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THE DETECTION OF POTASSIC ALTERATION BY GAMMA-RAY SPECTROMETRY—RECOGNITION OF ALTERATION RELATED TO MINERALIZATION

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ABSTRACT

Canadian case histories developed by the Geological Survey of Canada demonstrate the use of airborne and ground gamma ray spectrometry to map potassium alteration associated with different styles of mineralization. These include: volcanic hosted massive sulphides (Cu-Pb-Zn), Pilley's Island, Newfoundland; polymetallic, magmatic-hydrothermal deposits (Au-Co-Cu-Bi-W-As), Lou Lake, Northwest Territories; porphyry Cu-Au-(Mo), Mt. Milligan, British Columbia and Casino, Yukon Territory. Mineralization in two of these areas was discovered using airborne gamma-ray spectrometry.

In each case history, alteration associated with mineralization produces potassium anomalies which can be distinguished from normal lithologic potassium variation by characteristic eTh/K ratio lows. Interpretations incorporating airborne and ground spectrometry, surficial and bedrock geochemistry and petrology show that gamma-ray spectrometric patterns provide powerful guides to mineralization. This information compliments magnetic, electromagnetic, geological and conventional geochemical data commonly gathered during mineral exploration programs.

Worldwide, increased levels of airborne gamma-ray spectrometric surveying will foster increased ground spectrometric surveying and improvements to data processing, interpretation, case history development and presentation. More effective communication of these results will lead to better understanding and acceptance of the currently under-utilized gamma-ray spectrometric method in the next decade.

INTRODUCTION

The acceptance of a new technique usually follows an evolutionary path, from early testing through to case history development and, eventually, widespread use. Many geophysical techniques such as ground and airborne magnetic surveys have followed reasonably linear developmental courses, with understanding and levels of acceptance driven forward by ongoing case history development, and are fueled by technological advances such as increasingly sensitive magnetometers. In contrast, the acceptance path of gamma-ray spectrometry has had twists and setbacks related, ironically, to early successes in uranium exploration and to misunderstanding of limitations and capabilities. Morley (1969) and Darnley (1991) provide further discussion of these concepts.

Although the idea of using *total* radioactivity to locate ores other than those of uranium was suggested over 45 years ago (Gross, 1952), the development of gamma-ray spectrometers in the early 1960s enabled the identification of radioactivity specifically related to potassium, uranium and thorium concentrations. However, while several early workers soon recognised that spectrometric estimates of potassium, uranium and thorium (K, eU, eTh) concentrations and derived ratios could be applied to base metal deposit alteration studies as possible halo-like guides (Sikka, 1962; Moxham *et al.*, 1965), widespread application to *uranium-only* exploration prevailed.

Other basic concepts were also realised in the early years: the potential for spectrometry to indirectly detect non-radioactive elements, *by association*, such as Nb and Mo associated with radioelements U and Th; using characteristic *ratios* to *fingerprint* geological and geochemical environments; the understanding that *relative variations* in radioelement patterns may be more important than *absolute values* (Dodd *et al.*, 1969). Unfortunately, these early developments, case histories and resulting concepts did not foster widespread industrial application of gamma-ray spectrometry to non-uranium exploration. The myths that spectrometry is only useful for uranium exploration and where surficial cover is absent continued for many years, despite a growing number of case histories based on large scale surveys in many countries.

In Canada, many studies (see Shives *et al.*, 1995, and references therein) document application of gamma-ray spectrometry to surficial (glacio-fluvial deposits, tills, soils) and bedrock mapping at regional to

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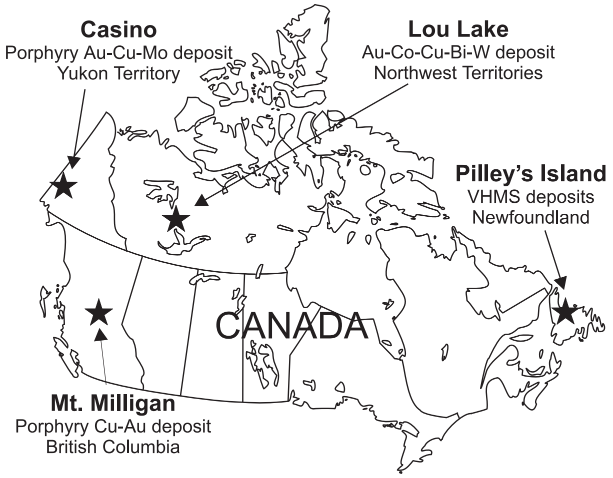


Figure 1: *Location of examples discussed in this paper.*

deposit scales, to exploration for a wide variety of commodities (rare, base and precious metals, granophile elements and industrial minerals) and to environmental studies. In Australia and elsewhere, where the effects of tropical weathering and landform development may significantly modify bedrock radioelement distribution (Dickson and Scott, 1997) the airborne patterns provide important information for soil, regolith and geomorphology studies used for land management and mineral exploration strategies (Wilford *et al.*, 1997).

Summaries of the development of gamma-ray spectrometry have been provided in volumes produced from three preceding conferences (Mining and Groundwater Geophysics, 1967; Geophysics and Geochemistry in the Search for Metallic Ores, 1977; Exploration '87, 1987), in articles by Morley (1969), Killeen (1979) and Darnley and Ford (1989). Major advances are marked by the development of high-sensitivity systems, proper calibration standards and procedures in the 1960-70s, the introduction of digital collection, processing and colour presentation methods in the 1970-80s, and the use of self-stabilising spectrometers, global positioning (GPS) and geographic information system (GIS) analyses in the 1980-90s. Recently, full-spectrum analytical techniques (Hovgaard and Grasty, this volume) and new standardization procedures have been developed (Grasty *et al.*, this volume). Principles of gamma-ray spectrometry and survey techniques established by the International Atomic Energy Agency (1991) are updated and explained more fully by Grasty and Minty (1995).

The use of gamma-ray spectrometry to determine concentrations of elemental potassium, regardless of the associated potassium mineral species, enables alteration mapping in a wide range of geological settings. For example, potassic alteration in the form of sericite is commonly associated with many types of volcanic-associated massive sulphide base metal and gold deposits (Franklin, 1996; Poulsen and Hannington, 1996). Potassium feldspar alteration has been documented as a regional alteration product at volcanic associated base metal deposits in the Bergelagen district, Sweden (Lagerblad and Gorbatschev, 1985), in the Mount Read volcanics, Tasmania (Crawford *et al.*, 1992) and at the Que River massive sulphide deposit, Tasmania (Offler and Whitford, 1992). Potassium alteration is common in shear hosted gold deposits, such as those at Hemlo, Ontario (Kuhns, 1986), Red Lake, Ontario (Durocher, 1983) and of many other deposit types (Hoover and Pierce, 1990).

Many alkaline and calc-alkaline porphyry Au-Cu (±Mo) deposits have extensive potassic hydrothermal alteration halos (Davis and Guilbert, 1973; Schroeter, 1995) which vary mineralogically, both laterally and vertically, with changes in pressure, temperature, eH, and pH during magmatic, hypogene, and subsequent supergene processes. A well-established alteration-mineralization potassic zoning sequence (Lowell and Guilbert, 1970) may be evident within a single deposit, ranging from a central, orthoclase and/or biotite core (± sericite as fracture controlled and pervasive replacements) outwards through successive phyllic (sericitic), argillic and propylitic zones. Although phyllic zones may contain less bulk potassium gain than potassic cores, their peripheral distribution commonly offers much larger targets for detection by gamma-ray spectrometry.

As thorium enrichment generally does not accompany potassium during hydrothermal alteration processes, eTh/K ratios provide excellent distinction between potassium associated with alteration and anomalies related to normal lithological variations (Galbraith and Saunders, 1983). This important correlation of low eTh/K ratio with alteration is evident in countless studies worldwide, including the four Canadian examples described herein and shown in Figure 1.

VOLCANIC-HOSTED MASSIVE SULPHIDES (VHMS)—PILLEY'S ISLAND, NEWFOUNDLAND

On the Island of Newfoundland, the Geological Survey of Canada has collected over 65 000 kilometres of gamma-ray spectrometric, total field magnetic and VLF-EM airborne data at 1000 m line spacing, covering approximately 50% of the island.

Airborne gamma-ray spectrometric surveys require a minimum of four maps (total count, potassium, equivalent uranium and equivalent thorium) to present the four primary variables measured. Important information is also obtained from four additional, derived products, eU/eTh, eU/K, eTh/K ratios and ternary K-eU-eTh radioelement maps. Figure 2a shows the potassium map from such a data set, compiled from six regional airborne gamma-ray spectrometric surveys. The regional compilation provides valuable geochemical and geophysical information throughout diverse lithotectonic terranes, including characterization and subdivision of granitic suites.

Within the major volcanic belts a number of potassium anomalies are directly associated with felsic volcanic units and past-producing or prospective VHMS alteration systems. Figure 2b shows the potassium distribution map for the western part of Notre Dame Bay. Corresponding geology for the area is shown in Figure 3b (Colman-Sadd *et al.*, 1990). High potassium concentrations west of Green Bay correspond to felsic intrusive units within the Siluro-Devonian, post-tectonic, King's Point Complex, which comprises units ranging from gabbro to syenite and peralkaline granite. The prominent area of low K values north of Halls Bay accurately reflects the distribution of primitive-arc ophiolitic mafic volcanic rocks. Southwest of Halls Bay, a broad region of moderate-to-high potassium values corresponds to felsic volcanic units of the Silurian Springdale Group (Coyle and Strong, 1986).

The northern part of the Robert's Arm Group (RAG, Figure 3b) contains lower tholeiitic and upper calc-alkaline suites of mafic volcanics

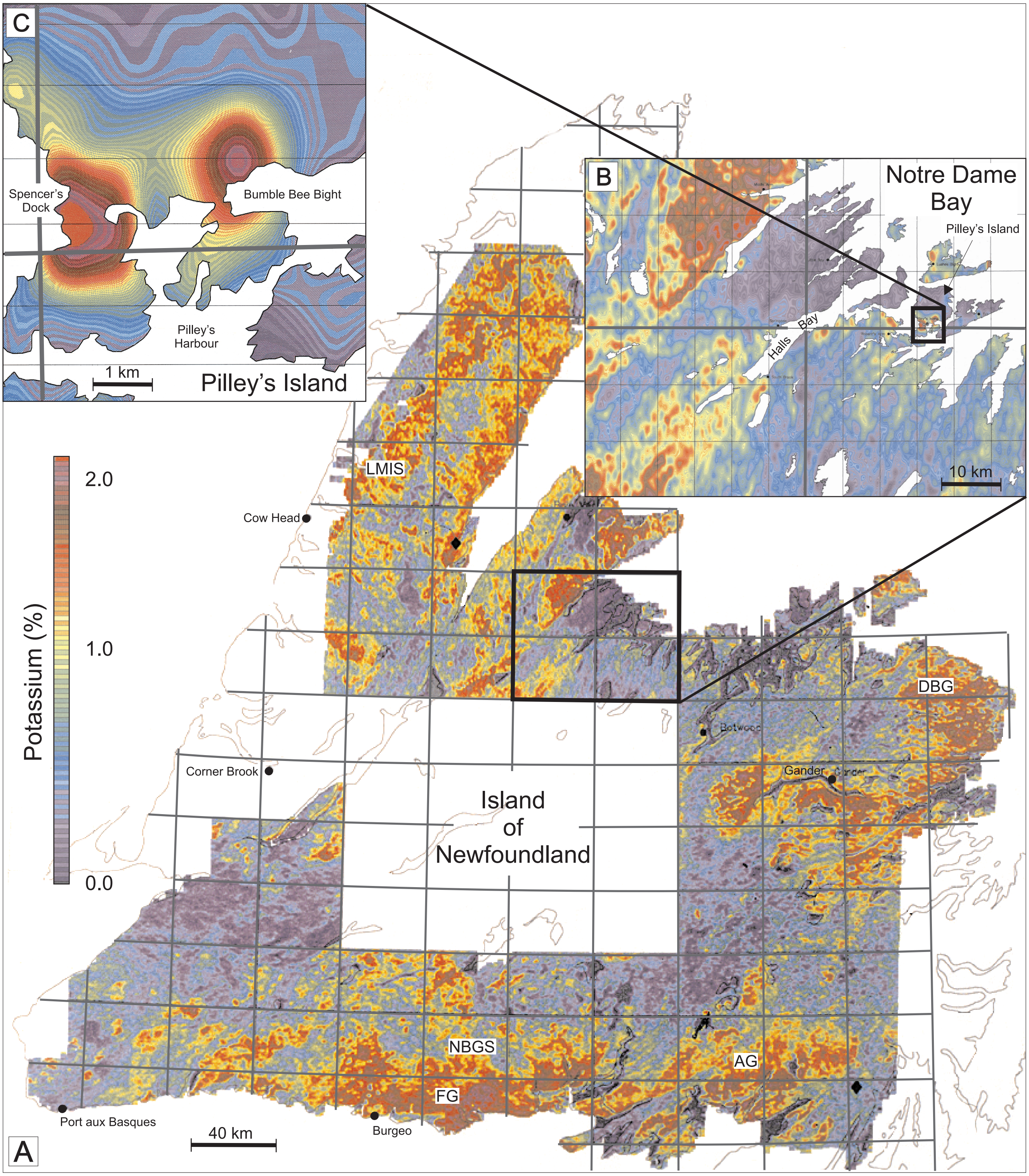


Figure 2: *Potassium maps compiled from airborne gamma-ray spectrometer surveys flown using 1 km line spacing. A: Island of Newfoundland (LMIS = Lake Michael Intrusive Suite; DBG = Deadman's Bay Granite; AG = Ackley Granite; FG = Granite; NBGS = North Bay Granite Suite); B: Notre Dame Bay area; C: Pilley's Island.*

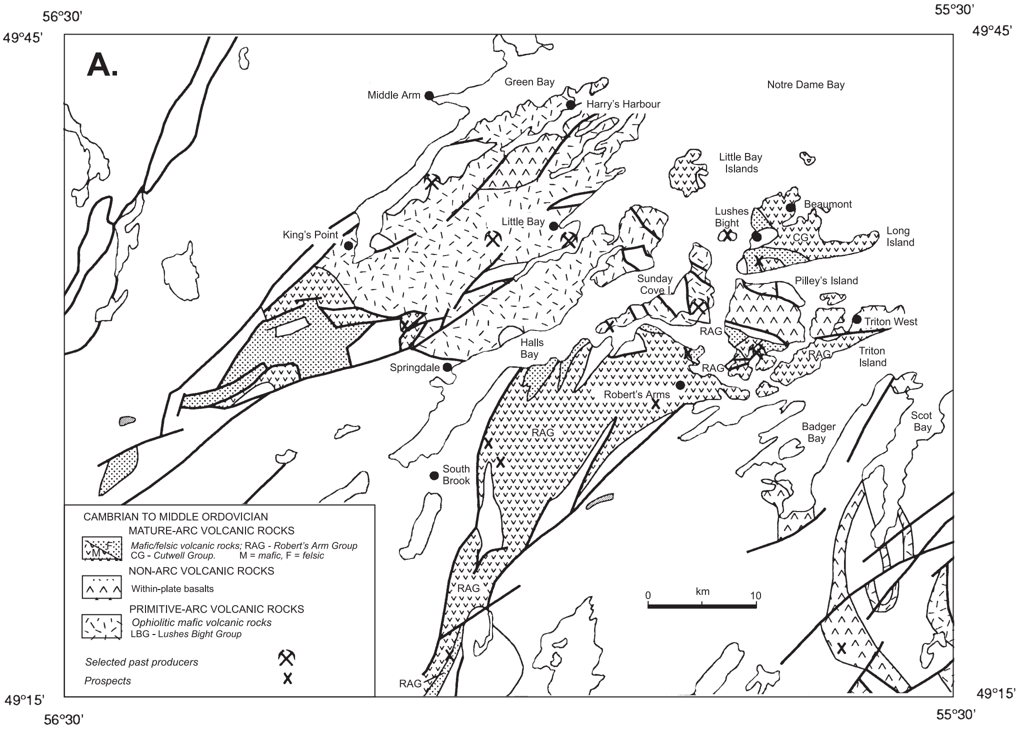


Figure 3a: *Simplified geology, corresponding to airborne potassium maps in Figures 2b and c.*

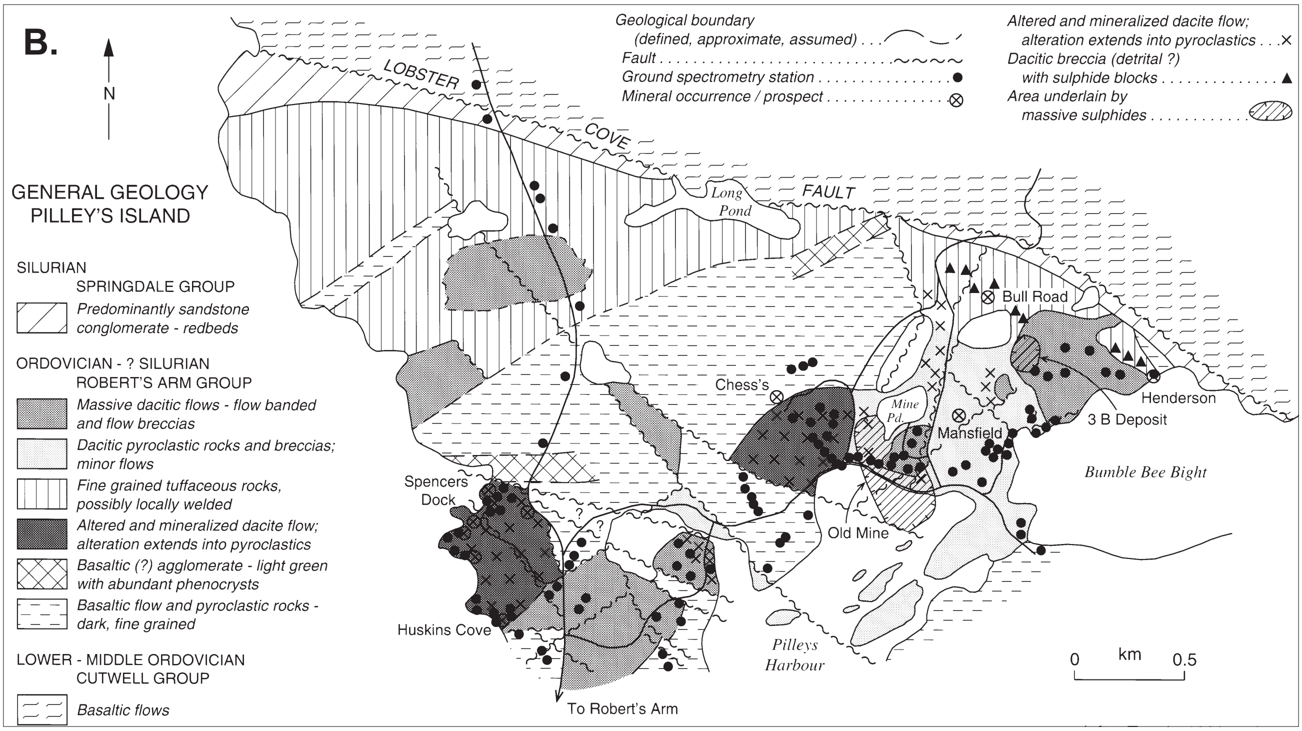


Figure 3b: *Notre Dame Bay area, showing distribution of major Cambrian to Ordovician volcanic rocks, derived from Colman-Sadd et al. (1990). B: General geology, southern Pilley's Island, derived from Tuach et al. (1991).*

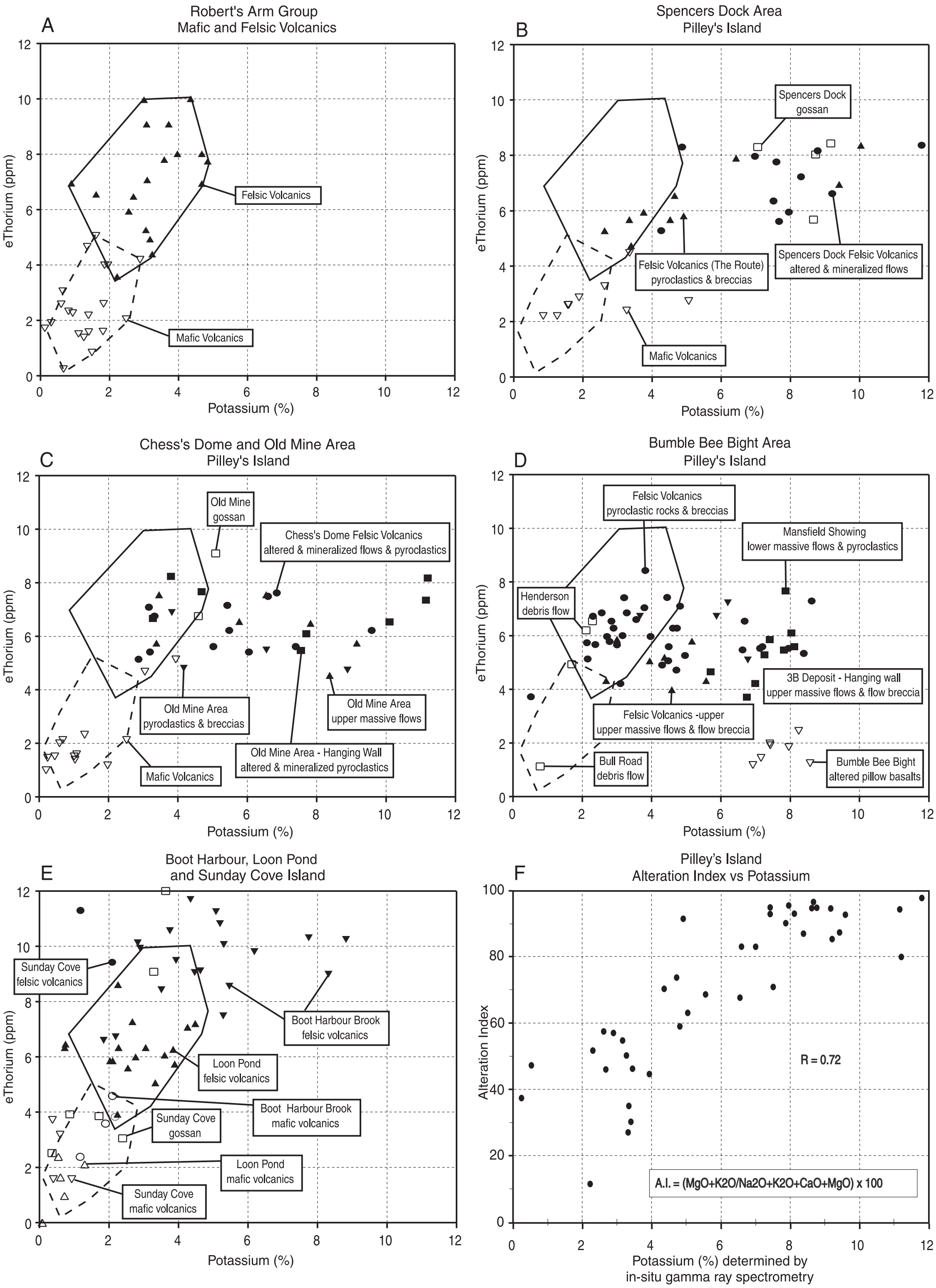


Figure 4: *Variations in equivalent thorium and potassium concentrations as measured by in situ gamma-ray spectrometry. A–E: unaltered and variably K-altered mafic and felsic volcanics of the Robert's Arm Group; F: Variation of lithogeochemical alteration index with increasing potassium concentrations as measured by in situ gamma-ray spectrometry.*

with localised felsic volcanic centres (Bostock, 1988). Figure 2b shows that small potassium anomalies overlie these felsic centres. Ground follow-up studies on southern Pilley's Island (Ford, 1993), including ground gamma-ray spectrometry, geological mapping, lithogeochemical and petrological investigations, have shown that two of the strongest potassium anomalies (Figure 2c) are associated with hydrothermally altered felsic pyroclastics and massive dacitic flows (Figure 3b; Tuach *et al.* 1991). Potassium anomalies at Bumble Bee Bight, Mansfield showing and 3B deposits are associated with narrow zones of hydrothermally altered pillow basalts, dacitic flows and pyroclastics in the hanging walls. The large range in K values (Figure 4d) reflects sporadic distribution of potassium enrichment. Maximum potassium concentrations at Bumble Bee Bight represent a 2- to 3-fold increase over the average potassium values (3.2% K ±1.0%, Figure 4a) for equivalent, unaltered to weakly altered felsic volcanic sequences within the Robert's Arm Group. Potassium enrichment at Spencer's Dock (Figure 4b), and the Old Mine area (Figure 4c), shows similar variability with maximum concentrations of 12% K.

Lithogeochemical alteration indices (Figure 4f) defined by $(K_2O+MgO)*100/(K_2O+MgO+CaO+Na_2O)$ generally range between 70 and 98 for samples containing greater than 7% K, and between 30–60 for less altered samples containing 2%–6% K. Maximum potassium concentrations are not associated with widespread sericitic alteration, but are associated with an unusual, fine-grained, K-feldspar alteration that Thurlow (1996) described as volumetrically equivalent to the sericitic alteration. In the Spencer's Dock area, Thurlow described felsic volcanic units affected by this alteration as "unremarkable, light grey-green, pyrite-free, hard, dacitic lavas having a weakly silicified aspect". K-feldspar alteration in the hanging wall of the Old Mine, Spencer's Dock and Bumble Bee Bight areas is overprinted by sericitic microfractures, suggesting that the K-feldspar alteration may precede the pervasive sericitization and massive sulphide mineralization (Santaguida *et al.*, 1992). Notably, no potassium enrichment is associated with *barren* pyritic gossans hosted by pillow basalts on Sunday Cove Island (Figure 4e).

Although the areas of intense K-feldspar enrichment are less directly associated with VHMS mineralization than sericitic and chloritic alteration, the proximity of potassium anomalies (Figure 2c) to mineralization provides evidence of significant fluid/rock interaction associated with the mineralizing event. The ability to map and quantify this potassium alteration, from the air and on the ground, has important implications for VHMS exploration and mapping.

POLYMETALLIC MAGMATIC-HYDROTHERMAL DEPOSITS (Au-Co-Cu-Bi-W-As), LOU LAKE, NWT

In 1974, the magnetite breccia/rhyodacite ignimbrite hosted Sue-Dianne Cu-U-Au deposit, (to date, 8 Mt grading 0.8% Cu, open to depth and along strike) was discovered as a result of an eU and eU/eTh ratio anomaly on a gamma-ray spectrometric survey with 5 km line spacing (Richardson *et al.*, 1974; Charbonneau, 1988). The deposit is located 20 km north of the Lou Lake area (Figure 1) in the southern part of the 1870–1840 Ma, Proterozoic volcano-plutonic Great Bear magmatic zone (GBmz) in northern Canada. Subsequent metallogenic studies (Gandhi, 1994) documented similarities between Sue-Dianne and the giant Olympic Dam polymetallic deposit in Australia, and promoted the exploration potential of the entire magmatic zone.

In 1993, the GSC, encouraged by the success of the Sue-Diane discovery, surveyed a selected part of the southern GBmz using 500 m line spacing, combining gamma-ray spectrometric, magnetic total field and VLF-EM sensors in a Skyvan fixed-wing aircraft. Results were published in 1994 in digital format and as a bound booklet containing twelve 1: 100 000 scale colour interval maps (K, eU, eTh, eU/eTh, eU/K, eTh/K, total count, ternary radiometric, magnetic total field, calculated magnetic vertical gradient, VLF-EM total field and quadrature), stacked profiles and a colour geology map with mineral occurrences (Hetu *et al.*, 1994). This more detailed survey provided a regional framework for ongoing geological mapping and metallogenic studies, and delineated several new and existing exploration targets. The survey clearly showed the previously unrealized significance of several known, small, scattered mineral occurrences at Lou Lake (Figure 1), placing them within the context of a large, potassium and iron enriched, polymetallic (Au-Co-Cu-Bi-W-As) hydrothermal system. Publication of the survey prompted extensive staking throughout the GBmz.

Airborne radioelement and magnetic signatures of the Lou Lake area are shown in Figure 5 and in profile format in Figure 6. The broad potassium anomaly (Figure 5a) covers a 3 × 4 km area and contains contoured values which locally exceed 7% K, southeast of Lou Lake. Corresponding profile data (Figure 6) across the same area are not subject to averaging inherent in the contouring process, resulting in values which exceed 8% K.

The potassium anomaly is coincident with a high magnetic total field anomaly, which has a peak intensity exceeding 2000 nanoteslas (Figure 5d). Polymetallic mineralization occurs where coincident potassium and magnetic intensities are greatest. The southeast trending axis of the magnetic anomaly parallels a belt of early Proterozoic metasedimentary rocks containing synsedimentary, stratiform magnetite beds and lenses, and later, hydrothermal polymetallic magnetite veins and disseminations.

The strong potassium anomaly is characterized by eTh/K ratio values of less than 2.5×10^{-4} (Figure 5b). In general, low eTh/K ratios are excellent indicators of potassium alteration (Shives *et al.*, 1995). Unaltered lithologies typically reflect the normal ratio of crustal abundances of K and Th, of approximately 5×10^{-4} (Galbraith and Saunders, 1983). During the process of potassium alteration, however, thorium does not usually accompany potassium. The resulting low eTh/K ratio, as observed at Lou Lake, thus enables distinction of potassium anomalies that have exploration significance from those related solely to lithological variations.

Uranium enrichment, evident on the eU/eTh ratio map (Figure 5c), is peripheral to the potassium anomaly and relates to numerous small pitchblende veins. This mineralization may represent uranium moved laterally away from the hydrothermal centre of the system.

Ground spectrometry across the mineralised zones at Lou Lake (N. Prasad, GSC, pers. comm.; Gandhi *et al.*, 1996) measured potassium concentrations as high as 15% K in K-feldspar altered rhyolitic units and up to 6% K in biotite altered metasediments (Figure 7). Unaltered equivalents of these rocks contain less than 4% K.

In addition, company reports indicate a 3 milligal gravity anomaly is coincident with the potassium and magnetic airborne anomalies, and resistivity lows which outline the mineralized zones. Exploration was in an early stage at the time of writing, but initial drill-indicated resources released by the company included 41.6 Mt grading 0.85 g/t Au, 0.11% Bi, 0.10% Co, 0.05% Cu and 0.03% WO_3 ("Deposit open on strike and dip," Fortune Minerals, press release, January 20, 1997). More recent drilling has substantially increased both tonnage and grade.

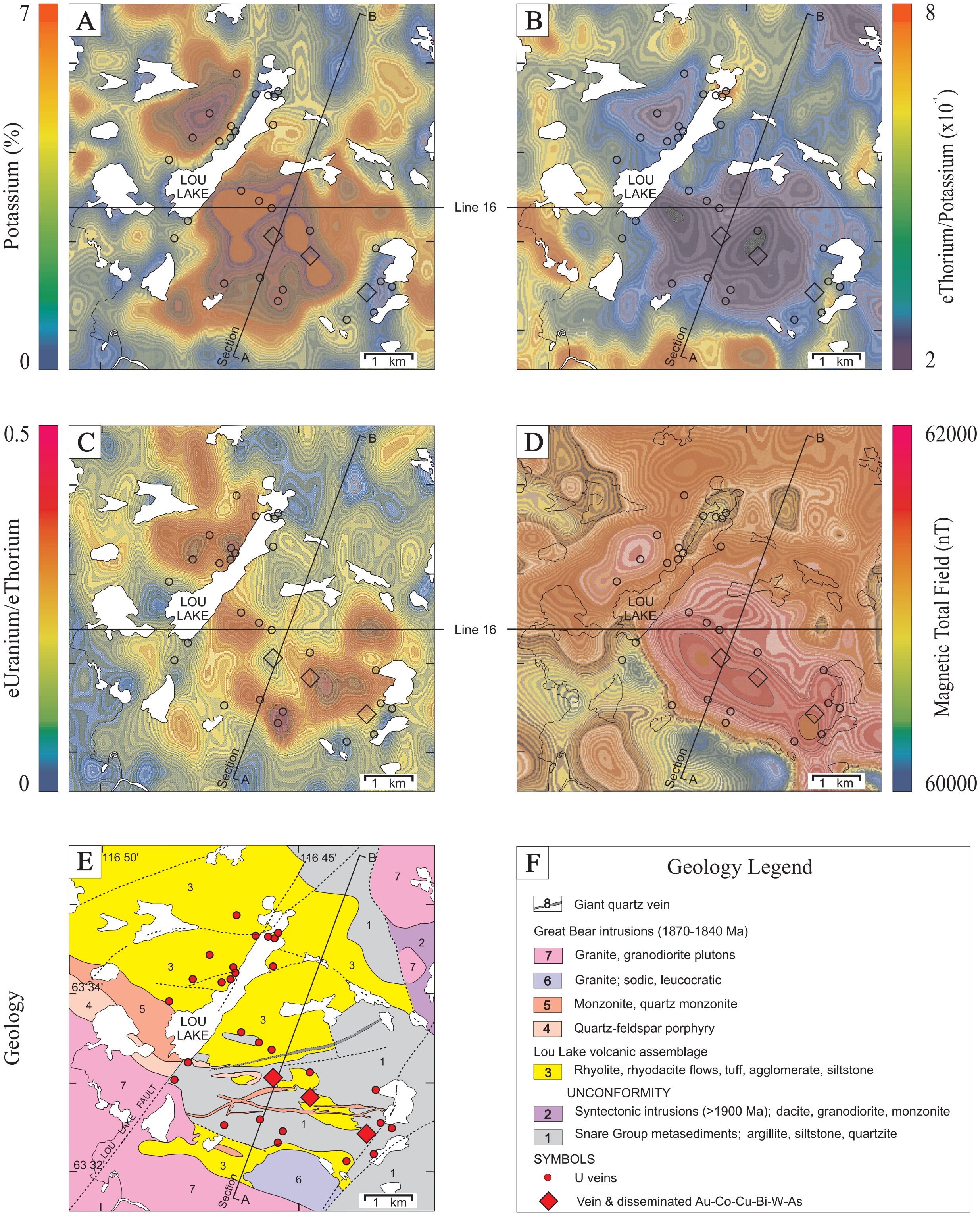


Figure 5: *Airborne geophysical patterns (A–D) and geology (E–F) for the Lou Lake area, NWT.*

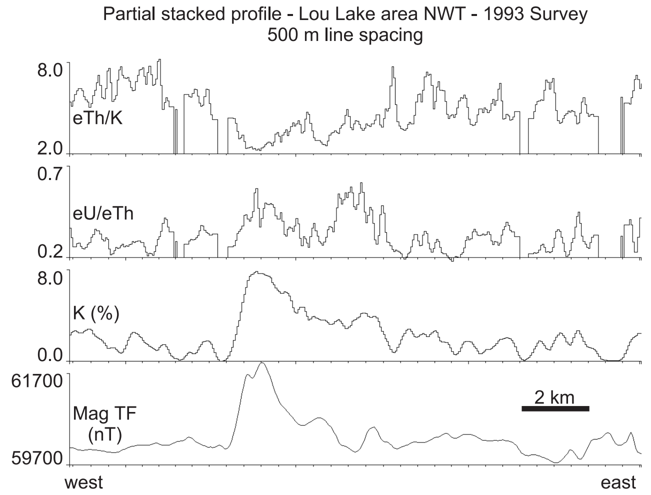


Figure 6: *Airborne geophysical stacked profile across Lou Lake area, NWT (line 16, position indicated in Figure 5).*

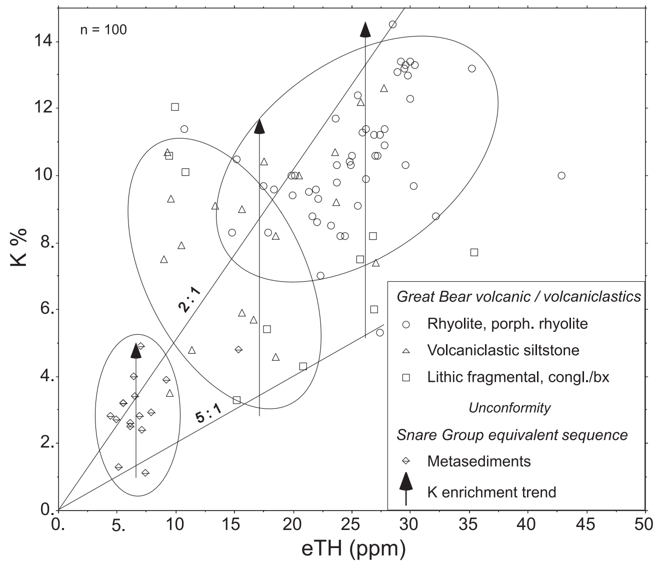


Figure 7: *Potassium vs. thorium concentrations determined by in situ gamma-ray spectrometry, Lou Lake area, NWT.*

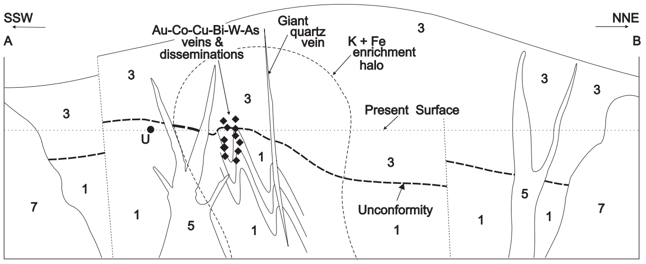


Figure 8: *Geological crosssection along line A–B (see Figure 5 for section location and geological legend). Note K and Fe enrichment halo associated with hydrothermal Au-Co-Cu-Bi-W-As mineralization. Modified from Gandhi et al. (1996).*

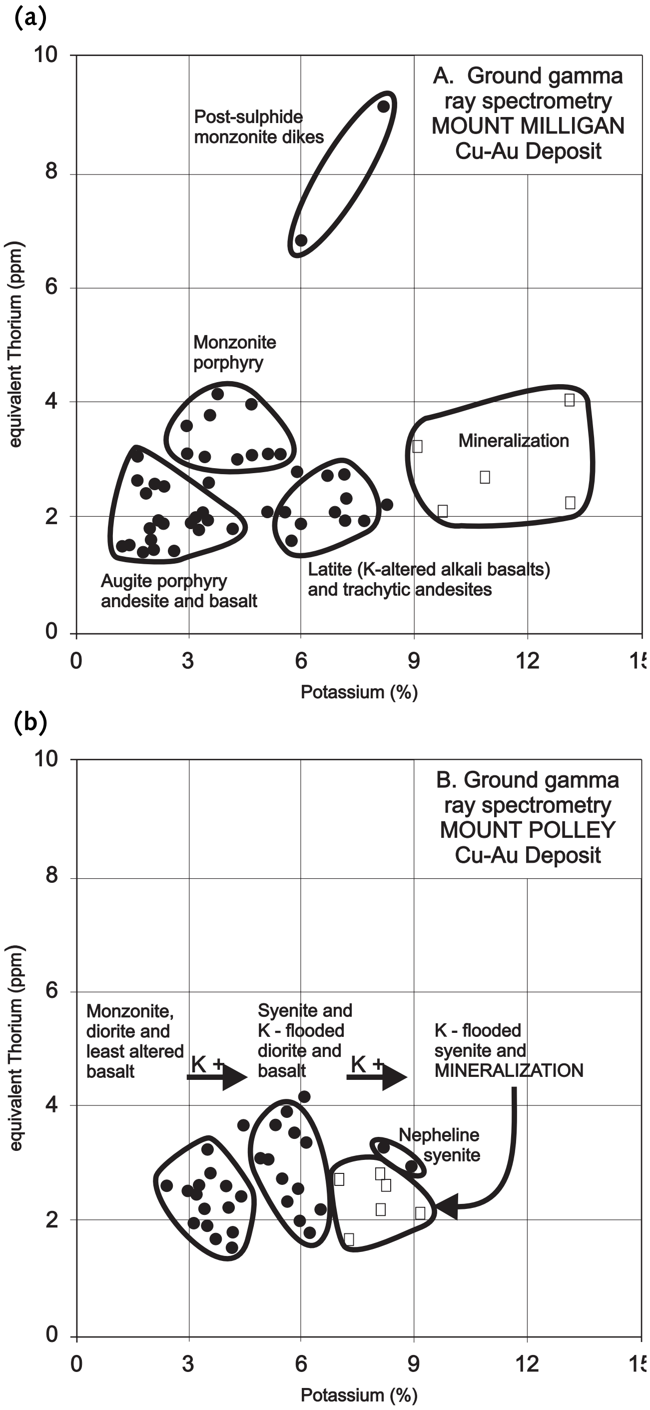
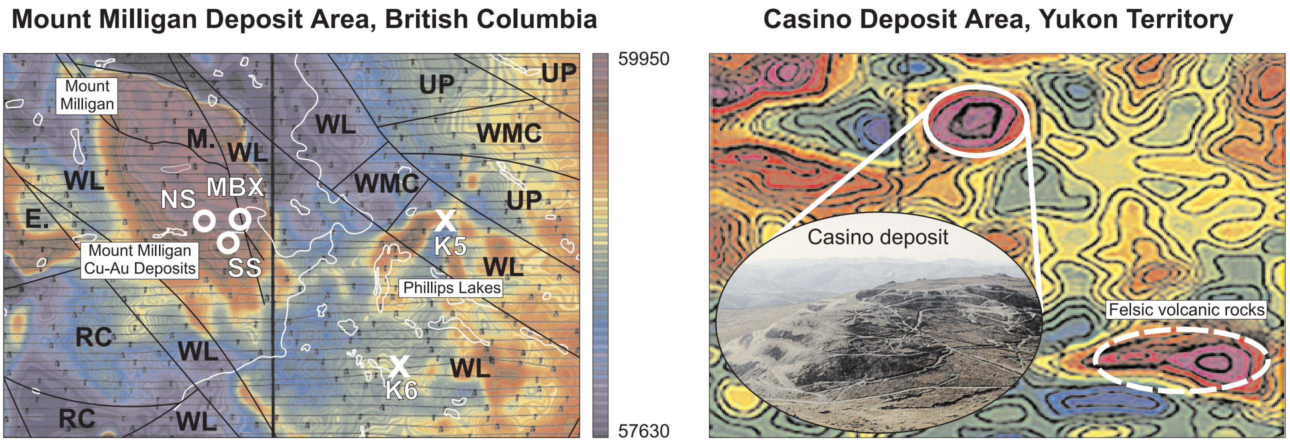
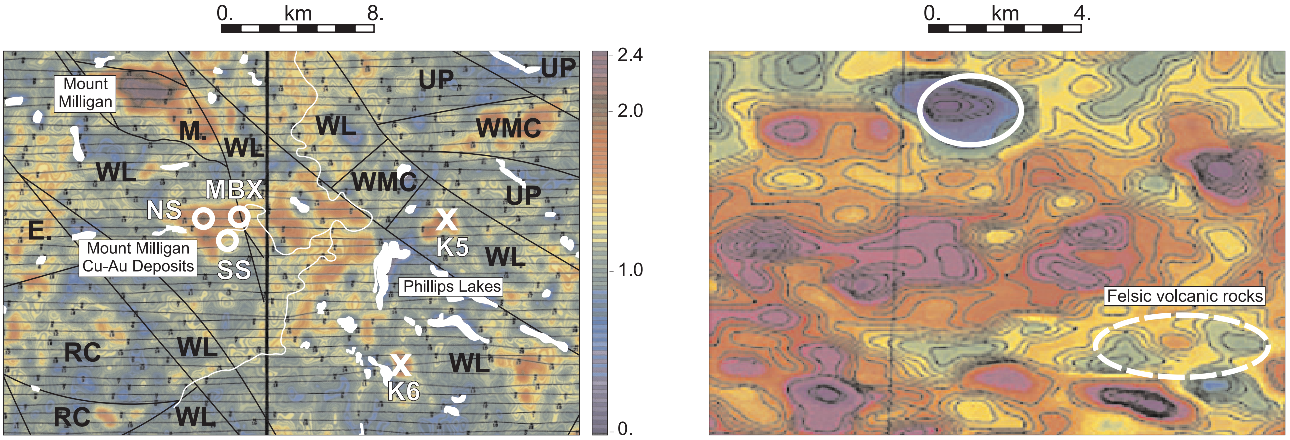


Figure 9: *Potassium vs. thorium concentrations determined by in situ gamma-ray spectrometry over deposits at (**a**) Mt. Milligan and (**b**) Mount Polley, approx. 250 km to the southwest, in British Columbia. Note progressive K enrichment, with maximum values associated with mineralization.*



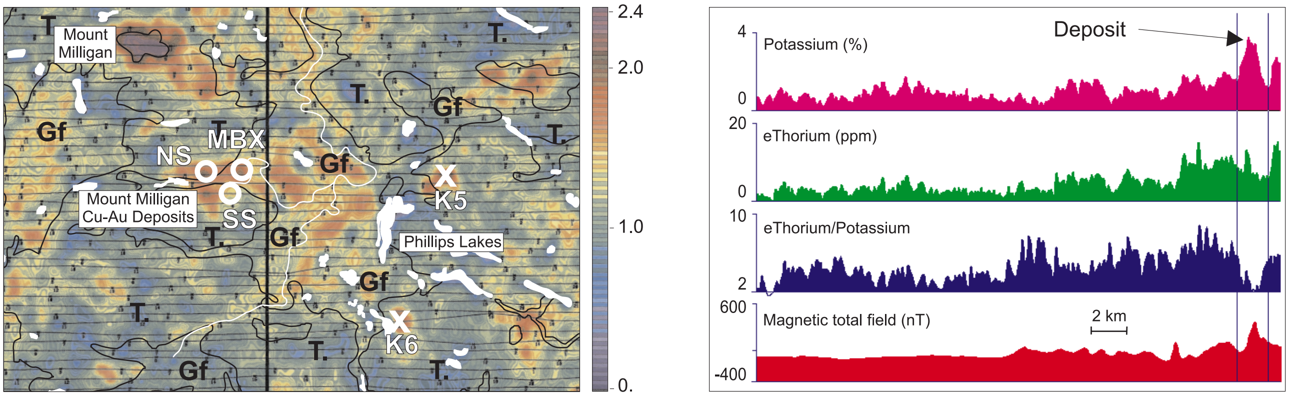
A. Magnetic Total Field (nT) with geology overlay

D. Potassium (%)



B. Potassium (%) with bedrock geology overlay

E. eThorium/Potassium ratio



C. Potassium (%) with surficial geology overlay

F. Stacked profile over the Casino deposit

Figure 10: *Airborne geophysical data compiled from surveys using 500 m line spacing, over the Mt. Milligan deposit area, British Columbia (A–C) and Casino deposit area, Yukon Territory (D–F). Mt. Milligan area bedrock geology after Nelsen et al. (1991); surficial geology after Kerr (1991).*

Based on geological mapping and metallogenic studies, the numerous polymetallic mineral occurrences at Lou Lake are interpreted as hydrothermal, related to a deep-seated granite pluton (Figure 8). It was suggested (Gandhi *et al.*, 1996) that the mineralizing solutions moved upwards through metal-rich argillaceous metasedimentary beds, scavenged the metals and re-deposited them at the unconformity with the overlying Lou Lake volcanics. The discovery of the large potassium and iron enrichment zone by the airborne spectrometric and magnetic survey further emphasizes the hydrothermal character and large size of the mineralizing system. This example underscores the importance of combining geophysical/geochemical information provided by regional airborne surveys with ground studies, good geological control and metallogenic models, to identify and delimit mineralization.

PORPHYRY AU-CU-(MO) DEPOSITS – MT. MILLIGAN, BC AND CASINO, YT

Exploration for porphyry copper and molybdenum in the Canadian Cordillera boomed in the 1960s and 1970s, respectively, when several successful mines were discovered. During those periods some researchers used ground gamma-ray spectrometry to measure potassium enrichment in porphyry deposits (Moxham, 1965; Davis and Guilbert, 1973; Portnov, 1987;) and a few enlightened explorationists attempted to use the technique to detect mineralizing intrusions or associated alteration. Unfortunately, despite the research successes, some of these early exploration tests were seen as failures, perhaps due to some combination of inferior instrumentation, incorrect techniques or inappropriate application to alkali-poor (low potassium) targets. Other geophysical techniques, such as magnetic and induced polarization surveys, proved far more successful and became well established, while spectrometry was virtually forgotten.

During the late 1980s, when exploration turned towards gold-bearing *alkalic* porphyry systems, several deposits were re-evaluated for their gold potential and new discoveries were made, including those at Mt. Milligan, BC, and Casino, YT (Figure 1). Despite the obvious potassium enrichment associated with these alkalic systems, ground gamma-ray spectrometers generally remained locked in company storage rooms. Field crews relied on qualitative staining of rock slabs and drill core, or sparse whole-rock geochemical analyses to map potassic alteration.

In 1990, two of the authors conducted brief ground spectrometric surveys over the Mt. Milligan and Mt. Polley (250 km south of Mt. Milligan) alkalic porphyry copper-gold deposits in British Columbia, to re-establish the applicability of the technique to porphyry deposit exploration. The results, which indicated strong potassium variations (Figures 9a and b), demonstrated the ability of the ground technique to detect potassium alteration associated with the deposits, and to distinguish various related intrusive and extrusive lithologies. This work encouraged subsequent, GSC fixed-wing and contracted helicopter-borne surveys over several porphyry systems throughout the Cordillera. Two examples are summarized below.

Mt. Milligan deposit area

The large, low-grade, Mt. Milligan porphyry copper-gold deposits occur within the early Mesozoic Quesnel Terrane in central British Columbia. The deposits are associated with early to middle Jurassic, alkalic, porphyritic monzonite stocks which intrude latitic, andesitic to high-potassium basaltic and trachytic volcanic rocks of the Witch Lake Formation (WL in Figures 10a and b).

Mineralization occurs in several zones (combined resource 299 Mt grading 0.45 g/t Au, 0.22% Cu) as pyrite, chalcopyrite, magnetite, bornite, molybdenite and gold. A detailed description of the exploration history, geology, alteration and mineral zoning of the deposits is provided by Sketchley *et al.* (1995).

In 1991, the GSC conducted the first *public domain*, high sensitivity gamma-ray spectrometric survey flown in British Columbia, combined with magnetic total field measurements, over the Mt. Milligan deposit area (Geological Survey of Canada, 1992). Magnetic total field and potassium maps for part of this survey, flown with 500 m line spacing, are shown in Figure 10. A broad, regional magnetic high is associated with exposed and buried portions of the Mount Milligan Intrusive Complex (Figure 10a). High potassium concentrations are associated with bedrock exposures of the complex at Mount Milligan (Figure 10b). To the south, discrete K anomalies associated with the Mt. Milligan deposits provide smaller, better-focused exploration targets relative to the regional magnetic signature. Elsewhere, despite generally few outcrop exposures and extensive, often thick overburden (till, glaciofluvial and colluvial deposits locally exceeding 100 m), potassium anomalies overlie several previously known and new mineral showings or prospects, providing significant exploration vectoring. Along the eastern margin of the survey, coincident uranium, thorium and potassium concentrations characterize rocks within the Wolverine Metamorphic Complex ("WMC" in Figure 10b).

Based on detailed ground spectrometry and correlation of the airborne survey with regional surficial geological mapping (Kerr, 1991), a threshold value of 1.2% potassium typically distinguishes higher concentrations associated with glaciofluvial deposits from lower values over glacial tills (Figure 10c). This offers substantial aid to ongoing surficial mapping. Although all potassium anomalies throughout the survey warrant careful field investigation, above-threshold values in tills overlying bedrock mapped as andesitic, may be considered first order anomalies.

Two of these anomalous-K till sites occur west of the Mt. Milligan deposits, in the Phillips Lakes area (labelled K5 and K6 in Figure 10). Ground follow-up at these sites included till, bedrock and biogeochemical sampling, ground spectrometry and magnetic susceptibility measurements. Bleached, K-altered andesitic volcanics outcropping in the K5 area contain pyrite and chalcopyrite in quartz carbonate veins. While no outcrop occurs in the K6 area, many large, angular, sulphide-bearing, quartz-veined, K-feldspar-altered porphyritic intrusive boulders define a *granite till*, containing numerous gold grains and high Cu and Au concentrations. These results prompted staking, and drilling has confirmed the presence of blind, low grade Au and Cu mineralization in a K-altered porphyritic intrusion, extending into the enclosing volcanic host rocks.

Casino deposit area

The Casino Au-Cu-Mo porphyry deposit is located in west central Yukon Territory (Figure 1), in deeply weathered, unglaciated terrain (extremely rare in Canada). The deposit is associated with the late Cretaceous Casino Intrusive Complex, which intrudes mid-Cretaceous granodiorites of the Dawson Range Batholith. A preserved, 70 m thick, gold-bearing, leached cap overlies a Cu-rich supergene zone, with the base of weathering extending to 300 m below surface. Geological reserves include: 28 Mt grading 0.68 g/t Au, 0.11% Cu, 0.024% Mo in the leached cap and supergene-oxide zone; 86 Mt grading 0.41 g/t Au, 0.43% Cu and 0.031% Mo in the supergene-sulphide zone; 445 Mt grading 0.27 g/t Au, 0.23% Cu, 0.024% Mo in the hypogene zone. A central, mineralized, potassic alteration zone consisting of K-feldspar and biotite is surrounded by barren, phyllic (sericite) and propylitic alteration. Detailed description of the deposit history, geology, alteration and mineralization is provided by Bower *et al.* (1995).

Ground spectrometry over the deposit and surrounding area (Figure 11) demonstrated that despite deep weathering, radioelement concentrations distinguish host lithologies and alteration. Maximum bedrock K concentrations (6% to 8% K) were measured in mineralized, felsic microbreccias within the leached cap. Maps of airborne potassium concentrations and eTh/K ratios for part of a 1993 helicopterborne survey (GSC, 1994), using 500 m line spacing, are shown in Figure 10. A unique, low eTh/K ratio bullseye (Figure 10e) clearly distinguishes high potassium associated with altered, mineralised bedrock in the Casino deposit, from similar high potassium patterns (Figure 10d) associated with felsic volcanic rocks in the older Yukon Metamorphic Terrane, which has normal eTh/K values. These radioelement and magnetic features are best viewed, in detail, on stacked profiles (Figure 10f).

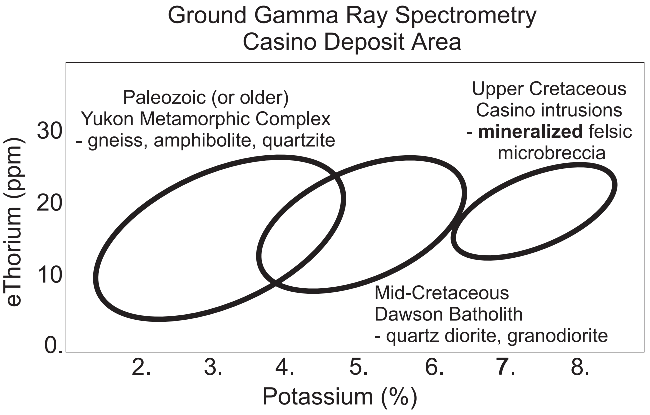


Figure 11: *Potassium vs. thorium concentrations determined by in situ gamma-ray spectrometry over the Casino deposit area, Yukon Territory.*

CONCLUSIONS / FUTURE TRENDS

The ability of gamma-ray spectrometry to map potassium, uranium and thorium enrichment or depletion provides powerful exploration guidance in a wide variety of geological settings. The case histories presented highlight the use of gamma-ray spectrometry to measure and map potassium enrichment related to volcanic hosted massive sulphide, polymetallic and porphyry mineralization. Potassium enrichment in these, and many other geological settings, is characterised by anomalously low eTh/K ratios relative to normal lithological signatures, thus providing significant exploration vectors.

Data processing and presentation methods may enhance or impede correct interpretation. Ratio maps, including ternary K-U-Th colour presentations are useful, but ambiguous, in the absence of corresponding radioelement concentration maps. Flight line data, presented in relatively unfiltered form as stacked profiles, provide better detail than the inherently smoothed contour maps.

Conventional geophysical methods such as magnetic, gravity and electromagnetic surveys require knowledge of rock properties to constrain modelling, but results can be interpreted mathematically as individual channels. Proper interpretation of gamma-ray spectrometric data, however, requires clear understanding of petrology, surficial and bedrock geology and geochemistry, of the gamma-ray spectrometric method itself, *and* of complimentary geophysical techniques. Few interpreters possess this diverse knowledge.

The sporadic evolution of gamma-ray spectrometry, from uranium-only prospecting to multi-element exploration, mapping and environmental applications, has only recently resulted in significant worldwide demand for the method. In spite of this, gamma-ray spectrometry remains under-utilised and poorly understood by many potential end-users. While extensive publications exist, university level geophysics and geochemistry courses generally provide new geoscientists with inadequate, outdated descriptions of the gamma-ray spectrometric method. Thus, the challenge remains to further develop the instrumentation, techniques, and case histories to clearly illustrate the broad range of applications, and to effectively disseminate this knowledge.

As the current surge in airborne gamma-ray spectrometric surveying will continue, probably for several years, new developments will include increased use of state-of-the-art ground spectrometers, refinements to new methods of full-spectral processing, advances in GIS modelling and data presentation methods.

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