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Front cover:
DJI Matrice 600 Pro aircraft mounted with a Radiation Solutions Inc. RS-530 gamma-ray spectrometer, transiting to survey area at a height of approximately 15 m above ground level. **Photo by Katya Zaborniak.**

Back cover:
Soil pit geochemical sampling site (survey 3); upper 30 cm of the soil profile is B-horizon. Pick for scale (65 cm). **Photo by Easton Elia**.

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Abstract
Although radiometric data are commonly used to aid bedrock mapping and prospecting, the radiometric signature of subglacial tills in extensively drift-covered areas such as the Interior Plateau is not commonly considered. To assess if potassium concentrations in surficial sediments can be measured reliably using a remotely piloted aircraft system (RPAS), we collected radiometric data above low-radioactivity subglacial tills (≤2.00% potassium) near porphyry deposits at the Mount Polley mine, Woodjam developed prospect, and Guichon Creek batholith areas. Using a low-volume crystal (0.35 L) designed for an RPAS-borne gamma-ray spectrometer, potassium data measured from near the Mount Polley mine compare well to in-situ potassium determinations by a handheld gamma-ray spectrometer (120 s count time) and lithium fusion ICP-ES determinations on samples of the same subglacial tills. In addition, our high-resolution RPAS potassium data (2.5-3.33 m cell) are in general agreement with overlapping regional fixed-wing data (100 m cell). RPAS radiometrics fill a scale gap between traditional airborne and ground surveys, can be collected efficiently and affordably, and can be processed in the field to guide geological surveys in near real-time. For high-quality data to be collected over low-radioactivity materials, the instrument must be flown slowly (1 m/s) and close to the ground (≤10 m above ground level). This limitation restricts surveys of low-radioactivity materials in the Interior Plateau to recent cutblocks, which hampers utility of the method. Nonetheless, extended to uranium and thorium, the method could prove useful over higher radioactivity materials where flying height could be increased, or in regions lacking significant vegetation such as deserts or above tree line in alpine or arctic settings.

Keywords: remotely piloted aircraft system, RPAS, drone, gamma-ray spectrometry, radiometrics, potassium, K_2O, subglacial till, drift prospecting, Mount Polley mine

1. Introduction

New discoveries in central British Columbia's drift-covered Interior Plateau will rely on geophysics and geochemistry to identify mineralized bedrock subcrop (Plouffe et al., 2016). Recent work on the use of surface sediments in mineral exploration has focussed on drainage geochemistry, mineral concentrates, and mineral chemistry (Ferbey et al., 2017; Mao et al., 2017; Rukhlov et al., 2020, 2024; Lee et al., 2021; Plouffe et al., 2024). Soil- and air-gas surveys are also being investigated (Lett et al., 2020; Rukhlov et al., 2021, 2022). Gamma-ray spectrometric surveys provide measured values of potassium, uranium, and thorium, which are used in modern bedrock mapping programs and prospecting to discern rocks and hydrothermal alteration related to critical mineral systems like porphyry Cu±Mo±Au, magmatic Ni±Cu±Co±PGE, and carbonatite- or related rock-hosted Ta-Nb-REE (Shives, et al., 2004; Shives, 2005, 2015; Logan and Mihalynuk, 2005a; Simandl and Paradis, 2018; Ootes et al., 2019). In British Columbia, regional-scale, potassium concentrations can be used to differentiate between arc-derived mafic rocks (Paleozoic to early Mesozoic), plateau basalts (late Cenozoic), and the intermediate to felsic intrusions (Mesozoic to Cenozoic) that are responsible for emplacement of these mineral systems. However, the use of geophysical techniques on surface sediments remains under-investigated.

Recent advancements in remotely piloted aircraft systems (RPAS), and the miniaturization of external sensors, have made collecting geological and geophysical data more accessible. Now, potassium, uranium, and thorium radiometric data can be affordably acquired at a higher spatial resolution than traditional fixed-wing and helicopter-mounted sensors. These data can be collected more efficiently than direct till sampling, and can extend across large areas more efficiently than ground-based methods, thereby filling a scale and resolution gap. The data can also be processed in the field and visualized in near-real time to guide geologic mapping or mineral exploration programs.

In 2019, the British Columbia Geological Survey started a program to assess applying RPAS to surficial geology mapping and drift prospecting programs. The project began with a small, consumer quadcopter RPAS with a fixed RGB camera to assist with surficial geology mapping in north-central British Columbia (Elia and Ferbey, 2020) and evolved to using a larger RPAS hexacopter with external geophysical payloads to evaluate the ability of RPAS-borne sensors to map and characterize the composition of surficial sediments in the Interior Plateau (Elia et al., 2023, 2024). From 2021 to 2022, 53 autopilot air photo, lidar, magnetic, and radiometric surveys were flown at 13 sites over subglacial tills derived from contrasting rock types (Fig. 1), the full results of which are in Elia et al. (2023). In the present study, we focus on three of these sites near the Mount Polley mine (Fig. 1) to assess the application of RPAS radiometric surveys for drift prospecting. We evaluate the ability of an RPAS-borne gamma-ray spectrometer to quantify the potassium composition of low-radioactivity subglacial tills by comparing our data to major oxide geochemistry analyses of bedrock and till samples, handheld spectrometer measurements, and traditional regional airborne radiometric data.

2. Geologic setting

We conducted RPAS surveys in the Interior Plateau, a region of central British Columbia where glacial sediments are areally extensive and bedrock outcrop is isolated and discontinuous (Holland, 1976; Fig. 1). This region is underlain by Quesnel terrane and Stikine terrane rocks (e.g., Nelson et al., 2013) that host numerous producing and past-producing porphyry mines and has potential for the discovery of other mineral systems. Subglacial tills derived from diverse rock types with contrasting potassium values were the focus of our surveys, which were completed in the Mount Polley mine (alkalic Au-Cu porphyry), Woodjam developed prospect (alkalic to calc-alkaline Cu-Au-Mo porphyry), and Guichon Creek batholith (Highland Valley calc-alkaline Cu-Mo porphyry mine and other occurrences) areas (Elia et al., 2023). Herein we focus on potassium radiometric data collected near the Mount Polley mine.

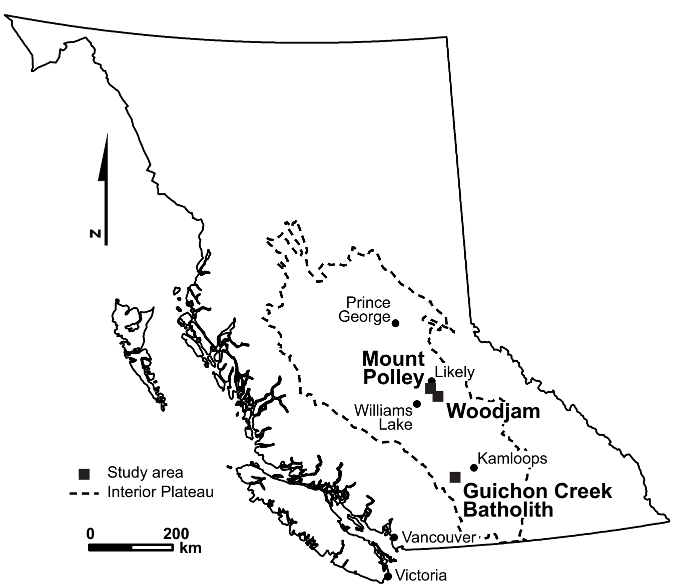

Fig. 1. RPAS radiometric surveys were flown in the Mount Polley, Woodjam, and Guichon Creek batholith areas.

2.1 Bedrock geology

The oldest rocks underlying the Mount Polley mine area include mainly Triassic mafic volcano-sedimentary strata of the Nicola Group (Fig. 2; Panteleyev et al., 1996; Logan et al., 2007; Schiarizza, 2016). Intruding into these rocks are syenites, monzonites, and hydrothermal breccias of the Mount Polley Intrusive complex (Late Triassic to Early Jurassic; Logan et al. 2007), a stock (4 by 6 km in plan) that hosts alkalic porphyry Cu-Au mineralization. To the south is the Bootjack stock (Late Triassic), a zoned intrusion of strongly undersaturated nepheline syenites. Magmatic differentiation of this stock and early potassic alteration in the Mount Polley Intrusive complex may be linked, but the stock is largely barren of mineralization and was therefore considered by Logan and Bath (2006) as a separate intrusion. Younger cover rocks include Lower-Middle Jurassic conglomerates and sandstones of the Ashcroft Formation and Eocene basalt flows and breccias of the Kamloops Group.

Mineralization at the Mount Polley mine has been described by Hodgson et al. (1976), Fraser et al. (1995), Logan and Mihalynuk (2005b), Rees (2013), and Pass et al. (2014). The central core of the deposit consists of low- to moderate-grade mineralization (chalcopyrite±bornite) disseminated in hydrothermal breccias or brecciated intrusive rocks. Most mine production has come from this central core (Cariboo, Springer and Bell pits), but higher grade mineralization (chalcopyrite±bornite) occurs in magmatic-hydrothermal breccias and immediate wall rocks at the northern periphery of the intrusive complex (Northeast and Boundary zones). Breccia clasts at the Boundary zone are potassic-altered monzonite to monzodiorite cemented by magnetite. Moderate to intense potassic and calc-potassic alteration is common in the intrusive complex core. In combination with primary rock types that are alkali-feldspar rich, this alteration produces a strong potassium signature in radiometric data; nepheline syenites of the Bootjack stock also contribute significantly to the regional signature (Fig. 3).

2.2. Quaternary geology

The Interior Plateau was covered by the Cordilleran ice sheet during the Late Wisconsinan Fraser Glaciation (Clague and Ward, 2011), and subglacial tills are the predominant surficial material in the area (Fig. 4; Bichler and Bobrowsky, 2003; Hashmi et al., 2015a). These tills are moderately consolidated to overconsolidated, commonly contain pebble to cobble clasts, and have a sandy-silt matrix (Hashmi et al., 2015b; Plouffe and Ferbey, 2016). At higher elevations, these thick (>2 m), locally streamlined tills transition to thinner veneers that include small areas of discontinuous bedrock outcrop. Modern rivers are typically confined by unstable valley sides with thick colluvial deposits and alluvial fans. Late Wisconsinan glaciofluvial sands and gravels are sparse in these valleys but are more common on the plateau surface as terrace, esker, and kame deposits (Bichler and Bobrowsky, 2003; Hashmi et al., 2015a).

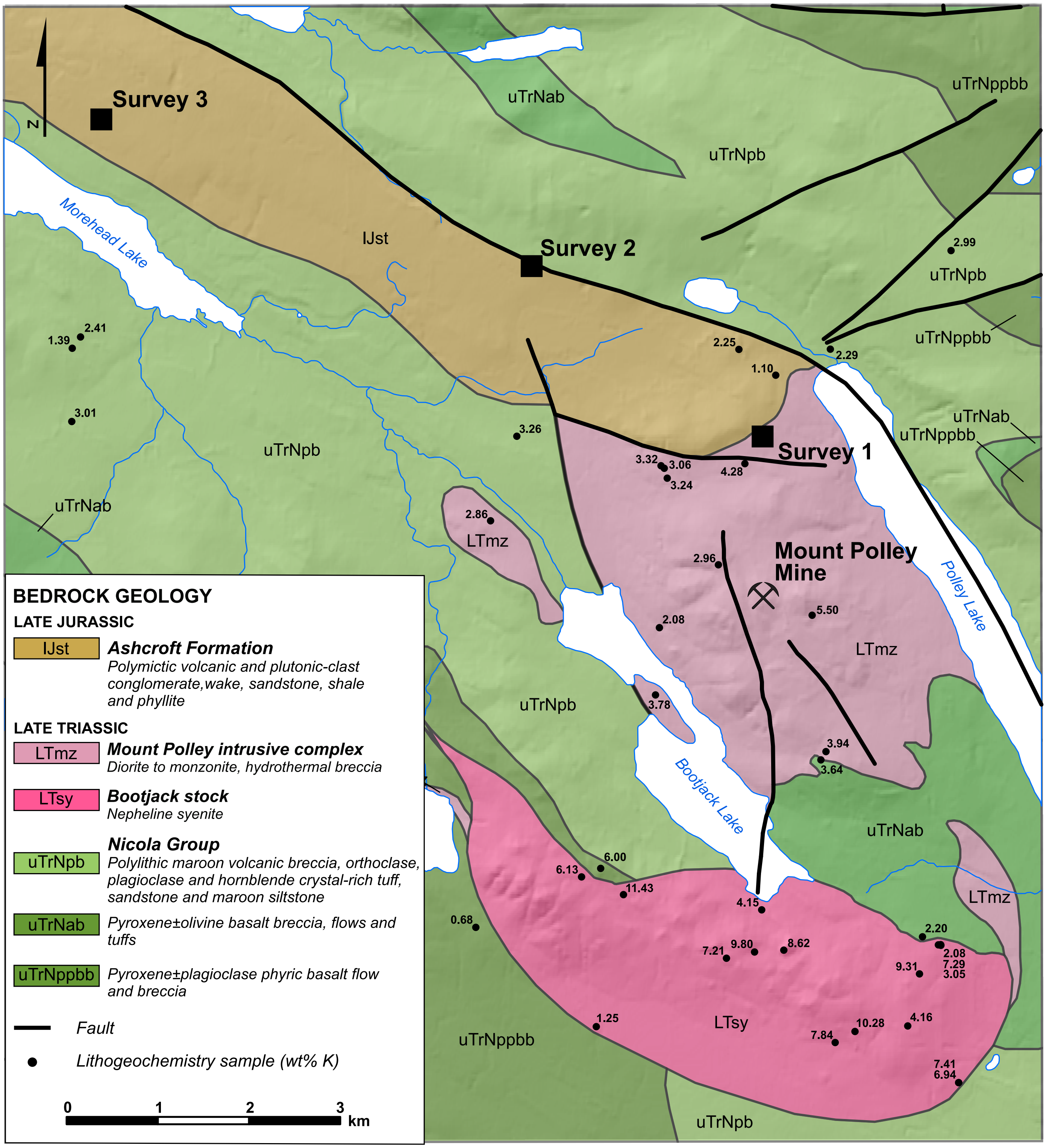

Fig. 2. Bedrock geology of Mount Polley mine area (after Logan et al., 2010). Regional lithogeochemistry samples from Han and Rukhlov (2020).

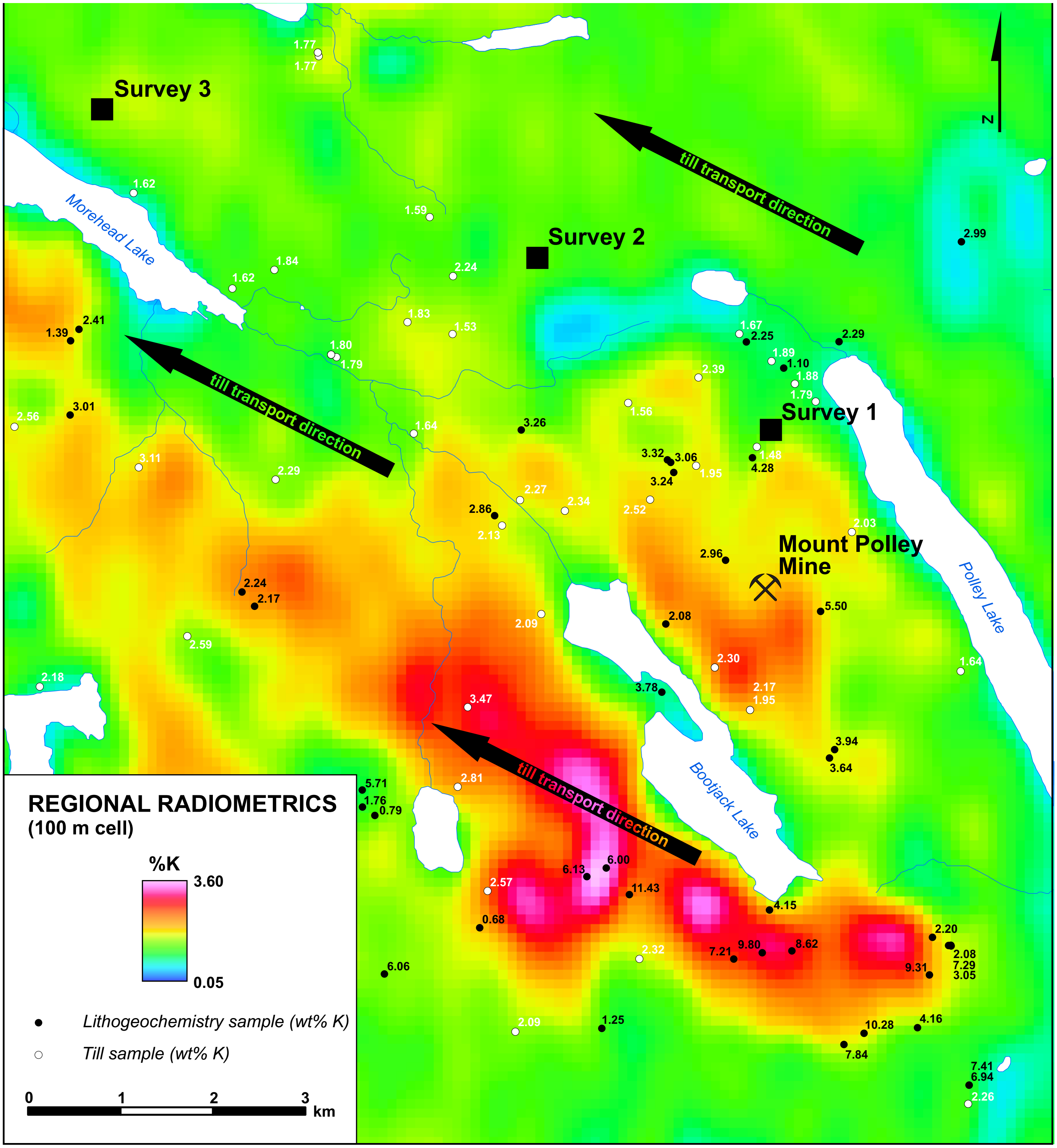

Fig. 3. Regional potassium airborne radiometrics for Mount Polley mine area (Shives et al., 1995). Potassium concentrations for regional till samples (Plouffe and Ferbey, 2016) and lithogeochemistry samples (Han and Rukhlov, 2020) represent local geochemical sample points within the broader surface measured by the gamma-ray spectrometer.

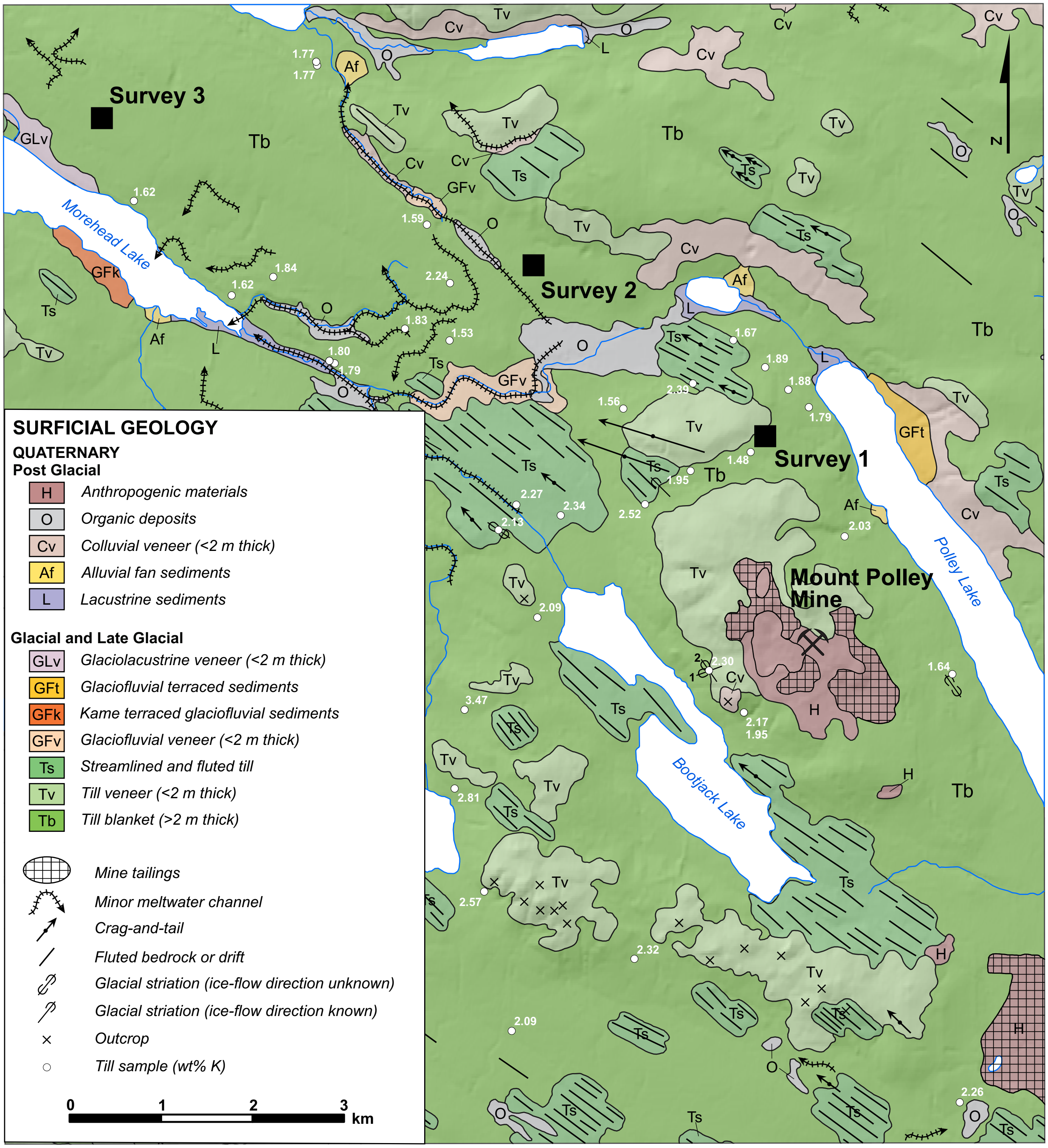

Fig. 4. Surficial geology of Mount Polley mine area (after Hashmi et al., 2015a). Regional till samples from Plouffe and Ferbey (2016).

Late Wisconsinan ice flow in the area was initially to the west to southwest and was followed by later north to northwest movement (Fig. 4), which resulted in a net till transport direction to the northwest (Plouffe and Ferbey, 2016). The superimposed flow directions are recognized in landform-scale features such as drumlins, flutes, and crag-and-tail ridges (Bichler and Bobrowsky, 2003; Hashmi et al., 2015a) and in outcrop-scale features such as striations and rat tails where crosscutting relationships enable the relative timing to be established (Hashmi et al., 2015a, b; Plouffe and Ferbey, 2016).

3. Soil profiles, drift prospecting, and gamma-ray spectrometry

3.1. Soil profiles

Understanding soil type is fundamental to interpreting surface sediment geochemical data. Soil formation, including thickness and the development of specific horizons, is dictated by climate, parent material, topography, flora, fauna, and time (Ashman and Puri, 2002). Soils are classified based on observable and measurable properties that reflect processes of soil genesis and local environmental conditions (Soil Classification Working Group, 1998). Each soil type can be subdivided into non-mineral (>30% organic matter by weight; O and LFH, Fig. 5) and mineral horizons (≤30% organic matter by weight; A, B, C, and R, Fig. 5). Material in the C-horizon may have been moved to its current location by wind, gravity, water, or glacial ice. Called a transported soil, this C-horizon may be unrelated to the bedrock it directly overlies, which is in contrast to a residual C-horizon soil developed directly from and on local bedrock. The C-horizon is the focus of surficial geology mapping and sampling for till geochemistry and mineralogy surveys and is the parent material for the overlying B- and A-horizons. Vertical and horizontal changes in soil texture and chemistry can result from groundwater movement in the A-horizon (eluviation) and the B-horizon (illuviation). The litter-fermentation-humic (LFH) horizon is the surface accumulation of organic material, which becomes increasingly decomposed with depth and can retain water.

Lett (2010) concluded that C-horizon geochemical anomalies are generally replicated in overlying B-horizon soils, but with a lower magnitude, and Cook and Dunn (2007) suggested that B-horizon soil geochemistry is ideally suited for large-scale surveys because this horizon is widely available for collection and can detect buried bedrock sources. For geochemical results to be correctly interpreted, field observations are required to establish the extent to which the soils formed from subjacent bedrock, versus another material type.

3.2. Drift prospecting

Drift prospecting uses the composition of C-horizon glacial sediments to infer bedrock source lithology (Levson, 2001). Till geochemistry and mineralogy surveys are a specific type of drift prospecting that focus on the matrix composition of subglacial tills. This till facies is the preferred sample medium because it can be a first derivative of bedrock (Shilts, 1993), has a predictable transport history, is deposited down-ice of its bedrock source, and produces a geochemical and mineralogical

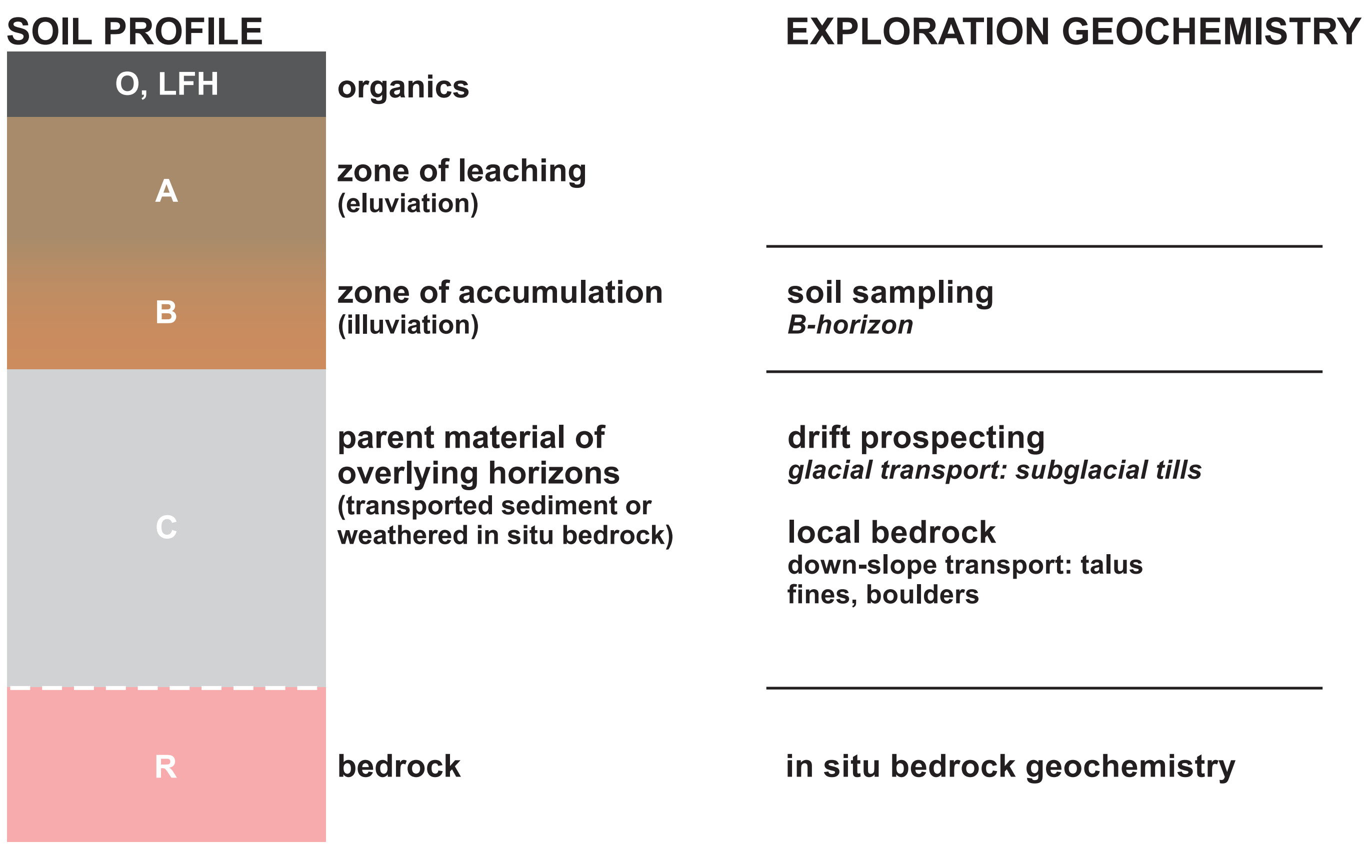

Fig. 5. Generalized soil profile with examples of exploration geochemistry sample media.

signature that is areally more extensive than its bedrock source (Levson, 2001; Fig. 6). The sand (0.063 - 2 mm), silt plus clay (<0.063 mm) and clay (<0.002 mm) size fractions are used for specific purposes, typically to increase the signal-to-noise ratio for specific elements or minerals (McClenaghan et al., 2013).

In various forms, drift prospecting has been used in British Columbia for more than 70 years (Kerr and Levson, 1995; Lett and Rukhlov, 2017; Bustard et al., 2020). Drift prospecting geochemical methods are well-established and recent research has focussed on indicator mineral recovery and chemistry (Bouzari et al., 2010; Hashmi et al., 2015b; Plouffe and Ferbey, 2016; Plouffe et al., 2016; Mao et al., 2017; Pisiak et al., 2017; Lee et al., 2021; Plouffe et al., 2024). Major oxide data (including K_2O) have been used recently in provenance (Makvandi et al., 2019; Rice et al., 2024) and drift prospecting (Shewchuk et al., 2020; Plouffe et al., 2022) studies, but are generally underused.

3.3. Gamma-ray spectrometry (radiometrics)

Gamma-ray spectrometry (or radiometrics) is a geophysical technique that has a geochemical application. Gamma-ray spectrometers measure gamma-ray emissions within specific energy windows, which are used to calculate radioelement concentrations (Telford et al., 1989). The radioelements potassium, uranium, and thorium occur in rock-forming minerals and so their concentrations (% and ppm) can be used to investigate the composition of bedrock and surficial sediments (Table 1; Telford et al., 1989; Ford et al., 2008; Shives et al., 2000). Potassium concentrations are determined directly by measuring the ^{40}K energy window; uranium and thorium concentrations are determined by measuring the daughter products ^{214}Bi (for uranium) and ^{208}Tl (for thorium), which are assumed to be in equilibrium (Fig. 7). Uranium and thorium values determined by gamma-ray spectrometry are therefore equivalent values, and the prefix 'e' is used to indicate this (i.e., eU, eTh).

Gamma-ray spectrometry is considered a surface geophysical technique because measurable gamma-ray emissions originate in the top 30 cm of the Earth's surface. These emissions can be measured on the ground using a handheld instrument or from the air using an aircraft-mounted instrument, earning the name 'airborne geochemistry' (Ford et al., 2008). Potassium concentrations (%) are calculated from gamma-rays being emitted from ^{40}K in solid mineral phases (e.g., potassium feldspar, biotite, muscovite; Ford et al., 2008; Killeen et al., 2015). Surface sediment radiometrics in glaciated terrain typically measure radioelement concentrations in the B-horizon because the C-horizon is commonly deeper than 30 cm below surface.

Radioactive decay is a random process, and gamma-ray counts from a given source will vary over consecutive measurements. The number of gamma-rays counted by a spectrometer depends on the radioactivity of the source, volume of the detector crystal, and measurement duration (Tammenmaa et al., 1976; van der Veeke et al., 2021). Increasing these variables will increase the likelihood of higher counts, as will decreasing the distance between the source and the spectrometer. In counting statistics, one standard deviation is equal to the square root of the measured counts, and so higher counts will result in a lower measurement error. An airborne gamma-ray spectrometer's field of view increases with an increase in distance between the ground source and detector (Killeen et al., 2015). Measurements at higher altitudes above ground therefore sample a larger volume of material. For reference, at 10 m above ground level,

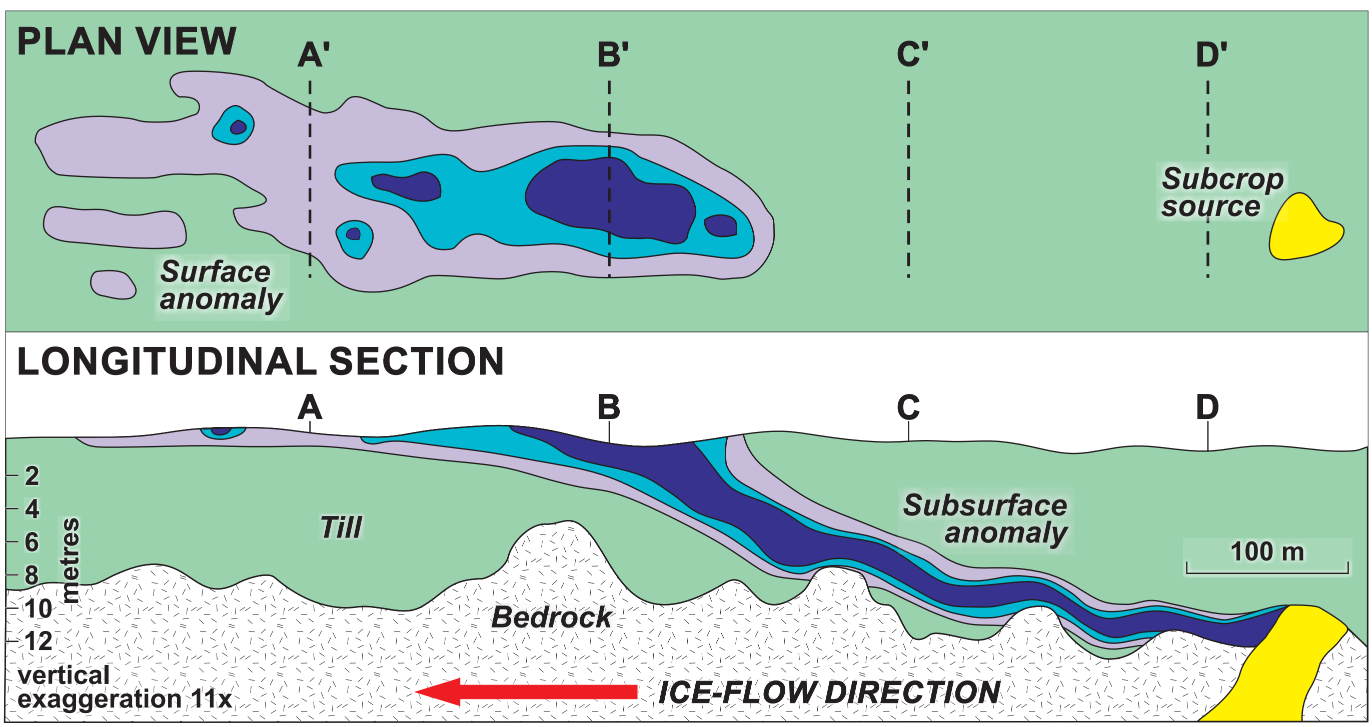

Fig. 6. Dispersal in subglacial till (after Miller, 1984). Dispersal trains are defined by contrast with the highest values (dark blue) at the dispersal train head. Values decrease exponentially in the down-ice direction (purple).

Table 1. Rock types and radioelement concentrations (after Killeen, 1979).

	Potassium (wt%)			Uranium (ppm)			Thorium (ppm)		
Rock Type	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Felsic extrusives	3.1	1	6.2	4.1	0.8	16.4	11.9	1.1	41
Felsic intrusives	3.4	0.1	7.6	4.5	0.1	30	25.7	0.1	253.1
Intermediate extrusives	1.1	1.1	2.5	1.1	0.2	2.6	2.4	0.4	6.4
Intermediate intrusives	2.1	0.1	6.2	3.2	0.1	23.4	12.2	0.4	106
Mafic extrusives	0.7	0.06	2.4	0.8	0.03	3.3	2.2	0.05	8.8
Mafic intrusives	0.8	0.01	2.6	0.8	0.01	5.7	2.3	0.03	15
Ultramafic rocks	0.3	0	0.8	0.3	0	1.6	1.4	0	7.5
Feldspathoidal intermediate extrusives	6.5	2	9	29.7	1.9	62	133.9	9.5	265
Feldspathoidal intermediate intrusives	4.2	1	9.9	55.8	0.3	720	132.6	0.4	880
Feldspathoidal mafic extrusives	1.9	0.2	6.9	2.4	0.5	12	8.2	2.1	60
Feldspathoidal mafic intrusives	1.8	0.3	4.8	2.3	0.4	5.4	8.4	2.8	19.6
Chemogenic sedimentary rocks	0.6	0.02	8.4	3.6	0.03	26.7	14.9	0.03	132
Carbonate rocks	0.3	0.01	3.5	2	0.03	18	1.3	0.03	10.8
Siliciclastic rocks	1.5	0.01	9.7	4.8	0.01	80	12.4	0.2	362
Metamorphosed igneous rocks	2.5	0.1	6.1	4	0.1	148.5	14.8	0.1	104.2
Metamorphosed sedimentary rocks	2.1	0.01	5.3	3	0.1	53.4	12	0.1	91.4

80% of the potassium signal originates from a 20 m radius circle below the aircraft.

Gamma-ray spectrometry is a well-established technique for mapping geological contacts (O'Reilly and Ford, 1988; Shives, et al., 2004; Shives, 2005, 2015; Logan and Mihalynuk, 2005a; Ootes et al., 2019) and differentiating soil types and textures (Dent et al., 2013; van der Veeke et al., 2021; Maino et al., 2022). Along with their fixed-wing and helicopter-borne counterparts, low-altitude RPAS-mounted gamma-ray spectrometers using low-volume crystals have detected radioelement anomalies related to bedrock Cu-Fe prospects (Martin et al., 2015, 2020) and uranium occurrences (Šálek et al., 2018).

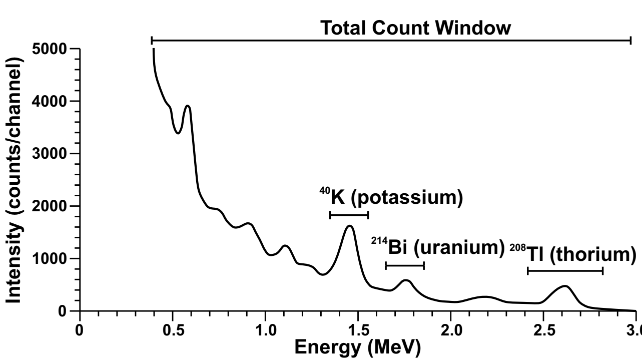

Fig. 7. Gamma-ray spectrum and radioelement energy windows (after Ford et al., 2008).

4. Methods

As described in detail by Elia et al. (2023), we used a DJI Matrice 600 Pro (M600) platform for our RPAS surveys. A Radiation Solutions Inc. (RSI) RS-530 gamma-ray spectrometer was mounted to the M600 to collect radiometric data (Fig. 8). The platform was modified with an SPH Engineering radar altimeter and SkyHub that integrates with the DJI flight control systems and Universal Ground Control Software (UgCS), the flight planning package used to design and fly autopilot surveys. Using the UgCS true terrain following mode, a preset altitude above ground was maintained autonomously in real-time. Maintaining a constant altitude above ground (±50 cm, depending on vegetation cover) is important for collecting radiometric data with a low-volume crystal because it helps ensure that measured variation is related to geology, not changes in distance between the source and detector. Because RPAS-borne gamma-ray spectrometry using a low-volume crystal is untested in surficial geology applications, we compared potassium data collected by the RS-530 against established methods for determining potassium concentrations including geochemical analysis of near-surface samples, ground measurements using a handheld spectrometer, and regional fixed-wing survey data.

Fig. 8. DJI Matrice 600 Pro (M600) RPAS. The RSI RS-530 gamma-ray spectrometer is mounted to underside of M600. An SPH Engineering radar altimeter is mounted to a forward motor boom and communicates through the Skyhub to flight controls to maintain a constant altitude above ground during autopilot surveys.

4.1. Survey design

The primary criterion used to select survey areas was that they be underlain by subglacial till. These areas were initially identified using existing surficial geology maps (Bichler and Bobrowsky, 2003; Hashmi et al., 2015a; Ferbey et al., 2016; Plouffe and Ferbey, 2018) and were confirmed in the field by assessing local exposures or digging soil pits. We also selected survey areas that had existing geological, geochemical, or geophysical datasets, which we used for survey design and to assess instrument performance. All surveys were flown in recent forestry cutblocks. This was necessitated by Transport Canada's requirement to always keep the RPAS and payload within visual line of sight and so that terrain-following surveys could be safely completed 5 to 10 m above ground level.

We conducted our hover survey at the Mount Polley mine property over a surface exposure of the Boundary zone (survey 1, Fig. 2), and two gridded surveys down-ice of the mine (over subglacial tills (surveys 2 and 3, Fig. 4). The RS-530 was flown 7.5 to 10 m above ground level, at 2 m/s, along traverse lines spaced 7.5 to 10 m apart, at a sampling rate of 1 Hz (Table 2). Obstructions within cutblocks like habitat trees, snags, wood waste piles, and early regrowth dictated how close to ground the instrument could be flown and the areal extent of the survey in the cutblock. These survey parameters contrast with those used in regional surveys with large-volume spectrometers and fixed-wing aircraft that acquire data at 125 m above ground level, at 53 m/s, along traverse lines spaced 500 m apart (Table 2; Shives et al., 1995).

The Boundary zone survey was conducted to better understand signal attenuation as a function of flying height, and to produce a potassium height correction factor. Measurements were taken at 0, 5, 10, and 15 m above ground level. Stated hover measurements are a mean value for a 120 s time window. Acquisition of all RPAS-borne and ground radiometric data began after 10:00 am local time, or 12 hours after a ground-soaking rain.

4.2. RPAS gamma-ray spectrometer

The Radiation Solutions Inc. (RSI) RS-530 gamma-ray spectrometer is a 3 kg, multi-channel sensor that uses a single 3" x 3" (0.35 l), thallium-doped, sodium iodide crystal scintillator, housed in a vertical carbon fibre tube (Fig. 8). It operates independently of the M600 (other than sharing power) and internally records gamma-ray spectrometric data as well as x, y, and z positions for each reading using its own global navigation satellite system antenna. The RS-530 integrates with RSI's propriety software, RadAssist, to visualize data in real-time during collection. RadAssist is also used to apply stripping

Table 2. Gamma-ray spectrometers and survey parameters. The RSI RS-530 and RSI RS-230 BGO Super-SPEC were used for this study. Shives et al. (1995) used a custom sensor for a regional survey including Mount Polley.

Sensor	**RSI RS-530**	**RSI RS-230 BGO Super-SPEC**	**Custom Sensor** (Shives et al. (1995)
Platform	DJI Matrice 600 Pro	Handheld	Skyvan
Sensor type	3” x 3” NaI (Tl) crystal (0.35 L)	2” x 2” BGO crystal (0.1 L)	12 - 16" x 4" x 4" NaI (Tl) crystals (50 L)
Weight	3 kg	2.6 kg	360 kg
Collection height	7.5 to 10 m above ground	0 m	125 m above ground
Line spacing	7.5 to 10 m	N/A	500 m
Collection speed	2 m/s	stationary	53 m/s
Sample rate	1 Hz	one measurement per 120 s	1 Hz
Spatial resolution	2.5 to 3.33 m	point	100 m

ratios, noise-adjusted singular value decomposition (NASVD), and height corrections after the completion of a survey. Oasis Montaj was used for final gridding and visualization.

4.3. Data processing

RS-530 data were downloaded, corrected, and processed using RadAssist. Stripping ratios, sensitivities, and height correction coefficients are specific to each instrument; these were supplied by RSI and applied in RadAssist. We used RSI’s height correction coefficients for uranium and thorium but produced our own for potassium (see survey 1). A cosmic or aircraft correction was not applied to these RPAS-borne radiometric data, as is done for traditional fixed-wing and helicopter-borne data. The instrument is directly exposed to the terrestrial signal, with no interference from the aircraft, and at a very low terrain clearance the cosmic signal becomes insignificant relative to terrestrial sources. Ground radiometric data were corrected in the handheld RS-230 instrument at the time of collection and so the displayed values are the final values.

NASVD has been widely used in airborne gamma spectrometry. It determines all statistically significant spectra for an entire gamma-ray dataset and then reconstructs the original dataset with a higher signal-to-noise ratio (Hovgaard and Grasty, 1997; Minty and Hovgaard, 2002). The technique uses up to 1024 channels of data from the entire survey dataset to identify all statistically significant spectral shapes, which are then used to reconstruct new potassium, uranium, and thorium windows. Because the procedure makes use of all the counts in the spectrum as well as the correlation between potassium, uranium and thorium, the reduction in statistical noise is significantly greater than for multi-channel spectral fitting, and resultant maps are likely to show more geological information than those produced by the standard three-window method.

NASVD processing is effective for data collected by small-volume RPAS instruments, which are inherently noisy. The resultant reduction in noise is equivalent to increasing the instrument’s detector volume by 3 or 4 times (Hovgaard and Grasty, 1997). Stripping ratios (to remove Compton scattering, or energy loss due to gamma-ray photon colliding with an electron), sensitivities (to convert gamma-ray counts to concentrations), and height correction coefficients (to convert air concentrations to ground concentrations, considering attenuation due to air) are then applied to the NASVD-filtered data. NASVD was applied in RadAssist to the RPAS-borne gamma-ray spectra. A subjective analysis of up to nine components was first completed in Excel. Typically, the first five to six components were used because they best represented the raw spectral data; rejected components typically showed high-frequency, high-magnitude, variability, which we considered noise.

Data were exported from RadAssist and then imported into ArcGIS where they were spatially edited to eliminate measurements collected while the spectrometer was transiting to and from the survey area, and when it was outside the survey area turning between flight lines. These edited data were then imported into Oasis Montaj for gridding using the minimum curvature function at one-third of flight line spacing, resulting in a 2.5 m cell size for 7.5 m line spaced data and 3.33 m cell size for 10 m line spaced data. Higher resolution grids could be produced by flying tighter traverse lines, but more traverse lines would have resulted in longer flight times and more battery changes.

The minimum curvature function also allows for the application of a low-pass desampling factor. We applied a factor of 2 to some datasets that still appeared noisy after NASVD (i.e., a large difference in potassium values between neighbouring data points), to simplify and smooth the resultant grids. The inverse distance weighting function was used in some instances when the minimum curvature function produced grids that extended beyond the bounds of the survey area.

4.4. Geochemistry of near-surface samples

Surface sediment samples weighing 1 to 2 kg were collected from hand-dug soil pits and road cuts approximately 1 m deep following protocols outlined by Spirito et al. (2011) and McClenaghan et al. (2013). One sample was collected from the C-horizon at the bottom of each pit, equivalent to a typical till sample collected as part of a regional till survey. A second sample was collected approximately 20 to 30 cm below surface from the B-horizon. Samples were sent to Bureau Veritas (Vancouver, BC) for processing and analysis. They were first dry sieved and a 5 g aliquot of the silt-plus clay sized fraction (<0.063 mm) was digested with lithium metaborate/tetraborate, fused at 980°C, dissolved in 5% HNO_3, and then analyzed by inductively coupled plasma emission spectrometry (ICP-ES). Bedrock samples from surface exposures were also sent to Bureau Veritas (Vancouver, BC) for processing and analysis.

The samples were crushed to ≥70% passing 2 mm, then 1 kg was pulverized to ≥85% passing 0.075 mm. A 5 g aliquot was analyzed using the same lithium fusion ICP-ES method as the till samples.

Quality control measures for this small geochemical dataset indicate that the K_2O data are suitable for geologic interpretation because the difference in K_2O for the analytical duplicates is only 0.9% and cross contamination in the blank sample determination is not indicated. A relative difference of 1.54 %, between the K_2O value from the certified standard and our determination for it, indicates these determinations are accurate (see Piercy, 2014). K_2O determinations were converted to potassium using a factor of 0.83, so that they could be compared to potassium concentrations measured by the RPAS gamma-ray spectrometer**.** Till data from Plouffe and Ferbey (2016), and bedrock data from Han and Ruhklov (2020), are also included in our comparison for regional context (Figs. 2-4).

4.5. Handheld spectrometer measurements

A Radiation Solutions Inc. RS-230 BGO Super-SPEC handheld gamma-ray spectrometer (Fig. 9a) was used to collect ground radiometric measurements (Table 2). This instrument is equipped with a single 2” by 2” bismuth germanate oxide crystal and was calibrated at Radiation Solutions Inc. before data collection. Each measurement of K, eU, and eTh is a mean of values collected during a 120 s time window while the instrument rested stationary on the ground surface (Fig. 9b). A longer time window enables higher total counts, which reduces measurement error, resulting in more accurate and precise data (Killeen et al., 2015). At surveys 2 and 3 (Fig. 4), 50 cm soil pits were dug after data collection and observations were made on the soil horizons present, thickness of organic materials at surface, and water content (Fig. 9b).

4.6. Existing regional radiometric data data

The Mount Polley mine area is included in a fixed-wing radiometric survey completed by Shives et al. (1995; Table 2). Based on elevated potassium concentrations alone, the Mount Polley intrusive complex and Bootjack stock can be clearly identified in this regional dataset (Fig. 3). Bichler and Bobrowsky (2003) and Hashmi et al. (2015a) showed that tills are the predominant surficial material near and down-ice of these intrusive rocks (Fig. 4) and so the above-background potassium values that decrease towards the northwest (i.e., down-ice direction) from the Mount Polley intrusive complex and Bootjack stock represent potassium dispersal in subglacial tills.

5. Results

Elia et al. (2023) provided raw and processed radiometrics data for each of the 13 survey areas collected as part of this program. Presented here are potassium RPAS radiometric results from a hover survey conducted on the Mount Polley mine property over a surface exposure of the Boundary zone (survey 1, Fig. 2), and two gridded surveys that were completed down-ice of the Mount Polley mine (surveys 2 and 3, Fig. 4), over subglacial tills. Summary statistics for RPAS potassium values, along with geophysical and geochemical results used to assess RPAS instrument accuracy, are presented in Table 3. The subglacial tills in surveys 2 and 3 are off-trend of northwest dispersal from potassium-rich rocks of the Mount Polley Intrusive complex and Bootjack stock (Figs. 2-4).

Fig. 9. a) RSI RS-230 BGO Super-SPEC (RS-230) handheld gamma-ray spectrometer used to collect ground radiometric data. **b)** Typical 50 cm deep soil pit dug to observe the soil profile measured by the RS-230.

5.1. Survey 1

A hover survey was completed over an isolated and glacially polished surface exposure of the Boundary zone, 1 m by 3 m (Fig. 10a). The exposure is in a till veneer (<2 m thick) which thickens to a till blanket (>2 m thick) towards the south and east. At 0 m, the measured potassium concentration was 3.33%. This is lower than the mean handheld spectrometer value for the same site (4.83% potassium) and a hand sample of the bedrock exposure analyzed by lithium fusion ICP-ES (4.47% potassium). From here, potassium values decrease with an increase in height above ground level (5 m = 2.82%, 10 m = 2.44%, and 15 m = 2.37%; Fig. 10b).

We can estimate the potassium attenuation rate as the volume of air between the sensor and the ground increases by fitting an exponential curve to these data (Fig. 10b). This potassium attenuation coefficient (0.035) was applied to all RPAS potassium data collected in the Mount Polley mine area

Table 3. Potassium values determined by different methods for surveys 1, 2, and 3.

		Potassium (%)				
	n=	Min	Max	Std. Dev.	Mean	Value
Survey 1						
bedrock sample	1					4.47
ground radiometrics	3	4.20	5.60	0.71	4.83	
gridded regional radiometrics (Shives et al., 1995)	1					1.24
RPAS radiometrics (10 m AGL) in hover	120	2.13	4.75	0.53	3.41	
Survey 2						
B-horizon sample	1					1.88
C-horizon sample	1					1.77
ground radiometrics	4	0.30	1.00	0.26	0.73	
gridded regional radiometrics (Shives et al., 1995)	3	1.23	1.27	0.02	1.25	
gridded RPAS radiometrics (7.5 m AGL)	215	0.67	1.07	0.09	0.89	
Survey 3						
B-horizon sample	1					2.00
C-horizon sample	1					1.85
ground radiometrics	7	1.40	2.50	0.50	1.89	
gridded regional radiometrics (Shives et al., 1995)	4	1.42	1.46	0.02	1.44	
gridded RPAS radiometrics (10 m AGL)	860	1.65	2.08	0.06	1.89	

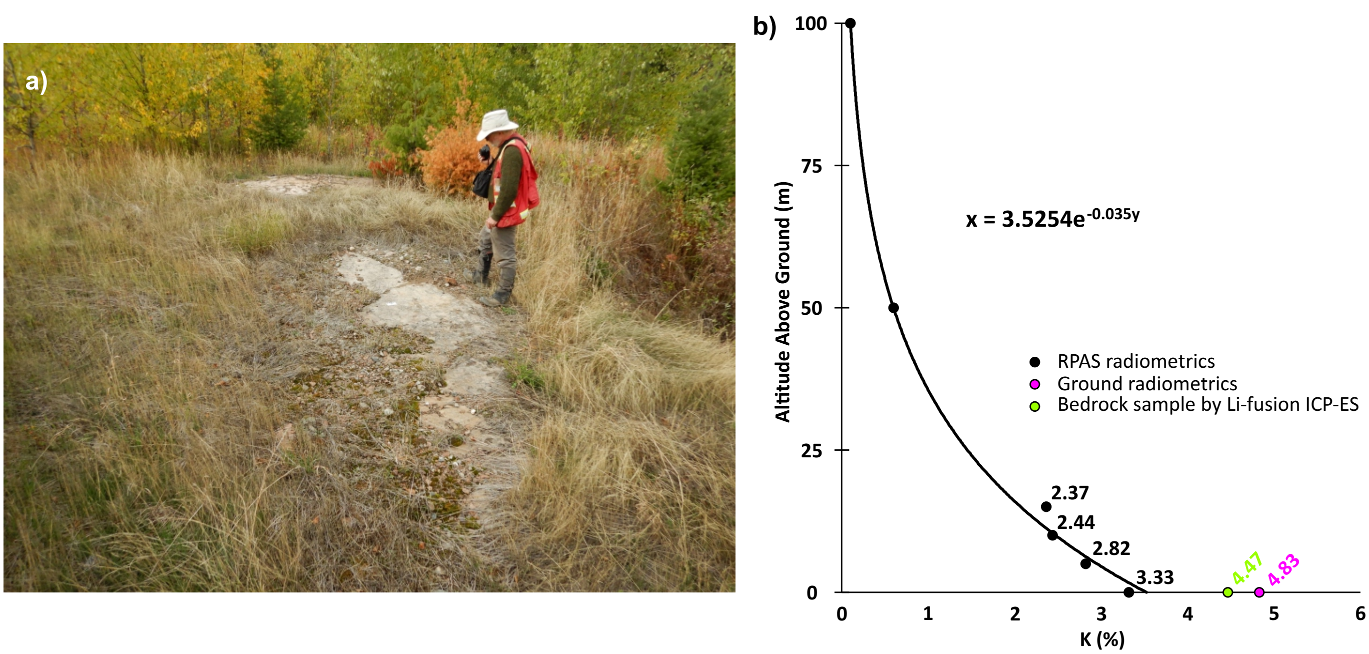

Fig. 10. Survey 1 over surface exposure of magnetite-cemented, potassium-altered, monzodiorite to monzonite crackle breccia, Mount Polley mine, Boundary zone. **a)** RPAS radiometric data were collected over the main part of this outcrop (foreground). Ground radiometric measurements were collected on the same surface and a representative sample of the exposure was collected for a lithium-fusion ICP-ES determination. **b)** RPAS radiometric hover survey data. Attenuation by air, as a function of height over bedrock outcrop, is expressed in equation coefficient. Ground radiometric and analytical results shown for comparison.

to convert RPAS (or air) potassium concentrations to ground concentrations. At 10 m above ground level, a typical flying height for a gridded RPAS radiometric survey, the height-corrected potassium value for Boundary zone is 3.41% potassium. This value is close to the RPAS value measured at 0 m (3.325% potassium), is lower than both the mean ground handheld spectrometer (4.83% potassium) and the lithium fusion ICP-ES (4.47% potassium) values for the same exposure, but higher than that measured in the higher altitude, lower spatial resolution, regional-scale radiometrics survey (1.24% potassium).

This 3 m^2 surface exposure of Boundary zone falls within a single 100 m cell (10,000 m^2) of the regional radiometric dataset. These regional data were collected at 125 m above ground level with a larger instrument field of view, and so the measured potassium value (1.24%) is biased towards the more extensive and lower radioactivity subglacial till surrounding the surface exposure.

5.2. Survey 2

Survey 2 was conducted 3 km northwest (down-ice) of the Boundary zone in a recent cutblock underlain by subglacial till (Figs. 4, 11). Bedrock is not exposed within or adjacent to the survey area, but potassium-rich phases of the Mount Polley Intrusive complex and conglomerates and sandstones of the Ashcroft Formation are mapped immediately up-ice (Fig. 2). The survey area is approximately 25 m by 60 m and the processed grid consists of 215 cells, each 2.5 m. Potassium values in the grid range from 0.67 to 1.07%, with a mean of 0.89% and a standard deviation of 0.09% (Table 3). There is spatial variability in the gridded data across a small range of values, but potassium concentrations do not define coherent spatial trends such as a dispersal train. A low standard deviation indicates minimal variability in the measured data, suggesting that potassium concentrations in subglacial tills here are relatively homogenous. The RPAS survey area falls within three cells (100 m cell size) of the regional radiometric dataset. Potassium values in these 3 cells range from 1.23 to 1.27% and have a mean of 1.25%.

Ground handheld spectrometer measurements were collected at four sites (Fig. 11). These values range from 0.30 to 1.0%, with a mean of 0.73%. At sites 22EEL0010 and 22EEL0011 there is little difference between ground measurements and the RPAS cell they fall in (up to 15%; Table 3), but at 22EEL0009 and 22EEL0012 this difference is greater (up to 112%; Table 3). We attribute the large difference at 22EEL0012 to the ground spectrometer being placed on top of a slash pile, as would be measured by the RPAS spectrometer, rather than

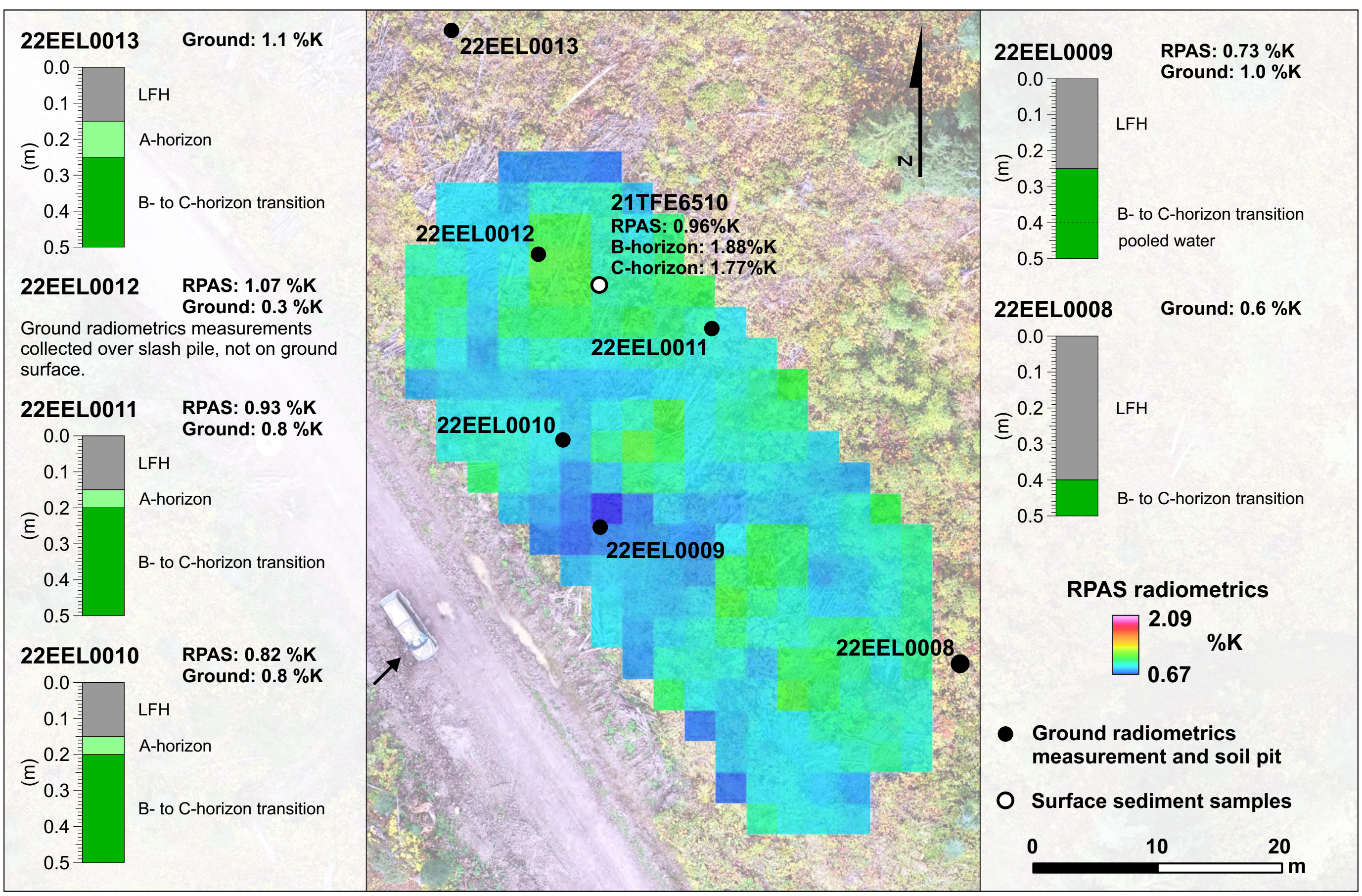

Fig. 11. Survey 2 over subglacial till. RPAS radiometric potassium data are gridded at 2.5 m cell size. Ground radiometric potassium, and B- and C-horizon potassium by lithium fusion ICP-ES are provided for comparison. Soil pits depict lithic and non-lithic soil components for top 50 cm of soil profile. Pick-up truck for scale (black arrow).

the ground surface. The top of the C-horizon is >30 cm below surface at 22EEL0010 and 22EEL0011, and >50 cm below surface at 22EEL0009. Water pooled in the bottom of soil pits at 22EEL0009 and 22EEL0010 (Fig. 11).

At 21TFE6510, a C-horizon sample was collected 90 cm below surface and returned a value of 1.77% potassium (Figs. 11, 12a). The overlying B-horizon sample was collected 20 cm below surface and returned a value of 1.88% potassium. Over this site, the gridded cell value in RPAS radiometrics potassium is 0.96% (Table 3).

5.3. Survey 3

Survey 3 was conducted 7 km northwest (down-ice) of Boundary zone in a recent cutblock underlain by subglacial till (Figs. 4, 13). As with survey 2, bedrock is not exposed. We consider this till is mostly derived from Ashcroft Formation conglomerates and sandstones but that potassium-rich phases of the Mount Polley Intrusive complex (Fig. 2) may contribute to the till geochemistry here. The RPAS survey area is approximately 105 m by 105 m and the processed grid consists of 860 cells, each 3.33 m. Potassium values in the grid range from 1.65 to 2.08%, with a mean of 1.89% and standard deviation of 0.06% (Table 3). As with survey 2, spatial variability in the gridded data is random and they do not define coherent spatial trends or down-ice dispersal. Potassium concentrations in subglacial tills here also appear to be relatively homogenous given the low standard deviation for the gridded dataset. The RPAS survey area falls within four cells (100 m cell size) of the regional radiometric dataset, with values that range from 1.42 to 1.46% and have a mean of 1.44%.

Ground handheld spectrometer measurements were collected at seven sites in the RPAS survey area. These values range from 1.40 to 2.50% potassium, with a mean of 1.89% potassium. This mean value is very close to the mean for the larger gridded RPAS potassium dataset, but the range is larger. Ground and RPAS radiometrics potassium values for the same location consistently differ by up to 35% (Table 3), except for at 22EEL0004 where the difference is only 4.3%. The top of the C-horizon is consistently ≥30 cm below surface. Soil pits at survey 3 were drier than those dug at survey 2, with water pooling only at 22EEL0004.

At 21TFE6508, a C-horizon sample was collected 108 cm below surface and returned a value of 1.85% potassium (Figs. 12b, 13). The overlying B-horizon sample was collected 20 cm below surface and returned a value of 2.00% potassium. The gridded cell value over this sample site for RPAS potassium is 1.78% (Table 3).

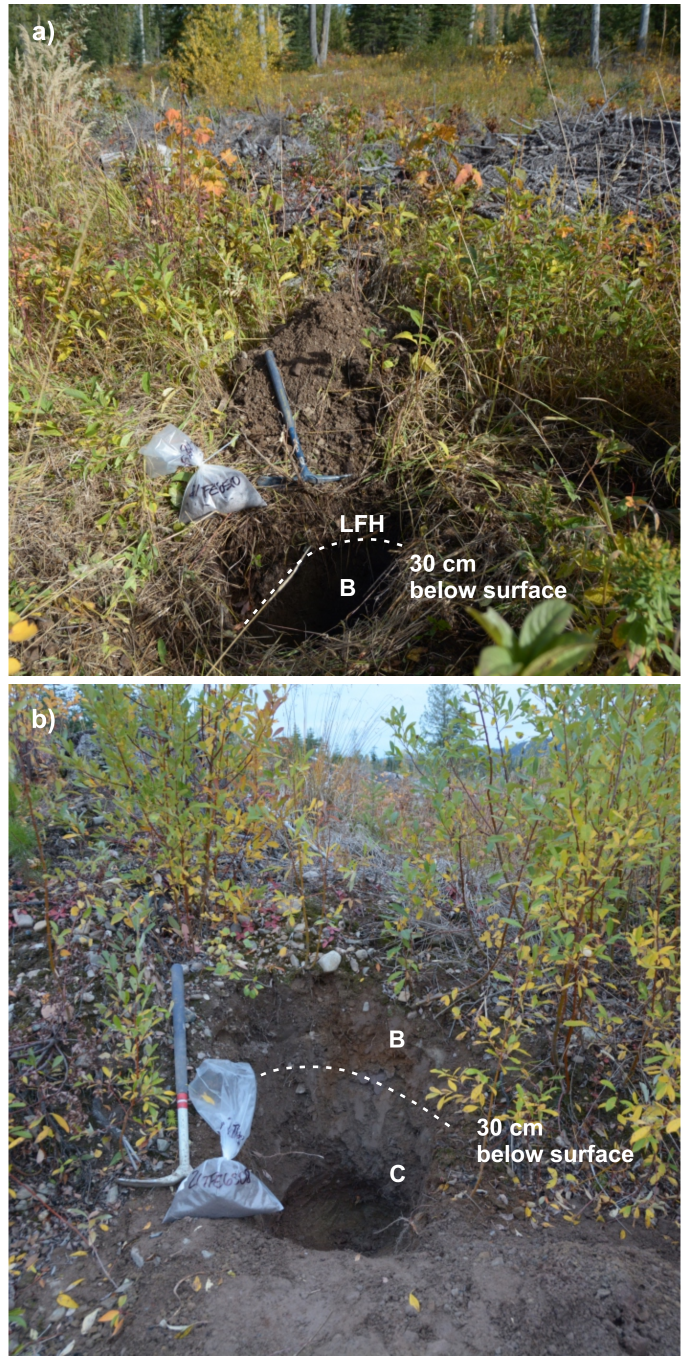

Fig. 12. B- and C-horizon soil sample sites. **a)** Survey 2. The top 30 cm of soil profile consists of 20 cm LFH and 10 cm B-horizon. C-horizon is exposed in the lower portion of soil pit. **b)** Survey 3. The top 30 cm of the soil profile is B-horizon. Pick for scale (65 cm).

6. Discussion

Potassium values measured by an RPAS-mounted gamma-ray spectrometer above low-radioactivity materials are similar to values measured by commonly used geophysical and geochemical methods. Although we focus on three surveys completed near the Mount Polley mine, data from 10 other sites surveyed as part of the RPAS program (Elia et al., 2023) show similar results. A robust assessment of accuracy using statistics like coefficient of variation or relative standard deviation (cf. Abzalov, 2008; Piercy, 2014) is not possible because these methods are not expected to produce the same value for the same location. Each provides a 'different' potassium concentration due to how the concentration was determined (measuring gamma-ray counts for a specific radioelement energy window versus electromagnetic radiation wavelengths for a specific element), the volume of material measured (instrument field of view versus volume of physical sample), or the grain-size fraction measured (bulk versus sieved sample). For example, all gamma-ray spectrometric techniques count gamma-ray emissions from the top 30 cm below surface, however, the instrument field of view increases with an increase in height

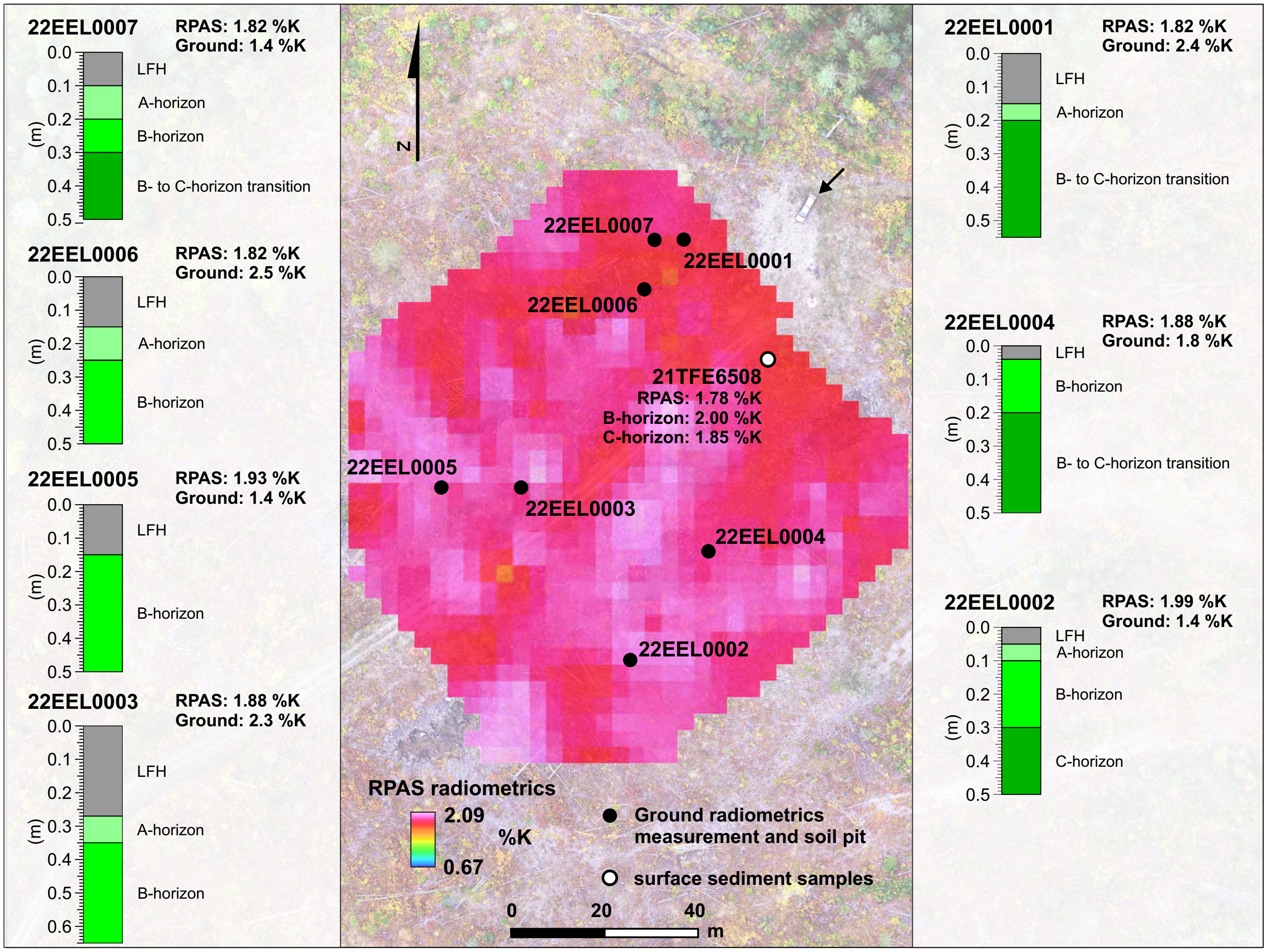

Fig. 13. Survey 3 over subglacial till. RPAS radiometric potassium data are gridded at 3.33 m cell size. Ground radiometric values, and B- and C-horizon lithium fusion ICP-ES are provided for comparison. Soil pits depict lithic and non-lithic soil components for top 50 cm of soil profile. Pick-up truck for scale (black arrow).

from the source resulting in an increase in the measured volume. Different volumes will have different gamma-ray emissions, especially in the case of a heterogeneous source. Instrument count times could also account for some of the differences in radiometric potassium data presented here (i.e., longer count times result in lower error and a more accurate determination), but identical count times for each instrument would not normalize the volume of material each is measuring. Similarly, the process of gridding radiometric data has an averaging effect, but it also cannot account for different volumes measured.

The differences between RPAS radiometric potassium and potassium determined by lithium fusion ICP-ES are explained in part by the volume of material measured (instrument field of view versus volume of physical sample) but also by the grain size fraction measured. Gamma-ray spectrometry provides a bulk measure from all in situ materials including those that emit gamma-rays and those that can attenuate gamma-ray emissions (e.g., organics and water). This contrasts with B- or C-horizon soil samples where lithic material is collected at a specific location in the soil profile and then sieved to a specific size-fraction for analysis.

RPAS gamma-ray spectrometry could be used as a drift prospecting tool to identify subglacial tills that are derived from bedrock sources elevated in potassium, uranium, or thorium. In this application, it is important to recognize that the gamma-ray spectrometer is measuring radioelement concentrations in the top 30 cm of the soil profile and that the C-horizon (i.e., where subglacial till samples are collected from) is more commonly at a greater depth. Radioelement concentrations in these upper soils can be used as a proxy for radioelement concentrations in deeper soils if the two are genetically linked. Cook and Dunn (2007) and Lett (2010) showed that a B-horizon geochemical response is positively correlated to the response in the underlying C-horizon. The potassium geochemistry values we present here for B- and C-horizon soil samples also indicate this.

A significant limitation of applying the RPAS radiometrics technique to drift prospecting over low radioactivity materials in forested terrain is the requirement to fly surveys close to the ground (≤10 m above ground level) to maximize gamma-ray counts. This limited our work to forestry cutblocks. Although geology was considered when selecting survey locations,

Fig. 14. Typical Interior Plateau cutblock. RPAS radiometric data were collected here at 7.5 m above ground level. Cutblock was replanted approximately 5 years ago, and regrowth is minimal, but survey area was limited by taller cutblock obstructions. Pick-up truck (T) and geologist (G) for scale.

surveys could only be conducted in cutblocks devoid of obstructions to the RPAS (Fig. 14). For example, the closest down-ice and flyable cutblocks to Boundary zone (a high-potassium bedrock source for subglacial tills) were survey 2 (3 km down-ice) and survey 3 (7 km down-ice). At these distances, the high-potassium signature in till from Boundary zone is diluted by the geochemical signatures of intervening bedrock sources. Additionally, potassium values in subglacial tills over these small survey areas are not expected to significantly vary, making it difficult to depict down-ice dispersal due to restricted range of potassium concentrations. The RPAS radiometric method would perform well over higher radioactivity materials or in areas where survey locations are not dictated by trees or vegetation such as in deserts, high-altitude (alpine), or high-latitude (arctic) settings.

7. Conclusion

RPAS-borne radiometric data were collected using a Radiation Solutions Inc. RS-530 gamma-ray spectrometer mounted to a DJI Matrice 600 Pro in forested terrain of the Interior Plateau, where subglacial tills are common and bedrock exposures are limited or discontinuous. Potassium data from this instrument show that low crystal volume spectrometers (0.35 L) can be used to measure small changes in potassium concentrations (0.10%) in surface sediments and bedrock, the same way large-volume airborne gamma-ray spectrometers (up to 50 L) have for decades. RPAS data from this low-volume detector are inherently noisy and so benefit from a statistical treatment such as noise-adjusted singular value decomposition (NASVD).

A comparison of gridded RPAS-borne potassium data (2.5-3.33 m cells) shows they are similar to potassium concentrations determined by lithium fusion ICP-ES (converted from K_2O), a handheld ground gamma-ray spectrometer, and gridded regional fixed-wing radiometrics (100 m cell) for the same location. Small differences are expected and can be explained by the method by which potassium concentrations were determined and the volumes and size fractions measured.

RPAS radiometrics fill a scale and resolution gap between traditional airborne and ground surveys, can be collected efficiently and affordably, and can be processed in the field to guide geological surveys in near real-time. Over low radioactivity materials, the instrument must be flown slowly (1 m/s) and close to the ground (≤10 m above ground level) for high-quality data to be collected. This restricts survey areas in the Interior Plateau to recent cutblocks, limiting the utility of this method in drift prospecting studies. However, the method would be useful over higher radioactivity materials containing uranium- and/or thorium-bearing minerals where flying height could be increased or in higher altitude, higher latitude or arid settings lacking significant tall vegetation.

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