Age and geochemistry of middle to late Paleozoic volcanism along the western edge of Ancestral North America in north-central British Columbia

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Abstract

Legacy U-Pb zircon analyses from samples collected during systematic mapping in north-central British Columbia in the late 1980s and 1990s yielded ages of ca. 350 to 320 Ma for rocks of the Big Creek Group at the top of the Cassiar terrane (Ancestral North America) section near Germansen Landing and the Osilinka River (Gilliland tuff) and ca. 255 Ma from felsic tuffs occupying the upper part of Big Creek sratigraphy in the north. A sample from the upper part of the Lay Range assemblage, the local basement to the Upper Triassic to Lower Jurassic Nicola Group arc volcanic rocks in Quesnel terrane yielded an age of ca. 275 Ma. Lithogeochemical data (whole rock, trace, and rare earth element) for the Lay Range assemblage are consistent with eruption in an arc setting. Geochemical data for felsic rocks from the Big Creek Group suggest derivation from continental lithosphere. Geochemical results for mafic igneous rocks in the Big Creek Group indicate within-plate affinities. Sm-Nd isotopic geochemistry suggests an older, evolved, continental lithosphere as the source of magma that supplied the Big Creek Group felsic volcanic rocks. Isotopic data from the Lay Range assemblage point to a less evolved, mantle source.

Keywords: U-Pb zircon geochronology, Sm/Nd isotopes, geochemistry, Lay Range assemblage, Big Creek Group, Ingenika Group, Cassiar terrane, Quesnel terrane, Gilliland tuff

1. Introduction

In the late 1980s and 1990s, the British Columbia Geological Survey carried out a systematic mapping program near the Lay Range in the north-central part of the province (Fig. 1) focused on a corridor of metal-rich volcanic and intrusive rocks of Quesnel terrane and adjoining rocks of Ancestral North America (Ferri, 1989; Ferri and Melville, 1988a, b, 1989a, b, 1990a, b, 1994; Ferri et al., 1988, 1989, 1992a, b, 1993a, b; Ferri, 1997, 2000; Ferri et al., 2001a, b). In addition, workers examined Alaskan-type ultramafic rocks in the area (Nixon et al., 1993, 1998) and mapped the northern extent of Triassic volcanic rocks in Quesnellia (Schiarizza, 2004; Schiarizza et al., 2004; Schiarizza et al., 2005; Schiarizza and Tan, 2005; MacIntyre et al., 2005). More recently, Ootes et al. (2019a, b, 2020a, b) investigated the northern half of Hogem batholith and provided fossil and detrital zircon U-Pb constrains on the timing of deposition of the lower sedimentary division of the Lay Range assemblage (Ootes et al., 2022).

This paper presents previously unreleased vintage multigrain U-Pb zircon data on samples collected as part of regional mapping. Four samples are from the Big Creek Group at the top of the Cassiar terrane section (Ancestral North America), and one is from the Lay Range assemblage, the local basement to Nicola Group arc volcanic rocks that are predominant in Quesnel terrane. We also present lithogeochemical and Sm-Nd isotopic data from these and other units.

2. Location and geological setting

Regional mapping of the late 1980s and 1990s spanned the area between Manson Creek and the Lay Range (Fig. 2). Road access is afforded by an all-season forestry road network extending from Manson Creek to Germansen Landing and continues north to Aiken and Johanson lakes. Samples were collected near Germansen Landing, Wasi Lake, northeast of Aiken Lake, and in the Lay and Wrede ranges (Fig. 3).

The area straddles the boundary between rocks of Ancestral North America, here represented by the Cassiar terrane, and those of oceanic and arc affinities belonging to the Slide Mountain and Quesnel terranes (Fig. 1). The Cassiar terrane section includes Neoproterozoic siliciclastic and carbonate rocks of the Ingenika Group that are overlain by a predominantly carbonate succession of Cambrian to Middle Devonian rocks (Fig. 4). At the top of the stratigraphic section are Upper Devonian to Permian dark shales of the Big Creek Group that contain felsic volcanic rocks, which we sampled for geochronologic study (Fig. 5). The northward disappearance of the lower and middle Paleozoic succession between the Wrede-Lay ranges section and the Manson Creek-Wasi Lake section (Fig. 4) suggests a

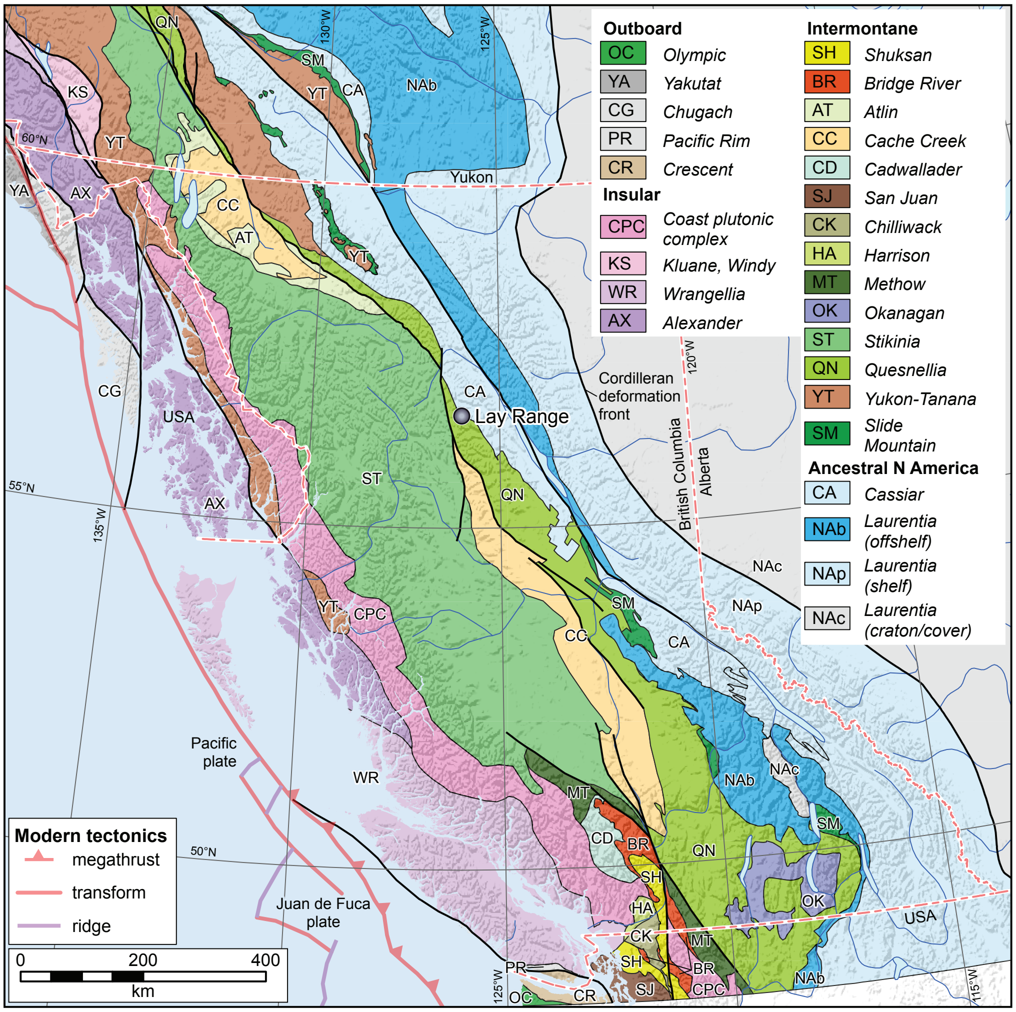

Fig. 1. Tectonic elements of the Canadian Cordillera in British Columbia and location of study area. Terranes after Colpron (2020).

major unconformity at the base of the Big Creek Group in the north. South of Wasi Lake, upper Paleozoic mafic volcanic and sedimentary rocks of the Slide Mountain terrane (Nina Creek Group) sit structurally above Cassiar terrane rocks (Fig. 4). This structurally interleaved sequence represents rocks of oceanic affinity that are considered to have been emplaced onto Cassiar rocks in the Early Jurassic. In the same structural position north of Wasi Lake are upper Paleozoic rocks of the Lay Range assemblage, which constitute basement to the Upper Triassic to Lower Jurassic mafic to intermediate arc volcanic rocks that are predominant in Quesnel terrane (Figs. 2, 4).

The Lay Range assemblage is subdivided into the "lower sedimentary" and "upper mafic tuff" divisions (Fig. 6). The lower sedimentary division is Late Mississippian to Middle Pennsylvanian (Ferri, 1997; Ootes et al., 2022) and consists of siliciclastic, carbonate, and mafic volcanic rocks. The 'upper mafic tuff' division is Middle Pennsylvanian to Permian and contains mafic flows to fragmental volcanic rocks with local felsic units. Above the Lay Range assemblage basement are predominantly volcanic rocks which, as discussed by Ootes et al. (2020a), are referred to in Quesnel terrane as the Nicola Group (Fig. 2); equivalent rocks in Stikine terrane are termed the Takla Group. The multiphase Hogem batholith has Late Triassic to Early Jurassic phases likely comagmatic with the Nicola Group and later post-accretionary Cretaceous intrusions (e.g., Ootes et al., 2020a, b).

3. U-Pb zircon geochronology

We carried out U-Pb zircon geochronology on four samples from the Big Creek Group, and one from the Lay Range assemblage (Fig. 2). Big Creek analyses include two from the Gilliland tuff and two from felsic tuff in the upper part of the unit.

3.1. Methods

Zircons were separated from a ~20 kg sample using conventional crushing, grinding, Wilfley table, heavy liquids and Frantz magnetic separator techniques. U-Pb analyses were done by University of British Columbia using methods for zircon grain selection, abrasion, dissolution, geochemical

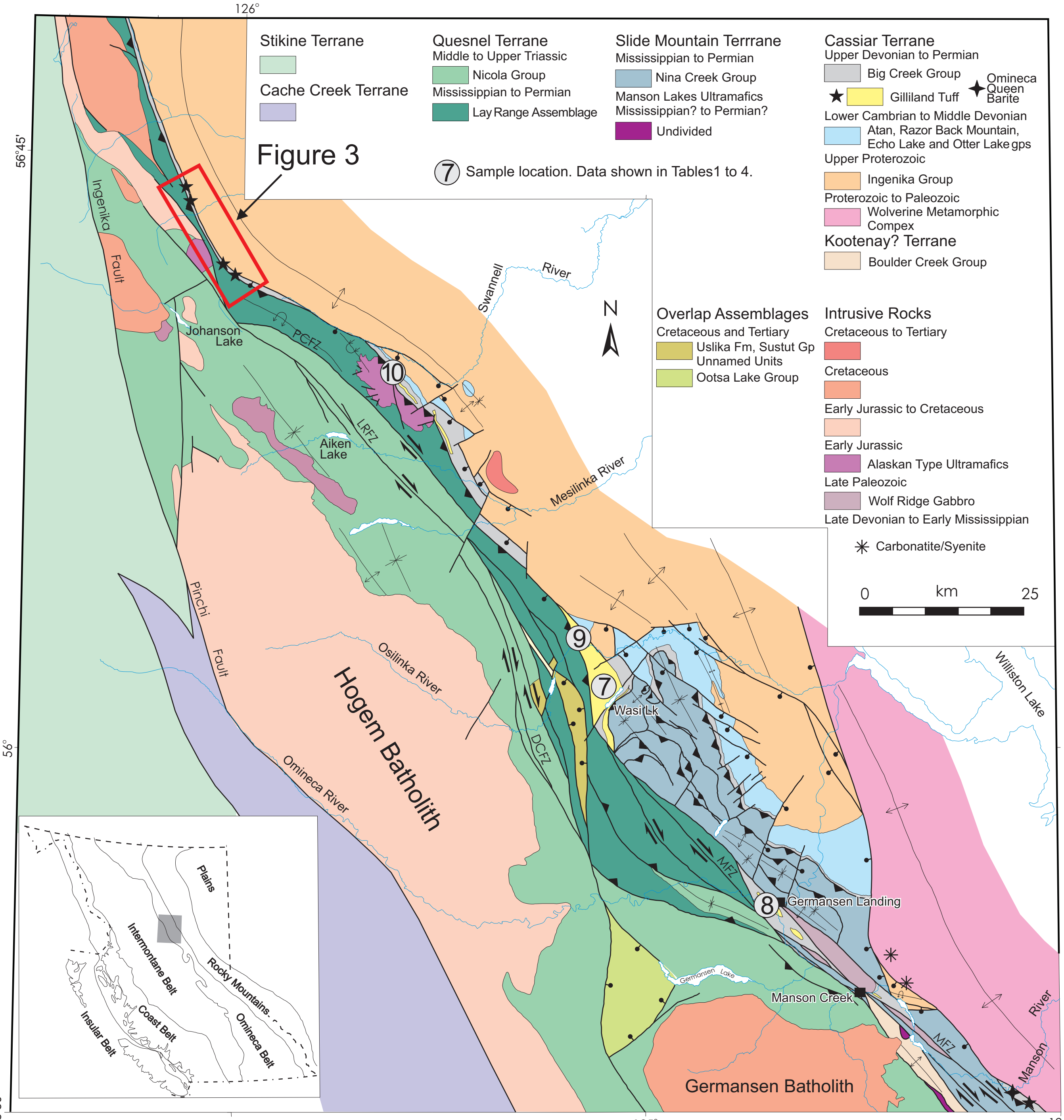

Fig. 2. Regional geological map.

preparation, and mass spectrometry as described by Mortensen et al. (1995). Procedural blanks for Pb and U were 2 and 1 pg, respectively. Errors attached to individual analyses were calculated using the numerical error propagation method of Roddick (1987). Decay constants used are those recommended by Steiger and Jäger (1975). Compositions for initial common Pb were taken from the model of Stacey and Kramer (1975). All errors are given at the 2 sigma level.

3.2. Results

3.2.1. Big Creek Group, Gilliland tuff, sample FFe88-34-2

We resampled rocks at the type locality of the Gilliland tuff near Germansen Landing (Figs. 2, 5) that previously yielded a minimum U-Pb age of 377 ±12 Ma but with evidence of inheritance and lead loss (Ferri and Melville, 1994).

Abundant pale yellow, clear zircon was recovered from the

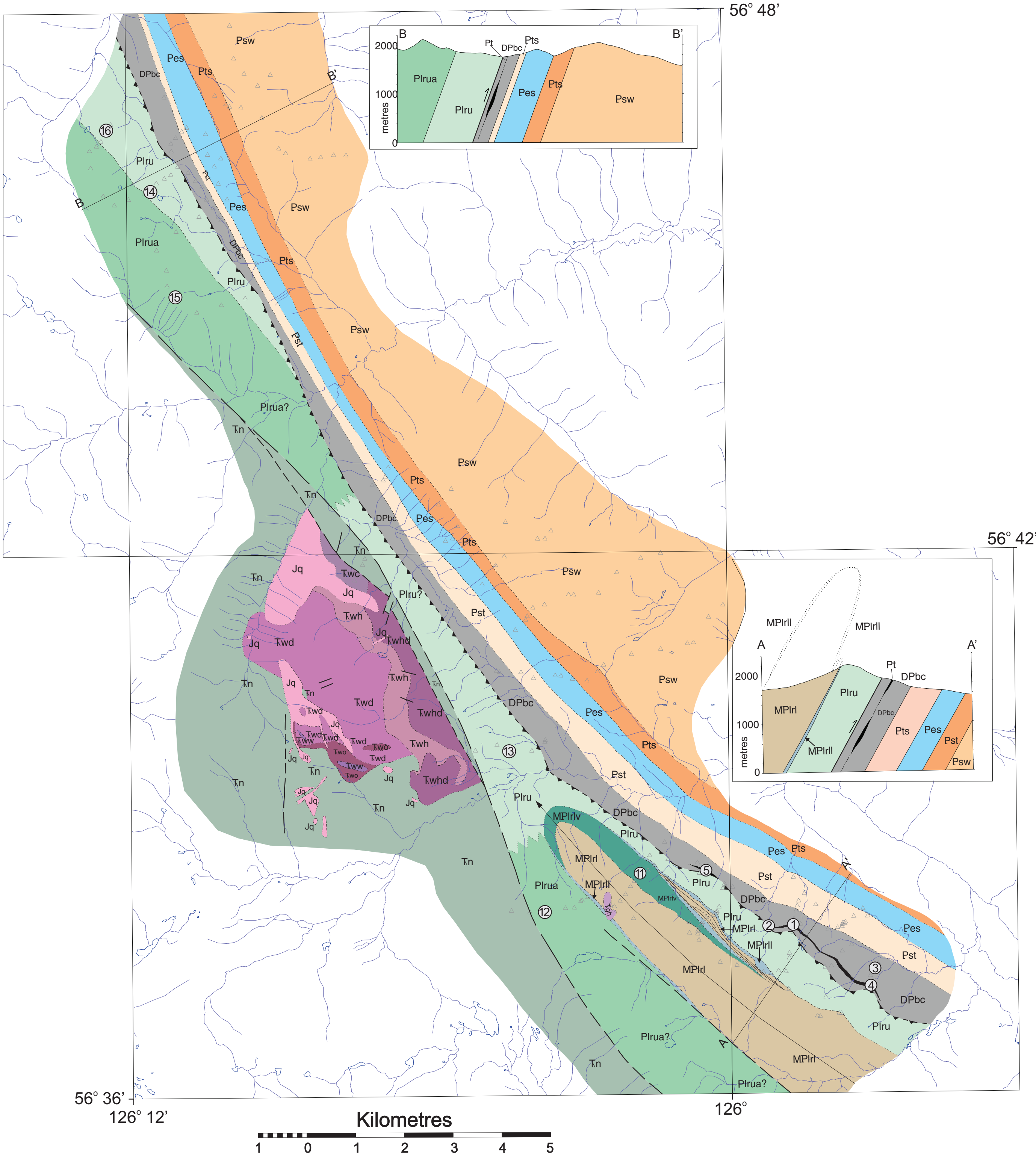

Fig. 3a. Geology of the Lay and Wrede ranges.

MIDDLE JURASSIC

Jq Buff-white weathering, white to pale grey, medium grained, equigranular hornblende-bearing quartz monzonite/monzonite/quartz diorite/diorite

LATE TRIASSIC

Wrede Complex

Twhd Pale grey to black weathering, fine to coarse grained hornblende diorite or gabbro/clinopyroxene-hornblende diorite or gabbro plagioclase

Twh Medium brown weathering, coarse grained hornblende clinopyroxenite

Twc Dark to medium grey-green weathering, medium to coarse grained undifferentiated clinopyroxenite, includes hornblende clinopyroxenite, olivine clinopryoxenite and olivine-hornblened clinopyroxenite

Two Medium to pale grey-green weathering, medium to coarse grained olivine clinopyroxenite

Tww Dark to medium brown weathering predominantly medium grained or medium to coarse grained wehrlite

Twd Pale buff-orange weathering, dark grey to black, fine to medium grained dunite

Tgh Rusty weathering, grey-green, biotite-bearing gabbro and grey to orange weathering coarsely crystalline hornblendite

Nicola Group

Tn Pale to medium grey-green weathering, dark grey-green augite-feldspar bearing volcanic breccia, tuffs and flows

Lay Range assemblage

MIDDLE PENNSYLVANIAN? TO PERMIAN

Upper Mafic Tuff division

Plrua Grey-geen or maroon weathering, pale to dark green and maroon, feldspar-pyroxene lapilli tuffs volcanic breccia, flows and lesser crystal tuffs. Rare grey limestone

Plru Pale greenish grey to green weathering, green to grey green thin to thickly bedded and well laminated tuff. Locally dark green aphanitic basalt with associated lapilli tuff and volcanic breccia. Rare rusty weathering, quartz-bearing tuff to sericite schist

Lower Sedimentary division

LATE MISSISSIPPIAN TO MIDDLE PENNSYLVANIAN

MPlrll Grey to buff weathering grey limestone. Massive to platy, locally bioclastic with interlayers of beige to pale grey chert. Locally contains maroon and green siltstone or tuffaceous horizons. Tan to buff weathering white to cream recrystallized massive dolomite

MPlrlv Grey-brown weathering, dark green, aphanitic basalt, lesser volcanic breccia and tuff. Locally spheriolitic. Pale to green, medium to coarsely crysalline gabbro to quartz monzonite, locally foliated

MPlrl Thick to massively bedded, beige to brown weathering tan to greenish brown calcareous sandstone, very fine to granule conglomerate. Interlayered with black argillite, green tuffaceous siltstone, thin bedded whiite to grey chert and brown to orange weathering grey platy limestone

LATE DEVONIAN TO PERMIAN

Big Creek Group

DPbc Dark grey, dark blue-grey to black slate and thin to moderately bedded argillite. Minor horizons of dark grey to black quartz-chertz wackes, sandstones and lesser granule conglomerate. ★ Locally contains thin horizons of light coloured quartz-feldspar-bearing felsic tuff and dark green basalt.

Pt Rusty to tan weathering, pale grey to dark grey or greenish grey, quartz-feldspar tuff to lapilli tuff. Sericitic and locally contains pryrite and ankerite porphyroblasts. Minor argillite clasts. Locally contains tan to grey weathering, very fine to medium crystalline diorite or quartz diorite which can be associated with dark green basalt.

LATE PROTEROZOIC

Ingenika Group

Stelkuz Formation

Pst Rusty brown weathering, greenish grey slate, lesser thin to massively bedded cream impure quartzite and quartz sandstone and thinly bedded, grey limestone

Espee Formation

Pes Grey to buff weathering, platy and blocky, finely recrystallized limestone and dolomitic limestone, grey calcareous slate. Cross-cutting zones of orange weathering, coarsely crystalline dolostone are locally present.

Tsaydiz Formation

Pts Thinly interlayered, grey to orange-brown weathering, grey to green-grey slate, calcareous slate and grey to orange weathering, grey limestone.

Swannell Formation

Psw Thickly bedded, grey-green to green, feldspar-bearing quartz sandstone to wacke, quartz sandstone, slate, siltstone, impure quartzite and rare grey limestone. Schistose in its lowest parts, locally containing biotite porphyroblasts.

Geologic boundary (approximate, assumed):

Thrust Fault (approximate, assumed):

Fault, unknown displacement (approximate, assumed):

Fold axis, overturned (anticline, syncline):

Field station:... △

(12) Sample location. Data shown in Tables1 to 4.

Fig. 3b. Legend.

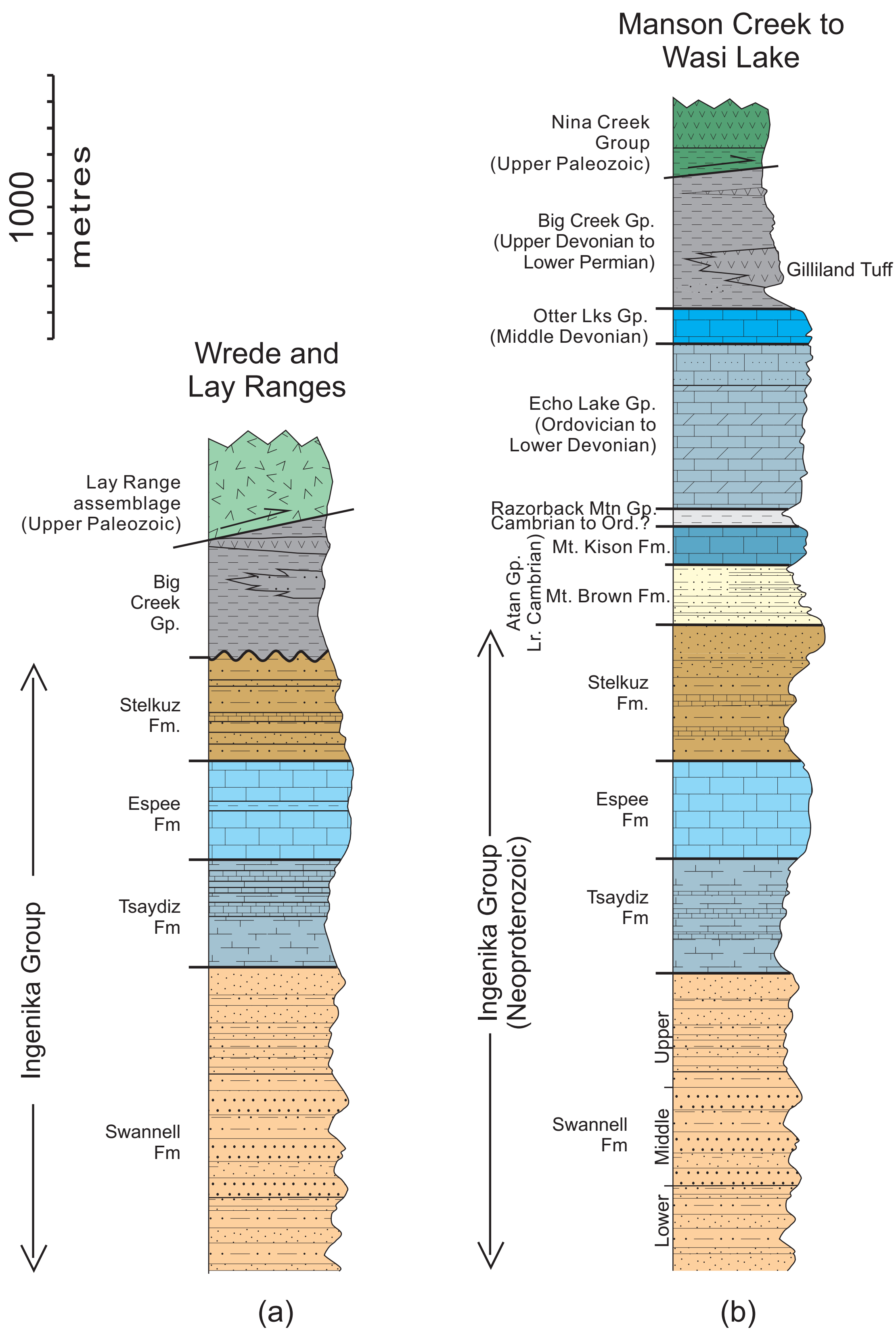

Fig. 4. Cassiar terrane generalized stratigraphic columns. **a)** Wrede and Lay ranges. **b)** Manson Creek to Wasi Lake. The column in b) shows the removal of Lower Paleozoic stratigraphy below the sub-Big Creek unconformity.

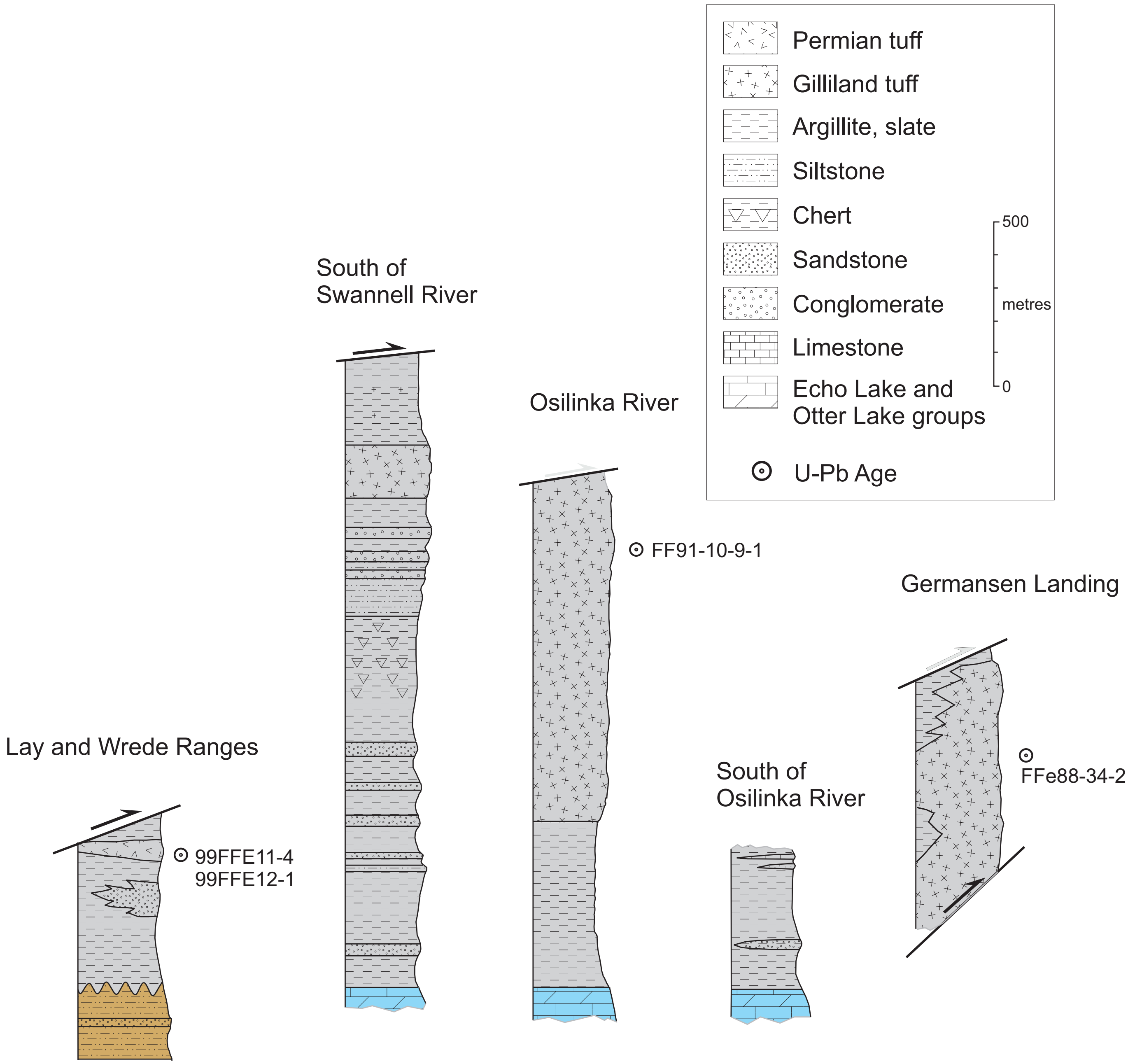

Fig. 5. Local stratigraphic columns and context of Big Creek Group geochronologic samples.

sample. The zircons included stubby to elongate prismatic grains and equant to stubby prismatic multifaceted grains that appeared to represent a single population. Evidence of detrital or xenocrystic components was lacking but cloudy cores were present in a small proportion of the grains. Zircon grains with fractures parallel to the c-axis, and ones with elongate clear tube- or rod-shaped inclusions that passed through the centres of the grains were considered to be least likely to include inherited cores, and these grains were specifically selected for analysis in an attempt to minimize the possibility of inherited zircon. Approximately 30 grains were picked from the coarsest, least magnetic fraction, strongly abraded (Krogh, 1982) to minimize the effects of post-crystallization Pb-loss, and split into five multi-grain fractions for analysis. A sixth fraction comprising fine, clear, elongate prismatic grains was also selected and analyzed without abrasion.

The analytical results (Table 1) indicate that this approach to grain selection was reasonably successful. Selection of grains that contained significant numbers of inclusions results in a somewhat higher proportion of common Pb in the analyses, and consequently slightly less precise analyses. Fraction D gave a slightly younger $^{206}Pb/^{238}U$ age, which is interpreted

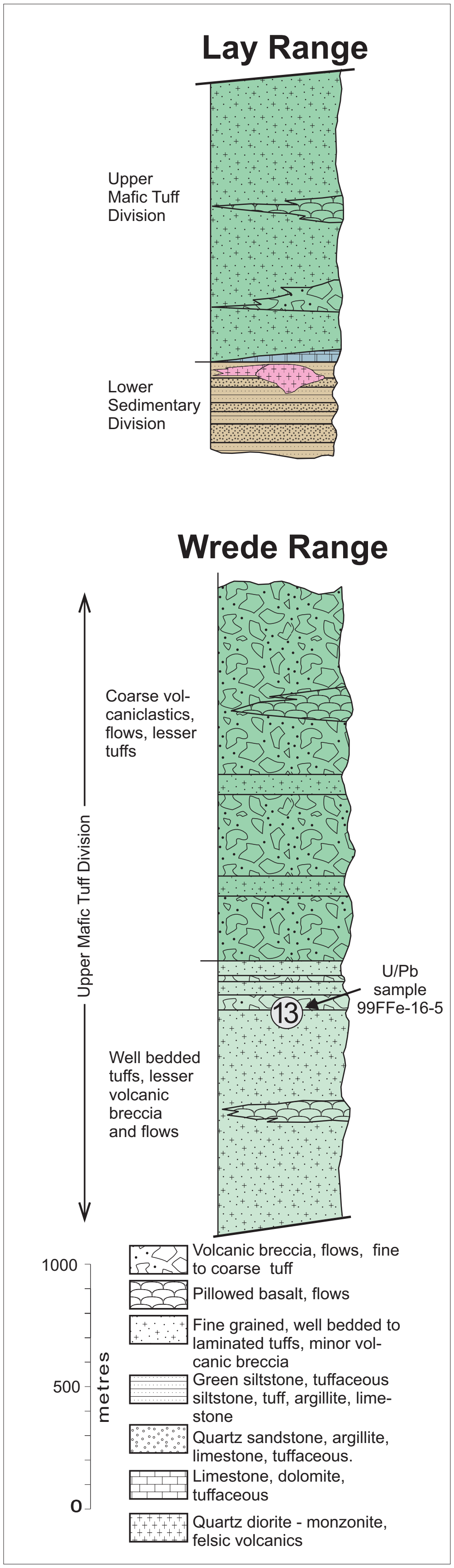

Fig. 6. Generalized stratigraphic columns of the Lay Range assemblage in the Wrede and Lay Ranges.

to indicate minor Pb-loss effects that were not completely eliminated by the strong abrasion. Fraction F, which was not abraded, yielded a much younger $^{206}Pb/^{238}U$ age, indicating significant post-crystallization Pb-loss. Fraction E gave a slightly older $^{206}Pb/^{238}U$ age and fractions A and C give much older $^{206}Pb/^{238}U$ ages, indicating that these fractions contained a significant component of older inherited zircon despite efforts to avoid this complication (Figs. 7a, b). Two-point regressions through fraction B and the two most discordant fractions yield calculated upper concordia intercept ages of 2.06 and 2.71 Ga. This gives an indication of the range of ages of the inherited zircon component in the sample. However, two of the fractions (B and D) yielded concordant analyses (Figs. 7a, b). Fraction B gives the oldest $^{206}Pb/^{238}U$ age of 354.5 ±0.9 Ma, which is considered to be the best estimate for the crystallization age of the sample.

3.2.2. Big Creek Group, Gilliland tuff, sample FF91-10-9-1

Sample FF91-10-9-1 is a slightly foliated quartz and feldspar tuff, collected from the Gilliland tuff unit of the Big Creek Group near Osilinka River (Figs. 2, 5). Five multi-grain zircon fractions were analyzed in 1993 (Table 2; Figs. 7c, d). The coarse fractions C and F (Table 2) are highly discordant due to a large component of inherited zircon. The other three fractions all plot near concordia. Fraction A is concordant at 319 ±31 Ma (Fig. 7d), which is considered the age of crystallization, although an older age should not be ruled out considering the effects of lead loss. An upper limit of 417.1 ±4.0 Ma is the $^{206}Pb/^{238}U$ age of fraction D, the oldest of the three nearly concordant fractions.

3.2.3. Big Creek Group, felsic tuff, sample 99FFE11-4

This felsic tuff yielded clear, pink, euhedral and rarely slightly rounded prismatic grains. Six multi-grain zircon fractions were analyzed (Table 1; Fig. 8a). Fraction F is marginally concordant; it is interpreted to have suffered minor Pb loss and to contain no inherited zircon. Fraction B likely contains inheritance and underwent minor Pb loss. Concordant fraction E and discordant fractions A, D, and C define a linear array of data. The former fraction yielded a $^{206}Pb/^{238}U$ age of 253.6 ±0.5 Ma and also anchors a lower intercept through discordant fractions A-D, and is therefore considered as the best estimate for the age of the rock. The upper intercept of a chord fit to the data gives an upper intercept of 2.5 ±0.3 Ga (mean square weighted deviation=0.56), which provides an estimate for the age of inherited zircon in the latter fractions.

3.2.4. Big Creek Group, felsic tuff, sample 99FFE12-1

This felsic tuff yielded clear, pink, stubby to elongate zircons. Four fractions were analyzed, three of which are strongly discordant (A, B, and C; Table 1; Fig. 8b). Based on the data alone this rock could be as young as ca. 236 Ma.

Table 1. Multigrain U-Pb zircon analyses performed at Pacific Centre for Isotopic and Geochemical Research, Earth and Ocean Sciences, University of British Columbia in 2000.

Fraction[1]	Wt	U^2	Pb^3	$^{206}Pb^4$	Pb^5	$^{208}Pb^3$	Isotopic ratios (±1-sigma, %) [6]			Apparent ages (±2-sigma, Ma) [6]		
	mg	ppm	ppm	^{204}Pb	pg	%	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
99FFE11-4 Big Creek Group felsic tuff[a] (location 4 on Fig. 3)												
A cc,N2,p,1	0.020	364	15	2206	8.4	12	0.04033 (0.13)	0.2881 (0.22)	0.05181 (0.15)	254.9 (0.6)	257.0 (1.0)	276.9(6.8)
B c,N2,p,7	0.030	696	29	224	255	13	0.03983 (0.28)	0.2875 (0.95)	0.05236 (0.77)	251.8 (1.4)	256.6 (4.3)	301(35/36)
C c,N2,p,13	0.050	680	28	2328	38	11	0.04050 (0.11)	0.2932 (0.20)	0.05251 (0.12)	255.9 (0.5)	261.1 (0.9)	307.5(5.3)
D m,M2,p,30	0.040	409	17	3023	14	12	0.04045 (0.10)	0.2913 (0.18)	0.05223 (0.11)	255.6 (0.5)	259.6 (0.8)	295.5(5.1)
E f,N2,p,p,e	0.040	403	16	5614	7.1	10	0.04012 (0.10)	0.2837 (0.18)	0.05129 (0.12)	253.6 (0.5)	253.6 (0.8)	253.8(5.3)
F ff,N2,p,p,e	0.015	331	13	5460	2.2	11	0.03934 (0.20)	0.2782 (0.27)	0.05130 (0.21)	248.7 (1.0)	249.3 (1.2)	254.2(9.6)
99FFE12-1 Big Creek Group felsic tuff[a] (location 5 on Fig. 3)												
A m,N2,p,s,3	0.025	505	52	16530	4.5	12	0.09526 (0.10)	1.5484 (0.16)	0.11789 (0.07)	586.6 (1.1)	949.9 (1.9)	1924.5(2.6)
B f,N2,p,s,15	0.035	385	26	4537	12	11	0.06518 (0.10)	0.7475 (0.17)	0.08319 (0.09)	407.0 (0.8)	566.8 (1.5)	1273.5(3.4)
C f,N2,p,s,23	0.030	215	16	2354	12	15	0.06959 (0.10)	0.8318 (0.18)	0.08669 (0.11)	433.7 (0.8)	614.6 (1.6)	1353.6(4.2)
D ff,N2,p,e,25	0.010	256	9.8	1336	4.5	11	0.03741 (0.15)	0.2646 (0.31)	0.05130 (0.26)	236.7 (0.7)	238.4 (1.3)	254(12)
99FFE 16-5 Lay Range assemblage felsic tuff[a] (location 13 on Fig. 3)												
A f,N2,p,na	0.015	113	5.4	1853	2.5	17	0.04356 (0.29)	0.3110 (0.54)	0.05179 (0.47)	274.8 (1.5)	275.0 (2.6)	276(22)
B f,N2,b,na	0.015	176	9.7	3794	2.2	19	0.04967 (0.17)	0.3645 (0.27)	0.05322 (0.22)	312.5 (1.1)	315.6 (1.5)	338(10)
C ff,N2,p,b,na	0.010	357	21	1840	6.5	16	0.05294 (0.13)	0.4864 (0.26)	0.06664 (0.19)	332.5 (0.9)	402.5 (1.7)	826.5(7.9)
D ff,N2,p,na,3	0.007	154	7.1	755	3.8	17	0.04211 (0.38)	0.3196 (0.57)	0.05504 (0.35)	265.9 (2.0)	281.6 (2.8)	414(15/16)
FFe88-34-2 Big Creek Group, Gilliland tuff[b] (location 8 on Fig. 2)												
A N2,+104	0.03	196	26	1014	43	9.8	0.12641(0.11)	1.77115(0.23)	0.10162(0.15)	767.3(1.6)		1653.9(5.5)
B N2,+104	0.01	367	20	663	24	8	0.056533(0.13)	0.41795(0.66)	0.05362(0.60)	354.5(0.9)		355.1(27.2)
C N2,+104	0.02	190	32	930	30	13	0.14854(0.11)	2.98375(0.22)	0.14569(0.14)	892.8(1.9)		2295.9(4.7)
D N2,+104	0.02	361	22	453	43	15	0.05608(0.18)	0.41540(2.08)	0.05372(2.00)	351.7(1.2)		359.5(90.2)
E N2,+104	0.02	256	15	1236	13	13	0.05683(0.12)	0.42474(0.29)	0.05421(0.22)	356.3(0.8)		379.6(10.1)
F N2,62-74,e,u	0.07	398	20	1223	73	7.3	0.05117(0.13)	0.37787(0.65)	0.05356(0.60)	321.7(0.8)		352.5(27.2)

[a]Richard Friedman (2000); [b]Jim Mortensen (2000).

[1] Upper case letter is fraction identifier used in Fig. 7. All zircon fractions air abraded; Grain size, intermediate dimension in micrometres: cc=>149, c=149-134, m=134-104, f=104-74, ff=<74; Magnetic codes: Franz magnetic separator sideslope at which grains are Nonmagnetic (N) or Magnetic (M); e.g., N1=nonmagnetic at 1°; Field strength for all is 1.8A; Front slope for all is 20°; Grain codes: b=broken fragments, e=elongate, eq=equant multifaceted, ov=ovoid, p=prismatic, s=stubby, t=tabular, ti=tips; Additional for detrital grains: colour: co=colourless, pp=pale pink, vp=vivid pink, py=pale yellow, tan=tan; clarity; cl=clear; tr=translucent; Numeral some fractions (listed last) gives number of grains dissolved.
[2] U blank correction of 1pg ±20%; U fractionation corrections were measured for each run with a double ^{233}U-^{235}U spike (about 0.004/amu).
[3]Radiogenic Pb.
[4]Measured ratio corrected for spike and Pb fractionation of 0.0037-0.0043/amu ±20% (Daly collector) and 0.0012/amu (Faraday collector), which were determined by repeated analysis of NBS Pb standard throughout the course of this study.
[5]Total common Pb in analysis based on blank isotopic composition.
[6]Corrected for blank Pb (2-10 pg, zircon; 20 pg, titanite), U (1 pg, all) and common Pb concentrations based on Stacey and Kramers (1975) model Pb at the age or the $^{207}Pb/^{206}Pb$ age of the rock.

Table 2. Multigrain U-Pb zircon analyses performed at Department of Geological Sciences, University of British Columbia in 1993.

Fraction[1,2]	Wt	U^3	Pb^3	$^{206}Pb^4$	$^{208}Pb^3$	Isotopic ratios (±1-sigma, %)			Apparent ages (±2-sigma, Ma)		
	mg	ppm	ppm	^{204}Pb	%	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
FF91-10-9-1 Gilliland tuff[a]											
A NM2A/1° abr -104+74m needles	0.44	360	18	427	8.2	0.05004(.119)	0.3642(.723)	0.05277(.675)	314.8(0.7)	315.3(3.9)	319(31)
C NM2A/1° abr +104m	0.35	267	34	3890	12	0.11620(.161)	1.8358(.180)	0.11459(.055)	708.6(2.2)	1058.4(2.4)	1873.4(2.0)
D NM2A/1° abr -74+44m needles	0.26	374	21	1905	9.1	0.05526(.263)	0.4200(.298)	0.05512(.090)	346.7(1.8)	356.0(1.8)	417.2(4.0)
E NM2A/1° abr -44m needles	0.07	395	20	1580	8.7	0.05109(.105)	0.3862(.204)	0.05482(.150)	321.2(0.7)	331.6(1.2)	405.0(6.7)
F M2A/1° abr -104+74m lozenges	0.12	353	36	4295	9.1	0.09731(.086)	1.2811(.119)	0.09548(.055)	598.6(1.0)	837.4(1.4)	1537.6(2.1)

[a]Analyses by J. Gabites, 1993.

IUGS conventional decay constants (Steiger and Jäger, 1977) are: ^{238}Ul=1.55125x10^{-10}a^{-1}, ^{235}Ul=9.8485x10^{-10}a-1, $^{238}U/^{235}U$=137.88 atom ratio.

[1] A, B, C, D, E, F refers to labels in Fig. 7.

[2] Zircon fractions are labelled according to magnetic susceptibility and size. NM = non magnetic at given amperes on magnetic separator, M = magnetic. Side slope is in degrees. Abr = air abraded. The "-" indicates zircons are smaller than, "+" larger than the stated mesh (l).

[3]U and Pb concentrations in mineral are corrected for blank U and Pb. Isotopic composition of laboratory Pb blank is 206:207:208:204 = 17.299:15.22:35.673:1.00, based on ongoing analyses of total procedural blanks of 37 ±5 pg (Pb) and 6 ±0.5 pg (U).

[4]Initial common Pb is assumed to be Stacey and Kramers (1975) model Pb at the $^{207}Pb/^{206}Pb$ date for each fraction.

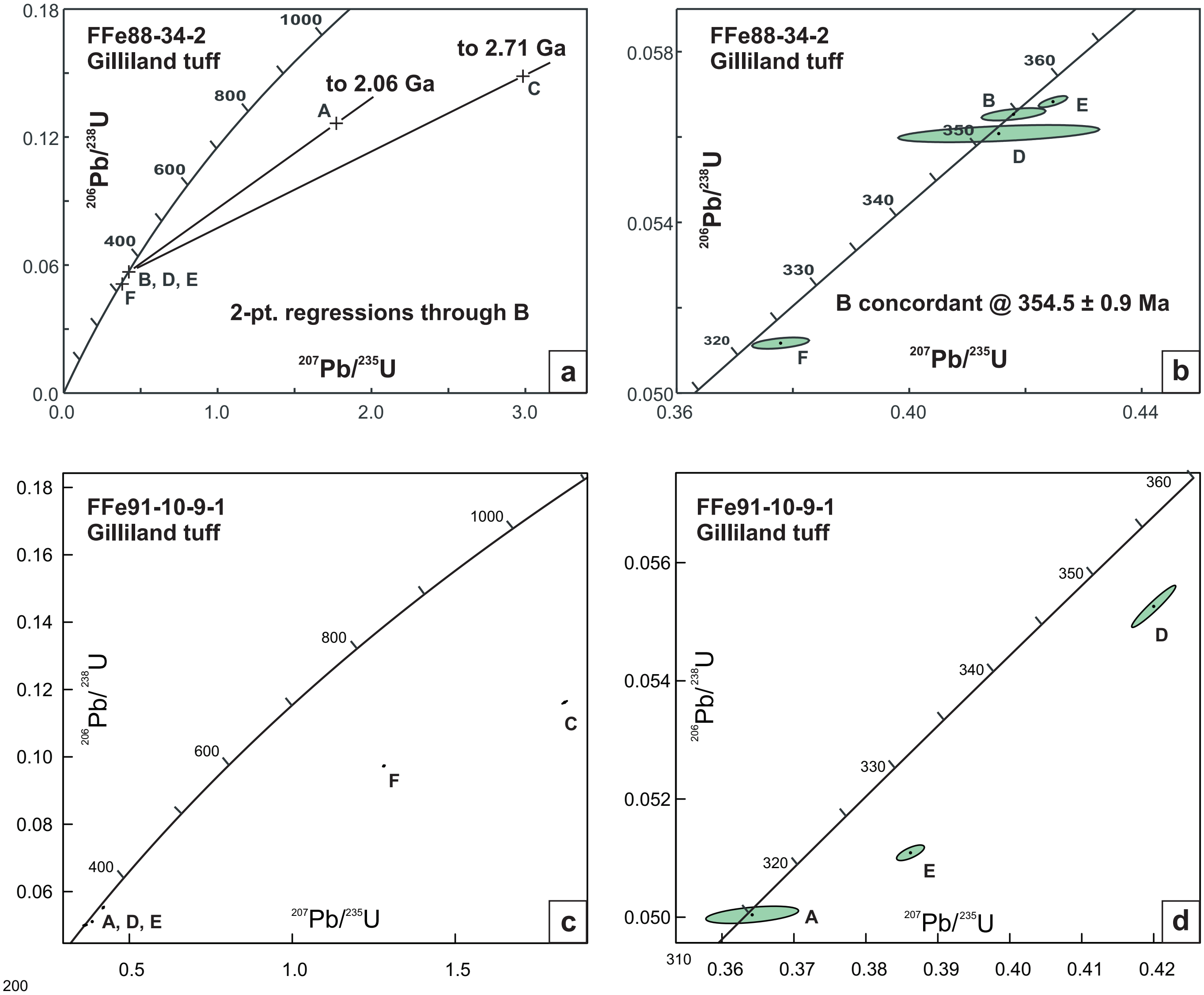

Fig. 7. a) and **c)** U-Pb concordia diagrams for samples collected from the Gilliland tuff of the Big Creek Group. **b)** and **d)** Close ups of the points clustering close to the concordia line, in a) and c), respectively.

Upper intercept ages of about 1.9-2.7 Ga, based on regressions through the quasi-linear data array (chords ABCD, BCD, and ABC), suggest the presence of old inherited zircon in three of the analyzed fractions. Fraction D is only weakly discordant; it yielded a $^{206}Pb/^{238}U$ age of 254 ±12 Ma, which is considered as a good estimate for the age of the rock.

3.2.5. Lay Range assemblage, felsic tuff, sample FFe99-16-5

This felsic tuff yielded a modest quantity of clear, pale tan euhedral to very slightly rounded prismatic zircons. The coarser zircons (>74 mm) were commonly broken euhedral grains. Due to the scarcity of material, abrasion was not carried out. Grains were divided in four multi-grain fractions on the basis of size and shape (euhedral vs. slightly rounded). Three of the four fractions (B-D) yielded discordant results (Table 1; Fig. 8c). Two-point reference chords constructed through AB and AC suggest that inherited zircon components with a range of ages are present. Results for fraction D are consistent with the presence of minor inheritance and subsequent Pb loss. Fraction A is concordant with an $^{206}Pb/^{238}U$ age estimate of 274.8 ±1.5 Ma.

4. Lithogeochemical data

Whole rock, trace and rare earth element analyses were obtained from 16 igneous rock samples from the Big Creek Group and Lay Range assemblage (Table 3). In addition, the Sm-Nd isotopic geochemistry of a subset of these samples was also determined (Table 4).

The Lay Range assemblage contains predominantly mafic volcanic flows and fragmental rocks together with a sub-volcanic intrusion to flow of intermediate composition (Fig. 9).

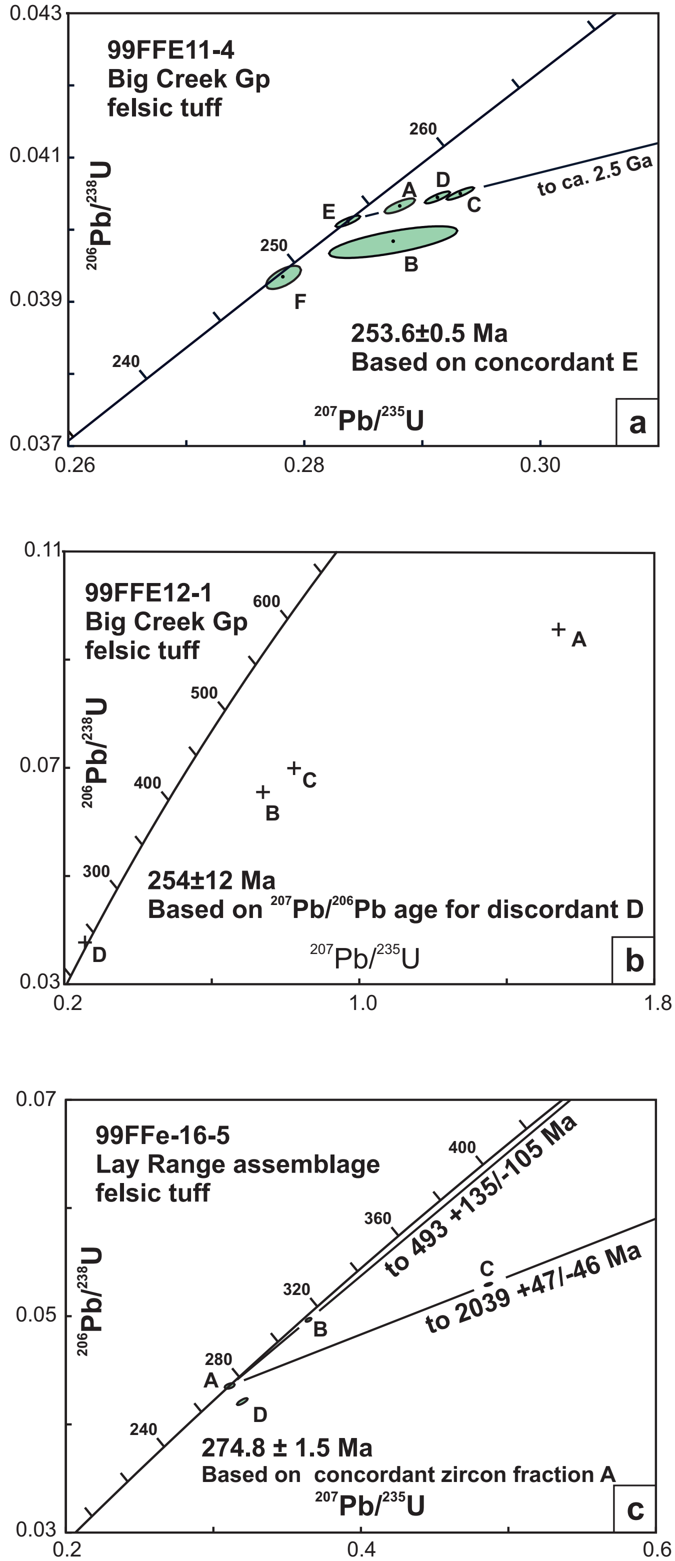

Fig. 8. U-Pb concordia diagrams for samples collected from **a)** and **b)** the Big Creek Group and **c)** the Lay Range assemblage.

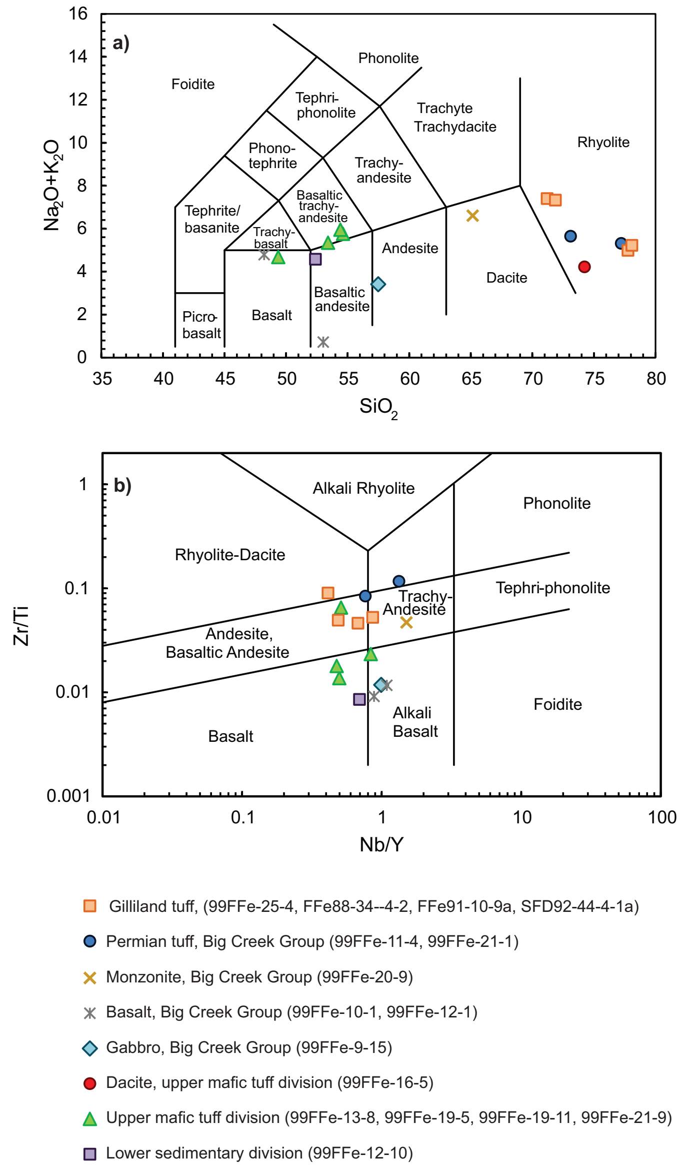

Fig. 9. a) Total alkali-silica plot (Le Bas et al.,1986) re-calculated for water-free compositions. **b)** Rock classification based on Zi/Ti vs. Nb/Y (Pearce, 1996). This plot bypasses any issues related to remobilization of alkali metals.

Compositionally they range from basalt to basaltic andesite. These are calc-alkaline to tholeiitic and predominantly metaluminous, although sample 99FFe-16-5 is strongly peraluminous (Figs. 9, 10). Elemental abundances and REE patterns suggest incipient arc magmatism for rocks in the upper mafic tuff division as indicated by Th/Nb vs. Nb/Yb ratios plotting above the MORB to OIB corridor (Fig. 11a) and the weak but discernable Ti and Nb anomalies (Fig. 11b). Basalt from the lower sedimentary division displays elemental abundances suggestive of an E-MORB setting (Fig. 11). The arc setting for volcanic rocks of the Lay Range assemblage based on geochemical abundances is similar to results for this unit in the southern Lay Range (Ferri, 1997).

Table 3. Major oxide, trace and rare earth element analysis for selected samples of the Big Creek Group and Lay Range assemblage.

Sample	99FFe-9-15 Gabbro	99FFe-10-1 Basalt	99FFe-11-2 Basalt	99FFe-11-4 Tuff	99FFe-12-1 Tuff	99FFe-20-9 Monzonite	99FFe-25-4 Tuff	FFe88-34-2* Flow	FFe91-10-9a Tuff	SFD92-44-4-1a Tuff	99FFe-12-10 Basalt	99FFe-13-8 Volc. Brec.	99FFe-16-5 Tuff	99FFe-19-5 Basalt	99FFe-19-11 Basalt	99FFe-21-9 Basalt
Unit	Big Ck Gp	Big Ck Gp	Big Ck Gp	Big Ck Gp	Big Ck Gp	Big Ck Gp	Gilliland tuff	Gilliland tuff	Gilliland tuff	Gilliland tuff	LRA-LSD	LRA-UMTD	LRA-UMTD	LRA-UMTD	LRA-UMTD	LRA-UMTD
Map No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
UTM E	317286[a]	316796[a]	318879[a]	318790[a]	683450[b]	672021[b]	369071[b]	393078[b]	365605[b]	338030[b]	682108[b]	680162[b]	679335[b]	671585[b]	671982[b]	670671[b]
UTM N	6280282	6280271	6279287	6278928	6281435	6295823	6216514	6183563	6223737	6267169	6281324	6280469	6283754	6294998	6292868	6296240
SiO_2	54.15	45.5	40.88	70.52	74.56	61.11	69.12	70.25	74.57	75.97	49.84	49.74	71.02	46.88	52.33	51.34
TiO_2	2.01	0.75	2.25	0.25	0.15	0.43	0.61	0.71	0.32	0.65	3.8	0.89	0.44	1.37	1.37	1.16
Al_2O_3	14.34	11.25	12.64	14.28	14.1	15.5	14.02	14.66	12.00	12.36	14.1	15	12.93	18.75	16.34	16.57
Fe_2O_3	2.77	2.45	6.49	0.68	0.65	1.57	1.96	2.09	-	-	3.55	4.41	1.77	5.51	8.53	4.71
FeO	8.49	9.58	5	2.79	0.43	2.66	1.72	1.27	-	-	7.43	3.31	1.47	4.47	2.24	5.14
$\sum Fe_2O_3$	12.20	13.10	12.05	3.78	1.13	4.53	3.87	3.50	0.68	1.76	11.81	8.09	3.40	10.48	11.02	10.42
MnO	0.07	0.37	0.14	0.01	0.01	0.07	0.02	0.03	0.05	0.04	0.17	0.14	0.05	0.18	0.14	0.15
MgO	6.4	7.32	3.23	2.05	1.41	2.14	1.73	0.83	0.65	0.66	4.86	3.98	3.55	3.85	3.28	5.21
CaO	1.57	6.63	9.25	0.11	0.05	3.63	0.37	0.44	2.68	0.60	5.65	7.78	0.18	8.71	5.67	5.9
Na_2O	3.21	0.11	1.72	2.97	1.72	4.8	1.83	1.46	1.47	1.47	4.09	3.71	0.79	3.43	4.73	3.51
K_2O	0.01	0.51	2.34	2.48	3.42	1.4	5.36	5.71	3.32	3.62	0.27	1.54	3.25	1.02	1	1.63
P_2O_5	0.25	0.3	0.28	0.01	0.01	0.2	0.15	0.17	0.16	0.16	0.56	0.18	0.05	0.31	0.3	0.23
LOI	6.63	14.29	15.33	3.2	2.78	5.75	2.67	2.16	3.70	2.15	5.45	8.95	3.96	5.29	3.87	3.98
SUM	99.91	99.09	99.68	99.46	99.44	99.31	99.64	99.78	99.6	99.44	99.78	99.65	99.54	99.81	99.85	99.59
Cu	15	44	30	<1	<1	30	8	12	9	8	7	39	14	182	53	109
Pb	8	26	8	4	26	2	20	15	16	-	8	6	4	8	8	6
Zn	94	280	82	68	26	96	46	63	45	43	186	64	40	66	90	82
Ni	47	519	76	2	<1	3	12	10	-	-	88	31	<1	22	6	23
Cr	95	1760	242	86	102	32	97	-	-	-	93	123	75	69	23	69
Co	33	68	38	5	2	9	9	24	-	-	39	26	3	28	29	29
Ba	254	292	1329	907	1076	593	988	2400	1174	1369	122	205	860	415	451	428
Rb	<3	25	73	85	167	57	192	190	118	114	4	31	69	21	17	29
Sr	133	169	158	42	34	244	69	110	129	38	174	213	12	416	426	466
Sn	<3	5	<3	<3	4	5	<3	-	-	18	<3	<3	<3	<3	<3	<3
V	166	244	234	9	12	73	49	-	48	32	192	206	62	286	273	260
Nb	19	10	23	14	17	23	19	15	9	16	16	14	13	13	14	13
Zr	142	41	157	126	105	121	192	210	173	179	194	124	172	112	147	122
Y	19.1	11.3	21.1	18.3	12.8	15.2	22.0	30	21	24	23.1	16.7	25.3	26.1	29.4	24.9
La	20.5	1.6	20.6	12.4	27.2	22.3	43.2	26.22	39.50	32.73	12.7	14.0	14.6	12.6	17.5	12.8
Ce	39.3	3.8	46.4	21.7	50.1	46.5	85.5	62.38	80.18	67.66	37.7	30.6	31.5	31.1	40.4	30.0
Pr	5.0	0.6	5.8	2.3	5.0	5.5	9.9	6.40	8.93	7.80	6.5	4.1	3.8	4.2	5.4	4.2
Nd	20.4	3.0	23.3	9.7	16.8	22.2	34.3	24.42	31.97	29.18	33.4	16.0	16.2	19.7	24.1	18.7
Sm	5.8	1.3	6.2	2.9	3.0	5.2	6.8	5.29	6.04	5.53	10.3	4.3	4.2	5.9	6.8	5.3
Eu	1.6	0.5	2.0	0.6	0.5	1.4	1.2	1.09	1.16	0.84	3.2	1.4	0.6	1.7	1.9	1.6
Gd	5.6	1.7	5.9	2.8	2.3	3.1	4.6	4.46	4.88	4.38	8.6	3.9	3.1	4.4	5.3	4.0
Tb	0.9	0.3	0.9	0.5	0.4	0.5	0.7	0.66	0.68	0.62	1.3	0.6	0.6	0.7	0.9	0.7
Dy	4.5	2.3	6.1	3.7	2.4	3.3	4.1	4.24	3.60	3.34	7.3	4.1	4.3	4.6	6.1	4.8
Ho	0.8	0.4	1.0	0.7	0.4	0.6	0.8	0.80	0.63	0.63	1.0	0.7	0.8	0.9	1.1	0.9
Er	2.2	1.3	2.9	2.5	1.4	1.8	2.4	2.25	1.72	1.73	2.5	2.3	3.0	2.7	3.5	2.6
Tm	0.3	0.2	0.3	0.4	0.2	0.3	0.3	0.32	0.23	0.25	0.3	0.3	0.4	0.4	0.5	0.4
Yb	1.5	1.0	2.2	2.4	1.2	1.7	1.9	2.09	1.41	1.51	1.7	1.9	3.1	2.5	3.0	2.5
Lu	0.2	0.2	0.3	0.4	0.2	0.2	0.3	0.31	0.20	0.22	0.3	0.3	0.4	0.3	0.4	0.3
Hf	4.1	1.1	5.8	3.5	3.5	3.6	5.4	4.84	4.25	4.12	6.8	4.2	5.0	3.5	4.9	3.5
Ta	1.3	0.1	1.9	0.3	1.2	1.2	1.4	1.19	0.66	1.01	1.2	0.7	0.5	0.4	0.5	0.4
Th	3.7	0.7	3.1	4.5	21.8	5.8	14.3	14.8	11.6	12.8	0.7	2.2	5.2	1.5	3.0	1.7

LRA: Lay Range Assemblage; UMTD: upper mafic tuff division; LSD: lower sedimentary division. [a]: NAD 83 UTM Zone 9; [b]: NAD 83 Zone 10

Major oxides, U, V, Sn, Sr, Rb, Co, Cs, Nb, Y and Zr determined by x-ray fluorescence at Cominco Laboratories; sample FFe-88-34-2 analyzed at the British Columbia Ministry of Energy, Mines and Petroleum Resources.

Trace elements (Cu, Pb, Zn, Li, Cr, Ni) by atomic absorbtion at Cominco Laboratoires. La to Ta and Th analyses determined by neutron activation analysis at laboratories of Memorial University.

Table 4. Neodymium isotope data for Big Creek Group and Lay Range assemblage.

Unit	Sample Number	Map Label	Age (T) (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$e_{Nd}(T)$[1]	$e_{Nd}(0)$[1]	T_{DM}[2] (Ga)
Gilliland tuff	FFe91-10-9-1	9	355	6.02	31.37	0.11858(10)	0.511895(13)	-11.0	-14.5	2.02
Gilliland tuff	FFe88-34-2	8	355	4.97	30.19	0.10160(08)	0.511679(20)	-14.4	-18.7	2.01
Gilliland tuff	SFD91-44-4-1	10	355	5.64	33.98	0.10251(08)	0.511618(21)	-15.6	-19.9	2.11
Gilliland tuff	99FFe-25-4	7	355	6.17	35.50	0.10723(11)	0.511625(15)	-15.7	-19.8	2.19
Big Ck. Gp. Permian tuff	99FFe-11-4	4	254	2.03	9.87	0.12706(12)	0.511964(15)	-10.9	-13.1	2.10
Big Ck. Gp. Permian tuff	99FFe-12-1	5	254	3.13	19.19	0.10073(09)	0.511653(17)	-16.1	-19.2	2.03
Upper mafic tuff division, felsic tuff	99FFe-16-5	13	275	3.20	14.24	0.13572	0.512651(06)	2.4	0.3	1.00
Upper mafic tuff division, basalt	99FFe-19-11	15	275	6.25	26.52	0.14252	0.512861(05)	6.3	4.4	0.65

LA-ICP-MS analysis in laboratories of Memorial University of Newfoundland.

Estimated uncertainties in paranthesis at the 2s level; number in paranthesis is the uncertainty in the last two decimal places.

[1]Calculated using $^{143}Nd/^{144}Nd$ of chondrite reservoir (CHUR) = 0.512638 and $^{147}Sm/^{144}Nd$ = 0.1966 (Hamilton et al., 1983).

[2]Calculated using the values of $^{143}Nd/^{144}Nd$ = 0.513163 and $^{147}Sm/^{144}Nd$ = 0.2137 for the depleted mantle (DM) reservoir (Goldstein et al., 1984).

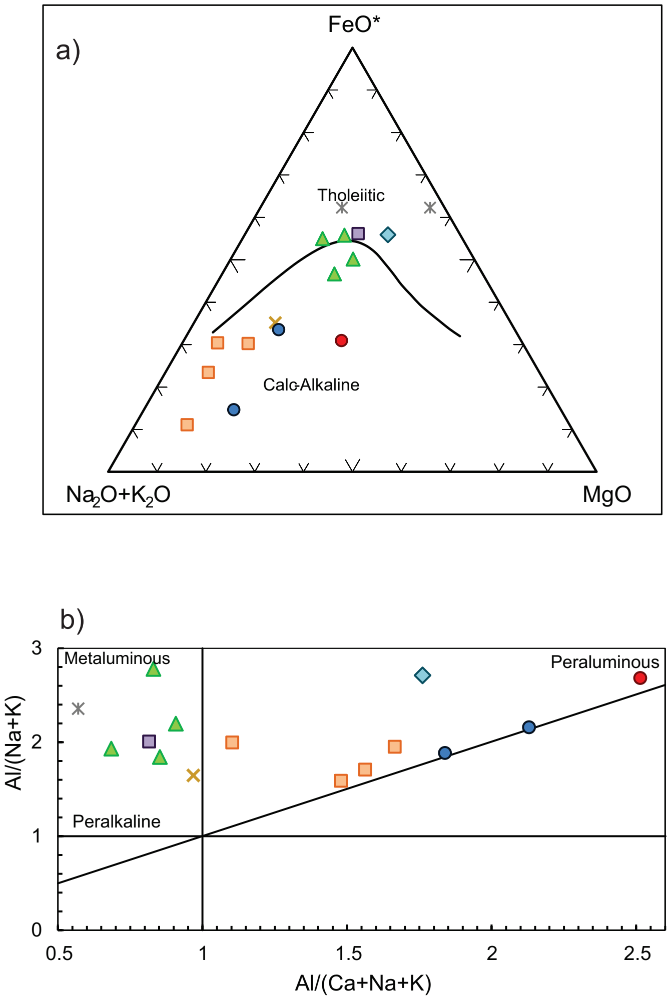

Fig. 10. a) Calc-alkaline to tholeiitic trend from Irvine and Baragar (1971). **b)** Shand's index diagram from Maniar and Piccoli (1989). Symbology is the same as in Figure 9.

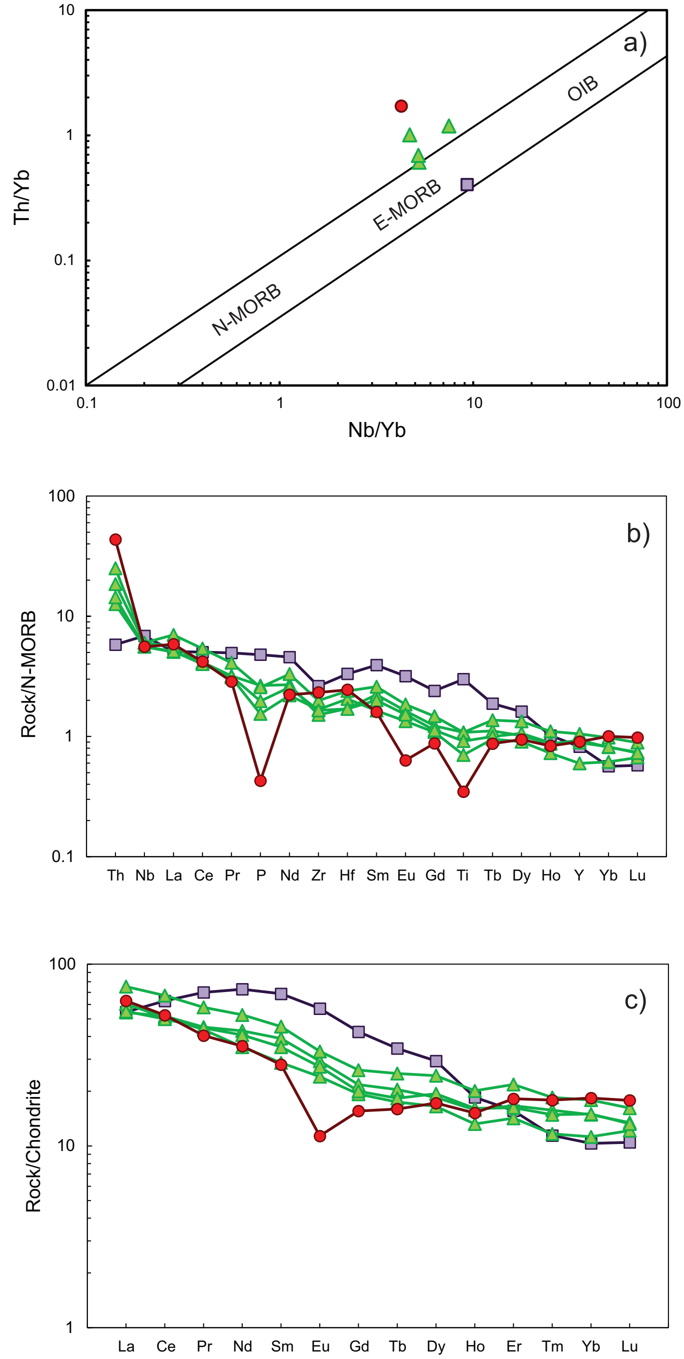

Fig. 11. a) Tectonic discrimination diagram for rocks of the Lay Range assemblage usingTh/Yb vs. Nb/Yb as proposed by Pearce (1998). **b)** Extended rare earth element plot for rocks of the Lay Range assemblage. The Ti and Nb negative anomalies suggest an arc setting for rocks from the upper mafic tuff division. **c)** Rare earth element plot for volcanic rocks of the Lay Range assemblage. Normalizing values from Sun and McDonough (1989). Symbology is the same as in Figure 9.

Igneous rocks of the Big Creek Group have a varied composition. Gilliland tuff and Permian tuff are rhyolitic, calc-alkaline and generally peraluminous (Figs. 9, 10), although the spread of data in Figure 10b may be a function of alteration. Trace and rare earth element abundances, particularly with the Ti and Nb anomalies, are indicative of a volcanic arc setting (Fig. 12).

Rocks of a more mafic nature in the Big Creek Group are basaltic to basaltic-andesite in composition and calc-alkaline to tholeiitic (Figs. 9, 10a, b). Trace and rare earth element data indicate an E-MORB or within-plate tectonic setting for these samples (Fig. 13a). Rare earth element distributions generally support this, although sample 99FFe-10-1 has lower abundances.

Sm-Nd isotopic geochemistry (Table 4) indicates evolved Precambrian continental lithosphere as the source of magma that supplied the felsic volcanic rocks in the Big Creek Group. This contrasts with data from igneous rocks in the Lay Range assemblage that point to a less evolved oceanic mantle source, similar to younger Quesnellia (Table 4; Fig. 14; Ootes et al., 2022).

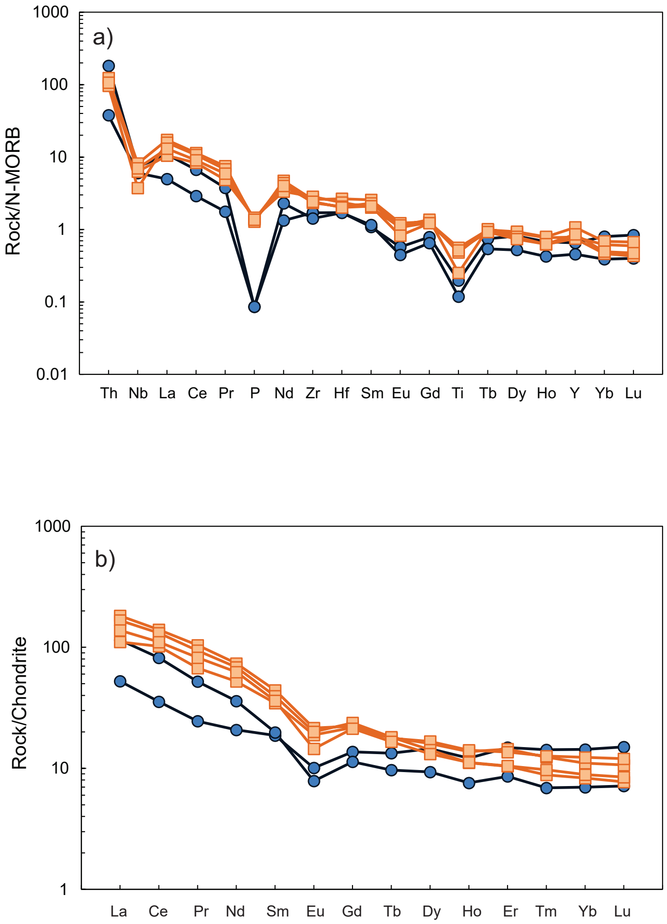

Fig. 12. Extended rare earth element plot **a)** and rare earth element plot **b)** for samples of the Gilliland tuff and felsic Permian volcanics of the Big Creek Group. The strong negative Nb and Ti anomalies suggest arc-related volcanism, although this chemistry could be a reflection of inheritance from continental lithosphere, which is strongly suggested by Nd-Sm isotopic data. Symbology is the same as in Figure 9. Normalized values from Sun and McDonough (1989).

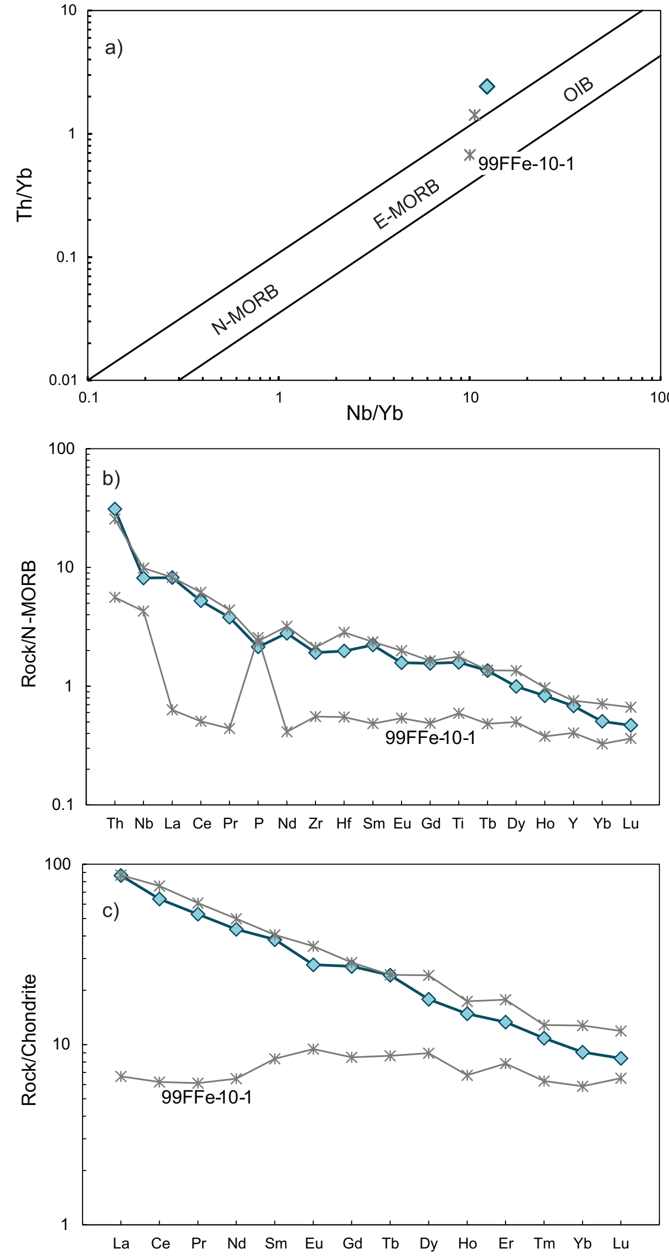

Fig. 13. a) Tectonic discrimination diagram for mafic igneous rocks of the Big Creek Group using Th/Yb vs. Nb/Yb as proposed by Pearce (1998). **b)** Extended rare earth element plot for mafic igneous rocks of the Big Creek Group. **c)** Rare earth element plot for mafic igneous rocks of the Big Creek Group. Normalizing values from Sun and McDonough (1989). Symbology is the same as in Figure 9.

5. Summary

Previously unreleased multigrain U-Pb zircon geochronologic work carried out in 1993 and 2000 from mapping near the Lay Range in the north-central part of the province yielded ca. 350 to 320 Ma ages for the Gilliland tuff in the lower part of the Big Creek Group near Germansen Landing and the Osilinka River in the southern part of the region and ca. 255 Ma from felsic tuffs in the upper part of the unit in the northern Lay Range. Felsic volcanic rocks in the 'upper mafic tuff division' of the Lay Range assemblage, the local basement to the Upper Triassic to Lower Jurassic mafic to intermediate arc volcanic rocks that are predominant in Quesnel terrane (Nicola Group) yielded an age of ca. 275 Ma. Lithogeochemical data from the Lay Range assemblage suggest a volcanic arc setting of these basaltic to andesitic rocks. Similar data from Mississippian and Permian felsic volcanic rocks of the Big Creek Group suggest an origin from partial melting of the continental lithosphere. The arc signature of these felsic rocks may be inherited from the continental lithosphere. Mafic igneous rocks of the Big Creek Group have E-MORB (within-plate) signatures. Sm-Nd isotopic data points to evolved continental lithosphere for the source of felsic volcanics in the Big Creek Group whereas a less evolved oceanic mantle source is suggested for mafic and felsic rocks of the Lay Range assemblage.

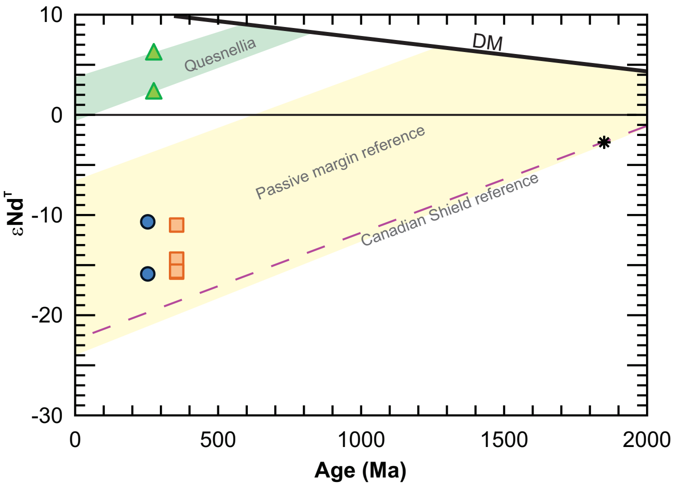

Fig. 14. Age vs. eNdT for samples in this study (Table 4; symbols follow the key in Figure 9). For comparison, Quesnellia reference (green band) constructed using whole rock Sm-Nd isotopic data from intrusive rocks (n=6 $^{147}Sm/^{144}Nd$=0.112) in Hogem batholith (Jurassic-Cretaceous; 200 to 130 Ma; Ootes et al., 2020c). DM: depleted mantle evolutionary curve as defined by Goldstein et al. (1984). Passive margin reference constructed using whole rock Sm-Nd isotopic data (n=8 $^{147}Sm/^{144}Nd$=0.112) from sedimentary rocks of the Road River Group (Silurian; ca. 425 Ma) in the Mackenzie Mountains (data in Rasmussen et al., 2023). Canadian Shield reference line constructed using whole rock Sm-Nd isotopic data (n=67, average $^{147}Sm/^{144}Nd$=0.11) from igneous rocks in Wopmay orogen of the western Canadian Shield (data from Jackson et al., 2022). Asterix at ca. 1.85 Ga represents youngest intrusive rocks exposed in the western Canadian Shield, where most exposures range between Neoarchean and Paleoproterozoic. The line represents approximate maximum eNdT at a given time for magmas derived exclusively from Canadian Shield melt sources.

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