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Paleotectonic Setting of Cambro-Ordovician Volcanic Rocks in the Canadian Appalachians

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Article abstract

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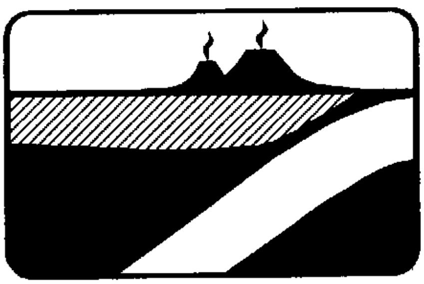
Passive-margin, rift-related volcanic rocks include Late Precambrian to Early Cambrian, within-plate, tholeiitic to transition alalkalic basalts and associated per alkaline rhyolites of the Sutton Mountains in Québec and the Cloud Mountain and Deer Lakeare as of Newfoundland. These volcanic rocks were extruded onto Grenville crustalong the northwestern margin of the Appalachian Orogen and, together with the Late Precambrian Long Range dyke swarm, indicate that a period of crustal extension, related to the formation of an ancient oceanbasin, persisted for at least 60 million years.

Sub-arc ophiolltes include Early Ordovician ophiolite complexes from the Eastern Townships of Québec and Baie Verte Peninsula of northwestern Newfoundland. The presence of boninites and primitive-arc volcanic rocks suggests that these ophiolltes represent the foundation to arc systems rather than ocean floor generated at a mid-oceanic ridge. Volcanic-arc suites in central Newfoundland range from Late Cambrian to Early Ordovician in age and commonly varyin composition from primitive-arc tholeiites to mature-arc, calc-alkaline volcanic rocks inthe lower parts, to rocks similar to ocean floor and ocean island basalts in the upper parts of the successions. This variation ingeochemistry suggests a change in tectonicenvironment from long-established subduc-tion-related to back-arc-related volcanism. Early Ordovician ophiolite complexes inparts of central Newfoundland contain volcanic rocks with ocean floor geochemical characteristics and are believed to have been generated in back-arc basins.

An ophiolite complex in northern New Brunswick, which is some 20 million years younger than those in Newfoundland, contains volcanic rocks that are transitional between ocean floor and island-arc basalts — a feature typical of many back-arc oceanic settings. Early Ordovician volcanic rocks in northwestern New Brunswick possess a mature-arc character, but do not appear to record a period of back-arc development; non-arc volcanic rocks are, however, a bundant inadjacent areas of Maine. Volcanic rocks in central and northern New Brunswick and in southern Newfoundland are dominated by Early Ordovician, silica-rich felsic flows and tuffs that are intercalated with, and overlain by, Early to Late Ordovician mafic volcanic rocks ranging in composition from continental tholeiites to within-plate alkali basalts.These bimodal suites are interpreted to havef ormed within back-arc basins underlain bysialic crust of possible Avalonian affinity.

Articles



Paleotectonic Setting of Cambro-Ordovician Volcanic Rocks in the Canadian Appalachians

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ABSTRACT

Recent advances in the understanding of petrogenetic processes at plate boundaries, coupled with improved trace-element and geochronological analytical techniques, permit a more sophisticated approach to paleogeographic reconstructions of ancient volcanic environments. This paper reviews published geochemical data on Cambro-Ordovician volcanic rocks of the Canadian Appalachians and uses these data to interpret the plate tectonic setting of the volcanic activity. Synthesis of the data suggests that some spatial relationships among the various volcanic suites may have been maintained with respect to the Laurentian and Avalonian continental margins despite considerable crustal shortening across, and transcurrent displacement parallel to, the Appalachian Orogen. Six tectonovolcanic environments are recognized, including passive-margin rift volcanic rocks, oceanic island volcanic rocks, sub-arc ophiolites, island-arc volcanic rocks, back-arc ophiolites, and continental-margin back-arc volcanic rocks.

Passive-margin, rift-related volcanic rocks include Late Precambrian to Early Cambrian, within-plate, tholeiitic to transitional alkalic basalts and associated peralkaline rhyolites of the Sutton Mountains in Québec and the Cloud Mountain and Deer Lake areas of Newfoundland. These volcanic rocks were extruded onto Grenville crust along the northwestern margin of the Appalachian Orogen and, together with the Late Precambrian Long Range dyke swarm, indicate that a period of crustal extension, related to the formation of an ancient ocean basin, persisted for at least 60 million years.

Sub-arc ophiolites include Early Ordovician ophiolite complexes from the Eastern Townships of Québec and Baie Verte Peninsula of northwestern Newfoundland. The presence of boninites and primitive-arc volcanic rocks suggests that these ophiolites represent the foundation to arc systems rather than ocean floor generated at a mid-oceanic ridge. Volcanic-arc suites in central Newfoundland range from Late Cambrian to Early Ordovician in age and commonly vary in composition from primitive-arc tholeiites to mature-arc, calc-alkaline volcanic rocks in the lower parts, to rocks similar to ocean floor and ocean island basalts in the upper parts of the successions. This variation in geochemistry suggests a change in tectonic environment from long-established subduction-related to back-arc-related volcanism. Early Ordovician ophiolite complexes in parts of central Newfoundland contain volcanic rocks with ocean floor geochemical characteristics and are believed to have been generated in back-arc basins.

An ophiolite complex in northern New Brunswick, which is some 20 million years younger than those in Newfoundland, contains volcanic rocks that are transitional between ocean floor and island-arc basalts — a feature typical of many back-arc oceanic settings. Early Ordovician volcanic rocks in northwestern New Brunswick possess a mature-arc character, but do not appear to record a period of back-arc development; non-arc volcanic rocks are, however, abundant in adjacent areas of Maine. Volcanic rocks in central and northern New Brunswick and in southern Newfoundland are dominated by Early Ordovician, silica-rich felsic flows and tuffs that are intercalated with, and overlain by, Early to Late Ordovician mafic volcanic rocks ranging in composition from continental tholeiites to within-plate alkali basalts. These bimodal suites are interpreted to have formed within back-arc basins underlain by sialic crust of possible Avalonian affinity.

RÉSUMÉ

De récentes percées réalisées dans la compréhension des processus pétrogénétiques aux frontières des plaques tectoniques, ainsi que l'amélioration des techniques analytiques basées sur les éléments-traces et la géochronologie permettent une approche plus sophistiquée de la reconstruction paléogéographique des anciens environnements volcaniques. Le présent document passe en revue les données géochimiques publiées sur les roches volcaniques cambro-ordoviciennes des Appalaches canadiennes, et utilise ces données pour interpréter le cadre de la tectonique de plaque associé à l'activité volcanique. La synthèse de ces données laisse supposer que certaines relations spatiales parmi les diverses paragenèses volcaniques auraient pu être maintenues par rapport aux marges continentales laurentiennes et avaloniennes en dépit d'un raccourcissement crustal transversal et d'un déplacement transcourant parallèle à l'orogène des Appalaches. On reconnaît six environnements tectonovolcaniques, notamment les roches volcaniques de fossés tectoniques à marge passive, les roches volcaniques d'îles océaniques, les ophiolites d'arc inférieur, les roches volcaniques d'arc insulaire, les ophiolites arrière-arc et les roches volcaniques arrière-arc de la marge continentale.

Les roches volcaniques classées comme roches reliées aux fossés tectoniques à marge passive comprennent les basaltes tholéiitiques à l'intérieur des plaques jusqu'aux basaltes alcalins transitionnels du Précambrien supérieur au Cambrien inférieur et les rhyolites paralcalines connexes des monts Sutton, au Québec, et des régions du mont Cloud et du lac Deer, à Terre-Neuve. Ces roches volcaniques ont été expulsées sur l'écorce de Grenville le long de la marge nord-ouest de l'orogène des Appalaches et, conjointement au groupe de dykes de Long Range du Précambrien supérieur, elles révèlent qu'une période d'extension crustale, liée à la formation d'un ancien bassin océanique, a persisté pendant au moins 60 millions d'années.

Les ophiolites d'arc inférieur comprennent les complexes ophiolitiques de l'Ordovicien inférieur des Cantons de l'est, au Québec, et de la péninsule de Baie Verte, à Terre-Neuve. La présence de boninites et de roches volcaniques d'arc primitif révèle que ces ophiolites constituent la fondation de systèmes d'arcs plutôt que d'un fond océanique produit à une crête de dorsale océanique. Les paragenèses d'arcs volcaniques dans le centre de Terre-Neuve s'étalent du Cambrien supérieur à l'Ordovicien inférieur, et leur composition varie habituellement des tholéiites d'arc primitif aux roches volcaniques calcaires alcalines d'arc évolué, dans les parties inférieures, jusqu'aux roches similaires au fond océanique et aux basaltes d'îles océaniques, dans les parties supérieures des paragenèses. Cette variation de la géochimie laisse supposer une modification de l'environnement tectonique, marquant le passage d'un volcanisme, lié à la subduction, établi de longue date, à un volcanisme arrière-arc. Les complexes ophiolitiques de l'Ordovicien inférieur de certaines parties du centre de Terre-Neuve sont formés de roches volcaniques ayant les caractéristiques géochimiques d'un fond océanique et auraient été produites dans des bassins arrière-arc.

Un complexe ophiolitique dans le nord du Nouveau-Brunswick, de quelque 20 millions d'années plus jeune que ceux de Terre-Neuve, est formé de roches volcaniques transitionnelles entre un fond océanique et des basaltes d'arc insulaire — trait typique d'un grand nombre de cadre océaniques arrière-arc. Les roches volcaniques de l'Ordovicien inférieur, dans le nord-ouest du Nouveau-Brunswick, possèdent un caractère d'arc évolué, mais ne semblent pas comporter une période de développement arrière-arc. Les roches volcaniques non arciennes se trouvent toutefois en abondance dans les régions adjacentes du Maine. Les roches volcaniques du centre et du nord du Nouveau-Brunswick et du sud de Terre-Neuve sont dominées par des écoulements et des tufs felsiques riches en silice, de l'Ordovicien inférieur, intercalés et recouverts par des roches volcaniques mafiques, de l'Ordovicien inférieur à l'Ordovicien supérieur, et dont la composition varie des tholéiites continentales aux basaltes alcalins à l'intérieur des plaques. On considère que ces paragenèses bimodales se sont formées au sein de bassins arrière-arc reposant sur une écorce sialique ayant probablement une affinité avalonienne.

INTRODUCTION

The geochemical signatures of volcanic rocks generated in specific plate tectonic settings provide vital information for the reconstruction of ancient plate configurations. In recent years, the development of rapid and more precise analytical techniques for a wide variety of trace elements at low concentrations has made it possible to identify distinctive geochemical signatures in volcanic rocks that are empirically related to their plate tectonic environment. These same analytical techniques, applied to ancient volcanic rocks, permit a comparison of their geochemical signatures with modern rocks from known tectonic settings, and provide a useful line of evidence in the interpretation of paleotectonovolcanic settings.

Petrogenetic processes in the different plate tectonic settings produce characteristic geochemical signatures that are preserved in the volcanic rocks (Wood *et al.*, 1979; Perfit *et al.* 1980; Saunders *et al.*, 1980; Sun, 1980; Pearce, 1982; Kay, 1984; Meschede, 1986). For example, island-arc volcanic rocks generated at converging plate margins display an overall depletion in the high-field-strength elements (*e.g.*, Nb, Ta, Zr, Hf, and Ti), and enrichment in the low-field-strength elements (*e.g.*, Cs, Rb, K, Ba, Sr, Th) compared to ocean floor basalts formed at diverging plate boundaries (Saunders *et al.*, 1980). In addition, they commonly display a characteristic anomalous depletion in Nb and Hf relative to the light-rare-earth elements of similar geochemical character (*i.e.*, La, Ce) (Wood *et al.*, 1979). Island-arc, calc-alkaline volcanic rocks exhibit enrichment in light-rare-earth elements relative to chondrite, while preserving the depletion in the high-field-strength elements, whereas typical ocean floor basalts are depleted in these elements. Within-plate basalts, which are commonly interpreted to be generated over thermal plumes, fall into two geochemical categories, ocean island tholeiites and ocean island alkalic basalts, reflecting at least in part differences in the nature of their mantle sources. The two types commonly occur together in both oceanic and continental settings.

This paper reviews the geochemical data available on Cambrian and Ordovician volcanic rocks of the Canadian Appalachians (Figure 1) and groups these rocks according to tectonic setting within the Appalachian orogenic cycle. Early Paleozoic volcanic rocks in the Appalachian Orogen were generated in response to opening and closing of oceanic basins bordered by the Laurentian craton to the northwest and the Avalon block to the southeast (Williams, 1964; Wilson, 1966; Strong, 1974, 1977). The relationship of volcanic rocks within the Humber, Dunnage, and Gander zones (Williams, 1979; Williams *et al.*, 1988) to the plate tectonic evolution of the Appalachians is reasonably well understood, but the significance of the Precambrian and Cambrian volcanic rocks of the Avalon zone to the Appalachian cycle is less certain (Murphy and Nance, 1989). Six Early Paleozoic tectonovolcanic suites are recog-

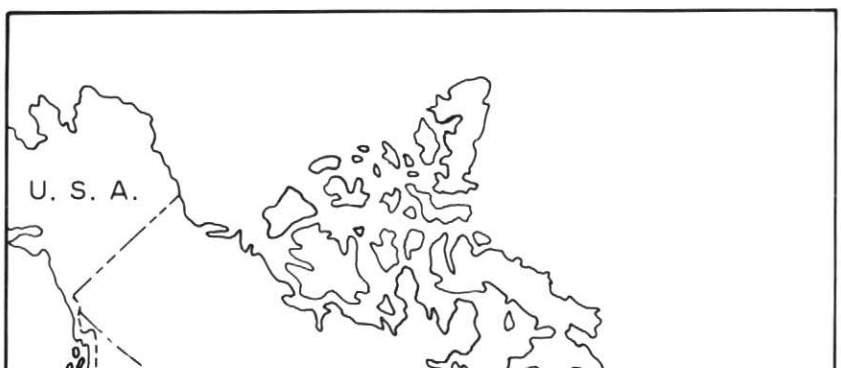

Figure 1 *Location of Eastern Townships and Gaspé Peninsula, Québec and Province of New Brunswick (Figure 2), and the Island of Newfoundland (Figure 3) within the Canadian Appalachians.*

nized in the Canadian Appalachians: (1) passive-margin rift volcanic rocks; (2) oceanic island volcanic rocks; (3) sub-arc ophiolites; (4) island-arc volcanic rocks; (5) back-arc ophiolites; and (6) continental-margin back-arc volcanic rocks (Figures 2 and 3). Suite 1 is located within the Humber Zone; suites 2 to 5, within the Dunnage Zone (and as allochthons on Humber), and suite 6, within the Gander Zone. Volcanic rocks of the Avalon Zone are not included in this review.

The volcanic suites are distributed in several northeast-trending belts within the various tectonostratigraphic zones and will be described below generally from the northwest to southeast. Space limitations permit only a brief summary of the local stratigraphic successions and the reader is referred to the referenced literature for more detailed information. There is a considerable variation in the nature and quality of geochemical information available in the different areas. For example, not all workers have analyzed the rare-earth elements, and the analyses of the highly incompatible, high-field-strength elements (*e.g.*, Nb, Ta) are not always sufficiently precise and accurate at the very low concentrations to provide diagnostic information as to their setting. Most recent workers report good quality Ti, Zr, and Y data, and for ease of visual presentation, the geochemical data from the various belts are herein illustrated on a ternary Ti-Zr-Y discrimination diagram (Pearce and Cann, 1973). It should be noted that the defined fields on this diagram may exhibit considerable overlap (Holm, 1982). Other geochemical data, including rare-earth elements, Th, and precise determinations of the high-field-strength elements at low concentrations, are available for many of the volcanic belts and can be found in the appropriate references. In many cases, these additional data provide less ambiguous interpretations of the tectonic environments than are possible using the Ti-Zr-Y diagram alone.

This paper attempts to present a regional synthesis of Cambro-Ordovician volcanic activity in the Canadian Appalachians, based mainly on published geochemical information. It should be borne in mind that a review of this kind, covering such a large geographical region, necessarily requires some simplification of what is undoubtedly a very complex tectonic history. Likewise, ambiguities remain concerning the tectonic settings of some specific volcanic belts that can only be addressed by more detailed studies in these areas.

PASSIVE-MARGIN RIFT VOLCANIC ROCKS

Crustal extension along the northwestern margin of the Appalachian Orogen apparently took place over at least 60 million years (m.y.), beginning in the Late Proterozoic (615 Ma, U-Pb) — the emplacement age of the Long Range dyke swarm into Grenville gneisses on the southeastern coast of Labrador (Kamo *et al.*, 1989) — and continuing into the Early Cambrian (554 Ma, U-Pb) — the age of the Tibbit Hill Formation (Kumarapeli *et al.*, 1989), which underlies the Sutton Mountains in the Eastern Townships of Québec (Figure 2). The Sutton Mountains are part of a nappe complex emplaced to the northwest over Ordovician shelf carbonate rocks of the Laurentian foreland. However, to the southwest in the Green Mountains of Vermont, volcanic rocks of the Tibbit Hill Formation rest directly on Grenvillian basement, confirming their continental setting (St-Julien and Hubert, 1975). High-field-strength-element (HFSE) ratios (Figure 4a) and rare-earth-element (REE) profiles (chondrite-normalized $(La/Yb)_N$ = 5) from mafic flows of the Tibbit Hill Formation indicate that they are compositionally transitional to ocean island alkalic basalts (OIA). These basalts and associated peralkaline

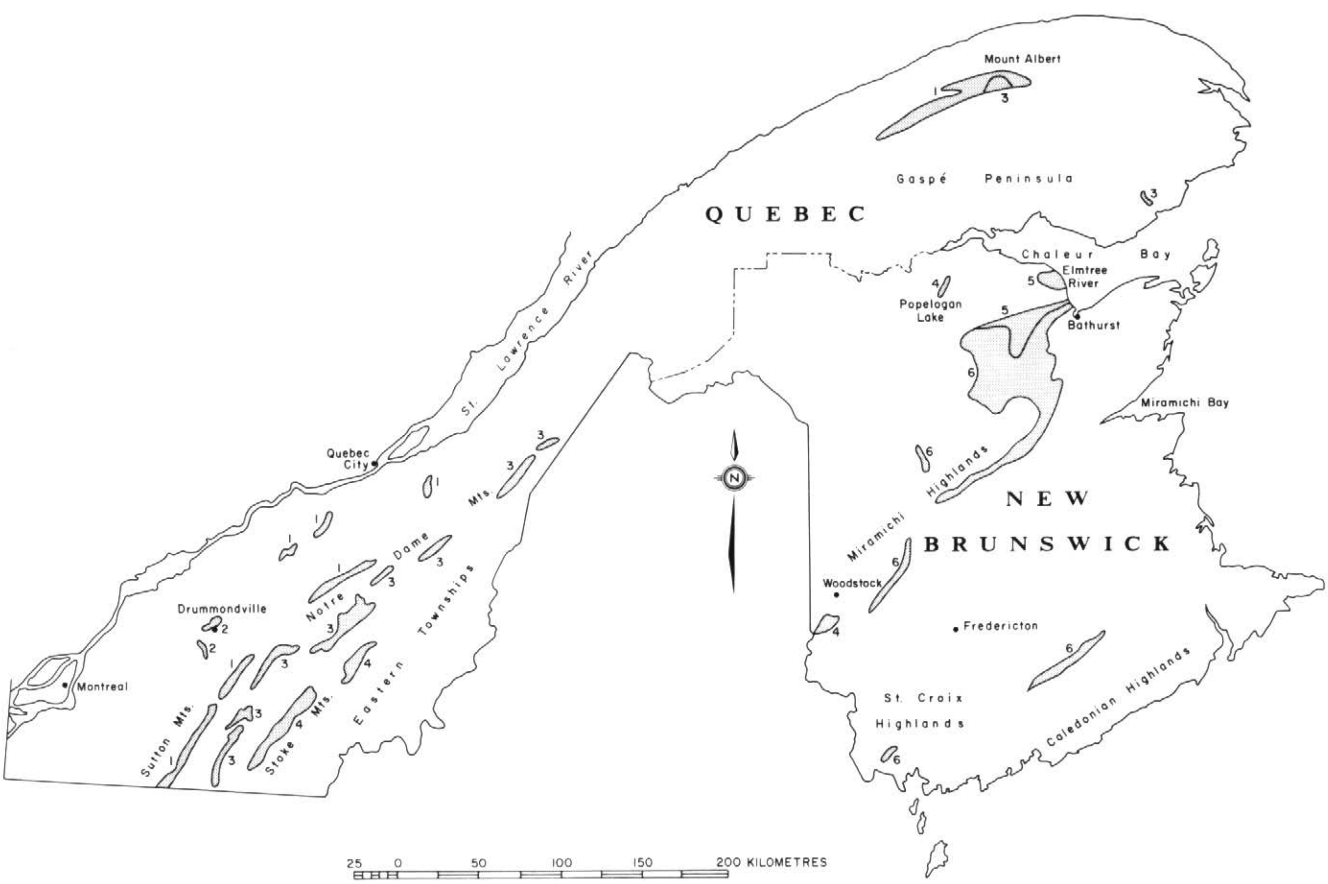

Figure 2 *Distribution of Early Paleozoic ophiolitic and volcanic rocks in Québec and New Brunswick. The volcanic rocks are divided into six tectonic suites on the basis of regional stratigraphic relationships and geochemistry. Volcanic suites:* ***1****, passive margin rift;* ***2****, oceanic island;* ***3****, sub-arc ophiolite;* ***4****, island-arc;* ***5****, back-arc ophiolite;* ***6****, continental-margin back-arc.*

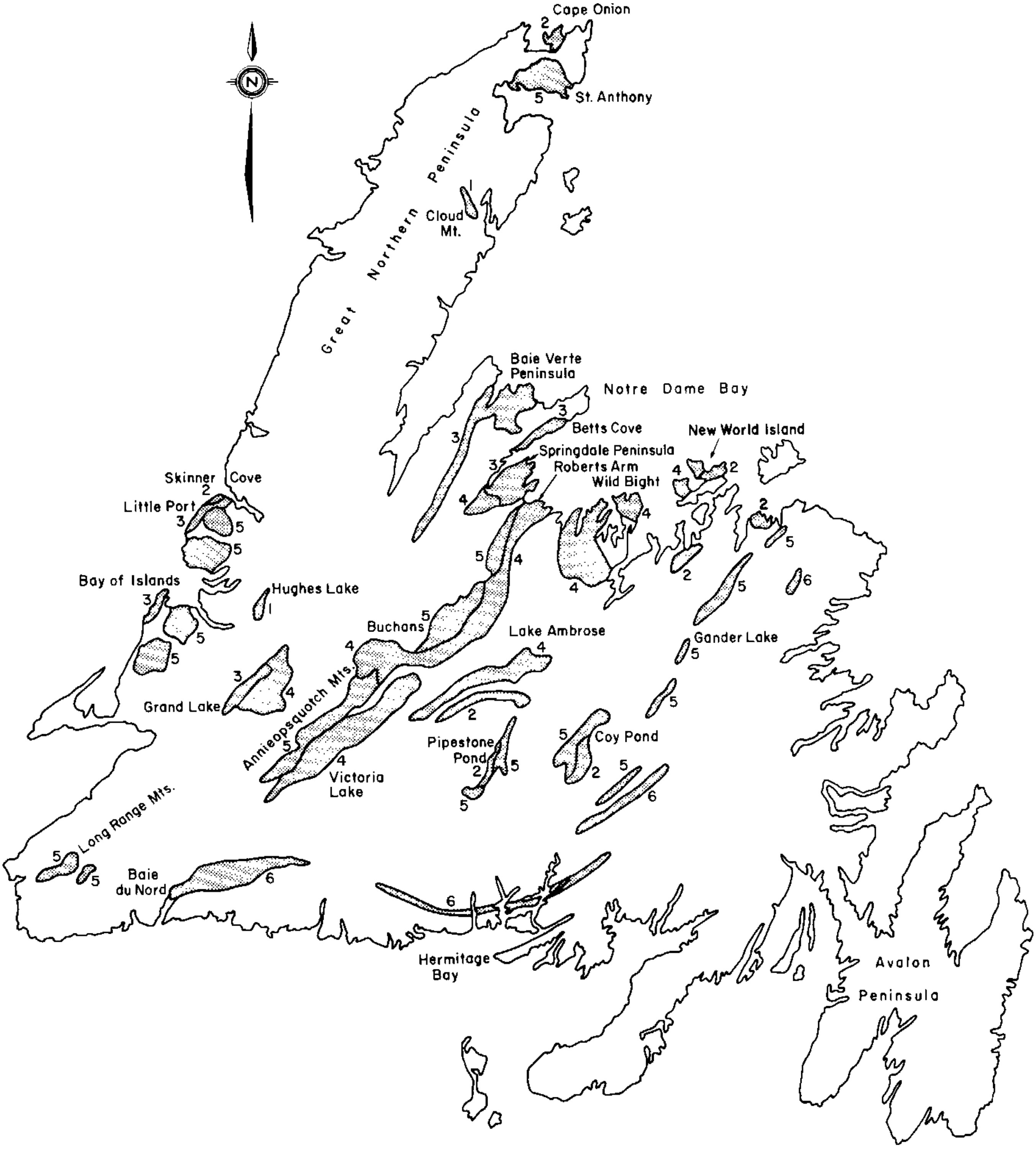

Figure 3 *Distribution of Early Paleozoic ophiolites and volcanic rocks in Newfoundland. (See Figure 2 for legend).*

rhyolites are typical of within-plate, rift lavas (Pintson *et al.*, 1985; Kumarapeli *et al.*, 1989). Structural slices of alkalic basalts within the Montagne de Saint-Anseline Formation to the northeast of the Sutton Mountains are correlated with the Tibbit Hill Formation (Vallières *et al.*, 1978).

Late Precambrian to Early Cambrian mafic volcanic rocks underlie the Cloud Mountain area on the Great Northern Peninsula of northwestern Newfoundland (Figure 3). The Cloud Mountain flows, which lie unconformably on Grenvillian basement, are columnar-jointed and about 10 m thick. Hypersthene-normative mineralogy, FeO:MgO ratios and TiO_2:Zr ratios indicate an ocean island tholeiite (OIT) composition consistent with generation in a rifted continental margin setting (Strong and Williams, 1972; Strong, 1974). The relationship of tholeiitic diabases of the Long Range dyke swarm to the Cloud Mountain basalts is uncertain; the diabases possess significantly higher TiO_2:Zr ratios and may represent an earlier period of rifting or contemporaneous generation from a separate source region (Strong, 1974). Tholeiitic basalts similar to the Cloud Mountain flows (Figure 5a) are associated with alkali rhyolites within the Hughes Lake structural slice near Deer Lake in western Newfoundland (Williams *et al.*, 1985).

OCEANIC ISLAND VOLCANIC ROCKS

Isolated sections of Early Ordovician(?) massive mafic flows up to 75 m thick, interbedded with grey shale, occur at the contact of two thrust sheets to the north of the Sutton Mountains near Drummondville, Québec (Figure 2) (Kumarapeli *et al.*, 1988). The flows possess HFSE-ratios typical of OIA basalts (Figure 4b). Along the western coast of Newfoundland, pillow lavas, breccias, flow-banded trachytes, and associated fossiliferous limestone of the Late Cambrian to Early Ordovician Skinner Cove Formation occur within a structural slice underlying the allochthonous Bay of Islands ophiolite (Figure 3). High TiO_2 (1.67-4.02%), Zr (196-444 ppm), and Nb (17-90 ppm) contents indicate an OIA affinity (Strong, 1974). The Cape Onion and Irish Point pillow lavas beneath the St. Anthony ophiolite on the tip of the Great Northern Peninsula are chemically similar to those at Skinner Cove (Jamieson, 1977). The volcanic rocks at Cape Onion are associated with black shale containing Early Ordovician graptolites. According to the cited authors, the available stratigraphic and geochemical evidence favours generation of the volcanic rocks at Drummondville, Skinner Cove, Cape Onion and Irish Point at seamounts located on ocean crust proximal to the Laurentian continental margin. However, the data do not preclude generation beneath the rifted continental margin, itself.

Early Ordovician pillow lavas within the Cold Spring Pond Formation in the Pipestone Pond area of south-central Newfoundland (Figure 3) are OIT ($(La/Yb)_N$ = 5.4) (Swinden, 1988) (Figure 5f). Ordovician basalts within the Summerford Group on New World Island along the northeastern coast of Newfoundland are also similar to OIT (Jacobi and Wasowski, 1985) (Figure 5a). These oceanic island volcanic rocks are interpreted to have formed in a back-arc basin setting (Swinden, 1988, 1991).

SUB-ARC OPHIOLITES

Ultramafic-mafic complexes of the Eastern Townships of Québec occur as a northeast-trending series of fault slices forming an ophiolitic mélange thrust onto miogeoclinal clastic rocks of the Notre Dame Mountains (Figure 2). Many of these Early Ordovician complexes are dismembered, but the Thetford Mines complex contains a nearly complete, southeast-facing ophiolitic assemblage with 4.5 km of peridotite tectonite at the base overlain successively by up to 2.2 km of layered dunite and pyroxenite, gabbro, sheeted diabase, and pillow lavas (Laurent, 1975; Williams and St-Julien, 1982; Harnois, 1989). The mafic lavas of the Thetford Mines complex are separated into a 900 m thick lower and an 850 m thick upper unit by a 50 m thick layer of cherty argillite. The basal 200 m of the lower unit contain high TiO_2-low MgO basalts with flat REE profiles ($(La/Yb)_N$ = 0.8) and trace-element abundances (Figure 4c) similar to primitive island-arc tholeiites (IAT). The mafic volcanics in the higher part of the lower unit and the entire upper unit are low in TiO_2, high in MgO, and possess concave-upward REE profiles ($(La/Yb)_N$ = 1.4) resembling present-day boninites from the Mariana fore-arc basin (Pearce *et al.*, 1984; Church, 1987; Oshin and Crocket, 1986; Crocket and Oshin, 1987; Laurent and Hebert, 1989).

The Betts Cove complex on the eastern shore of the Baie Verte Peninsula in Newfoundland contains a complete, 1750 m thick, southeast-facing ophiolitic assemblage (Figure 3). Gabbro from the complex has been dated as late Tremadocian to early Arenigian (489 Ma, U-Pb; Dunning and Krogh, 1985). The overlying Arenigian Snooks Arm Group comprises 2750 m of intercalated mafic flows, wackes and felsic tuffs — a sequence that is atypical of ophiolites generated in a mid-oceanic ridge setting (Upadhyay and Neale, 1979). Pillow lavas from the Betts Cove complex vary from high-MgO (9.31-21.62%), low-TiO_2 (0.10-0.17%) basalts with extremely low trace HFSE concentrations and concave-upward REE patterns typical of boninites in the lower member of the succession, to basalts with intermediate TiO_2 contents (0.31-0.53%), generally LREE-depleted patterns ($(La/Yb)_N$ = 0.3-1.1), and low Nb concentrations characteristic of IAT in the middle member, to high-TiO_2 (0.78-2.22%) basalts with depleted to enriched LREE patterns ($(La/Yb)_N$ = 0.4-1.4) resembling oceanic floor basalts (OFB) in composition in the upper member (Upadhyay, 1978; Coish and Church, 1979; Coish *et al.*, 1982; Swinden *et al.*, 1989). In contrast, the pillow lavas of the Snooks Arm Group possess TiO_2 contents (1.27-2.27%) and HFSE ratios (Figure 5b) typical of OIT (Jenner and Fryer, 1980). This systematic variation in geochemistry closely parallels that documented by Crawford *et al.* (1981) and Johnson and Fryer (1990) for the rifted Mariana fore-arc region in the Pacific Ocean (Sun and Nesbitt, 1978; Coish *et al.*, 1982; Upadhyay, 1982; Swinden *et al.*, 1989). A similar geochemistry is present within the Point Rousse ophiolite complex and Pacquet Harbour Group on western Baie Verte Peninsula (Gale, 1973; Norman and Strong, 1975; Kidd, 1977; Hibbard, 1983; Swinden *et al.*, 1989), and within the ophiolitic Lushes Bight Group and overlying Western Arm Group to the southeast on the Springdale Peninsula (Smitheringale, 1972; Swinden *et al.*, 1989). Correlatives of these rocks inland to the southwest include the Grand Lake ophiolite complex and overlying Arenigian Glover Formation (Williams and St-Julien, 1982).

ISLAND-ARC VOLCANIC ROCKS

The Early Ordovician volcanic rocks, wackes and slates of the Ascot Formation, which underlie the Stoke Mountains of the Eastern Townships (Figure 2), occupy a higher thrust slice to the southeast of the ophiolitic rocks (Labbé and St-Julien, 1989). The volcanics are predominantly basaltic flows with rarely preserved pillows and felsic pyroclastic rocks; porphyritic andesites are a minor portion of the sequence. Pervasive alteration has caused considerable scatter in the HFSE ratios of the mafic volcanics (Figure 4d) (Hynes, 1980); however, REE profiles confirm the presence of both IAT ($(La/Yb)_N$ = 0.3-0.8) and boninites ($(La/Yb)_N$ = 0.9-2.6) corresponding, respectively, to high TiO_2 (0.8-1.0%) and low TiO_2 (0.3-0.5%) basalts. Marked enrichment of light-rare-earth (LREE) and low-field-strength elements (LFSE) in some of the felsic tuffs indicates that part of the arc may have formed on a continental foundation (Tremblay *et al.*, 1989). Recent seismic investigations confirm that the island-arc volcanics of the Stoke Mountains allochthonously overlie Grenvillian continental crust (Spencer *et al.*, 1989). The site of origin of these volcanics is, therefore, uncertain. However, the geochemistry of the basalts and their close spatial association with ophiolites support an intra-oceanic setting, although the rhyolite geochemistry suggests that the arc may have fringed sialic crust (Tremblay *et al.*, 1989).

The Ordovician Bronson Hill volcanics (453 Ma, 449 Ma, U-Pb) and Upper Cambrian Boil Mountain ophiolite constitute a volcanic-arc complex to the southwest of the Chain Lakes massif in New England and may have formed, in part, on continental crust (Leo, 1985; Hynes, 1976; Coish and Rogers, 1987;

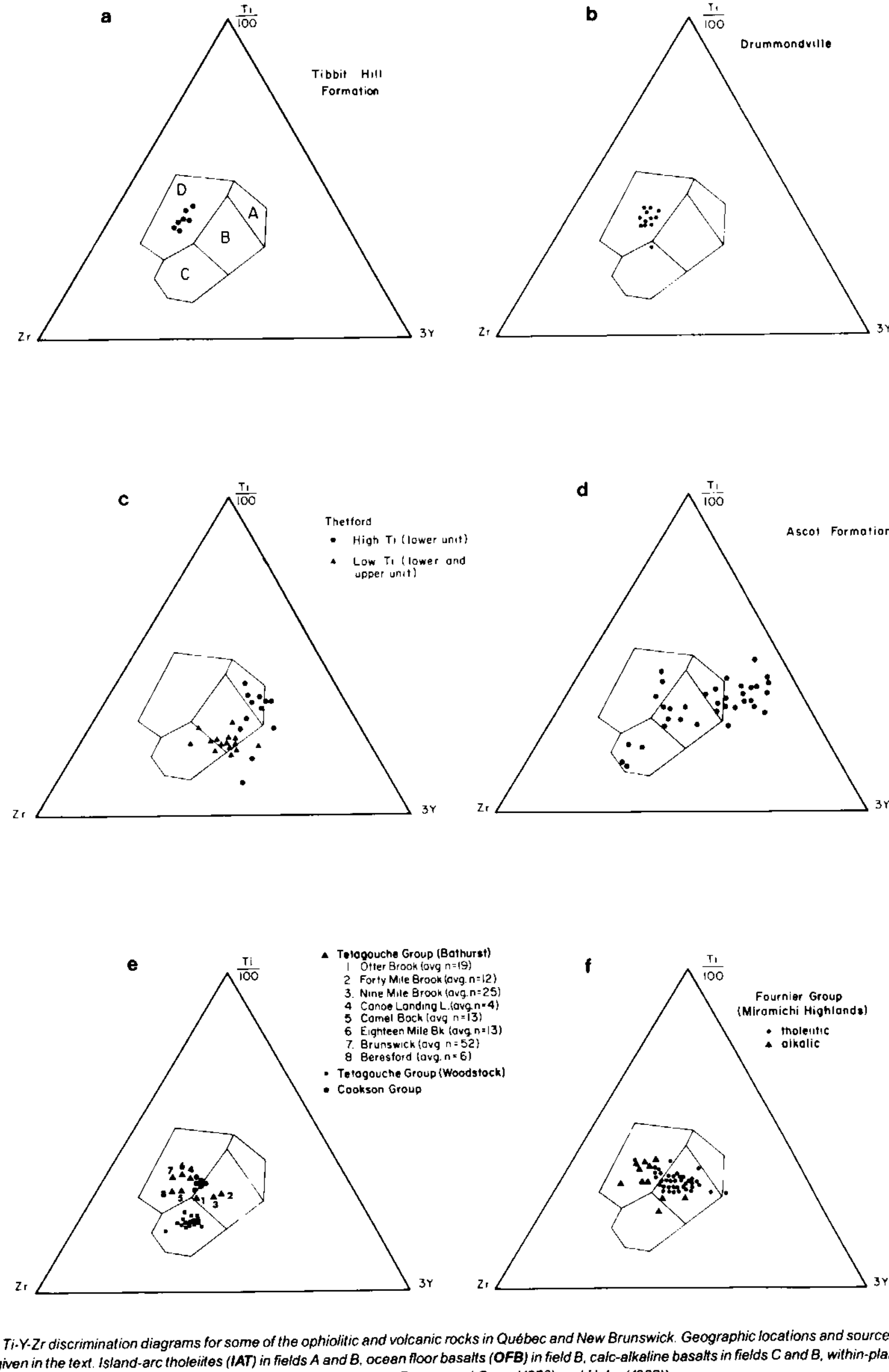

Figure 4 *Ti-Y-Zr discrimination diagrams for some of the ophiolitic and volcanic rocks in Québec and New Brunswick. Geographic locations and sources of the plotted data are given in the text. Island-arc tholeiites (**IAT**) in fields A and B, ocean floor basalts (**OFB**) in field B, calc-alkaline basalts in fields C and B, within-plate alkali basalts (**OIA**) in field D, and within-plate tholeiites (**OIT**) in fields D and B (after Pearce and Cann (1973) and Holm (1982)).*

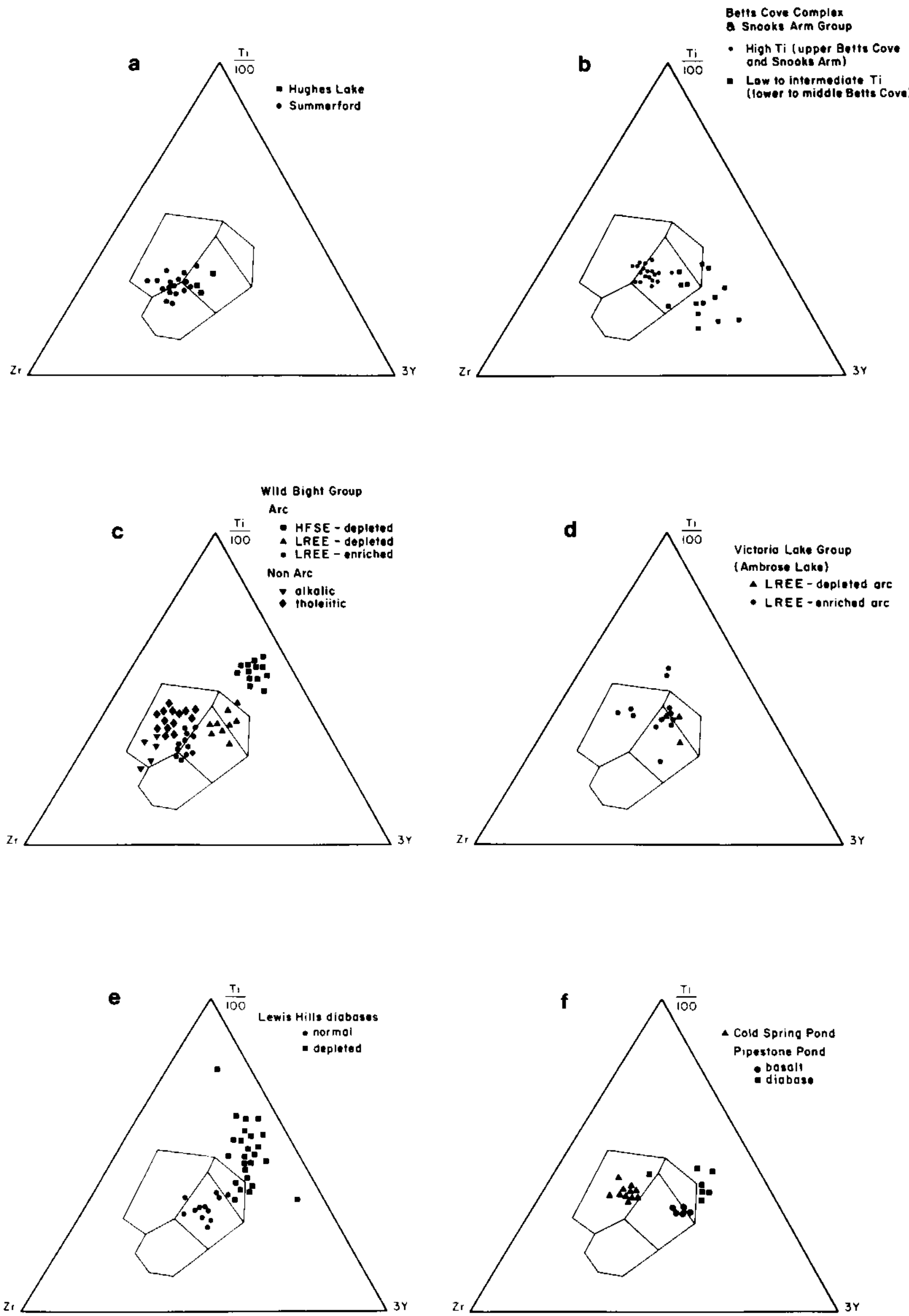

Figure 5 *Ti-Y-Zr discrimination diagrams for some of the ophiolitic and volcanic rocks in Newfoundland. (See Figure 4 for field designations).*

Schumacher, 1988; Boone and Boudette, 1989; Tucker and Robinson, 1990). Andesitic rocks in the Popelogan Lake inlier of north-central New Brunswick (Philpott, 1988) lie on-strike and may also be part of the Bronson Hill arc system (Figure 2). Ordovician mafic volcanic rocks at Oak Mountain near Woodstock, in west-central New Brunswick, possess a range of SiO_2 content (46-55%), high Al_2O_3 (avg. 17.6%), low TiO_2 (avg. 0.53%), low Fe to Mg ratios, HFSE ratios (Figure 4e), and LREE-enrichment ($(La/Yb)_N$ = 5.4) that are consistent with a calc-alkaline affinity. Clinopyroxenes in these rocks are low-Al and low-Ti augites typical of arc-related magmatism (Dostal, 1989). Graptolites from associated feldspathic wackes suggest a Llandeilian age for the mafic sequence (Fyffe *et al.*, 1983). The Woodstock volcanics may be a distinct arc or a remnant of the Bronson Hill arc that became separated by back-arc extension.

The Roberts Arm Group on western Notre Dame Bay in north-central Newfoundland (Figure 3) comprises mainly mafic pillow lavas and breccias distributed within three structural slices; massive, flow-banded and brecciated felsic flows are abundant only in the upper (northwestern) slice. Geochemical data indicate that the mafic volcanic rocks are arc-related (Strong, 1973; Bostock, 1988; Swinden, 1991). Felsic volcanics in the upper slice of the Roberts Arm Group have been dated as late Arenigian-Llanvirnian (473, U-Pb), identical to the age of the middle part of the Buchans Group, the inland continuation of the Roberts Arm Group (Dunning *et al.*, 1987). The Buchans Group is an 8 km thick succession of intercalated felsic and intermediate pyroclastic rocks, pillow lavas, and epiclastic rocks. Whole-rock and trace-element geochemistry confirm the presence of abundant calc-alkaline andesites throughout the stratigraphy (Thurlow *et al.*, 1975; Henley and Thornley, 1981; Swinden, 1991); REE patterns from unmineralized dacite and rhyolite exhibit steep slopes typical of calc-alkaline assemblages (Strong, 1974).

The Wild Bight Group in the central Notre Dame Bay area is an 8 km thick sequence of Early Ordovician (pre-Llandeilo) volcanic and epiclastic sedimentary rocks. The mafic volcanic rocks are generally pillowed and are locally interbedded with felsic crystal tuffs. The mafic volcanic rocks in the lower parts of the succession contain island-arc geochemical signatures, *i.e.*, depleted in HFSE and enriched in LFSE relative to OFB (Pearce *et al.*, 1984). These IAT include three groups: LREE-enriched ($(La/Yb)_N$ = 2.8-3.8), LREE-depleted ($(La/Yb)_N$ = 0.4-1.2), and strongly depleted with extremely low concentrations of incompatible elements ($(La/Yb)_N$ = 0.3-0.6). Associated felsic rocks are high in silica and sodium, low in incompatible elements, and are slightly depleted in LREE relative to HREE. The upper part of the succession contains mafic rocks with intraplate geochemical signatures (Figure 5c) including OIA basalts ($(La/Yb)_N$ = 5.8-8.7), strongly LREE-enriched OIT ($(La/Yb)_N$ = 2.7-7.4), and slightly LREE-enriched OIT ($(La/Yb)_N$ = 1.6-3.6) (Swinden *et al.*, 1990). A similar geochemical variation is also present within the composite Upper Cambrian to Lower Ordovician (513 Ma, 498 Ma, U-Pb) Victoria Lake Group, 100 km inland to the southwest, but calc-alkaline andesites ($(La/Yb)_N$ = 2.4-4.1) and felsic volcanic rocks form a portion of this succession in the Lake Ambrose area (Figure 5d) (Evans *et al.*, 1990; Dunning *et al.*, 1991). The presence of a fault sliver of ophiolitic rocks in the Wild Bight Group and lack of inheritance in zircons from the felsic volcanic rocks of the Victoria Lake Group support an intra-oceanic setting (Lorenz and Fountain, 1982; Swinden *et al.*, 1989; Dunning *et al.*, 1991). Early subduction-related volcanism followed by overlapping arc and non-arc volcanism recorded in the Wild Bight and Victoria Lake groups is consistent with a change in tectonic environment from an island-arc to rifted-arc setting and establishment of a back-arc basin (Swinden *et al.*, 1989, 1990).

BACK-ARC OPHIOLITES

A fragment of ophiolite within the Fournier Group of the Ordovician Elmtree River inlier is unconformably overlain by Lower Silurian conglomerate along Chaleur Bay in northern New Brunswick (Pajari *et al.*, 1977; Rast and Stringer, 1980) (Figure 2). Mafic rocks of the Fournier Group occur in two south-directed thrust sheets that are separated from underlying mid-Ordovician quartz wacke and slate of the Elmtree Formation by a tectonic mélange. The upper thrust sheet contains gabbros, mylonitic amphibolites, plagiogranites, diabase dykes, and pillow lavas of the Devereaux Formation. These are separated by a high strain zone from feldspathic and lithic wacke, red siltstone, grey slate, pillow lavas, chert, and minor felsic volcanic rocks comprising the Pointe Verte Formation of the lower sheet. Graptolites from black slate and conodonts from limestone pods within pillow lavas of the Pointe Verte Formation are late Llandeilian to early Caradocian in age (Fyffe, 1986). A radiometric date of 464 Ma (U-Pb) indicates that the coarse-grained gabbro and plagiogranite of the Devereaux Formation are Llandeilian-early Caradocian (van Staal *et al.*, 1988; Spray *et al.*, 1990).

Volcanic rocks in the Devereaux Formation include both tholeiites chemically similar to OFB with flat REE profiles ($(La/Yb)_N$ = 0.9), and HFSE-depleted basalts with LREE-enriched profiles ($(La/Yb)_N$ = 2.8) that are chemically transitional between OFB and IAT (Langton and van Staal, 1989). Such compositions, referred to as BAB, are typical of immature back-arc oceanic settings (Saunders and Tarney, 1984). By contrast, the pillow lavas of the Pointe Verte Formation are highly evolved OIA basalts and trachyandesites ($(La/Yb)_N$ = 6.7) associated with minor trachyte flows (Pajari *et al.*, 1977; Flagler, 1989), which may have been generated above a deep-seated mantle plume within the back-arc basin.

Geochemically similar rocks, comprising the Sormany Formation, occur structurally above a blueschist zone in the northernmost part of the Miramichi Highlands of New Brunswick (Figure 2). These rocks include an upper suite (Lincour basalt) of low-Cr, HFSE-depleted tholeiites (BAB) with gently sloping rare-earth element profiles ($(La/Yb)_N$ = 1.9) and a lower suite (Armstrong Brook basalt) of high-Cr, OFB-like tholeiites with flatter REE profiles ($(La/Yb)_N$ = 1.3) that are structurally underlain in the west by a high-Cr, OIA suite (Murray Brook basalt) (Figure 4f). Each of these suites resembles basalts from the Elmtree River inlier, and the Sormany Formation is, therefore, assigned to the Fournier Group (van Staal *et al.*, 1991).

The Bay of Islands ophiolite complex is preserved as four erosional remnants of a probable once-continuous thrust sheet overlying allochthonous Late Precambrian to Early Ordovician clastic sedimentary rocks on the western coast of Newfoundland (Figure 3). The Blow-Me-Down Mountain and North Arm Mountain remnants contain a complete ophiolite suite, whereas only the lower levels are preserved in the Lewis Hills to the southwest and on Table Mountain to the northeast. The basal peridotite tectonite section is up to 5 km thick and is overlain successively by 4 km of layered gabbro, 2 km of sheeted dykes, 300 m of pillow lava, and 200 m of sandstone and shale (Williams, 1971; Malpas, 1978). The gabbro unit has been dated as Tremadocian or Arenigian (501 Ma, Sm-Nd; 484 Ma, U-Pb) and plagiogranite near the top of the gabbro unit has been dated as early Arenigian (486 Ma, U-Pb) (Jacobsen and Wasserburg, 1979; Dunning and Krogh, 1985). Radiometric dates on amphibolites from the underlying metamorphic sole indicate that the Bay of Islands complex was obducted onto the Laurentian margin in the early Llavirnian (469 Ma, Ar-Ar; 464 Ma, K-Ar) (Dallmeyer and Williams, 1975; Archibald and Farrar, 1976; Dunning and Krogh, 1985; Jenner *et al.*, 1991). An Arenigian date (489 Ma, Ar-Ar) on the metamorphic sole of the St. Anthony ultramafic complex, located 300 km to the northeast on the Great Northern Peninsula, demonstrates that the obduction process was diachronous (Dallmeyer, 1977; Dunning and Krogh, 1985). Previously published geochemical data indicate an OFB-like composition for the Bay of Islands complex suggesting generation at either a major mid-oceanic-ridge or a mature back-arc spreading centre (Malpas, 1978; Suen *et al.*, 1979; Casey *et al.*, 1985); however, the local presence of depleted diabases (Casey *et al.*, 1985) (Figure 5e) and the recently recognized presence of transitional arc basalts (BAB) suggest proximity to an arc (Swinden, 1991; Jenner *et al.*, 1991). The highly deformed, early Tremadocian (508 Ma, 505 Ma, U-Pb) Little Port Complex, which occurs as a structural slice beneath the Bay of Islands Complex, may be a fragment of sub-arc ophiolite (Malpas *et al.*, 1973; Mattinson, 1975; Malpas, 1979; Jenner *et al.*, 1991).

The Annieopsquotch complex is the largest of several ophiolite fragments that extend in a belt from Buchans in central Newfoundland to the Long Range Mountains on the southwestern coast of Newfoundland. The complex is in fault contact with the Victoria Lake Group to the southeast and is intruded by tonalite plutons to the northwest. The southeast-facing ophiolite sequence begins with a narrow zone of interlayered pyroxenite, olivine gabbro, and anorthosite followed by a 2.3 km thick massive gabbro zone with local pods of plagiogranite near the top, a 1.5 km thick sheeted dyke zone, and a 1.5 km thick pillow lava zone. Two samples of plagiogranite yielded Arenigian (481 Ma, 478 Ma; U-Pb) crystallization ages. High TiO_2 contents (0.57-2.27%) and LREE-depleted patterns for diabasic dykes and pillow lavas are typical of OFB (Dunning and Chorlton, 1985; Dunning and Krogh, 1985; Dunning, 1987).

The Pipestone Pond complex of south-central Newfoundland is a west-facing ophiolite sequence that is disrupted by numerous faults; consequently, no single section contains a complete succession and only approximate thicknesses can be determined. The east-facing ophiolitic suite at Coy Pond is interpreted to be part of the same ophiolitic sheet. Peridotite tectonite up to 1.5 km thick in the lower part of the Pipestone Pond complex is overlain by about 700 m of interlayered pyroxenite and gabbro, followed by 2 km of massive gabbro intruded by mafic dyke swarms and pods of plagiogranite in the upper parts, and topped by 800 m of pillow lavas and minor tuffaceous sedimentary rocks (Swinden, 1988). A sample of the plagiogranite yielded a Tremadocian (494 Ma, U-Pb) crystallization age (Dunning and Krogh, 1985). Contacts between the Pipestone Pond complex and adjacent rocks to the east and west are faulted. Basalts from the complex have HFSE ratios and LREE-depleted patterns ($(La/Yb)_N$ = 0.7) similar to OFB. The associated diabases have much lower TiO_2 contents and very low concentrations of Zr, Y, Nb, and REE (Figure 5f) and were probably derived by melting of depleted sub-arc mantle during the initial stages of back-arc formation (Swinden, 1988). The OIT basalts of the Cold Spring Pond Formation, which are in fault contact with the Pipestone Pond complex, were presumably generated farther to the west in the same back-arc basin (Swinden, 1988).

CONTINENTAL-MARGIN BACK-ARC VOLCANIC ROCKS

The Miramichi Highlands of New Brunswick are underlain by a Lower to Middle Ordovician, bimodal volcanic suite, extending from Chaleur Bay in the northeast to near the Maine border in the southwest (Figure 2). These volcanic rocks, together with associated feldspathic wackes and varicoloured slates, constitute the Tetagouche Group. Brachiopods in a thin unit of limestone at the base of the Tetagouche Group are Arenigian in age (Neuman, 1984). Underlying quartz wackes and slates of the Miramichi Group (van Staal and Fyffe, 1991) have been interpreted as part of a clastic turbidite wedge deposited off the margin of Avalon (Schenk, 1971; Helmstaedt, 1971; Rast and Stringer, 1974).

The lower portion of the felsic volcanic suite in the Tetagouche Group of northern New Brunswick is dominated by greenschist-facies porphyritic flows containing abundant, large quartz and feldspar phenocrysts (Nepisiguit Falls Formation). A thin unit of chlorite schist and iron formation separates the coarsely porphyritic felsic rocks from fine-grained, sparsely feldspar-phyric and aphyric felsic flows, and minor intercalated mafic volcanic rocks that form the upper part of the suite (Flat Landing Brook Formation). The felsic pile was extruded in the latest Llanvirnian (468-466 Ma, U-Pb; van Staal and Fyffe, 1991). The felsic volcanic rocks of the Bathurst area range in composition from dacite to rhyolite with rhyolite being the most voluminous; andesites typical of volcanic-arc suites are virtually absent (Whitehead and Goodfellow, 1978a,b). The coarsely porphyritic felsic flows are highly LREE-enriched with a distinct negative Eu-anomaly (McCutcheon *et al.*, 1989). Intercalated mafic volcanic rocks range from LREE-enriched ($(La/Yb)_N$ = 3.5) low-Cr, Otter Brook basalts, similar to continental tholeiites, in the lower part of the felsic pile to high-Cr, Forty Mile Brook basalts with flat REE profiles ($(La/Yb)_N$ = 1.0), resembling OFB, in the upper part (Figure 4e) (van Staal *et al.*, 1991).

A thick sequence of pillow lavas generally structurally overlies the felsic volcanic pile in the Bathurst area. This mafic sequence is divisible on the basis of HFSE ratios into OIT and OIA suites (Figure 4e) (Whitehead and Goodfellow, 1978a,b; van Staal *et al.*, 1991). The Nine Mile Brook OIT suite has chemical similarities with Otter Brook basalts in the underlying felsic pile, except that it is characterized by lower Zr/Y ratios and displays less LREE enrichment ($(La/Yb)_N$ = 2.3). The OIT suite immediately underlies and is locally intercalated with the lower part of the OIA suite. The OIA suite — which includes the high-Cr, Canoe Landing Lake basalt; intermediate-Cr, Brunswick, Eighteen Mile Brook and Beresford basalts; and low-Cr, Camel Back basalt — is dominated by evolved alkalic basalts ($(La/Yb)_N$ = 6.3) with subordinate trachyandesites, trachytes, and comenditic lavas. This OIA suite is directly overlain by a blueschist-bearing, high-strain zone that separates the Tetagouche Group from previously described basalts of the Fournier Group. Fossils from crystalline limestone and black slate together with radiometric dates on associated trachyte (472 Ma, 457 Ma; U-Pb) indicate a late Arenigian to early Caradocian age for the alkaline suite (Skinner, 1974; Kennedy *et al.* 1979; Riva and Malo, 1988; van Staal *et al.*, 1991), which must, therefore, be in part laterally equivalent to the felsic volcanic rocks of the Tetagouche Group.

The felsic volcanic rocks and structurally overlying basalts of the Tetagouche Group are interpreted as the volcanic products of rift-related magmatism generated along a continental margin during opening of a back-arc basin in the Ordovician, as both possess chemical compositional ranges consistent with such a model. The contemporary basaltic rocks of the Fournier Group in the thrust sheet overlying the blueschist-bearing zone are interpreted as a fragment of back-arc ocean floor that was transported southward over the continental rift-sequence during closure of this basin (van Staal, 1987; van Staal *et al.*, 1990).

A belt of Ordovician sedimentary and volcanic rocks, referred to as the Cookson Group, underlies the St. Croix Highlands in southwestern New Brunswick. The relationships of the Cookson Group to the Cambro-Ordovician succession in the Miramichi Highlands to the northwest and to Precambrian Avalonian rocks to the southeast are obscured by intervening Silurian rocks (Fyffe and Riva, 1990). Pillow lavas interbedded with Tremadocian black shales at the base of the Cookson Group are evolved, mildly LREE-enriched, OIT basalts ($(La/Yb)_N$ = 1.3) that may have formed by back-arc rifting of continental crust in the Early Ordovician (Figure 4e) (Fyffe *et al.*, 1988).

The Baie du Nord Group along the Hermitage flexure of southwestern Newfoundland contains submarine felsic flows and tuffs and minor mafic tuffs intercalated with epiclastic sedimentary rocks. Radiometric dating yielded a Llanvirnian (466 Ma, U-Pb) age for a felsic tuff (Dunning *et al.*, 1990). The abundant felsic rocks and high titanium contents of the mafic tuffs are consistent with deposition within an ensialic back-arc basin (Wynne and Strong, 1984).

SUMMARY AND CONCLUSIONS

The generally systematic distribution of distinct Paleozoic volcanic suites across the northeastern Appalachian orogen (Figures 2 and 3) suggests that their relative spatial relationships have been maintained to some extent with respect to the Laurentian and Avalonian continental margins, despite considerable crustal shortening across, and transcurrent displacement along, the orogen. These suites include: (1) intraplate volcanic rocks erupted on the Laurentian platform, signifying that rifting of the continental margin began in the Late Proterozoic to Early Cambrian; (2) Early Ordovician ophiolites with overlying boninitic and primitive mafic volcanic-arc lavas, traceable from the Eastern Townships of Québec to the Baie Verte Peninsula of Newfoundland (Baie Verte-Brompton Line), delineating a possible collision zone between the Laurentian craton and intra-oceanic volcanic-arcs (Williams and St-Julien, 1982); (3) outboard mature volcanic-arc suites recording the consumption of oceanic crust between the Late Cambrian and Late Ordovician; (4) ophiolites with BAB-like chemistry indicating episodic formation of back-arc oceanic crust between the Early and Late Ordovician; and (5) extensive felsic volcanic rocks generated in rifts proximal to the Avalonian margin (van Staal, 1987; Evans *et al.*, 1990; Dunning *et al.*, 1991; O'Brien *et al.*, 1991). The relative influence of the respective continental margins in the generation of the volcanic suites appears to be reflected in the lead isotope signatures of their associated massive sulphide deposits. The Stoke Mountains and Buchans-Roberts Arm suites possess distinctly less radiogenic signatures compared to the Wild Bight-Victoria Lake, Hermitage and Miramichi suites, suggesting the influence of relatively non-radiogenic Laurentian crust in the former and more radiogenic Avalonian-like crust in the latter (Swinden and Thorpe, 1984; Swinden *et al.*, 1988).

A subduction zone dipping away from the Laurentian craton most readily accounts for the obduction of ophiolitic complexes onto the Grenvillian continental margin and for the formation of the Stoke Mountains and Buchans-Roberts Arm intra-oceanic arcs (Church and Stevens, 1971; St-Julien and Hubert, 1975; Searle and Stevens, 1984). The presence of boninites along the Baie Verte-Brompton Line to the northwest of these arcs supports such a model (Sun and Nesbitt, 1978; Pearce *et al.*, 1984). The existence of a separate, southeast-dipping subduction zone to generate the Little Port volcanic arc in Newfoundland (Searle and Stevens, 1984) would not be necessary if, as seems likely, considerable transcurrent displacement has occurred between the continental margin and the arc terrane subsequent to obduction (Webb, 1969; Goodwin and Williams, 1989).

Many of the volcanic arcs in Newfoundland are now known to be older than associated oceanic crustal remnants, implying that most of the ophiolite complexes were generated in back-arc basins (Dunning and Krogh, 1985; Dunning *et al.*, 1991) in accord with their BAB-like chemistry. The formation of young back-arc oceanic crust in the Fournier Group of northern New Brunswick may be related to delayed continental collision within the Québec Reentrant (van Staal, 1987; Stockmal *et al.*, 1987). The protracted history of arc and back-arc basin evolution, recorded by the disparate ages of the various arc and ophiolite sequences in the northeastern Appalachians, is unlikely to be related to a single subduction zone (Dunning *et al.*, 1991), and probably involved both arc-arc and continent-arc collisions. Additional information, particularly from detailed radiometric and paleomagnetic studies, will be required before the paleogeographic relationship between these volcanic suites can be reconstructed with some degree of confidence.

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