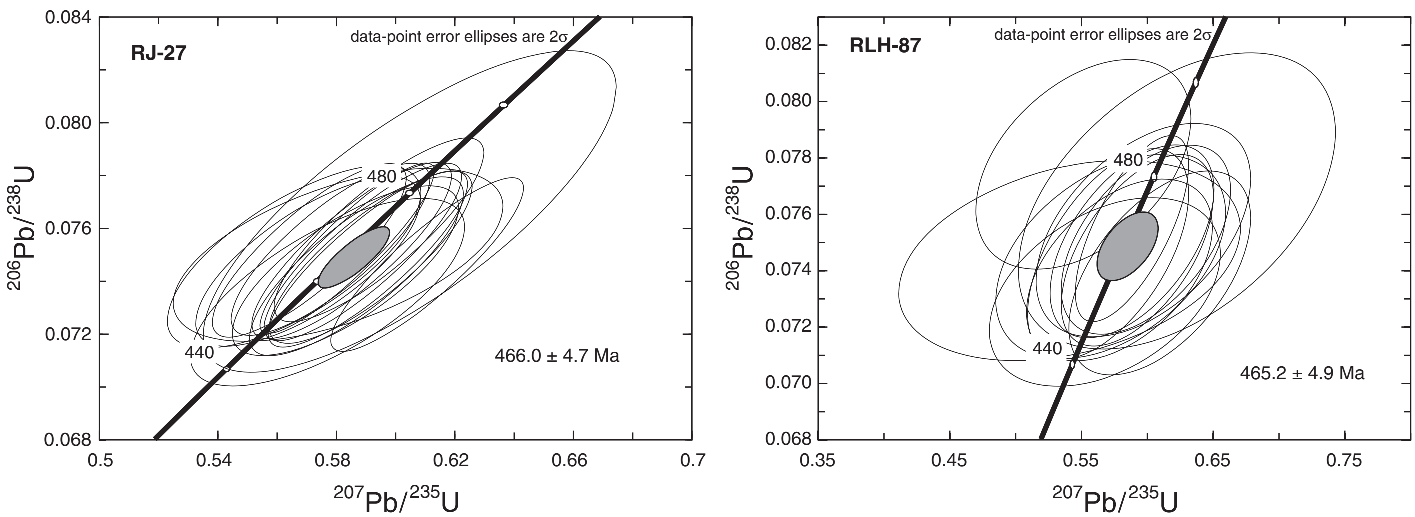


Figure 10. U-Pb zircon concordia diagrams for new age determinations from igneous clasts of the Garin Formation: (A) monzonite RJ-27, and (B) porphyritic rhyodacite/dacite RLH-87.

the geochemical data on volcanic and intrusive rocks of the Annieopsquotch accretionary tract, a recently recognized and well-studied tectonic collage of volcanic terranes in Newfoundland's Notre Dame subzone (Lissenberg et al., 2005b; Zagorevski et al., 2006). The Annieopsquotch accretionary tract is the most outboard tectonic unit of the peri-Laurentian Notre Dame subzone, and it is closest to the Red Indian Line and the peri-Gondwanan Exploits subzone (van Staal, 2007). It is composed of remnants of ophiolitic and arc–back-arc complexes that were generated over ~20 m.y. above a single west-dipping subduction zone outboard of the Laurentian margin, and it records the final Late Ordovician closure of the main tract of the Iapetus Ocean along the Red Indian Line (Zagorevski et al., 2006; van Staal, 2007). The Annieopsquotch ophiolite belt, the oldest and most inboard unit of the Annieopsquotch accretionary tract, marks the initiation of westward subduction beneath the Laurentian margin at ca. 480 Ma. The Lloyds River ophiolite complex (ca. 473 Ma) preserves a fragment of younger, more MORB-like back-arc oceanic crust, which originated as a back-arc to the Buchans Group (ca. 473 Ma) continental bimodal calc-alkaline arc. These units were stitched and overlain by continental magmatic rocks of the Otter Pond Complex (ca. 468 Ma) immediately after their accretion

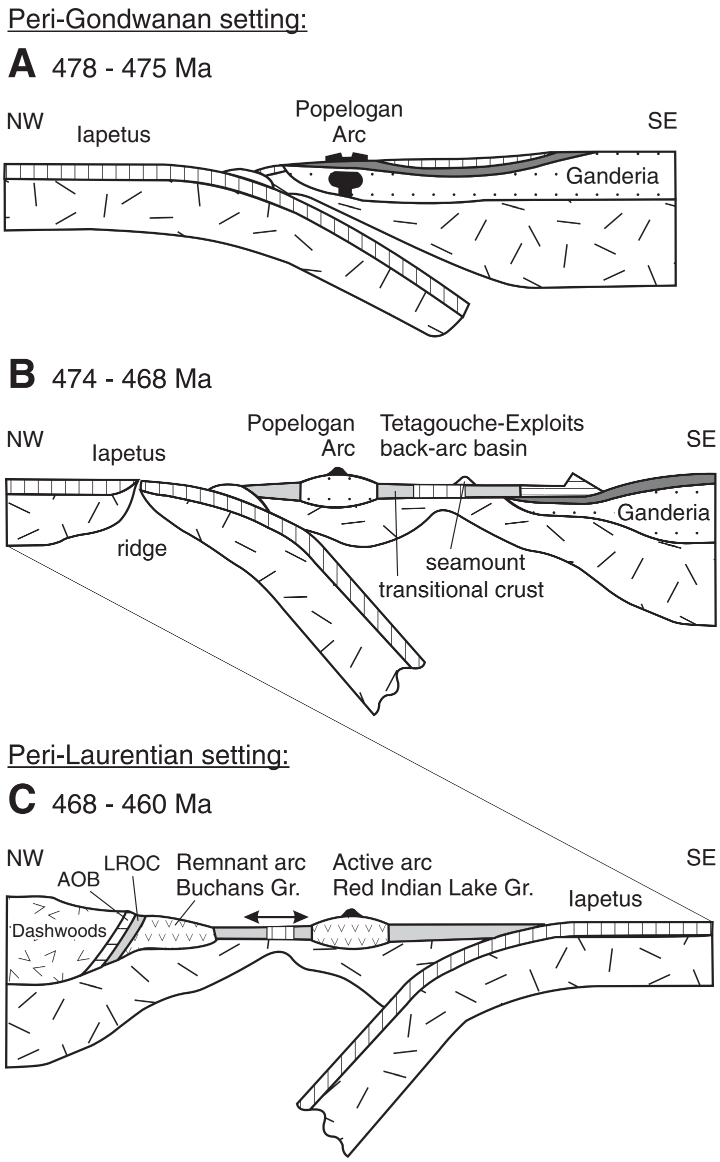


Figure 11. (A–B) Middle Ordovician tectonic evolution of the Dunnage oceanic tract (Exploits subzone) in Gaspé, New Brunswick, and northern Maine (modified after van Staal et al., 2003): (A) calc-alkaline magmatism of the Popelogan arc; and (B) rifting and opening of the Tetagouche-Exploits back-arc basin. (C) Middle Ordovician tectonic evolution of the Annieopsquotch accretionary tract (Notre Dame subzone) (modified after Zagorevski et al., 2006): rifting of the remnant Buchans arc and formation of the new active Red Indian Lake arc. Annieopsquotch ophiolite belt (AOB) and Lloyds River ophiolite complex (LROC) are already accreted on the Dashwoods microcontinent.

to composite Laurentia. Following the ca. 468 Ma accretion event, the accreted Buchans arc rifted due to continuing subduction, leaving most of the exposed Buchans Group in a remnant arc position (Fig. 11C). The younger Red Indian Lake Group (465–460 Ma) records the opening of this new back-arc basin and the subsequent establishment of a bimodal continental calc-alkaline arc sequence (Fig. 11C). The main tract of the Iapetus Ocean closed at ca. 450 Ma, resulting in a collision between peri-Laurentian Red Indian Lake arc and peri-Gondwanan Victoria Lake arc (the Newfoundland equivalent of the Popelogan arc; van Staal et al., 1998) and incorporation of the Red Indian Lake Group into the Annieopsquotch accretionary tract.

Origin of the Pabos Suite

Gabbros of the Pabos Suite in the Gaspé Peninsula have a primitive oceanic signature (Fig. 6A) and are interpreted to represent a tensional event and/or an episode of rifting in a marginal basin (Bédard, 1986; De Broucker, 1987). Geochemical comparisons are consistent with the possibility that gabbroic intrusions in the Mictaw Group (Neckwick Formation) (Bédard, 1986) and diabasic intrusions in the Arsenault Formation (Malo et al., 1992b) are cogenetic with the Pabos Suite. Our preferred Early Ordovician age for the Pabos Suite (471.2 ± 11.2 Ma) is therefore consistent with paleontological constraints, since the Arsenault and Neckwick Formations are of Llanvirnian age (Fig. 3; ca. 464 Ma), based on the presence of diagnostic graptolites (Riva and Malo, 1988) from the *murchisoni* zone of Great Britain or the upper part of the *callotheca* zone of North America. The paleontological age is within the error limits of our age determination for the Pabos Suite (482.4–460 Ma). Moreover, the geochemical signatures of the Pabos Suite rocks are fairly similar to the older Annieopsquotch accretionary tract ophiolitic rocks (480–473 Ma), which represent peri-Laurentian supra-subduction zone and continental arc–oceanic back-arc complexes (Lissenberg et al., 2005a; Zagorevski et al., 2006).

Should the older age of 489.4 ± 5.0 Ma be retained instead, then the Pabos Suite would be coeval with the development of pericontinental ophiolites all along the Laurentian margin (from southern Québec to Newfoundland). This would imply that the MORB-like intrusions that cut the Llanvirnian Arsenault and Neckwick Formations (Mictaw Group) would represent a second, much younger unrelated phase of back-arc(?) rifting that must postdate accretion of the McCrea mélange to Laurentia. We cannot discriminate unambiguously between these two possibilities, but we tentatively retain the younger age (471.2 Ma) because it is more consistent with the geological relationships, ages, and lithostratigraphic correlations between the different host rocks, and it provides a simpler geological history.

Comparison of Garin Clasts with Potential Source Terranes

Calc-Alkaline Intermediate-Felsic Suite

Most of the HREE-poor rocks of the Garin calc-alkaline intermediate-felsic suite show a fair resemblance to the intermediate volcanic to felsic rocks of the Meductic Group (480–473 Ma) in the Exploits subzone of southern New Brunswick (Figs. 6C, 12A, and 12B).

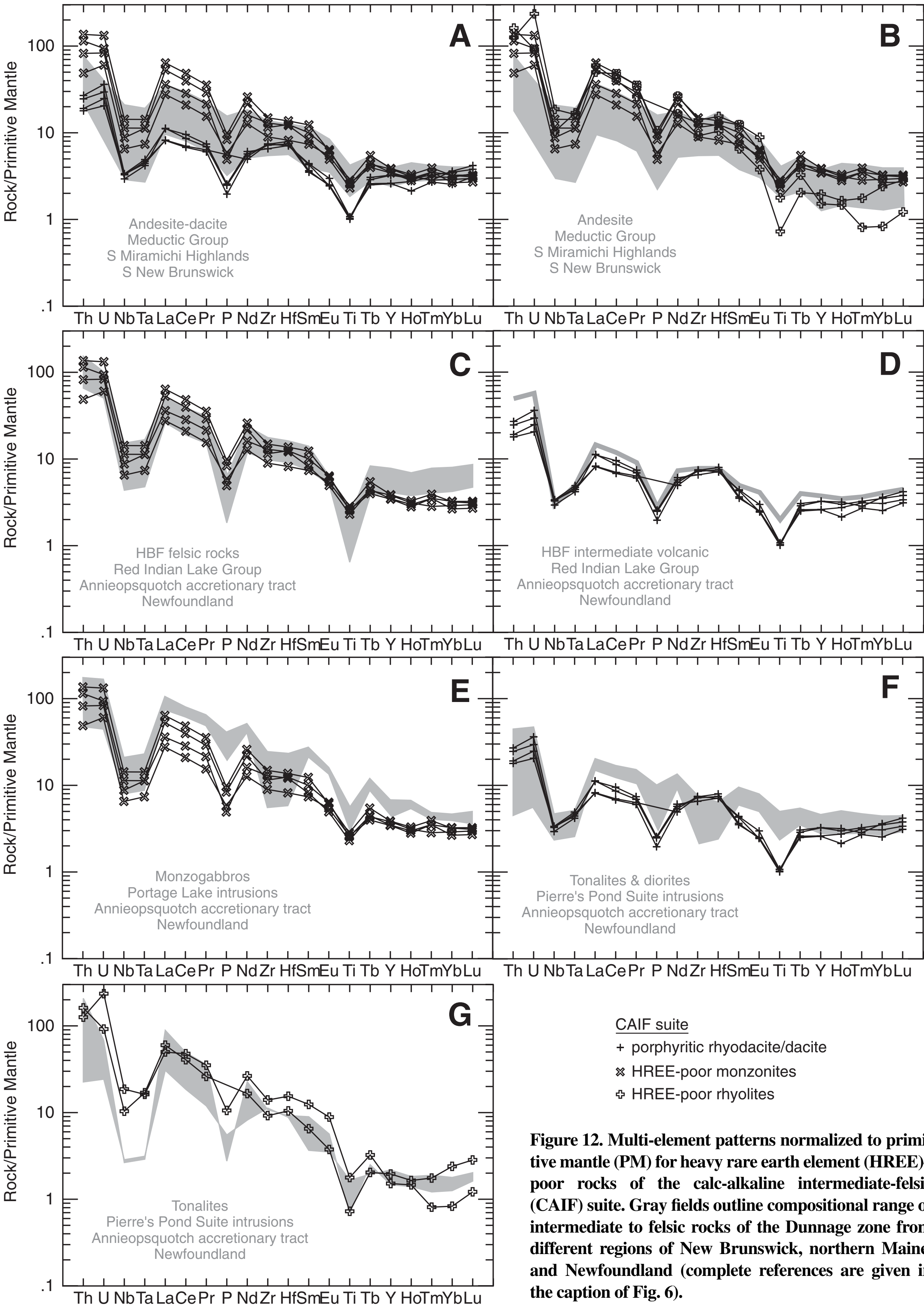


Figure 12. Multi-element patterns normalized to primitive mantle (PM) for heavy rare earth element (HREE)–poor rocks of the calc-alkaline intermediate-felsic (CAIF) suite. Gray fields outline compositional range of intermediate to felsic rocks of the Dunnage zone from different regions of New Brunswick, northern Maine, and Newfoundland (complete references are given in the caption of Fig. 6).

However, they show a much closer resemblance to intermediate and felsic rocks of the Red Indian Lake Group (465–460 Ma) in the peri-Laurentian Annieopsquotch accretionary tract of Newfoundland (Figs. 8E and 12C–12G). Our U-Pb dating on zircons of the HREE-poor rocks of the calc-alkaline intermediate-felsic suite (465–466 Ma, Fig. 10) precludes a correlation with the Meductic Group and favors a correlation with the Red Indian Lake Group of Newfoundland. We conclude that clasts of HREE-poor rocks of the calc-alkaline intermediate-felsic suite in the Garin Formation probably record Late Ordovician erosion of calc-alkaline magmatic rocks formed in a Llanvirn peri-Laurentian continental arc (Fig. 11C).

The HREE-rich rocks of the Garin calc-alkaline intermediate-felsic suite are evolved magmas with signatures typical of calc-alkaline continental arcs, and they are geochemically similar to many Exploits subzone volcanic rocks (Figs. 6B–6D and 13B–13D), including: (1) andesites of the Popelogan inlier, (2) dacites-rhyolites of the Tetagouche and California Lake Groups in northern New Brunswick, (3) dacites-rhyolites of the Meductic Group in southern New Brunswick, and (4) felsic volcanic rocks of the Winterville, Munsungun, Castle Hill, and Weeksboro-Lunksoos inliers in northern Maine. They are also similar to granitic rocks of the McCrea mélange from the Notre Dame subzone of the Gaspé Peninsula (Figs. 6A and 13A). However, the strongest geochemical correlation observed is with dacites and rhyolites of the Middle Ordovician Tetagouche and California Lake Groups (Figs. 6B and 13C).

If the HREE-rich calc-alkaline intermediate-felsic rocks are correlatives of the ca. 466 Ma HREE-poor calc-alkaline intermediate-felsic suite that we have dated, then their age overlaps with the period of rifting of the calc-alkaline Popelogan arc (471–465 Ma) and deposition of the Tetagouche and California Lake Groups (474–465 Ma) in the resultant back-arc basin. Based on the geochemical similarities (e.g., Fig. 6B), the HREE-rich calc-alkaline intermediate-felsic rocks thus also may represent continental extension and rifting of a calc-alkaline continental arc. A correlation between the HREE-rich calc-alkaline intermediate-felsic clasts and the Tetagouche and California Lake Groups is thus possible. However, since HREE-rich and HREE-poor clasts are found in the same conglomerate beds, and since granitic rocks with similar geochemical signatures are found in the McCrea mélange (Figs. 6A and 13A), a simpler interpretation seems to be that HREE-rich calc-alkaline intermediate-felsic rocks represent continental extension and rifting of the peri-Laurentian calc-alkaline arc thought to be the source for the HREE-poor calc-alkaline intermediate-felsic suite. Nonetheless, we cannot exclude the possibility of an Exploits zone provenance for the HREE-rich calc-alkaline intermediate-felsic suite.

Volcanic rocks of the Miguasha-Est no. 1 well represent HREE-rich magmas with signatures typical of calc-alkaline continental arcs, and they are geochemically similar to Popelogan arc volcanic rocks and Tetagouche and California Lake dacite-rhyolites (Figs. 6B–6E and 14B–14E). Furthermore, these rocks are located on the extension of the Popelogan anticlinorium (Fig. 2), and, hence, we infer that they should either be correlated with calc-alkaline rocks of the Popelogan arc (Fig. 11A), or they represent remelting of Popelogan arc crust during Gander margin continental extension and rifting (Fig. 11B).

Transitional-Alkaline Suite

Rocks of the Garin tholeiitic-to-alkaline suite are transitional to alkaline magmas derived from an enriched mantle source of within-plate type (Figs. 7 and 9D). The geochemical signature of basaltic andesite RJ-24 also indicates either a minor subduction zone component or a continental crustal contamination component. Tholeiitic-to-alkaline diabase RLH-34 correlates well with alkaline basalts of the Tetagouche Group in northern New Brunswick (Figs. 7B and 15A), and with alkaline basalts of the Winterville Formation and Stacyville volcanics in northern Maine (Figs. 7D and 15C). These alkaline volcanic rocks erupted in Llanvirnian to middle Caradocian times and were accompanied by deposition of epiclastic turbidites, following rift-related volcanism (van Staal et al., 1991). Their strongly positive ε_{Nd} values indicate derivation from a long-term depleted mantle, and they have been related to a late period of extension in the Popelogan arc–Tetagouche–Exploits back-arc system (Schulz and Ayuso, 2003). Basaltic andesite RJ-24 correlates better with Llanvirnian tholeiites of the Tetagouche Group (Fig. 15B), which are inferred to have experienced crustal contamination during rift volcanism through thinned continental crust (van Staal et al., 1991). Note that neither alkaline nor transitional-alkaline mafic lavas have been recognized in the Annieopsquotch accretionary tract of Newfoundland. Hence, clasts of the tholeiitic-to-alkaline suite in the Garin Formation may be samples of the magmatism associated with the inferred of late rifting phase of the Popelogan arc (Fig. 11B). Alternatively, they may originate from a geodynamically similar peri-Laurentian back-arc basin (Fig. 11C) that has not yet been identified.

Mafic-Intermediate Suite

Rocks of the Garin mafic-intermediate suite are interpreted to have crystallized from tholeiitic to slightly calc-alkaline magmas derived from a moderately depleted mantle source affected by an oceanic subduction component. Basaltic rocks of the mafic-intermediate suite do not correlate with lavas of the Maquereau Group (Bédard and Wilson, 1997), and there is little resemblance with gabbros of the Pabos Suite (Figs. 7A and 16A), or with older (480–473 Ma) ophiolitic rocks of the Annieopsquotch accretionary tract (Lissenberg et al., 2005a; Zagorevski et al., 2006). Basalts (subgroup 1) of the mafic-intermediate suite are similar to mafic rocks of the Exploits subzone, including: tholeiites of the Fournier, Tetagouche, and California Lake Groups in northern New Brunswick (Figs. 7B and 16B); and basalts of the Winterville Formation and Stacyville volcanics in northern Maine (Figs. 7C and 16C). However, they also closely resemble mafic rocks of the Notre Dame subzone, including: mafic lavas of the McCrea mélange in the Gaspé Peninsula (Figs. 7A and 16A); and mafic rocks of the Red Indian Lake Group in Newfoundland (Figs. 7E and 16E).

Andesitic rocks (subgroup 2) of the mafic-intermediate suite show some resemblances to: the Duncan's Brook tholeiites of the Fournier Group in northern New Brunswick (Figs. 7B and 17B); basalt and andesite of the Meductic Group in southern New Brunswick (Figs. 7C and 17C); and andesites of the Winterville Formation and Mount Chase deposit in northern Maine (Figs. 7D and 17D). However, andesitic mafic-intermediate suite rocks show a much better correlation with lavas of the McCrea mélange in the Gaspé Peninsula (Figs. 7A and 17A); and with mafic to intermediate rocks of the Red Indian Lake Group in Newfoundland (Figs. 7E and 17E–17G).

Thus, rocks of the mafic-intermediate suite are best interpreted as products of arc rifting and back-arc basin formation in a peri-Laurentian setting. In support of this interpretation, we note that when the Garin Formation was being deposited (latest Caradoc), the oceanic rocks of the Fournier Group were still part of the back-arc basin's seafloor (van Staal et al., 2003; Wilson et al., 2004) and were unlikely to have been exposed and available for erosion.

TECTONIC EVOLUTION OF THE DUNNAGE ZONE

In terms of terrane analysis, the middle Paleozoic Gaspé belt is clearly an overlap assemblage that covers the early Paleozoic Humber, Dunnage, and Gander zones (Williams and Hatcher, 1982). However, the overstepping

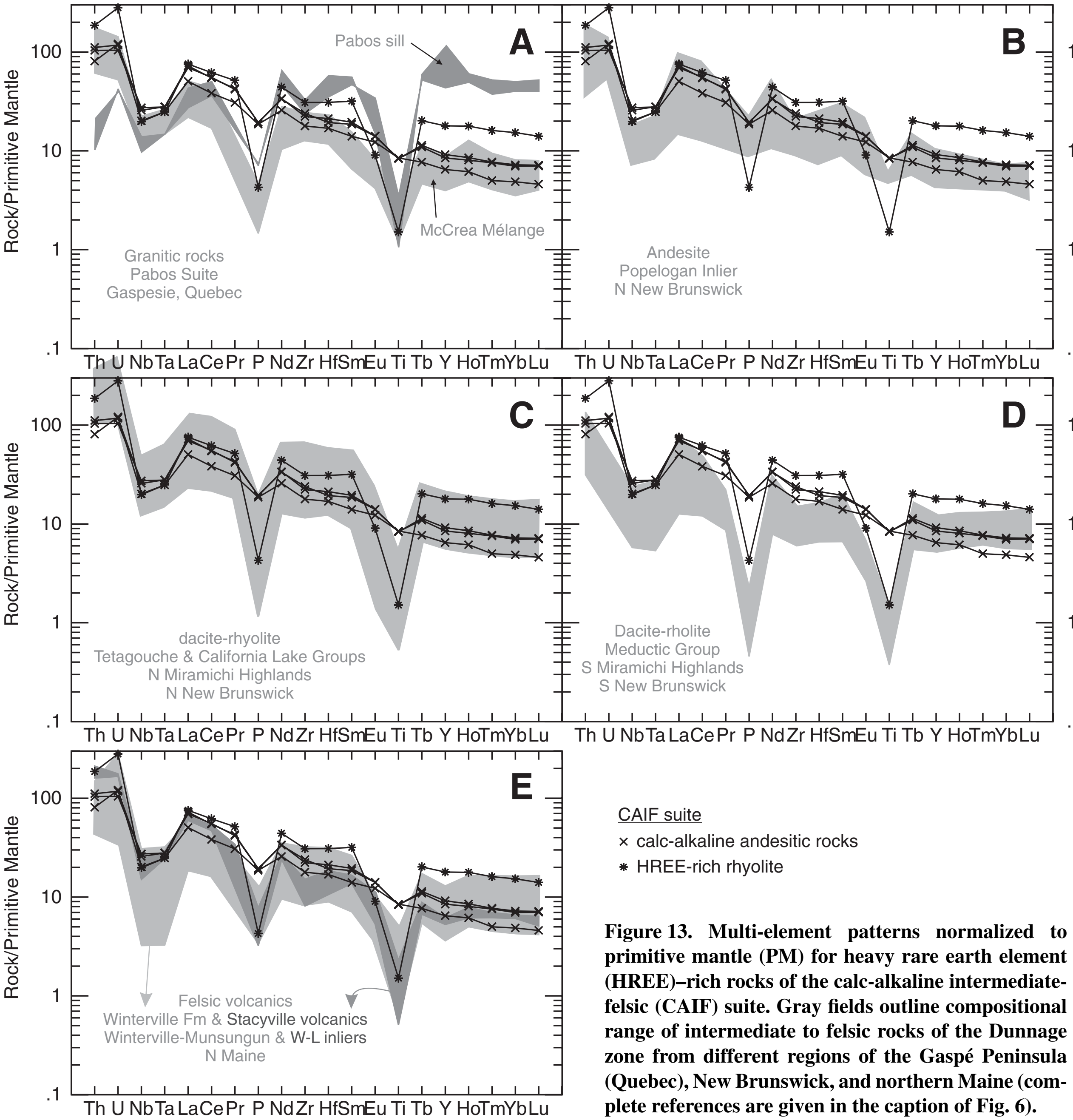


Figure 13. Multi-element patterns normalized to primitive mantle (PM) for heavy rare earth element (HREE)–rich rocks of the calc-alkaline intermediate-felsic (CAIF) suite. Gray fields outline compositional range of intermediate to felsic rocks of the Dunnage zone from different regions of the Gaspé Peninsula (Quebec), New Brunswick, and northern Maine (complete references are given in the caption of Fig. 6).

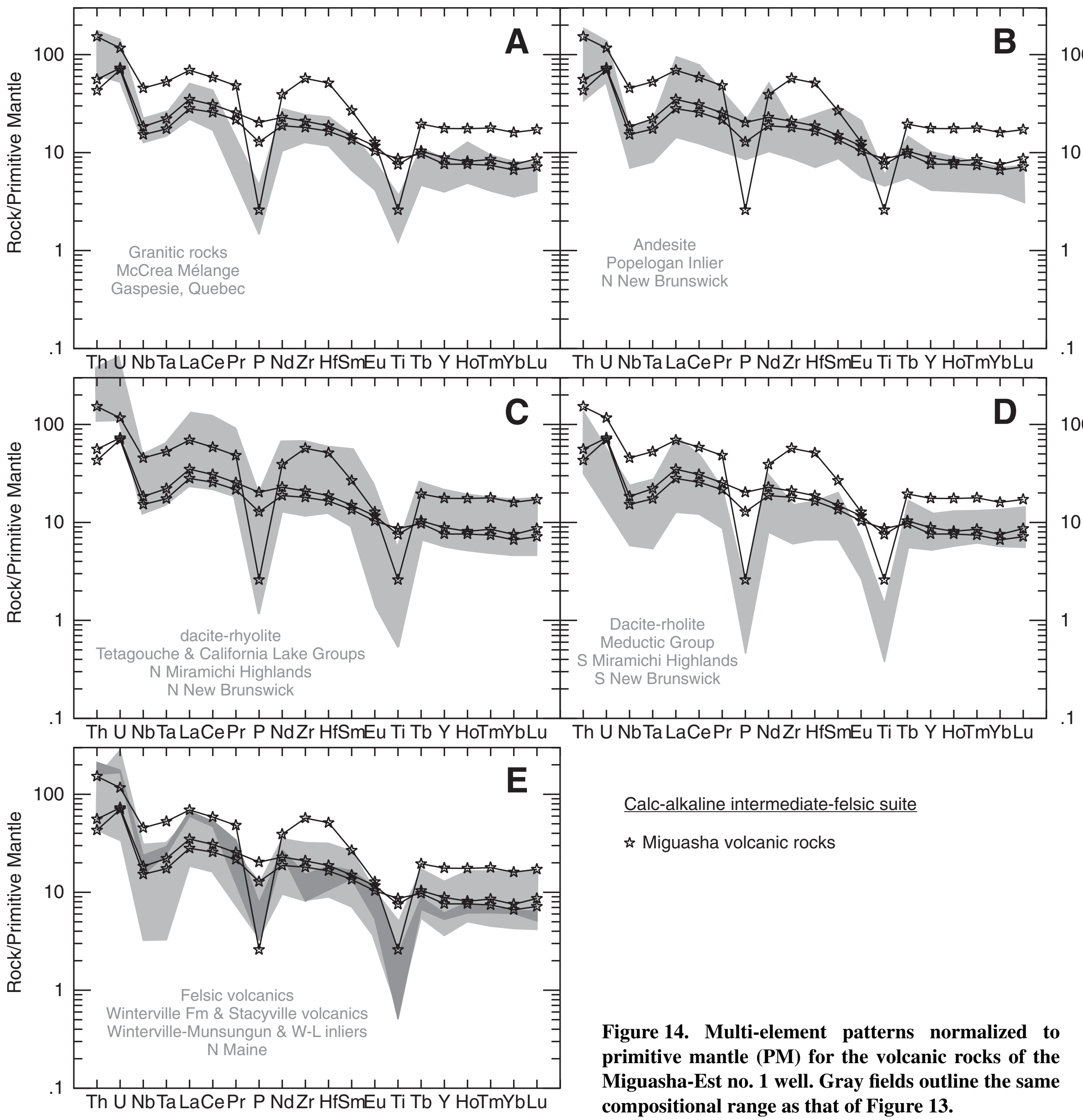


Figure 14. Multi-element patterns normalized to primitive mantle (PM) for the volcanic rocks of the Miguasha-Est no. 1 well. Gray fields outline the same compositional range as that of Figure 13.

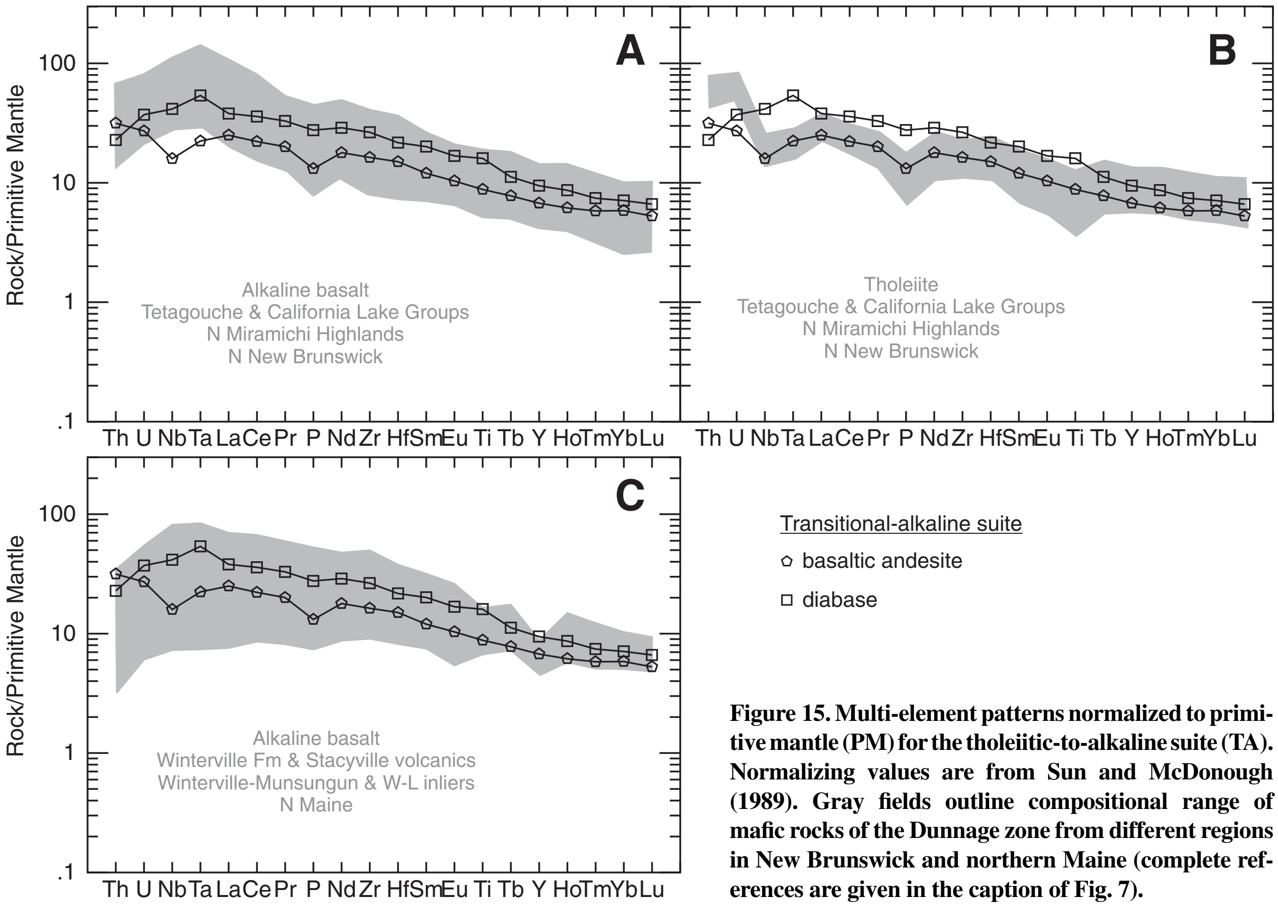


Figure 15. Multi-element patterns normalized to primitive mantle (PM) for the tholeiitic-to-alkaline suite (TA). Normalizing values are from Sun and McDonough (1989). Gray fields outline compositional range of mafic rocks of the Dunnage zone from different regions in New Brunswick and northern Maine (complete references are given in the caption of Fig. 7).

strata are not part of a single lithostratigraphic unit, and the age of the lowermost overstepping strata varies geographically (Fig. 3). The Garin Formation and correlative Grog Brook Group represent the oldest overlapping rock units in the McCrea and Popelogan inliers, respectively (columns 2 and A, Fig. 3), but they do not overstep rocks of the peri-Laurentian Notre Dame and peri-Gondwanan Exploits subzones elsewhere (e.g., Maquereau-Mictaw inlier in the Gaspé, column 3, Fig. 3; and Elmtree-Belledune inlier in New Brunswick, column B, Fig. 3). How then do we distinguish a peri-Laurentian from a peri-Gondwanan provenance for the igneous clasts of the Garin Formation?

Their geochemical characteristics indicate that the igneous clasts in the Garin conglomerates record the evolution of a continental arc–back-arc complex during Late Ordovician time. Since both peri-Laurentian and peri-Gondwanan terranes have experienced coeval but unrelated arc-building events on opposite sides of the Iapetus Ocean, neither provenance can be entirely ruled out. However, the very good age and geochemical correlation that is observed with units of the Red Indian Lake Group clearly favors a peri-Laurentian origin for rocks of the calc-alkaline intermediate-felsic and mafic-intermediate suites. The transitional to alkaline signatures of the tholeiitic-to-alkaline suite are also consistent with the rifting of a continental arc and opening of a back-arc basin. However, magmas similar to the tholeiitic-to-alkaline suite have not been sampled in Newfoundland's Red Indian Lake Group. We do not see this as a strong argument against a peri-Laurentian origin of the tholeiitic-to-alkaline suite rocks, however, since alkaline magmas are inherently sparse in occurrence, and the Red Indian Lake Group is not widely exposed. We suggest that tholeiitic-to-alkaline-like rocks may have existed in the Red Indian Lake Group or correlatives elsewhere, but they have not yet been sampled.

The Red Indian Lake Group of Newfoundland records arc rifting and the opening of a new back-arc basin, followed by establishment of a new continental calc-alkaline arc sequence (Fig. 11C; van Staal et al., 1998). While these rocks were probably much too distant to act as the direct source for the Garin clasts, we propose that the west-directed subduction responsible for the Red Indian Lake Group also affected the Laurentian margin at the latitude of Gaspé. If this interpretation is correct, then the igneous clasts within the Upper Ordovician Garin Formation sampled a largely unexposed terrane of the Notre Dame subzone that had not previously been recognized in this part of the Québec Appalachians. Considering the good correlations of the HREE-rich rocks of the calc-alkaline intermediate-felsic suite with granitic clasts in the McCrea mélange, and of rocks of the mafic-intermediate suite with mafic lavas of the McCrea mélange, as well as the good correlations between the McCrea mélange lavas and rocks of the Red Indian Lake Group in general, we infer that the tectonic slices of mafic lavas and granitic rocks of the McCrea mélange that are caught up in the Grand Pabos fault zone are the only expression of this poorly exposed arc terrane in Gaspé.

The discovery of this "new" terrane has paleogeographic and chronological implications for the evolution of Appalachians in Québec, New Brunswick, and northern Maine. The Garin Formation, the basal unit of the Gaspé belt basin, was deposited beginning in the late Caradocian (*spiniferus* zone) (Fig. 3), and it was later deformed during the Early Silurian Salinic and Middle Devonian Acadian orogenesis, together with younger Silurian-Devonian rocks

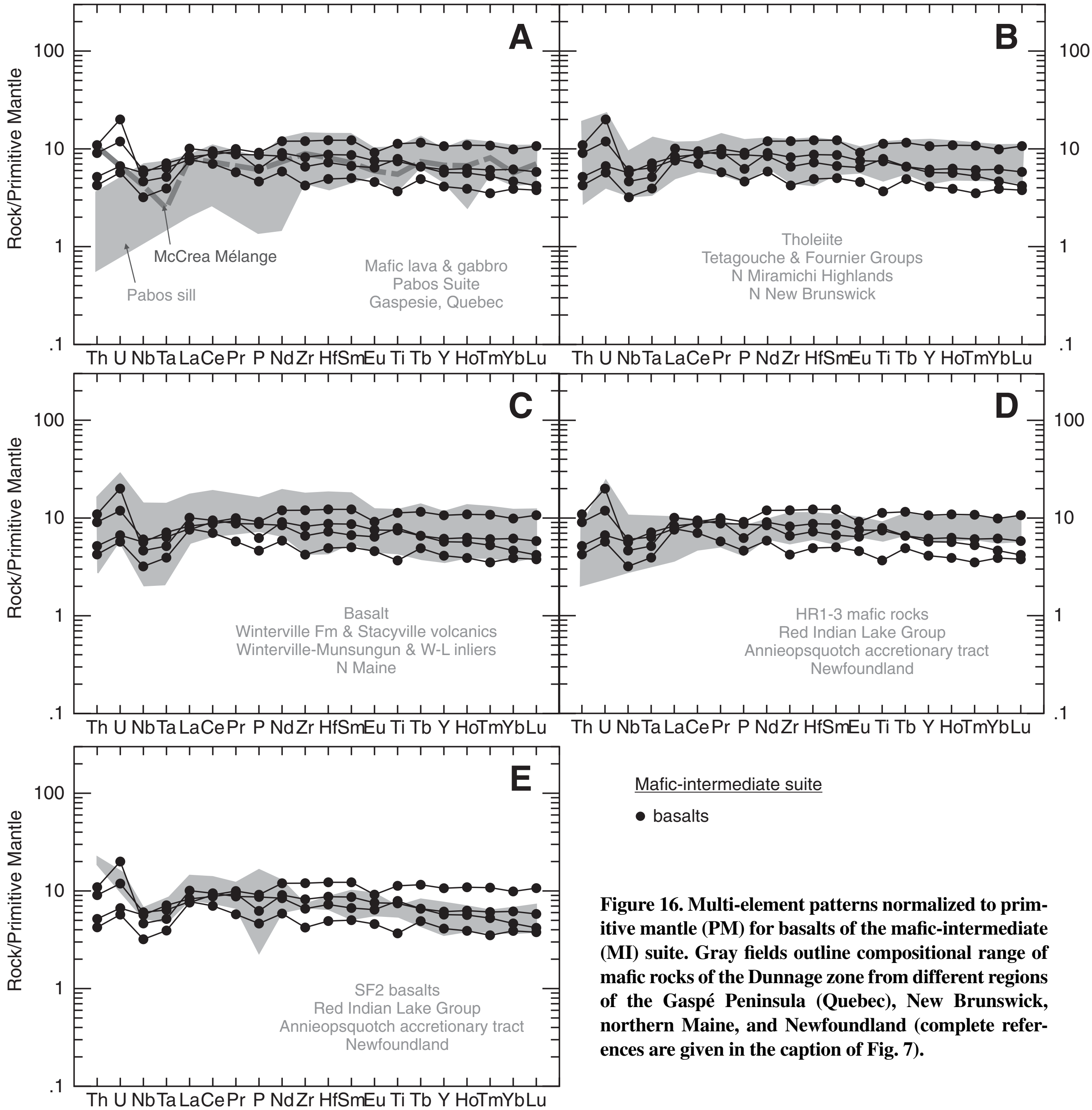
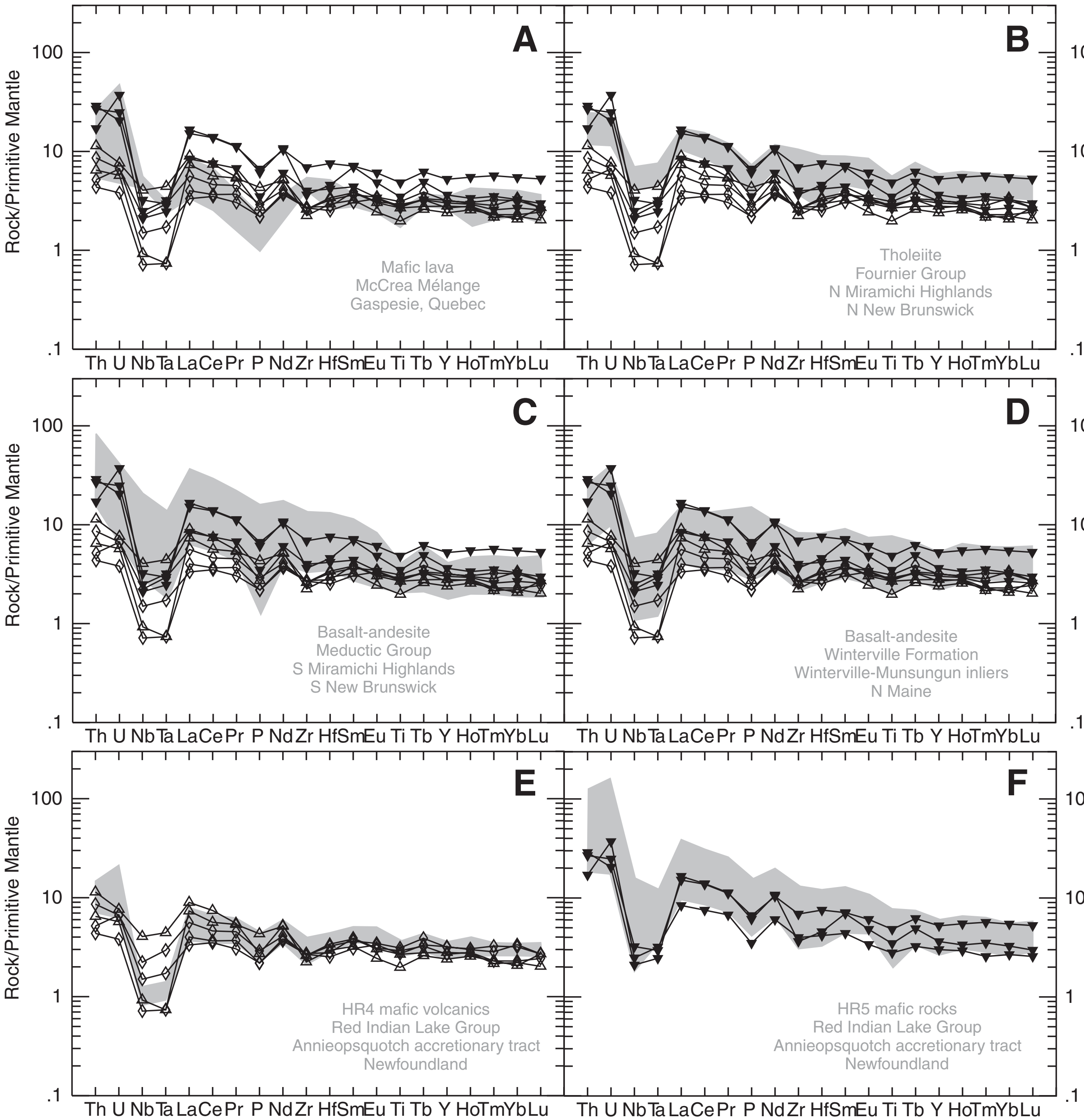
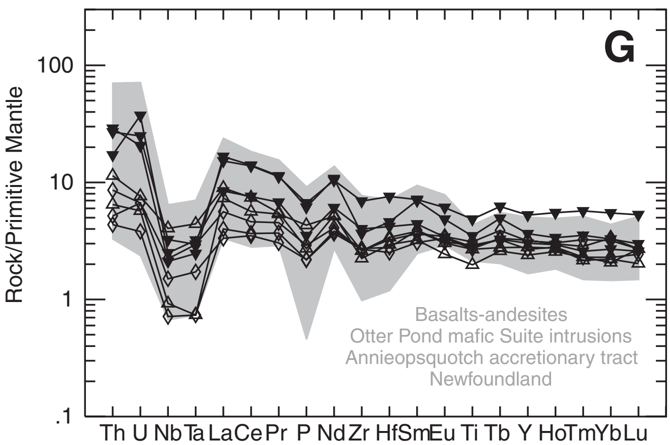


Figure 16. Multi-element patterns normalized to primitive mantle (PM) for basalts of the mafic-intermediate (MI) suite. Gray fields outline compositional range of mafic rocks of the Dunnage zone from different regions of the Gaspé Peninsula (Quebec), New Brunswick, northern Maine, and Newfoundland (complete references are given in the caption of Fig. 7).





Mafic-intermediate suite
◊ tholeiitic gabbros
△ andesites
▼ calc-alkaline andesitic rocks

Figure 17. Multi-element patterns normalized to primitive mantle (PM) for basaltic to andesitic rocks of the mafic-intermediate (MI) suite. Gray fields outline compositional range of mafic to intermediate rocks of the Dunnage zone from different regions of the Gaspé Peninsula (Quebec), New Brunswick, northern Maine, and Newfoundland (complete references are given in the caption of Fig. 7).

of the basin (Malo and Bourque, 1993). The pre-Acadian palinspastic position of the Garin Formation indicates that it was deposited within the Iapetus oceanic domain to the south of the Taconian-modified Laurentian margin (Malo, 2004). The absence of any clasts in the Garin Formation that could have been derived from continental lavas typical of the Humber zone (e.g., Maquereau Group) supports the inferred oceanic tectonic setting. In addition, the Garin Formation igneous clasts were only affected by low-grade, hydrous metamorphism, and they lack any evidence of accompanying penetrative deformation that could be Taconian-related. On the other hand, volcanic rocks of the Miguasha-Est no. 1 well are not exotic blocks and are located along the inferred extension of the arc volcanic rocks of the Popelogan inlier (anticlinorium) (Fig. 2), which is consistent with their geochemical signatures. The proposed Notre Dame subzone provenance for the bulk of the igneous clasts in the Garin Formation and Exploits subzone volcanic rocks of the Miguasha-Est no. 1 well implies that the Red Indian Line must pass through the southern Gaspé Peninsula, beneath the thick sedimentary cover sequences (Fig. 1). The inferred location and setting of the new terrane, bound to the north by the Grand Pabos fault and to the south by the Red Indian Line, are similar to that of the Annieopsquotch accretionary tract in Newfoundland.

CONCLUSIONS

N-MORB–like gabbros of the Pabos Suite (Gaspé Peninsula) are probably Early Ordovician (471.2 ± 11.2 Ma) in age. This age is similar to that of other gabbroic intrusions in the McCrea inlier. Moreover, the geochemical signatures of the Pabos Suite rocks are fairly similar to those of the Annieopsquotch ophiolite belt and Lloyds River ophiolite complex (480–473 Ma). Hence, these magmas are interpreted to represent an extensional event, possibly rifting in a marginal basin that was later accreted to Laurentia.

Igneous clasts in conglomerates of the Upper Ordovician Garin Formation, the basal unit of the middle Paleozoic Gaspé belt in the Gaspé Appalachians of Québec, are undeformed and were affected solely by low-grade hydrous metamorphism, which confirms that the source area was not the Laurentian margin affected by Taconian deformation, but the Iapetus oceanic domain. Igneous clasts define three populations, all of which can be related to the post-Taconian tectonic evolution of the Dunnage oceanic tract during Ordovician time.

(1) The calc-alkaline intermediate-felsic suite has signatures typical of continental arc magmas. Variations in HREE abundances allow two subgroups to be defined. (1a) HREE-poor monzonite and rhyolite are geochemically most similar either to volcanic rocks of the Meductic Group (Exploits subzone, New Brunswick, 480–473 Ma), or to igneous rocks of the Red Indian Lake Group (Notre Dame subzone, Newfoundland, 465–460 Ma). U-Pb zircon ages of 465–466 Ma for HREE-poor Garin pebbles preclude correlation with the Meductic Group and suggest derivation from igneous rocks similar to the Red Indian Lake Group or from equivalent rocks at the latitude of Gaspé. Hence, based on geochemical similarities and geochronological ages, clasts of the calc-alkaline intermediate-felsic suite in the Garin Formation are interpreted to record the calc-alkaline magmatism of a Llanvirn peri-Laurentian continental arc. (1b) HREE-rich andesites and rhyolites can be correlated with volcanic rocks of the Andean-type Popelogan arc (Exploits subzone), or with rocks derived from magmas formed by melting of this crust during Gander margin continental extension. However, they also correlate well with granitic rocks of the McCrea mélange from the Notre Dame subzone of the Gaspé Peninsula. Given the spatial association with HREE-poor clasts, we favor a Notre Dame subzone provenance.

(2) Mafic rocks of the tholeiitic-to-alkaline suite have enriched geochemical signatures typical of within-plate settings, a minor continental crustal contamination component, and they resemble tholeiites and alkaline basalts of the Tetagouche and California Lake Groups (New Brunswick) and alkaline basalts of the Winterville Formation and Stacyville volcanics (Maine). They are interpreted to record magmatism associated with the rifting and initiation of an embryonic back-arc basin, but we cannot be certain of their provenance.

(3) Rocks of the mafic-intermediate suite have geochemical signatures that are common in oceanic arcs and back-arcs. Rocks of this suite are similar to mafic rocks of the Exploits subzone in northern New Brunswick and Maine, but they correlate best with mafic to intermediate rocks of the Notre Dame subzone in the Gaspé Peninsula and in Newfoundland. They are interpreted to represent the products of spreading and off-axis magmatism in a peri-Laurentian back-arc basin.

Igneous clasts within the Upper Ordovician Garin Formation are therefore interpreted to have been eroded from a predominantly weakly or unmetamorphosed arc coeval with development of the Red Indian Lake Group of Newfoundland (Notre Dame subzone) that is only exposed at the latitude of the Gaspé Peninsula in the McCrea mélange.

The correlation between volcanic rocks of the Miguasha-Est no. 1 well in Gaspé with arc volcanic rocks of the Popelogan inlier (New Brunswick) along strike suggests that rocks of the Exploits subzone extend across Chaleurs Bay to the Gaspé Peninsula, but they are now buried beneath the Middle to Upper Paleozoic sedimentary cover sequence. This implies that the Red Indian Line passes through the southern Gaspé Peninsula. The inferred position of the Red Indian Line in the Gaspé Peninsula is similar to what is observed in Newfoundland, where volcanic rocks of the McCrea mélange occur on the Laurentian side and those of the Balmoral Group occur in the Popelogan inlier on the Gondwanan side. The data presented in this paper provide evidence that Newfoundland's geological template may continue into the Québec Appalachians and beyond (New England).

APPENDIX 1. GEOCHEMICAL ANALYTICAL METHODS

Whole rocks were analyzed by alkaline fusion inductively coupled plasma–atomic-emission spectrometry (ICP-AES) for major elements and ICP-MS (mass spectrometry) (VG Turbo Plasma Quad^{2+}) for trace elements, including rare earth elements (Laboratoire Institut National de la Recherche Scientifique–Eau, Terre et Environnement, Québec, Canada). Complete data are available in the GSA Data Repository.[1] Sample dissolution was accomplished by flux fusions (Claisse fluxor). For major elements in weight percent, accuracy is better than ±5%, although the acceptable analytical precision is set to better than ±2.5%. Compositions used in the graphs have been normalized on an anhydrous basis. The Fe_2O_3 content is assumed to represent 10% of total iron analyzed. Analytical precision and data for U.S. Geological Survey basalt and andesite standards analyzed with the same method at the same laboratory are reported in La Flèche et al. (1998).

APPENDIX 2. AR-AR GEOCHRONOLOGY

Methodology

Hornblende was processed for $^{40}Ar/^{39}Ar$ analysis of whole rock by standard preparation techniques, including handpicking of unaltered pieces in the size range 0.25 to 0.50 mm. Individual mineral separates were loaded into aluminum foil packets along with a single grain of Fish Canyon Tuff Sanidine (FCT-SAN) to act as flux monitor (apparent age = 28.03 ± 0.15 Ma; Renne et al., 1998). The sample packets were arranged radially inside an aluminum can. The samples were then irradiated for 12 hr at the research reactor of McMaster University in a fast neutron flux of ~3×10^{16} neutrons/cm^2.

Laser $^{40}Ar/^{39}Ar$ step-heating analysis was carried out at the Geological Survey of Canada (GSC) laboratories in Ottawa, Ontario. Upon return from the reactor, samples were split into two aliquots and loaded into individual 1.5-mm-diameter holes in a copper planchet, where each was run as a separate step-heating experiment. Heating of individual sample aliquots in steps of increasing temperature was achieved using a Merchantek MIR10 10W CO2 laser equipped with a 2 mm × 2 mm flat-field lens. The released Ar gas was cleaned over getters for 10 min and then analyzed isotopically using the secondary electron multiplier system of a VG3600 gas source mass spectrometer;

details of data collection protocols can be found in Villeneuve and MacIntyre (1997) and Villeneuve et al. (2000). Error analysis on individual steps follows numerical error analysis routines outlined in Scaillet (2000); error analysis on grouped data follows algebraic methods of Roddick (1988).

Corrected argon isotopic data are available in the GSA Data Repository (see footnote 1) and are presented (Fig. 9) as spectra of gas release and on inverse-isochron plots (Roddick et al., 1980). Each gas-release spectrum plotted contains step-heating data from up to two aliquots, alternately shaded and normalized to the total volume of ^{39}Ar released for each aliquot. Such plots provide a visual image of replicated heating profiles, evidence for Ar-loss in the low-temperature steps, and the error and apparent age of each step.

Neutron flux gradients throughout the sample canister were evaluated by analyzing the sanidine flux monitors included with each sample packet and interpolating a linear fit against calculated J-factor and sample position. The error on individual J-factor values is conservatively estimated at ±0.6% (2σ). Because the error associated with the J-factor is systematic and not related to individual analyses, correction for this uncertainty is not applied until calculation of dates from isotopic correlation diagrams (Roddick, 1988). Blanks were measured prior and after each aliquot and levels vary between ^{40}Ar = 2.5–3.6 × 10^{-7} nm, ^{39}Ar = 4.2–13.3 × 10^{-9} nm, ^{38}Ar = 0.4–1.7 × 10^{-9} nm, ^{37}Ar = 0.41.7 × 10^{-9} nm, ^{36}Ar = 0.7–1.3 × 10^{-9} nm, all at ±10% uncertainty. Nucleogenic interference corrections are (^{40}Ar/^{39}Ar)K = 0.025 ± 0.005, (^{38}Ar/^{39}Ar)K = 0.011 ± 0.010, (^{40}Ar/^{37}Ar)Ca = 0.002 ± 0.002, (^{39}Ar/^{37}Ar) Ca = 0.00068 ± 0.00004, (^{38}Ar/^{37}Ar)Ca = 0.00003 ± 0.00003, and (^{36}Ar/^{37}Ar)Ca = 0.00028 ± 0.00016. All errors are quoted at the 2σ level of uncertainty.

APPENDIX 3. U-PB GEOCHRONOLOGY

Analytical Method

Zircon concentrates were prepared by standard crushing, Wilfley table, and heavy liquid methods and sorted by magnetic properties using a Frantz isodynamic separator. Zircons were selected and mounted in epoxy together with GSC internal zircon calibration standard 6266 (^{206}Pb/^{238}U age = 559 Ma) and the Temora 2 zircon (Black et al., 2003), polished to expose grain centers, and coated with ~10 nm of Au. The internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized with cathodoluminescence and backscattered electron (BSE) imaging utilizing a Cambridge Instruments scanning electron microscope. SHRIMP analytical procedures follow those described by Stern (1997), and standards and U-Pb calibration methods follow Stern and Amelin (2003). Analyses were conducted using a $^{16}O^-$ primary beam, projected onto the zircons at 10 kV. The sputtered area used for analysis was ~16 µm × 25 µm in diameter with a beam current of ~8 nA. The count rates of ten isotopes of Zr^+, U^+, Th^+, and Pb^+ in zircon were sequentially measured over six scans with a single electron multiplier and a pulse counting system with dead time of 24 ns. Offline data processing was accomplished using customized in-house software. The 1σ external errors of ^{206}Pb/^{238}U ratios reported in Table DR4 incorporate a ±1.7% error in calibrating the standard zircon (see Stern and Amelin, 2003). An age of 416.4 ± 4.1 Ma was determined for the Temora standard, during this analytical session, within error of its accepted age. Isoplot v. 3.01 (Ludwig, 2001) was used to generate concordia plots and calculate ages. All data points plotted in the figures have errors reported at the 2σ uncertainty level. Complete data are available in the GSA Data Repository (see footnote 1)

Results

Sample RJ-27: Monzonite

Zircon in this sample dominantly consists of prismatic euhedral grains with moderate oscillatory zoning typical of igneous growth, and no evidence of inherited core material. The U concentrations vary from ~300 to 1000 ppm, with relatively high Th/U ratios ranging from 0.6 to 2.0. The compositions are consistent with the interpretation of a simple zircon population, and the relatively high Th/U ratios are consistent with the rock composition. Seventeen grains were analyzed. All of the analyses cluster and define a concordia age of 466 ± 4.7 Ma (2σ, decay-constant errors included; mean square of weighted deviates [MSWD] of concordance = 3.3; probability of concordance = 0.07). This is interpreted as the crystallization age of the monzonite.

Sample RLH-87: Porphyritic Rhyodacite/Dacite

Zircon in this sample is dominated by euhedral prismatic morphologies, with prominent oscillatory zoning. Eighteen zircon grains were analyzed, 15 of which define a concordia age of 465.2 ± 4.9 Ma (2σ, decay-constant errors included; MSWD of concordance = 0.23; probability of concordance = 0.63). This is interpreted as the crystallization age of the porphyritic rhyodacite/dacite. Uranium content of these zircons ranges from 108 to 360 ppm (Table DR4). Two grains have significantly higher uranium content (1100–2100 ppm) and older ^{206}Pb/^{238}U ages of 482 and 492 Ma. These grains are interpreted to be inherited and were excluded from the age calculation. One analysis (9015-28.1) has a slightly younger ^{206}Pb/^{238}U age, possibly due to Pb loss, and it was also excluded from the age calculation.

ACKNOWLEDGMENTS

We would like to thank the funding organization National Sciences and Engineering Research Council of Canada (grant RGPIN/1908 to M. Malo) for financial support. We are also grateful to the Geological Survey of Canada for financial support via the Energy program. The first author also thanks Institut National de la Recherche Scientifique–Eau, Terre et Environnement for a postdoctoral fellowship. We would also like to thank Claude Morin from Hydro-Québec for providing us with the Miguasha-Est no. 1 well volcanic samples. We are also thankful to M. Choquette for assistance with microprobe analyses and to R. Gosselin for geochemical analyses. The manuscript has benefited from critical comments by Cees van Staal, Reginald Wilson, Alex Zagorevski, and an anonymous referee. We would like to particularly thank Cees van Staal for his tremendous revision work. This is Geological Survey of Canada contribution 20070521.

REFERENCES CITED

Bédard, J.H., 1985, Les Suites Magmatiques Paléozoiques de la Gaspésie Orientale: Pétrologie, Géochimie et Affinité Tectonique: Ministère de l'Énergie et des Ressources, Québec, Rapport Géologique ET84–09, 111 p.

Bédard, J.H., 1986, Pre-Acadian magmatic suites of the southeastern Gaspé Peninsula: Geological Society of America Bulletin, v. 97, p. 1177–1191, doi: 10.1130/0016-7606(1986)97<1177:PMSOTS>2.0.CO;2.

Bédard, J.H., and Wilson, C., 1997, Fractionation and contamination of Maquereau Group lavas, southern Gaspé, Québec Appalachians, *in* Sinha, A.K., Whalen, J.B., and Hogan, J.P., eds., The Nature of Magmatism in the Appalachian Orogen: Geological Society of America Memoir 191, p. 87–106.

Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., and Foudoulis, C., 2003, TEMORA 1: A new zircon standard for Phanerozoic U-Pb geochronology: Chemical Geology, v. 200, p. 155–170, doi: 10.1016/S0009-2541(03)00165-7.

Bourque, P.A., Malo, M., and Kirkwood, D., 2000, Paleogeography and tectono-sedimentary history at the margin of Laurentia during Silurian to earliest Devonian time: The Gaspé belt: Geological Society of America Bulletin, v. 112, p. 4–20, doi: 10.1130/0016-7606(2000)112<0004:PATSHA>2.3.CO;2.

Cabanis, B., and Lecolle, M., 1989, Le diagramme La/10-Y/15-Nb/8: Un outil pour la discrimination des séries volcaniques et la mise en évidence des processus de mélange et/ou de contamination crustale: Comptes Rendus de l'Académie des Sciences Série II, v. 309, p. 2023–2029.

Chagnon, A., 1988, Géologie des Argiles, Diagenèse et Altération Hydrothermale, dans l'Anticlinorium d'Aroostook-Percé, Québec, Canada [Ph.D. thesis]: Neufchâtel, Université de Neufchâtel, Suisse, 367 p.

De Broucker, G., 1987, Stratigraphie, pétrographie et structure de la boutonnière de Maquereau-Mictaw (région de Port-Daniel, Gaspésie): Ministère de l'Énergie et des Ressources, Québec, Rapport MM 86–03, 160 p.

Dostal, J., 1989, Geochemistry of Ordovician volcanic rocks of the Tetagouche Group of southwestern New Brunswick: Atlantic Geology, v. 25, p. 199–209.

Ducharme, D., 1979, Pétrographie du Flysch de l'Ordovicien Supérieur et du Silurien Inférieur—Anticlinorium d'Aroostokk-Percé, Gaspésie, Québec [M.Sc. thesis]: Montréal, Université de Montréal, Canada, 92 p.

Fyffe, L.R., 2001, Stratigraphy and geochemistry of Ordovician volcanic rocks of the Eal River area, west-central New Brunswick: Atlantic Geology, v. 37, p. 81–101.

Gerbi, C.C., Johnson, S.E., and Aleinikoff, J.N., 2006, Origin and orogenic role of the Chain Lakes massif, Maine and Quebec: Canadian Journal of Earth Sciences, v. 43, p. 339–366, doi: 10.1139/E05-112.

Gosselin, C., 1988, Géologie de la Région de Maria (Gaspésie): Ministère de l'Énergie et des Ressources, Québec, Rapport ET 87–01, 28 p.

Hart, S.R., Erblank, A.J., and Kable, E.J.D., 1974, Sea floor basalt alteration: Some chemical and Sr-isotopic effects: Contributions to Mineralogy and Petrology, v. 44, p. 219–230, doi: 10.1007/BF00413167.

Hesse, R., and Dalton, E., 1991, Diagenetic and low-grade metamorphism terranes of the Gaspé Peninsula related to the geological structure of the Appalachians: Journal of Metamorphic Geology, v. 9, p. 775–790, doi: 10.1111/j.1525-1314.1991.tb00565.x.

La Flèche, M.R., Camiré, G., and Jenner, G.A., 1998, Geochemistry of post-Acadian, Carboniferous continental within-plate basalts from the Maritimes Basin, Magdalen Islands, Québec, Canada: Chemical Geology, v. 148, p. 115–136, doi: 10.1016/S0009-2541(98)00002-3.

Lavoie, D., Burden, E., and Lebel, D., 2003, Stratigraphic framework for the Cambrian-Ordovician rift and passive margin successions from southern Quebec to western Newfoundland: Canadian Journal of Earth Sciences, v. 40, p. 177–205, doi: 10.1139/e02-078.

Lissenberg, C.J., van Staal, C.R., Bédard, J.H., and Zagorevski, A., 2005a, Geochemical constraints on the origin of the Annieopsquotch ophiolite belt, Newfoundland Appalachians: Geological Society of America Bulletin, v. 117, p. 1413–1426, doi: 10.1130/B25731.1.

Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R., and Whalen, J.B., 2005b, Assembly of the Annieopsquotch accretionary tract, Newfoundland Appalachians: Age and geodynamic constraints from syn-kinematic intrusions: The Journal of Geology, v. 113, p. 553–570, doi: 10.1086/431909.

Ludwig, K.R., 2001, User's Manual for Isoplot/Ex Rev. 2.49: A Geochronological Toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication 1a, 55 p.

Malo, M., 1988, Stratigraphy of the Aroostook-Percé anticlinorium in the Gaspé Peninsula, Québec: Canadian Journal of Earth Sciences, v. 25, p. 893–908.

Malo, M., 1989, Stratigraphie et Structure de l'Anticlinorium d'Aroostook-Percé de la Region d'Honorat (Gaspésie): Ministère de l'Énergie et des Ressources, Québec, Rapport ET 88–01, 48 p.

Malo, M., 2001, The Late Silurian–Early Devonian tectonosedimentary history of the Gaspé belt in the Gaspé Peninsula: From a transtensional Salinic basin to an Acadian foreland basin: Bulletin of Canadian Petroleum Geology, v. 49, p. 202–216, doi: 10.2113/49.2.202.

Malo, M., 2004, Paleogeography of the Matapédia Basin in the Gaspé Appalachians: Initiation of the Gaspé belt successor basin: Canadian Journal of Earth Sciences, v. 41, p. 553–570, doi: 10.1139/e03-100.

Malo, M., and Bourque, P.A., 1993, Timing of deformation events from Late Ordovician to Mid-Devonian in the Gaspé Peninsula, *in* Roy, D.C., and Skehan, J.W., eds., The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland: Geological Society of America Special Paper 275, p. 101–122.

Malo, M., Kirkwood, D., De Broucker, G., and St-Julien, P., 1992a, A reevaluation of the position of the Baie Verte–Brompton Line in the Quebec Appalachians: The influence of Middle Devonian strike-slip faulting in Gaspé Peninsula: Canadian Journal of Earth Sciences, v. 29, p. 1265–1273.

Malo, M., Moritz, R., Chagnon, A., and Roy, F., 1992b, Géologie et Métallogénie du Segment est de la Faille de Grand Pabos, Gaspésie: Ministère de l'Énergie et des Ressouces, Québec, Rapport MB 93–55, 114 p.

Nowlan, G.S., and Barnes, C.R., 1987, Thermal Maturation of Paleozoic Strata in Eastern Canada from Conodont Color Alteration Index (CAI) Data with Implications for Burial History, Tectonic Evolution, Hotspot Tracks and Mineral and Hydrocarbon Exploration: Geological Survey of Canada Bulletin 367, 47 p.

Pearce, J.A., 1996, A user's guide to basalt discrimination diagrams, *in* Wyman, D.A., ed., Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration: Geological Association of Canada, Short Course Notes, v. 12, p. 79–113.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 956–983.

Pincivy, A., Malo, M., Ruffet, G., Tremblay, A., and Sacks, P., 2003, Regional metamorphism of the Appalachian Humber Zone of the Gaspé Peninsula: ^{40}Ar/^{39}Ar evidence for crustal thickening during the Taconian orgeny: Canadian Journal of earth Sciences, v. 40, p. 301–315.

Prave, A.R., Kessler, L.G., II, Malo, M., Bloechl, W.V., and Riva, J., 2000, Ordovician arc collision and foredeep evolution in the Gaspé Peninsula, Québec: The Taconic orogeny in Canada and its bearing on the Grampian orogeny in Scotland: Journal of the Geological Society of London, v. 157, p. 393–400.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in ^{40}Ar/^{39}Ar dating: Chemical Geology, v. 145, p. 117–152, doi: 10.1016/S0009-2541(97)00159-9.

Riva, J., and Malo, M., 1988, Age and composition of the Honorat Group, southern Gaspé Peninsula: Canadian Journal of Earth Sciences, v. 25, p. 1618–1628.

Roddick, J.C., 1988, The assessment of errors in ^{40}Ar/^{39}Ar dating, *in* Radiogenic Age and Isotopic Studies, Report 2: Geological Survey of Canada Paper 88–2, p. 7–16.

Roddick, J.C., Cliff, R.A., and Rex, D.C., 1980, The evolution of excess argon in alpine biotites—A ^{40}Ar/^{39}Ar analysis: Earth and Planetary Science Letters, v. 48, p. 185–208, doi: 10.1016/0012-821X(80)90181-8.

Rogers, N., van Staal, C.R., McNicoll, V., and Thériault, R., 2003a, Volcanology and tectonic setting of the northern Bathurst Mining Camp. Part 1: Extension and rifting of the Popelogan arc, *in* Goodfellow, W.D., McCutcheon, S.R., and Peters, J.M., Massive sulfide deposits of the Bathurst Mining camp, New Brunswick and northern Maine: Economic Geology Monograph 11, p. 157–179.

Rogers, N., van Staal, C.R., Winchester, J.A., and Fyffe, L.R., 2003b, Provenance and chemical stratigraphy of the sedimentary rocks of the Lower to Middle Ordovician Miramichi, Tetagouche, California Lake and Fournier Groups in northern New Brunswick, *in* Goodfellow, W.D., McCutcheon, S.R., and Peters, J.M., Massive sulfide deposits of the Bathurst Mining camp, New Brunswick and northern Maine: Economic Geology Monograph 11, p. 111–128.

Rollinson, H.R., 1993, Using Geochemical Data: Evaluation, Presentation, Interpretation: Harlow, Pearson Education, 352 p.

Scaillet, S., 2000, Numerical error analysis in ^{40}Ar/^{39}Ar dating: Chemical Geology, v. 162, p. 269–298, doi: 10.1016/S0009-2541(99)00149-7.

Schulz, K.J., and Ayuso, R.A., 2003, Lithogeochemistry and paleotectonic setting of the Bald Mountain massive sulfide deposit, northern Maine, *in* Goodfellow, W.D., McCutcheon, S.R., and Peters, J.M., Massive sulfide deposits of the Bathurst Mining camp, New Brunswick and northern Maine: Economic Geology Monograph 11, p. 79–109.

Simard, M., 1986, Géologie et Évaluation du Potentiel Minéral de la Région de Carleton: Ministère de l'Énergie et des Ressources, Québec, Rapport ET 84–11, 27 p.

Slivitzky, A., St-Julien. P., and Lachambre, G. 1991, Synthèse Géologique du Cambro-Ordovicien du Nord de la Gaspésie: Ministère de l'Énergie et des Ressources, Québec, Rapport ET 88–14, 61 p.

Stern, R.A., 1997, The GSC sensitive high resolution ion microprobe (SHRIMP): Analytical techniques of zircon U-Th-Pb age determinations and performance evaluation, *in* Radiogenic Age and Isotopic Studies, Report 10: Geological Survey of Canada, Current Research, v. 1997-F, p. 1–31.

Stern, R.A., and Amelin, Y., 2003, Assessment of errors in SIMS zircon U-Pb geochronology using a natural zircon standard and NIST SRM 610 glass: Chemical Geology, v. 197, p. 111–146, doi: 10.1016/S0009-2541(02)00320-0.

St-Julien, P., and Hubert, C., 1975, Evolution of the Taconian orogen in the Quebec Appalachians: American Journal of Science, v. 275-A, p. 337–362.

Sun, S.S., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes: Geological Society of London Special Publication 42, p. 313–345, doi: 10.1144/GSL.SP.1989.042.01.19.

Tremblay, A., Malo, M., and St-Julien, P., 1995, Dunnage Zone—Québec, Chapter 3, *in* Williams, H., ed., Geology of the Appalachian/Caledonian Orogen in Canada and Greenland: Ottawa, Geological Survey of Canada, Geology of Canda, v. 6, p. 179–197.

van Staal, C.R., 1987, Tectonic setting of the Tetagouche Group in northern New Brunswick: Implications for plate tectonic models of the northern Appalachians: Canadian Journal of Earth Sciences, v. 24, p. 1329–1351.

van Staal, C.R., 2007, Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians, *in* Goodfellow, W.D., ed., Mineral Resources of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: St. John's, Newfoundland, Mineral Deposit Division of the Geological Association of Canada and the Geological Survey of Canada, 793–818.

van Staal, C.R., Winchester, J.A., and Bédard, J.H., 1991, Geochemical variations in Middle Ordovician volcanic rocks of the northern Miramichi Highlands and their tectonic significance: Canadian Journal of Earth Sciences, v. 28, p. 1031–1049.

van Staal, C.R., Dewey, J.F., Mac Niocaill, C., and McKerrow, W.S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: History of a complex west and southwest Pacific-type segment of Iapetus, *in* Blundell, D.J., and Scott, A.C., eds., Lyell: The Past Is the Key to the Present: Geological Society of London Special Publication 143, p. 199–242.

van Staal, C.R., Wilson, R.A., Rogers, N., Fyffe, L.R., Langton, J.P., McCutcheon, S.R., McNicoll, V., and Ravenhurst, C.E., 2003, Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp, and its relationships to coeval rocks in southwestern New Brunswick and adjacent Maine—A synthesis: Economic Geology Monograph 11, p. 37–60.

Vennat, G., 1979, Structure et Stratigraphie de l'Anticlinorium d'Aroostook-Percé dans la Région de St-Omer–Carleton, Gaspésie, Appalaches du Québec [M.Sc. thesis]: Montréal, Canada, Université de Montréal, 67 p.

Villeneuve, M.E., and MacIntyre, D.G., 1997, Laser ^{40}Ar/^{39}Ar ages of the Babine porphyries and Newman volcanics, Fulton Lake map area, west-central British Columbia, *in* Radiogenic Age and Isotopic Studies, Report 10: Geological Survey of Canada, Current Research, v. 1997-F, p. 131–139.

Villeneuve, M.E., Sandeman, H.A., and Davis, W.J., 2000, A method for the intercalibration of U-Th-Pb and ^{40}Ar/^{39}Ar ages in the Phanerozoic: Geochimica et Cosmochimica Acta, v. 64, p. 4017–4030, doi: 10.1016/S0016-7037(00)00484-1.

Webby, B.D., Cooper, R.A., Bergström, S.M., and Paris, F., F., 2004, Stratigraphic framework and time slices, *in* Webby, B.D., Paris, F., Droser, M., and Percival, I.G., eds., The Great Ordovician Biodiversity Event: New York, Columbia University Press, p. 41–47.

Williams, H., 1995, Temporal and spatial divisions, *in* Williams, H., ed., Geology of the Appalachian/Caledonian Orogen in Canada and Greenland: Ottawa, Geological Survey of Canada, Geology of Canada, v. 6, p. 21–44.

Williams, H., and Hatcher, R.D., Jr., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v. 10, p. 530–536, doi: 10.1130/0091-7613(1982)10<530:STAAHO>2.0.CO;2.

Williams, H., and St-Julien, P., 1982, The Baie Verte–Brompton Line: Early Paleozoic continent ocean interface in the Canadian Appalachians, *in* St-Julien, P., and Béland, J., eds., Major Structural Zones and Faults of the Northern Appalachians: Geological Association of Canada Special Paper 24, p. 177–208.

Wilson, R.A., 2003, Geochemistry and petrogenesis of Ordovician arc-related mafic volcanic rocks in the Popelogan inlier, northern New Brunswick: Canadian Journal of Earth Sciences, v. 40, p. 1171–1189, doi: 10.1139/e03-034.

Wilson, R.A., Burden, E.T., Bertrand, R., Asselin, E., and McCracken, A.D., 2004, Stratigraphy and tectonosedimentary evolution of the Late Ordovician to Middle Devonian Gaspé belt in northern New Brunswick: Evidence from the Restigouche area: Canadian Journal of Earth Sciences, v. 41, p. 527–551, doi: 10.1139/e04-011.

Winchester, J.A., and Floyd, P.A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–343, doi: 10.1016/0009-2541(77)90057-2.

Winchester, J.A., and van Staal, C.R., 1994, The chemistry and tectonic setting of Ordovician volcanic rocks in northern Maine and their relationship to contemporary volcanic rocks in northern New Brunswick: American Journal of Science, v. 294, p. 641–662.

Winchester, J.A., van Staal, C.R., and Langton, J.P., 1992, The Ordovician volcanics of the Elmtree-Belledune inlier and their relationship to volcanics of the Northern Miramichi Highlands, New Brunswick: Canadian Journal of Earth Sciences, v. 29, p. 1430–1447.

Zagorevski, A., Rogers, N., van Staal, C.R., McNicoll, V., Lissenberg, C.J., and Valverde-Vaquero, P., 2006, Lower to Middle Ordovician evolution of peri-Laurentian arc and back-arc complexes in Iapetus: Constraints from the Annieopsquotch accretionary tract, central Newfoundland: Geological Society of America Bulletin, v. 118, p. 324–342, doi: 10.1130/B25775.1.

Manuscript Received 19 April 2007
Revised Manuscript Received 4 April 2008
Manuscript Accepted 15 April 2008

Printed in the USA