Geochemistry of Devono–Mississippian volcanic and intrusive rocks of the Finlayson Lake district, Yukon-Tanana terrane, Yukon

M.J. Manor and S.J. Piercey
Department of Earth Sciences, Memorial University of Newfoundland

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Abstract

The Finlayson Lake district in southeastern Yukon is a remnant of a Late Paleozoic arc–back-arc system that consists of metamorphosed volcanic, plutonic, and sedimentary rocks of the Yukon-Tanana and Slide Mountain terranes. These rocks host more than 40 Mt of polymetallic resources in numerous occurrences and styles of volcanogenic massive sulphide (VMS) mineralization. Geochemical data from these rocks support previous interpretations that volcanism and plutonism occurred in arc–marginal arc (e.g., Fire Lake formation) and continental back-arc basin environments (e.g., Kudz Ze Kayah formation, Wind Lake formation, and Wolverine Lake group) where felsic magmatism formed from varying mixtures of crust and mantle-derived material. The rocks have elevated high field strength element (HFSE) and rare earth element (REE) concentrations in VMS-proximal stratigraphy relative to VMS-barren assemblages, suggesting that the petrogenetic conditions that generated felsic rocks likely played a role in the localization of VMS mineralization. Future work aims to constrain magmatic processes and outline prospectivity criteria for delineating productive VMS assemblages within the district, and in similar geodynamic settings globally.

* mjmanor@mun.ca

Introduction

The Finlayson Lake district occurs in one of the Canada's best exposed ancient convergent continental margin systems and contains more than 40 Mt of polymetallic (Zn-Pb-Cu-Co-Au-Ag) volcanogenic massive sulphide (VMS) mineralization (Galley *et al.*, 2007; Peter *et al.*, 2007). Exploration and development in the area are currently focused on the Kudz Ze Kayah Zn-Pb-Cu-Ag-Au deposit which has an indicated mineral resource of 18.3 Mt at 6.3% Zn, 1.9% Pb, 0.9% Cu, 148 g/t Ag, and 1.4 g/t Au, and an additional inferred resource of 0.9 Mt at 6.9% Zn, 1.6% Pb, 1.1% Cu, 138 g/t Ag, and 1.1 g/t Au (BMC Minerals Ltd., 2017). Past geochemical studies have defined the tectonic setting of the Finlayson Lake district as an evolving Late Paleozoic continental arc to evolving back-arc basin assemblage. In this paper, we report new major and trace element lithogeochemical results for mafic to felsic volcanic and intrusive rocks of the Grass Lakes group—Fire Lake, Kudz Ze Kayah, and Wind Lake formations, and Grass Lakes plutonic suite—and the Wolverine Lake group. Our new high-precision data add to existing databases (Piercey, 2001; Piercey *et al.*, 2001, 2002a,b,c, 2003, 2004, 2008, 2012) and are part of a larger, ongoing initiative to evaluate prospectivity of felsic-hosted VMS deposits and their host assemblages in the Finlayson Lake district using lithogeochemistry as well as detailed regional-scale geochronology, radiogenic isotopic geochemistry, and mineral chemistry. Furthermore, we conclude that our new lithogeochemical results overlap with analyses completed 15+ years ago, and support previous geodynamic interpretations for the genesis of the Yukon-Tanana terrane in the mid-Paleozoic.

Geological Setting

The Finlayson Lake district of southeastern Yukon is found within a fault-bounded portion of the peri-Laurentian Yukon-Tanana and Slide Mountain terranes, which are made up of assemblages that were deposited or intruded from the Devonian to Permian (Fig. 1; Tempelman-Kluit, 1979; Mortensen and Jilson, 1985; Murphy *et al.*, 2006). Yukon-Tanana terrane arc and back-arc assemblages are composed of variably deformed and metamorphosed volcanic, plutonic, and sedimentary rocks that locally retain primary geological and geochemical features; these rocks were deposited or intruded above a pre to Late Devonian basement (Colpron *et al.*, 2006; Murphy *et al.*, 2006; Piercey *et al.*, 2006; Piercey and Colpron, 2009). The Jules Creek transform fault juxtaposes the Yukon-Tanana terrane and ophiolitic rocks of the Slide Mountain terrane (Murphy *et al.*, 2006); both terranes were together thrust onto the North American craton along the Inconnu thrust in the Late Jurassic (Murphy *et al.*, 2002). The present-day location of the Finlayson Lake district was achieved during the Eocene with its displacement from the main segment of the Yukon-Tanana terrane in central Yukon by ~430 km along the Tintina strike-slip dextral fault system (Figs. 1 and 2; Gabrielse *et al.*, 2006).

Yukon-Tanana terrane rocks within the Finlayson Lake district are hosted in three thrust sheets: the Big Campbell, Money Creek, and Cleaver Lake thrust sheets (Fig. 2; Murphy *et al.*, 2006). Pre-Upper Devonian metasedimentary rocks of the North River formation make up the basement to the Big Campbell and Money Creek thrust sheets. The Big Campbell thrust sheet is structurally deepest and is bounded below by the post-Late Triassic Big Campbell thrust fault and above by the Early Permian Money Creek thrust fault (Fig. 2). Rocks in the Big Campbell thrust sheet are primarily Middle to Upper Devonian, lower to middle greenschist facies mafic and felsic metavolcanic and metasedimentary rocks of the Grass Lakes group, which includes the basal pre-Upper Devonian North River formation and overlying Fire Lake, Kudz Ze Kayah, and Wind Lake formations (Fig. 2). Late Devonian granitic intrusions of the Grass Lakes plutonic suite cut the Grass Lakes group and then both are unconformably overlain by Lower Mississippian metaclastic and mafic to felsic metavolcanic rocks of the Wolverine Lake group (Fig. 2). The Grass Lakes group contains VMS mineralization at the Kudz Ze Kayah, GP4F, and Fyre Lake deposits, and the Wolverine Lake group contains the Wolverine deposit (Piercey *et al.*, 2001; Sebert *et al.*, 2004; Peter *et al.*, 2007; Bradshaw *et al.*, 2008; Piercey *et al.*, 2016); together, these deposits are interpreted to have formed in an evolving continental arc to back-arc basin tectonic setting (Piercey *et al.*, 2001, 2002b, 2004, 2006; Murphy *et al.*, 2006). The Money Creek thrust sheet comprises the pre-Upper

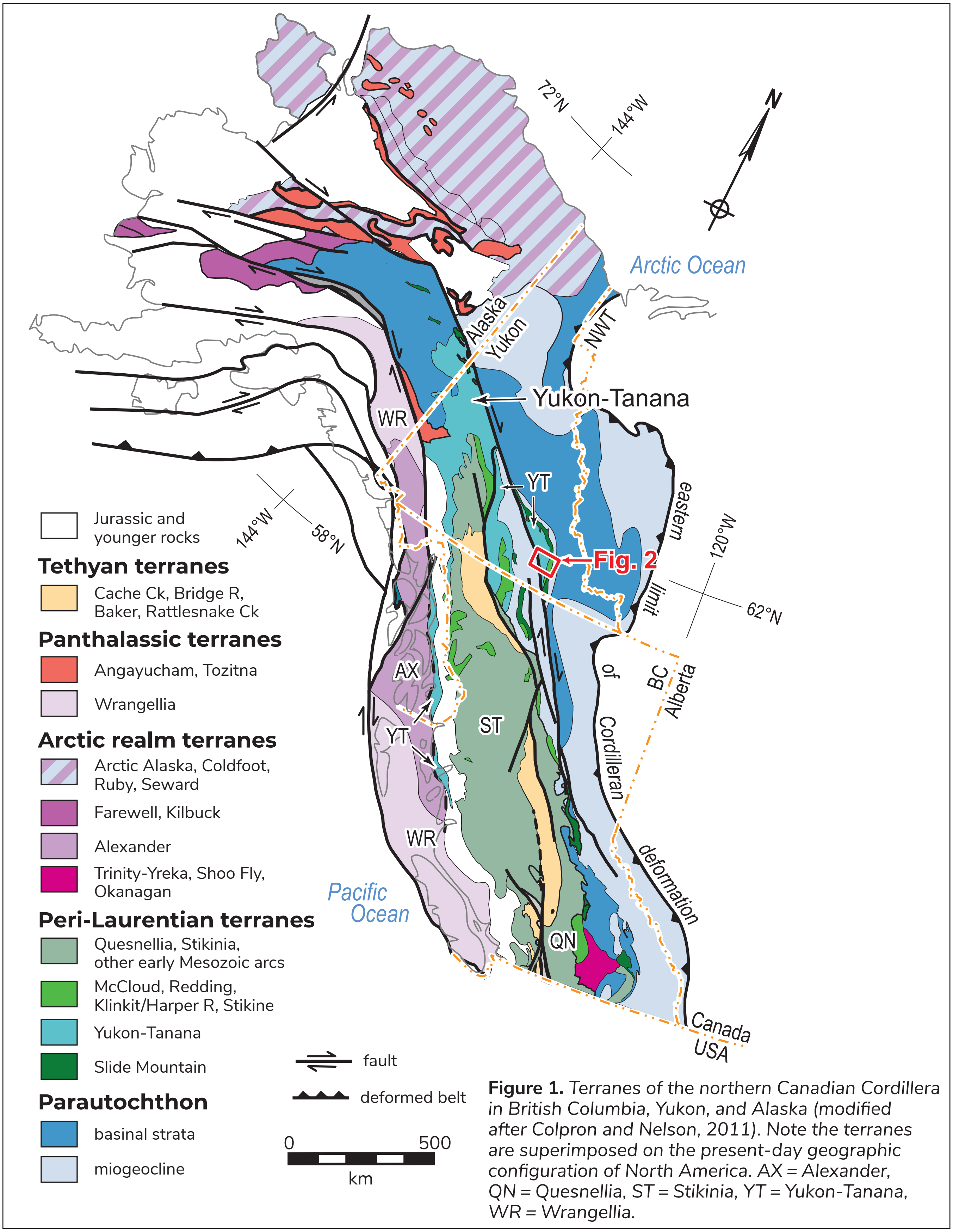

Figure 1. *Terranes of the northern Canadian Cordillera in British Columbia, Yukon, and Alaska (modified after Colpron and Nelson, 2011). Note the terranes are superimposed on the present-day geographic configuration of North America. AX = Alexander, QN = Quesnellia, ST = Stikinia, YT = Yukon-Tanana, WR = Wrangellia.*

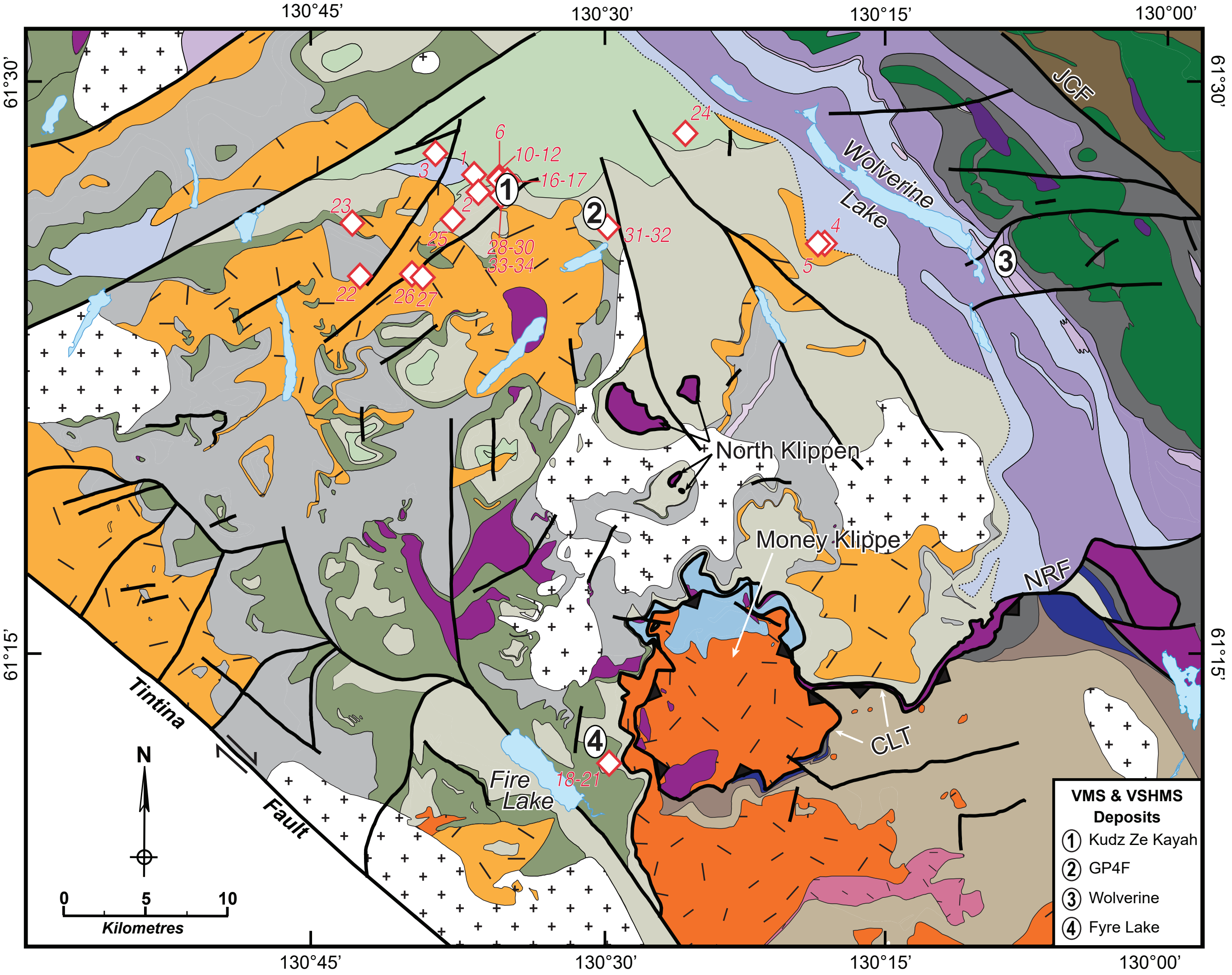

Figure 2. *Regional geologic setting of the south-central Finlayson Lake region, Yukon-Tanana terrane (modified after Piercey et al., 2003, and Yukon Geological Survey, 2018). The Money Creek thrust fault crops out south of the extent of the figure. Diamonds and numbers correspond to sample locations and lithogeochemical results in Table 1. Numbers indicate locations of prospective VMS deposits in the region. VMS = volcanogenic massive sulphide; VSHMS = volcanic sediment-hosted massive sulphide. See legend on next page.*

Devonian North River formation and overlying Upper Devonian to Lower Mississippian felsic-intermediate metavolcanic and metasedimentary rocks (Waters Creek and Tuchitua River formations). These formations are intruded by granitic rocks of the Late Devonian to Early Mississippian Simpson Range plutonic suite, then capped by Mississippian to Lower Permian limestone, mafic metavolcanic and metaclastic rocks (Fig. 2; Mortensen, 1992; Grant, 1997; Murphy et *al.*, 2006). The Money Creek thrust sheet is structurally overlain by the Cleaver Lake thrust sheet, an assemblage of relatively undeformed and unmetamorphosed Late Devonian mafic and felsic volcanic rocks (Cleaver Lake formation) that overlie mafic and ultramafic rocks and are intruded by Early Mississippian granitoid rocks of the Simpson Range plutonic suite (Tempelman-Kluit, 1979; Piercey and Murphy, 2000; Murphy et *al.*, 2006). The Cleaver Lake thrust sheet was thrust above the Money Creek thrust sheet along the Early Permian Cleaver Lake thrust fault after the Early Permian (Murphy et *al.*, 2006). The rocks in the Money Creek and Cleaver Lake thrust sheets were generated in a continental arc setting to the southwest of the Big Campbell thrust sheets and are not associated with any known VMS mineralization (Grant, 1997; Piercey et *al.*, 2001, 2003, 2006; Murphy et *al.*, 2006).

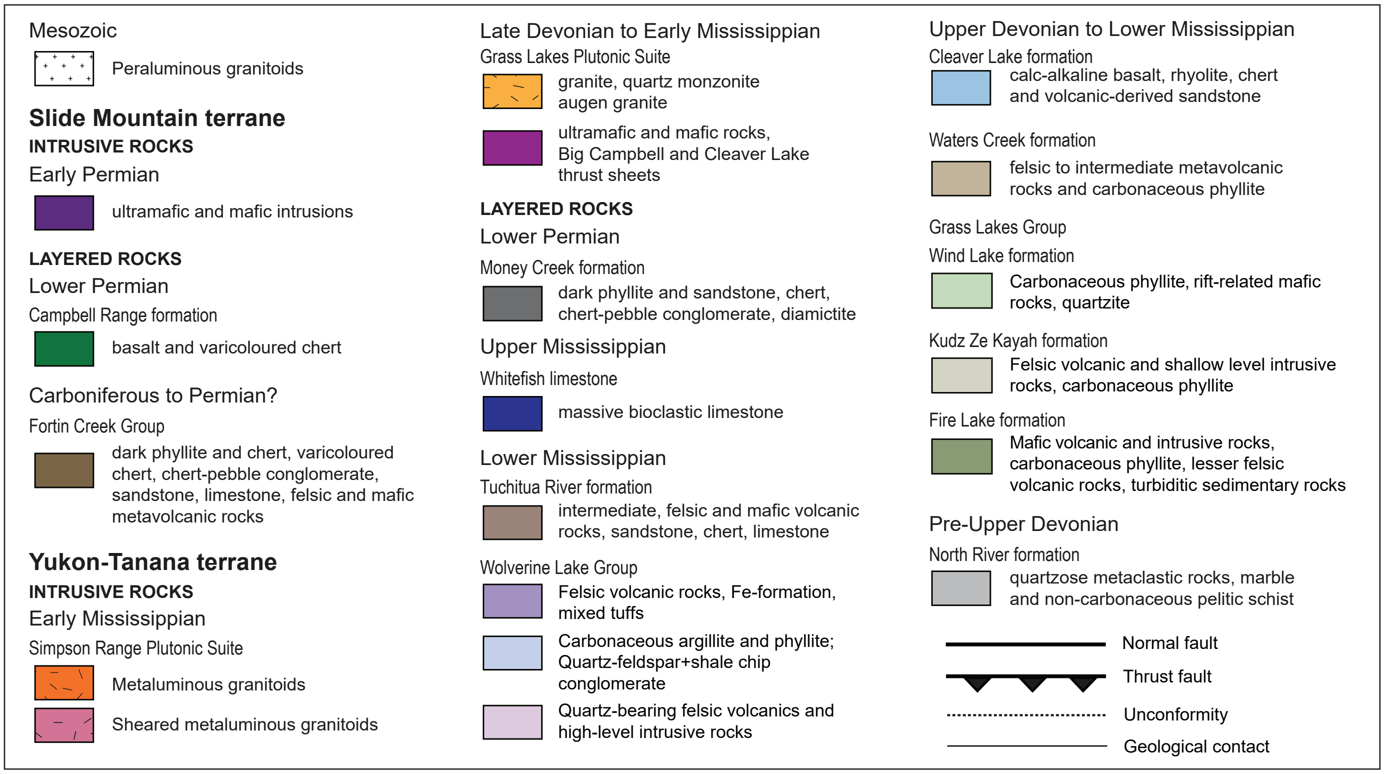

***Figure 2**. Map legend.*

Previous Work

The first integrated geological mapping and lithogeochemical characterization for rocks in the Finlayson Lake district was addressed by Piercey (2001). Mafic volcanic rocks of the Fire Lake formation in the Big Campbell thrust sheet have enriched mid-ocean ridge basalt (E-MORB), back-arc basin basalt (BABB), alkalic ocean island basalt (OIB), and low-Ti tholeiite to boninite affinities (Piercey et *al*., 2002a,b, 2004, 2006). The variation in geochemical affinities—especially the presence of boninite—suggests that the Fire Lake formation was formed due to the initiation of spreading in an arc built above a composite continental–oceanic basement domain (Piercey et *al*., 2002b, 2004). Subsequent work on the overlying felsic volcanic rocks of the Kudz Ze Kayah formation and granitic rocks of the Grass Lakes plutonic suite show overlapping HFSE-REE-enriched, A-type back-arc signatures (Piercey et *al*., 2001, 2003). Both rock packages contain significant crustal contamination from Precambrian continental basement and are inferred to have formed from extensive crustal melting in a continental back-arc inboard of the Fire Lake arc (Mortensen, 1992; Grant, 1997; Piercey et *al*., 2001, 2003). Continued spreading and increased asthenospheric mantle contributions to the crust facilitated the transition from felsic-dominated to alkalic mafic volcanism of the Wind Lake formation (Piercey et *al*., 2002a). The deposition of the Grass Lakes group (ca. 358 Ma; Murphy et *al*., 2006) was followed by a period of deformation and erosion, and then by unconformable deposition of the Wolverine Lake group. Volcanism in the lower Wolverine Lake group footwall subsequently produced rocks with HFSE-REE contents similar to the Kudz Ze Kayah formation and Grass Lakes plutonic suite (Piercey et *al*., 2001). A geochemical shift is observed in higher stratigraphic levels of the Wolverine Lake group, notably to rocks less enriched in HFSE and REE (Piercey et *al*., 2001); at its highest levels, strata are composed of enriched and normal mid-ocean ridge basalt (E-, N-MORB) and back-arc basin basalts (BABB; Piercey et *al*., 2002c).

Sampling and Analytical Methods

During the 2017 field season, 28 samples of felsic and mafic volcanic, plutonic, and sedimentary rocks were taken from outcrops and drill core at different stratigraphic levels of the Grass Lake group and deepest levels of the Wolverine Lake group (Fig. 3; Table 1). Samples were taken from the Kudz Ze Kayah formation (n = 10), Wind Lake formation (n = 6), Fire Lake formation (n = 6), Grass Lakes plutonic suite (n=5), and Wolverine Lake group (n = 1). Mafic volcanic and sedimentary rocks were taken from the Fire Lake and Wind Lake formations to confirm the geodynamic variations set forth by earlier workers (e.g., Piercey et al., 2001, 2002a,b,c, 2003, 2004, 2008, 2012) and to set the groundwork for future isotopic studies. Drilling into the Kudz Ze Kayah formation allowed for sampling of core from previously inaccessible deeper parts of the formation and provided the means to evaluate its lithological and lithogeochemical character. At the Kudz Ze Kayah and GP4F VMS deposits, felsic rocks were sampled from the immediate footwall and hanging wall of mineralization to help identify additional geochemical prospectivity criteria in ancient, felsic-hosted VMS systems.

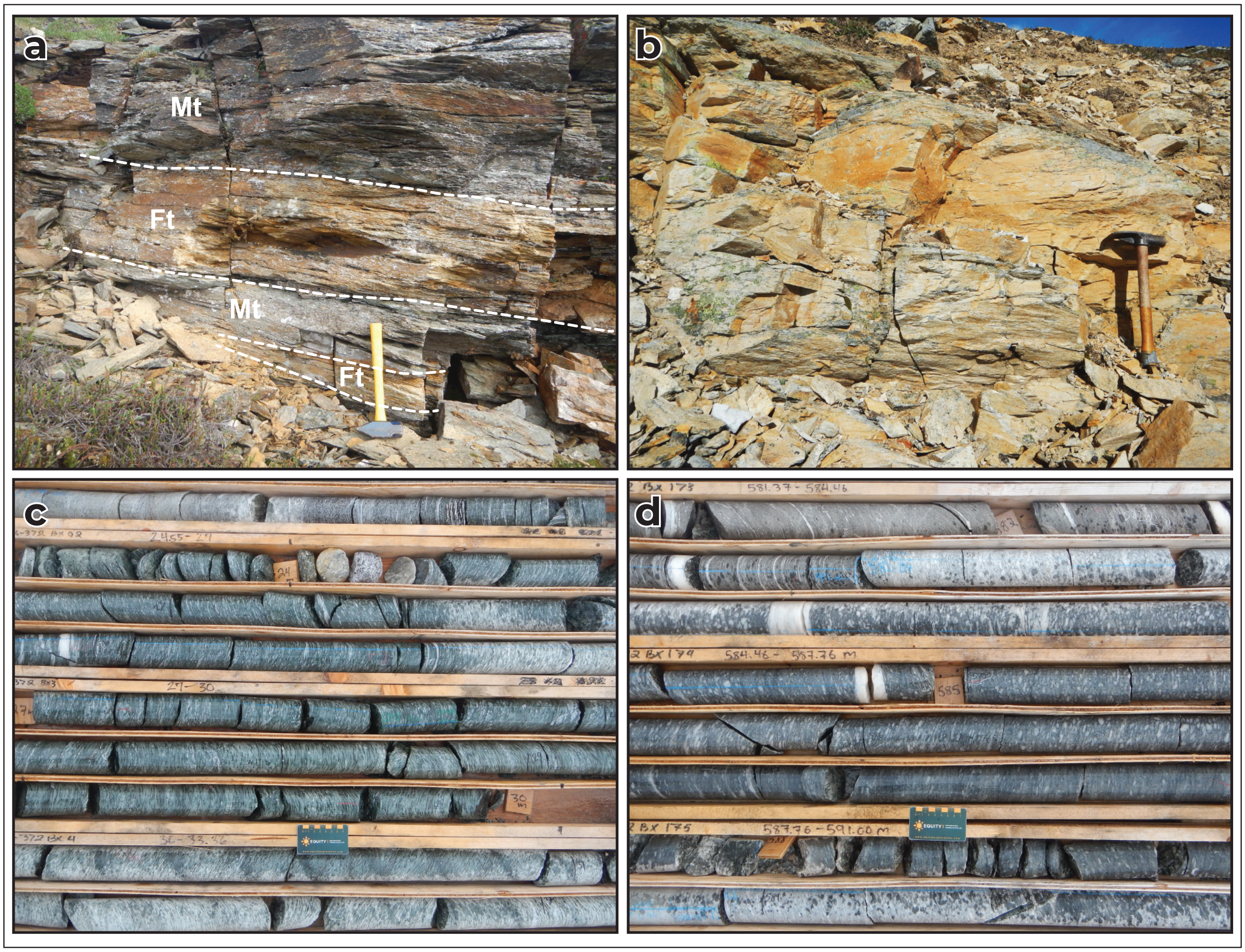

Figure 3. *Field photographs of 2017 sampling locations in the Finlayson Lake region. Sample location coordinates reported as UTM Zone 9N and NAD 83.* **(a)** *17MM-001: Wind Lake formation, felsic tuff (Ft) interbedded with mafic tuff (Mt) ~300 m above the contact with Kudz Ze Kayah formation (413749 E, 6815933 N);* **(b)** *17MM-055: Kudz Ze Kayah formation, massive aphyric rhyolite (413086 E, 6813844 N);* **(c)** *17MM-060: Wind Lake formation (?), biotite-chlorite altered mafic dike that crosscuts KZK stratigraphy (415122 E, 6814798 N);* **(d)** *17MM-062: Grass Lakes plutonic suite, quartz-feldspar porphyry immediately below the deepest known KZK volcanic rocks (~580 m depth; 415122 E, 6814798 N); (e) and (f) on next page.*

Figure 3** continued.* ***(e) *17MM-074: Kudz Ze Kayah footwall, feldspar-blue quartz eye crystal tuff in the GP4F footwall; and* ***(f)*** *17MM-004: Wolverine Lake group, massive and foliated quartz-feldspar grit (429446 E, 6812106 N). Hammer (35 cm) for scale in panels* **a,b**.

Sample preparation and measurement of major and trace element data were performed at ALS Laboratories, North Vancouver, British Columbia. Rock samples were crushed and pulverized using steel plates and agate mills, respectively. Sample powders (~0.2 g) were fused with a lithium metaborate flux (0.9 g) at 1000°C. The fused bead was cooled and digested using 100 mL of a 4% HNO_3–2% HCl mixture. Analyses of the sample solutions were completed using inductively coupled plasma-atomic emission spectrometry (ICP-AES) for major elements and inductively coupled plasma-mass spectrometry (ICP-MS) for trace elements.

Two in-house reference materials, two blind duplicates, and one lab duplicate were measured throughout the run to monitor analytical accuracy and reproducibility (Table 1). The SLV-MC basalt and WP-1 dacite (Watts Point, Coast Plutonic Complex) in-house reference materials yielded values generally within 8% of unpublished SLV-MC data and 12% of published WP-1 values (Piercey *et al.*, 2001). The analyses were reproducible to <3% for major elements and <5% for most trace elements (<8% for Nd, Lu [SLV-MC], and Zr [WP-1]; <35% for Cs, Ta, and U [WP-1]; and undetectable W; Appendix 1). The two blind duplicates (17MM-031, 17MM-062) show relatively larger RSD values presumably due to the natural heterogeneity of the rocks. For 17MM-031, the reproducibility of analyses is better than 10% for major elements (17% for CaO) and <20% for trace elements. Results for 17MM-062 gave RSD values better than 5% for major elements (except for <17% for MgO and Fe_2O_3, and 30% for CaO), and <12% for most trace elements except for Cs and U (<22%; Appendix 1). The lab duplicate chosen at ALS (17MM-066) yielded a good reproducibility of <3% for major and trace elements, and <8% for MnO, Tm, and V (Appendix 1).

Geochemical Results

We follow the methodology of Piercey *et al.* (2001) and use immobile elements and ratios that contain Al_2O_3, TiO_2, high field strength elements (HFSE; Zr, Hf, Nb, Ta, Y, Th), and rare earth elements (REE; La to Lu) to evaluate the primary geochemical characteristics of the rocks (Fig. 4). The alkali elements (e.g., Na, K, and Ca) and large ion lithophile elements (LILE; e.g., Cs, Ba, Rb, K, Sr, U) can be significantly affected by hydrothermal alteration and metamorphism (e.g., Fig. 4e); alteration of least-altered felsic rocks resulted in sericite, chlorite-pyrite, and alkali feldspar assemblages, while mafic rocks typically exhibit more abundant carbonate, epidote, and chlorite-pyrite alteration (Fig. 4e; Ishikawa *et al.*, 1976; Lentz, 1999; Large *et al.*, 2001).

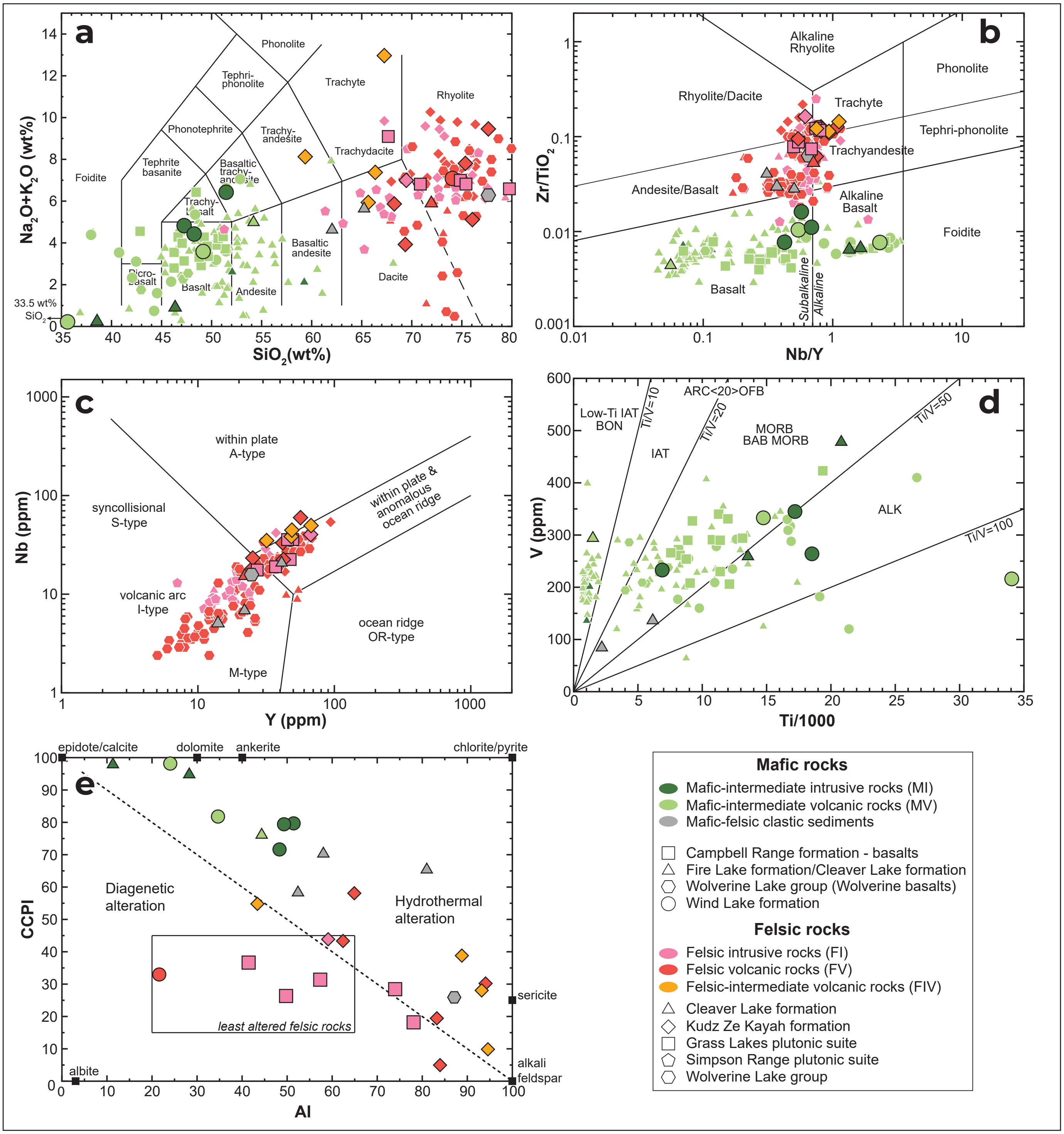

Figure 4. *Major and trace element discrimination diagrams for felsic and mafic rocks in the Finlayson Lake region. Samples from this study are shown as the largest symbols with black outlines; archival data are smaller symbols with white outlines (Piercey, 2001; Piercey et al., 2001, 2002a,b,c, 2003, 2004, 2008, 2012).* **(a)** *SiO_2 vs. $Na_2O + K_2O$, analyses from the Wolverine deposit hanging wall have SiO_2 contents above 80 wt% and are not included;* **(b)** *Nb/Y vs. Zr/TiO_2 (Pearce, 1996 after Winchester and Floyd, 1977);* **(c)** *Y vs. Nb (Pearce et al., 1984);* **(d)** *Ti/1000 vs. V (Shervais, 1982); and* **(e)** *CCPI (chlorite-carbonate-pyrite index) vs. AI (Ishikawa alteration index; Ishikawa et al., 1976) from Large (2001). IAT = island arc tholeiite; BON = boninite; OFB = ocean floor basalt; MORB = mid-ocean ridge basalt; BAB = back-arc basin; ALK = alkaline.*

Grass Lakes group

Fire Lake formation

Samples from the Fire Lake formation comprise ultramafic rocks (metapyroxenite?), a single mafic tuff, and intermediate–felsic clastic sedimentary rocks (Figs. 4–6; Table 1). The ultramafic rocks contain between 38 and 46 wt% SiO_2 and show Nb/Y, Zr/Nb, Ti/V, and Zr/Y ratios indicative of an alkalic affinity, whereas the mafic tuff is relatively more intermediate ($SiO_2 = 54.2$ wt%) with lower Ti/V and Zr/Y and has an island-arc tholeiitic to boninitic signature (Figs. 4 and 5; e.g., Piercey et al., 2002b, 2004). The ultramafic rocks have steep primitive mantle-normalized patterns with elevated LREE relative to HREE ratios ($La/Yb_{PM} = 5–34$; $La/Sm_{PM} = 1.5–9.1$; $Gd/Lu_{PM} = 2.7-3.2$) similar to Nb-enriched basalts (NEB; Piercey et al., 2004), whereas the mafic tuff has a relatively flatter pattern ($La/Yb_{PM} = 0.4$; $La/Sm_{PM} = 1.2$; $Gd/Lu_{PM} = 0.4$) and overlaps with the boninite field (Fig. 6f). The intermediate–felsic clastic sediments are primarily siltstone ($SiO_2 = 62–65$ wt%) and rare Si-rich clastic sediments ($SiO_2 = 84$ wt%) that occur proximal to massive sulphide mineralization at the Fyre Lake VMS deposit (Sebert et al., 2004). Trace element ratios (Nb/Y and Zr/Y) distinguish these sediments as derivatives of calc-alkaline arc rocks (Figs. 4 and 5) and have similar upper continental crustal-normalized patterns ($La/Yb_{UCN} = 0.65–0.91$) and neutral to weakly negative Eu anomalies (Eu/Eu* = 0.75–1.0; Fig. 6c).

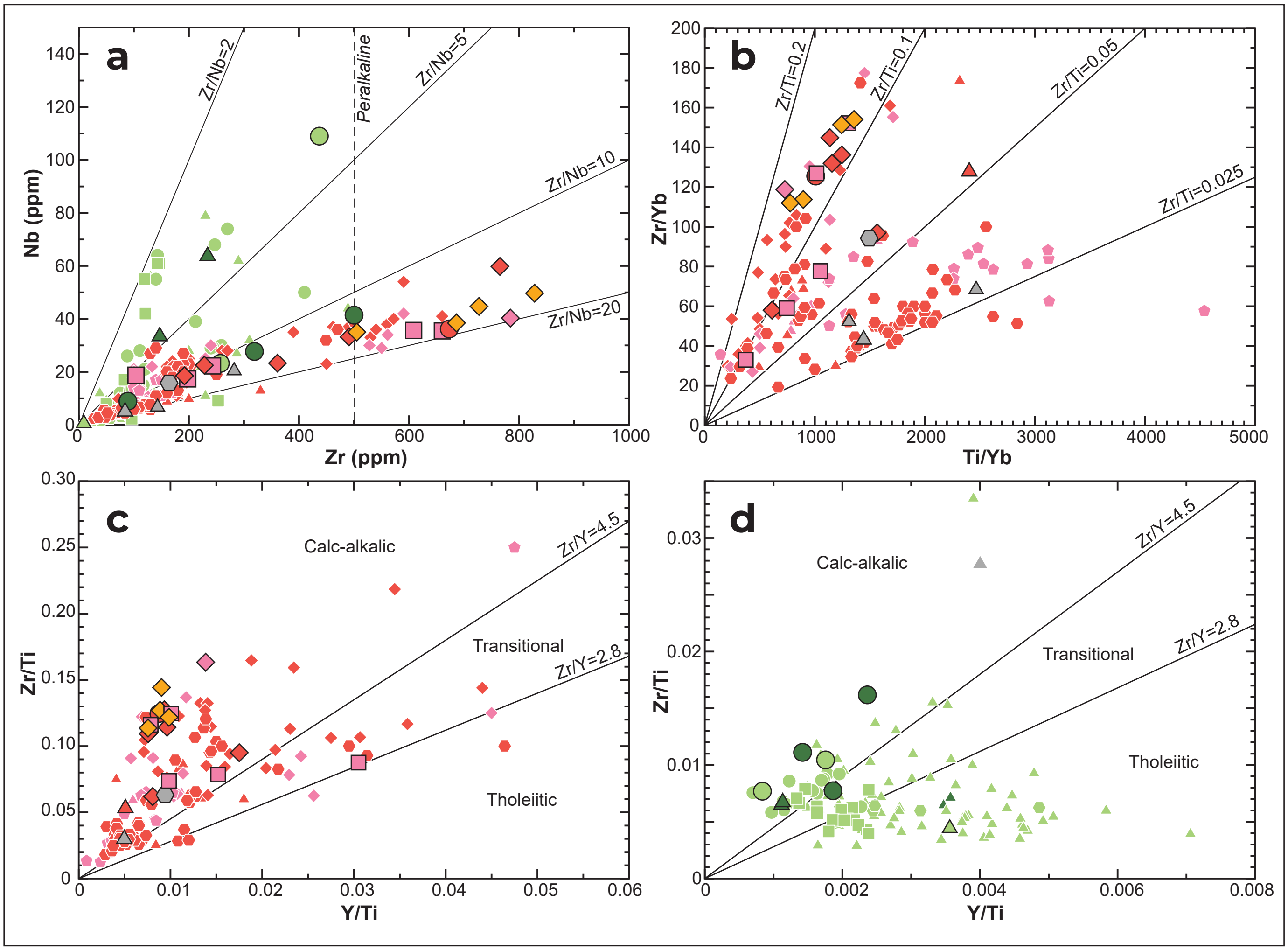

Figure 5. *High field strength element diagrams for felsic and mafic rocks in the Finlayson Lake region.* **(a)** *Zr vs. Nb (Leat et al., 1986);* **(b)** *Ti/Yb vs. Zr/Yb;* **(c)** *Y/Ti vs. Zr/Ti for felsic rocks; and* **(d)** *Y/Ti vs. Zr/Ti for mafic rocks. Panels c and d are modified after (Lentz, 1998, 1999); Zr/Y values defining magmatic affinity classes from Ross and Bédard (2009). Symbol styles as in Figure 4.*

Kudz Ze Kayah formation

Felsic tuffs and coherent rhyolite flows of the Kudz Ze Kayah formation reveal broadly similar geochemical compositions in the hanging wall and footwall of the Kudz Ze Kayah VMS deposits (Figs. 4–6; Table 1). The rocks display a range of SiO_2 contents (59–78 wt%) and have variable alkali concentrations due to hydrothermal alteration (Fig. 4a). The lithofacies have dacite, rhyolite, and trachyte compositions with calc-alkalic to alkalic, within-plate affinities (Nb/Y = 0.74–1.1; Zr/Y = 7.7–16; Ross and Bédard, 2009) except for two samples from the immediate hanging wall and footwall of GP4F mineralization (17MM-066 and 17MM-074, respectively) that have subalkaline affinities (Nb/Y = 0.54–0.61; Zr/Y = 5.4–12; Figs. 4 and 5). Upper continental crust-normalized immobile elements reveal relatively flat patterns with near-neutral LREE (La/Sm_{UCN} = 0.83–1.1) and relatively more abundant HREE (Gd/Lu_{UCN} = 0.57–1.9), and variably negative Eu (Eu/Eu* = 0.39–1.1) and Ti (Ti/Ti* = 0.32–1.0) anomalies (Fig. 6a) that directly overlap with A-type volcanic signatures from Piercey et *al.* (2001).

Wind Lake formation

The Wind Lake formation is composed primarily of carbonaceous argillite; geochemically similar mafic volcaniclastic, volcanic, and intrusive rocks; and lesser felsic volcaniclastic units that are geochemically similar to the underlying Kudz Ze Kayah formation (Figs. 4–6; Table 1). The mafic rocks have low SiO_2 (34–51 wt%) and correspond to basalt and alkaline basalt to basaltic trachyandesite compositions (Fig. 4a,b). They have back-arc basin MORB to alkalic geochemical affinities (Ti/V = 30–160; Fig. 4d; Shervais, 1982) and straddle the subalkaline to alkaline boundary with Nb/Y = 0.42–2.3 (Fig. 4b). Primitive mantle-normalized diagrams show steep patterns with LREE enrichment relative to HREE (La/Yb_{PM} = 3.9–22) and elevated Eu and Ti (Eu/Eu* = 1.9–4.5; Ti/Ti* = 5.9–32) similar to non-arc, ocean island basalt rift-related alkalic basalts (Fig. 6e; Piercey et *al.*, 2002a). The felsic tuff sample has significantly higher SiO_2 (74 wt%) and displays nearly identical trace element compositions to the intermediate–felsic volcanic and volcaniclastic rocks from the Kudz Ze Kayah formation (Figs. 4–6). The sample exhibits a trachytic composition (Fig. 4b) and has an alkalic and peralkaline, within-plate geochemical affinity (Nb/Y = 0.76; Zr/Y = 14.2; Zr/Nb = 125; Figs. 4 and 5). The upper continental crust-normalized pattern is relatively flat (La/Yb_{UCN} = 0.86) and overlaps directly with patterns from the Kudz Ze Kayah formation (Fig. 6a).

Grass Lakes plutonic suite

Most samples of the Grass Lakes plutonic suite come from a laterally extensive batholith-sized intrusion lying south of and stratigraphically beneath the Kudz Ze Kayah VMS deposit (Fig. 2). It is composed of high-silica, peraluminous alkali feldspar augen to megacrystic granitic rocks with apophyses of feldspar-porphyritic granitic rocks that are geochemically similar to, and contemporaneous with, the Kudz Ze Kayah strata (Figs. 4–6; *e.g.*, Piercey et *al.*, 2003; Murphy et *al.*, 2006). Samples from the pluton contain between 68 and 79 wt% SiO_2 and abundant HFSE concentrations which correspond to calc-alkalic, within-plate affinities (Zr/Y = 2.9–14; Nb/Y = 0.52–0.80; Figs. 4c and 5c). The upper continental crust-normalized diagrams show distinct trends for the pluton (La/Yb_{UCN} = 0.64–0.92) and feldspar porphyry dikes (La/Yb_{UCN} = 1.1–1.8); the dikes contain higher concentrations of HFSE and REE compared to the pluton (*e.g.*, Eu/Eu* = ~0.91 vs. 0.45; Zr/Zr* = ~1.4 vs. 0.55; Fig. 6b). These new results overlap with A-type, within-plate Grass Lakes granitic rocks documented by Piercey et *al.* (2003) and calc-alkalic to alkalic Kudz Ze Kayah volcanic rocks (Piercey et *al.*, 2001; Fig. 6a).

Wolverine Lake group

The Wolverine Lake group overlies the Grass Lakes group above a marked angular unconformity (Murphy et *al.*, 2002). One sample of quartz-feldspar grit (17MM-004) from immediately above the unconformity was analyzed. The grit displays high SiO_2 (78 wt%) and HFSE and REE compositions (Nb/Y = 0.65; Zr/Y = 6.7) comparable to the underlying calc-alkalic, arc to intraplate rocks of the underlying Kudz Ze Kayah formation and Grass Lakes plutonic suite (Piercey et *al.*, 2001; Figs. 4c, 5c, and 6). This sample

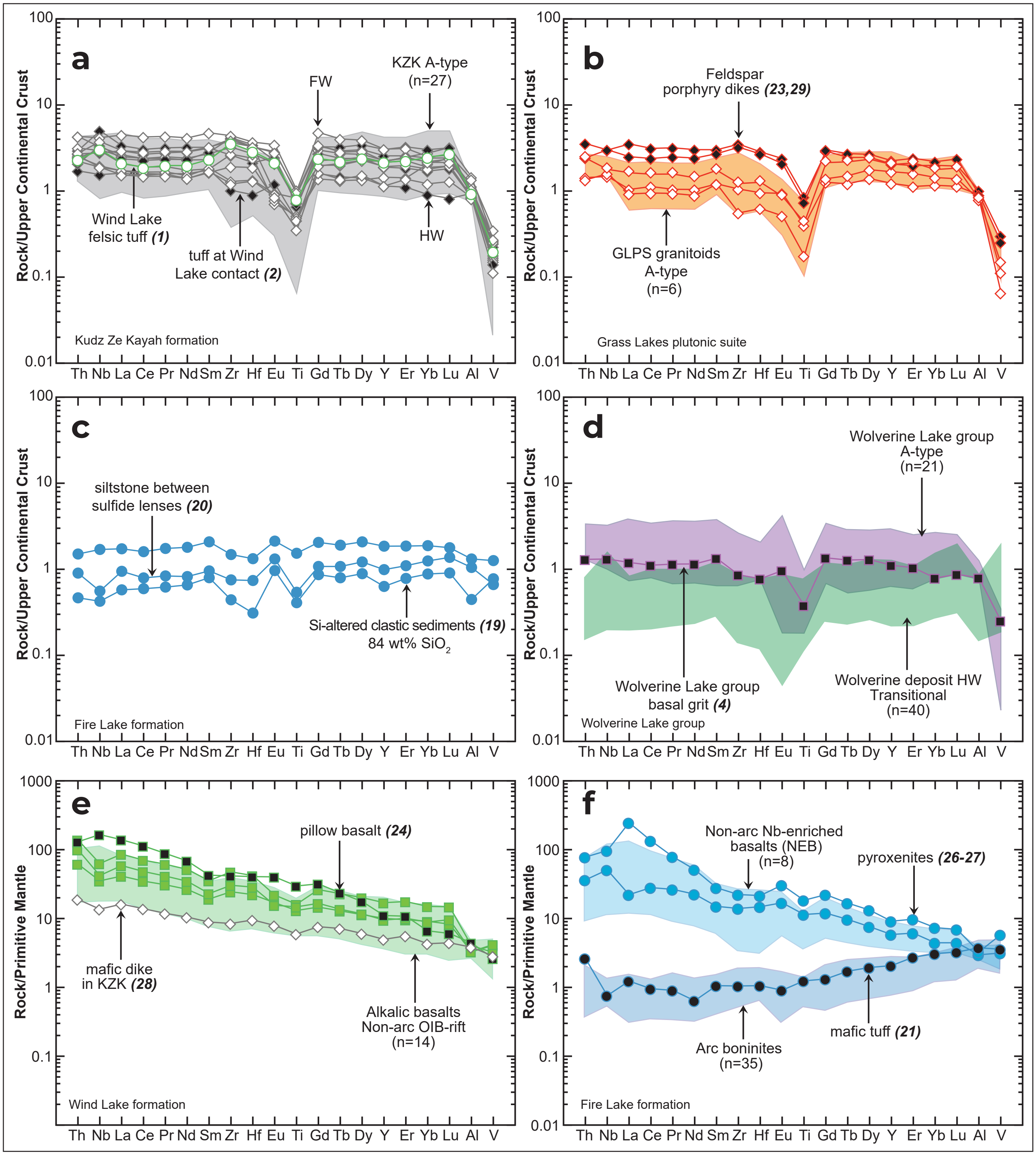

Figure 6. *Immobile trace element variations for felsic rock (***a–d***) and mafic rock (***e,f***) suites in the Finlayson Lake region. Results for felsic and mafic rocks are normalized to upper continental crust (McLennan, 2001) and primitive mantle (McDonough and Sun, 1995), respectively. Bold numbers in brackets correspond to sample numbers in Fig. 2 and Table 1. Shaded fields represent archival data with associated magmatic affinities (cf. references in Fig. 4). In panel* **(f)***, only results with similar trace element patterns are shown as fields (boninites and Nb-enriched basalts, 43 of 76 total analyses for the Fire Lake formation).*

exhibits a relatively flat upper continental crust-normalized pattern with relatively more abundant LREE ($La/Sm_{UNC} = 0.89$) than HREE ($Gd/Lu_{UNC} = 1.5$; Fig. 6d). The immobile element concentrations overlap with other intraplate rocks of the Wolverine Lake group, primarily from the footwall of the Wolverine VMS deposits, and are distinctly more elevated compared to the hanging wall felsic rocks (Fig. 6d; Piercey et *al.*, 2001, 2008).

Discussion and Future Work

New lithogeochemical data from outcrop and drill core in the Finlayson Lake district overlap with existing data sets for rock units of the Grass Lakes and Wolverine Lake groups, despite a difference in the age of the data sets of 15+ years (Figs. 4–6). These data further support the interpretations of Piercey et *al.* (2001, 2002a) that these rocks formed during the evolution of a mid-Paleozoic convergent margin system on edge of western Laurentia, analogous to the development of the Japanese arcs, Sea of Japan, and Sino-Korean craton tectonic arrangement (Piercey et *al.*, 2006).

The Fire Lake formation represents the first stage of tholeiitic to boninitic arc to marginal-arc magmatism built atop a composite Yukon-Tanana basement (Grant, 1997; Piercey et *al.*, 2002b, 2004). Siltstones in the immediate hanging wall and those interbedded with Fyre Lake VMS mineralization have MORB to BAB MORB affinities that reflect erosion from source rocks formed during the onset of back-arc extension that led to separation of the Yukon-Tanana terrane from the western Laurentian continental margin (Figs. 4–6; Piercey et *al.*, 2002b, 2004). Ongoing spreading of the continental back-arc basin facilitated upwelling of asthenospheric mantle, partial melting, basaltic underplating, crustal melting and basalt–crustal melt mixing that led to calc-alkalic to alkalic, intraplate felsic volcanism associated with the Kudz Ze Kayah formation (Figs. 2, 4, and 5; Piercey et *al.*, 2001). The spatial and geochemical overlap between the Grass Lakes granite and porphyritic dikes and the Kudz Ze Kayah formation is shown in Figures 4 to 6 and supports the interpretation by Piercey et *al.* (2003) that the batholith may have been a staging chamber for extrusive volcanism. Overlying alkalic basalt from the Wind Lake formation, expressed as effusive and volcaniclastic eruptions or as deeper intrusive dikes, further corroborate the addition of high-temperature basaltic melts to the upper crust from ongoing back-arc extension and associated decompression melting of the mantle (*e.g.*, Piercey et *al.*, 2002a). Following a period of regional deformation and erosion between 361 and 358 Ma (Murphy et *al.*, 2002, 2006), basal quartzo-feldspathic grits of the Wolverine Lake group were deposited; their geochemical similarity to Kudz Ze Kayah volcanic rocks and Grass Lakes granitoid rocks indicate derivation from these or similar sources (Figs. 4–6; Piercey et *al.*, 2001).

Felsic rocks in the immediate hanging wall and footwall of the Kudz Ze Kayah VMS deposits have the highest Zr compositions (<830 ppm) and comparable HFSE and REE abundances (Zr/Yb = 111–154; Nb/Y = 0.74–1.1; Zr/Y = 11.9–15.9; Nb/Ta = 15.1–17.2; Figs. 4 and 5) of any published results from the Kudz Ze Kayah formation. Distal felsic volcanic rocks, however, show lower HFSE and REE (Zr/Yb = 58–118; Nb/Y = 0.53–0.74; Zr/Y = 7.7–11.8; Nb/Ta = 11.8–12.4). Variations in the Nb/Ta ratio (11.8–17.2, average = 14.8; n = 10) suggests mixing of crustal and mantle sources (*e.g.*, Piercey et *al.*, 2008). The elevated HFSE and REE concentrations in Kudz Ze Kayah felsic volcanic rocks have been attributed to high-temperature melting of continental crust and subsequent dissolution of HFSE-REE-rich accessory minerals (*e.g.*, zircon, monazite, apatite; Piercey et *al.*, 2001). This increased incompatible element budget has been shown to be associated with high temperature felsic melts in VMS belts worldwide, as in the VMS-hosting felsic rocks in the Abitibi greenstone belt (Barrie, 1995), the Iberian Pyrite Belt (Barrie et *al.*, 2002; Rosa et *al.*, 2009; Codeço et *al.*, 2018), and the Wolverine Lake group, Finlayson Lake district (Piercey et *al.*, 2008). Moreover, VMS deposits in crustal regimes are generally associated with thermally anomalous magmas and regional heat corridors that are conducive to the formation of VMS-related hydrothermal systems (Piercey, 2011).

Future work will investigate variations in the mineral-scale geochronological and geochemical characteristics of the felsic rocks throughout the Finlayson Lake district to assess their value as an indicator of prospectivity in mineral exploration and ancillary crustal evolution studies (*e.g.*, Piercey *et al.*, 2017; Manor and Piercey, 2018). High-precision chemical abrasion isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb zircon dating is underway to determine the temporal variations in VMS-related felsic volcanism throughout the Kudz Ze Kayah formation and the Wolverine Lake group. Whole-rock lithogeochemistry, Nd-Hf isotopic compositions, and *in situ* geochemical and isotopic analysis on mineral separates (zircon, monazite, and apatite) will be integrated in order to characterize the petrogenetic conditions and processes leading to magma genesis with potential links to VMS formation (*e.g.*, T, redox, metal and sulphur budgets, fluid compositions). These results will complement existing studies (*e.g.*, Piercey, 2001; Piercey *et al.*, 2002a, 2003, 2004, 2017) to further evaluate and test crustal evolution models for the northern Cordillera and also to test the role of asthenospheric mantle in the formation of the VMS-bearing and VMS-barren rock packages. The work will continue to refine existing models of VMS formation with respect to broad aspects of heat supply, fluid circulation, timing/episodicity of mineralizing events, and the interplay of tectonics, magmatism, and ore formation. Ultimately, this work will provide a unique integrated approach to magma prospectivity in an ancient, mid-Paleozoic felsic-hosted VMS terrane.

Conclusions

The new lithogeochemical results presented here support the current interpretations of an evolving, mid-Paleozoic (*ca.* 365-355 Ma) continental arc, marginal arc, and back-arc basin configuration at the western Laurentian margin. Results from strata immediately above and below the Kudz Ze Kayah VMS deposit place new constraints on the HFSE and REE end-member compositions (*e.g.*, Zr, Nb/Ta) and indicate a distinct period of high-temperature alkalic felsic volcanism within the Kudz Ze Kayah formation. Further work aims to identify mineral-scale and whole-rock geochemical characteristics of VMS-bearing stratigraphy to develop prospectivity criteria for future exploration in orogenic belts globally.

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Table 1. *Lithogeochemical results for felsic and mafic rocks in the Finlayson Lake region, Yukon.*

Sample	17MM-002	17MM-007	17MM-031	17MM-033	17MM-034	17MM-055*	17MM-066	17MM-074	17MM-075	17MM-077	17MM-001*	17MM-003*	17MM-038	17MM-040	17MM-054*
# on map[1]	2	6	10	11	12	25	31	32	33	34	1	3	16	17	24
Unit[2]	KZK - HW	KZK - HW	KZK - HW	KZK - FW	KZK - FW	KZK - HW	KZK - FW	KZK - FW	KZK - FW	KZK - FW	Wind Lake	Wind Lake	Wind Lake	Wind Lake	Wind Lake
UTME[3]	413907	415074	415049	415049	415049	366940	419500	419500	415122	415122	413749	412065	415397	415397	423699
UTMN[3]	6815182	6815570	6815467	6815467	6815467	6801900	6813355	6813355	6814798	6814798	6815933	6816318	6815422	6815422	6816422
Drillhole		K15-299	K15-301	K15-301	K15-301		K15-302	K15-302	K16-372	K16-372			K17-439	K17-439	
Depth (m)		66.35	30.13	118.37	128.51		46.71	175.31	62.22	401.11			23.61	70.50	
Lithology[4]	Felsic LT	Felsic LT	Felsic LT	Felsic LT	Felsic intrusive	Aphyric rhyolite	Felsic intrusive	Felsic CT	Felsic tuff	Felsic LT	Felsic tuff	Mafic tuff	Mafic intrusive	Mafic intrusive	Pillow basalt
Major elements (wt%)															
SiO_2	76	68.2	69.3	59.3	67.2	77.6	69.4	75.3	66.3	65.6	74	49.1	48.2	51.4	33.5
TiO_2	0.31	0.6	0.43	0.54	0.35	0.33	0.48	0.24	0.68	0.64	0.54	2.46	3.09	2.87	5.68
Al_2O_3	14	15	11.85	21	17.25	12.75	12.95	12.1	20.2	15.4	14	13.65	17.05	14.2	18.7
$Fe_2O_{3\,(T)}$	1.47	3.64	4.27	3.55	1.33	0.45	4.76	1.35	1.96	5.8	3.32	12.1	14.4	13.15	15.4
MnO	0.02	0.08	0.09	0.04	0.01	0.01	0.11	0.04	0.01	0.09	0.02	0.14	0.09	0.13	0.22
MgO	0.89	1.21	1.61	1.95	0.21	0.08	1.18	0.66	1.1	1.98	0.49	5.22	4.37	4.35	4.81
CaO	0.32	1.72	2.81	1.18	0.16	0.21	2.3	1.15	0.45	2.2	0.14	6.78	2.59	3.37	15.3
Na_2O	0.08	1.58	0.1	0.11	0.52	1.36	2.01	0.43	0.12	3.55	5.92	3.39	2.95	3.94	0.24
K_2O	5.04	4.29	3.83	8.02	12.45	8.1	4.99	7.38	7.26	2.39	1.17	0.2	1.48	2.49	0.11
Cr_2O_3	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.02	0.01	0.01	0.03
P_2O_5	0.15	0.17	0.18	0.07	0.05	0.04	0.06	0.07	0.21	0.2	0.08	0.41	0.88	0.54	1.06
SrO	bdl	bdl	bdl	bdl	0.02	bdl	0.02	0.01	bdl	bdl	bdl	0.01	bdl	0.01	0.14
BaO	0.28	0.22	0.11	0.4	1.37	0.12	0.24	0.09	0.31	0.26	0.08	<0.01	0.23	0.25	0.02
LOI	2.19	4.16	5.65	4.19	1.05	0.61	3.14	1.62	3.04	3.61	1.53	6.67	5.05	3.02	4
Total	100.75	100.87	100.23	100.35	101.97	101.66	101.64	100.44	101.64	101.72	101.29	100.15	100.39	99.73	99.21
Trace elements (ppm)															
Cs	2.19	2.17	1.78	3.37	2.13	1.54	2.15	4.48	3.39	1.46	1.85	0.43	0.86	9.14	0.18
Rb	180	135	130	349	283	240	104	162	203	71.1	43.9	10.6	40	98.4	3.6
Ba	2450	1905	981	3490	abl	1060	2190	806	2790	2290	661	40.5	2060	2180	149.5
Th	18.2	31.5	28.6	45.7	33.6	26.4	22.2	23.5	45.7	29.3	24.5	4.92	11.05	7.94	10.35
U	1.89	4.63	3.21	11.25	9.87	4.25	5.8	6.25	5.03	4.15	7.17	1.35	2.92	3.02	1.82
W	1	3	2	7	2	2	1	2	5	3	1	bdl	1	1	4
Nb	18.5	59.8	33.2	38.5	35	23.3	40.3	22.5	49.7	44.7	36.2	23.2	41.4	27.7	109
Ta	1.5	3.6	2	2.5	2.2	1.9	2.6	1.9	3.3	2.6	2.4	1.5	2.7	1.9	6.3
La	48	100	87.3	78.3	61.7	50.9	70.5	45.7	133.5	87.6	62.9	26.8	55.9	38.1	90.3
Ce	96.7	194	170	151.5	120.5	101.5	144	94.1	270	179.5	119	58.5	118	80.7	189.5
Pr	11.2	22.4	19.6	16.9	13.55	11.05	16.45	10.5	30.4	20.5	13.95	7.85	15.6	10.5	22.4
Sr	7.8	62.7	69.7	63.2	224	23.7	200	72.2	20.9	69.6	41	157.5	78.5	101	1150
Nd	41.1	83.1	73.5	59.2	44.9	36.1	60	36.1	107	74.5	51	33.2	64.6	43.5	85.8
Sm	7.85	14.4	14.1	10.35	8.08	7.35	12.7	7.5	21.2	14.5	10.45	7.79	14.4	9.35	17.3
Zr	192	765	491	686	505	361	784	228	828	727	673	257	500	319	437
Hf	5.2	18.7	12.3	18.8	13.8	10.8	19.8	7.5	21.3	18.7	16.5	6.3	11.9	8.1	11.5
Eu	1.05	2.5	2.15	0.82	0.62	0.68	1.95	0.74	3.02	2.43	1.87	2.61	3.38	2.4	6.2
Gd	6	12.5	10.3	7.5	5.21	6.14	12.35	7.38	18.05	12.85	9	7.97	14.3	9.04	17.35
Tb	0.93	1.86	1.52	1.27	0.84	0.87	2.06	1.33	2.56	1.8	1.4	1.28	2.27	1.35	2.33
Dy	4.92	10.5	8.3	7.9	4.68	5.3	11.95	7.89	13.55	10.05	8.32	7.69	13.55	7.89	11.9
Y	25	56	41.4	47.9	31.6	25	66.4	42	66.9	48.4	47.2	43.2	73	40.8	47.6
Ho	0.91	2.07	1.54	1.73	0.97	1.01	2.44	1.52	2.52	1.92	1.7	1.6	2.66	1.57	1.98
Er	2.53	5.86	4.2	5.68	3.25	3.13	7.45	4.52	7.13	5.62	5.11	4.21	7.73	4.41	4.73
Tm	0.36	0.81	0.59	0.84	0.61	0.4	1.09	0.66	0.91	0.73	0.83	0.66	1.04	0.63	0.57
Yb	1.98	5.28	3.72	6.03	4.51	2.65	6.6	3.93	5.47	4.72	5.36	4.02	6.61	3.92	2.92
Lu	0.26	0.77	0.58	1.02	0.77	0.41	1.01	0.62	0.83	0.68	0.86	0.56	1	0.65	0.41
Cr	20	20	20	20	30	20	10	10	20	20	10	130	50	70	220
V	24	26	19	28	18	17	15	12	37	29	21	333	264	345	216
Sn	6	5	4	17	9	7	7	7	6	4	3	3	2	2	6
Ga	20.7	26.7	19.6	37.4	22.9	20.6	23.6	18.6	35.4	23.5	21.2	22.2	27.2	21.3	39.7

*Outcrop samples
1 Number corresponds to sample locations on Figure 2
2 KZK = Kudz Ze Kayah formation; GLPS = Grass Lakes plutonic suite; HW = hanging wall; FW = footwall
3 Coordinates in NAD83 Zone 9N
4 LT = lapilli tuff; CT = crystal tuff; Fsp = feldspar; Qtz = quartz
bdl = below detection limit; abl = above detection limit

Table 1. *Lithogeochemical results for felsic and mafic rocks in the Finlayson Lake region, Yukon.*

Sample	17MM-060	17MM-043	17MM-047	17MM-049	17MM-050	17MM-056*	17MM-057*	17MM-004*	17MM-005*	17MM-051*	17MM-053*	17MM-061	17MM-062
# on map[1]	28	18	19	20	21	26	27	4	5	22	23	29	30
Unit[2]	Wind Lake?	Fire Lake - HW	Fire Lake - HW	Fire Lake - HW/FW	Fire Lake - FW	Fire Lake	Fire Lake	Wolverine Lake	GLPS	GLPS	GLPS	GLPS?	GLPS
UTME[3]	415122	419346	419346	419346	419346	411343	411789	429446	429291	409304	408605	415122	415122
UTMN[3]	6814798	6788812	6788812	6788812	6788812	6811450	6811402	6812106	6812095	6811726	6813581	6814798	6814798
Drillhole	K16-372	FL97-109	FL97-109	FL97-109	FL97-109							K16-372	K16-372
Depth (m)	27.14	87.40	203.94	265.54	352.44							103.45	585.00
Lithology[4]	Mafic intrusive	Siltstone	Si-altered clastic?	Siltstone	Mafic tuff/flow	Ultramafic	Ultramafic	Felsic grit	Granite	Granite	Fsp porphyry	Fsp-qtz porphyry	Granite
Major elements (wt. %)													
SiO_2	47.2	62	84.3	65.2	54.2	46.3	38.5	77.6	75.3	79.7	67.6	70.8	74.8
TiO_2	1.15	1.02	0.28	0.36	0.25	2.26	3.47	0.26	0.27	0.12	0.57	0.49	0.31
Al_2O_3	16.25	19.5	6.81	15.7	16.5	12.95	13.65	12.05	13.4	11.95	15	13.2	12.8
$Fe_2O_{3\,(T)}$	10.4	7.04	3.57	4.36	8.92	10.7	9.39	1.48	1.93	1.33	3.88	1.69	3.18
MnO	0.12	0.07	0.11	0.15	0.16	0.2	0.21	0.02	0.03	0.01	0.02	0.07	0.02
MgO	9.17	2.31	2.27	3.89	7.83	7.04	3.02	0.87	0.7	0.26	0.66	1.18	1.19
CaO	6.2	0.57	0.59	2.43	5.96	17.35	24.4	0.82	0.27	0.13	1.49	2.67	0.26
Na_2O	4.03	0.84	1.58	3.23	4.5	0.8	0.15	0.23	3.64	1.42	3.32	0.14	4.68
K_2O	0.78	3.75	0.74	2.37	0.48	0.12	0.1	6.06	3.2	5.16	5.78	6.67	2.33
Cr_2O_3	0.05	0.01	0.01	0.01	0.01	0.04	0.06	bdl	bdl	bdl	bdl	bdl	bdl
P_2O_5	0.14	0.16	0.04	0.05	0.02	0.29	0.74	0.15	0.15	0.08	0.15	0.15	0.08
SrO	0.01	0.02	bdl	0.04	0.01	0.07	0.12	bdl	bdl	bdl	0.02	bdl	bdl
BaO	0.03	0.09	0.2	0.61	0.09	0.01	0.02	0.13	0.08	0.03	0.18	0.16	0.06
LOI	5.1	3.88	1.4	2.27	1.94	1.71	6.38	2.05	1.24	1.29	0.76	3.66	0.88
Total	100.63	101.26	101.9	100.67	100.87	99.84	100.21	101.72	100.21	101.48	99.43	100.88	100.59
Trace elements (ppm)													
Cs	2.16	2.61	2.23	18.4	5.01	0.12	0.07	0.43	0.78	3.92	2.86	1.44	2.22
Rb	34.4	161.5	21.6	76.5	15	2.3	2.1	131	113.5	185.5	180	171	80.4
Ba	227	839	1820	5320	807	44.2	143	1105	750	298	1600	1450	509
Th	1.51	16.1	4.99	9.66	0.21	2.89	6.21	13.95	15.2	14.3	37.8	25.9	27.1
U	0.43	3.74	0.9	3.47	0.19	1.71	4.22	5.66	3.23	3.75	3.63	4.71	7.72
W	1	3	2	1	1	1	2	2	2	4	2	3	2
Nb	9	20.4	5.1	6.7	0.5	33.5	63.8	15.8	17.6	19	35.7	35.9	22.5
Ta	0.6	1.5	0.4	0.5	0.1	2.1	3.9	1.4	1.6	1.8	2.2	2.3	1.6
La	10.5	51.9	17.3	28.4	0.8	14.4	160	36	31.1	27.6	105	74.6	51.4
Ce	23.2	102.5	38.1	50.8	1.6	47.1	226	71.4	71.6	60.3	199	152	105.5
Pr	3.02	12.4	4.41	5.94	0.23	6.74	20.1	8.16	7.38	6.61	22.4	17.6	11.75
Sr	129.5	215	87.5	385	168.5	621	979	57.1	47.3	23.7	248	64.7	37
Nd	13.1	46.8	17.1	21.4	0.8	28.2	64.3	30	26.9	22.9	78.1	62.3	38.9
Sm	3.61	9.38	3.59	4.31	0.43	6.1	11.35	6.05	5.41	5.38	13.5	12.15	8.23
Zr	89	282	84	143	11	147	234	164	199	105	661	609	244
Hf	2.7	7.7	1.8	4.3	0.3	4.2	6.1	4.5	5.5	3.6	16.4	15.5	7.7
Eu	1.22	1.87	0.85	1.16	0.14	2.61	4.72	0.85	0.82	0.45	2.08	1.82	0.8
Gd	4.14	7.8	3.29	4.1	0.72	6.52	12.1	5.16	4.77	5.24	10.95	11.3	8.53
Tb	0.71	1.22	0.51	0.69	0.17	0.96	1.66	0.82	0.77	0.96	1.56	1.73	1.47
Dy	4.08	7.29	3.11	4.26	1.31	5.13	8.94	4.54	4.83	6.14	8.55	9.27	8.6
Y	21.4	40.8	13.9	21.8	8.9	25.2	39.3	24.5	26.8	36.6	44.9	49.1	47
Ho	0.87	1.44	0.62	0.86	0.33	1	1.7	0.84	1	1.24	1.63	1.91	1.76
Er	2.45	4.28	1.8	2.53	1.2	2.69	4.29	2.4	2.58	3.65	4.51	5.48	5.13
Tm	0.32	0.67	0.29	0.4	0.19	0.34	0.52	0.28	0.36	0.46	0.68	0.73	0.68
Yb	1.9	4.14	1.94	2.75	1.36	1.96	3.25	1.74	2.55	3.14	4.34	4.79	4.11
Lu	0.3	0.57	0.29	0.44	0.22	0.3	0.47	0.28	0.36	0.44	0.62	0.75	0.62
Cr	390	110	100	50	80	260	450	20	20	20	20	20	20
V	233	135	83	71	294	259	478	27	12	7	32	27	16
Sn	1	4	2	3	<1	3	4	6	4	7	4	4	4
Ga	18.1	26.9	11.9	19.7	14.4	20.2	22.9	19.1	19.1	19.5	24.6	24.7	21

*Outcrop samples
1 Number corresponds to sample locations on Figure 2
2 KZK = Kudz Ze Kayah formation; GLPS = Grass Lakes plutonic suite; HW = hanging wall; FW = footwall
3 Coordinates in NAD83 Zone 9N
4 LT = lapilli tuff; CT = crystal tuff; Fsp = feldspar; Qtz = quartz
bdl = below detection limit; abl = above detection limit

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***Appendix 1.** QA/QC results for ALS lithogeochemical analyses of the Finlayson Lake district, Yukon.*

	SLV-MC basalt							WP-1 Watts Point dacite (Coast Plutonic Complex)					17MM-031 KZK					17MM-062 Grass Lakes plutonic suite					17MM-066 KZK (GP4F)				
Sample	Q931840	Q931840 (ALS dup)	Q931840 (ALS dup)	Q931842	Mean	σ	% RSD	Q931841	Q931843	Mean	σ	% RSD	17MM-031	Q931876 (17MM-031)	Mean	σ	% RSD	17MM-062	Q931885 (17MM-062)	Mean	σ	% RSD	17MM-066	17MM-066	Mean	σ	% RSD
Rock Type	SLV-MC basalt	SLV-MC basalt	SLV-MC basalt	SLV-MC basalt				WP-1 dacite	WP-1 dacite				Felsic ash-lapilli tuff	Felsic ash-lapilli tuff				Qtz-Fsp porphyry	Qtz-Fsp porphyry				Int. intrusive	Int. intrusive			
Major elements (wt%)																											
SiO_2	49.8	49.8	49.8	50.3	49.93	0.25	0.50	65.6	65.3	65.45	0.21	0.32	69.3	65.1	67.20	2.97	4.42	74.8	75.8	75.30	0.71	0.94	69.4	68.2	68.80	0.85	1.23
Al_2O_3	15.6	15.6	15.6	15.65	15.61	0.03	0.16	16.75	16.45	16.60	0.21	1.28	11.85	12.1	11.98	0.18	1.48	12.8	13.05	12.93	0.18	1.37	12.95	12.7	12.83	0.18	1.38
Fe_2O_3	12.85	12.85	12.9	13.05	12.91	0.09	0.73	4.41	4.39	4.40	0.01	0.32	4.27	4.44	4.36	0.12	2.76	3.18	2.49	2.84	0.49	17.21	4.76	4.68	4.72	0.06	1.20
CaO	8.62	8.62	8.59	8.82	8.66	0.11	1.22	4.91	4.98	4.95	0.05	1.00	2.81	3.61	3.21	0.57	17.62	0.26	0.4	0.33	0.10	30.00	2.3	2.25	2.28	0.04	1.55
MgO	7.57	7.57	7.57	7.59	7.58	0.01	0.13	2.62	2.58	2.60	0.03	1.09	1.61	1.8	1.71	0.13	7.88	1.19	0.99	1.09	0.14	12.97	1.18	1.15	1.17	0.02	1.82
Na_2O	3.61	3.61	3.63	3.59	3.61	0.02	0.45	4.46	4.32	4.39	0.10	2.26	0.1	0.11	0.11	0.01	6.73	4.68	4.82	4.75	0.10	2.08	2.01	2.03	2.02	0.01	0.70
K_2O	0.54	0.54	0.55	0.53	0.54	0.01	1.51	1.64	1.63	1.64	0.01	0.43	3.83	4.05	3.94	0.16	3.95	2.33	2.27	2.30	0.04	1.84	4.99	4.91	4.95	0.06	1.14
Cr_2O_3	0.03	0.03	0.03	0.03	0.03	0.00	0.00	0.01	0.01	0.01	0.00	0.00	bdl	bdl				bdl	bdl				<0.01	bdl			
TiO_2	1.5	1.5	1.5	1.47	1.49	0.02	1.01	0.49	0.47	0.48	0.01	2.95	0.43	0.5	0.47	0.05	10.64	0.31	0.29	0.30	0.01	4.71	0.48	0.47	0.48	0.01	1.49
MnO	0.17	0.17	0.17	0.17	0.17	0.00	0.00	0.08	0.08	0.08	0.00	0.00	0.09	0.09	0.09	0.00	0.00	0.02	0.02	0.02	0.00	0.00	0.11	0.1	0.11	0.01	6.73
P_2O_5	0.25	0.25	0.25	0.24	0.25	0.01	2.02	0.17	0.17	0.17	0.00	0.00	0.18	0.19	0.19	0.01	3.82	0.08	0.08	0.08	0.00	0.00	0.06	0.06	0.06	0.00	0.00
SrO	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.09	0.08	0.09	0.01	8.32	bdl	bdl				bdl	bdl				0.02	0.02	0.02	0.00	0.00
BaO	0.02	0.02	0.02	0.02	0.02	0.00	0.00	0.07	0.07	0.07	0.00	0.00	0.11	0.1	0.11	0.01	6.73	0.06	0.06	0.06	0.00	0.00	0.24	0.23	0.24	0.01	3.01
LOI	-0.85			-0.72	-0.79	0.09	-11.71	0.2	0.17	0.19	0.02	11.47	5.65	6.5	6.08	0.60	9.89	0.88	0.95	0.92	0.05	5.41					
Total	99.76			100.79	100.28	0.73	0.73	101.5	100.7	101.10	0.57	0.56	100.23	98.59	99.41	1.16	1.17	100.59	101.22	100.91	0.45	0.44					
Trace elements (ppm)																											
Ba	165	165	163	156.5	162.38	4.03	2.48	645	613	629.00	22.63	3.60	981	927	954.00	38.18	4.00	509	521	515.00	8.49	1.65	2190	2130	2160.00	42.43	1.96
Ce	22.7	22.7	22.4	21.6	22.35	0.52	2.32	29.1	28.3	28.70	0.57	1.97	170	143.5	156.75	18.74	11.95	105.5	94.9	100.20	7.50	7.48	144	143	143.50	0.71	0.49
Cr	240	240	250	240	242.50	5.00	2.06	80	80	80.00	0.00	0.00	20	20	20.00	0.00	0.00	20	20	20.00	0.00	0.00	10	10	10.00	0.00	0.00
Cs	0.12	0.12	0.06	0.07	0.09	0.03	34.61	0.43	0.35	0.39	0.06	14.50	1.78	1.97	1.88	0.13	7.17	2.22	1.64	1.93	0.41	21.25	2.15	2.24	2.20	0.06	2.90
Dy	3.67	3.67	3.73	3.8	3.72	0.06	1.66	2.43	2.4	2.42	0.02	0.88	8.3	9	8.65	0.49	5.72	8.6	8.15	8.38	0.32	3.80	11.95	11.7	11.83	0.18	1.49
Er	1.86	1.86	1.84	1.89	1.86	0.02	1.11	1.39	1.49	1.44	0.07	4.91	4.2	5.3	4.75	0.78	16.38	5.13	5.04	5.09	0.06	1.25	7.45	7.21	7.33	0.17	2.32
Eu	1.45	1.45	1.44	1.43	1.44	0.01	0.66	0.93	0.92	0.93	0.01	0.76	2.15	1.94	2.05	0.15	7.26	0.8	0.7	0.75	0.07	9.43	1.95	1.92	1.94	0.02	1.10
Ga	22	22	21.1	21.6	21.68	0.43	1.97	19.3	19.8	19.55	0.35	1.81	19.6	20.4	20.00	0.57	2.83	21	20.1	20.55	0.64	3.10	23.6	23.1	23.35	0.35	1.51
Gd	3.88	3.88	4.14	4.18	4.02	0.16	4.04	2.78	2.79	2.79	0.01	0.25	10.3	9.78	10.04	0.37	3.66	8.53	7.5	8.02	0.73	9.09	12.35	12.5	12.43	0.11	0.85
Hf	2.6	2.6	2.7	2.8	2.68	0.10	3.58	3.5	3.3	3.40	0.14	4.16	12.3	14	13.15	1.20	9.14	7.7	6.6	7.15	0.78	10.88	19.8	19.6	19.70	0.14	0.72
Ho	0.7	0.7	0.71	0.68	0.70	0.01	1.80	0.48	0.48	0.48	0.00	0.00	1.54	1.89	1.72	0.25	14.43	1.76	1.71	1.74	0.04	2.04	2.44	2.4	2.42	0.03	1.17
La	10	10	10.3	9.3	9.90	0.42	4.29	14.4	13.3	13.85	0.78	5.62	87.3	74	80.65	9.40	11.66	51.4	46.6	49.00	3.39	6.93	70.5	70	70.25	0.35	0.50
Lu	0.24	0.24	0.23	0.21	0.23	0.01	6.15	0.21	0.2	0.21	0.01	3.45	0.58	0.75	0.67	0.12	18.08	0.62	0.61	0.62	0.01	1.15	1.01	1.05	1.03	0.03	2.75
Nb	8.9	8.9	8.5	8.5	8.70	0.23	2.65	3.6	3.5	3.55	0.07	1.99	33.2	35.5	34.35	1.63	4.73	22.5	22.6	22.55	0.07	0.31	40.3	40.7	40.50	0.28	0.70
Nd	14.8	14.8	14.5	13	14.28	0.86	6.04	15.7	14	14.85	1.20	8.09	73.5	63.1	68.30	7.35	10.77	38.9	36.1	37.50	1.98	5.28	60	58.9	59.45	0.78	1.31
Pr	3.2	3.2	3.16	2.94	3.13	0.12	3.99	3.85	3.62	3.74	0.16	4.35	19.6	16.75	18.18	2.02	11.09	11.75	10.75	11.25	0.71	6.29	16.45	16.6	16.53	0.11	0.64
Rb	6.1	6.1	6.2	5.5	5.98	0.32	5.36	23.7	22	22.85	1.20	5.26	130	143.5	136.75	9.55	6.98	80.4	69.4	74.90	7.78	10.38	104	102.5	103.25	1.06	1.03
Sm	4.02	4.02	3.87	3.8	3.93	0.11	2.82	3.03	2.98	3.01	0.04	1.18	14.1	11.75	12.93	1.66	12.86	8.23	7.76	8.00	0.33	4.16	12.7	12.85	12.78	0.11	0.83
Sn	2	2	2	2	2.00	0.00	0.00	2	2	2.00	0.00	0.00	4	4	4.00	0.00	0.00	4	4	4.00	0.00	0.00	7	7	7.00	0.00	0.00
Sr	497	497	505	478	494.25	11.47	2.32	789	743	766.00	32.53	4.25	69.7	88	78.85	12.94	16.41	37	39.9	38.45	2.05	5.33	200	199	199.50	0.71	0.35
Ta	0.6	0.6	0.5	0.5	0.55	0.06	10.50	0.3	0.2	0.25	0.07	28.28	2	2.1	2.05	0.07	3.45	1.6	1.9	1.75	0.21	12.12	2.6	2.7	2.65	0.07	2.67
Tb	0.64	0.64	0.63	0.66	0.64	0.01	1.96	0.41	0.43	0.42	0.01	3.37	1.52	1.67	1.60	0.11	6.65	1.47	1.36	1.42	0.08	5.50	2.06	1.97	2.02	0.06	3.16
Th	0.94	0.94	0.94	0.92	0.94	0.01	1.07	2.14	2.14	2.14	0.00	0.00	28.6	23.4	26.00	3.68	14.14	27.1	23.4	25.25	2.62	10.36	22.2	22	22.10	0.14	0.64
Tm	0.26	0.26	0.24	0.27	0.26	0.01	4.89	0.19	0.2	0.20	0.01	3.63	0.59	0.75	0.67	0.11	16.89	0.68	0.68	0.68	0.00	0.00	1.09	0.97	1.03	0.08	8.24
U	0.33	0.33	0.3	0.31	0.32	0.02	4.72	1.12	0.84	0.98	0.20	20.20	3.21	3.59	3.40	0.27	7.90	7.72	5.67	6.70	1.45	21.65	5.8	5.67	5.74	0.09	1.60
V	197	197	204	196	198.50	3.70	1.86	92	90	91.00	1.41	1.55	19	25	22.00	4.24	19.28	16	16	16.00	0.00	0.00	15	14	14.50	0.71	4.88
W	1	1	1	1	1.00	0.00	0.00	bdl	bdl				2	2	2.00	0.00	0.00	2	2	2.00	0.00	0.00	1	1	1.00	0.00	0.00
Y	18.2	18.2	18.2	17.3	17.98	0.45	2.50	13.7	12.8	13.25	0.64	4.80	41.4	50.6	46.00	6.51	14.14	47	46.1	46.55	0.64	1.37	66.4	64.3	65.35	1.48	2.27
Yb	1.6	1.6	1.44	1.48	1.53	0.08	5.39	1.26	1.29	1.28	0.02	1.66	3.72	4.51	4.12	0.56	13.58	4.11	4.09	4.10	0.01	0.34	6.6	6.57	6.59	0.02	0.32
Zr	104	104	105	95	102.00	4.69	4.60	133	119	126.00	9.90	7.86	491	595	543.00	73.54	13.54	244	206	225.00	26.87	11.94	784	775	779.50	6.36	0.82