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Age and tectonic significance of the Benton pluton, Eel River area, west-central New Brunswick, Canada
Âge et importance tectonique du pluton de Benton, secteur d'Eel River, centre-ouest du Nouveau-Brunswick, Canada

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Article abstract

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Age and tectonic significance of the Benton pluton, Eel River area, west-central New Brunswick, Canada

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ABSTRACT

The Benton pluton, located in the Eel River area of west-central New Brunswick, Canada, consists of two components—the Caldwell Brook quartz monzonite and Dugan Road monzogranite. Field relations suggest that the two are essentially coeval, the Dugan Road being slightly younger. The Benton pluton intrudes Cambrian to Early Ordovician sedimentary rocks of the Woodstock Group and overlying Early to Middle Ordovician calc-alkaline rhyolitic, andesitic, dacitic, and basaltic rocks of the lower Meductic Group. A new U–Pb (LA-ICP-MS) zircon age of 467 ± 2 Ma indicates that the Dugan Road monzogranite component of the Benton pluton was emplaced during the Middle Ordovician (late Dapingian to early Darriwilian). The Dugan Road monzogranite is ca. 7 million years younger than the nearby arc-related Connell Mountain tonalite and Gibson granodiorite, and ca. 13 million years younger than arc-related volcanic rocks of the Porten Road Formation, the oldest unit of the Meductic Group. The Benton pluton is interpreted to have been emplaced in an active extensional arc setting, coinciding with a shift in the focus of subduction-related volcanism from the Eel River area of New Brunswick to the Greenfield area of adjacent Maine, USA.

RÉSUMÉ

Le pluton de Benton, situé dans le secteur d'Eel River dans le centre-ouest du Nouveau-Brunswick, au Canada, est constitué de deux éléments : la monzonite de quartz du ruisseau Caldwell et le monzogranite du chemin Dugan. Leurs rapports sur le terrain laissent supposer que les deux éléments sont essentiellement du même âge, celui du chemin Dugan étant légèrement plus récent. Le pluton de Benton pénètre des roches sédimentaires du Cambrien à l'Ordovicien précoce du groupe de Woodstock ainsi que des roches sus-jacentes calco-alcalines rhyolitiques, andésitiques, dacitiques et basaltiques de l'Ordovicien précoce à moyen de la partie inférieure du groupe de Meductic. Une nouvelle datation U–Pb (LA-ICP-MS) sur zircon de 467 ± 2 Ma révèle que l'élément de monzogranite du chemin Dugan du pluton de Benton s'est mis en place durant la période de l'Ordovicien moyen (du Dapingien tardif au Darriwilien précoce). Le monzogranite du chemin Dugan est plus récent d'environ sept millions d'années que la granodiorite de Gibson et la tonalite du mont Connell apparentées à un arc voisines, et plus récent d'environ 13 millions d'années que les roches volcaniques d'un arc de la Formation de Porten Road, l'unité la plus ancienne du groupe de Meductic. Le pluton de Benton est interprété comme un élément s'étant mis en place dans le cadre d'un arc d'extension active coïncidant avec un déplacement du foyer du volcanisme lié à une subduction depuis le secteur d'Eel River au Nouveau-Brunswick au secteur de Greenfield dans l'État voisin du Maine, aux États-Unis.

[*Traduit par la redaction*]

INTRODUCTION

The Benton granite (Venugopal 1978), here referred to as the Benton pluton, is a relatively small (ca. 20 km^2) felsic body inferred to intrude Ordovician volcanic rocks of the Meductic Group in the Eel River area, south of Woodstock in Carleton County, New Brunswick (Fig. 1). Two nearby Early Ordovician felsic plutons (Figs. 2, 3), which intrude Cambrian–Ordovician sedimentary rocks of the Woodstock Group, have been dated as Early Ordovician (Floian)—the

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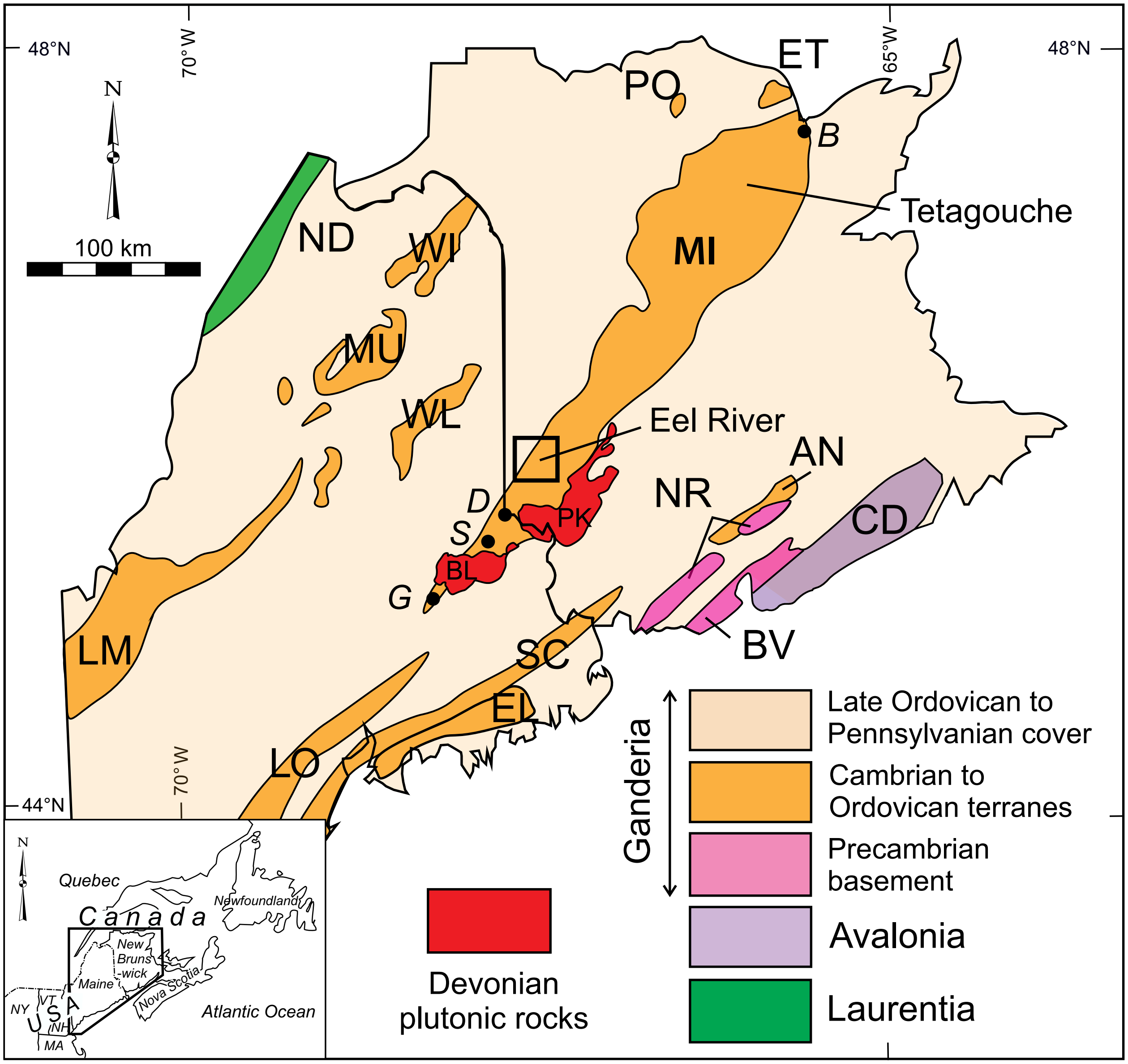

Figure 1. Lithotectonic framework of New Brunswick and Maine showing distribution of accreted terranes and location of volcanic arcs and backarcs discussed below. Rectangle shows location of Figure 3 and the Meductic arc. Terranes: AN-Annidale; BV-Brookville; CD-Caledonia; EL-Ellsworth; ET-Elmtree; LM-Lobster Mountain; LO-Liberty-Orrington; MI-Miramichi; MU-Munsungun; ND-Notre Dame; NR-New River; PO-Popelogan; WI-Winterville; WL-Weeksboro-Lunksoos Lake. Plutonic complexes-place names: B-Bathurst; BL-Bottle Lake; D-Danforth; G-Greenfield; PK-Pokiok; S-Stetsom Mountain (modified from van Staal *et al.* 2016; Ludman *et al.* 2021; Fyffe *et al.* 2023).

Gibson granodiorite at 473 ± 1 Ma (preliminary TIMS age, Bevier 1989) and more recently, the Connell Mountain tonalite at 474 +1/-4 Ma (van Staal *et al.* 2016). Prior to our study, the undated Benton pluton was also assumed to have a similar Early Ordovician age of emplacement as the Gibson and Connell Mountain plutons (Whalen 1993; Whalen *et al.* 1998; van Staal *et al.* 2016). Both the Benton and Gibson plutons have been shown to possess arc-like trace element signatures (Whalen 1993; Whalen *et al.* 1998) and to be significantly younger than the basal Porten Road Formation of the Meductic Group (480 ± 3Ma; Mohammadi *et al.* 2019), the only dated Miramichi volcanic unit in the Eel River area.

The purpose of this study was to determine the age of the Benton pluton relative to the nearby dated Early Ordovician plutons, and to possibly provide further insight into the time span of Popelogan–Meductic arc volcanism. Moreover, comparison of the Meductic Group in New Brunswick with recently dated Ordovician volcanic rocks in Greenfield area of Maine (Figs. 1, 2) has proven difficult (Ludman 2023; Ludman *et al.* 2021), so the age obtained from the Benton pluton should help clarify the stratigraphic relation-

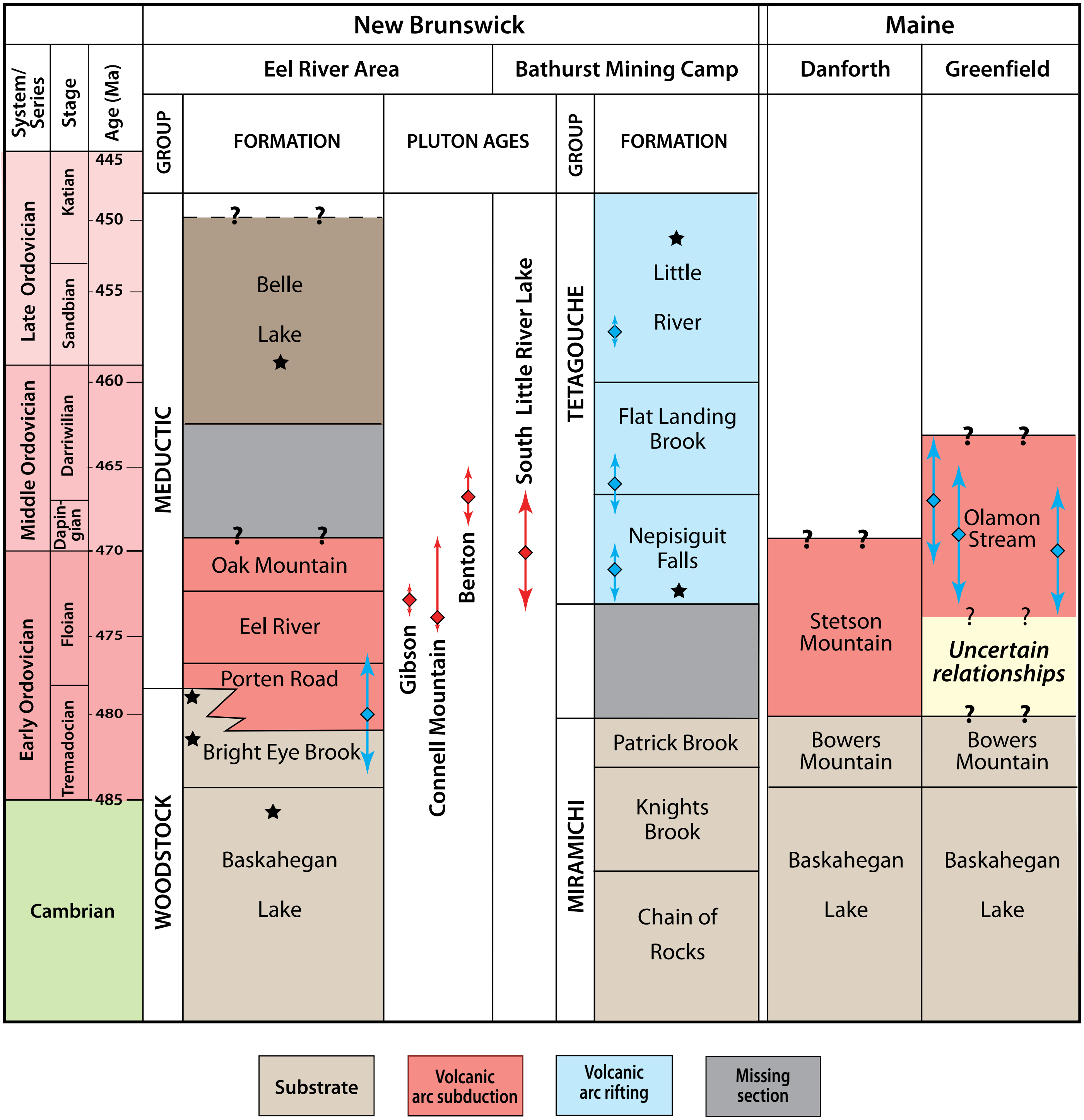

Figure 2. Stratigraphic columns showing correlations between volcanic and plutonic rocks in the Eel River area of southwestern New Brunswick, in the Bathurst Mining Camp area of northeastern New Brunswick, and in the Danforth and Greenfield areas of eastern Maine (see Fig. 1). Stars indicate fossil age control for sedimentary and volcanic rocks. Blue arrows = radiometric ages of Ordovician volcanic rocks. Red arrows = radiometric ages of Ordovician granitic plutons, including the age of the Benton pluton reported in this paper. Stage boundaries after Cohen *et al.* 2013, updated 2022. See van Staal *et al.* (2016), Ludman *et al.* (2021), and Fyffe *et al.* (2023) for references on paleontological and radiometric age controls.

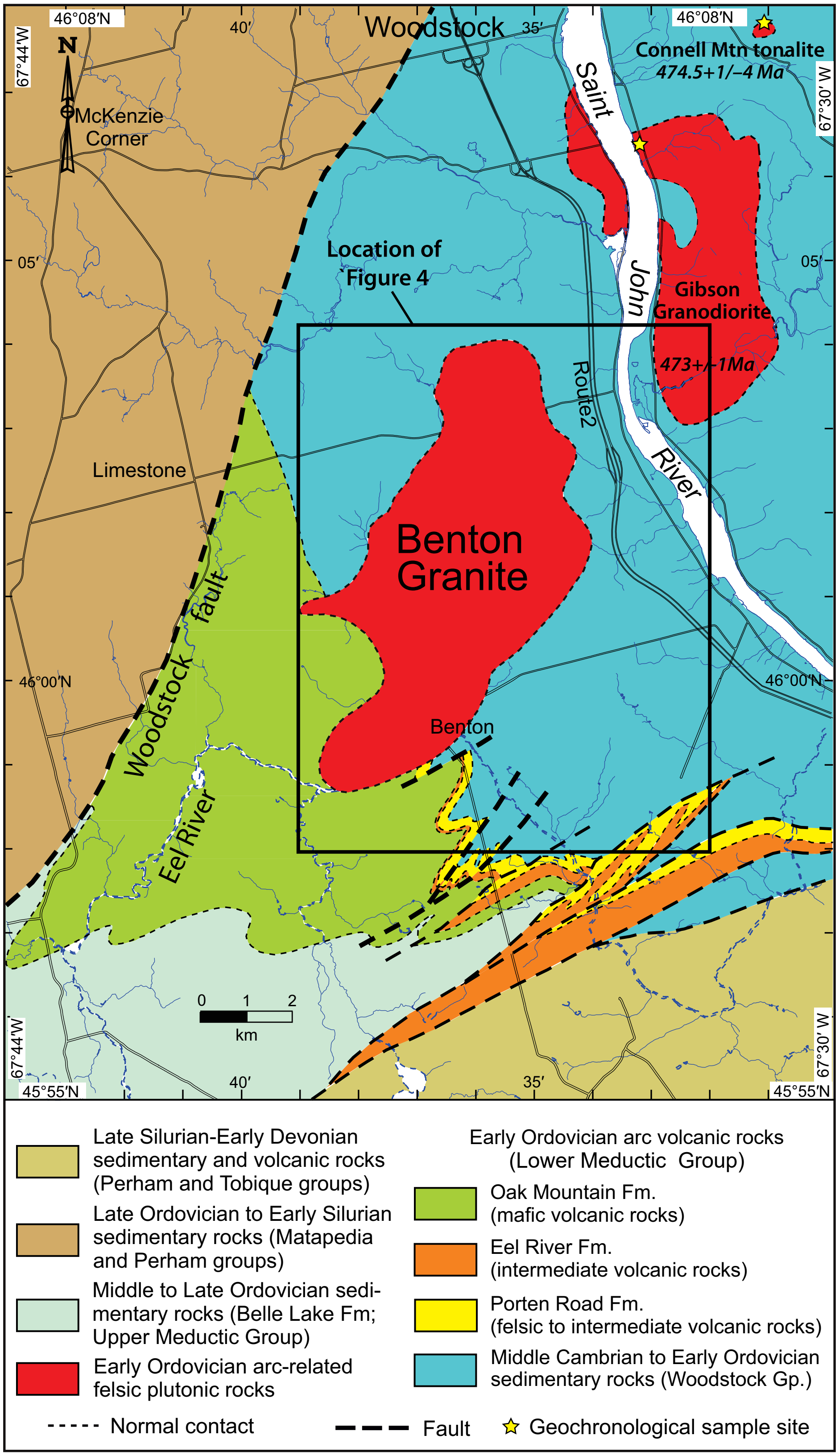

Figure 3. **Simplified geologic map of the Eel River area (modified from Fyffe 2001), illustrating the relationships of the Benton pluton, Gibson granodiorite (age from Bevier 1989), and Connell Mountain tonalite (age from van Staal *et al.* 2016).**

ships between the Miramichi volcanic rocks on opposite sides of the Canada–USA border (Figs. 1, 2).

TECTONIC SETTING

The Miramichi terrane of New Brunswick and eastern Maine (Fig. 1) is one of several Ganderian continental fragments interpreted to have been rifted from the Gondwanan craton during the late Precambrian to early Paleozoic opening of the Iapetus Ocean (van Staal *et al.* 1991, 2003; van Staal and Fyffe 1995). The arc and back-arc processes involved in the tectonic evolution of the Miramichi terrane are considered analogous to complex Tertiary interactions between the Japanese arc and multistage opening of the Japan Sea (backarc basin) (van Staal *et al.* 1998, 2003).

Closure of the Iapetus Ocean and accretion of the Ganderian terranes to the ancient continental margin of North America (Laurentia) involved two cycles of arc volcanism: the middle Cambrian to Early Ordovician Penobscot arc/backarc system and the Early to Middle Ordovician Popelogan–Meductic arc/Tetagouche backarc system (Fyffe *et al.* 2023, and references therein). Polydeformation in the Miramichi terrane has been attributed to oblique closure of the Tetagouche backarc basin during the Late Ordovician to Silurian Salinic orogeny, and subsequent collision with the Laurentian continental margin during Early to Middle Devonian Acadian orogenesis (van Staal and deRoo 1995). Deposition of an Early Ordovician conglomerate in the Miramichi terrane marks a period of uplift related to the initial opening of the Tetagouche backarc basin. The pebbles in the conglomerate contain no evidence of a folding event associated with the earlier closure of the Penobscot backarc basin in southern New Brunswick. The pebbles contain no obvious pre-depositional cleavage nor do the strata above and below the conglomerate display any differences in their structural history (van Staal and Fyffe 1995; Poole and Neuman 2002).

The volcanic rocks in the southwestern Miramichi terrane include the Meductic Group in the Eel River area of New Brunswick, and the Stetson Mountain (Danforth area) and Olamon Stream (Greenfield area) formations in adjacent Maine (Figs. 1, 2). These volcanic rocks are characterized by a sequence of Early to Middle Ordovician calc-alkaline volcanic rocks, underlain by a substratum of Ganderian quartz-rich sedimentary rocks of the Woodstock Group in New Brunswick and correlatives in Maine (Fyffe 2001; McClenaghan *et al.* 2006; Ludman *et al.* 2021). Trace element characteristics of the volcanic-arc rocks in New Brunswick and Maine indicate that they are underlain by continental crust (Dostal 1989; Ludman *et al.* 2021).

The tectonic setting of calc-alkaline magmatism in the southwestern Miramichi terrane in New Brunswick (Meductic Group) contrasts markedly with the bimodal rifted arc to backarc magmatism (Tetagouche Group) in the Bathurst Mining Camp of the northeastern Miramichi terrane (van Staal *et al.* 2016; Fyffe *et al.* 2023). This transition from arc to backarc volcanism in the Miramichi terrane appears to overlap in time based on a combination of paleontological and geochronological data (Fig. 2). The emplacement age of the Benton pluton and its relationships to its host volcanic rocks therefore play an important role in determining the spatial and temporal relationships between subduction-related and backarc-related rifting in west-central New Brunswick and adjacent Maine (see below).

REGIONAL GEOLOGY

The regional geology of the southwestern Miramichi terrane in New Brunswick was surveyed by Anderson (1968), Venugopal (1978, 1979), and Fyffe (2001). In the Eel River area (Fig. 3), major faults mark the boundary between the Miramichi terrane and younger rocks in New Brunswick and into Maine (Venugopal 1978, 1979; Fyffe and Fricker 1987; Fyffe *et al.* 2011; Osberg *et al.* 1985; Ludman *et al.* 2018; Ludman and Berry 2003; Ludman 2020, 2023). To the northwest, the Woodstock fault separates the Miramichi terrane from the Matapedia Basin, a sequence of latest Ordovician to early Silurian limestone and shale of the Matapedia Group and ferromanganiferous siltstone of the Perham Group. To the southeast, a fault separates the Miramichi terrane from an outlier of Silurian polymictic conglomerate and minor crystalline limestone of the Perham Group and Early Devonian felsic and mafic volcanic rocks of the Tobique Group.

The oldest rocks exposed in the southwestern Miramichi terrane are included in the Woodstock Group, which comprises Cambrian–Ordovician quartzose and quartzofeldspathic sandstone of the Baskahegan Lake Formation and conformably overlying black shale and siltstone of the Bright Eye Brook Formation (Figs. 2, 3). The Baskahegan Lake Formation cannot be older than early Cambrian based on the radiometric date of 525 ± 6 Ma obtained from its youngest contained detrital zircon population (Fyffe *et al.* 2009). The trace fossil *Circulichnis montanus* found near Woodstock, New Brunswick, suggests that part of the Baskahegan Lake Formation is as young as Early Ordovician (Pickerill and Fyffe 1999). The overlying Bright Eye Brook black shale contains late Tremadocian to earliest Floian graptolites of the *Adelograpus tenellus* zone on the Eel River near Benton; and Early Ordovician (early Floian) graptolites of the *Tetragraptus approximatus* zone along Temple Road (old Trans-Canada Highway), just below the conformable contact with overlying volcanic rocks assigned to the Porten Road Formation (Fyffe *et al.* 1983; Pickerill and Fyffe 1999; Fyffe 2001; Fyffe and Wilson 2012).

The lower part of the Meductic Group consists of three volcanic units that lie conformably on black shale of the Bright Eye Brook Formation and range in composition upward from mainly felsic, to intermediate, to mafic. The basal Porten Road Formation contains mostly dacite and rhyolite with minor interlayered basalt; andesite and sparse black shale horizons occur near the base of the formation (Fyffe

2001; McClenaghan *et al.* 2006). The overlying Eel River Formation is dominated by andesite, followed by the Oak Mountain Formation, which is composed almost entirely of basalt. The boundaries of the three units are marked by relatively thin horizons of maroon to olive green ferromanganiferous siltstone (Fyffe 2001). A dacitic tuff from the Porten Road Formation yielded a zircon age of 480 ± 3 Ma (Fig. 2), consistent within error limits with the presence of the late Early Ordovician graptolites found in the black shale of the Bright Eye Brook Formation (Mohammadi *et al.* 2019; Fyffe *et al.* 2023). A sample of andesitic tuff taken from the Eel River Formation failed to yield enough zircon grains for dating purposes.

The Belle Lake Formation in the upper part of the Meductic Group comprises a feldspathic wacke-shale sequence that overlies the lower Meductic volcanic rocks with possible disconformity (Fig. 2). Grey silty shale, located just above the red chert horizon that defines the top of the Oak Mountain Formation, contains Late Ordovician (early Sandbian) graptolites of the *Nemagraptus gracilis* zone, so Meductic arc activity must have ceased prior to the late Darriwilian and possibly as early as the Dapingian stage of the Middle Ordovician (Fyffe *et al.* 1983; Fyffe 2001; Fyffe and Wilson 2012).

The intrusive contact of the Benton pluton with the Baskahegan Lake Formation of the Woodstock Group is exposed in the northeastern part of the Eel River area (Pickerill and Fyffe 1999; Fyffe 2001). The previously dated Early Ordovician Gibson and Connell Mountain plutons, located on the east side of the St. John River (Fig. 3), also have exposed intrusive contacts with the Baskahegan Lake Formation. The southwestern lobe of the Benton pluton appears to intrude both the Bright Eye Brook black shale of the Woodstock Group and overlying volcanic rocks of the Meductic Group (Fig. 3), although that actual contact is not exposed (Venugopal 1978, 1979; Fyffe 2001; Fyffe and Wilson 2012). The emplacement of the Benton pluton across the Woodstock–Meductic boundary is supported by the radiometric age obtained for the Benton pluton reported in this paper (see below).

DETAILED GEOLOGY OF THE BENTON PLUTON

The Benton pluton is a poorly exposed oblong granitoid body that trends north-northeast from the Eel River at Benton to Dugan Road, a distance of about 8 km (Fig. 4). Anderson (1968) and Venugopal (1978, 1979) noted that the northeastern part of the Benton pluton is more felsic than the southwestern part but did not delineate the areal extent of the different components. Sparse exposures of bedrock on main roads and along all-terrain vehicle (ATV) trails in the interior of the pluton were examined by Fyffe in the summer of 2022 in an attempt to map out the compositional variation. Locally fractured and altered outcrops on hillsides and flat, glacially polished surfaces in roadbeds provided enough information to divide the pluton into two distinctive granitoid components and to determine contact relationships between them. Modal mineral and chemical data on the Benton pluton are limited (see below) so the two components, referred to herein as the 'Caldwell Brook quartz monzonite' and 'Dugan Road monzogranite', should strictly be considered only as field terms.

Caldwell Brook quartz monzonite

The Caldwell Brook quartz monzonite forms the southwestern lobe of the Benton pluton and also crops out in a large area within the adjacent Dugan Road monzogranite, where it is interpreted as a roof pendant (Fig. 4). Contacts of the Caldwell Brook quartz monzonite with the sedimentary rocks of the Baskahegan Lake Formation to the north and south and volcanic rocks of the Meductic Group to the west are not exposed (Fig. 4) but have been interpreted to be intrusive (Venugopal 1978, 1979; Fyffe 2001).

The Caldwell Brook component of the Benton pluton is equigranular and medium- grained, typically grey on weathered surfaces (Fig. 5a), and mottled light pink and greyish green on fresh surfaces (Fig. 5b). Plagioclase crystals are saussuritized and mafic minerals are altered to chlorite. Exposures locally display a tectonic foliation and associated strong alteration, giving the rock a dark greyish green color. Point counts on cut slabs by Whalen (1993) give the following modal ranges for the least altered samples: 16.5–21.1% quartz; 32.6–36.2% plagioclase; 32.5–35.7% alkali feldspar; and 10.6–14.6% mafic minerals (amphibole, biotite, chlorite, epidote, and opaque minerals). Quartz-epidote veins up to a centimetre thick fill many fractures (Fig 5b).

Although previously considered to be coeval with the Gibson granodiorite by Whalen (1993), his modal analyses indicate that the Caldwell Brook component of the Benton pluton is mineralogically distinct, falling on average into the quartz monzonite rather than the granodiorite field on a QAP diagram (Fig. 6). In addition, chemical analyses (X-ray fluorescence) by Whalen (1993) indicate that the Caldwell Brook component (ignoring highly altered sample G10-40) contains significantly higher K_2O, Na_2O, TiO_2, P_2O_5, and TTE (total trace elements), and lower CaO, FeO, MgO, and MnO contents than the Gibson granodiorite (Table 1).

Dugan Road monzogranite

The Dugan Road monzogranite underlies the central and northeastern parts of the Benton pluton (Fig. 4). It is is best exposed in a roadcut on Dugan Road (loc 2 on Fig. 4) and in the Dugan Road crushed rock quarry (loc 3 on Fig. 4). Its contact with the Baskahegan Lake Formation to the east is exposed at a roadcut at the intersection of Dugan and Critter roads (Fig. 4), and in the Dugan Road crushed rock quarry (loc 3 on Fig. 4). Baskahegan Lake hornfels within 5 m of the contact contains abundant cordierite porphyroblasts (Fig 7a) and wispy fine-grained grey granite dykelets. Inclusions of the Baskahegan Lake Formation are engulfed by medium grained light greyish pink monzogranite along a woods-road at the eastern boundary of the intrusion north

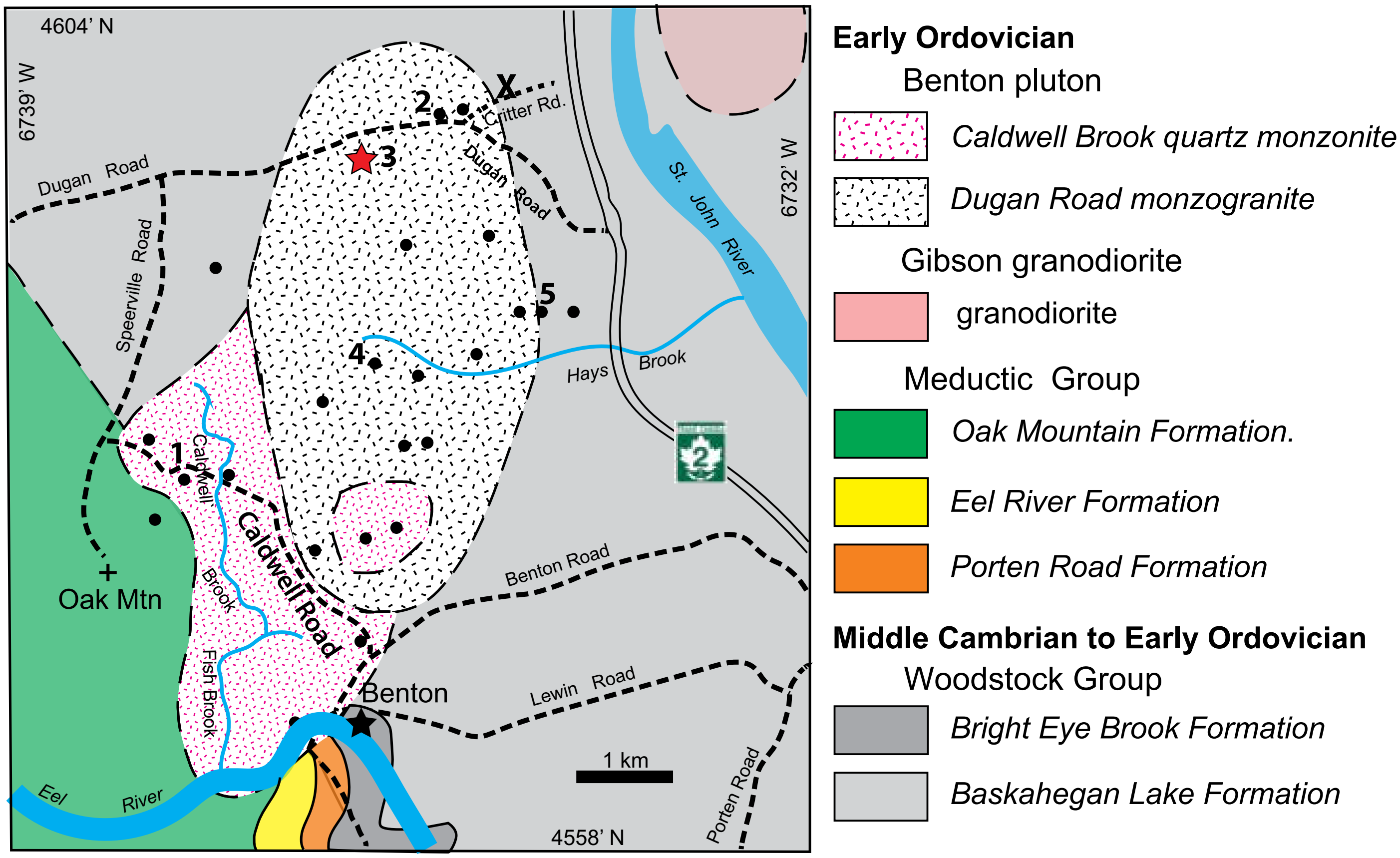

Figure 4. Detailed geologic map of the Benton pluton and adjacent rocks of the Woodstock and Meductic groups. Dots = outcrops; numbers refer to outcrops described in the text. X=quarries. Red star is location of dated U–Pb sample from quarry [lat. 46.04943, long. -67.59912]. Black star shows fossil locality.

of Hays Brook (Fig 7b), and at the contact with a roof pendant in the Dugan Road quarry (Fig 7c).

The Dugan Road component of the Benton pluton is typically a pink, medium-grained, equigranular monzogranite (Fig. 8a) that grades locally to medium-grained (Fig. 8b) and fine-grained, porphyritic varieties (Fig. 8c), containing partially saussuritized white plagioclase phenocrysts. Angular brecciated fragments occur within cataclastic shear zones in the granite (Fig. 8d). Visible estimations by Venugopal (1978) yielded the following modal ranges for the Dugan

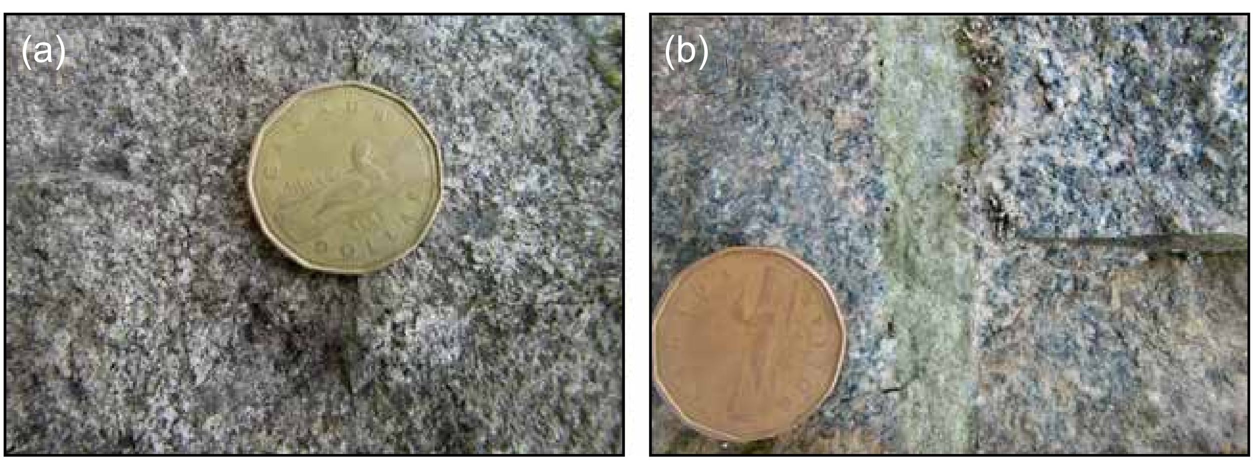

Figure 5. Caldwell Brook quartz monzonite. (a) Weathered grey Caldwell Brook quartz monzonite on Caldwell Road (loc. 1 on Fig. 4). (b) Fresh mottled light pink and greyish green Caldwell Brook quartz monzonite on Caldwell Road cut by quartz - epidote vein (loc. 1 on Fig. 4). Coin is 25 mm in diameter.

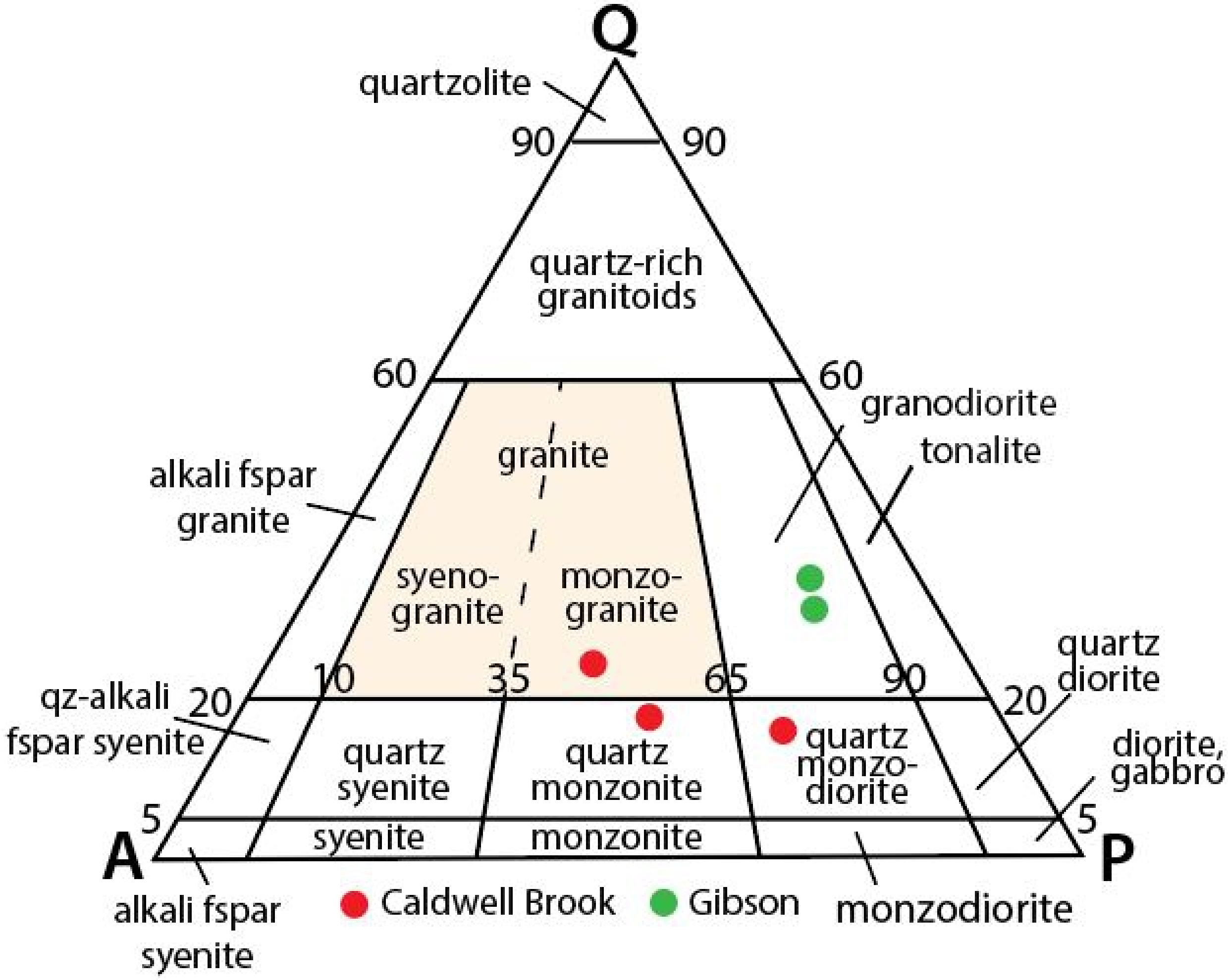

Figure 6. Modal quartz (Q)-alkali feldspar (A)-plagioclase (P) diagram. Data from Whalen 1993.

Road monzogranite: 20–25% quartz; 15–20% plagioclase; 15–25%, alkali feldspar; 15–20% granophyric intergrowth (quartz plus alkali feldspar); 1–10% chlorite; 1–5% epidote; and minor opaque minerals. The only chemical analyses available from the Dugan Road component are X-ray fluorescence data listed in Crocco (1975) from an unpublished M.Sc. thesis by Martin 1966). These results are of low quality compared to modern standards but the reported alkali feldspar to plagioclase ratios and SiO_2 contents are consistent with a monzogranite composition for the Dugan Road component (Table 1).

Relationship between the Dugan Road and Caldwell Brook components

Evidence for the relationship between the Dugan Road and Caldwell Brook components of the Benton pluton is provided in a large outcrop exposed along the southern margin of a beaver pond on the headwaters of Hays Brook in the central part of the Benton pluton (loc 4 on Fig. 4). The flat-lying exposure displays medium-grained, pink, porphyritic granite dykes intermingled with finer grained, equigranular, grey igneous inclusions up to 20 cm long (Fig. 9a). The dyke is interpreted to represent Dugan Road monzogranite that has engulfed and partially assimilated a large block of grey Caldwell Brook quartz monzonite. The irregular margins of the Caldwell Brook inclusions suggest the block was not completely crystallized at the time that the dykes were injected (Fig. 9b), and that the two magmas were at least partly coeval.

AGE OF THE BENTON PLUTON

Like most of the relatively undeformed intrusions in the Miramichi Highlands, the Benton pluton was assigned a Devonian age by Anderson (1968), Venugopal (1978, 1979), and Fyffe *et al.* (1981). However, Bevier (1989), Whalen (1993), and van Staal *et al.* (2016) subsequently reported Early Ordovician ages from the nearby Gibson granodiorite and Connell Mountain tonalite (Fig. 2). This evidence of Early Ordovician plutonism in the Eel River area suggested that the Benton pluton might also have been emplaced at that time and could potentially be coeval with the volcanic rocks of the Meductic Group (van Staal *et al.* 2016).

To test this hypothesis, fresh samples of the Dugan Road

Table 1. Major element compositions (wt. %) of the Benton and Gibson plutons.

	Benton Pluton				Gibson Pluton[2]		
	Dugan Road[1]		Caldwell Brook[2]				
Sample	BH-7347	BH-7348	G10-39	G10-40	G10-41	G10-42	G10-43
SiO_2	72	73	66.5	59	68.9	67.5	65.65
TiO_2	0.5	0.4	0.5	0.84	0.41	0.35	0.35
Al_2O_3	16	16	15.2	15.9	14.3	14.4	14.7
Fe_2O_3	3.3	3.9	2.01	3.31	1.22	1.91	1.81
FeO			1.7	3.8	1.6	2.35	2.9
MnO	0.05	0.09	0.06	0.13	0.06	0.08	0.09
MgO	0.9	1.4	1.19	2.5	1.28	1.66	2.2
CaO	2.9	1.4	2.83	5.23	1.01	4.09	4.58
Na_2O	3.4	3.9	4.29	3.51	4.35	3.61	3.58
K_2O	3	3.6	3.37	2.86	3.94	2.03	2.1
P_2O_5			0.15	0.28	0.11	0.06	0.06
LOI			1.39	1.54	1.54	1.77	1.73
TTE			0.24	0.25	0.2	0.12	0.13
Total			99.43	99.15	98.92	99.92	99.89
A/P	0.8	0.9	0.9	0.4	1.1	0.2	0.2

Data: [1]Martin (1966) in Crocco (1975); [2]Whalen (1993).TTE = total trace elements (wt. %). Analysis by X-ray fluorescence. A/P = alkali feldspar:plagioclase feldspar ratio.

monzogranite were collected from the Dugan Road quarry (loc 3 on Fig. 4) in the summer of 2022 and sent to Overburden Drilling Management Ltd. (Ottawa, Ontario) for electric pulse disaggregation and initial zircon separation. This initial separate, containing thousands of euhedral gem-quality zircon grains (Fig. 10), was sent to the University of New Brunswick geochronology centre for final separation and dating.

Analytic methods

Analyses were conducted at the University of New Brunswick using an ASI M-50 193 nm excimer laser ablation system (Complex Pro 110) with a 20 ns pulse width. The ablation system is equipped with a Laurin Technic Pty S–155 two–volume ablation cell coupled, using 4mm OD Nylon tubing, to an Agilent 8900 triple-quad ICP-MS. Ablated material was transported to the ICP-MS using a mixed He (300 mL/min) and Ar (930 mL/min) carrier gas. Sensitivity was enhanced by adding N_2 (2.0 mL/min) downstream of the cell. Due to isobaric interference of ^{204}Pb with ^{204}Hg impurities within the carrier gas, direct measurement of the ^{204}Pb signal was permitted by using in-line high-capacity Vici Metronics Hg traps on all gas lines ensuring that ^{204}Hg remains <150 cps under maximum sensitivity conditions. Correction of the ^{204}Hg interference on ^{204}Pb was then performed via peak–stripping using the measured ^{202}Hg on the gas background and assuming a canonical value for ^{202}Hg/^{204}Hg. Results are presented in Appendix A (Table A1).

Analyses of all unknowns were bracketed with at least 16 spots on primary reference material to monitor and correct for instrument drift and time-dependent down-hole fractionation (Appendix A, Table A2). A 14 μm crater size, 3 J/cm^2 laser energy, and a repetition rate of 4 Hz was used for all unknowns and standards. The following elements were monitored during each ablation (dwell time provided in brackets); ^{90}Zr (0.01s), ^{202}Hg (0.01s), ^{204}Pb (0.04s), ^{206}Pb (0.06s), ^{207}Pb (0.08s), ^{208}Pb (0.008s), ^{238}U (0.02s), and ^{232}Th (0.01s). Zircon FC-1 was used as the primary reference standard (1099 Ma; Paces and Miller 1993), whereas Plešovice was used as the secondary standard (337 Ma; Sláma *et al.* 2008). ^{90}Zr was used as a guide mass for ablations and internal standardization using an estimated value of 48 wt% Zr. NIST 610 was used for instrument tuning and as a concentration standard. Drift was modelled using Iolite3.7™ automatic fit function whereas down-hole fractionation was modelled using the automatic exponential fit option. The net ^{204}Pb (cps) signal was used for common Pb corrections (if required) for zircon and incorporated into the VizualAge U–Pb data reduction scheme (DRS) (Petrus and Kamber 2012) operating under Iolite3.7™. The routine uses an age estimate based on the measured ^{206}Pb/^{238}U and common Pb ratios based on the evolution curves of Kramers and Tolstikhin (1997). Common Pb corrections to the unknowns were applied to points with ^{204}Pb >50 net cps and <20% 1σ internal errors.

Results

Concordia ages were calculated for clusters of three or

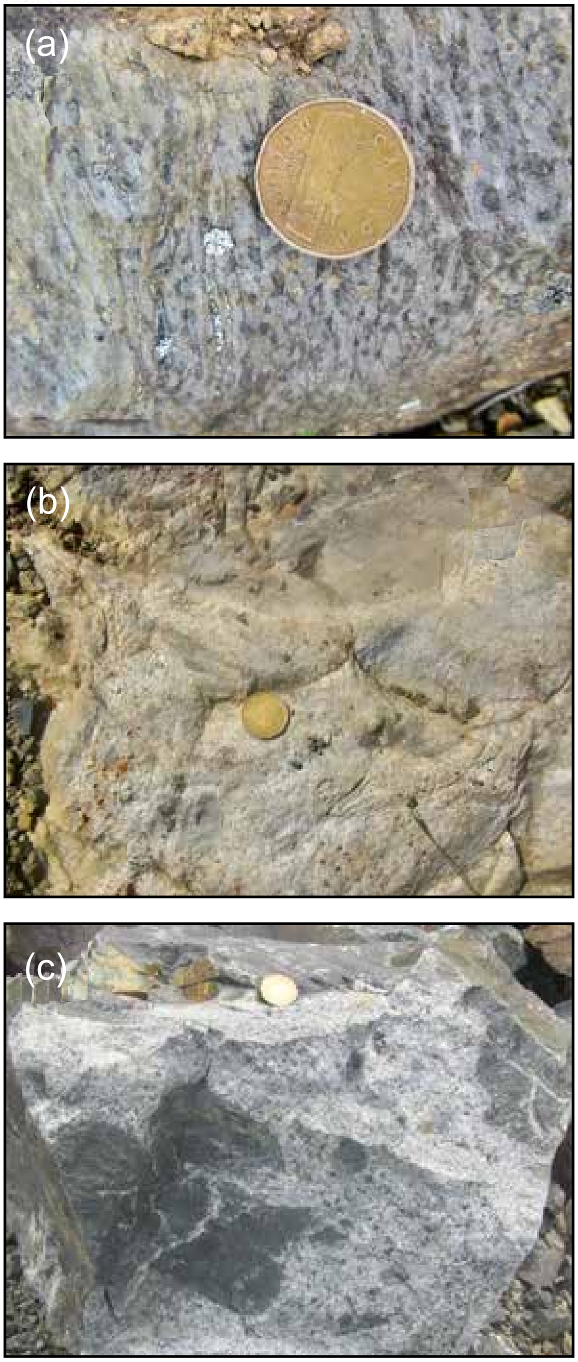

Figure 7. Features at contacts between the Dugan Road monzogranite and Baskahegan Lake Formation. (a) Cordierite porphyroblasts in hornfelsed Baskahegan Lake sedimentary rocks near contact (loc 2 on Fig. 4). (b) Small dykes of of Dugan Road monzogranite cutting quartzoze sandstone of the Baskahegan Lake Formation at its eastern contact (loc. 5 on Fig. 4). (c) Sedimentary xenoliths in Dugan Road monzogranite at contact with a Baskahegan Lake roof pendant in the Dugan Road quarry (loc 3 on Fig. 4).

more near-concordant points using Isoplot versions 3.75 and 4.15 (Ludwig 2003, 2012). Three Concordia diagrams are used to illustrate the results obtained from the analysed zircon grains separated from the Dugan Road monzogranite (Fig. 11). The first diagram (Fig. 11a) presents the results for the entire set of individual analysed spot sample sites listed in Appendix A (Table A1) and shown as back-scatter images in Appendix B.

The second diagram plots only the highly concordant spot sample sites (shown by '*' in Appendix A, Table A1), which were used to determine the age of the monzogranite (Fig. 11b). These results indicate that the Dugan Road monzogranite was most likely emplaced during the late Dapingian to early Darriwilian stage of the Middle Ordovician at 467 ± 2 Ma, centered just above the Dapingian/Darriwilian stage boundary defined at 467.3 ± 1.1 Ma (Fig. 2). Field relationships described above (Fig. 9) suggest that intrusion of the Dugan Road monzogranite and Caldwell Brook quartz monzonite was at least partly coeval, so this Middle Ordovician age can likely be attributed to the entire pluton. Thus, the age of the Benton pluton is considerably younger than that of the Gibson granodiorite (473 ± 1 Ma) and Connell Mountain tonalite (474 +1/-4 Ma); the significance of this result is discussed below.

The third Concordia diagram plots spots from four zircon grains that yielded inheritance ages ranging from 524 ± 12 Ma to 519 ± 13 Ma (Fig. 11c; shown by '×' in Appendix A, Table A1). These ages overlap with the youngest 525 ± 6 Ma detrital zircon population identified in the Cambrian–Ordovician sedimentary rocks of Baskahegan Lake Formation near Woodstock, New Brunswick (Fyffe *et al.* 2009). The source of these inherited early Cambrian zircons is obscure, but they do overlap within two sigma error with the eruptive age of the older volcanic rocks in the Penobscot arc (515 Ma) in southern New Brunswick (Fyffe *et al.* 2023).

DISCUSSION

Duration of magmatism in the Eel River area

Eruption of calc-alkaline volcanic rocks of the Meductic Group in the Eel River area of west-central New Brunswick has been attributed to southeasterly subduction of Iapetan oceanic crust that began in the Early Ordovician. The 480 ± 3 Ma age of a dacitic tuff near the base of the Porten Road Formation marks the initiation of this volcanic-arc activity. The timing of the cessation of Meductic volcanism is uncertain since neither of the overlying formations, the Eel River and Oak Mountain, has been dated. However, the deposition of the graptolite-bearing Belle Lake feldspathic wacke-shale sequence in the upper part of the Meductic Group indicates that volcanism in New Brunswick had ceased prior to early Sandbian of the Late Ordovician (Fig. 2). The sharp contact which separates the volcanic rocks from the overlying Belle Lake sedimentary rocks is interpreted as a hiatus that may have lasted over a poorly defined time interval of

Figure 8. Dugan Road monzogranite outcrops. (a) Pink, medium-grained, equigranular monzogranite on Dugan Road (loc. 2 on Fig. 4). (b) Pink, medium-grained, porphyritic monzogranite containing white plagioclase phenocrysts cross-cut by a narrow cataclastic shear zone (lower right corner) on Dugan Road (loc. 2 on Fig. 4). (c) Pink, fine-grained, porphyritic monzogranite containing saussauritized white plagioclase phenocrysts in Dugan Road quarry (loc. 3 on Fig. 4). (d) Pink zone of cataclastic monzogranite on Dugan Road (loc. 2 on Fig. 4).

ca. 7 million years. As such, volcanic arc activity in the Eel River area probably occurred over a period of at least 10 million years (Fyffe *et al.* 1983; Fyffe 2001).

The geochemistry of the dated Ordovician plutons in the Eel River area (Fig. 3) can be used to provide some support for the duration of volcanism in the region. The subduction-related Early Ordovician (Floian) Gibson granodiorite and Connell Mountain tonalite (Fig. 12), both of which may be comagmatic with the volcanic rocks of Meductic Group (Whalen 1993; Whalen *et al.* 1998; van Staal *et al.* 2016), are 6 or 7 million years younger than the base of the Porten Road Formation (Fig. 2). In particular, the geochemistry of these plutons suggests that they were more likely associated with the dacitic to andesitic rocks of the Eel River Formation than with the younger, dominantly basaltic Oak Mountain Formation. A successful attempt at dating the Eel River Formation would test the above assumptions although the radiometric error limits could be too large to yield a conclusive outcome.

The Middle Ordovician (late Dapingian to early Darriwilian) age of the Benton pluton falls within the proposed limits of the hiatus separating the volcanic sequence in the lower Meductic Group from the overlying Belle Lake sedimentary sequence of the upper Meductic Group (Fig. 2). As discussed below, the Benton pluton possesses some arc-like characteristics (Fig. 12) that could indicate the existence of subduction-related volcanic rocks post-dating those of the lower Meductic Group. No such volcanic rocks are known in the Eel River area of New Brunswick but have been identified by Ludman *et al.* (2021) in the Greenfield area of adjacent Maine (Figs. 1, 2).

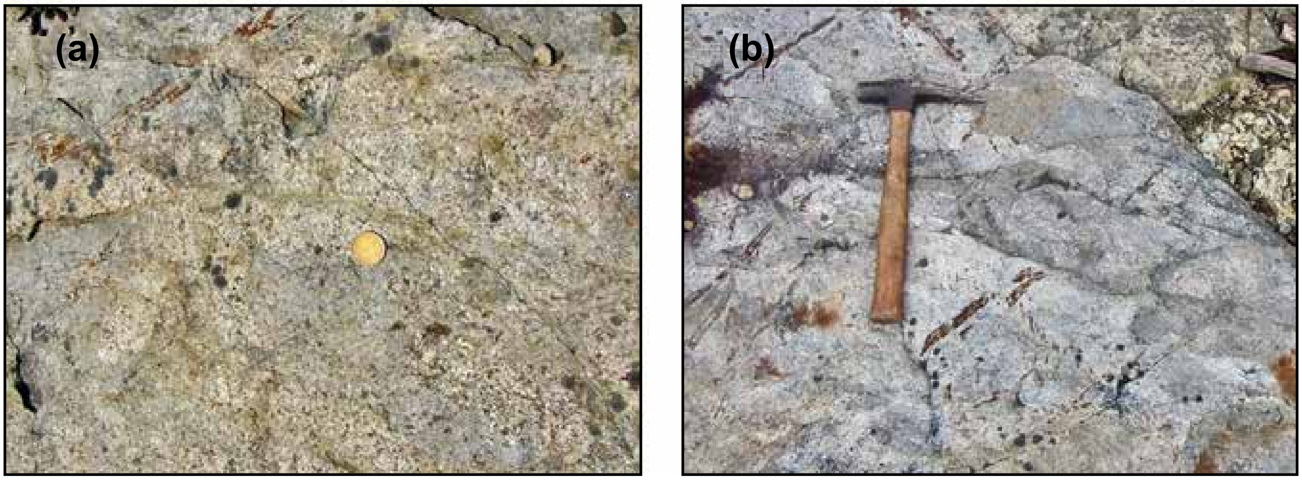

Figure 9. Relationship between Dugan Road monzogranite and Caldwell Brook quartz monzonite. (a) Pink, medium-grained, porphyritic granite dykes intermingled with finer grained, equigranular, grey igneous inclusions (below coin) on headwaters of Hays Brook (loc. 4 on Fig. 4); the irregular margins of the grey inclusions suggests that they were was not completely crystallized at the time that the porphyritic granite dykes were injected into them. (b) Irregular outlined inclusions of Caldwell Brook quartz monzonite in Dugan Road monzogranite. A narrow cataclastic shear zone in the flat outcrop (to the right of hammer handle) contains comminuted granite fragments (loc. 4 on Fig. 4). Hammer is 30 cm in length.

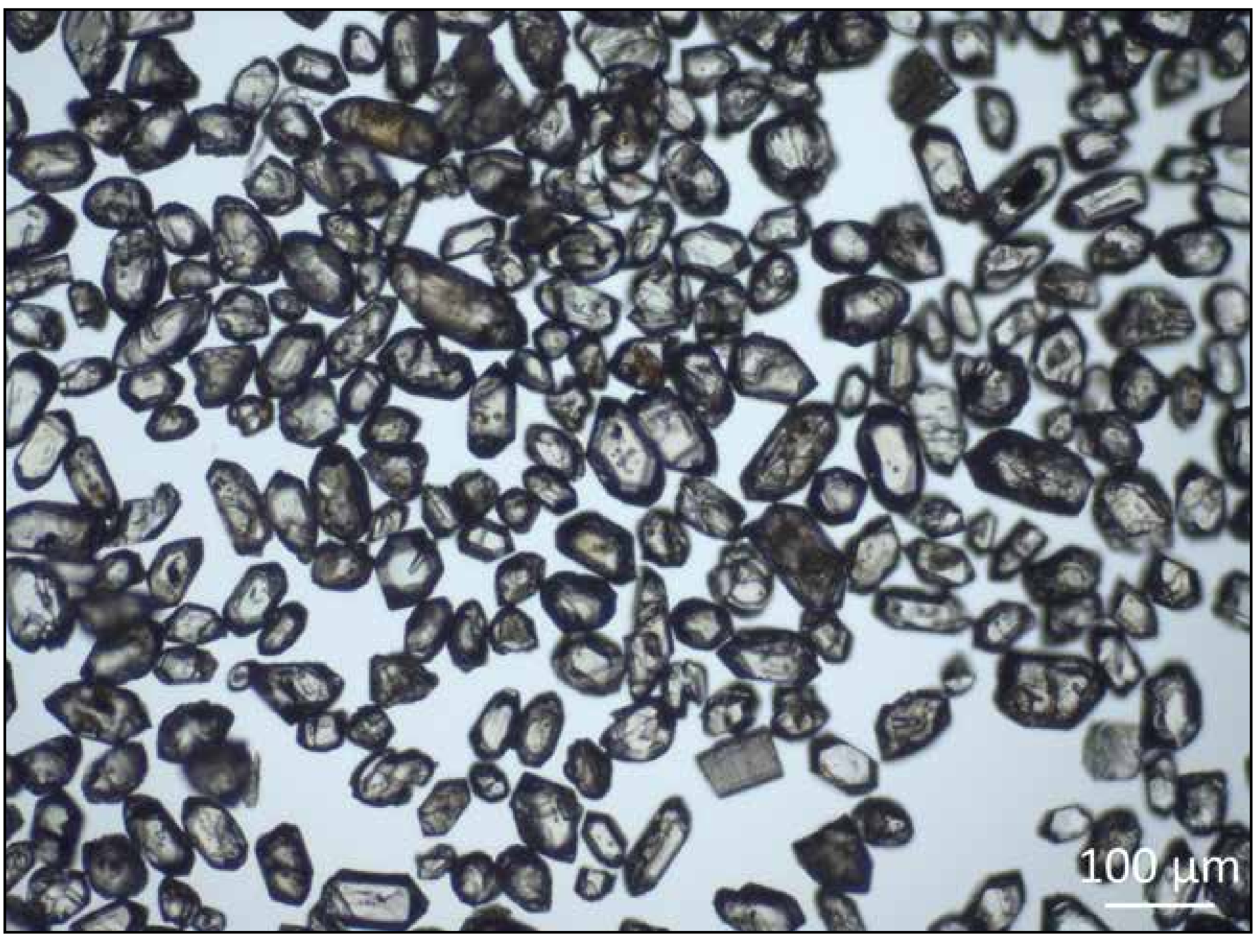

Figure 10. Zircons from the Dugan Road monzogranite.

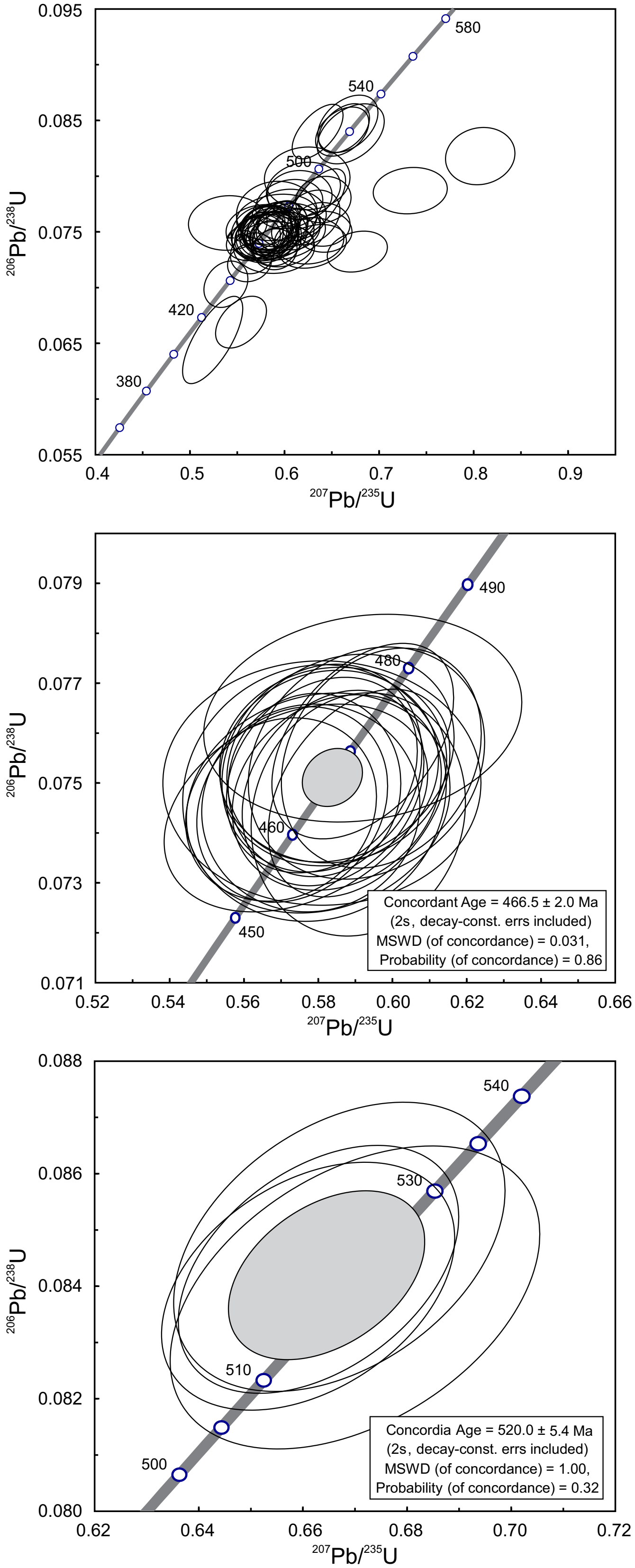

Figure 11. Concordia diagrams for Benton pluton zircon analyses. (a) All zircon analyses (b) Closeup of concordant group (c) Inherited group.

Tectonic signature of the Benton pluton

It has been proposed that rollback of the Meductic subduction slab led to formation of intra-arc grabens, eruption of felsic volcanic rocks onto thinned Ganderian continental crust, and to diachronous development of the Tetagouche backarc basin during the Middle Ordovician (van Staal and Fyffe 1995; van Staal *et al.* 2003, 2016). Plutons emplaced into the rift-related volcanic rocks of the Tetagouche Group are rare so it is difficult to make comparisons with the intrusive rocks of the Eel River area. However, a small (ca. 10 km^2), elongated body of foliated, medium-grained, granophyric, leucocratic granite, referred to as the South Little River Lake Granite, was emplaced into tuffaceous sedimentary rocks at the base of the Nepisiguit Falls Formation in the Heath Steele Mine area of the Bathurst Mining Camp in the northeastern Miramichi terrane (Wilson 1993; Wilson and Fyffe 1996). Dated at 470 ± 3 Ma (McNicoll *et al.* 2003), it is similar in age to the Benton pluton of the Eel River area (Fig. 2). However, the chemistry of the South Little River Lake and Benton plutons differs markedly in major and trace element characteristics. The South Little River Lake pluton has an SiO2 content of ca. 76% compared to ca. 73% and ca. 68% for the Dugan Road and Caldwell Brook components of the Benton pluton, respectively (Whalen 1993, Martin 1966).

The Rb vs Y+Nb granite tectonic discrimination diagram of Pearce *et al.* (1984) separates volcanic-arc (VAG) granites with Y + Nb < 50 ppm from within-plate (WPG) granites with Y + Nb >50 ppm (Fig. 12). This diagram clearly distinguishes the Benton (Caldwell Brook quartz monzonite), Gibson, and South Little River Lake plutons from each other (Fig. 12). The Caldwell Brook quartz monzonite plots in the volcanic-arc field whereas the South Little River Lake granite falls in the within-plate field. The Gibson granodiorite also plots in the volcanic-arc field, but is clearly distinct from the Caldwell Brook quartz monzonite (Whalen 1993; Whalen *et al.* 1998). Martin (1966) listed chemical analyses of two samples from the Dugan Road monzogranite in his study of New Brunswick granites, but the elements Y and Nb were not included. However, field relations noted above suggest that both components of the Benton pluton should likely carry an arc-related signature.

Ordovician volcanic-arc rocks in Maine

The Pokiok and Bottle Lake intrusions interrupt the southwestward continuity of the Miramichi terrane from the Eel River area, obscuring relationships between the volcanic rocks of the Meductic Group and those in the Danforth and Greenfield areas in Maine. (Figs. 1, 2). The Stetson Mountain Formation of the Danforth segment has been correlated with the Meductic Group (Sayres 1986; Winchester *et al.* 1992; van Staal *et al.* 2016; Ludman 2020, 2023) for several reasons: (1) Both the Meductic and Stetson Mountain suites lie conformably on a common substrate; indeed, the type locality of the Baskahegan Lake Formation is in the Danforth

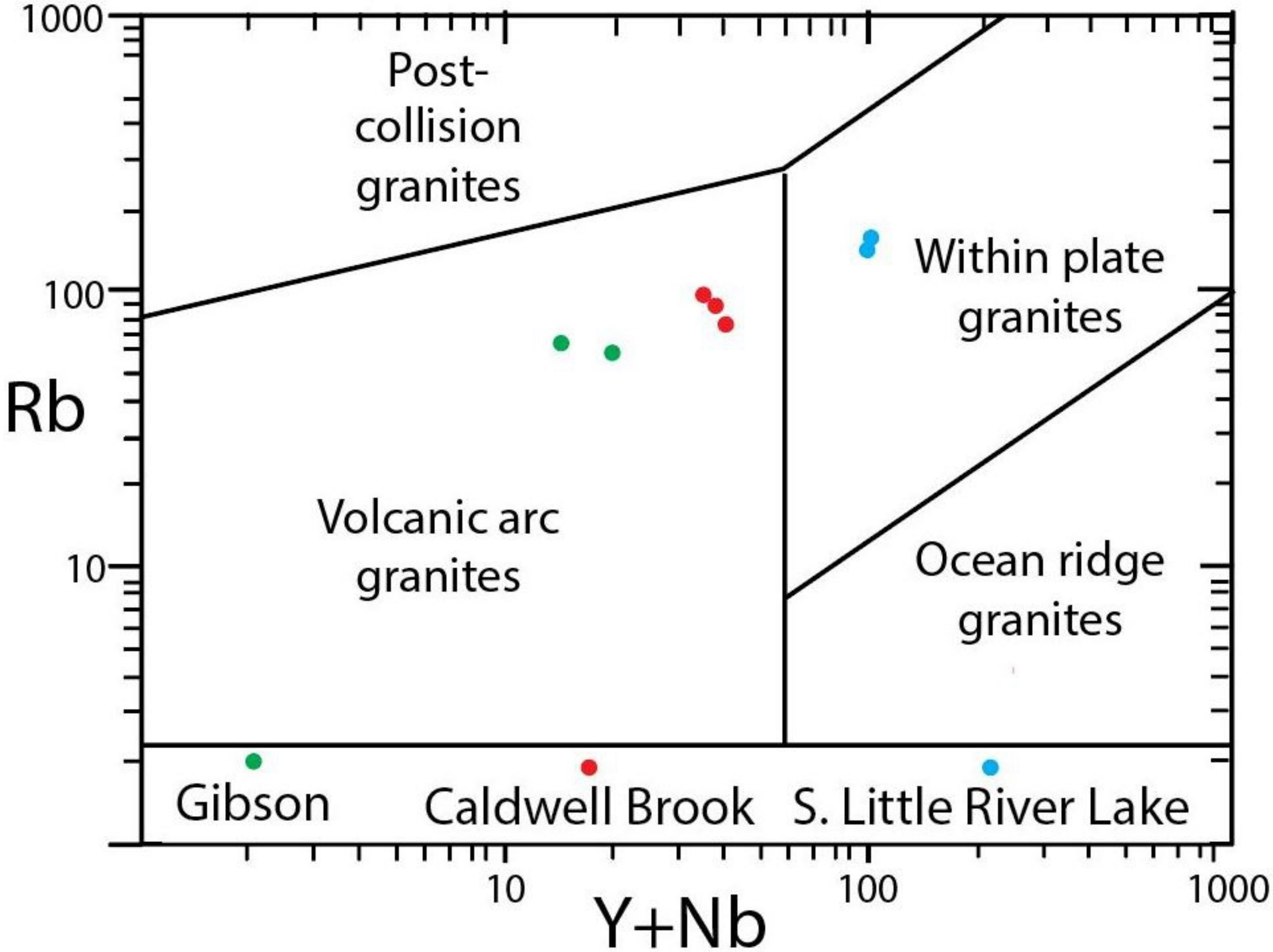

Figure 12. Granite tectonic discrimination diagram: chart after Pearce *et al.* 1984; data from Whalen 1993.

segment. The Baskahegan Lake Formation is overlain there by anoxic shale and sandstone of the Bowers Mountain Formation, very similar to the Bright Eye Brook Formation (Ludman 1991). (2) The oldest rocks in the Stetson Mountain Formation are pyroclastic rhyolites and dacites (Sayres 1986) like those of the basal Porten Road Formation, and pass upward into andesites comparable to the Eel River Formation. (3) The proportions of andesite, dacite, and rhyolite are very similar in both the Meductic and Stetson Mountain suites (Ludman *et al.* 2021); and (4) both suites are located along the trend of the Miramichi terrane at its western margin. The principal difference is the absence of basalt from the Stetson Mountain Formation, unlike the progressively more mafic volcanic rocks of the Meductic Group.

Relationships between the Olamon Stream Formation and its substrate in the Greenfield section are less certain. The Baskahegan Lake and Bowers Mountain formations crop out in the northern part of the section but are separated by a broad area of till from the Olamon Stream volcanic rocks (Ludman 2023). Like the Stetson Mountain Formation, the Olamon Stream Formation comprises mostly pyroclastic andesite, dacite, and rhyolite, but also contains a distinctive basalt member, whose stratigraphic position is unknown.

Ironically, attempts to date the Stetson Mountain Formation, whose stratigraphic position is best known, proved unsuccessful, whereas less well constrained Olamon Stream tuffs and a lava flow yielded Middle Ordovician ages of 470 ± 4 Ma, 467 ± 4 Ma, and 469.3 ± 4.6 Ma. These ages are 10–13 million years younger than the Porten Road Formation (480 ± 3 Ma), so that the eruption of the dated part of the Olamon Stream was not coeval with the lower part of the Meductic Group, and possibly may have occurred later than the entire Meductic volcanic suite. Ages similar to the Olamon Stream Formation have been found along trend in arc-related volcanic rocks in the Casco Bay Group (472 ± 5, 469 ± 3, and 465 ± 4 Ma) in coastal Maine (West *et al.* 2004; Johnson *et al.* 2022).

The Olamon Stream Formation also overlaps in age with volcanic rocks of the Nepisiguit Falls, and Flat Landing Brook formations of the Tetagouche and California Lake groups (Fyffe *et al.* 2023), indicating the existence of a subduction-related episode that is younger than the known Meductic arc volcanism, and is in part contemporaneous with rifting within the Tetagouche backarc basin (Fig. 2). It is suggested here that the eruption of the Olamon Stream volcanic rocks represents the re-location of plate subduction to the Greenfield segment following shut-down of the Meductic arc at ca. 470 Ma. Slab rollback subsequently led to the incursion of late stage backarc rifting into the southwestern Miramichi terrane during northwest migration in the Popelogan–Meductic arc system (Fig. 1), similar to that proposed by van Staal *et al.* (2003, 2016). A dacitic tuff related to the rifting of the Popelogan arc in northern New Brunswick (Fig. 1) has been dated 467.4 ± 0.4 Ma (van Staal *et al.* 2016), so the emplacement of the Benton pluton into the Meductic volcanic sequence at 467 ± 2 Ma in west-central New Brunswick is consistent with intra-arc extension associated with the propagation of a branch of the Tetagouche backarc basin into the Eel River area of the southwestern Miramichi terrane (see fig. 4d of Fyffe *et al.* 2023). However, details of the differences in timing of the Olamon Stream, Stetson Mountain, and Meductic eruptions are presently poorly understood (Figs. 1, 2), and may be difficult to discern given the margin of error associated with radiometric dating techniques.

Suggestions for future work

It is clear that the geology of the southwestern New Brunswick and Maine segments of the Miramichi terrane is more complex than previously understood, and that more geochronological studies are needed to unravel those complexities.

The U–Pb zircon age reported here dates intrusion of the Dugan Road monzogranite at 467 ± 2 Ma, but the age of the associated Caldwell Brook quartz monzonite is not known with certainty. There is also some confusion in the literature about a 479 ± 7 Ma age initially attributed to the Gibson granodiorite (Whalen 1993) but later listed as coming from the Benton granite (Whalen *et al.* 1998). At the time, both the Benton and Gibson plutons were treated in the literature essentially as a single entity. Given confusion in regard to the location of the dated sample, its large error limits, and field evidence that the Caldwell Brook quartz monzonite intrudes the contact between the Woodstock and Meductic groups, the Caldwell Brook body should be dated to confirm that the two components of the Benton pluton were, indeed, coeval.

The single age of the base of the Porten Road Formation is not sufficient to characterize the entire lower Meductic Group, nor the duration of the volcanism it records. Measured ages of the Eel River Formation, and possibly the Oak Mountain Formation would be more convincing in regard to the span of Meductic arc activity than inferences about relationships to associated volcanic and plutonic rocks. Similarly, more of the Miramichi volcanic rocks in Maine need to be dated. The three ages in the Greenfield section are a beginning, but additional ages over a wider area could help establish a better understanding of the stratigraphy within the Olamon Stream Formation (Ludman 2023). Any age from the Stetson Mountain Formation would be an improvement, and would be critical in correlation with the Meductic Group and interpretation of structural relationships in Maine and New Brunswick.

Structural relationships in the Eel River, Danforth, and Greenfield areas should be re-examined. It is not clear whether contacts between the Olamon Stream and the underlying Baskahegan Lake and Bowers Mountain formations in the Greenfield area are conformable, unconformable, or tectonic. Similarly, determining the structural relationship between the Gibson, Connell Mountain, and Benton plutons and their host rocks could lead to a better understanding of their possible comagmatic relationships with Ordovician volcanic rocks in the southwestern Miramichi terrane.

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APPENDIX A

Table A1. LA-ICP-MS U–Pb isotopic analyses of zircons (University of New Brunswick) from the Dugan Road monzogranite.

Comments		(ppm)			Common-Pb			Final isotope ratios							Final ages (Ma)						
		U	Th	U/Th	^{204}Pb cps	^{206}Pb/^{204}Pb cps	%Pb*	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	err. corr.	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	% conc
z_BT1_core - 1		150	190	0.79	20	376	98.07	0.807	0.030	0.082	0.002	0.10	0.073	0.002	972	70	603	16	507	13	84.0
z_BT1_core - 4		358	487	0.74	27	570	98.71	0.677	0.026	0.073	0.002	0.22	0.067	0.002	832	66	526	15	456	9	86.6
z_BT1_core - 13		465	474	0.98	16	1509	99.19	0.642	0.024	0.075	0.002	0.01	0.061	0.002	619	66	502	15	466	9	92.9
z_BT1_core - 5		229	161	1.43	11	865	99.16	0.554	0.022	0.067	0.002	0.44	0.061	0.002	625	69	448	14	417	11	93.1
z_BT1_core - 7		412	369	1.12	5	3934	99.25	0.640	0.024	0.076	0.002	0.00	0.061	0.002	627	69	502	15	470	10	93.6
z_BT1_core - 19		321	297	1.08	-20	17340	99.53	0.598	0.027	0.074	0.002	0.17	0.059	0.002	564	80	475	17	458	9	96.5
z_BT1_core - 17		462	523	0.88	2	11321	99.40	0.634	0.025	0.078	0.003	0.66	0.060	0.002	592	58	498	16	482	15	96.8
z_BT1_core - 10	*	390	407	0.96	22	980	99.49	0.591	0.022	0.074	0.002	0.10	0.059	0.003	561	89	471	14	463	12	98.3
z_BT1_core - 3	*	151	152	0.99	-2	6810	99.76	0.586	0.025	0.076	0.002	0.20	0.057	0.002	454	78	469	17	469	10	100.1
z_BT1_core - 8	*	195	196	0.99	-1	10000	99.64	0.574	0.029	0.075	0.002	0.33	0.056	0.002	449	94	459	18	463	10	101.0
z_BT1_core - 12	*	481	431	1.12	-7	24890	99.73	0.597	0.022	0.076	0.002	0.22	0.056	0.002	442	74	475	14	469	11	98.8
z_BT1_core - 6	*	85	74	1.15	2	1854	99.78	0.580	0.029	0.075	0.002	0.14	0.057	0.003	430	96	461	18	464	11	100.6
z_BT1_core - 18	×	312	265	1.18	-6	16492	99.73	0.663	0.022	0.084	0.002	0.42	0.057	0.001	499	46	519	13	522	11	100.6
z_BT1_core - 11		172	211	0.82	-1	9710	99.65	0.620	0.032	0.079	0.002	0.15	0.058	0.003	490	100	490	20	489	12	99.7
z_BT1_core - 15	×	317	311	1.02	14	1337	99.57	0.667	0.026	0.085	0.002	0.39	0.058	0.002	503	65	517	16	524	12	101.3
z_BT1_core - 2		283	229	1.24	1	13445	99.74	0.576	0.020	0.075	0.002	0.26	0.056	0.002	441	57	461	13	469	10	101.7
z_BT1_core - 20		388	282	1.38	-11	20920	99.80	0.635	0.022	0.084	0.002	0.60	0.055	0.001	424	51	501	14	520	12	103.8
z_BT1_og - 1		190	159	1.20	19	406	98.59	0.733	0.032	0.079	0.002	0.09	0.067	0.003	863	78	560	19	488	10	87.2
z_BT1_og - 23		134	94	1.42	-3	5440	99.11	0.630	0.029	0.074	0.002	0.27	0.062	0.002	628	83	493	18	459	10	93.0
z_BT1_og - 17		122	125	0.97	3	1713	99.13	0.626	0.030	0.074	0.002	0.09	0.061	0.003	647	89	492	19	462	10	93.8
z_BT1_og - 10		632	395	1.60	25	959	99.35	0.524	0.026	0.065	0.003	0.72	0.059	0.002	554	74	427	17	408	19	95.6
z_BT1_og - 25		205	194	1.06	-3	8300	99.35	0.628	0.025	0.076	0.002	0.28	0.060	0.002	608	75	494	15	474	12	95.9
z_BT1_og - 11		407	371	1.10	11	1655	99.45	0.641	0.024	0.078	0.002	0.08	0.060	0.002	592	67	502	15	484	10	96.3
z_BT1_og - 19		368	250	1.47	9	1866	99.43	0.612	0.021	0.075	0.002	0.16	0.059	0.002	557	65	484	13	468	9	96.6
z_BT1_og - 16		280	164	1.71	13	845	99.41	0.590	0.019	0.073	0.002	0.04	0.058	0.002	544	58	471	12	457	9	97.1
z_BT1_og - 15		196	119	1.64	20	460	99.59	0.605	0.027	0.076	0.002	0.12	0.058	0.002	524	86	481	17	470	9	97.7
z_BT1_og - 12		182	149	1.22	4	1813	99.40	0.589	0.035	0.074	0.002	0.03	0.058	0.004	510	130	468	22	458	12	97.8
z_BT1_og - 34		124	69	1.81	4	1443	99.57	0.597	0.028	0.075	0.002	0.20	0.058	0.002	507	88	474	17	465	10	98.1
z_BT1_og - 20		149	141	1.06	-4	6990	99.48	0.598	0.037	0.075	0.002	0.23	0.059	0.003	570	110	473	24	465	11	98.3

Table A1. Continued.

		(ppm)			Common-Pb			Final isotope ratios							Final ages (Ma)						
Comments		U	Th	U/Th	^{204}Pb cps	^{206}Pb/^{204}Pb cps	%Pb*	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	err. corr.	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	% conc
z_BT1_og - 7		437	362	1.21	22	643	99.64	0.538	0.019	0.070	0.002	0.23	0.056	0.002	419	68	437	12	438	10	100.3
z_BT1_og - 21		613	594	1.03	42	697	99.79	0.563	0.019	0.072	0.001	0.14	0.056	0.001	467	61	453	13	450	8	99.2
z_BT1_og - 33		329	190	1.73	-3	14700	99.59	0.566	0.019	0.073	0.002	0.12	0.056	0.002	443	59	454	12	455	9	100.1
z_BT1_og - 30		699	724	0.97	1	30660	99.69	0.585	0.016	0.074	0.001	0.05	0.057	0.001	510	40	468	10	462	8	98.7
z_BT1_og - 3	*	334	167	2.00	-11	12090	99.80	0.570	0.021	0.074	0.002	0.14	0.056	0.002	429	64	457	13	463	9	101.3
z_BT1_og - 18	*	271	191	1.42	18	571	99.73	0.578	0.024	0.075	0.002	0.04	0.057	0.002	437	81	465	16	463	10	99.6
z_BT1_og - 37	*	241	172	1.40	13	842	99.70	0.573	0.021	0.075	0.002	0.19	0.056	0.002	421	69	459	14	464	9	101.0
z_BT1_og - 27	*	165	97	1.70	1	7940	99.48	0.579	0.029	0.075	0.002	0.07	0.057	0.003	490	110	465	18	465	12	100.0
z_BT1_og - 9	*	381	399	0.95	-3	14290	99.60	0.591	0.020	0.075	0.002	0.38	0.058	0.001	523	52	472	13	465	10	98.6
z_BT1_og - 35	*	183	136	1.34	2	4075	99.58	0.585	0.023	0.075	0.002	0.20	0.057	0.002	486	70	467	14	465	10	99.6
z_BT1_og - 32	*	235	198	1.19	4	2695	99.72	0.584	0.020	0.075	0.002	0.27	0.056	0.002	450	58	467	12	466	10	99.8
z_BT1_og - 24	*	324	236	1.37	3	4483	99.71	0.579	0.019	0.075	0.002	0.02	0.056	0.002	422	60	463	12	466	9	100.7
z_BT1_og - 38	*	214	125	1.72	22	527	99.67	0.581	0.035	0.075	0.002	0.00	0.058	0.003	500	120	467	24	466	12	99.8
z_BT1_og - 39	*	419	358	1.17	-3	17830	99.66	0.581	0.021	0.075	0.002	0.24	0.057	0.002	468	62	465	13	467	10	100.5
z_BT1_og - 8	*	445	373	1.19	23	855	99.65	0.583	0.024	0.075	0.002	0.08	0.057	0.002	493	83	466	15	468	10	100.5
z_BT1_og - 29	*	136	111	1.22	-6	5520	99.73	0.593	0.026	0.075	0.002	0.18	0.057	0.002	472	85	470	17	468	11	99.7
z_BT1_og - 36	*	188	145	1.30	10	877	99.75	0.581	0.022	0.075	0.002	0.14	0.056	0.002	446	72	464	14	469	10	101.0
z_BT1_og - 4	*	144	104	1.39	-6	5780	99.78	0.584	0.025	0.075	0.002	0.06	0.056	0.002	448	81	467	16	469	10	100.4
z_BT1_og - 26	*	370	323	1.15	17	958	99.72	0.592	0.020	0.076	0.002	0.44	0.057	0.001	486	52	472	13	471	9	99.8
z_BT1_og - 13	*	106	94	1.12	17	296	99.92	0.592	0.035	0.076	0.002	0.15	0.056	0.003	410	120	471	22	474	10	100.6
z_BT1_og - 14		105	89	1.17	6	780	99.65	0.605	0.032	0.077	0.002	0.03	0.057	0.003	490	100	481	20	475	11	98.8
z_BT1_og - 6		71	52	1.36	-6	3001	99.85	0.592	0.035	0.077	0.002	0.03	0.057	0.004	410	130	471	23	476	14	101.1
z_BT1_og - 22		117	101	1.16	-3	5170	99.84	0.605	0.029	0.078	0.002	0.17	0.057	0.003	426	97	479	19	481	11	100.4
z_BT1_og - 28		140	94	1.50	1	6290	99.79	0.616	0.028	0.078	0.002	0.00	0.057	0.003	480	93	486	18	486	11	99.9
z_BT1_og - 5		73	55	1.32	3	1143	99.87	0.624	0.037	0.080	0.002	0.03	0.057	0.003	450	130	489	23	495	14	101.2
z_BT1_og - 31	×	174	159	1.09	1	8390	99.65	0.670	0.029	0.084	0.002	0.42	0.058	0.002	492	70	521	17	519	13	99.6
z_BT1_og - 2	×	446	518	0.86	-7	15690	99.71	0.661	0.023	0.084	0.002	0.39	0.058	0.001	507	55	517	14	520	11	100.5
z_BT1_og - 40		97	68	1.43	9	551	100.19	0.540	0.034	0.076	0.002	0.05	0.052	0.003	290	120	439	22	471	12	107.2

Abbreviations and symbols: * and X used to calculate young and old concordant ages, respectively; core = grain core; og = grain overgrowth; % conc. = percent concordancy [(^{206}Pb/^{238}U) /(^{207}Pb/^{235}U) *100]

Table A2. LA-ICP-MS U–Pb isotopic analyses of zircon standard (University of New Brunswick).

	(ppm)			Common-Pb			Final isotope ratios							Final ages (Ma)						
Comments	U	Th	U/Th	^{204}Pb cps	^{206}Pb/^{204}Pb cps	%Pb*	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	err. corr.	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{206}Pb	2σ	^{207}Pb/^{235}U	2σ	^{206}Pb/^{238}U	2σ	% conc
z_Plesovice - 3	719	75	9.5	2	12435	99.62	0.407	0.019	0.053	0.001	0.16	0.056	0.003	440	110	347	14	336	8	96.8
z_Plesovice - 11	658	64	10.4	-12	26490	99.88	0.389	0.013	0.054	0.001	0.15	0.053	0.002	311	64	334	9	336	7	100.7
z_Plesovice - 4	748	87	8.6	-1	26190	99.63	0.413	0.014	0.054	0.001	0.29	0.056	0.001	439	55	350	10	337	7	96.1
z_Plesovice - 8	612	52	11.9	11	1653	99.81	0.395	0.013	0.054	0.001	0.32	0.054	0.001	351	50	339	9	337	7	99.3
z_Plesovice - 9	605	58	10.4	5	4692	99.69	0.401	0.015	0.054	0.001	0.19	0.055	0.002	400	71	342	11	338	7	98.7
z_Plesovice - 10	413	35	12.0	27	581	99.80	0.396	0.023	0.054	0.001	0.14	0.053	0.003	340	110	338	16	338	8	99.9
z_Plesovice - 7	1012	94	10.8	-8	34290	99.64	0.405	0.012	0.054	0.001	0.01	0.055	0.001	422	49	345	9	338	7	98.0
z_Plesovice - 12	665	65	10.3	10	2638	99.64	0.399	0.017	0.054	0.001	0.28	0.054	0.002	371	94	343	11	340	8	99.0
z_Plesovice - 13	692	71	9.8	21	1322	100.10	0.390	0.018	0.055	0.001	0.31	0.052	0.002	258	77	334	13	343	8	102.6
z_Plesovice - 5	918	86	10.6	0	32690	99.72	0.411	0.016	0.055	0.001	0.26	0.055	0.002	399	72	350	12	343	8	98.1
z_Plesovice - 1	697	71	9.8	-20	24730	99.83	0.409	0.020	0.056	0.001	0.07	0.053	0.003	308	100	347	14	349	8	100.6
z_Plesovice - 2	703	73	9.6	22	1109	99.80	0.404	0.016	0.056	0.001	0.07	0.053	0.002	330	80	344	11	350	8	101.9
z_Plesovice - 6	617	51	12.0	-11	17530	99.87	0.412	0.013	0.056	0.001	0.24	0.053	0.001	323	50	351	9	351	7	100.2

% conc. = percent concordancy [(^{206}Pb/^{238}U) /(^{207}Pb/^{235}U) *100]

APPENDIX B

Backscattered electron (BSE) images of individual zircon grains separated from the Dugan Road monzogranite. Red ellipses represent a 14 μm crater sampling site.