Petrography, geochemistry, age, and stratigraphic significance of the Mississippian Boyd Creek tuff, southern New Brunswick, Canada

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ABSTRACT

The Boyd Creek tuff consists of two pyroclastic flow deposits and more widespread air-fall tuff within a Mississippian red bed sequence located in outcrop and boreholes around Weldon and Pre d'en Haut, Albert and Westmorland counties, New Brunswick. Long recognized as an important stratigraphic marker, it has been placed in either the Tournaisian Weldon Formation or Visean Hillsborough Formation by previous workers, with a position in the upper Tournaisian Weldon Formation being the most recent interpretation. A Visean laser ablation-inductively coupled plasma-mass spectrometry U–Pb zircon age of 336.9 ± 2.0 Ma is consistent with the interpretation that the tuff is part of the Windsor Group and within a fine-grained red and grey sequence of the Hillsborough Formation. Although the tuff is altered and contains abundant xenoliths and xenocrysts, petrography and chemistry are consistent with rhyolite or dacite composition. Its composition and age suggest that the Boyd Creek tuff is one of several volcanic units interpreted to be in the Windsor Group or its temporal equivalents, including rhyolite-trachyte lavas of Cumberland Hill (Cumberland Hill Formation, Mabou Group), tuff in carbonate-evaporite sequence at the Picadilly Mine (Penobsquis), and the red bed Shin Formation (Mabou Group) at Hurley Creek near Minto. Locating and dating other 'ash beds' in the Windsor Group offer a way to resolve long-standing issues of correlation in the Visean of New Brunswick and Nova Scotia.

RÉSUMÉ

Le tuf de la crique Boyd est constitué de deux dépôts de coulées pyroclastiques et de tuf de retombées plus étendu à l'intérieur d'une séquence de couches rouges mississippienne présente dans un affleurement et des puits de forage près de Weldon et de Pré-d'en-Haut, dans les comtés d'Albert et de Westmorland, au Nouveau-Brunswick. Longtemps reconnu comme un repère stratigraphique important, il a été classé au sein de la Formation tournaisienne de Weldon ou de la Formation viséenne de Hillsborough par des chercheurs antérieurs, son inclusion dans la Formation du Tournaisien supérieur de Weldon constituant l'interprétation la plus récente. Une datation U-Pb sur zircon par spectrométrie de masse à plasma inductif-ablation par laser viséenne de 336,9 ± 2,0 Ma est compatible avec l'interprétation considérant le tuf comme une partie du groupe de Windsor se trouvant à l'intérieur d'une séquence rouge et grise à grain fin de la Formation de Hillsborough. Même si le tuf est altéré et renferme une abondance de xénolites et de xénocristaux, la pétrographie et la constitution chimique correspondent à la composition de la rhyolite et de la dacite. Sa composition et son âge laissent supposer que le tuf de la crique Boyd est l'une de plusieurs unités volcaniques interprétées comme un tuf faisant partie du groupe Windsor ou de ses équivalents temporels, notamment les laves rhyolitiques-trachytiques de la colline Cumberland (Formation de Cumberland Hill, groupe de Mabou), le tuf dans une séquence carbonatée-évaporitique à l'emplacement de la mine Picadilly (Penobsquis) et la Formation de couches rouges Shin (groupe de Mabou) dans la crique Hurley près de Minto. La localisation et la datation des autres « couches de cendres » dans le groupe de Windsor représentent une façon de résoudre les problèmes de corrélation de longue date au sein du Viséen au Nouveau-Brunswick et en Nouvelle-Écosse.

[*Traduit par la redaction*]

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INTRODUCTION

Since first being described by Wright (1922) the Boyd Creek tuff has been considered an important stratigraphic marker in the predominantly red clastic succession of the Mississippian rocks of southeastern New Brunswick (Figs. 1, 2, 3). Originally described from the exposed section in Boyd Creek, south of Gautreau (Westmorland County), the tuff forms two layers separated by red and green/grey silty shales. Outcrop is limited to the section in Boyd Creek and a similar series of exposures in Steeves Creek west of the Petitcodiac River north of Weldon (Fig. 2). An exposure at the mouth of a creek south of Pré-d'en-Haut, east of the estuary, reported by Shroder (1963), is no longer extant. The tuff has also been located in boreholes west of the surface showing in Boyd Creek as far Berryton, but the unit has not been identified south of the St-Joseph Fault, and the unconformities beneath the Mabou and Cumberland groups cut out the layer along its northern margin below the younger Hopewell Cape and Boss Point formations (Figs. 2, 3).

Wright (1922) and subsequent workers (see below) agreed that the Boyd Creek tuff is part of a 'lower Carboniferous' succession, but whether it is Tournaisian (see St. Peter and Johnson 2009) or Visean has been a source of controversy. St. Peter and Johnson (2009), using detailed surface mapping, borehole analysis, and limited seismic reflection data, placed the Boyd Creek tuff in the Tournaisian Sussex Group (Fig. 3).

Here we report new radiometric data from zircon grains in the Boyd Creek tuff that yield a Visean age, comparable to recent dates reported from similar felsic pyroclastic and extrusive rocks in sequences that are either known to be Windsor Group, or time-equivalents thereof, based on stratigraphic evidence. The Boyd Creek tuff may be part of a newly defined felsic volcanic province that stretched over a substantial part of southern and central New Brunswick, seen in Sussex (Penobsquis), at Cumberland Hill (near Chipman), and Hurley Creek (near Minto, see Fig. 1). This province was active at the same time as carbonates and evaporites of the Windsor Group were being deposited in the Moncton sub-basin part of the Maritimes Basin.

GEOLOGICAL BACKGROUND

Wright (1922) described the Boyd Creek tuff and included it in his 'Boyd Series', part of the now abandoned 'Moncton Group' of Carboniferous red beds in the area south of

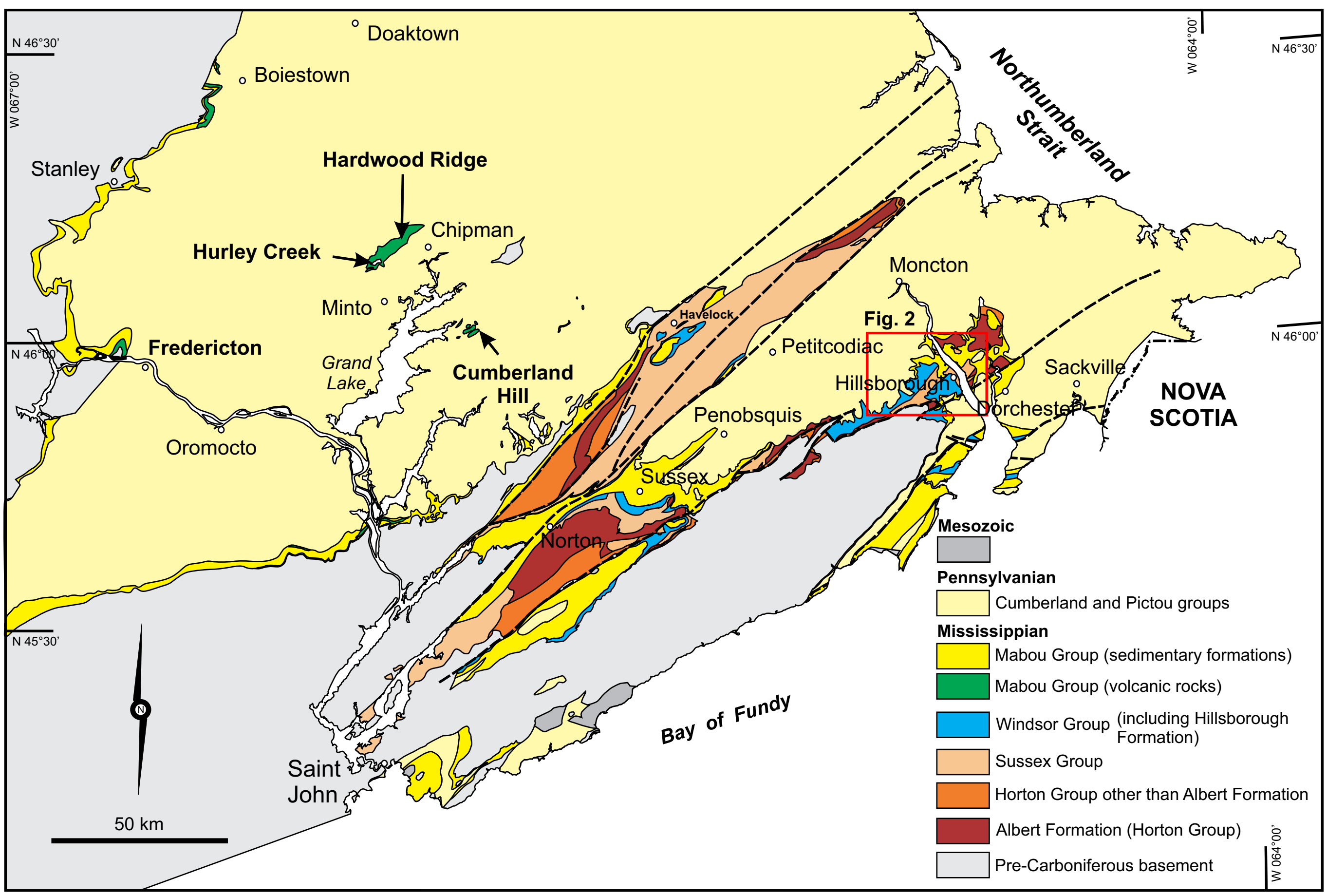

Figure 1. Geological map of southeastern New Brunswick after St. Peter and Johnson (2009) and New Brunswick Department of Natural Resources (2008) showing distribution of Carboniferous units and locations mentioned in the text.

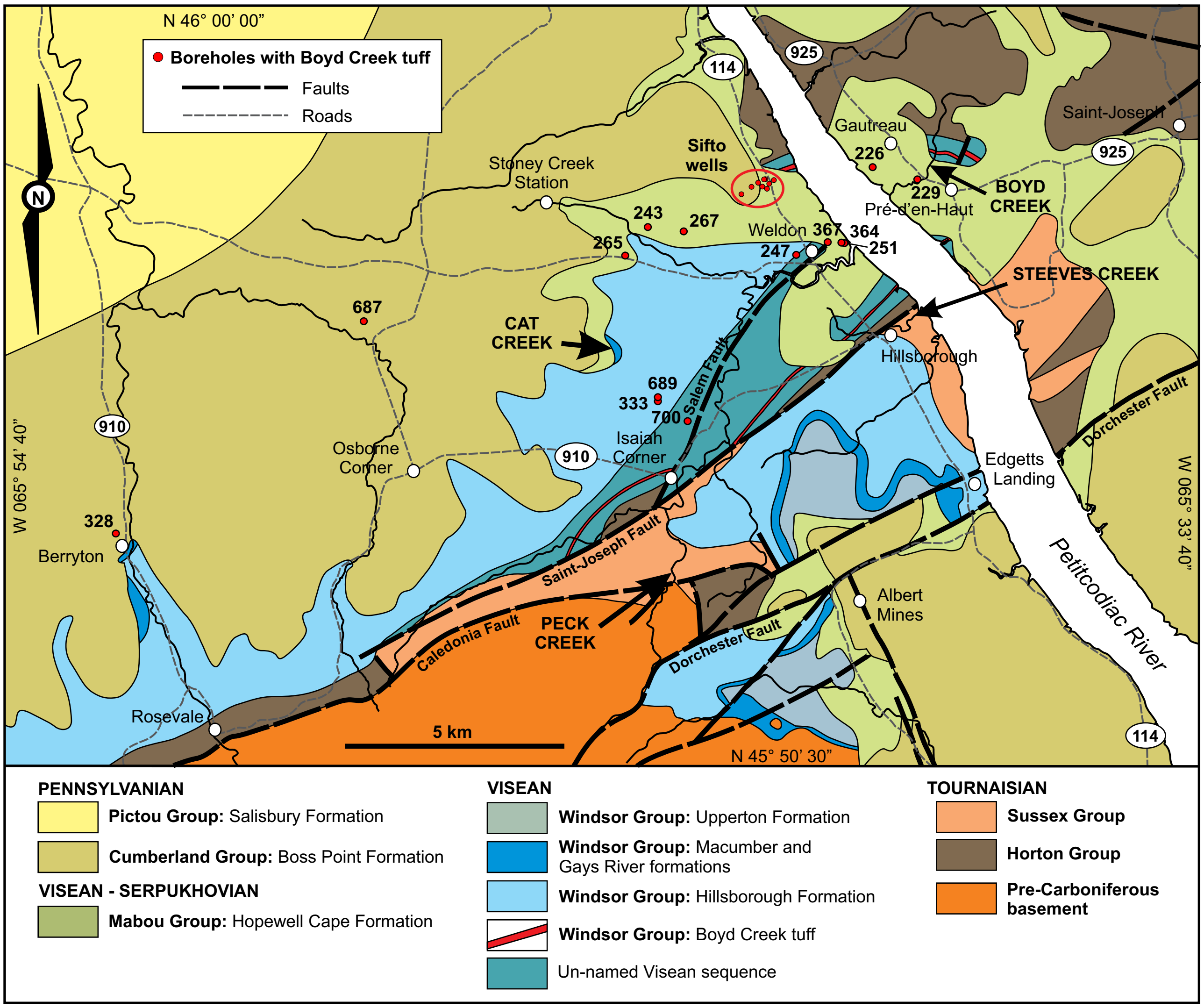

Figure 2. Geological map of parts of Westmorland and Albert counties, New Brunswick, showing the locations of outcrop of the Boyd Creek tuff and boreholes that encounter it below ground. Map is based on St. Peter and Johnson (2009) with modifications after this study and MacRae *et al.* (2017).

Moncton. Wright (1922) described two tuff layers (his Zones 2 and 4 of the 'Boyd Series') and noted that they lie above the fine- to medium-grained red clastic rocks of the 'Weldon Series', and beneath the coarse-grained red clastic rocks of the 'Hillsborough Series'. Wright (1922) concluded that the rocks are 'Lower Carboniferous', and in the absence of diagnostic macro-fossils, probably Visean. Norman (1941) included the tuff in a redefined 'Weldon Formation' and part of the Horton Group, along with the oil-shale-bearing Albert Formation and the evaporite-bearing 'Gautreau Formation', below an unconformity at the base of the 'Hillsborough Series'. This suggested the tuff is Tournaisian, although again, no macrofossil evidence was forthcoming. Gussow (1953) recognized the unconformity between the Weldon and Hillsborough formations but placed the Boyd Creek tuff above the erosion surface and in the Hillsborough Formation, implying that it is Visean. Remapping by McLeod (1980) suggested that the tuff locally lies within both the coarse-grained Hillsborough Formation and the fine-grained Weldon Formation, implying a diachronous boundary, rather than an unconformity. St. Peter (1992), working with borehole analyses and limited seismic reflection data, separated the Weldon Formation from the Horton Group, placed it in the newly defined 'Sussex Group', and reverted to the interpretation of Norman (1941), placing the tuff in the Weldon Formation. Based on miospore evidence both Horton and Sussex groups were identified as Tournaisian (see St. Peter and Johnson 2009), and the Boyd Creek tuff, by implication, lies in the upper Tournaisian interval (Figs. 2, 3).

Based on interpretation of the Boyd Creek section St. Peter (1992) suggested that the Boyd Creek tuff forms part of the Weldon Formation, part of the 100–120 m section seen in local drill core (St. Peter and Johnson 2009). This interpretation is consistent with the borehole occurrences west as far as Berryton (Figs 2, 3). By contrast, the thick Weldon Formation section (200m+) south of the St-Joseph Fault

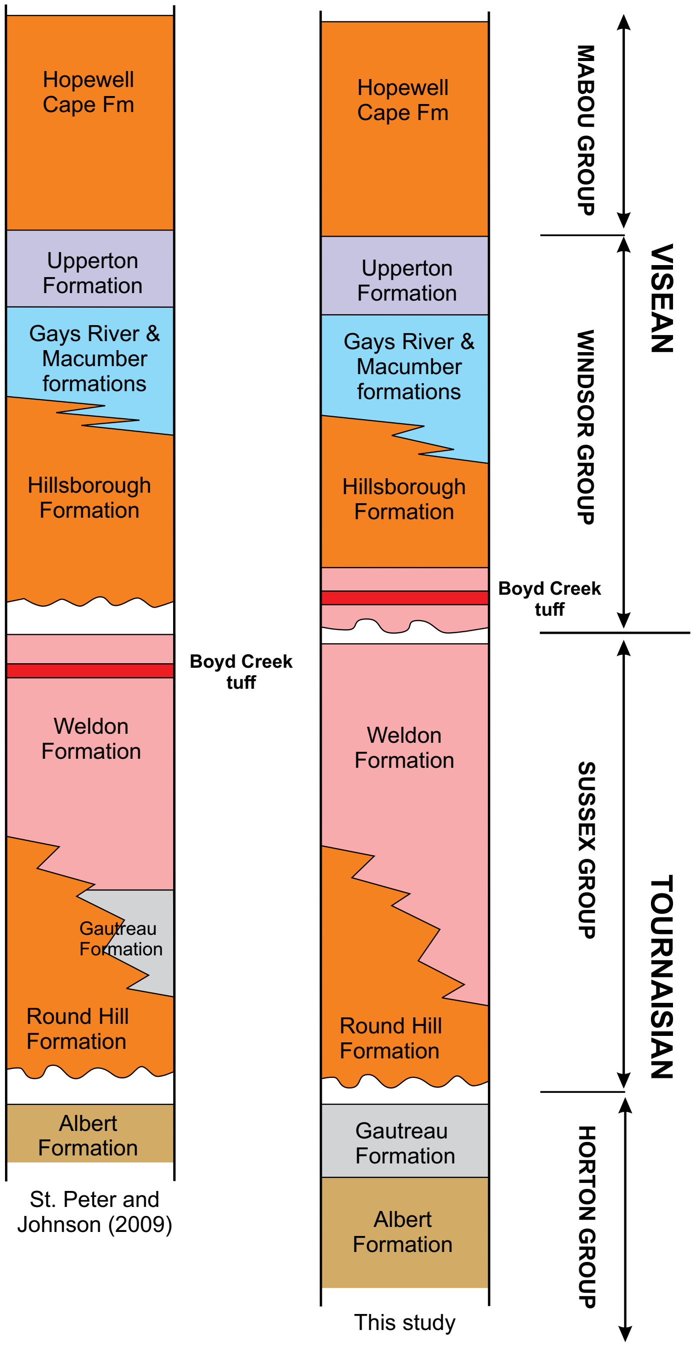

Figure 3. Carboniferous stratigraphy in the area of the map in Figure 2. Two versions show the stratigraphy from St. Peter and Johnson (2009) and the modifications following this study and MacRae *et al.* (2017).

in the Weldon area, does not include the tuff (St. Peter and Johnson 2009).

Outcrop and borehole intersections of the Boyd Creek tuff define a broad, open syncline (Weldon syncline) plunging gently to the WSW and closing east of the Petitcodiac River (Fig. 2). In the northern limb of the syncline the Boyd Creek tuff is truncated beneath the angular unconformities below the Hopewell Cape Formation (Mabou Group, Upper Visean–Serpukhovian) and overlying Boss Point Formation (Cumberland Group, Bashkirian–Yeadonian) (St. Peter and Johnson 2009). Above the Boyd Creek tuff the coarse red clastic rocks of the Hillsborough Formation (Windsor Group) make up much of the rest of the section, although carbonate rocks of the Windsor Group (Macumber Formation) are recorded above the Hillsborough Formation in Cat Creek, 3 km west of Weldon, and Gays River Formation is present in outcrop above the tuff along the strike of the northern limb of the syncline at Berryton (St. Peter *et al.* 2005; see Figs. 2, 3).

In Boyd Creek, Wright (1922) described a ca. 50 m tuff section, two 6–7 m-thick tuff layers separated by ca. 30 m of red and greenish silty shale. In nearby boreholes (the Sifto wells and others on both sides of the Petitcodiac River north of Weldon), two layers of tuff are present with an intervening shale interval, the whole sequence generally 40–60 m thick (Fig. 2). This section thins to the west, and only one tuff layer is present at Berryton, where it is less than 3 m thick. However, local complications occur within this overall pattern of thinning. In the boreholes north of Weldon on both sides of the Petitcodiac River and especially in the Sifto wells, the thickness of the tuff varies considerably between adjacent holes less than 100 m apart, and one or other of the two layers are either absent, or they have merged. These variations could be an effect of original paleo-topography, a consequence of movement of the underlying salt, or a combination of both factors (St. Peter and Johnson 2009). Data points are insufficient to create a detailed isopach map given that the closely spaced Sifto wells display rapid changes in thickness over a relatively small area; however, the map in Figure 4 suggests overall thinning to the west-southwest, implying emplacement from the east-northeast.

McLeod (1980) reported the occurrence of a felsite dyke in the Round Hill Formation (Sussex Group) in Peck Creek southwest of Hillsborough (Fig. 2), and both he and subsequently St. Peter and Johnson (2009) suggested this dyke and the Boyd Creek tuff are co-magmatic and contemporaneous, a suggestion that is tested here.

PETROGRAPHY OF THE BOYD CREEK TUFF

Although Wright (1922), Norman (1941), and Gussow (1953) described the Boyd Creek tuff, it was not until Shroder (1963) that a comprehensive petrographic analysis was made. Using surface outcrop from Boyd Creek and Steeves Creek (and a since-vanished exposure on the coast south of Pré-d'en-Haut), Shroder (1963) defined the rock as an 'air-fall ash' in which pumice fragments, glass shards and 'accidental' xenoliths show random rather than aligned orientation. Welding was described as minimal. Concentrating on the then-recent Sifto cores, Hounsell (1986) concentrated his study on one complete core and defined two eruptive units with welded and non-welded intervals. He recognized two pyroclastic flows, each unit beginning with a 'plinian crystal-rich air-fall' succeeded by partially welded flow units

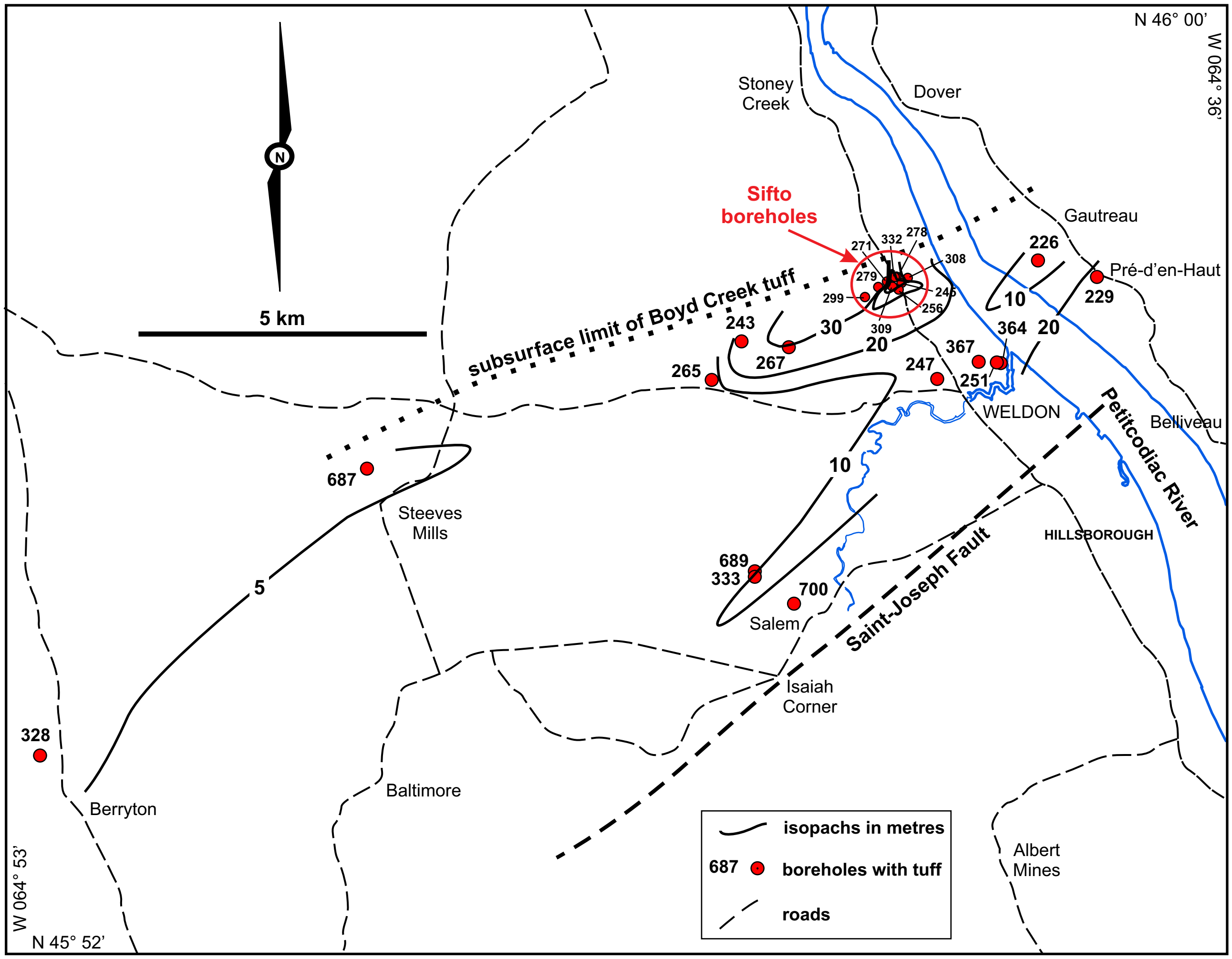

Figure 4. Isopach map for the Boyd Creek tuff: see text for details and caveats.

with peripheral air-fall and epiclastic components (Fig. 5). The samples, detailed logs, and thin sections from the study of Hounsell (1986) were re-examined for this study, augmented by surface samples from a small stone quarry adjacent to Boyd Creek excavated since the mid-1980s. Based on the older mapping and the Hounsell (1986) logs, the upper eruptive unit was exposed in the quarry, and one of us (PC) sampled bedrock there in 2004. The quarry was subsequently back-filled with loose tuff debris and no bedrock is currently exposed. The Sifto borehole core, including the core examined by Hounsell (1986), has been lost.

The Boyd Creek tuff is a pale purple rock when freshly exposed, weathering to pink-grey or buff-cream depending on the degree of alteration (Figs. 6a, b). The matrix is fine-grained, consisting predominantly of glass shards, all devitrified and altered to varying degrees, replaced by irresolvable clay minerals and fibrous chalcedony (Fig. 7). Larger shards and pumice fragments, up to 4 mm diameter, are replaced by chalcedony/jasper, or a matte of iron hydroxides (Fig. 7), consistent with hydrothermal vapour-phase activity during primary cooling (Cas and Wright 1988). Relict structures and textures are, however, abundant in the tuffaceous matrix. Lapilli with amygdules of quartz, local flow-banding textures, flattening of pumice shards as *fiamme*, and some welding are evident, although much of the matrix does not show signs of welding, or even preferred orientation (Fig. 7). Crystals are abundant, with quartz the most common, followed by sodic plagioclase and alkali feldspar, Ti-Fe oxide, apatite, and zircon (Fig. 8). These features were previously described by Gussow (1953), Shroder (1963), and Hounsell (1986) and are confirmed here; however, barite crystals are described for the first time in this study (Fig. 8). Lithic fragments are also abundant — described by Shroder (1963), Hounsell (1986), and St. Peter and Johnson (2009) as 'accidental', they most commonly consist of red shaly siltstone and fine-grained red sandstone; less commonly, they are schistose fragments of mafic or variegated metavolcanic rocks (St. Peter and Johnson 2009; Fig. 6). Gussow (1953) recorded the presence of garnet grains, not confirmed in the present study.

Mineral compositions were determined by electron microprobe analysis at the Electron Microscopy Unit, University of New Brunswick (by PC). Quartz and sodic (An_{5-8}) plagioclase lapilli show least alteration (Figs. 8a, b). Both

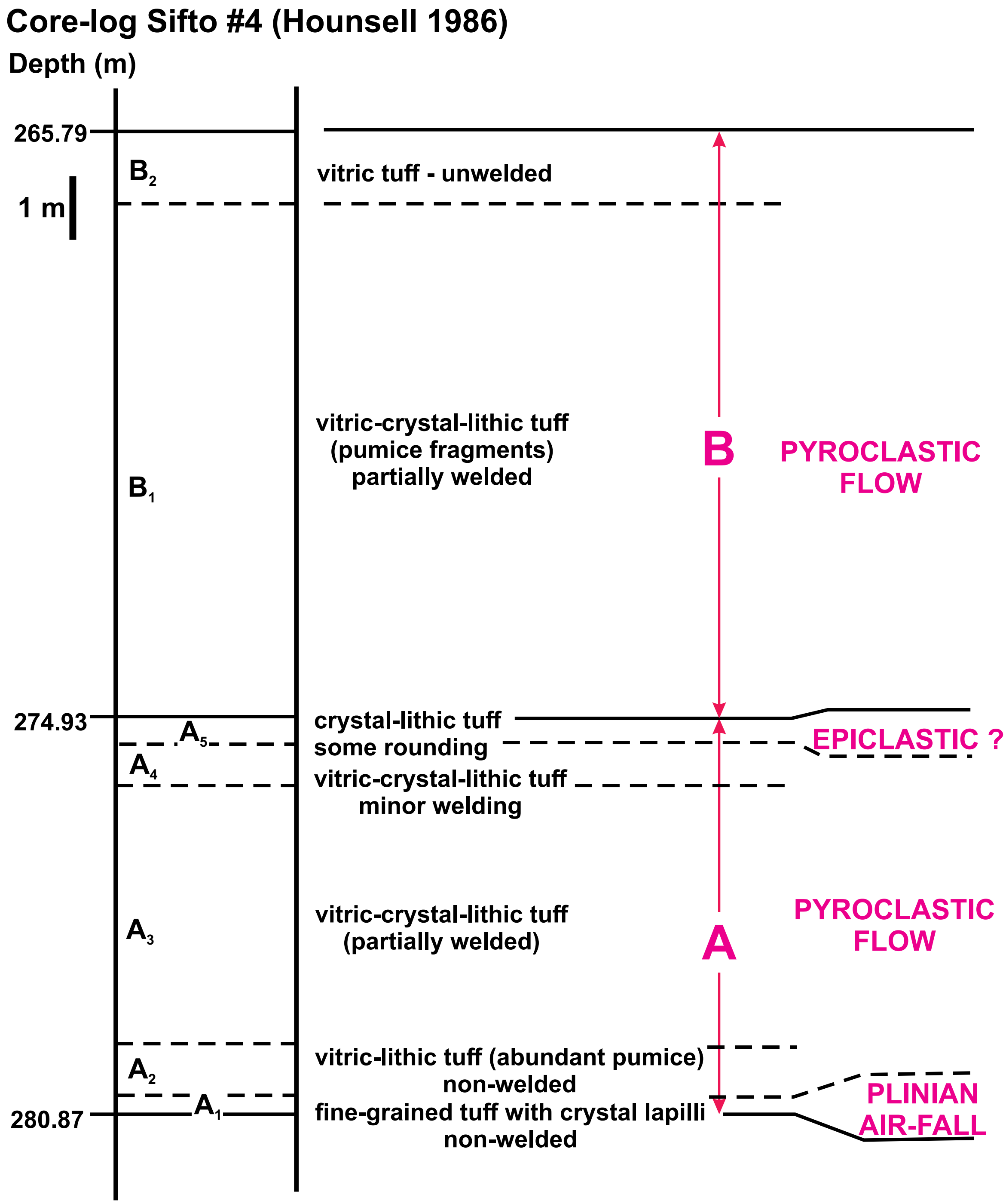

Figure 5. Interpretation of a complete core-log through the Boyd Creek tuff from the Sifto #4 well north of Weldon from Hounsell (1986).

minerals display resorbed margins in anhedral grains that are up to 3 mm diameter. Alkali feldspar grains are heavily altered but most probably orthoclase (Fig. 8c) rather than sanidine (optical determination). Barite phenocrysts are subhedral to euhedral in outline (1–2 mm diameter) but are internally complex with intergrowths picked out by irregular extinction under crossed nicols (Fig. 8d). The Ti-Fe oxide grains are intergrown at a scale too fine to resolve but bulk compositions are consistent with a Ti-spinel-rutile exsolution. The largest examples (2 mm) show internal grain boundaries indicating they are fragments and probably xenocrystic. These grains generally have a rim of titanian hematite (Fig. 8g).

Mineral modes and textures indicate a rhyolite/dacite source magma with quartz and both feldspars, plus barite, at the liquidus. By the time of eruption quartz and sodic plagioclase show signs of back-reaction or resorption with the melt (Figs. 8e, f).

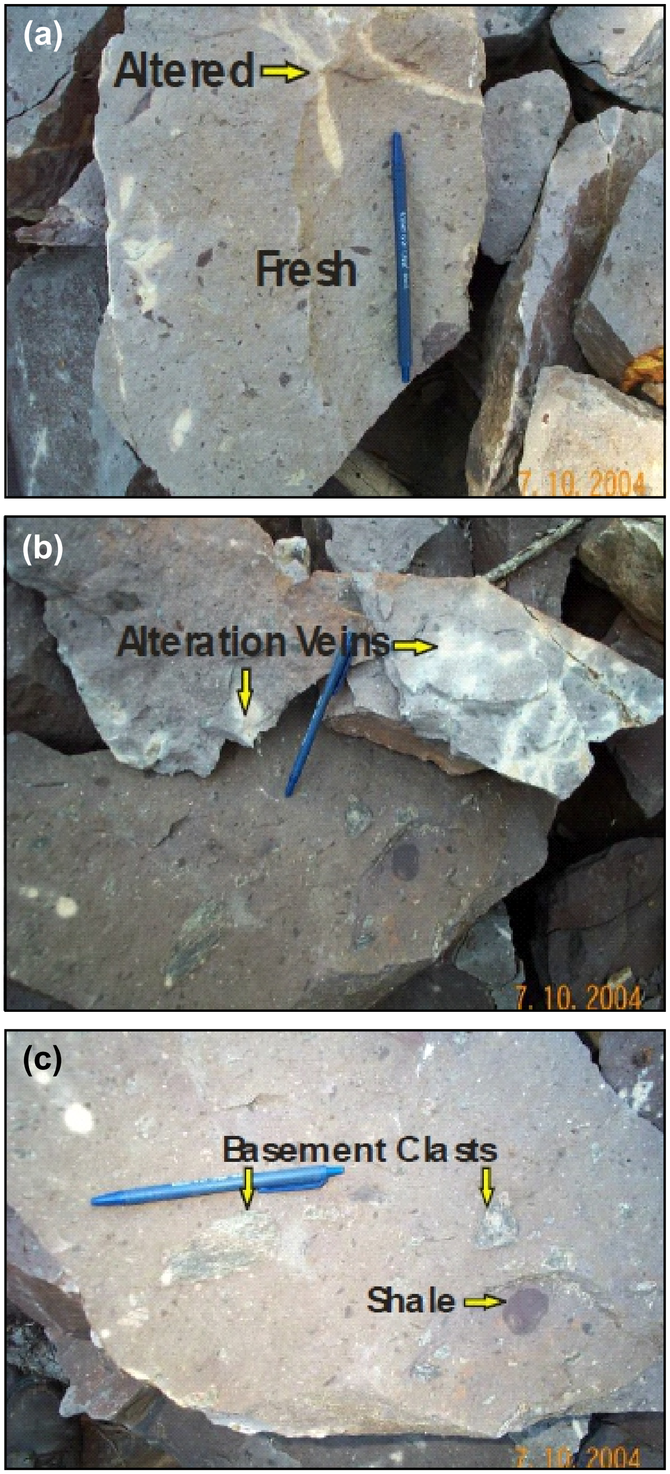

Figure 6. Field photographs of the Boyd Creek tuff from the stone quarry along Boyd Creek, Pré-d'en-Haut (Fig. 2). (a) and (b) show the fresh tuff with pale alteration zones; (c) shows inclusions of red shale and amphibolite/metavolcanic 'basement'.

The Peck Creek felsite is a fine- to medium-grained quartz-feldspar rock, largely altered and cut by macro- to micro-veins of quartz and calcite. This dyke-like body has a blocky and discontinuous form, broken up by red sedimentary screens, or smaller apophyses of disrupted red mudrock. Some of the felsite masses resemble pillows or tubes. Fine-grained margins are preserved suggesting quenching, and these margins also display 'cauliflower' textures associated with small apophyses of sediment suggesting magma-wet sediment interaction. Most dyke margins are sheared, and the entire intrusion appears to be contained within a fault zone, which McLeod (1980) suggested was contemporary with emplacement. This fault is one of several in the Peck Creek section that cut Sussex Group rocks but are truncated by the unconformity beneath the Hillsborough Formation (Park *et al.* 2010). Hence the Peck Creek felsite intruded during deformation of the Sussex Group and predates deposition of the Hillsborough Formation.

The Peck Creek felsite is thoroughly altered to a fine-grained sericite felt with quartz and calcite, cut by micro-veins of quartz and calcite. Relict grains of both alkali feldspar and sodic plagioclase survive, as do primary quartz grains, though they commonly display recrystallization. Alkali feldspar may have comprised 50% of the original assemblage, and quartz around 30%, with the remainder being plagioclase. Some of the sericite felt is foliated, generally close to dyke margins that show signs of shearing, and some of the recrystallized quartz displays a fine-grained mosaic with a c-axis preferred orientation indicative of deformation at high temperature with no subsequent annealing (Wilson *et al.* 2004). These features are consistent with a dyke intruded into an active fault.

GEOCHEMISTRY

Samples for chemical analysis (Table 1) were collected in two batches. One of us (PC) collected from the Peck Creek felsite at its only outcrop in Peck Creek, and the Boyd Creek tuff at outcrops in Boyd Creek, plus a stone quarry near Boyd Creek in 2004 (GPS N 45.969°, W 064.631°). This collection was augmented by a sample from the outcrop in Steeves Creek held in the NB GSB archive. The tuff was sampled again (AFP&SJH) in 2015 at the stone quarry near Boyd Creek. As noted, core from the Sifto hole studied by Hounsell (1986) is no longer available.

Given the evident alteration, samples were hand-sorted as rock chips and cut slices to remove obvious alteration, xenolithic material, and veins. This process did not, however, eliminate chalcedony replacement of glass, or other secondary minerals. Hence analyses that have more than 80 wt% SiO_2 and/or >10 wt% loss on ignition are excluded from the discussions below.

The 2004 samples were analyzed at SGS Mineral Services, with major element oxides, Sr and Ba analyzed by X-ray Fluorescence (XRF); other trace elements, including rare-earth elements (REE) were analyzed by inductively couple plasma-mass spectrometry (ICP-MS). The 2015 samples were analyzed by ActLabs, with major element oxides and Sr by lithium borate fusion finished by inductively couple plasma optical emission spectroscopy (ICP-OES) and trace

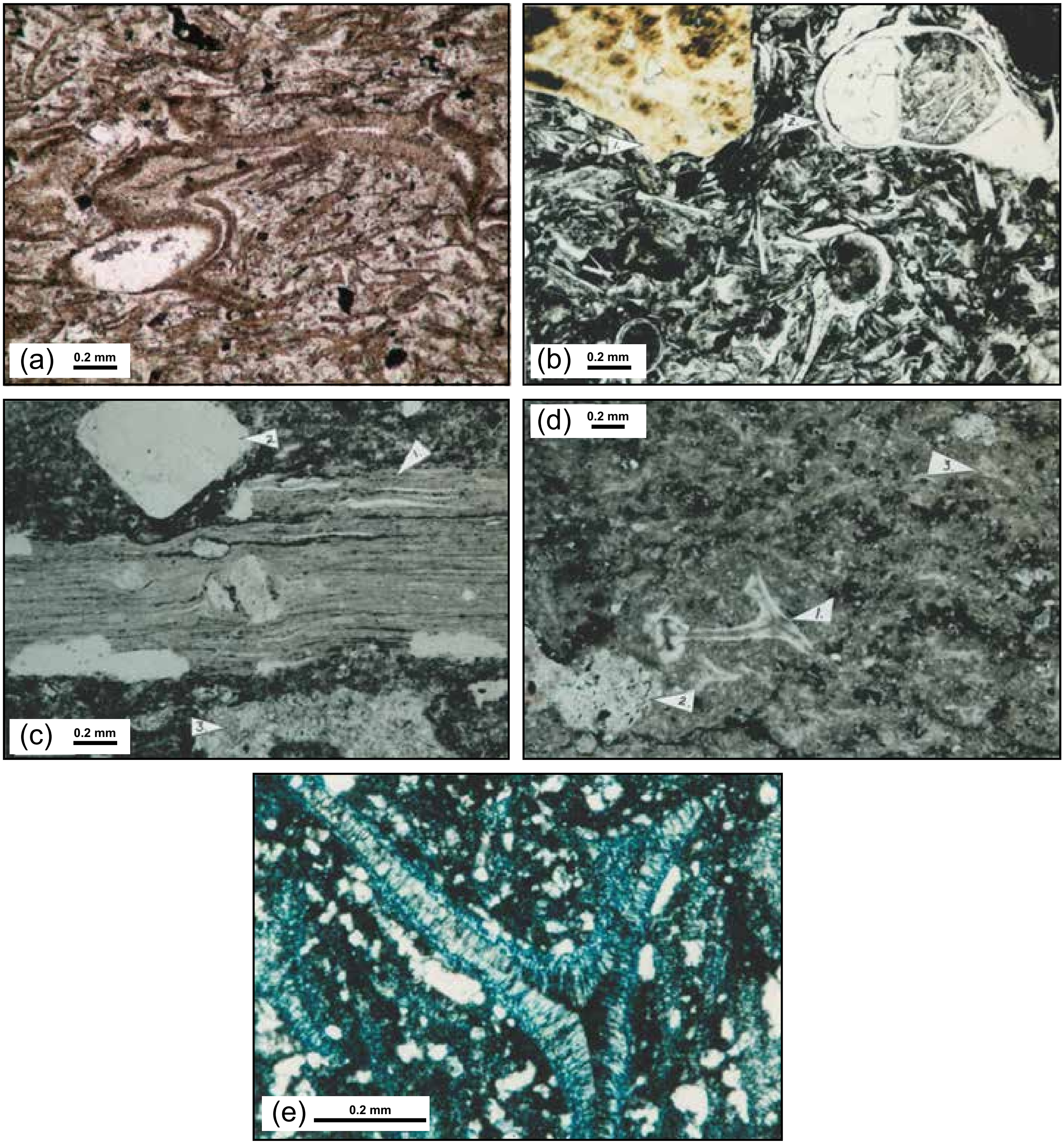

Figure 7. Photomicrographs illustrating textures in the Boyd Creek tuff: (a) pumice shard and amygdale in partly welded tuff now largely replaced with chalcedony and clay minerals; (b) 'bubble' vesicles and replaced glass shards; (c) welded rhyolitic clast in matrix of glass shards with phenocrysts; (d) glass shards from broken vesicular pumice; (e) detail of glass shard showing replacement by fibrous chalcedony. Images (b to d) are from Hounsell (1986). All photomicrographs are with plane polarized light.

elements and REE by sodium peroxide fusion followed by ICP-OES and ICP-MS.

All Boyd Creek tuff samples correspond to the upper eruptive unit as defined by Hounsell (1986). The fact that these samples are tuffaceous combined with the petrographic evidence described above for vapour-phase interaction

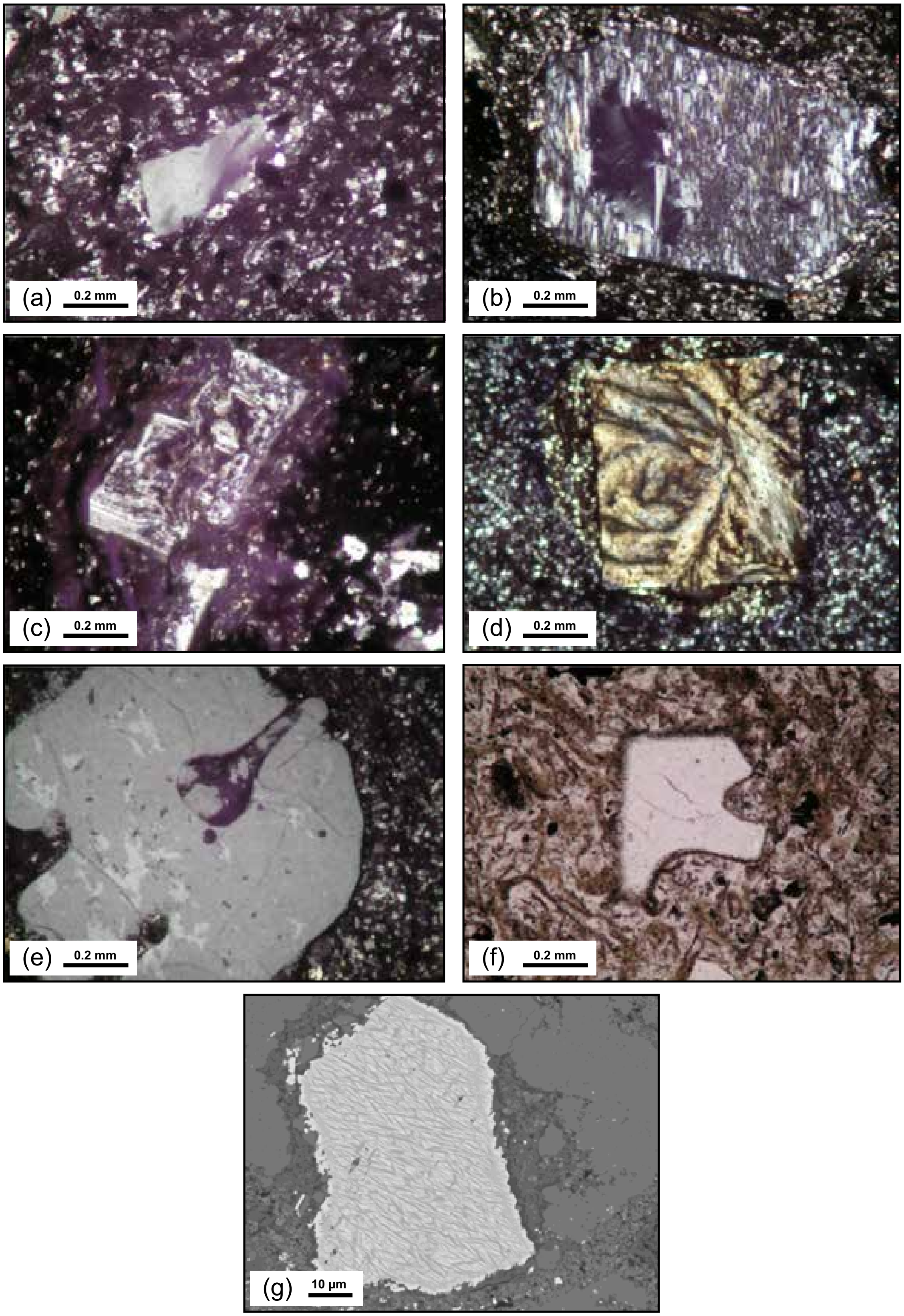

Figure 8. **Photomicrographs and SEM backscatter images of crystal lapilli in the Boyd Creek tuff: (a) recrystallized and partly resorbed quartz; (b) albite; (c) zoned alkali feldspar; (d) barite with 'feathery' texture and undulose extinction; (e) quartz with resorbed margins and melt inclusion; (f) quartz with resorbed margins; (g) Ti-Fe oxide showing irresolvable core of intergrown Ti-Fe oxides and pale rim of titanian hematite. (a) to (f) are photomicrographs under crossed nicols; (g) is an SEM back-scatter image.**

Table 1. Geochemical analyses of the Boyd Creek tuff and Peck Creek felsite. Major element oxides as weight %, trace elements as ppm.

Sample	AM-50	04-BC-01	CS04-100	V22-92	128	129	130	134	135	136	137
					Major Oxides (wt%)						
SiO_2	70.00	74.60	73.20	73.80	65.60	67.90	67.80	67.70	68.50	67.10	68.00
Al_2O_3	11.70	11.20	11.30	11.40	12.40	11.00	10.70	11.00	11.00	11.50	11.30
Fe_2O_3	0.77	3.40	4.41	3.71	2.52	2.67	2.55	2.74	1.81	2.25	3.02
MnO	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03
MgO	0.20	2.54	3.64	2.35	2.71	2.36	2.28	1.95	1.62	2.16	1.97
CaO	5.97	0.24	0.18	0.22	0.17	0.20	0.18	0.21	0.25	0.27	0.19
Na_2O	4.50	0.45	2.35	2.12	0.66	0.67	0.67	0.48	0.62	0.61	0.51
K_2O	1.98	3.48	0.49	0.76	4.45	4.36	4.20	4.50	4.96	4.47	4.56
H_2O (LOI)	4.30	2.80	3.20	3.60	4.57	3.81	3.78	3.57	3.17	3.78	3.70
Total	100.20	100.00	99.30	100.00	93.50	93.30	92.50	92.50	92.30	92.50	93.60
					Trace Elements (ppm)						
Cs	2.0	0.4	0.5	0.3	0.4	0.5	0.4	0.3	0.4	0.4	0.3
Ba	760	670	150	190	322	501	451	228	279	257	242
Rb	56.8	46.8	6.7	8.0	47.2	50.9	45.5	51.7	63.0	53.2	50.3
Th	1.9	12.8	12.5	11.6	8.8	9.4	8.8	9.7	9.9	9.4	9.2
Nb	5	43	41	38	46	42	41	42	45	43	42
Ta	<0.5	4.4	3.6	3.2	1.9	1.6	1.4	1.3	1.4	1.2	1.2
Sr	350	40	70	70	31.4	36.9	32.7	40.4	49.4	52.3	33.8
P	44	101	172	136	308	176	220	220	176	176	264
Zr	55	561	563	541	440	415	386	408	412	417	402
Hf	2	13	13	11	14	13	12	13	13	13	12
Ti	480	1500	1620	1560	1680	1380	1320	1380	1440	1440	1440
Y	8.0	93.0	48.0	44.0	69.0	54.9	46.4	66.1	60.1	63.1	76.2
					Rare Earth Elements (ppm)						
La	7.6	62.2	75.7	71.6	65.5	64.9	56.2	67.3	72.0	61.6	61.4
Ce	15	132	160	152	134	110	104	163	156	127	159
Pr	1.8	17.2	20.0	19.2	18.6	17.4	15.8	18.3	20.1	17.3	17.3
Nd	6.3	71.1	83.2	81.6	73.9	68.3	63.7	74.0	79.5	67.2	68.6
Sm	1.2	14.0	17.0	15.5	15.3	12.9	12.2	16.1	16.4	14.0	15.4
Eu	0.40	1.63	1.62	1.54	1.48	1.26	1.10	1.47	1.67	1.43	1.55
Gd	1.46	15.10	13.80	13.00	13.70	11.70	10.10	14.60	14.40	13.40	15.80
Tb	0.20	2.71	1.78	1.72	2.13	1.79	1.55	2.32	2.19	2.10	2.44
Dy	1.24	16.30	8.96	8.24	13.20	10.60	8.58	13.10	12.30	12.10	14.90
Ho	0.29	3.42	1.84	1.79	2.79	2.26	1.88	2.75	2.59	2.70	3.00
Er	0.77	9.94	5.61	5.44	8.98	6.87	6.09	8.59	8.22	8.21	8.89
Tm	0.15	1.41	0.91	0.80	1.44	1.11	1.04	1.33	1.26	1.29	1.28
Yb	1.0	10.3	7.3	6.8	9.9	7.7	7.3	8.9	8.9	9.3	8.7
Lu	0.17	1.47	1.03	1.03	1.48	1.21	1.12	1.39	1.41	1.41	1.31

Samples:
AM-50 Peck Creek felsite, Peck Creek
04-BC-01 Boyd Creek tuff, outcrop in Boyd Creek
CS04-100 Boyd Creek tuff, outcrop in Steeves Creek
V22-92 Boyd Creek tuff, stone quarry in Boyd Creek
128 – 137 Boyd Creek tuff, stone quarry in Boyd Creek.

during cooling of the tuff, the data reflect an irreducible degree of chemical alteration that is most obvious in the broad scatter of major element oxides in the various plots presented here. This feature is not generally as apparent in the trace and rare-earth element plots, and they are considered petrogenetically the more reliable and diagnostic with an important caveat concerning TiO_2. No detailed petrogenetic study is attempted here, and the data are used mainly for the purpose of comparison with other Mississippian felsic volcanic rocks in New Brunswick.

Major element plots involving SiO_2 — such as SiO_2 vs. alkali/alumina and SiO_2 vs. Zr/TiO_2 — show considerable scatter through the fields for trachyte, rhyolite and dacite (and alkali rhyolite-commendite) (Figs. 9a, b), probably reflecting a mixed origin of the tuffaceous material, including Ti-oxide minerals, and vapour-phase alteration. The diagnostic trace element plots, such as the Zr/TiO_2 vs. Nb/Y show some scatter, but compositions are more constrained within the rhyolite field (Fig.9b), consistent with modal mineral abundances described above. Tuffaceous heterogeneity and alteration may also account for the difference compared to Cumberland Hill rhyolite lavas in the same plots. The alkali/alumina plot places the Boyd Creek tuff data in the peraluminous field, possibly on a trend toward higher alumina compared to the Cumberland Hill rhyolites. The Peck Creek felsite falls well away from this trend in the metaluminous field (Fig. 9c). Ambiguity is also apparent in the tectonic discrimination plots (Figs. 9d, e). The Cumberland Hill rhyolite/trachyte fall mainly in the 'within plate' field whereas the Boyd Creek tuff compositions cross into the 'A-type' and 'orogenic' fields.

Using niobium as a differentiation index (cf. White *et al.* 2006), other major and trace element abundances display scatter indicative of compositional heterogeneity and alteration rather than magma fractionation. Nb abundances fall in a very small range, but SiO_2, TiO_2, Ba, Zr, La, and Yb scatter widely. SiO_2 dilution during tuff-forming processes and alteration rather than crystal fractionation or magma differentiation seems to be the underlying causes of variation, and differences compared to the Cumberland Hill rhyolites are also striking (Fig. 10).

Rare earth abundance diagrams display more uniformity in the Boyd Creek samples, with light REE enrichment compared to the heavy REE, and a marked negative europium anomaly (Fig. 11). The Peck Creek felsite differs from the Boyd Creek samples, with an order of magnitude lower normalized REE abundances (Fig. 11a). The slope of the REE and the Eu anomalies in the Boyd Creek tuff samples parallel the pattern seen in the Cumberland Hill rhyolite samples at a slightly lower abundance and overlap with the range in the Cumberland Hill trachyte (Fig. 11).

The same features are apparent in the incompatible element spider diagrams (Fig. 11b). The difference shown by the Peck Creek felsite is clear, whereas the Cumberland Hill trachyte samples overlap the Boyd Creek range and the Cumberland Hill rhyolite displays suggests that it is somewhat more fractionated or less altered (Fig. 11b).

GEOCHRONOLOGY

Sample collection and preparation

Rock samples for geochronological analysis were collected from the disused stone quarry close to Boyd Creek (GPS N 45.969˚, W 064.631˚), identified as the upper unit of the tuff (Hounsell 1986). Two samples were chosen (SH15-164, AP 2 — see Supplementary Data Table S1) to have as little of the pale alteration and veinlets as possible, and to contain less than average xenolithic material. Jaw-crushing to ca. 0.5 cm chips allowed the material to be further screened for xenoliths and alteration. The screened material was prepared for heavy mineral separates by AGAT Laboratories. Hand picking of zircons was undertaken at the University of New Brunswick Laser Ablation Centre.

Methodology

Data were collected in three sessions at the University of New Brunswick Micro-Analysis of Natural Trace-element and Isotope Systematics (MANTIS) laboratory using an Australian Scientific Instruments M-50 193 nm excimer laser system coupled Agilent 7700× and 8900 ICP-MS. Data were collected using the 8900 QQQ-ICP-MS which employed sufficient NH_3 in the reaction cell (~20% flow rate) to eliminate ^{204}Hg interference on ^{204}Pb to more accurately assess the effect of common-Pb on U–Pb isotope data. Ablation was performed in a large-volume Laurin Technic Pty S-155 cell connected to the ICP-MS using Nylon tubing and two in-line 'squid' smoothing devices. Sensitivity and plasma robustness was tuned on each ICP-MS platform using NIST610 glass. All zircon ablations were performed using an on-sample energy (fluence) of 3 J/cm^2, a laser firing rate of 4 Hz, and a beam size of 17–24 µm. Each analysis consisted of 30 seconds of ablation followed by a gas background of 30 seconds. Samples and standards were distributed through the sequence to correct for instrument drift and mass bias. The FC-1 zircon (Paces and Miller, 1993) was used as a primary standard for all U–Pb measurements and age determinations, while Plešovice zircon was run as an unknown for quality control (QC) purposes; the measured age of 337.1 ±1.9 Ma for Plešovice zircon is within error of the accepted value of 337.13 ± 0.37 Ma by Slama *et al.* (2008). Approximate concentrations for U, Th, and Pb isotopes were calculated using NIST610 as primary standard and assuming 48% Zr in zircon.

Offline data reduction was performed using the Iolite 3.7 software with the "VizualAge" data reduction scheme (DRS). This data reduction includes a calculation of ^{204}Pb-corrected isotope ratios based on the terrestrial Pb-Pb evolution model of Kramers and Tolstikhin (1997). Concordia ages and inverse-concordia regressions and lower intercept ages were calculated using Isoplot 4.15 (Ludwig 2012).

Results

U–Pb zircon data for the Boyd Creek tuff are shown in Figure 12 and Supplementary Data Table S1. Zircon grains recovered from the Boyd Creek tuff are generally elongate prisms ranging from 50–170 µm on the long axis and subhedral to euhedral in shape. A combination of backscattered electron (BSE) imaging and optical cathodoluminescence

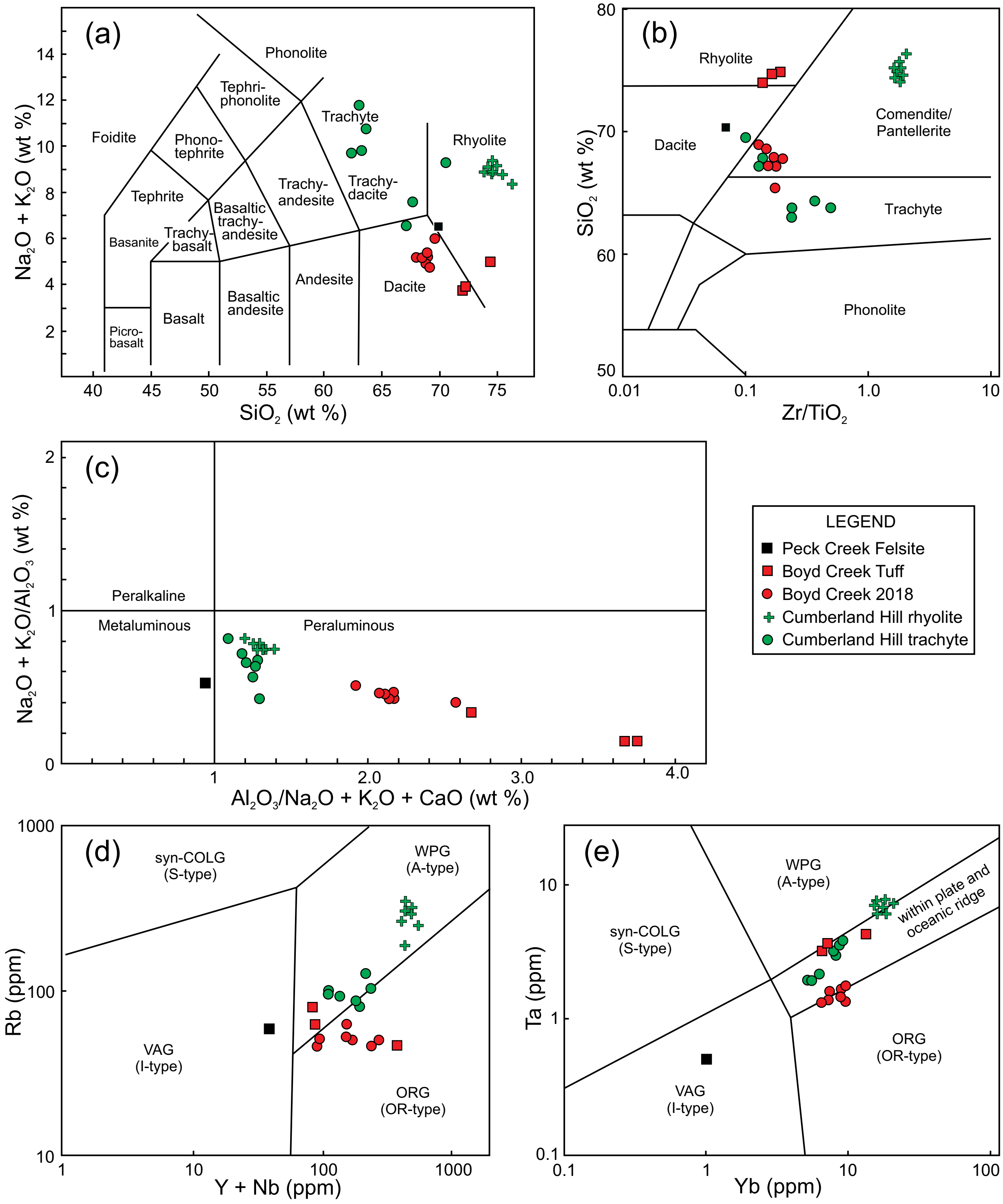

Figure 9. Major oxide and trace element plots for the Boyd Creek tuff, Cumberland Hill rhyolite/trachyte and Peck Creek felsite. Cumberland Hill data are from Gray *et al.* (2010). (a) Alkalis versus SiO_2 classification diagram after LeMaitre *et al.* (1989). (b) SiO_2 versus Zr/TiO_2 classification plot after Winchester and Floyd (1977). (c) Alkali-alumina plots for felsic igneous rocks after LeMaitre *et al.* (1989) distinguishing meta-aluminous, peraluminous, and peralkaline types. (d) and (e) Trace element discrimination plots for felsic igneous rocks and plate tectonic settings, after Pearce *et al.* (1984).

(CL) imaging reveal rare resorbed core domains (antecrysts) surrounded by planar- to oscillatory-zoned autocrysts. The euhedral terminations of these autocrystic domains were preferentially targeted for laser ablation dating (see Fig. 13). The overall bright yellow-blue CL response indicates minimal metamictization.

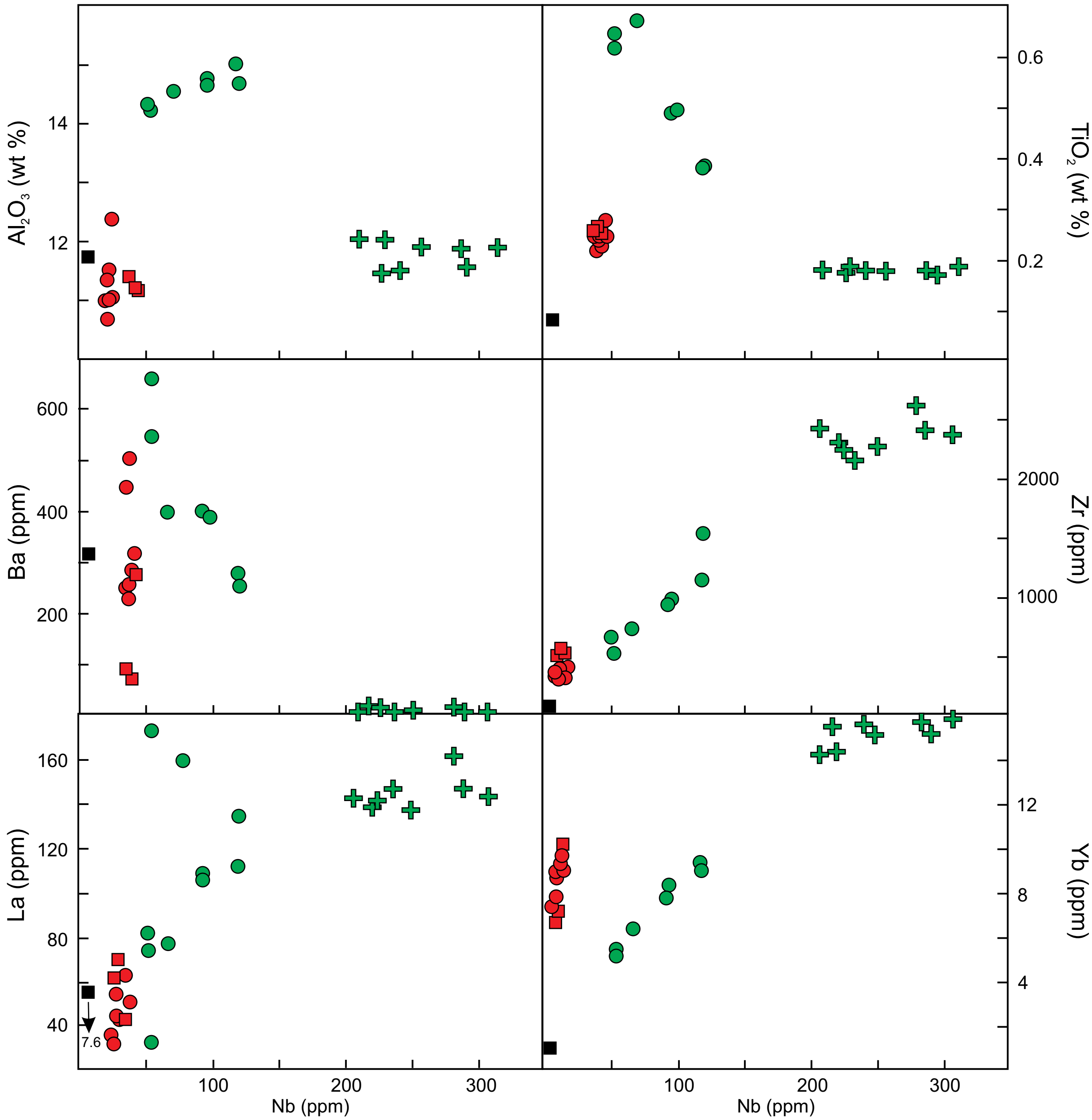

Figure 10. Trace element plots against Nb for the Boyd Creek tuff, Cumberland Hill trachyte and rhyolite, and Peck Creek felsite. Cumberland Hill data are from Gray *et al.* (2010). Symbols as in Figure 9. Nb is used as a fractionation index after White *et al.* (2006) – see text for details.

A total of 116 spot analyses were collected over the course of three separate analytical sessions. The preliminary date reported in Park *et al.* (2019) resulted from the first session, and the total data set reported here accounts for the slight difference in reported age. Taken as a whole, the resulting U–Pb dataset reveals a complex distribution of isotope ratios that reflect a combination of (1) inheritance, (2) common-Pb incorporation, and (3) mixing between antecryst/autocryst domains. As a result, the data require careful filtering to assess the crystallization age of the tuff. This filtering was accomplished in several stages. First, obvious xenocrystic components were grouped. These include spots that yielded ages of ~900 to 1100 Ma (n = 18), ~585–620 Ma (n = 4), and ~390–450 Ma (n = 6). Next, spots that displayed a net ^{204}Pb counts/sec >50 cps were identified (n =14) and ^{204}Pb-corrected ratios calculated using the standard approach. The remaining subset consists of 74 spots, 43 of which contain >99% Pb*. No correction was applied to these data. The remaining 31 spots in this subset contain sufficient common-Pb to move them off Concordia but have insufficient net ^{204}Pb counts to make a conventional common-Pb correction. For these 31 spots we adopted a ^{207}Pb-based correction scheme assuming a true radiogenic ^{207}Pb/^{206}Pb value of 0.05326 ± 0.00011 (equivalent to 340 ± 5 Ma), a

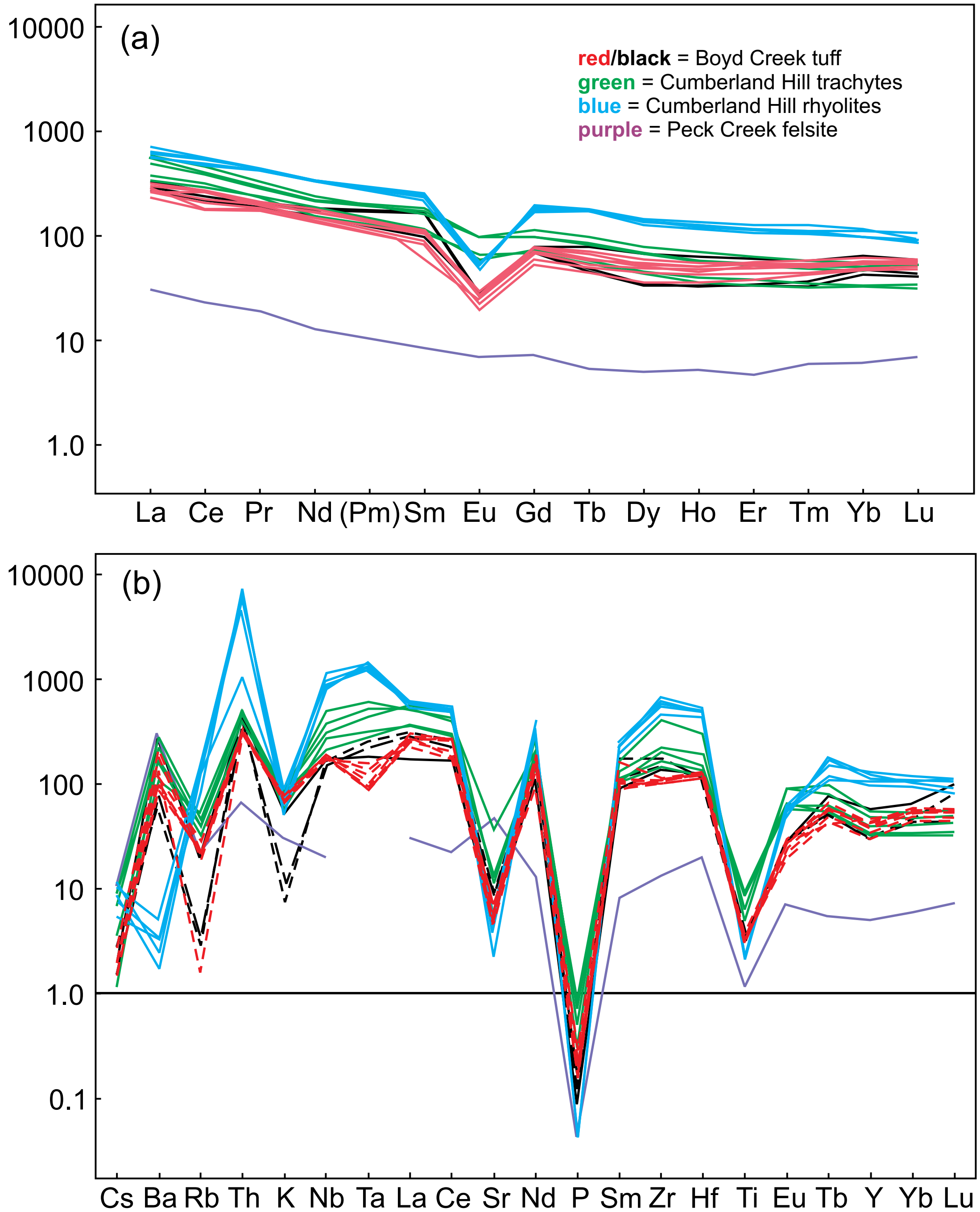

Figure 11. Rare earth (a) and incompatible element diagrams (b) for the Boyd Creek tuff, Peck Creek felsite, and Cumberland Hill trachyte and rhyolite. Cumberland Hill data are from Gray *et al.* (2010). Chondrite-normalization values are from McDonough and Sun (1995).

common-Pb ^{207}Pb/^{206}Pb value of 0.85 ± 0.01, and a ^{238}U/^{235}U value of 137.818. An error propagation analysis indicates that the ^{207}Pb-correction contributes an additional ~2% error to the corrected Pb/U ratios and ages.

The majority of the inherited zircons in this study are ~1120 Ma, 1020 Ma, and 950 Ma as well as single near-concordant analyses at 610 Ma and 585 Ma. (Fig. 12d). In an unpublished report, Van Breeman and St. Peter (1999) recorded similar inherited grains with discordant ages at 912 and 1206 Ma, also with large errors. The younger inherited ages around 950 Ma, plus the presence of Ti-Fe oxide xenocrysts (see below) is consistent with contamination from the Lower Coverdale complex, a concealed gabbro-anorthosite body identified in boreholes (Barr *et al.* 2007; Miller *et al.* 2018). The older Mesoproterozoic inheritance is typical of detrital zircon patterns in southern New Brunswick (e.g., Barr *et al.* 2019) and Grenville basement (e.g., the Blair River inlier, Cape Breton Island, Nova Scotia, Miller and Barr 2000).

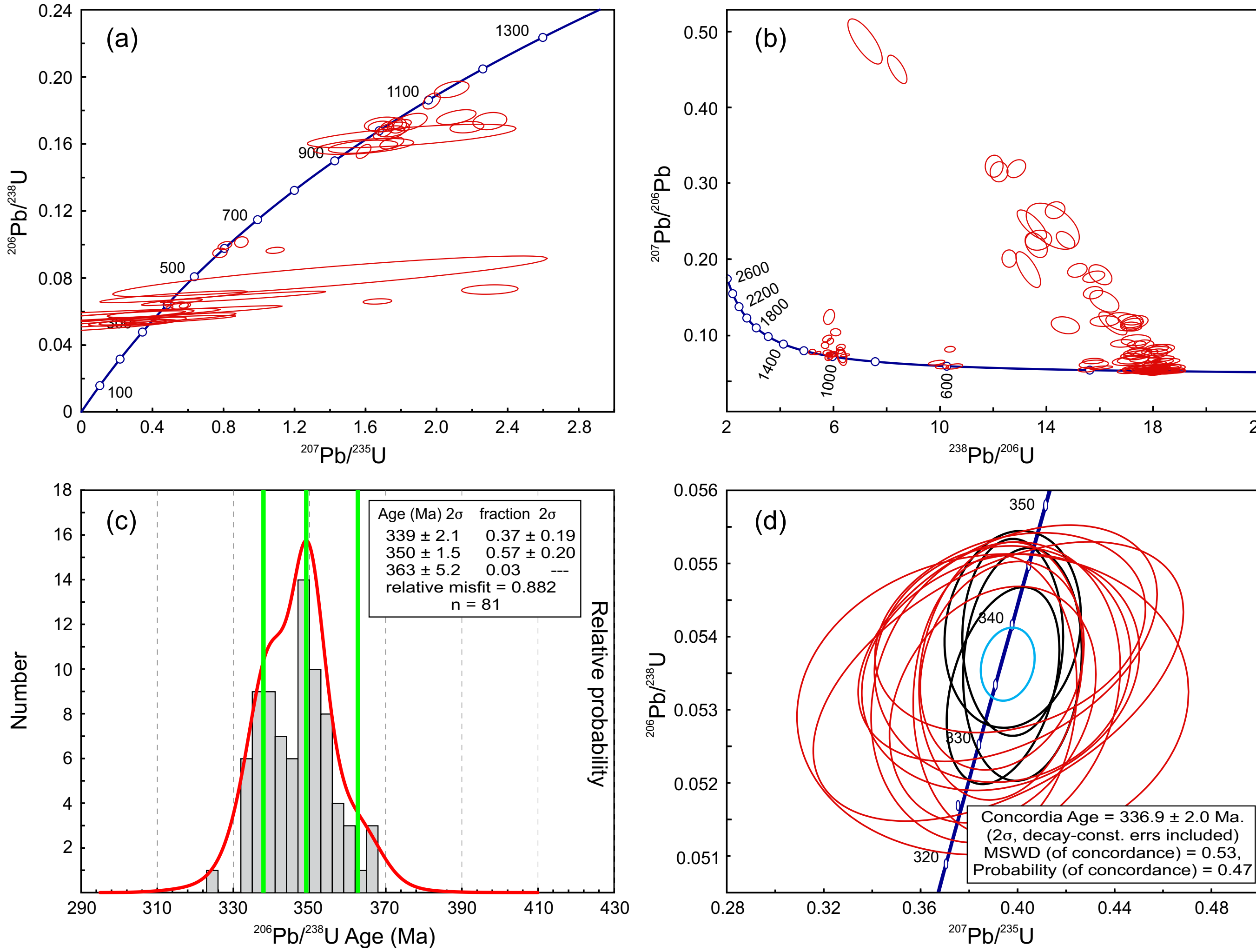

Figure 12. U–Pb zircon data for the Boyd Creek tuff. (a) Entire dataset plotted on conventional concordia diagram. Highly elongate ellipses are ^{204}Pb-corrected data. (b) Inverse concordia diagram. (c) Frequency (probability) – age histogram for the Boyd Creek tuff illustrating the populations defining the age of the tuff and several inherited populations. (d) Concordia diagram including uncorrected and ^{207}Pb-corrected data that give the ca. 339 Ma population in Figure 12c, giving a concordia age of 336.9 ± 2.0 Ma (n = 15; MSWD = 0.53).

The 336.9 ± 2.0 Ma age obtained from zircon in the Boyd Creek tuff is significant for two main reasons. Firstly, a maximum age from the zircons combined with biostratigraphic data places the Boyd Creek tuff well within the Visean (Holkerian; Menning *et al.* 2006) and is the time-equivalent of the Windsor Group. Secondly, the ages of (1) 338 ± 9 Ma reported by McFarlane *et al.* (2015) for tuff in the Windsor Group at the Picadilly mine (Fig. 1), in what is informally the basal anhydrite member of the Upperton Formation of McCutcheon (1981), 335 ± 2 Ma reported by Smith (2007) for rhyolite-trachyte flows at Cumberland Hill, and 335.4 ± 1.1 Ma reported by Jutras *et al.* (2018) for the lower felsic tuff in the Shin Formation in Hurley Creek, Minto area (Fig. 1) suggest the existence of a distinctive volcanic province that is part of or contemporaneous with the Windsor Group. The upper tuff at Hurley Creek, dated at 327.7 ± 0.9 Ma by Jutras *et al.* (2018) is somewhat younger. The Boyd Creek tuff is of similar age (within error) to all these units.

DISCUSSION

Compared to the type section in central Nova Scotia, the Windsor Group in New Brunswick is somewhat restricted. Only two subzones are recognized (A and B): limestone correlated with the Macumber/Gays River Formation from sub-zone A, and the Limekiln Brook Formation from sub-zone B (see McCutcheon 1981 for review and formal subdivision, and St. Peter and Johnson 2009 for correlation with Limekiln Brook Formation). In New Brunswick Windsor Group rocks from the Sussex area to the Hillsborough area are correlated with sub-zone A in central Nova Scotia. The sequence begins with the Macumber/Gays River Formation, overlain by two evaporite cycles, the Upperton Formation and Cassidy Lake Formation (confined to the Moncton sub-basin of McCutcheon 1981). In contrast to Nova Scotia, in New Brunswick the underlying red-brown polymictic sandy pebble-cobble conglomerate of the Hillsborough Formation

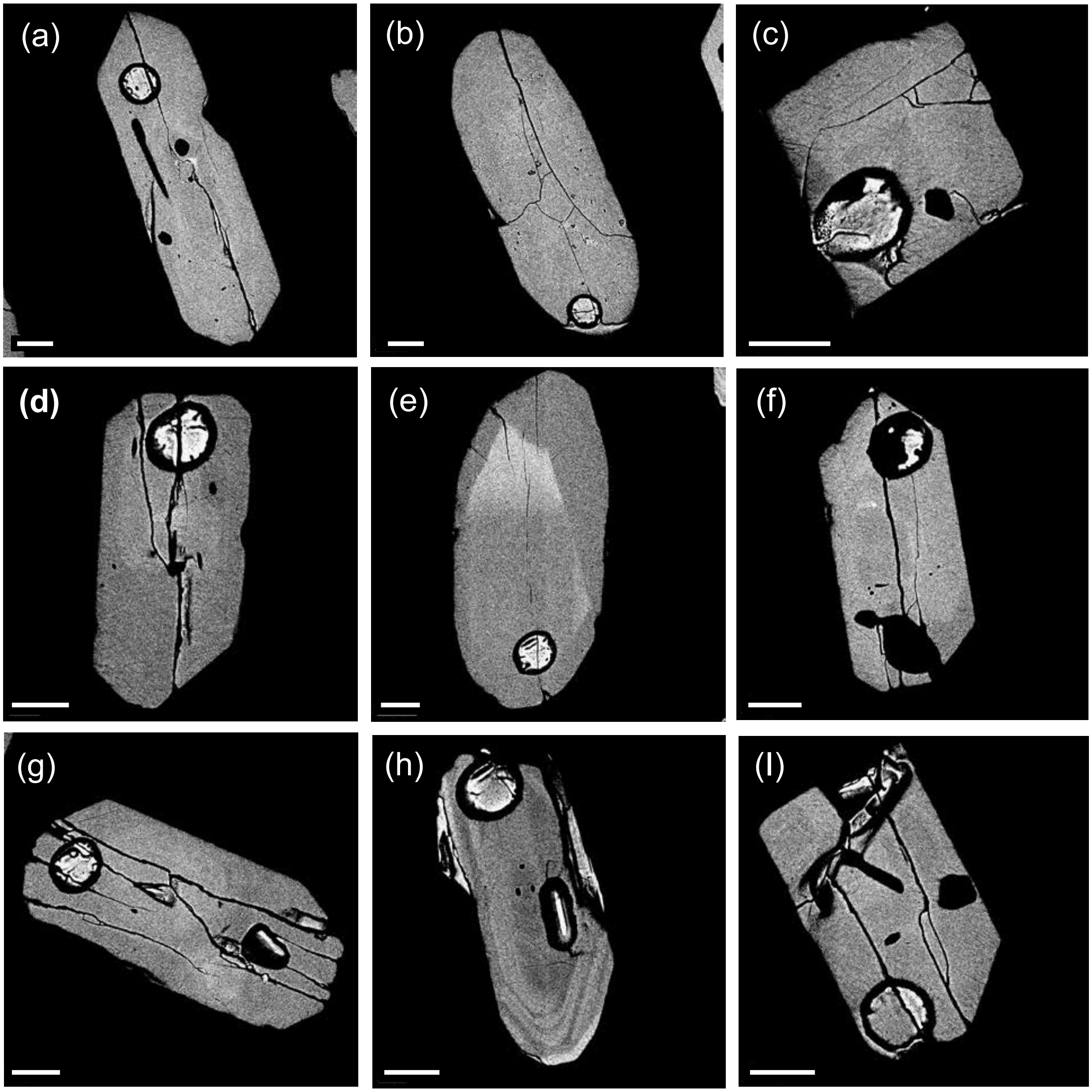

Figure 13. Selected euhedral to subhedral zircon grains from the Boyd Creek tuff in SEM back-scatter electron images. Circular ablation pits are visible in each grain. Cores are visible in some of the grains (a, b, d, e, f, g, h) and oscillatory zonation is apparent in others (a, f, g, h especially). The apical regions of the grains generally are least metamict. White scale bar (lower left in each image) is 20 μm.

is also included in the Windsor Group (St. Peter and Johnson 2009). The Limekiln Brook Formation is restricted to the Dorchester, Maringouin Peninsula and Hopewell areas marginal to the Cumberland basin and is not seen in the Moncton subbasin.

Biostratigraphic correlation largely relies on macrofaunal assemblages (Bell 1929) for both Macumber/Gays River Formation and Limekiln Brook Formation. Most attempts to identify the more definitive microfossil assemblages have not yielded distinctive forms (Mamet 1970; Globensky 1967, 1970), though McCutcheon (1981) reported conodonts (*Diplognathodus*) from the Wilson Brook section (Fig. 2) considered restricted to the base of sub-zone A and the Macumber/Gays River Formation in Nova Scotia, Cape Breton Island, and SW Newfoundland (von Bitter *et al.* 2007). In the Hillsborough area the Upperton Formation is represented only by the Basal Anhydrite member. The Halite member of the Upperton Formation and the overlying Cassidy Lake and Clover Hill formations of the Sussex area are absent, and the local top of the Windsor Group is defined by paleokarst overlain by coarse red-brown conglomerate of the Hopewell Cape Formation, part of the Mabou Group, that locally fills sinkholes and caverns (Webb 1977; McLeod 1980; St. Peter and Johnson 2009).

Chronostratigraphic constraints on the Windsor Group in Nova Scotia remain contentious (von Bitter *et al.* 2007, see discussion in Waldron *et al.* 2017), especially for sub-zone A and the Macumber/Gays River Formation. The distinctive conodont biozone in the Macumber/Gays River Formation is restricted to the Maritime Provinces and Newfoundland, making correlation with the western Europe biozones questionable (von Bitter *et al.* 2007). Ages ranging from late Chadian to early Asbian are possible, and Waldron *et al.* (2017) chose a middle Holkerian date. This age is consistent with miospores recovered from the Macumber Formation around Edgetts Landing (Fig. 2) reported in St. Peter and Johnson (2009), and hence this age is used here. Chronostratigraphic constraints on sub-zones C, D and E are better defined (von Bitter *et al.* 2007; Waldron *et al.* 2017), but they are not present in New Brunswick, where the upper age limit for the Windsor Group is indicated by Pendleian miospores from the Shepody Formation in the overlying Mabou Group (St. Peter and Johnson 2009). Notably the Shepody Formation on the Maringouin Peninsula contains Windsor Group limestone clasts (St. Peter and Johnson 2009).

The Mabou Group is sub-divided into the Maringouin and Shepody formations on the Maringouin Peninsula marginal to the Cumberland basin, Maringouin and Hopewell Cape formations around Dorchester, Hopewell Cape Formation along the southern edge of the Moncton subbasin, and Shin Formation on the New Brunswick platform northwest of the Belleisle Fault. By this sub-division, some formations in the Mabou Group are lateral equivalents of much of the Windsor Group sub-zone B and higher (Hopewell Cape and Maringouin formations especially, and the Shin Formation of the New Brunswick platform).

Red beds in the Shin Formation of the New Brunswick platform have few age constraints. The unit overlies Parleeville Formation to the southwest of Sussex and on both sides of the Saint John River on the platform margin northwest of the Belleisle Fault, but elsewhere sits with angular unconformity on pre-Carboniferous basement (McCutcheon 1981). The Shin Formation is overlain with marked unconformity by the Yeadonian-Langsettian Boss Point Formation and Langsettian-Bolsovian Minto Formation. The Shin Formation contains a number of volcanic units, including the Hardwood Ridge, Royal Road, and Queenstown basalts, and rhyolite and trachyte of Cumberland Hill Formation. The dates for the Cumberland Hill rhyolite and lower Hurley Creek felsic tuff (identical within error) are the only geochronological constraint, and these lie within the red bed sequence beneath the Hardwood Ridge basalts. Red beds have now been confirmed to also underlie the Cumberland Hill Formation (New Brunswick Department of Transport roadstone quarry, S. MacDonald, personal communication 2019)

The radiometric calibration for the Visean to early Serpukhovian time-scale used here is the one utilized by Waldron *et al.* (2017) based on Davydov et al (2012) and adopted by the ISC chronostratigraphic chart (Cohen *et al.* 2012, revised 2023), though noting that the division of the Brigantian sub-stage between uppermost Visean and lowermost Serpukhovian follows Menning *et al.* (2006). This timescale is also employed in Figure 14.

Of the five dated volcanic units, the new age reported here from the Boyd Creek tuff, as well as those from the Cumberland Hill rhyolite and lower Hurley Creek tuff are the most precise and reliable, the latter two being identical within error (Jutras *et al.* 2018). The upper Hurley Creek tuff date is based on one ablation spot analysis on one zircon grain (Jutras *et al.* 2018), and the Picadilly Mine tuff has the largest error (McFarlane *et al.* 2015). The latter result is especially unfortunate as of all these volcanic units it has the best constrained stratigraphic position (within the basal anhydrite member of the Upperton Formation). The Visean date on the Boyd Creek tuff, which is near the base of the Hillsborough Formation, demonstrates the Visean age of that formation and constrains it to the Holkerian sub-stage. If the Macumber/Gays River Formation is also Holkerian then the section from the Boyd Creek tuff through the Hillsborough Formation to the first marine transgression represent by this carbonate unit is no more than a few million years. The two dates for the contemporaneous lower Hurley Creek tuff and Cumberland Hill rhyolite units most probably fall into the interval represented by the upper part of sub-zone A, i.e. they are contemporary with the evaporite rocks of the Upperton, Cassidy Lake, and Clover Hill formations. The younger date but less reliable date of ca. 327 Ma from the upper Hurley Creek tuff suggests a Brigantian or Pendleian age, depending on which time-scale for the upper Visean/lower Serpukhovian is used — Davydov *et al.* (2012) or Menning *et al.* (2006) — contemporaneous with subzones C, D, or E of the Windsor Group and younger than any of the carbonate-evaporites of the Windsor Group in New Brunswick.

No detailed stratigraphic study of the marine Windsor Group in New Brunswick has been undertaken since McCutcheon (1981). The work by St. Peter and Johnson (2009) was confined to the southeastern area around Hopewell, Dorchester, and the Maringouin Peninsula (part of the Cumberland basin). This latter study was the most recent to attempt a correlation with the Windsor Group in Nova Scotia. Current understanding, based on broad lithostratigraphic correlation of carbonate-evaporite successions suggests that the marine Windsor Group in the Moncton subbasin consists of a carbonate-dominated lower succession (Macumber and Gays River formations, laterally grading to Parleeville Formation to the southwest) overlain by two evaporite cycles, the Upperton and Cassidy Lake formations. The carbonates overlie and locally interfinger with red-brown coarse clastic rocks of the Hillsborough Formation. This package is correlated with the lower Windsor Group of Nova Scotia. Along the Petitcodiac River estuary, this succession is seen around Hillsborough, especially in the Kings Quarry (Edgetts Landing), where the Cassidy Lake Formation is absent, and in a restricted succession of Macumber and Gays River formation in Cat Creek, around Berryton, and in boreholes beneath Pennsylvanian cover to

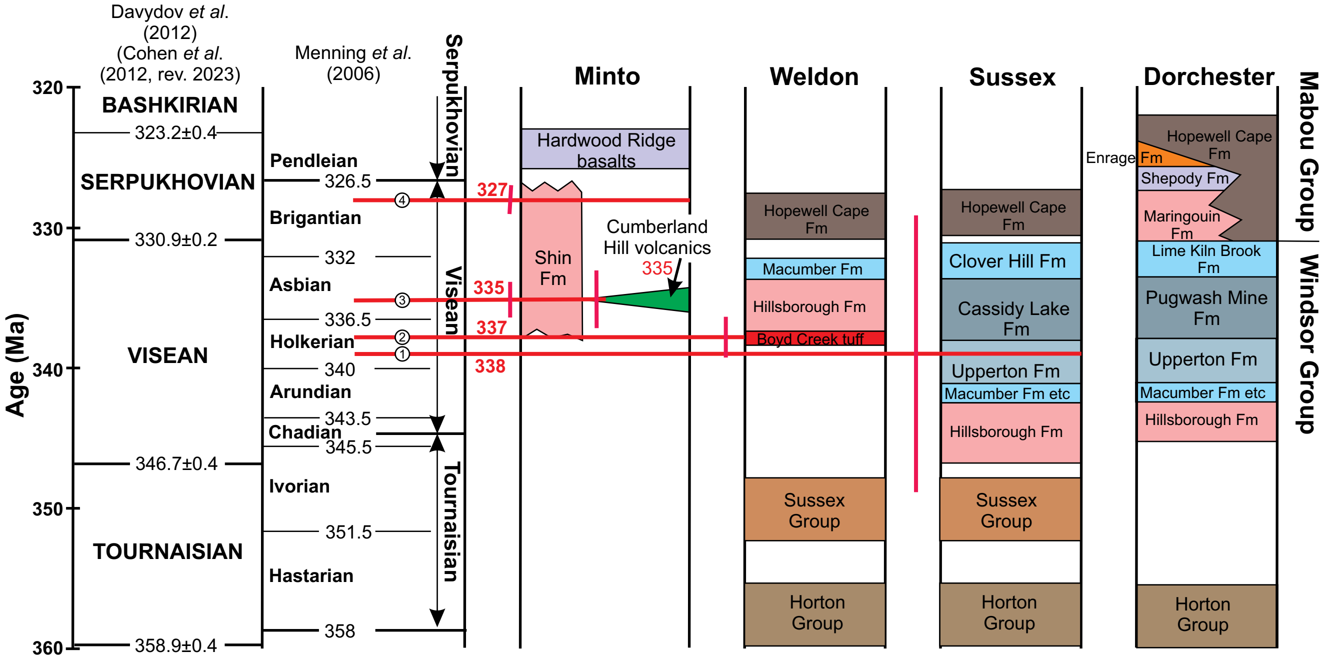

Figure 14. Possible lithostratigraphic and chronostratigraphic correlation in the Windsor Group of New Brunswick based on dated tuff markers. The Hurley Creek, Minto section is based on Smith and Fyffe (2006) and Jutras *et al.* (2018). The Weldon section is from St. Peter and Johnson (2009) with modifications based on this study and MacRae *et al.* (2017). The Picadilly mine section is based on McCutcheon (1981) modified after McFarlane *et al.* (2015). The Dorchester section is based on St. Peter and Johnson (2009) and their correlation with the Cumberland basin. Dated tuff layers (red lines) are numbered 1–4: 1, Picadilly mine (McFarlane *et al.* 2015); 2, Boyd Creek tuff, this paper; 3, lower tuff bed, Hurley Creek (Jutras *et al.* 2018); 4, upper tuff bed, Hurley Creek (Jutras *et al.* 2018). Horizontal red lines represent the mean for each radiometric age, with vertical lines the error. Note the wide range of possible correlations within error for the Picadilly mine tuff.

the west (Fig. 2). The overlying evaporites of the Upperton Formation do not recur until the Elgin area. No tuff has been identified in the succession around Hillsborough (Fig. 14).

The middle Windsor Pugwash Mines Formation (evaporite rocks) and overlying Lime Kiln Brook Formation (carbonate rocks) above the Macumber/Gays River and Upperton formations is complete only in boreholes around Dorchester, although limestone of the Lime Kiln Brook Formation and overlying and inter-fingered red-brown coarse clastic rocks of the Hopewell Cape Formation are exposed around Hopewell Cape. This correlation is based on macro-fossil biozones (St. Peter and Johnson 2009). Above the Windsor Group carbonate rocks the red beds of the Maringouin and Hopewell Cape formations are overlain by the Shepody Formation that has yielded Pendleian miospores: constituting the oldest demonstrated Serpukhovian unit and establishing an upper age for the underlying Windsor Group (St. Peter and Johnson 2009; Fig. 14).

The dated tuff in the Picadilly mine section at Penobsquis is located within the lower part of the Upperton Formation evaporites in the basal anhydrite member of McCutcheon (1981) (McFarlane *et al.* 2015), and above the carbonate Macumber/Gays River Formation. Coarse red clastic rocks of the Hillsborough Formation lie beneath both these units. Around Minto and Chipman the dated volcanic rocks of the Cumberland Hill Formation lie beneath the basal unconformity to the Pennsylvanian Minto Formation and have an ambiguous relationship to older rocks (Fig. 14). However recent quarrying activity has exposed red clastic rocks of the Shin Formation beneath the rhyolite (New Brunswick Department of Transport, S. MacDonald, personal communication 2019). The lower tuff layer in the Shin Formation at Hurley Creek west of Minto that was dated by Jutras *et al.* (2018) has an age within error of the Cumberland Hill rhyolite and Picadilly Mine tuff. The date on the upper tuff, some 6 million years younger, may be Brigantian or Pendleian depending on which version of the Visean timescale is used: Davydov *et al.* (2012), has this as Pendleian whereas in Menning *et al.* (2006) the same age would be Brigantian (Fig. 14). This sequence lies beneath the Hardwood Ridge basalts. The implication here is that the Shin Formation red bed and felsic volcanic rocks of the central New Brunswick Platform (Cumberland Hill rhyolite and lower Hurley Creek tuff) are contemporaneous with the marine rocks of the Windsor Group in the Moncton subbasin, and the lithostratographic units (Macumber, Gays River and Upperton formations) are potentially diachronistic across southeastern New Brunswick (Fig. 14).

CONCLUSIONS

1. A new U–Pb LA-ICP-MS date of 336.9 ± 2.0 Ma reported here for the Boyd Creek tuff falls within error of 335–338 U–Pb zircon ages previously reported for the Picadilly mine tuff, the Cumberland Hill rhyolite, and the lower tuff in the Hurley Creek section. Geochemical similarities between the Boyd Creek tuff and Cumberland Hill felsic volcanic rocks suggest that they are related, and all four felsic volcanic occurrences may indicate that they are part of a contemporary igneous province. The date reported for the upper felsic tuff at Hurley Creek (327 Ma) suggests that it may be somewhat younger. On geochemical grounds the Peck Creek felsite dike does not appear to be related to this felsic volcanic province.
2. The age of 336.9 ± 2.0 Ma for the Boyd Creek tuff is consistent with the limited available biostratigraphic data (miospores) and places the tuff in the lower/middle Visean (Holkerian, Menning *et al.* 2006, Cohen *et al.* 2012, revised 2023).
3. The Boyd Creek tuff contains Tonian and Mesoproterozoic inherited zircon and Ti-Fe oxides that may have been derived from the underlying Lower Coverdale gabbro-anorthosite. Older Mesoproterozoic is typical of sedimentary cover units in southern New Brunswick, likely derived from Ganderian basement or concealed Grenville basement.
4. The date from the Boyd Creek tuff, combined with previously reported ages from tuff and rhyolite in southern New Brunswick indicate that volcanic activity was occurring in the area during deposition of the marine Windsor Group. Identifying and dating other tuff layers offers the prospect for refining the lower Carboniferous stratigraphy and its correlation across the Maritime Provinces.

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URL LINKS TO SUPPLEMENTARY DATA

Supplementary Data Table S1: https://journals.lib.unb.ca/index.php/ag/article/view/33475/1882529735

The Supplementary Data Table S1 is also available through the University of New Brunswick Dataverse repository: https://doi.org/10.25545/7FYZBN

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