Using gamma ray spectrometry to find rare metals

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Summary

For decades, gamma ray spectrometry has been used worldwide to map rocks and locate mineralization in diverse geological settings (Shives et al., 1997). The method is particularly well suited to rare metal and REE (rare earth element) exploration because primary host rocks are enriched in incompatible elements known as LILE (large-ion lithophile elements K, Rb, Cs, Sr, Ba) and HSFE (high field strength elements Zr, Nb, Hf, REEs, Th, U and Ta). As a result, the ores of REEs are commonly radioactive because host rocks, ore-bearing minerals, or associated accessory minerals may contain trace to anomalous concentrations of radioactive elements K, U and Th. These radioactive elements provide a useful and direct exploration vectors. Gamma ray data are often collected simultaneously with magnetic, electromagnetic, and gravity data in multisensor surveys.

The objective of this extended abstract is to emphasize the importance of gamma ray spectrometry as a primary exploration tool for rare metal deposits. Case histories presented herein illustrate radioactive element and magnetic signatures associated with diverse rare metal deposit types in different geological settings. Canadian examples include: Cantley, Quebec (Quinnville and Templeton carbonatites); Oka, Quebec (carbonatite); Bancroft, Ontario (pegmatites); Allan Lake, Ontario (a blind carbonatite discovery); Nechalacho, Northwest Territories (previously called Thor Lake; altered ultra-alkaline layered complex); Strange Lake, Quebec (peralkaline granite, pegmatite); and one each from British Columbia and Labrador. Also presented are examples from Greenland, Norway, and Mozambique.

1. Introduction

Gamma ray spectrometry provides quantitative measurements of radioactive elements that emit gamma rays contained in natural or man-made materials. Wide-ranging applications include geological mapping of bedrock and surficial geology, environmental concerns (mine tailings, radioactive waste, recycling and garbage disposal), detection of lost sources, emergency response, and a long list of transportation, engineering and medical uses.

Geological applications rely on measuring naturally occurring radioactive isotopes of potassium (K^{40}), uranium (Bi^{214}) and thorium (Tl^{208}), using spectrometers in properly calibrated airborne, vehicle-borne, handheld, or borehole systems. The abundance and chemical behavior of K, U and Th are quite different. Although K is abundant (%), U and Th are trace elements (ppm); U is mobile whereas Th is immobile. Thorough interpretation of gamma ray data requires consideration of these chemical attributes.

2. Radioactive elements in rare metal deposits

Rare metals and REE are most commonly found in carbonatites, peralkaline granites, silica-undersaturated rocks, peraluminous granites, and pegmatites. Associated accessory minerals may include sphene, allanite, apatite, monazite, xenotime, zircon, pyrochlore, bastnäsite, parisite, synchysite, gadolinite, wodginite, ferrocolumbite-manganotantalite, microlite, tapiolite and others. These contain the incompatible LILE and HFSE, including K, U and Th. Table 1 lists the REE and radioactive elements contained in common REE ore minerals, illustrating why the gamma ray method is so usefully applied to rare metal and REE exploration. Note that thorium is particularly common in the REE minerals.

3. Case histories

The following case histories very briefly illustrate results of airborne and ground gamma ray spectrometric surveys conducted at early exploration stages to advanced exploration and development stage deposits. The examples span various geological settings, deposit types, and ages.

3.1. Red Wine Mountain, Labrador: Peralkaline granites

This grass-roots-phase property was staked over the site of the second highest heavy-REE (HREE) value in the entire Newfoundland regional lake sediment database, containing greater than 80 ppm HREE and including europium, terbium, ytterbium and lutetium. Airborne thorium concentrations determined by a 2010 airborne gamma ray spectrometric survey (Fig. 1) show strong coincidence with TREO values in float samples (Silver Spruce, 2015). The area of host peralkaline granite (not illustrated) has no outcrop, but angular float and subcrop contained 2500 ppm La, 1520 ppm Nd and 4360 ppm Ce. Seven samples contained greater than 1% TREO; one assayed 2.58% TREO, as indicated.

Table 1. REE-bearing ore minerals commonly contain detectable concentrations of radioactive elements K, U, Th (latter is particularly common). These are pathfinder elements used in gamma ray spectrometry.The REE are shown in red, and the radioactive elements in blue.

Aeschynite	Y, Ca, Fe, Th, Ti, Nb, O, H
Allanite	Ce, La, Y, Th, U, Zr, P, Ba, Cr
Apatite	Ca, P, O, F, Cl, H, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Yb, U, Th
Bastnäsite	Y, Ce, La, C, O, F, Th
Britholite	Ce, Ca, Th, La, Nd, Si, O, P, H, F
Brockite	Ca, Th, Ce, P, O, H
Cerite	Ce, La, Ca, Mg, Fe, Si, O, (+/- uraninite inclusions)
Columbite	Nb, Ta, Y, U, Mn, Fe, Sn, W, O,
Fergusonite	Nb, Y, Ce, Nd, Ta, Ti, U, Th, O
Fluocerite	Ce, La, F, Th
Fluorite	Ca, F, Y, Yb, (+/- uraninite, thorite inclusions)
Gadolinite	Ce, La, Nd, Y, Fe, Be, Si, Th
Monazite	Ce, La, Nd, Sm, Gd, U, Th, Y, Pr, He, P, O
Parisite	Ce, La, Nd, Ca, C, O, F, Ba
Pyrochlore	Nb, Ta, La, Y, Dy, Gd, Sc, U, Th, Ru, Ca, Ti, Zr, Mo, O
Stillwellite	Ce, La, Ca, B, Si, O (+/- thorite, uranothorite, thorianite)
Synchysite	Ce, Nd, Y, Ba, La, C, O, F, Ca, Th
Titanite/Sphene	Ca, Ti, Si, O, Fe, Al, Ce, Y, U, Th
Wakefieldite	La, Ce, Nd, Y, Bi, V, O, Th
Xenotime	Y, P, O, U, Th, As, Si, Ca, Dy, Er, Tb, Yb, Gd
Zircon	Zr, Si, O, Hf, U, Th

1. There are 100s of REE-bearing minerals.
2. Elements listed are not exclusive, and may not all be present in a single mineral.
3. Radioactive elements may occur in the REE molecules, as mineral inclusions in REE-minerals, or within the same rocks.

3.2. Strange Lake, Quebec: Peralkaline granites and pegmatites

The original discovery at this advanced project (278 Mt at 0.93% TREO+Y indicated + 214 Mt at 0.85% TREO+Y inferred, (Quest, 2015) was aided by airborne gamma ray results over mineralization dispersed glacially from the host peralkaline intrusive complex (Fig. 2). The dispersal trend crosses bedrock contacts at a high angle and is defined by anomalous till concentrations of ore-related elements (Th, U, Be and others).

3.3. Oka Carbonatite, Quebec

This composite alkaline intrusion hosts a niobium resource (10.63 Mt M+I (Measured plus Indicated) at 0.68% Nb_2O_5) (Niocan, 2015) related to pyrochlore group minerals enriched in Nb, Ti, LREE (Light Rare Earth Elements), U and Th, in calciocarbonatite (sövite) phases. Airborne eU (Fig. 3) and eTh patterns accurately delineate the mineralized units and overall boundary of the intrusion. Local development regulators compared the strong airborne eU anomalies with indoor radon to assess where future housing may develop, subject to building code modifications designed to mitigate indoor radon levels and reduce radon-related health risks.

3.4. Cantley Carbonatites, Quebec

This area hosts two carbonatite-fenite fields with contrasting features (Fig. 4). The Quinnville carbonatite-fenite is non-magnetic (hematite), has K-rich bedrock (12% K due to microcline alteration), high Th (to 300 ppm), moderate U (to 50 ppm) and contains La-Ce fluorocarbonates (La >1.3%), uraninite and monazite. The Templeton carbonatite-fenite has low K, U and Th, and a positive aeromagnetic response (due

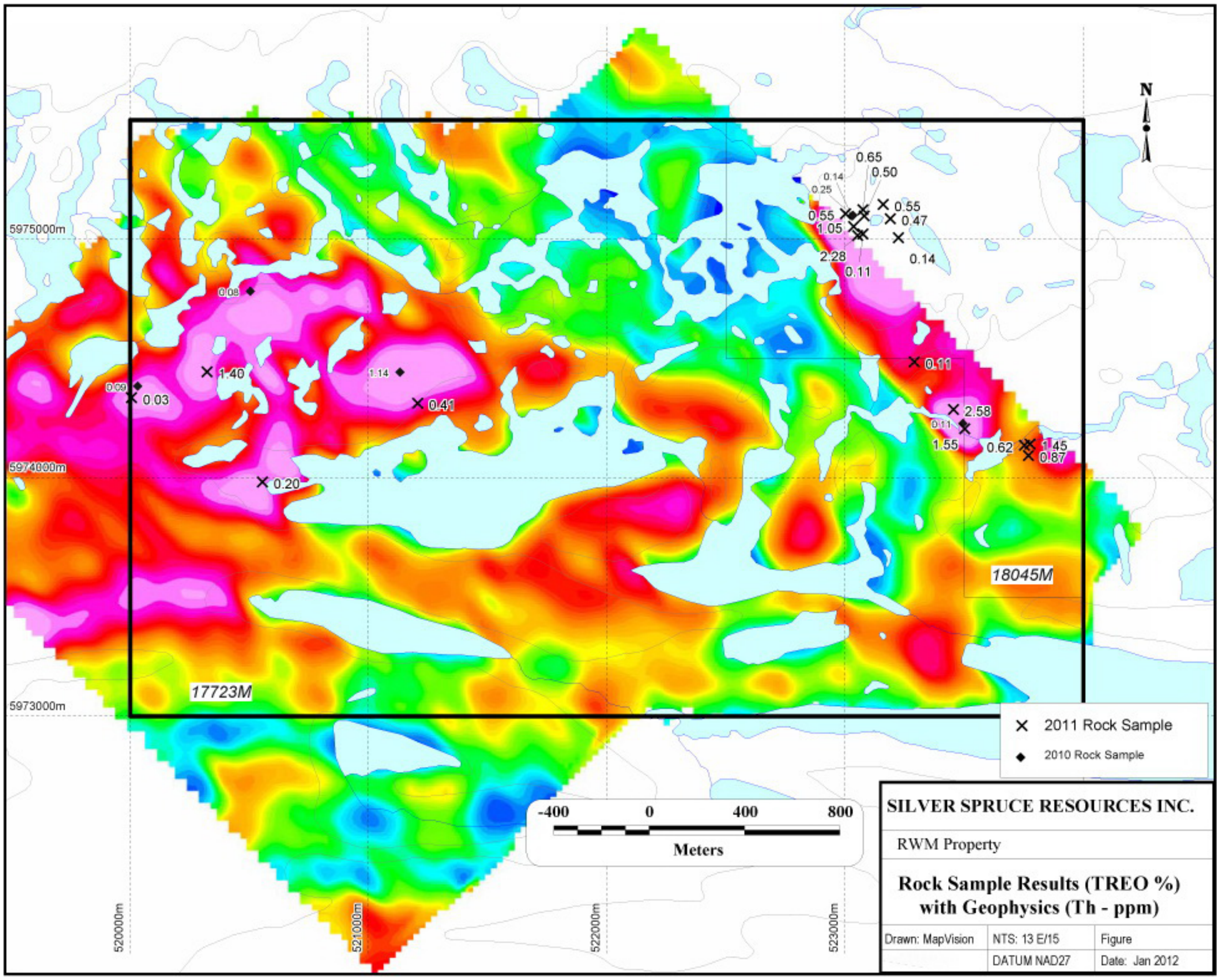

Fig. 1. Thorium concentrations estimated by airborne gamma ray spectrometry surveys over the Red Wine Mountain, Labrador property show strong correlation with TREO (Total Rare Element Oxide) values in rock samples. Pink contoured areas have relatively higher airborne Th concentrations than yellow-green areas, blue shades represent lowest airborne Th values. Map from Silver Spruce (2015).

to magnetite), but low REE concentrations (Charbonneau and Hogarth, 1988).

3.5. Bancroft, Ontario: U-pegmatites

In the Bancroft Ontario area, hundreds of uranium showings in metasedimentary rocks, granites, and pegmatites lie in well-defined U and Th anomalies at the margins of large gneissic domes (Fig. 5). Many contain uraninite, thorite and uranothorite. Associated REEs, Nb, Ta, Y, Ce, La, Nd, and Er occur in minerals such as columbite-tantalite, fergusonite, pyrochlore and gadolinite (Satterly and Hewitt, 1955). Uranium (at grades 0.05–1% U) was historically produced from four mines. Economic REE deposits are considered unlikely in this region.

3.6. Allan Lake, Ontario: Ankerite-siderite carbonatite

This unexposed, small (0.4 km^2), non-magnetic, intrusive plug was discovered in 1977 in a provincial park, through ground follow-up to a strong airborne eTh-only anomaly related to a textbook example of a glacial till dispersal train (Fig. 6). Nearest outcrops of fenitized felsic gneisses are cut by radial dikes and breccias anomalous in eTh. Drilling confirmed the presence of carbonatite containing Ce, La, Nb, Y, Zn, Th, P, Ba, Cu, Pb, Mo, Co. REEs are associated mainly with synchesite-bastnaesite and apatite (Ford et al., 1988).

3.7. British Columbia: Carbonatite sills and dikes

K, U and Th variations can commonly distinguish different carbonatite phases and REE contents. In this example, ground spectrometry refined airborne results, identifying known and new occurrences and separating them into Nb or Ta enriched sövitic (Ca) or beforsitic (Mg) types (Fig. 7; Shives, 2009).

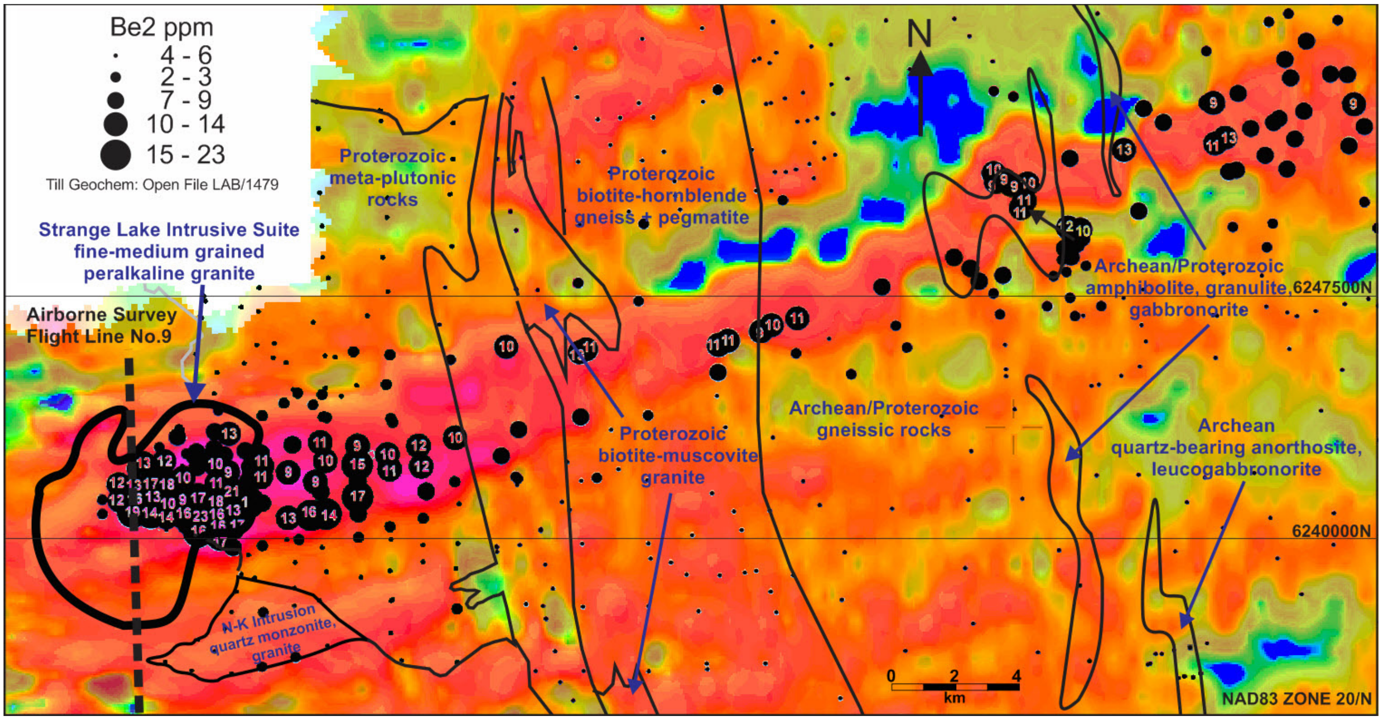

Fig. 2. Airborne survey, Strange Lake intrusive complex. Thorium patterns (relative highs are pink, lows are blue) define a 42 km-long, ENE-trending dispersal train at Strange Lake that crosses bedrock contacts (black lines) and correlates with ore-related elements in till such as Be (dots; Batterson and Taylor, 2009).

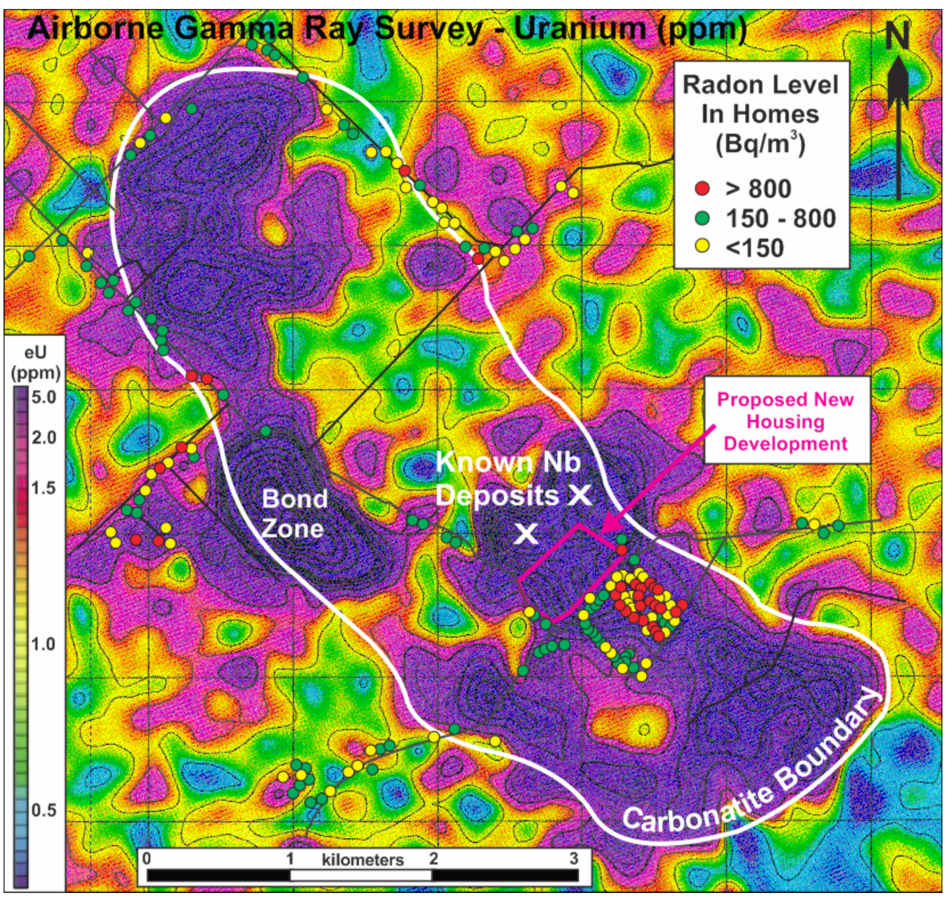

Fig. 3. Airborne eU highs (purple) outline mineralized phases of the Oka Carbonatite, Quebec, and map high indoor Rn potential (modified from Ford et al., 2001).

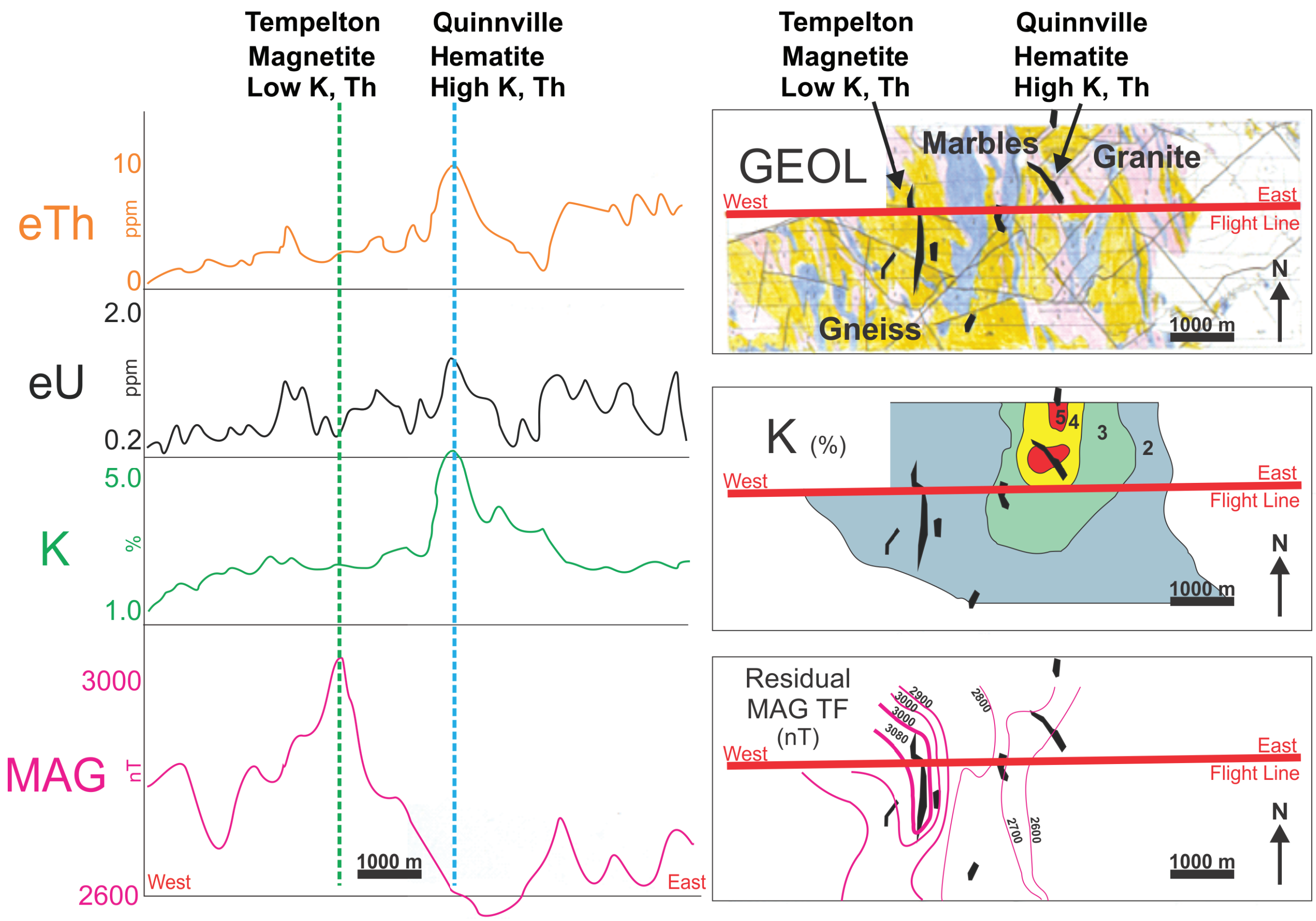

Fig. 4. Geology, airborne K and aeromagnetic maps (right) and airborne stacked profile (left) over the Templeton and Quinnville carbonatite and fenites (black on map views) at Cantley, Quebec.

3.8. Nechalacho, Northwest Territories: Alkaline complex

A 1971 airborne gamma ray spectrometric survey flown by the Geological Survey of Canada detected a strong eTh response over this deposit, which is now an advanced project (estimated measured mineral resource 12.56 million tonnes averaging 1.71% TREO, 0.38% HREO and 22.5% HREO/TREO plus Zr, Ta, Nb and total indicated mineral resource 95.54 million tonnes averaging 1.57% TREO, 0.25% HREO and 16% HREO/TREO; Avalon, 2015). Detailed gamma ray and magnetic surveys (Fig. 8) provide regional and local mapping aids.

3.9. Fen, Norway: Alkaline intrusive and carbonatite complex

Here, airborne gamma ray eTh values reflect low-Th, Nb-bearing sövite, intermediate-Th rauhaugite and high-Th, REE-rich rodberg phases (Fig. 9). REEs include La and Ce and others in monazite, bastnaesite, synchesite and parasite (Lie and Ostergaard, 2011).

3.10. Carbonatites, southwestern Greenland: Peralkaline intrusions

These two carbonatites contain low, but detectable Th, (Fig. 10) which guides to REEs and other metals of interest. Highest airborne eTh values at the Tikiusaaq (discovered in 2005) carbonatite mark the best REE grades in float (9.6% TREO; Nuna, 2015a). At the Qeqertaasaq carbonatite, eTh correlates with sövitic ring dikes cut by REE-bearing carbonatite veins. Mineralization includes Ce, La, Nb, Ta, P, Sr, Zr, and Zn (Nuna, 2015b).

3.11. Mount Muambe, Mozambique: Carbonatites and fenites

Ground gamma ray results correlate well with the location of HREO (Dy+Eu)-enriched carbonatite phases (1.22% TREO, 426 ppm Dy_2O_3, 198 ppm Eu_2O_3) within the Mount Muambe intrusion, and will guide future exploration at this grass-roots exploration project (Fig. 11). The project hosts an inferred fluorite resource of 1.63 Mt at 19% CaF_2 (fluorite) for a contained 310,000 t of CaF_2 (Globe, 2011).

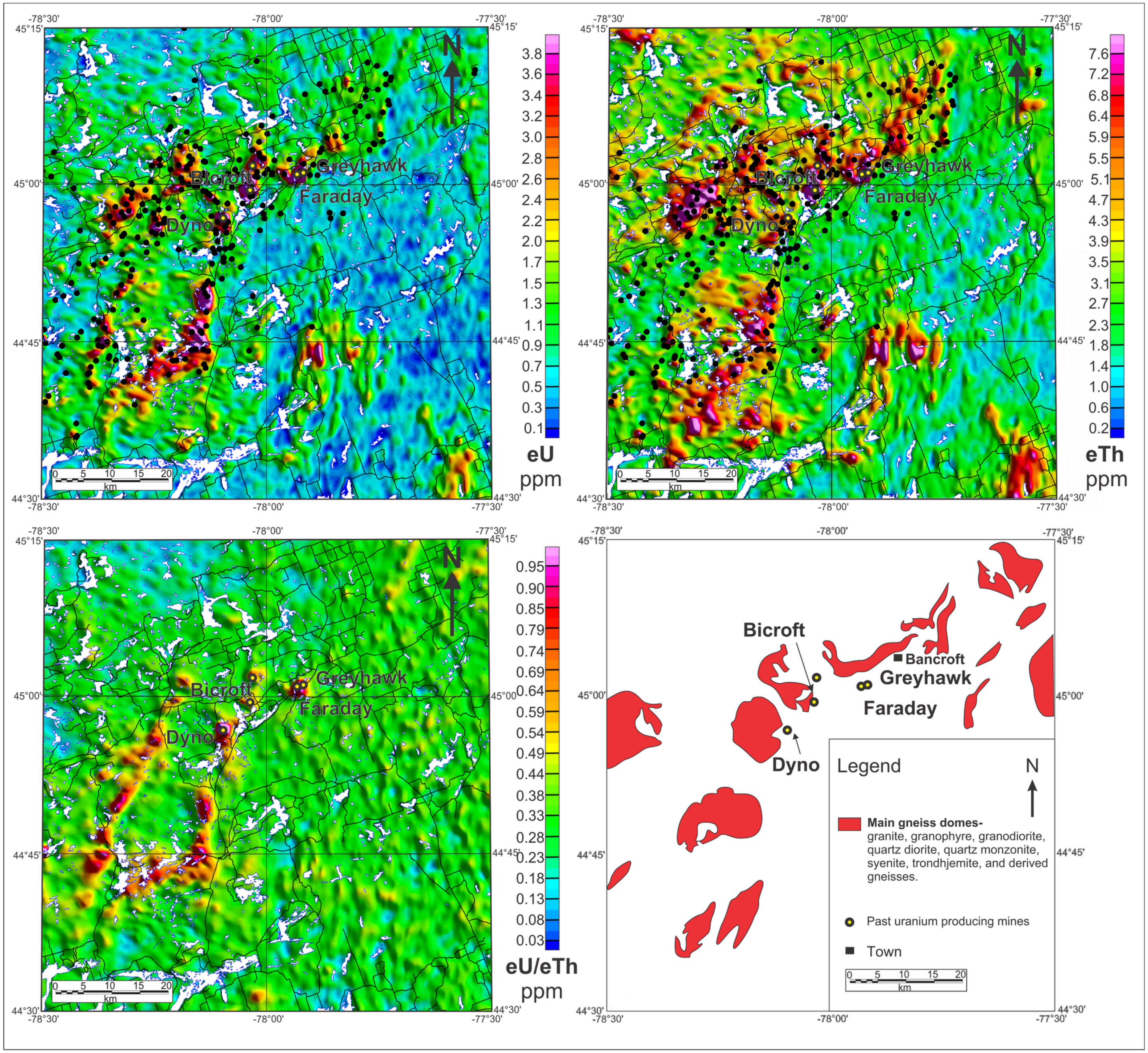

Fig. 5. Airborne eU, eTh and eU/eTh highs mimic contacts of large gneissic domes in the Bancroft area, Ontario. Black dots mark mineral occurrences. Past U mines (labeled) produce discrete anomalies on the eU/eTh map. Location of large gneissic domes from Freeman (1978).

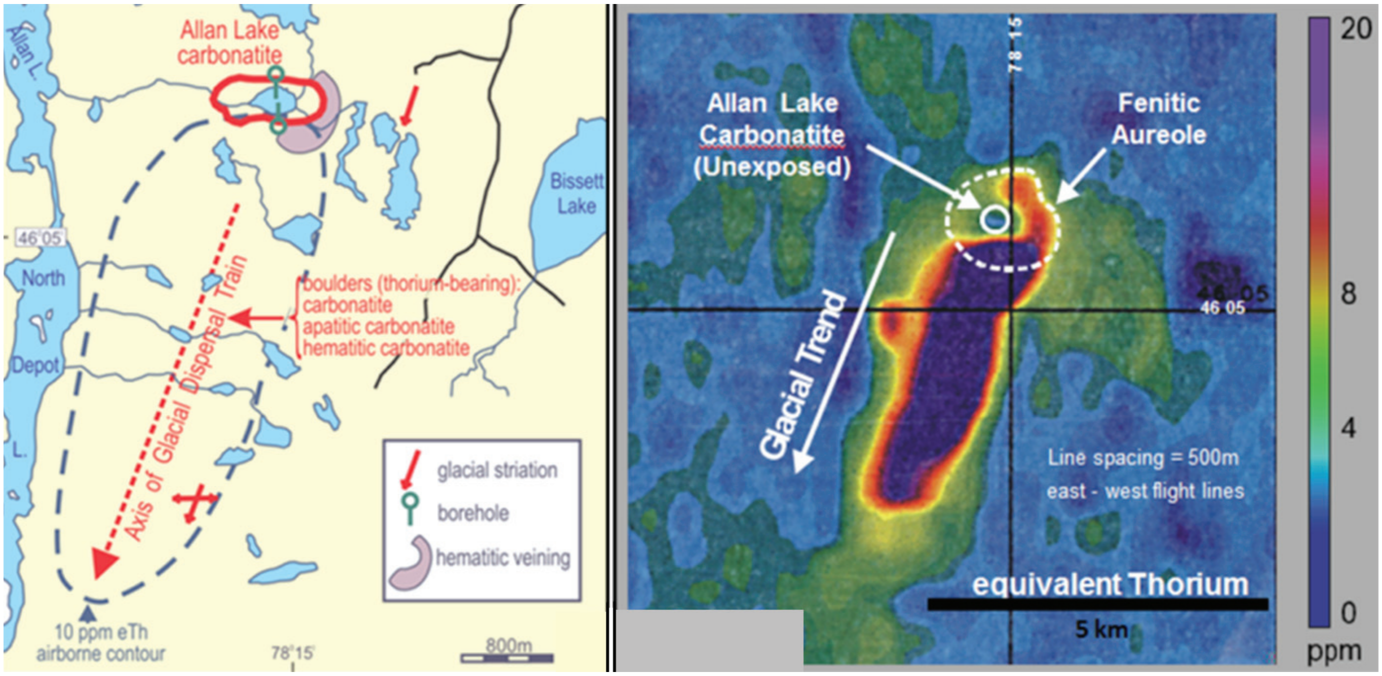

Fig. 6. Airborne eTh patterns (Geological Survey of Canada archives) map glacially dispersed Allan Lake carbonatite material versus local background till deposited on regional gneissic host rocks.

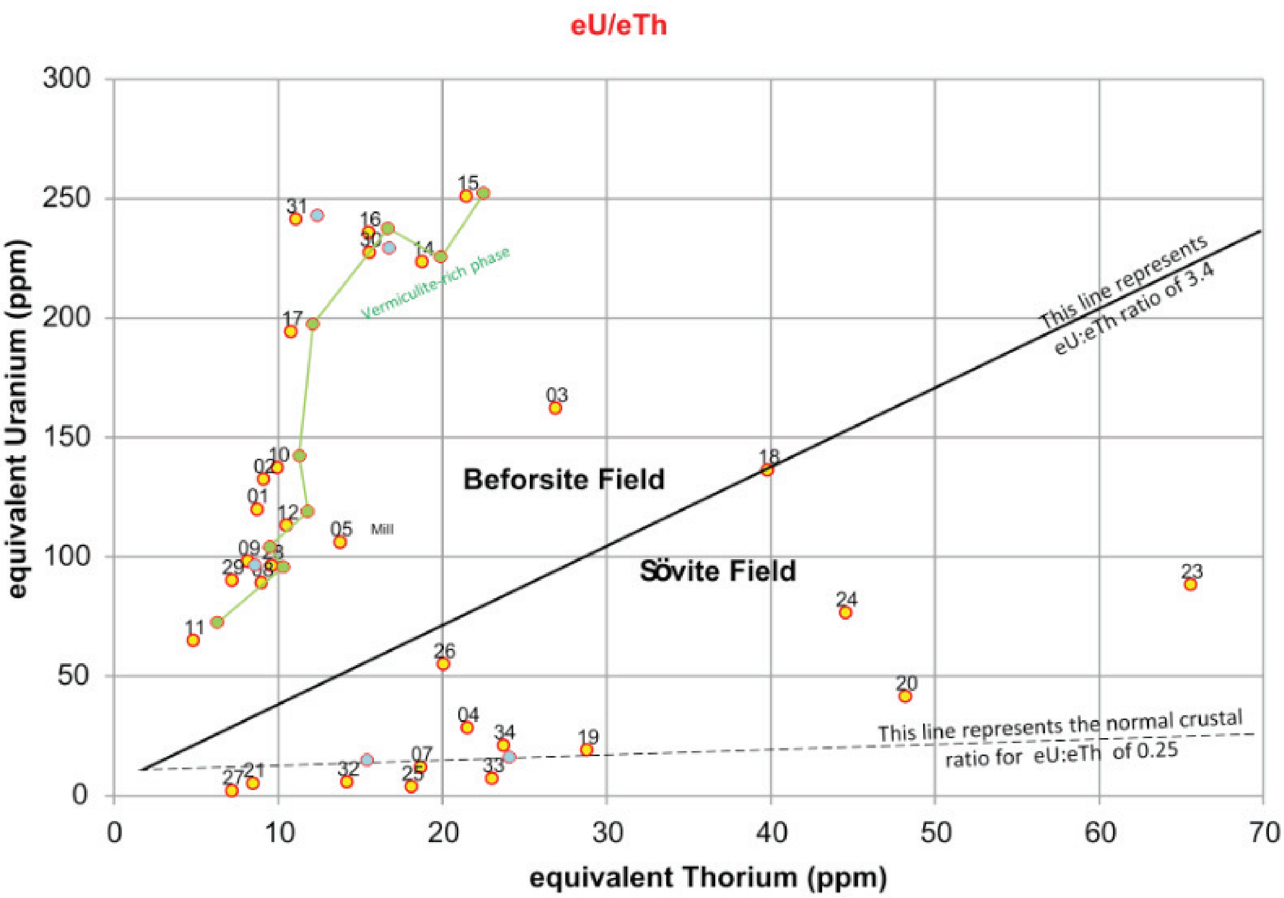

Fig. 7. Bivariate plot of ground spectrometric data (yellow dots) over unidentified carbonatites located in western Canada. Here, Ta-enriched beforsitic phases are also relatively enriched in uranium, whereas Nb-enriched sövitic phases contain relatively more thorium. Several readings taken on a vermiculite-rich phase (the smaller, green dots and trend-line) show that this phase relates to beforsitic magma, rather than sövitic (Shives, 2009).

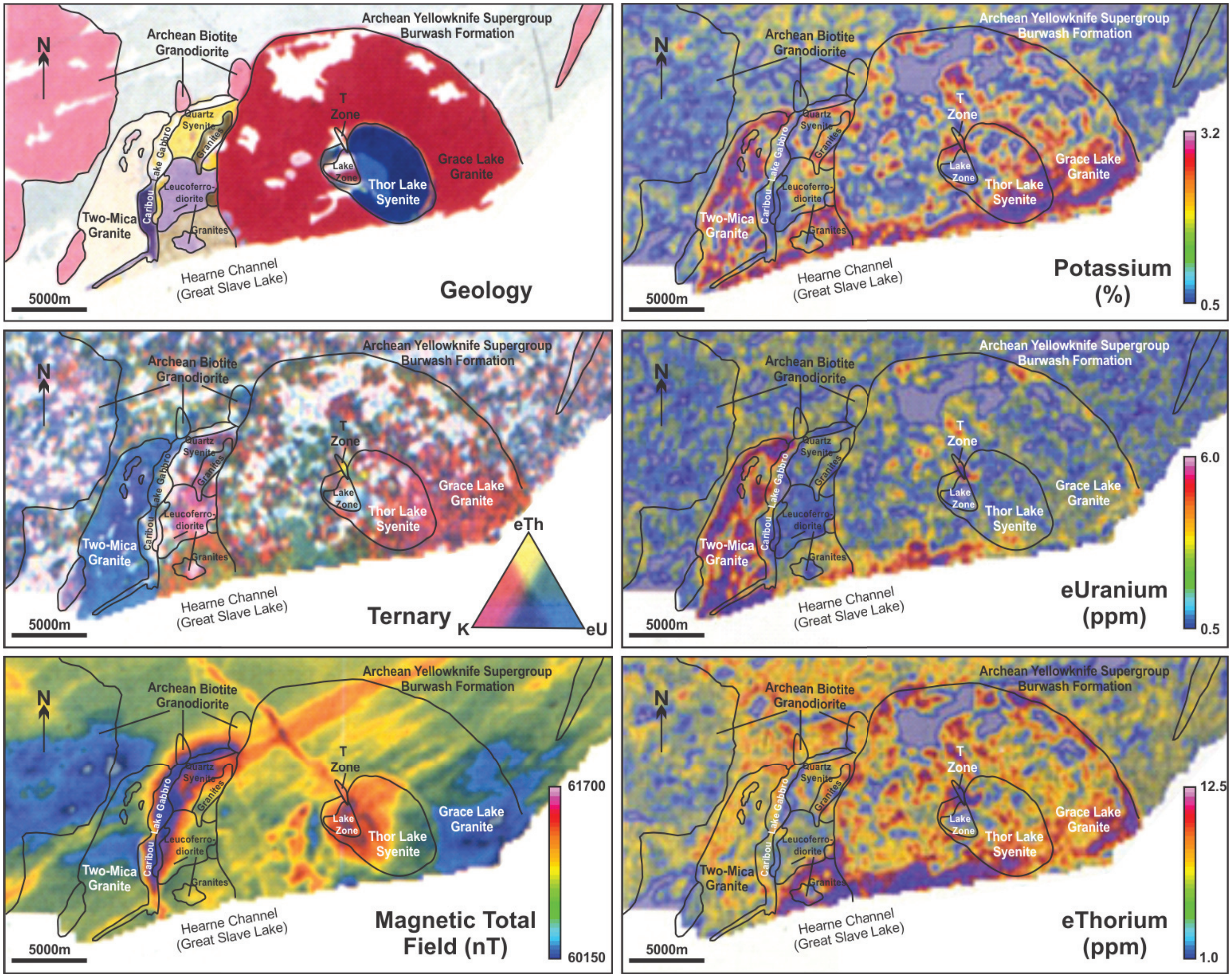

Fig. 8. Strong gamma ray and magnetic contrasts over the Nechalacho deposit in Northwest Territories, Canada, provide bedrock mapping and exploration guides. For example, the positive magnetic response over the Caribou Lake gabbro, and high equivalent uranium (eU) associated with the two-mica granite on the west side of the image, can be used to map their contacts. Note the equivalent thorium (eTh) anomaly over the T-Zone at Nechalacho. These radioactive element relative variations produce marked colour contrasts on the ternary image. Geology from Henderson et al. (1981).

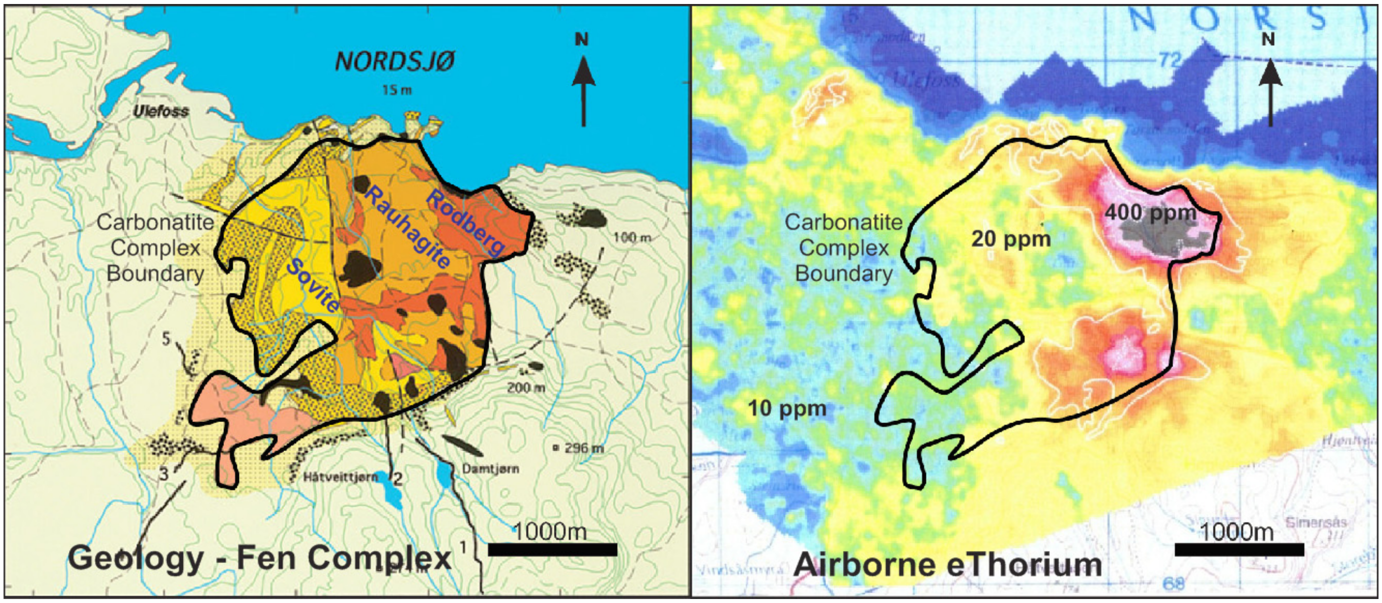

Fig. 9. The Fen Complex, Norway, hosts deposits of REEs + Y, Th and Fe (left). Airborne eTh concentrations reflect various phases (right), low-Th, Nb-bearing sövite, intermediate-Th rauhaugite and high-Th, REE-rich rodberg phases and REE, Nb, and Y mineralization (Lie and Ostergaard, 2011).

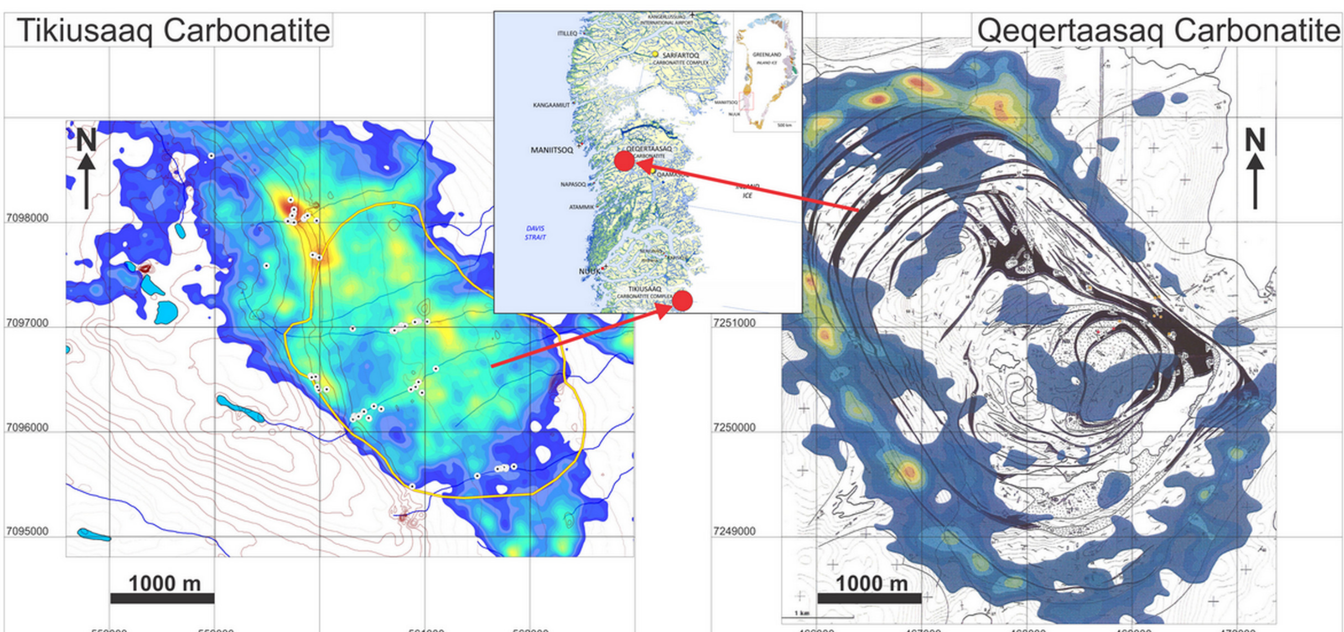

Fig. 10. Highest airborne eTh concentrations overlie Archean REE-bearing peralkaline rocks at two carbonatite complexes in southwestern Greenland. Tikiusaaq (left, outlined by yellow line) thorium values correlate with highest REE concentrations (9.6% TREO). At Qeqertaasaq (right, with eTh contours superimposed on 1987 geological map by the Geological Survey of Denmark and Greenland), thorium overlies peripheral sövitic ring dikes and veins containing Ce, La, Nb, Ta and other REEs. From Nuna (2015b).

4. Conclusion

Geological applications of gamma ray spectrometry include mapping and exploration for a wide variety of deposits, such as those containing REE, Zr, Ta, Nb, Ta, and U. The method uses absolute and relative variations of K, U, and Th to detect primary lithological signatures and subsequent alteration. Where one or more of these elements is associated with elements of economic interest, their concentrations and ratios, as determined by gamma ray spectrometry, can serve as guides to mineralization. Where political and environmental concerns exist regarding radioactivity of ores and waste products, the spectrometric data also offer important baseline information useful to all development stages from early exploration through to post-extraction reclamation.

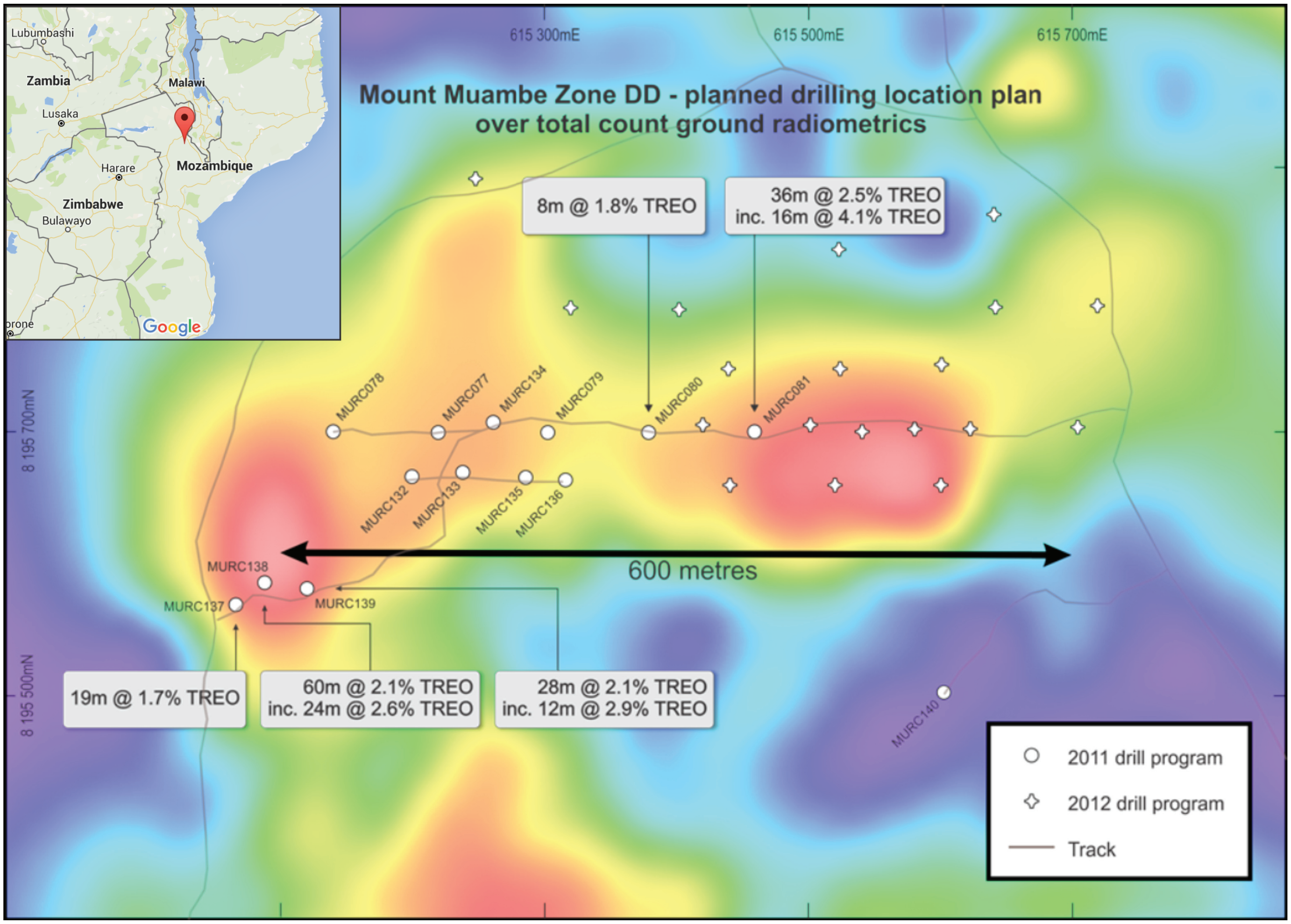

Fig. 11. At the Mount Muambe Carbonatite, Mozambique, ground gamma ray surveys have provided guides to HREO and fluorite prospects explored in 2011-2012. Higher total count values are shown in hotter pink colours, low values in blue tones. Correlation between the gamma ray results and drilling results is apparent. From Globe (2011).

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