Stratigraphy and geochemistry of Ordovician volcanic rocks of the Eel River area, west-central New Brunswick

L.R. Fyffe

New Brunswick Department of Natural Resources and Energy, Geological Surveys Branch, P.O. Box 6000, Fredericton, New Brunswick E3B 5H1, Canada

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Early Paleozoic turbiditic sedimentary rocks and submarine volcanic-arc rocks in the Eel River area have been designated, respectively, as the Woodstock and Meductic groups and divided into six formations. The Woodstock Group includes interbedded Cambrian to Early Ordovician quartz wacke, sandstone, and shale of the Baskahegan Formation and overlying Early Ordovician silty mudstone and shale of the Bright Eye Brook Formation. The conformably overlying Meductic Group is divided into the Early Ordovician Porten Road Formation (mainly rhyolite), Eel River Formation (mainly andesite), and Oak Mountain Formation (basalt), and Late Ordovician Belle Lake Formation (feldspathic wacke and shale).

Pyroxene-bearing, low-silica andesite in the lower part of the Porten Road Formation is highly enriched in LREE and LFSE, and depleted in HFSE relative to MORB, evidence of subduction in a compressional-continental arc setting. The upper part of the Porten Road Formation comprises an interlayered sequence of quartz-rich rhyolite and quartz-poor dacite, likely derived from melting of continental crust. The Eel River Formation contains hornblende-bearing, high-silica andesite moderately enriched in LFSE. Calc-alkaline basalt from the overlying Oak Mountain Formation includes low- and high-alumina basalt varieties like those formed in an extensional-continental arc setting. Volcanic activity in the Meductic Group ceased in the later part of the Early Ordovician as the arc rifted and the subduction zone migrated northwestward with the opening of the Tetagouche back-arc basin.

Des roches d'un arc volcanique sous-marin et des roches sédimentaires turbiditiques du Paléozoïque inférieur du secteur d'Eel River ont été désignées, respectivement, groupes de Meductic et de Woodstock et ont été subdivisées en six formations. Le groupe de Woodstock comprend du schiste et du grès à wacke quartzifère interlités du Cambrien à l'Ordovicien inférieur de la Formation de Baskahegan ainsi que du schiste et du mudstone silteux sus-jacent de l'Ordovicien inférieur de la Formation de Bright Eye Brook. Le groupe sus-jacent concordant de Meductic se subdivise en trois formations de l'Ordovicien inférieur, celle de Porten Road (essentiellement de la rhyolite), celle d'Eel River (essentiellement de l'andésite) et celle d'Oak Mountain (basalte), et une formation de l'Ordovicien supérieur, la Formation de Belle Lake (wacke feldspathique et schiste).

L'andésite à faible teneur en silice qui renferme de la pyroxène dans la partie inférieure de la Formation de Porten Road est fortement enrichie en ETRL (éléments de terres rares légers) et en EFIC (éléments à faible intensité de champ) et pauvre en EHIC (éléments à haute intensité de champ) comparativement aux BDMO (basaltes de la dorsale médio-océanique), ce qui témoigne d'une subduction au cours de l'établissement d'un arc compressif-continental. La partie supérieure de la Formation de Porten Road comporte une séquence interstratifiée de rhyolite riche en quartz et de dacite pauvre en quartz provenant vraisemblablement de la fusion de la croûte continentale. La Formation d'Eel River renferme de l'andésite riche en silice à hornblende moyennement enrichie d'EFIC. Le basalte calco-alcalin de la Formation sus-jacente d'Oak Mountain comprend des basaltes à faible et forte teneur en alumine comme ceux formés lors de l'établissement d'un arc d'accrétion-continental. L'activité volcanique dans le groupe de Meductic a cessé vers la fin de l'Ordovicien inférieur lorsque l'arc s'est effondré et que la zone de subduction a migré vers le nord-ouest avec l'ouverture du bassin marginal de Tétagouche.

Traduit par la rédaction

INTRODUCTION

The Eel River area of west-central New Brunswick (Figs. 1, 2) is underlain by Ordovician volcanic rocks that provide important constraints on the Paleozoic tectonic history of the Appalachian orogen (van Staal and Fyffe 1995a). These volcanic rocks have been previously interpreted on the basis of limited geochemistry as a bimodal assemblage generated in a supra-subduction zone setting (Dostal 1989). However, additional data reported here, indicate that rocks of intermediate composition form a significant proportion of the volcanic pile, a feature characteristic of many modern volcanic arcs.

Stratiform sulphide and epithermal gold mineralization is commonly associated with volcanic-arc complexes and such is the case in the Eel River area. BHP Minerals Canada Ltd. drilled several holes south of Benton in the early 1990's (Fig. 2). These holes included intersections of base metal mineralization contained in massive sulphide clasts and as disseminations in pyroclastic breccias that assayed up to 0.4% Zn and 0.6% Pb over 4 m. Freewest Resources Canada Inc. drilled an altered dacitic plug that intrudes volcanic breccia on Poplar Mountain, approximately 15 km southwest of the base metal occurrences (Fig. 1); significant gold mineralization was

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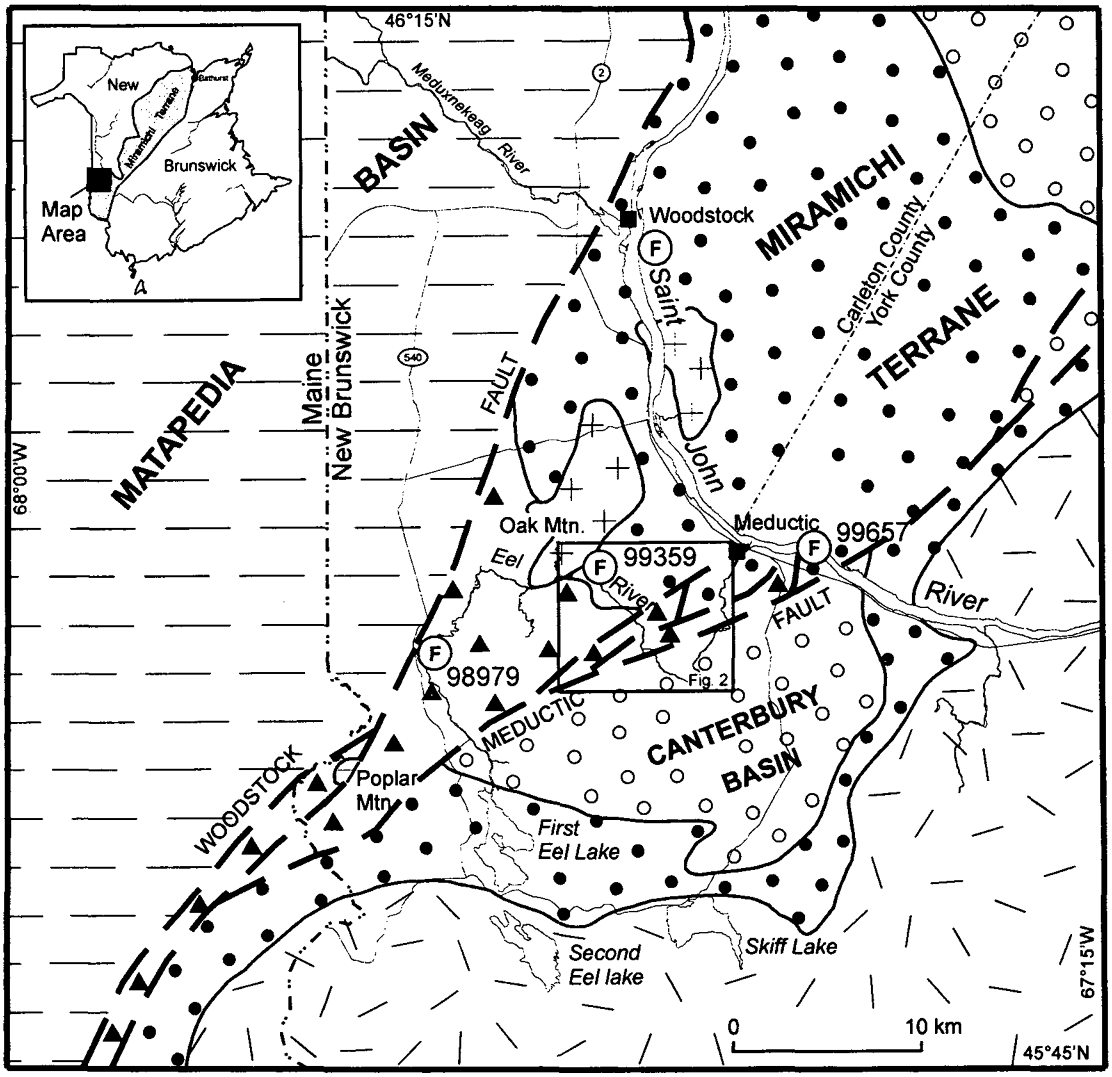

Fig. 1. Regional geological map of west-central New Brunswick and adjacent Maine (after Venugopal 1978, 1979, 1981: and Fyffe 1999). Dots = Cambrian-Early Ordovician Woodstock Group of Miramichi terrane: Triangles = Ordovician Meductic Group of Miramichi terrane; Crosses = Ordovician plutons. Horizontal Dashes = Late Ordovician–Silurian Matapedia basin: Circles = Siluro-Devonian Canterbury and Tobique basins: Random Dashes = Devonian Granite: Circled F = fossil locality.

intersected, the best assay yielding 4.03 g/t Au over 3.7 m. Because of its high mineral potential, a detailed geological survey at 1:10,000 scale was carried out in the Eel River area during the summer of 1999 in order to better document the volcanic stratigraphy.

The first breakthrough toward understanding the geological relationships in the Eel River area was made by Bailey in 1900 with the discovery of graptolites near Benton (Bailey 1901). Over half a century later, mapping by McAllister and Tupper (1957) broadly outlined the distribution of some of the volcanic rocks. More recently, a preliminary stratigraphic nomenclature for the volcanic sequence was introduced following geological surveys undertaken by Venugopal (1978, 1979) and Lutes (1979). However, the scale of mapping (one-inch to quarter-mile) at that time allowed only a rough division of the sequence into mafic and felsic units. The recognition of several new volcanic units during the bedrock mapping by Fyffe (1999) has required a substantial revision of the stratigraphic nomenclature. Samples were selected from the newly defined units for petrographic examination and chemical analysis to refine lithological classifications based on field observations.

Regional Tectonic Setting

The Eel River area is situated in west-central New Brunswick in the southwestern part of the Miramichi terrane (Fig. 1). The Miramichi terrane, an uplifted block underlying the axial region of the Province of New Brunswick, is characterized by a thick Cambro-Ordovician sequence of quartz-rich turbidites overlain by Ordovician volcanic rocks (Fyffe and Fricker 1987). The southwestern part of Miramichi terrane is flanked to the southeast by the Canterbury basin and to the northwest by the Matapedia basin (Fig. 2). The Canterbury basin contains shallow-water marine

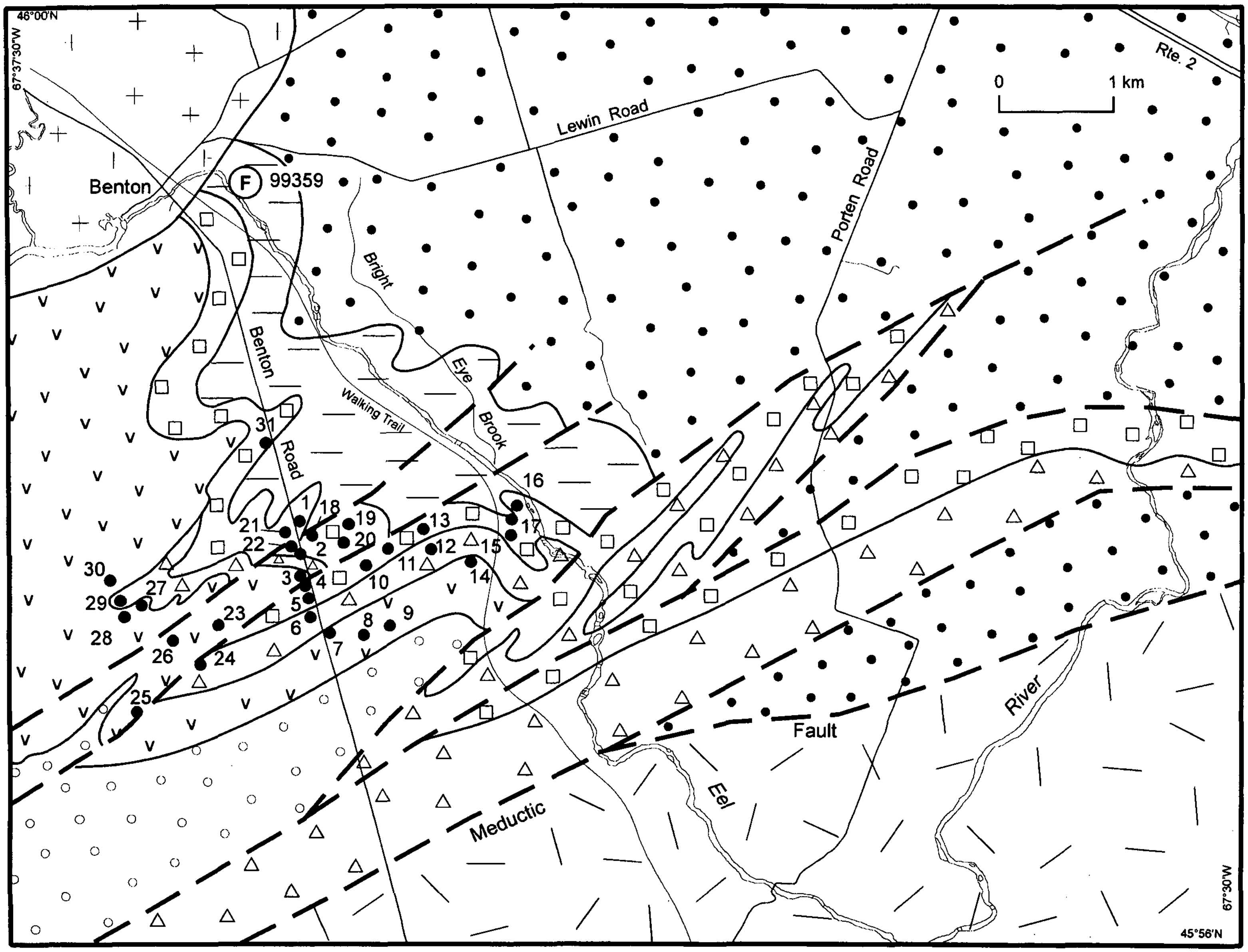

Fig. 2. Detailed geological map of the Eel River area with sample locations. Woodstock Group: Dots = Baskahegan Lake Formation; Horizontal Dashes = Bright Eye Brook Formation. Meductic Group: Squares = Porten Road Formation; Triangles = Eel River Formation; Chevrons = Oak Mountain Formation; Circles = Belle Lake Formation. Crosses = Benton Pluton. Random Dashes = Siluro-Devonian sedimentary and volcanic rocks. Circled F = fossil locality. Location of area is outlined on Fig. 1.

conglomerate, limestone, calcareous sandstone, and volcanic rocks of Siluro-Devonian age (Rast *et al.* 1980); its boundary with the Miramichi terrane is marked by the Meductic fault but an unconformable relationship is preserved in places. The Matapedia basin comprises deep-water, marine argillaceous carbonate rocks (Carys Mills Formation) and siliciclastic turbidites (Smyrna Mills Formation) of Late Ordovician to Late Silurian age (Bourque *et al.* 1995); its boundary with the Miramichi terrane is marked by the Woodstock fault. Strata within the Miramichi terrane are more complexly folded than those in the adjoining basins.

Detailed description of geological relationships in the Miramichi terrane, particularly with regard to the Bathurst area of northern New Brunswick, are given in van Staal and Fyffe (1991, 1995a, 1995b), Fyffe *et al.* (1997), and Wilson *et al.* (1998). In the Bathurst area, the Cambro-Ordovician sedimentary sequence beneath the volcanic rocks is referred to as the Miramichi Group (Fig. 3). The Miramichi Group is subdivided into a lower unit of thick-bedded quartzite (Chain of Rocks Formation), a middle unit of medium-bedded quartzite and shale (Knights Brook Formation), and an upper unit of medium-bedded, feldspathic wacke and shale (Patrick Brook Formation). Early to Middle Ordovician volcanic rocks unconformably overlying the Miramichi Group are included in the Tetagouche Group. The Tetagouche Group is subdivided into a lower unit of coarse quartz-feldspar crystal tuff and iron formation (Nepisiguit Falls Formation), a middle unit of aphyric to sparsely feldspar-phyric rhyolite flows (Flat Landing Brook Formation) and an upper unit of pillow basalt, basalt breccia, maroon ferro manganiferous siltstone and black shale (Little River Formation). Beds of conglomerate and sandy limestone at the base of the Nepisiguit Falls Formation contain rounded pebbles derived from the underlying Patrick Brook Formation. Conodonts from the limestone and brachiopods from associated calcareous siltstone, together with U-Pb dating of the crystal tuff, indicate that the Nepisiguit Falls Formation is late Arenigian in age; graptolites from black shale of the Little River Formation are late Caradocian in age. The bimodal volcanic rocks of the Tetagouche Group have been interpreted on the basis of their geochemical composition to have been generated in a back-arc basin (van Staal 1987; van Staal *et al.* 1991).

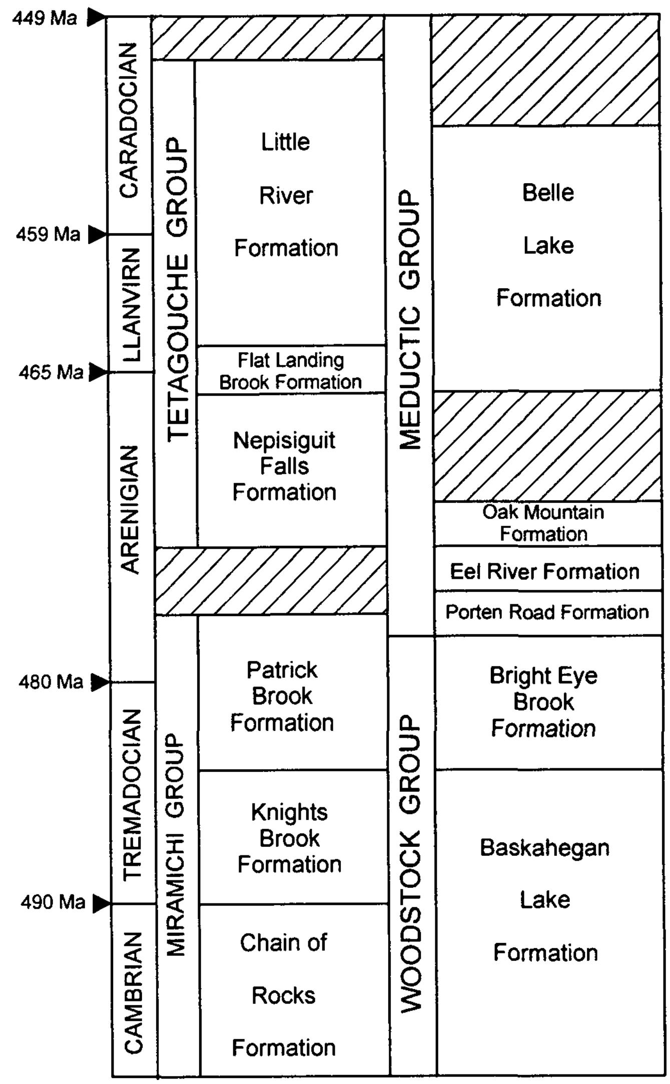

Fig. 3. Stratigraphic columns comparing Cambrian-Ordovician rock formations of the Miramichi terrane in west-central and northern New Brunswick. Absolute age of boundaries from McKerrow and van Staal (2000).

Stratigraphy of the Eel River area

In their synthesis of the early Paleozoic tectonic evolution of the Appalachian orogen within New Brunswick, van Staal and Fyffe (1991, 1995a, 1995b) included strata in the southwestern part of the Miramichi terrane in the Miramichi and Tetagouche groups, based on broad similarities to the sedimentary and volcanic sequences of the central and northern Miramichi Highlands. However, significant differences in detail occur between lithological components and contact relationships in the southwest compared to those in the central and northern regions. Moreover, as the southwestern part is fault-bounded and separated from the remainder by Siluro-Devonian sedimentary and volcanic strata of the Tobique basin to the northeast (Fyffe 1982a, 1982b) it is not possible to demonstrate stratigraphic continuity along the axis of the Miramichi terrane (Fig. 1). Formations mapped in the Eel River area by Fyffe (1999) are accordingly assigned to the newly established Woodstock and Meductic groups (Fig. 2) and described below under those headings.

Woodstock Group

Quartz-rich sedimentary strata within a fault-bounded triangular block, extending from the Nackawic River in York County, New Brunswick, southwestward for 75 km to the Baskahegan Lake area in the State of Maine, are herein named the Woodstock Group. These rocks were previously assigned to the lower part of the Tetagouche Group and considered to be a characteristic defining feature of the Miramichi terrane (Fyffe 1982b; Fyffe and Fricker 1987). Subsequently, the pre-volcanic part of the Tetagouche Group in northern New Brunswick was designated as the Miramichi Group and this terminology was extended to include quartzose turbidites of the Woodstock area (van Staal and Fyffe 1991, 1995a). These strata are herein named the Woodstock Group and include the previously defined Baskahegan and Bright Eye Brook formations. Features that distinguish the Woodstock Group of west-central New Brunswick from the Miramichi Group of northern New Brunswick are noted below.

Baskahegan Lake Formation

A thick succession of Cambro-Ordovician sandstone and shale in west-central New Brunswick was mapped at 1:63,390 scale by Anderson (1968) and in more detail at 1:15,480 scale by Venugopal (1979, 1981). This unnamed sequence includes light grey to light green, medium- to thick-bedded quartzite, grey to greenish grey, thin- to medium-bedded quartz wacke, olive-green silty shale and minor red sandstone and shale. The wacke beds are normally graded with laminated tops and locally exhibit load casts, current ripples, and flame structures. Such sedimentary features can best be observed in outcrops along Rte. 105 on the east side of the Saint John River from 1 to 5 km south of Woodstock in southern Carleton County, New Brunswick (Fig. 2). These easily accessible road exposures are therefore designated as the type-section. It should be noted that red sandstone and shale are unknown in the Miramichi Group of the Bathurst area.

The continuation of this belt of rocks into adjacent Maine is referred to as the Baskahegan Lake Formation (Ludman 1991; Ludman *et al.* 1993) and this terminology has been adopted in New Brunswick by Pickerill and Fyffe (1999). The base of the Baskahegan Lake Formation is not exposed either in New Brunswick or Maine. Lithologically similar quartz wacke-red shale beds are found in the Grand Pitch Formation to the northwest in central Maine. On the basis of this tentative correlation and the presence of the trace fossil *Oldhamia* in the red shale of the Grand Pitch Formation (Neuman 1984), the Baskahegan Lake Formation is likely partly Early to Middle Cambrian in age. However, the recent discovery of the trace fossil *Circulichnus montanus* in the Baskahegan Lake Formation south of Woodstock suggests that the upper part of the section is as young as Ordovician (Pickerill and Fyffe 1999).

Bright Eye Brook Formation

Dark grey to black silty mudstone and black shale that occur along Eel River southeast of Benton and on Rte. 2 southeast of Meductic (Fig. 2) have been named the Bright Eye Brook Formation by van Staal and Fyffe (1991, 1995a). Low-lying outcrops that are exposed intermittently on the banks of Eel River on the border between Carleton and York counties (NTS 21 G/13E) for a distance of 1.5 km upstream from its confluence with Bright Eye Brook are designated as the type-section. The section is only slightly oblique to strike and can best be viewed during the later part of summer when water levels in the river are at their lowest. Open folds plunging steeply to the southwest produce minor variations in bedding trend. Bedding in the mudstone is marked by 1–10 mm-thick laminations of light greyish brown silt separating 5 cm-thick intervals of dark grey to black silty mud. Black shale beds, which are less common in the section, are highly carbonaceous and pyritiferous. The Bright Eye Brook Formation is estimated to be 200 m thick using a dip of 80° in the section on Rte. 2. It appears to be much thicker (800 m using an average dip of 60°) in the Eel River section but this may be at least in part due to repetition by folding.

Grading in sandstone near the contact indicates that the Baskahegan Lake Formation underlies the mudstone and shale of the Bright Eye Brook Formation. The contact is poorly exposed on Rte. 2, but appears to be gradational, with both the proportion and bed thickness of the sandstone decreasing rapidly up-section over several tens of metres. Similarly, sandstone of the Baskahegan Lake Formation, near the contact with the Bright Eye Brook Formation about 1.5 km downstream on Eel River from Benton, displays bed thicknesses ranging from 2 to 20 cm compared to thicknesses of 15–100 cm typical of the lower part of the stratigraphic section. Graptolites in black shale of the Bright Eye Brook Formation on Eel River near Benton (GSC loc. 99359; Fig. 2) are late Tremadocian in age (Bailey 1901; Fyffe *et al.* 1983) whereas those found on Rte. 2 (GSC loc. 99657; Fig. 1) are early Arenigian (Pickerill and Fyffe 1999).

The Bright Eye Brook Formation of the southwestern Miramichi terrane is the age equivalent of the Patrick Brook Formation in the Bathurst area of the northern Miramichi terrane (see Regional Tectonic Setting above). However, the lithologic components of the two units are quite distinct; the former is largely mudstone whereas the latter is mainly feldspathic wacke. Moreover, the mudstone and shale of the Bright Eye Brook Formation have a unique trace-element geochemical signature that distinguishes them from shale of the Patrick Brook Formation (Fyffe and Pickerill 1993; Fyffe 1994; Hennessy and Mossman 1996). These differences justify removing the Bright Eye Brook Formation and conformably underlying Baskahegan Lake Formation from their previous assignment to the Miramichi Group and placing them in the newly established Woodstock Group. Furthermore, the gradational nature of the lithological and geochemical profiles through black shale and mudstone of the Bright Eye Brook Formation on Rte. 2, 2 km southeast of Meductic (Fig. 1), into overlying iron formation and volcanic rocks of the Meductic Group (Hennessy and Mossman 1996) suggests a conformable relationship, in contrast to the unconformity observed between the Miramichi and Tetagouche groups in the central and northern parts of the Miramichi terrane.

Meductic Group

Venugopal (1978, 1979) informally referred to Ordovician felsic and mafic volcanic rocks in the Eel River area as the Pocomoonshine Volcanics and overlying Ordovician sedimentary rocks as the Belle Lake Slates. The former geographic term has since become established in the published literature as a designation for a Silurian gabbro complex in adjacent Maine (West *et al.* 1992). As a consequence, van Staal and Fyffe (1991, 1995a) included these volcanic rocks in the newly introduced Oak Mountain Formation. In the present investigation, three units composed predominantly of felsic, intermediate and mafic volcanic rocks, respectively, have been mapped separately and each has been given formational status. It is felt appropriate that the Oak Mountain Formation be retained specifically for the mafic unit that underlies Oak Mountain and new names have been added to designate the felsic (Porten Road Formation) and intermediate (Eel River Formation) volcanic units. The Meductic Group is introduced herein as a broad term to encompass both the volcanic (in ascending order, the Porten Road, Eel River, and Oak Mountain formations) and overlying sedimentary rocks (Belle Lake Formation) that succeed the Woodstock Group.

The presence of early Ordovician (late Tremadocian to early Arenigian) graptolites in the underlying Bright Eye Brook Formation of the Woodstock Group (see above) and Late Ordovician (early Caradocian) graptolites in the overlying Belle Lake Formation of the Meductic Group (see below) restricts the depositional range of the volcanic components (Porten Road, Eel River, and Oak Mountain formations) of the Meductic Group to between early Arenigian and Llanvirnian time. The depositional period of the volcanic sequence of the Meductic Group, therefore, likely overlapped that of the Patrick Brook Formation of the Miramichi Group and Nepisiguit Falls Formation of the Tetagouche Group (Fig. 3). Granitic rocks of the Benton pluton, intruded into basaltic rocks of the Oak Mountain Formation west of Benton (Fig. 1), have been dated radiometrically by U-Pb in zircon as 479 ± 7 Ma (Whalen *et al.* 1998) and further constrain the age of the latter. According to the Paleozoic time-scale of McKerrow and van Staal (2000), the age of this granite indicates that volcanic activity in the Eel River area was limited to the early to mid-Arenigian. A hiatus in the section, marked by apparent absence of late Arenigian rocks, is therefore postulated to separate the volcanic from the overlying sedimentary rocks of the Meductic Group (Fig. 3).

Porten Road Formation

Various volcanic facies including massive porphyritic rhyolite, porphyritic rhyolite breccia, dacite breccia, and minor andesite breccia and flows have been recognized in the newly defined Porten Road Formation. The presence of tight folds with faulted limbs and scarcity of outcrop make it difficult to ascertain the lateral and vertical stratigraphic relationships between many of these facies. A tentative interpretation of these relationships is given below based on field observations, petrographic examinations and lithogeochemical analyses. However, further detailed mapping and examination of exploration drill core may lead to some modification and refinement of the stratigraphy presented herein. Nonetheless, it is hoped that these preliminary results will provide a guideline for future geological investigations in this area of high potential for base and precious metals.

Massive porphyritic rhyolite

The designated type section of the Porten Road Formation is located on the Porten Road, 2 km south of its intersection with the Lewin Road, in southern Carleton County, New Brunswick (NTS 21 G/13 E). In this section, massive, light greyish pink, porphyritic rhyolite with conspicuous quartz phenocrysts, 2–3 mm in size, and pink feldspar phenocrysts, 1–2 mm in length, is exposed in the road bed over a distance of 100 m. Its concordant nature to the overlying stratigraphy (see below) suggests that the massive rhyolite represents a thick flow or sill, possibly proximal to a volcanic dome. Venugopal (1979) reported that the rhyolite contains plagioclase, alkali feldspar, and embayed quartz phenocrysts set in a partially sericitized, aphanitic groundmass; a late phase of devitrification is indicated by oval patches of radiating plagioclase scattered throughout the finer groundmass. The base of the Porten Road Formation is not exposed on Porten Road, but shearing and brecciation in the nearby quartzose sedimentary rocks of the Baskahegan Lake Formation and absence of the Bright Eye Brook Formation in the section suggest that the contact with the underlying rocks is a fault.

Porphyritic rhyolite breccia

In other locations, the rhyolitic rocks that typify the Porten Road Formation exhibit features that are clearly of extrusive rather than possible subvolcanic origin. On Eel River, 2 km southeast of the Porten Road type-locality, massive light greyish green porphyritic rhyolite (Fig. 4a) with phenocrysts of quartz and feldspar varies to a monomictic breccia containing angular porphyritic felsic clasts from 2 to 10 cm in size that are barely discernable from the host rock. This texture is interpreted to have resulted from fragmentation of felsic lava as it flowed and solidified in a submarine environment to form an *in situ* hyaloclastic breccia (Cas 1992; McPhie et al. 1993). A few interbeds of dark grey shale and maroon iron formation attest to deposition of these volcanic rocks in a relatively deep marine setting. The total thickness of the rhyolite breccia along Eel River is estimated to be about 300–400 m.

Rhyolite breccia on Benton Road and wood roads trending east, 3.5 km south of the village of Benton, contains a greater variety of clast types than that to the east on Eel River. Comprising from 10 to 20% of the rock, fragments (1–15 cm in size) include greyish pink aphyric and porphyritic felsic volcanic rocks, dark grey mudstone, greyish green amygdaloidal mafic volcanic rocks, and rare clasts of massive sulphides. Although no shards were observed, an explosive, pyroclastic origin for this breccia is suggested by the abundance of broken quartz crystals in its matrix. As none of the included sedimentary fragments exhibit features that would indicate derivation from either a shallow marine or terrestrial source, the polymictic rhyolite breccia is interpreted to represent syn-eruptive debris flows deposited along the flanks of submarine felsic domes (Cas 1992). Such an origin for the polymictic breccia is consistent with its spatial and temporal association with the massive and *in situ* hyaloclastic facies noted above. Some stratified volcaniclastic intervals in the polymictic breccia, ranging from 50 cm to a few metres thick, may represent the finer fraction of pyroclastic material derived from the same, presumably submarine source. Flows of very fine-grained, black, feldspar-phyric rhyolite are locally interlayered with the breccia.

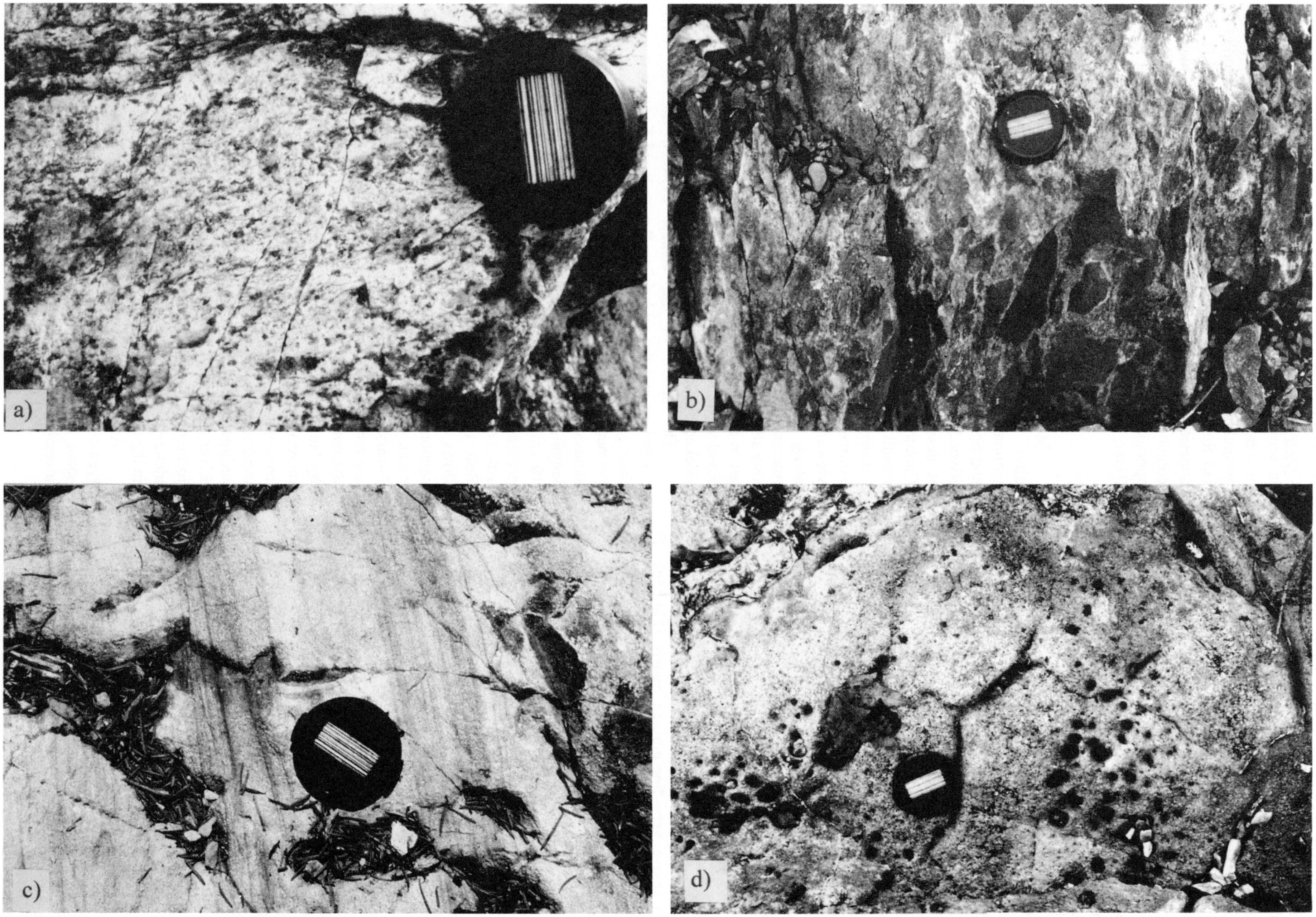

Fig. 4. Field photographs of volcanic rocks from the Meductic Group. a) quartz-phyric rhyolite of Porten Road Formation on Eel River, 700m below Bright Eye Brook; b) andesite breccia of Porten Road Formation on Benton Road, 3 km south of Benton (ER-1); c) stratified volcaniclastic rocks in Eel River Formation west of Benton Road (ER-28); d) amygdaloidal basalt flow, Oak Mountain Formation west of Benton Road (ER-23).

Quartz phenocrysts comprise 10–20% of the rhyolite breccia in Benton Road area, typically range from 1 to 2 mm in size, and vary from round and embayed to angular remnants of shattered grains indicative in part of an explosive origin (Fig. 5a). Feldspar phenocrysts comprise 10–15% of the rock, are subhedral in shape, commonly occur in clusters, and typically range from 1 to 1.5 mm in length. Alteration of the feldspars to epidote, calcite and titanite tends to render identification difficult but plagioclase phenocrysts appear to be more plentiful than alkali feldspar. The groundmass in some of the rhyolite examined microscopically comprises either flow-aligned feldspar microlites, or a very fine-grained, granular, quartzo-feldspathic mosaic, extensively replaced by sericite. Alkali feldspar laths up to 4 mm in length with patch perthite texture (Fig. 5b) are abundant in the rhyolite breccia on Eel River, where they occur in association with sparse blades of biotite partially altered to chlorite.

Dacite breccia

About 100 m of light greyish green porphyritic dacite breccia, intercalated with porphyritic rhyolite in the Benton Road area, 3 km south of the village of Benton, is included in the Porten Road Formation. The dacite contains significantly fewer quartz phenocrysts than the rhyolite but is otherwise difficult to distinguish from it; dacite is distinguished from andesite (see below) by the presence of quartz phenocrysts (Gill 1981). Fragments in the dacite breccia are angular and vary from 1 to 15 cm in size; they include abundant greyish green dacite, and scattered, accidental clasts of pale pink porphyritic rhyolite, light green chert and dark grey siltstone, all set in a sparse very fine-grained matrix (Fig. 5c). The dacite fragments contain between 30–40% plagioclase phenocrysts (1–2 mm in length) commonly occurring in clusters, and rare quartz phenocrysts (0.4–3 mm in size). The fragments were apparently derived from lava flows, as plagioclase microlites in their groundmass commonly exhibit weak flow-alignment. Similar dacite is interlayered with rhyolite in exploration drill holes about a kilometre farther east, indicating that the two compositional varieties of breccia were emplaced essentially contemporaneously, likely as syn-eruptive debris flows given the angularity of the fragments (Cas 1992).

Andesite breccia

A 250 m-thick unit of andesite breccia, found between black shale of the Bright Eye Brook Formation, and the dacite and rhyolite described above, appears to be restricted to the Benton Road area. Contacts with the adjacent units are not exposed. The breccia is typically composed largely of dark grey to medium greyish green andesite fragments ranging in size from 1 to 7 cm (Fig. 4b). The jigsaw-fit of the angular fragments suggests that brecciation took place *in situ* by quenching of lava in an aqueous environment (Cas 1992; McPhie *et al.* 1993). Large clasts of medium grey siltstone, common in exposures east of the Benton Road nearer the contact with the Bright Eye Brook Formation, were presumably incorporated into the hyaloclastic breccia as it spread onto the sea floor. The andesite fragments are generally porphyritic with up to 15% plagioclase phenocrysts, 1–1.5 mm in length, set in a matrix of plagioclase microlites. Clinopyroxene phenocrysts about 0.7 mm in size are preserved in some fragments. Titanite, calcite, epidote and chlorite are common alteration products of both phenocrysts and groundmass. The breccia matrix is compositionally similar to, but finer grained than, the enclosed fragments (Fig. 5d). The andesite breccia in the Benton Road area may be contemporaneous with andesite flows that can be traced in sporadic exposures as far as the north-flowing tract of Eel River, 5 km to the east.

Eel River Formation

Massive andesite breccia, stratified volcaniclastic rocks, olive green, and maroon ferro-manganiferous mudstone, laminated maroon iron formation, dark grey silty sandstone, and black silty mudstone are included in the newly defined Eel River Formation. The type-section of the Eel River Formation is designated as those exposures on Eel River in southern Carleton County (21 G/13 E), beginning 1.1 km below the mouth of Bright Eye Brook and continuing downstream for approximately 500 m. Only the lower part of the Eel River Formation is represented along the river; the upper part is best viewed along Benton Road (Fig. 2). The Eel River Formation along Benton Road and adjacent woods roads comprises an intercalated succession of light grey to greyish green, massive andesite breccia and stratified volcaniclastic rocks, and olive green and maroon ferro-manganiferous mudstone. The Benton Road section dips about 75° to the south and has an estimated thickness of approximately 250 m.

The nature of the contact between the Eel River Formation and the underlying Porten Road Formation varies throughout the region. In the section on Porten Road, it is defined as the base of a bed of medium grey, volcaniclastic sandstone containing clasts of plagioclase, about 1 mm in length, and angular fragments of porphyritic rhyolite from 1 to 10 cm in size; a few clasts of flow-banded rhyolite are also present. The matrix-supported nature of the fragments in the volcaniclastic sandstone suggests deposition as a distal debris flow that incorporated material from the underlying felsic flows of the Porten Road Formation. In the Eel River type-section, as noted below, beds of nodular mudstone are the first rocks encountered above the rhyolite of the Porten Road Formation; the very lowest beds of the Eel River Formation are not seen in this section. About a kilometre along strike to the northeast and southwest of the river, the contact is marked by laminated, maroon and light green iron formation, and in more continuous exposures to the west on Benton Road, by ferro-manganiferous, maroon, olive green, and dark grey mudstone in beds from 1 to 5 cm thick. These various sedimentary sections, which serve to define the base of the Eel River Formation, whether nodular mudstone, laminated iron formation, or ferro-manganiferous mudstone, are apparently along-strike facies equivalents of the coarse debris flow seen in the type-section of the Porten Road Formation.

As the section on Eel River has been designated as the type-section of the Eel River Formation, it is described in some detail below, although it was not sampled during this investigation. A petrographic description of sampled andesite

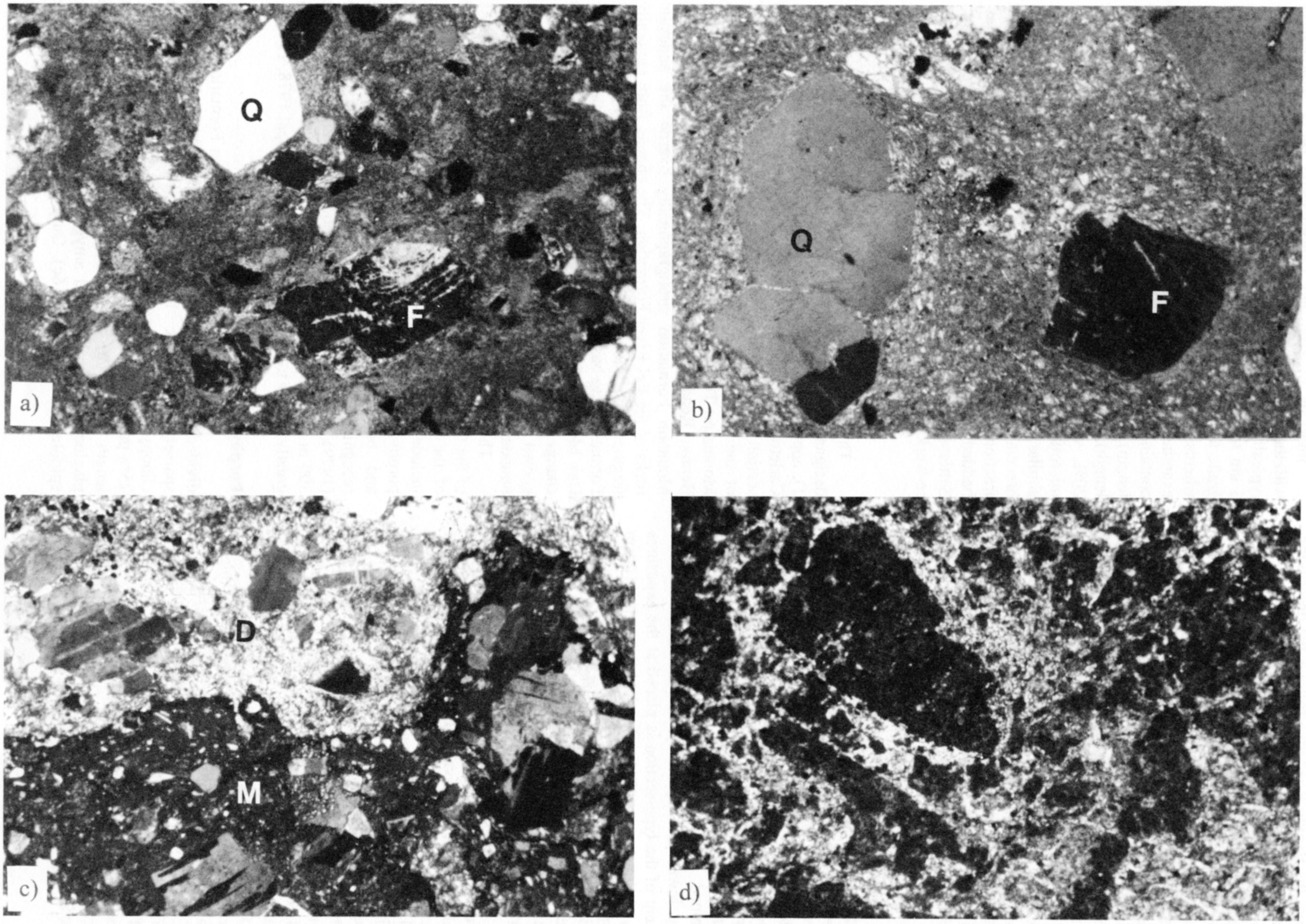

Fig. 5. Photomicrographs of volcanic rocks from the Porten Road Formation (field of view is 7 mm): a) rhyolite with crystals of angular quartz (Q), and saussuritized feldspar (F), set in very fine-grained quartzofeldspathic groundmass. Sample ER-20; b) rhyolite fragment containing phenocrysts of quartz (Q) and alkali feldspar (F). Sample ER-16; c) dacite containing irregular-shaped dacite fragment (D) with plagioclase and rare quartz phenocrysts (top), enclosed in a very fine-grained matrix (M) with angular crystals of plagioclase. Sample ER-31; d) andesite breccia containing irregular-shaped, saussuritized andesite fragments enclosed in a sparse, very fine-grained, siliceous matrix. Sample ER-19.

breccia and stratified volcaniclastic rocks of the Eel River Formation from the Benton Road area follows the description of the type-section.

Type-section description

The lowest beds exposed in the Eel River Formation along Eel River, as seen on the east bank on the upstream side of a large island, comprise dark greyish green silty mudstone, containing calcareous nodules from 3 to 5 cm in size. The nodular mudstone dips 80° to the south and is interpreted to overlie porphyritic rhyolite breccia of the Porten Road Formation, exposed 100 m farther upstream. The mudstone is interbedded with, and overlain by, medium green stratified volcaniclastic rocks. On the downstream tip of the island, dark grey silty sandstone contains oblong volcaniclastic fragments (3–5 cm in length) that suggest re-sedimentation of some of the stratified volcaniclastic rocks within coarse debris flows. Black, pyritiferous, silty mudstone is encountered 50 m farther downstream.

Another section of porphyritic rhyolite breccia of the Porten Road Formation is next encountered downstream along Eel River after a 100 m gap in exposure. The unexposed contact between black mudstone of the Eel River Formation farther upstream (see previous paragraph) and this rhyolite breccia is inferred to be faulted, judging from extensive quartz veining in the rhyolite. Rhyolite of the Porten Road Formation continues for another 100 m downstream and is followed after a gap of 50 m by greyish green silty mudstone interlaminated with fine-grained, greyish brown sandstone inferred to again represent the lower part of the Eel River Formation. The southern extent of the type-section is placed at the exposures of light greyish green, stratified volcaniclastic rocks, 100 m farther downstream on the west bank of the river; bed thicknesses in the volcaniclastic rocks varies from 1 to 2 m. As neither its top nor base is exposed along Eel River, only a minimum thickness of 200 m can be estimated for the Eel River Formation in this section.

Andesite breccia

Very thick, massive intervals of greyish green andesite breccia are exposed along Benton Road and on woods roads to the east and west. The breccia contains sparse to abundant, light grey, fine-grained, angular, amygdaloidal, porphyritic to aphyric andesite fragments from 1 to 20 cm in size set in a very fine-grained, feldspathic matrix (Fig. 6a, b). Black porphyritic rhyolite fragments derived from the underlying Porten Road Formation are present locally. Phenocrysts in the light grey andesite fragments typically include about 50% euhedral plagioclase (0.4–2 mm in length), 10% clinopyroxene (0.4–0.7 mm in length), 10% brown hornblende (0.4–0.8 mm in length), and 5% quartz (1 mm in size) set in a groundmass of flow-aligned, plagioclase microlites. The andesite breccia was clearly deposited in a marine environment as indicated by the intercalated ferro-manganiferous sedimentary rocks. The angularity of the fragments tends to suggest deposition as syn-eruptive, rather than as re-sedimented, debris flows (Cas 1992; McPhie *et al.* 1993).

Stratified volcaniclastic rocks

Intervals of stratified volcaniclastic rocks interlayered with the massive breccia sequence in the Benton Road area are typically only a few metres thick. Individual beds range from 3 cm to about 1 m in thickness (Fig. 4c). The thicker beds grade from a coarse base to a fine laminated top 2–5 cm thick whereas grading in thinner beds is more subtle. Microscopic examination of a coarser fraction of these beds show it to contain from 40 to 65% plagioclase phenoclasts (1–2 mm in length), about 5% clinopyroxene phenoclasts (0.4–0.7 mm in length), rare quartz phenoclasts (0.5–1 mm in size), and 10–20% volcanic clasts displaying flow-aligned plagioclase microlites. These stratified volcaniclastic rocks are thus very similar in mineralogy to the associated syn-eruptive andesite breccia and likely represent a finer, more distally transported fraction of the latter. Slump folds are present in medium-bedded volcaniclastic rocks exposed 800 m west of Porten Settlement and indicate some down-slope redistribution and re-working of the syn-eruptive deposits.

Oak Mountain Formation

The type-section of the Oak Mountain Formation is designated herein as those exposures on Oak Mountain (Fig. 1), approximately 3 km northwest of Benton in southwestern Carleton County, New Brunswick (NTS 21G/13E). This section is accessible from a new woods road running west off of the Oak Mountain Road along the north side of Oak Mountain. Tops from local pillow structures west of the Benton Road indicate that the basaltic rocks of the Oak Mountain Formation stratigraphically overlie the andesitic rocks of the Eel River Formation. The change from generally fragment-rich andesite breccia of the underlying Eel River Formation into basaltic rocks marks the lower boundary of the Oak Mountain Formation. However, the actual nature of this change, rather abrupt or interbedded and gradational, is not known due to the lack of continuous outcrop across the boundary.

The descriptions given below apply to the basaltic rocks of the Oak Mountain Formation exposed to the east and west of the Benton Road, about 4 km south of Benton. These include abundant dark green, fine-grained, amygdaloidal, porphyritic basalt flows, and lesser pillow lava, basalt breccia and bedded hyaloclastite. These facies have all been recognized in the Oak Mountain type-area by Venugopal (1979). The Oak Mountain Formation is estimated to be about 300 m thick in the Benton Road area but apparently thickens greatly farther to the west and north (Venugopal 1978, 1979).

Porphyritic basalt flows

Basalt flows in the Oak Mountain Formation can be divided into sparsely and highly porphyritic facies. The sparsely porphyritic facies contains 5–20% dark green clinopyroxene phenocrysts from 1 to 5 mm in size, and 10–25% pale green plagioclase phenocrysts from 0.5 to 3 mm in length set in a groundmass that includes flow-aligned plagioclase microlites and amygdules infilled with chlorite, epidote and calcite (Fig. 6c). Only a few pillow lavas were

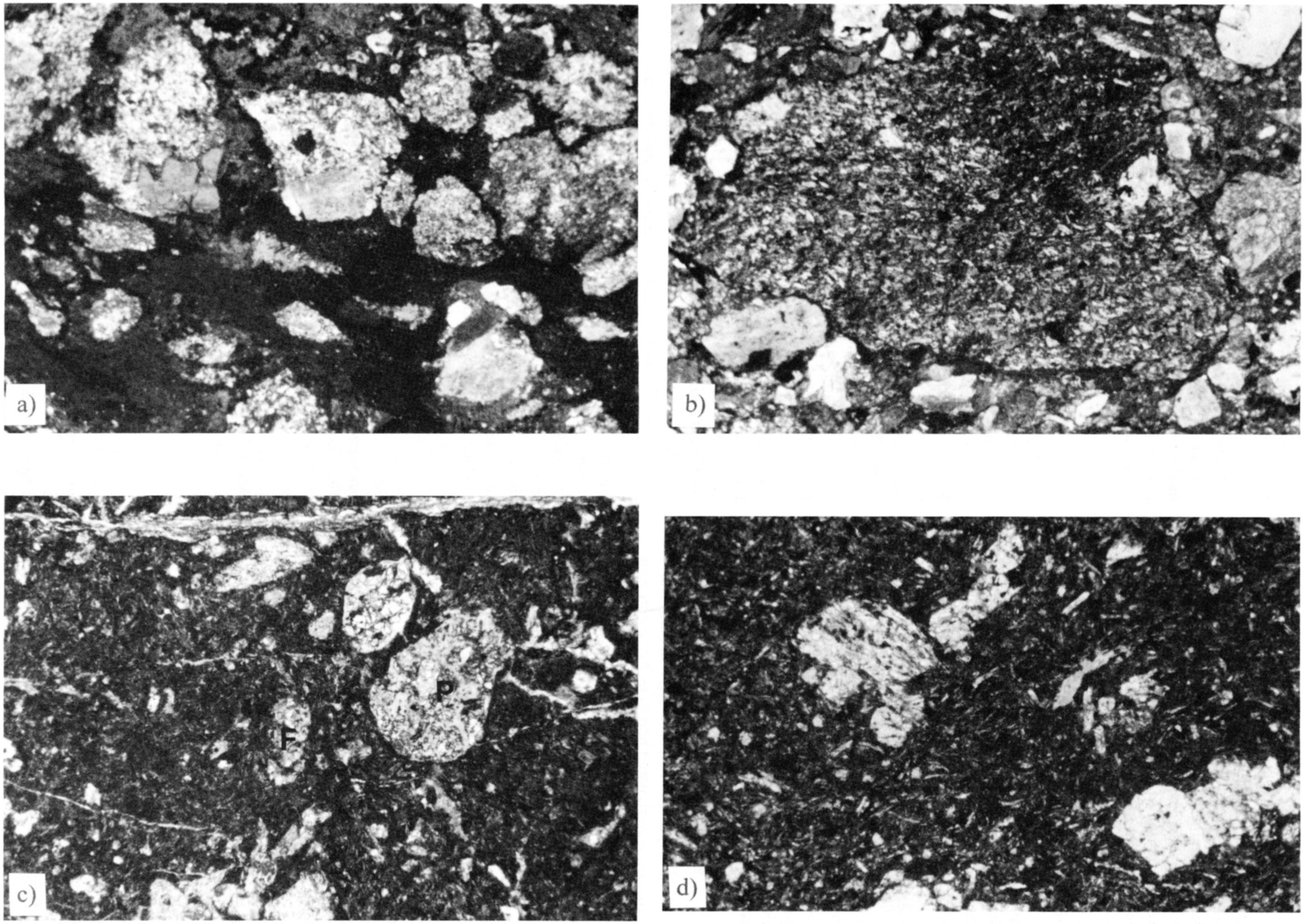

Fig. 6. Photomicrographs of volcanic rocks from the Eel River and Oak Mountain formations (field of view is 7 mm): a) andesite breccia of Eel River Formation containing plagioclase-phyric andesite fragments enclosed in fine-grained feldspathic matrix. Sample ER-12: b) andesite breccia of Eel River Formation containing rare aphyric andesite fragment with trachytic texture surrounded by close-packed. plagioclase-phyric andesite fragments. Sample ER-6: c) basalt of Oak Mountain Formation containing large phenocryst of clinopyroxene (P) and smaller plagioclase (F) phenocrysts. Sample ER-30: d) pillow basalt of Oak Mountain Formation with sparse plagioclase phenocrysts set in trachytic groundmass. Sample ER-25.

observed; they typically display flow-aligned plagioclase (Fig. 6d) with pillow structures typically about 50 cm in diameter.

The highly porphyritic facies is characterized by an abundance of conspicuous plagioclase (40–50%) from 1 to 3 mm in length, and typically large pyroxene (5–15%) phenocrysts from 1 to 7 mm in length set a very fine- to medium-grained, flow-aligned feldspathic groundmass (Figs. 7a, b). Sparse light grey volcanic fragments from 10 to 20 cm in size and irregular lenses of greyish pink chert from 3 to 5 cm thick are present in some of these flows. Amygdules up to 5 mm in diameter are common in the flows (Fig. 4d) and are infilled either entirely with calcite or with a combination of epidote, chlorite, and quartz.

Basalt breccia and hyaloclastite

The basaltic hyaloclastite occurs in beds from 3 cm to 1 m thick, interlayered with maroon mudstone beds from 1 to 15 cm thick. The hyaloclastic beds are composed of an aggregate of tightly packed and elongated fragments of porphyritic basalt, and lesser aphyric basalt, ranging in length from 5 mm to 1 cm (Fig. 7c). The bedded hyaloclastite is typically found associated with coarse-grained, monomictic, basalt breccia (Fig. 7d) containing somewhat rounded amygdaloidal fragments from 1 to 30 cm in size. The presumably more distally transported bedded hyaloclastite and more proximal brecciated facies are interpreted to be derived from re-working of the porphyritic flows (McPhie *et al.* 1993).

Belle Lake Formation

Following Venugopal (1978), the type section for the Belle Lake Formation is designated herein as those outcrops at the Hartin Settlement Road bridge over Eel River (just southeast of GSC loc. 98979 on Fig. 1) in southern York County, New Brunswick (21G/13E). The Belle Lake Formation is a clastic turbiditic succession of light grey to olive green, thin- to medium-bedded (2–25 cm thick), feldspathic wacke and medium grey to black shale with a thickness between 800 and 1000 m (Venugopal 1978). The base of the Belle Lake Formation is marked by a few metres of interbedded red laminated chert and maroon to light green mudstone. The transition from red chert, through to black shale, and into wacke can be seen on, and west of, Route 540, about 2 km north of the type-section.

Graptolites collected in 1982 from grey shale on Belle Brook (GSC loc. 98979; Fig. 1) include *Climacograptus bicornis* (Hall), *Orthograptus calcaratus* (Lapworth), *Pseudoclimacograptus scharenbergi* (Lapworth), *Climacograptus brevis brevis* (Elles and Wood), *Corynoides calicularis* (Hopkinson), *?Crytograptus tricornis* (Carruthers), and *?Nemagraptus exilis* (Lapworth) indicative of the upper *Nemagraptus gracilis* Zone (Fyffe *et al.* 1983). *Hallograptus mucronatus* (Hall) and *Climacograptus bicornis* (Hall) were found in dark grey to black shale interbedded with wacke in a new locality on Bull Creek just above Belle Brook during the recent mapping. The following graptolites occur in archived specimens collected in 1955 on Bull Creek just below Belle Brook (GSC loc. 27291): *Corynoides* sp., *Hallograptus mucronatus* (Hall), *Pseudoclimacograptus scharenbergi* (Lapworth), *Orthograptus calcaratus acutus* (Elles and Wood), *Climacograptus bicornis tridentatus* (Lapworth), and *Ensigraptus caudatus* (Lapworth) indicative of the *Diplograptus multidens* Zone (John Riva, written communication, 2001). Together, the graptolite collections indicate that the wacke and shale sequence of the Belle Lake Formation is early Caradocian in age. The red chert and mudstone unit at the base of the Belle Lake Formation is likely Llanvirnian in age, as its contact with the early Caradocian wacke and shale is conformable.

Geochemistry

Representative samples of the various volcanic rock types from the Porten Road, Eel River, and Oak Mountain formations were analysed for major, trace, and rare-earth elements (REE) at Memorial University of Newfoundland. Sample locations are shown on Fig. 2. Analytical methods are given in Appendix 1 and geochemical data are listed by formation in Table 1. Volcanic rocks are classified chemically on the basis of silica content following Gill (1981); basalt is defined as containing less than 53%, low-silica andesite from 53 to 57%, high-silica andesite from 57 to 63%, dacite from 63 to 70%, and rhyolite greater than 70% silica.

Dostal (1989) has previously shown that basalt from the Oak Mountain Formation and rhyolite from the Porten Road Formation of the Meductic Group (as defined herein) were generated at a destructive plate boundary. His conclusions are confirmed and augmented by the present regional study, which includes samples with a much wider areal distribution. As a result, volcanic rocks of intermediate composition are shown to be present in significant quantities in both the Porten Road and Eel River formations and the previous conclusion that the sequence is bimodal is now known to be incorrect. The unimodal character of the entire suite of samples collected from the Meductic volcanic suite is illustrated by the spread in silica content on the iron versus silica diagram (Fig. 8); the calc-alkaline affinity of the suite is indicated by the characteristic inverse variation of iron with respect to silica on this diagram (Miyashiro 1974).

The chemical variability of the volcanic rocks within and between formations is discussed below. Averages, ranges and ratios of some major and trace elements that vary significantly between lithotypes within each formation are given in the text. The trace elements used on various bivariate and multi-element diagrams to characterize fractionation trends and tectonic setting are considered to be relatively immobile during normal weathering and metamorphic processes (Pearce 1983). Representative samples of the various lithotypes are used to illustrate Rare Earth element (REE) patterns in order to avoid clutter on the diagrams.

Porten Road Formation

Specimens of andesite breccia chosen for analysis (Samples ER-1, -17, -18, -19, -21) were composed largely of homogeneous andesite fragments. SiO_2 in the breccia ranges from 51.9 to 58.1% with an average of 55.4% and MgO ranges from 3.4 to 7.1% with an average of 5.4%. Ba content

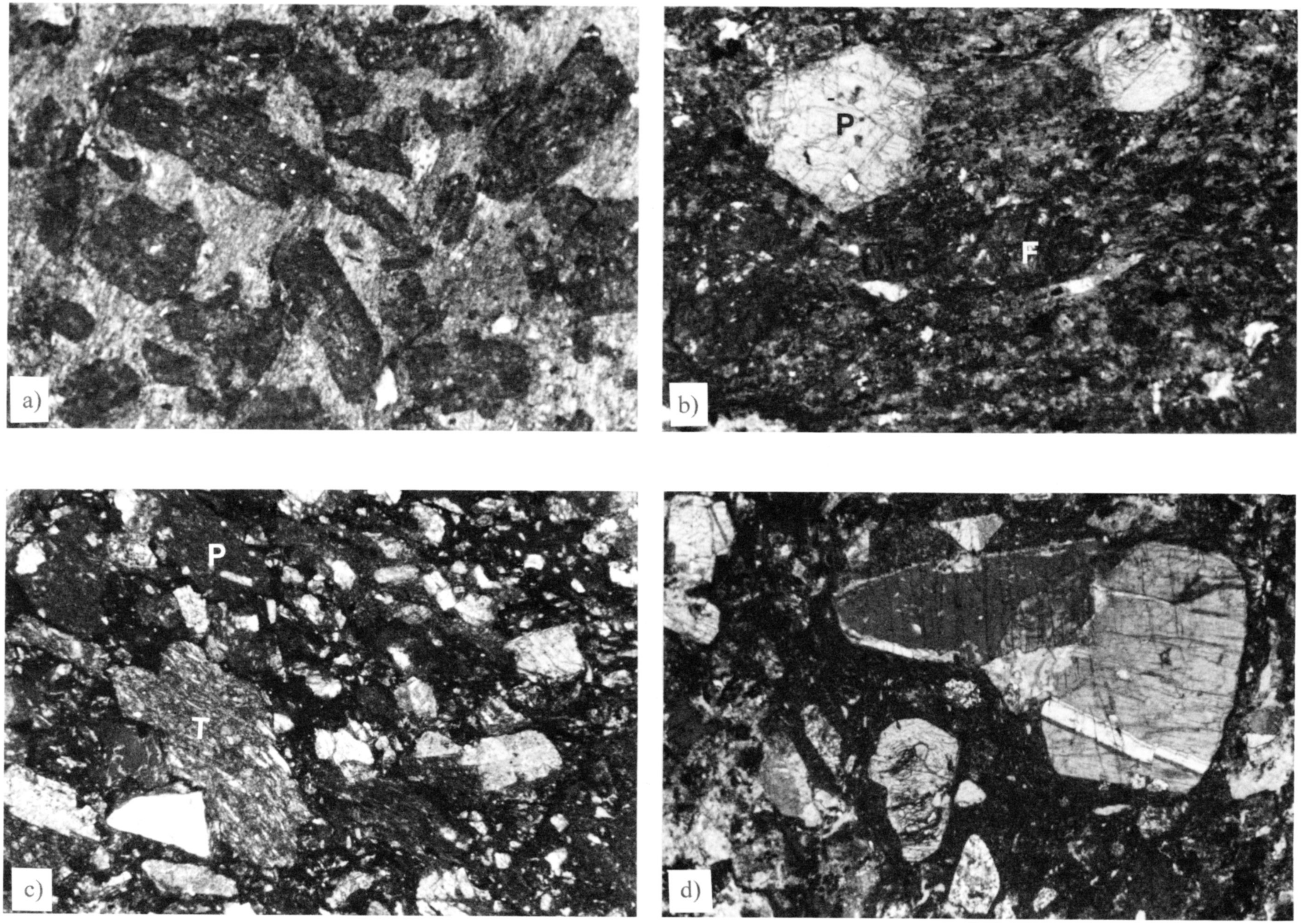

Fig. 7. Photomicrographs of volcanic rocks from the Oak Mountain Formation (field of view is 7 mm): a) basalt with abundant, saussuritized plagioclase phenocrysts, Sample ER-14; b) basalt with saussuritized plagioclase (F), and clinopyroxene (P) phenocrysts, Sample ER-27; c) bedded hyaloclastite containing plagioclase-pyric (P), and trachytic-textured (T) basalt fragments, Sample ER-7; d) monolithic basalt breccia containing plagioclase-clinopyroxene-phyric basalt fragments, Sample ER-29.

Table 1. Major-, trace-, and rare-earth-element analyses of volcanic rocks of the Meductic Group.

Sample	ER-18	ER-19	ER-17	ER-1	ER-21	ER-2	ER-31	ER-4	ER-16	ER-20	ER-15	ER-5	ER-11	ER-13	ER-10	ER-22	ER-28	ER-6	ER-24	ER-12
Unit	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	PR	ER	ER	ER	ER
wt %																				
SiO_2	51.93	55.21	55.91	56.03	58.08	59.34	61.30	66.01	68.08	69.30	72.40	73.88	74.35	77.31	80.06	-	56.49	58.50	59.86	60.53
TiO_2	0.58	0.56	0.63	0.52	0.53	0.46	0.48	0.55	0.32	0.18	0.17	0.18	0.18	0.09	0.08	-	0.48	0.40	0.91	0.40
Al_2O_3	18.83	18.60	19.28	18.34	18.54	17.94	17.25	16.47	16.59	13.56	13.78	13.58	13.67	11.76	10.74	-	17.59	16.72	16.43	17.22
$Fe_2O_3^t$	7.23	7.76	7.99	6.86	5.85	7.22	8.27	4.88	2.39	7.42	3.80	3.67	3.12	2.29	1.24	-	8.97	8.44	7.38	8.39
MnO	0.13	0.09	0.10	0.13	0.09	0.47	0.63	0.15	0.06	0.24	0.25	0.06	0.07	0.05	0.07	-	0.17	0.16	0.20	0.15
MgO	4.89	7.09	3.39	5.92	5.46	2.80	2.77	1.83	1.42	4.07	3.66	2.25	1.67	2.03	0.90	-	3.62	3.70	2.73	3.23
CaO	12.88	8.88	3.93	7.13	4.93	3.53	1.01	6.29	0.90	1.07	0.49	2.42	3.50	2.35	5.43	-	7.46	3.33	6.42	3.36
Na_2O	1.56	1.13	4.72	3.37	4.18	6.62	6.25	2.07	0.38	0.94	2.45	0.73	0.97	1.43	0.46	-	3.03	6.48	3.11	5.76
K_2O	0.26	0.40	1.70	0.58	0.43	0.25	0.21	1.19	8.40	1.20	2.24	2.38	1.61	1.03	0.21	-	0.97	0.15	1.43	0.30
P_2O_5	0.14	0.12	0.16	0.05	0.06	0.11	0.08	0.12	0.05	0.03	0.03	0.03	0.02	0.01	0.01	-	0.10	0.07	0.34	0.07
LOI	6.63	4.27	3.10	4.32	4.23	3.77	2.41	2.86	2.58	3.24	2.64	2.47	2.00	2.10	1.41	-	3.27	3.04	3.70	2.49
Total	105.04	104.11	100.91	103.25	102.38	102.51	100.65	102.41	101.17	101.25	101.91	101.65	101.19	100.44	100.60	-	102.16	101.00	102.50	101.89
ppm																				
Ba	264	1007	2536	4330	4599	117	73	658	1335	1267	451	3369	1226	358	30	-	488	39	501	237
Th	4.51	4.51	4.93	5.27	5.06	1.54	2.29	8.80	11.54	2.68	3.41	3.99	3.37	5.72	6.06	0.82	3.03	2.12	6.54	1.87
Y	8	6	10	6	7	30	14	25	33	28	24	34	26	27	30	12	13	13	18	11
Zr	93	95	108	107	103	68	66	205	145	90	153	174	161	145	165	42	72	64	154	61
Nb	4	4	5	5	5	4	2	14	17	7	6	9	5	10	7	2	5	3	15	5
Hf	3.00	3.08	3.39	2.98	2.87	1.96	1.80	5.40	5.07	2.67	4.12	4.88	4.68	4.26	5.17	1.12	1.86	1.82	3.91	1.73
Ta	0.26	0.25	0.30	0.19	0.25	0.22	0.13	0.73	1.53	0.42	0.32	0.53	0.25	0.56	0.45	0.13	0.26	0.15	0.78	0.11
Sc	15	30	26	17	26	24	29	33	24	23	8	10	18	20	11	-	46	24	12	37
V	176	174	219	171	174	54	160	57	51	4	12	0	12	0	0	-	188	174	116	163
Cr	118	87	92	94	76	16	35	50	74	26	47	75	72	65	210	-	56	38	24	50
S	132	27	248	52	65	81	15	13	265	226	20	6	327	63	124	-	54	25	127	301
Cl	321	790	591	961	1130	361	158	503	1241	1724	1428	1796	2126	951	890	-	208	1930	1048	1224
ppm																				
La	9.50	8.75	13.47	10.03	9.69	15.95	8.08	25.29	24.03	10.08	9.90	12.84	9.68	18.00	17.65	3.84	11.51	7.54	24.53	6.61
Ce	20.11	19.55	32.33	20.27	20.63	30.94	16.03	52.20	48.67	21.42	22.48	26.67	21.40	37.99	37.09	7.98	22.91	15.62	52.42	14.21
Pr	2.51	2.52	3.84	2.49	2.54	3.67	2.02	6.11	6.12	2.48	2.63	3.23	2.57	4.18	4.35	1.09	2.66	1.89	6.24	1.68
Nd	10.40	10.54	15.65	10.33	10.52	15.47	8.59	23.78	23.60	10.44	10.80	13.26	10.67	16.33	17.12	4.84	10.64	7.85	24.97	6.94
Sm	2.63	2.63	3.54	2.32	2.23	3.98	1.99	5.09	6.37	3.10	2.81	3.57	2.94	3.70	3.97	1.32	2.23	1.99	5.18	1.73
Eu	0.69	0.79	1.09	0.77	0.74	0.80	0.51	1.13	1.15	0.76	0.58	0.67	0.57	0.47	0.53	0.39	0.75	0.61	1.42	0.59
Gd	2.20	2.10	2.99	1.66	1.81	4.60	2.45	4.43	6.31	3.91	3.19	4.33	3.54	3.89	4.36	1.64	2.51	2.09	4.39	1.86
Tb	0.31	0.28	0.39	0.22	0.23	0.77	0.39	0.72	1.04	0.67	0.58	0.78	0.63	0.65	0.77	0.26	0.38	0.35	0.58	0.30
Dy	1.79	1.63	2.25	1.24	1.32	5.02	2.63	4.50	6.66	4.72	4.02	5.45	4.38	4.41	5.29	1.79	2.51	2.31	3.47	2.01
Ho	0.32	0.28	0.40	0.24	0.27	1.13	0.58	0.97	1.26	1.15	0.95	1.28	1.01	1.00	1.17	0.43	0.54	0.52	0.74	0.45
Er	0.99	0.82	1.19	0.72	0.79	3.60	1.84	3.11	3.97	3.95	3.37	4.45	3.45	3.24	3.66	1.43	1.77	1.71	2.28	1.47
Tm	0.13	0.11	0.16	0.10	0.10	0.48	0.26	0.43	0.55	0.59	0.51	0.67	0.51	0.45	0.50	0.20	0.25	0.24	0.31	0.21
Yb	0.88	0.68	0.98	0.68	0.63	2.96	1.67	2.75	3.55	4.05	3.63	4.67	3.58	3.02	3.14	1.25	1.61	1.57	1.99	1.39
Lu	0.15	0.11	0.17	0.10	0.10	0.43	0.24	0.42	0.60	0.66	0.58	0.75	0.57	0.46	0.46	0.19	0.24	0.25	0.30	0.21

Notes: PR = Porten Road Formation, ER = Eel River Formation, LOI = Loss-on-ignition.

Table 1 (continued).

Sample	ER-14	ER-3	ER-25	ER-8	ER-23	ER-7	ER-27	ER-30	ER-29	ER-9	ER-26
Unit	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM	OM
wt %											
SiO_2	44.99	46.14	46.59	47.71	48.57	49.91	50.65	50.79	51.31	51.74	-
TiO_2	0.66	0.63	0.93	0.93	0.82	0.66	0.66	0.87	0.46	0.90	-
Al_2O_3	21.91	19.32	17.83	17.46	20.32	19.74	17.86	13.91	15.75	17.67	-
$Fe_2O_3^t$	11.16	14.44	13.63	11.18	8.85	10.02	11.83	11.02	10.92	9.64	-
MnO	0.15	0.70	0.15	0.20	0.13	0.48	0.18	0.24	0.16	0.24	-
MgO	5.88	5.82	6.14	6.42	4.76	4.87	5.14	7.79	7.58	5.14	-
CaO	11.45	9.18	8.11	8.23	10.17	6.82	10.35	10.33	9.34	9.33	-
Na_2O	1.52	0.36	1.82	2.77	2.00	2.82	1.43	1.87	1.55	2.50	-
K_2O	0.12	1.25	1.60	1.75	1.63	3.12	0.75	1.19	0.81	2.08	-
P_2O_5	0.12	0.07	0.20	0.29	0.26	0.13	0.13	0.25	0.03	0.15	-
LOI	4.39	6.50	3.65	2.82	3.92	3.35	2.87	5.44	3.43	7.76	-
Total	102.35	104.41	100.66	99.77	101.44	101.91	101.85	103.71	101.34	107.14	-
ppm											
Ba	60	287	200	480	318	952	103	321	74	291	-
Th	5.15	1.46	4.98	6.94	5.83	5.13	3.13	5.45	1.31	6.76	3.35
Y	10	10	16	16	14	16	9	15	8	19	11
Zr	73	39	106	155	124	98	50	117	38	153	73
Nb	4	2	9	13	11	5	3	10	2	15	6
Hf	2.04	1.09	2.90	4.12	3.25	2.66	1.40	2.88	1.05	4.05	2.00
Ta	0.13	0.08	0.42	0.58	0.58	0.29	0.14	0.49	0.09	0.53	0.30
Sc	37	59	47	41	27	35	38	46	45	36	-
V	341	438	359	299	243	251	328	279	303	202	-
Cr	63	29	38	67	73	65	36	578	228	78	-
S	277	26	25	40	56	66	42	15	49	18	-
Cl	1562	251	1723	2187	1469	2275	1291	1664	1608	1901	-
ppm											
La	13.58	8.66	16.70	21.81	20.71	24.41	10.19	18.09	4.41	20.88	10.44
Ce	30.75	15.23	37.13	47.85	43.39	43.76	21.44	38.60	9.83	46.43	22.71
Pr	3.78	1.66	4.58	5.78	5.07	4.95	2.61	4.63	1.22	5.52	2.89
Nd	15.37	6.82	19.04	23.19	20.05	19.77	10.78	18.75	5.23	22.07	12.26
Sm	3.08	1.64	4.21	4.89	4.10	3.94	2.15	3.64	1.26	4.72	2.84
Eu	0.85	0.55	1.17	1.24	1.15	1.04	0.66	0.93	0.39	1.22	0.83
Gd	2.37	1.62	3.66	4.07	3.46	3.46	2.08	3.52	1.44	4.12	2.53
Tb	0.33	0.27	0.50	0.58	0.46	0.48	0.30	0.50	0.23	0.61	0.35
Dy	1.91	1.77	3.03	3.38	2.71	2.93	1.81	2.99	1.51	3.74	2.11
Ho	0.40	0.40	0.66	0.69	0.57	0.62	0.38	0.61	0.33	0.79	0.46
Er	1.24	1.30	2.05	2.06	1.75	1.92	1.17	1.85	1.05	2.51	1.41
Tm	0.17	0.18	0.28	0.27	0.23	0.26	0.16	0.25	0.15	0.35	0.19
Yb	1.10	1.20	1.79	1.67	1.48	1.65	0.98	1.56	0.96	2.33	1.22
Lu	0.17	0.19	0.27	0.24	0.22	0.25	0.15	0.22	0.14	0.36	0.19

Notes: OM = Oak Mountain Formation, LOI = Loss-on-ignition.

ranges from 264 to 4599 ppm with an average of 2547 ppm, Th ranges from 4.5 to 5.3 ppm with an average of 4.9 ppm, and Y ranges from 6 to 10 ppm with an average of 7 ppm. ΣREE ranges from 51 to 78 ppm with an average of 57 ppm and $(La/Yb)_N$ ranges from 7.2 to 10.4 with an average of 9.1 (Fig. 9). Enrichment in low-field-strength elements (LFSE) such as Ba and Th and depletion in high-field-strength elements (HFSE) such as Ti and Y relative to mid-oceanic-ridge basalt (MORB) as seen in the Porten Road andesite (Fig. 10a) are characteristic features of mafic to intermediate volcanic rocks generated in a subduction-zone setting (Pearce 1982, 1983; McCulloch and Gamble 1991; Woodhead and Johnson 1993). A similar subduction signature is exhibited by andesite and basalt of the Eel River and Oak Mountain formations (Fig. 10a, b). The light REE-enriched, concave-upward normalized REE profile of the Porten Road andesite (Fig. 11a) is typical of calc-alkaline volcanic rocks; in particular, the high light REE to heavy REE ratio (LREE/HREE) of the Porten Road andesite is like that found in high K andesite (Crow and Condie 1987; Whitford *et al.* 1979), and is suggestive of an Andean arc setting (Fig. 9). Andean-type continental arcs form in a compressional setting, in contrast to continental margin arcs with back-arc basins that form in an extensional setting (Uyeda 1982).

The rhyolite breccia can be divided into two types on the basis of distinctive light to heavy REE ratios (Fig. 11a). In the

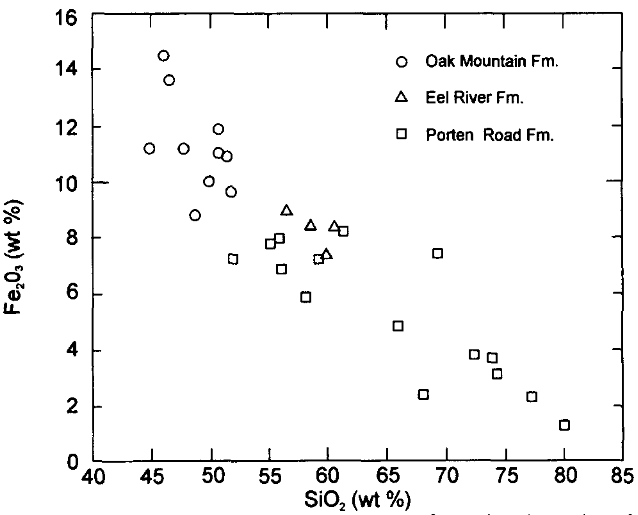

Fig. 8. Bivariate plot of total iron *vs* silica for volcanic rocks of the Meductic Group.

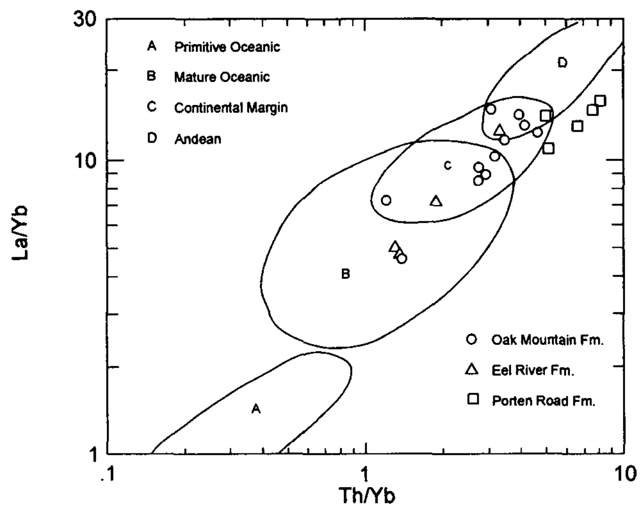

Fig. 9. Bivariate plot of La/Yb *vs* Th/Yb for mafic volcanic rocks of the Meductic Group. Fields for arc-related mafic volcanic rocks are after Crow and Condie (1987).

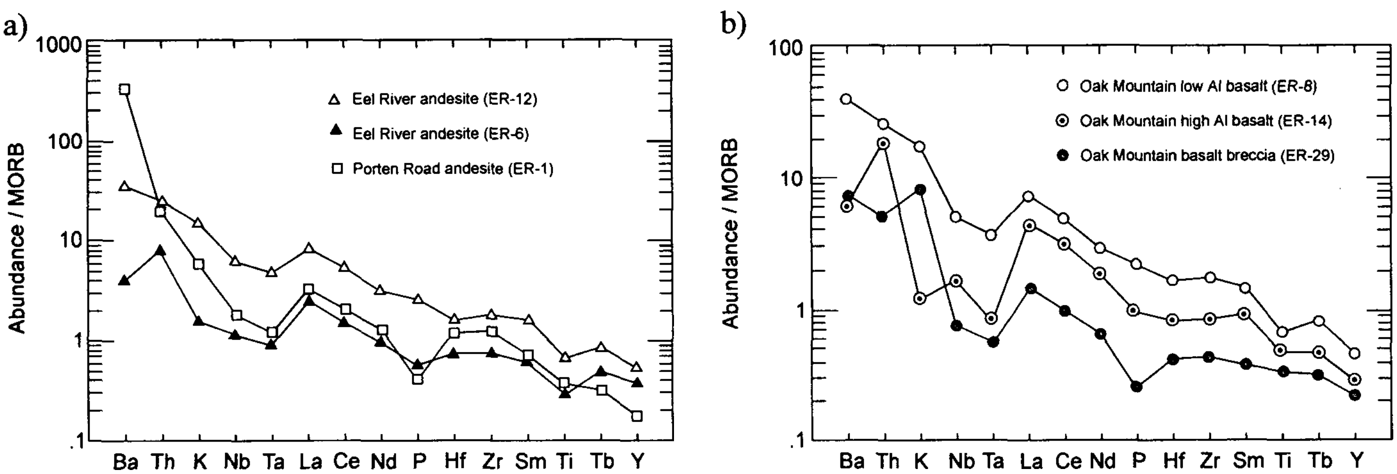

Fig. 10. MORB-normalized multi-element plots. a) Andesite of Porten Road and Eel River formations. b) Basalt of the Oak Mountain Formation. Normalization values are from Rollinson (1993, p. 143, column 10).

high-ratio type (Samples ER-10, -13, -16), SiO_2 ranges from 68.1 to 80.1% with an average of 75.2% and MgO ranges from 0.9 to 2.0% with an average of 1.5%; ΣREE ranges from 98 to 134 ppm with an average of 111 ppm and $(La/Yb)_N$ ranges from 3.8 to 4.5 with an average of 4.1. In the low-ratio type (Samples ER-5, -11, -15, -20, -22), SiO_2 ranges from 69.3 to 74.3% with an average of 72.5% and MgO ranges from 1.7 to 4.1% with an average of 2.9%; ΣREE ranges from 27 to 83 ppm with an average of 62 ppm and $(La/Yb)_N$ ranges from 1.7 to 1.8 with an average of 1.8. The Th content averages 7.8 ppm in the high $(La/Yb)_N$ rhyolite versus 2.9 ppm in the low $(La/Yb)_N$ rhyolite. Late stage fractionation of an accessory mineral such as allanite can significantly reduce LREE/HREE in felsic magma (Cullers and Graf 1982) and may account for the differing REE patterns and Th abundances observed in the Porten Road rhyolite. Alternatively, the two types of rhyolite may have been derived from distinct parental magmas.

In the dacite breccia (Samples ER-2, -4, -31), SiO_2 ranges from 59.3 to 66.0% with an average of 62.2% and MgO ranges from 1.8 to 2.8% with an average of 2.5%. The Th content ranges from 1.5 to 8.0 ppm with an average of 3.9 ppm. ΣREE ranges from 47 to 131 ppm with an average of 89 ppm and $(La/Yb)_N$ ranges from 3.2 to 6.2 with an average of 4.3 (Fig. 11a). The similarity of relative LREE/HREE enrichment in the dacite and high $(La/Yb)_N$ rhyolite (average $(La/Yb)_N$ of 4.1 *vs.* 4.3) and greater magnitude of the negative Eu anomaly in the rhyolite suggest the possibility that the latter may be derived from the dacite by fractional crystallization (*cf.* Wilson 1989).

Eel River Formation

In the andesite breccia (Samples ER-6, -12, -24), SiO_2 ranges from 58.5 to 60.5% with an average of 59.6%, and MgO ranges from 2.7 to 3.7% with an average of 3.2%. Ba content ranges from 39 to 501 ppm with an average of 259 ppm, Th ranges from 1.9 to 6.5 ppm with an average of 3.5 ppm, and Y ranges from 11 to 18 ppm with an average of 14 ppm. ΣREE ranges from 40 to 129 ppm with an average of 71 ppm. $(La/Yb)_N$ ranges from 3.2 to 8.2 with an average of 4.9 similar to that of medium K andesites (Whitford *et al.* 1979).

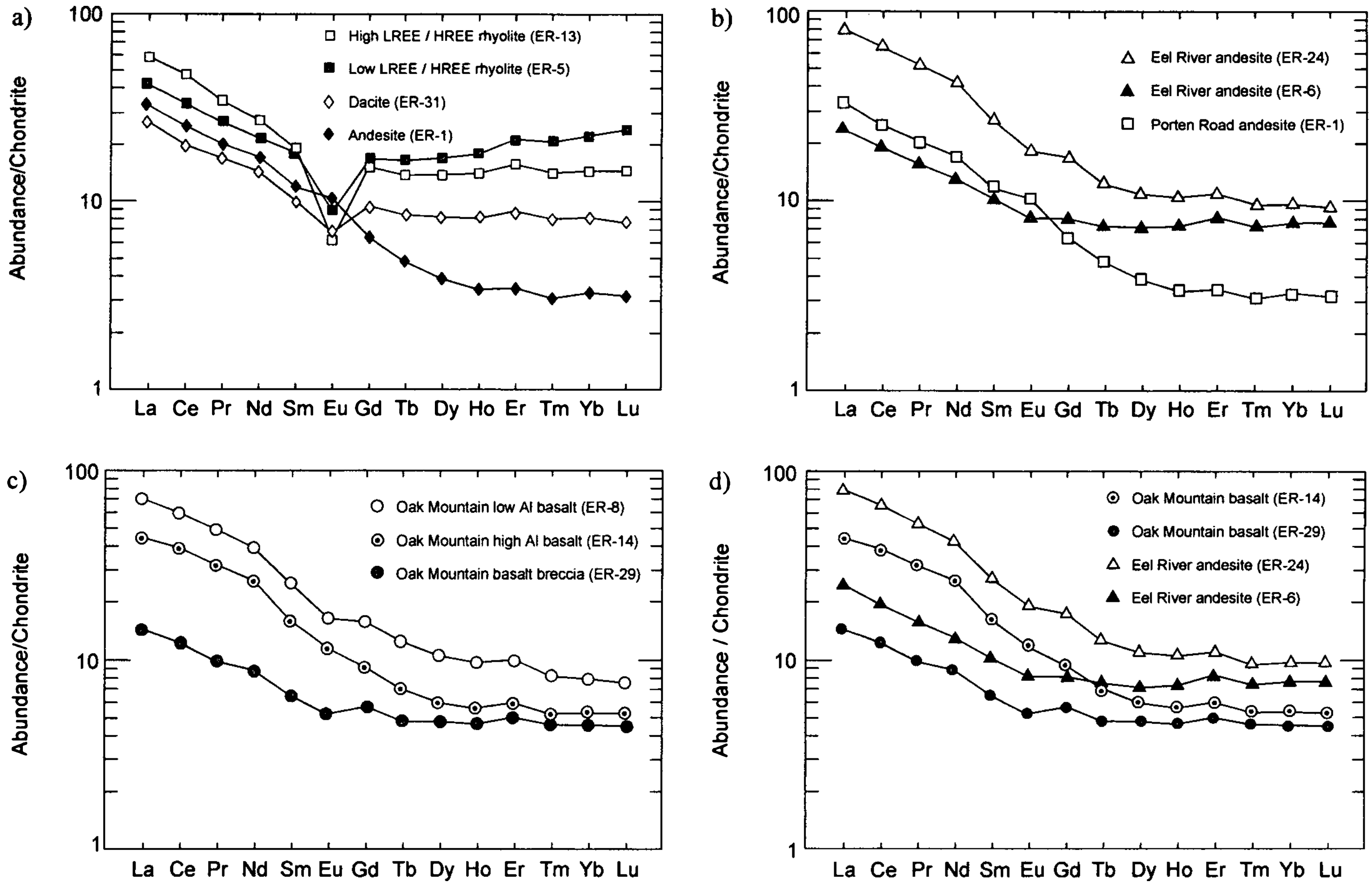

Fig. 11. Chondrite-normalized rare-earth-element profile for (a) andesite, dacite and rhyolite of Porten Road Formation; (b) andesite of Eel River Formation compared to andesite of Porten Road Formation; (c) basalt of Oak Mountain Formation; (d) basalt of Oak Mountain Formation compared to andesite of Eel River Formation. Normalization values are from Rollinson (1993, p. 134, column 6).

The stratified volcaniclastic rocks within the Eel River Formation (Sample ER-28) have an andesitic composition indistinguishable from that of the massive breccia (Table 1). Greater LREE enrichment in Sample ER-24 compared to samples ER-6 and -12 (Fig. 11b) is difficult to account for by fractionation of a single parental magma (*cf.* Wilson 1989). Ti and P are also considerably higher in Sample 24 than in samples ER-6 and -12 (Table 1).

Compared to the andesite from the Porten Road Formation, the andesite from the Eel River Formation is on average considerably higher in SiO_2 and lower in MgO, contains higher HREE abundances (average Yb of 1.6 *vs.* 0.8 ppm), and has less fractionated LREE/HREE ($(La/Yb)_N$ of 4.9 *vs.* 9.1) (Fig. 11b). The lesser enrichment in LFSE (such as Ba and Th) relative to MORB in the Eel River andesite (Fig. 10a) indicates that it possesses a smaller subduction-derived component than the stratigraphically lower Porten Road andesite (*cf.* Pearce 1983). The high Ba content of the Porten Road andesite may be attributed to incorporation of a significant sedimentary component from the melting of the sub ducting slab (*cf.* Kay 1984); notably, black shale from the Early Ordovician Bright Eye Brook Formation is greatly enriched in that element (Fyffe and Pickerill 1993).

Oak Mountain Formation

The sparsely porphyritic basalt flows that make up the bulk of the Oak Mountain Formation (Samples ER-8, -25, -26, -30) are relatively uniform in chemical composition. SiO_2 ranges from 46.6 to 50.8% with an average of 48.4% and MgO ranges from 6.1 to 7.8% with an average of 6.8%. Al_2O_3 ranges from 13.9 to 17.8% with an average of 16.4%. Ba content ranges from 200 to 480 ppm with an average of 334 ppm, Th ranges from 3.4 to 6.9 ppm with an average of 5.2 ppm, and Y ranges from 11 to 16 ppm with an average of 15 ppm. ΣREE ranges from 60 to 118 ppm with an average of 92 ppm. $(La/Yb)_N$ ranges from 5.7 to 8.8 with an average of 7.1 similar to that of high K calc-alkaline basalts (Whitford *et al.* 1979) (Fig. 11c). The bedded hyaloclastite (Samples ER-7, -9) has a trace-element and rare-earth-element content similar to the sparsely porphyritic basalt flows (Table 1).

In the highly porphyritic basalt (Samples ER-3, -14, -23, -27), SiO_2 ranges from 45.0 to 50.6% with an average of 47.6%, and MgO ranges from 4.8 to 5.9% with an average of 5.4%. Al_2O_3 ranges from 17.9 to 21.9% with an average of 19.9%, reflecting the high proportion of plagioclase phenocrysts in this unit. Ba content ranges from 60 to 318 ppm with an average of 192 ppm, Th ranges from 1.5 to 5.8 ppm with an average of 3.9 ppm, and Y ranges from 9 to 14 ppm with an average of 11 ppm. ΣREE ranges from 42 to 105 ppm with an average of 69 ppm. $(La/Yb)_N$ ranges from 4.8 to 9.4 with an average of 7.4 similar to that found in high K calc-alkaline basalts (Whitford *et al.* 1979) (Fig. 11c). Basalt with such high alumina contents as that within the Oak Mountain Formation likely forms as a result of convectional sorting of plagioclase crystals along the upper margins of the magma chamber (Crawford *et al.* 1987; Brophy 1989). In other aspects, the chemical characteristics of the highly porphyritic basalt overlap with those of the sparsely porphyritic facies. Both porphyritic facies plot in the continental margin (extensional) arc field on Fig. 9, corroborating the tectonic setting proposed by Dostal (1989).

A monolithic basalt breccia (Sample ER-29), from near the base of the Oak Mountain Formation (Fig. 2), possesses a uniquely low ΣREE compared to the porphyritic flows. Whereas major element contents in the breccia generally fall within the range of the sparsely porphyritic flows (Table 1), ΣREE is only 28 ppm and $(La/Yb)_N$ is 3.1 similar to that found in low K (tholeiitic) to medium K basalts (Fig. 11c). Trace elements such as Ba, Th, Y, Zr and Nb in the breccia are present in much smaller amounts than in the other Oak Mountain samples (Fig. 10b). The higher content of compatible elements such as MgO, lower content of incompatible elements such as Ba, Th, Y, ΣREE, and less LREE/HREE enrichment compared to the average of the more common Oak Mountain lavas are consistent with the breccia being derived by a greater degree of partial melting of the same mantle source rocks as the flows (Fujinawa 1992).

It is interesting to note that the variation in REE patterns exhibited by the basalt of the Oak Mountain Formation is similar to that displayed by andesite of the Eel River Formation (Fig. 11d). For example, the REE pattern of Oak Mountain basalt breccia (Sample ER-29) parallels that displayed by Eel River andesite with low LREE/HREE (represented by Sample ER-6), whereas the REE pattern of Oak Mountain porphyritic basalt (represented by Sample ER-14) parallels that of Eel River andesite with high LREE/HREE (represented by Sample ER-24). Perhaps these contrasting basaltic magmas each gave rise to andesitic fractionation products with corresponding degrees of LREE/HREE enrichment (*cf.* Wilson 1989).

Discussion and Conclusions

The Cambrian-Ordovician stratigraphy in the southwestern Miramichi terrane is now better understood as a result of recent mapping in the Eel River area. Lithological characteristics of the sedimentary and volcanic successions in the southwestern Miramichi terrane differ significantly enough from those comprising the Miramichi and Tetagouche groups of the northeastern Miramichi terrane to warrant a separate stratigraphic nomenclature. Therefore, the sedimentary substrate and volcanic arc sequence in the Eel River area have been designated, respectively, as the Woodstock and Meductic groups. The Woodstock Group includes interbedded quartz wacke sandstone and shale of the Baskahegan Formation and overlying Early Ordovician silty mudstone and shale of the Bright Eye Brook Formation. The conformably overlying Meductic Group is divided into contrasting volcanic assemblages of the Porten Road, Eel River, and Oak Mountain formations, and Middle to Upper Ordovician feldspathic wacke and shale of the Belle Lake Formation. The emplacement of granitic rocks of the Benton pluton into the volcanic rocks of the Meductic Group at 479 ± 7 Ma (Whalen *et al.* 1998) indicates that this arc sequence is older than all but the basal part of the Tetagouche back-arc succession in the northeastern Miramichi terrane (Fig. 3).

Lithogeochemical results document a systematic change in volcanic composition according to stratigraphic position within the Meductic Group, confirming the validity of formational divisions made on the basis of field observations. With the exception of the Porten Road andesite, lavas were, in general, erupted in order of decreasing silica content (Fig. 8). Analyses of the basal pyroxene-bearing unit of the Porten Road Formation indicate that the earliest volcanic rocks had the composition of a low-silica andesite. This andesite is highly enriched in LREE and LFSE, and highly depleted in HFSE relative to MORB (Figs. 10a, 11b), providing convincing evidence of a strong volatile influence on magma generation during the initial stages of the subduction process. Volcanic rocks in the upper part of the Porten Road Formation are an interlayered sequence of quartz-rich rhyolite and quartz-poor dacite. Dostal (1989) has proposed that the rhyolite were generated by partial melting of amphibolite-facies continental crust. In this scenario, rising basaltic magma provides the additional heat required to melt the lower crust. While this remains a likely mode of origin, the newly recognized abundance of andesitic volcanic rocks in the Eel River area opens the possibility that at least some of the felsic volcanic rocks were derived from fractional crystallization of more mafic magma.

Hornblende-bearing, high-silica andesite of the Eel River Formation, overlying the dacite and rhyolite of the Porten Road Formation, is not as enriched in LFSE as the basal Porten Road andesite (Fig. 10a). This chemical characteristic indicates a relatively lower subduction-related component into the source rocks of the Eel River andesite. Low-alumina, calc-alkaline basalt flows from the overlying Oak Mountain Formation are generally higher in ΣREE and LFSE than associated high-alumina basalt (Figs. 10b, 11c). The high-alumina flows are highly charged with plagioclase phenocrysts and were presumably tapped from near the top margins of a mafic magma chamber. A single analysed sample of basalt breccia from the near the base of the Oak Mountain Formation is relatively depleted in both REE and LFSE (Figs. 10b, 11c). This may be an indication that the degree of partial melting in the mantle source peaked and then subsequently decreased as the subduction process waned in the later part of the Early Ordovician. The cessation of volcanic activity in the Meductic Group is interpreted to be related to north-westward migration of the subducting slab as a result of arc-rifting and opening of the Tetagouche back-arc basin (van Staal 1987; van Staal *et al.* 1991). The decrease in La/Yb and Th/Yb values observed between the andesite of the Porten Road Formation and basalt of the Oak Mountain Formation (Fig. 9) is consistent with thinning of continental crust as the back-arc basin opened (*cf.* Uyeda 1982).

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APPENDIX I

Major elements were analyzed by X-Ray fluorescence procedures at Memorial University in St. John's, Newfoundland. Samples were ignited at 1050°C for seven hours to determine loss on ignition. The ignited powder (1.5 gm) was mixed with lithium tetraborate (1.5 gm) and lithium metaborate (6.0 gm). The sample and fluxes were mixed and poured into a platinum/gold crucible, along with lithium bromide. The mixture was fused using a Leco automatic fluxer at approximately 1400°C (measured outside the crucible) for 12.5 minutes. After casting and cooling the fused beads were analyzed using an ARL 8420+ sequential wave-length dispersive x-ray spectrometer. Ba, Sc, V, Cr, S and Cl were analyzed from pressed pellets. All elements were determined using a flow-proportional detector with the x-ray tube operated at 3 kW.

REE, Y, Th, Zr, Nb, Hf and Ta were analyzed at Memorial University by Inductively Coupled Plasma-Mass Spectrometry. Note that grinding samples in tungsten carbide-lined equipment can lead to severe Ta (+Nb?) contamination. The analytical procedure was as follows: (1) sintering of a 0.2 g sample aliquot with sodium peroxide, (2) dissolution of the sinter cake, separation and dissolution of REE hydroxide-bearing precipitate, (3) analysis by ICP-MS using the method of internal standardization to correct for matrix and drift effects. Full details of the procedure are given in Longerich *et al.* (1990) and Jenner *et al.* (1990). The advantage of the sintering technique is that it practically ensures complete digestion of resistant REE-bearing accessory phases (e.g. zircon, fluorite) which may not dissolve during an acid digestion. A pure quartz reagent blank and certified geological reference standards were prepared and analyzed with the samples. Reagent blank concentrations are generally insignificant and have not been subtracted from sample concentrations. Some of the unknown samples were prepared and analyzed in duplicate. Sample detection limits are generally about 10% of chondrite values.