

## Geophysical interpretation of U, Th, and rare earth element mineralization of the Bokan Mountain peralkaline granite complex, Prince of Wales Island, southeast Alaska

Anne E. McCafferty<sup>1</sup>, Douglas B. Stoesser<sup>2</sup>, and Bradley S. Van Gosen<sup>2</sup>

### Abstract

A prospectivity map for rare earth element (REE) mineralization at the Bokan Mountain peralkaline granite complex, Prince of Wales Island, southeastern Alaska, was calculated from high-resolution airborne gamma-ray data. The map displays areas with similar radioelement concentrations as those over the Dotson REE-vein-dike system, which is characterized by moderately high %K, eU, and eTh (%K, percent potassium; eU, equivalent parts per million uranium; and eTh, equivalent parts per million thorium). Gamma-ray concentrations of rocks that share a similar range as those over the Dotson zone are inferred to locate high concentrations of REE-bearing minerals. An approximately 1300-m-long prospective tract corresponds to shallowly exposed locations of the Dotson zone. Prospective areas of REE mineralization also occur in continuous swaths along the outer edge of the pluton, over known but undeveloped REE occurrences, and within discrete regions in the older Paleozoic country rocks. Detailed mineralogical examinations of samples from the Dotson zone provide a means to understand the possible causes of the airborne Th and U anomalies and their relation to REE minerals. Thorium is sited primarily in thorite. Uranium also occurs in thorite and in a complex suite of  $\pm\text{Ti} \pm \text{Nb} \pm \text{Y}$  oxide minerals, which include fergusonite, polycrase, and aeschynite. These oxides, along with Y-silicates, are the chief heavy REE (HREE)-bearing minerals. Hence, the eU anomalies, in particular, may indicate other occurrences of similar HREE-enrichment. Uranium and Th chemistry along the Dotson zone showed elevated U and total REEs east of the Camp Creek fault, which suggested the potential for increased HREEs based on their association with U-oxide minerals. A uranium prospectivity map, based on signatures present over the Ross-Adams mine area, was characterized by extremely high radioelement values. Known uranium deposits were identified in the U-prospectivity map, but the largest tract occurs over a radioelement-rich granite phase within the pluton that is likely not related to mineralization. Neither mineralization type displays a well-defined airborne magnetic signature.

### Introduction

Mineral deposits with rare earth element (REE) enrichment have gained more attention recently as the global demand for these elements has increased driven by technological developments, restrictions of rare earth oxide exports by China, and geologic factors affecting availability (U.S. Geological Survey, 2011; Alonso et al., 2012; Bleiwas and Gambogi, 2013). Although REEs as a group are not rare in terms of average (ave.) crustal abundance, concentrated and economic deposits of REEs are unusual (Adams and Staatz, 1973). Crustal abundances for heavy REEs (HREEs) ( $_{65}\text{Tb}$ ,  $_{66}\text{Dy}$ ,  $_{67}\text{Ho}$ ,  $_{68}\text{Er}$ ,  $_{69}\text{Tm}$ ,  $_{70}\text{Yb}$ ,  $_{71}\text{Lu}$ , and  $_{39}\text{Y}$ ) are lower compared to crustal concentrations of the light REEs (LREEs) ( $_{57}\text{La}$ ,  $_{58}\text{Ce}$ ,  $_{59}\text{Pr}$ ,  $_{60}\text{Nd}$ ,  $_{62}\text{Sm}$ ,  $_{63}\text{Eu}$ ,

and  $_{64}\text{Gd}$ ) (Lide, 2004). Intrusion-hosted REE deposits contain the range of REEs. Presently, deposits with economic concentrations of HREEs are fewer than deposits enriched in the LREEs (Bleiwas and Gambogi, 2013). Consequently, worldwide supply of the HREEs is less compared to the supply of LREEs. In 2010, China supplied 100% of the world's HREEs mostly from rare-earth-bearing ion-adsorption clays that are mined in various locations in China's southeastern provinces of Fujian, Guangdong, and Jiangxi (Wilburn, 2012). These deposits are valued for their medium REE and HREE content (Long et al., 2010). In 2010, China has begun to curb exports of rare earth oxides, raising international concern for adequate supply and encouraging increased REE exploration (Tse, 2011; Hatch,

<sup>1</sup>U.S. Geological Survey, Crustal Geophysics and Geochemistry Science Center, Denver, Colorado, USA. E-mail: anne@usgs.gov.

<sup>2</sup>U.S. Geological Survey, Central Mineral and Environmental Resources Science Center, Denver, Colorado, USA. E-mail: dstoesser@usgs.gov; bvangose@usgs.gov.

Manuscript received by the Editor 14 January 2014; revised manuscript received 25 July 2014; published online 10 October 2014; corrected version published online 24 October 2014. This paper appears in *Interpretation*, Vol. 2, No. 4 (November 2014); p. SJ47–SJ63, 6 FIGS., 2 TABLES.

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2012). Because of their global scarcity, prices for the HREE oxides are generally higher than prices paid for LREE oxides (Humphries, 2013).

Many (possibly most) of the known REE deposits were originally discovered by prospectors searching for uranium deposits. Most of the inadvertent discoveries of REE deposits in the United States occurred during the 1940s and 1950s when the Atomic Energy Agency was providing financial incentives for the discovery of uranium deposits. Examples of REE deposits in the United States that were first discovered by uranium prospectors include the REE-Th-U deposits of Bokan Mountain (Thompson, 1988; Long et al., 2010); the Mountain Pass deposit in California (Olson et al., 1954); the Wet Mountains area, Colorado (Christman et al., 1953, 1959; Armbrustmacher, 1988); the Diamond Creek area of Idaho (Anderson, 1958); the Lemhi Pass area of Idaho–Montana (Staat, 1972, 1979); the Capitan Mountains, south-central New Mexico (Griswold, 1959); the Laughlin Peak area, northeastern New Mexico (Staat, 1985); and the Lemitar and Chupadera Mountains, west-central New Mexico (Van Allen et al., 1986; McLemore, 1987). Gamma-ray surveying has been

used successfully to map several intrusion-hosted REE deposits worldwide because many rare earth minerals contain significant amounts of uranium and thorium (Verplanck et al., 2014). For example, in Canada, the St-Honoré carbonatite complex in Quebec was discovered when an airborne gamma-ray survey detected the high Th content of the complex; REE were found by follow-up geochemical studies within the area outlined by the most intense total count gamma-ray anomaly (Vallée and Dubac, 1970). The Th-rich Allan Lake carbonatite, Ontario, was discovered in 1977 by a reconnaissance airborne gamma-ray survey conducted by the Geological Survey of Canada's (GSC)'s Uranium Reconnaissance Program (Ford et al., 1988). Hence, gamma-ray surveying and methods that use gamma-ray data should be of particular interest to the exploration community worldwide.

Bokan Mountain is located near the southern tip of the Prince of Wales Island approximately 60 km southwest of Ketchikan, southeastern Alaska (Figure 1). The Bokan Mountain Granite complex is a Jurassic peralkaline intrusion composed mainly of arfvedsonite and aegerine granites that are host to over a dozen identified

uranium, thorium, and REE deposits and occurrences (MacKevett, 1963; Warner and Barker, 1989). The Ross-Adams uranium deposit was discovered in 1955 and mined for uranium intermittently from 1957 to 1971, producing a total of 87,300 short tons of uranium ore (Stephens, 1971). The uranium is hosted in aegerine syenite (Thompson et al., 1980, 1982) in the southeast part of the pluton. Current exploration efforts are focused on northwest-trending sets of structurally controlled felsic dikes (also referred to as *vein-dikes*), which are related to the granite complex and contain significant REE enrichments. In particular, the Dotson vein-dike system or zone, which extends in an east-southeasterly direction outward from the granite for a distance of more than 2 km (Figure 1), is the focus of an advanced mineral exploration program (UCore Rare Metals Inc., 2011). The deposit is notable because of its enrichment in the heavy REEs (HREE).

Early into their exploration program at Bokan Mountain, UCore Rare Metals acquired high-resolution airborne magnetic and gamma-ray (%K, percent potassium; eU, equivalent parts per million uranium; and eTh, equivalent parts per million thorium) data over the granite complex and surrounding geology (Figure 1). In our analyses, the airborne data are used to characterize the radioelement signatures of the REE mineralization at

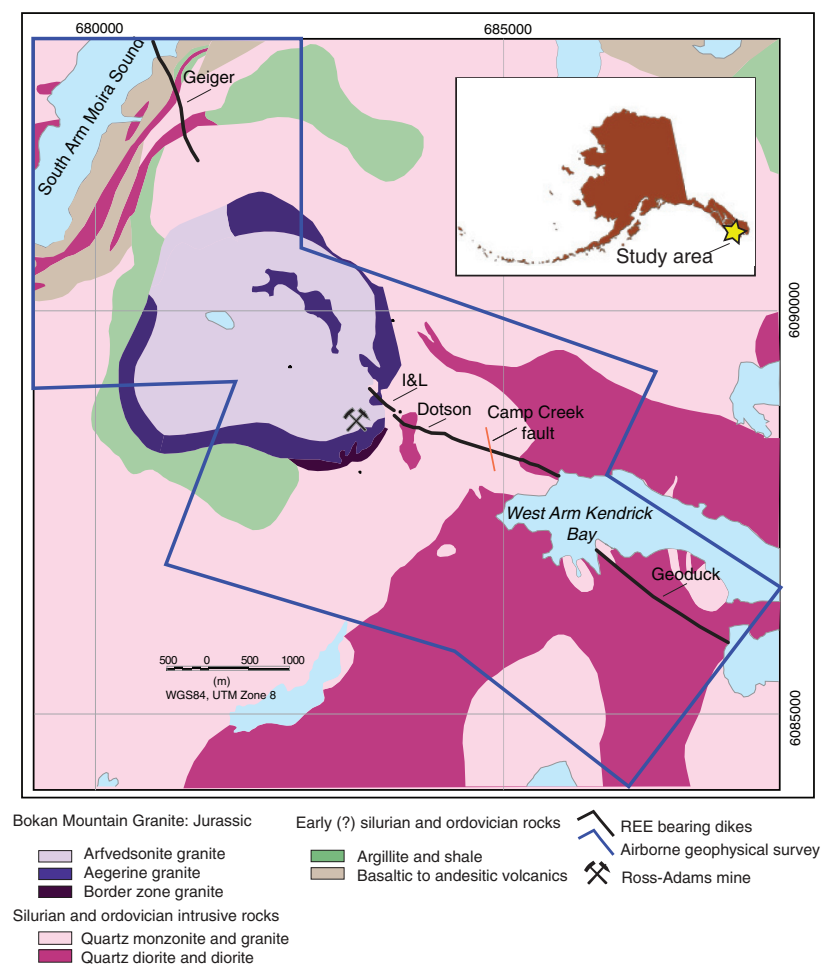


**Figure 1.** Generalized geologic map (after Gehrels and Saleeby, 1987; Thompson, 1988), major REE bearing vein-dike systems, and location of high-resolution airborne geophysical survey.

Bokan Mountain and estimate the size of the pluton that has been interpreted to be related to the mineralization. The radiometric results are compared to signatures of known uranium mineralization at the Ross-Adams mine.

The open pit at the Ross-Adams uranium deposit and the surface trace of the Dotson REE vein-dike system are used as training areas; the gamma-ray data are analyzed to identify specific eU, eTh, and %K concentrations that occur over the deposits. Gamma-ray values characteristic of the mineralization are then integrated in a ternary image to delineate other areas that share similar radioelement properties. The results are used to produce interpretive or “prospectivity” maps that show areas that may be favorable for similar uranium or REE mineralization.

The REE prospective areas are compared to locations of known REE, U, and Th mineralization (MacKevett, 1963; UCore Rare Metals Inc., 2011). We include a detailed mineralogical study describing the thorium and uranium mineralogy in samples collected from the Dotson vein-dike system, which provides a context to understand the influence of the radioelements on rare earth mineralization and as sources for the airborne gamma-ray anomalies. The REE prospectivity map also provides a framework to discuss recent insights into controls on the genesis of the Bokan Mountain Complex (BMC) and related mineralization (Thompson et al., 1982; Philpotts et al., 1996; Dostal et al., 2011).

### Geologic setting

The BMC is approximately 3 km in diameter and is composed of Jurassic (177 Ma) (Dostal et al., 2011; 2013) zoned peralkaline granites (Figure 1). Detailed mapping has defined slightly different subdivisions of the granite (MacKevett, 1963; Thompson et al., 1980, 1982; de Saint-Andre et al., 1983; Gehrels and Saleeby, 1987; Thompson, 1988). Chiefly, the BMC includes two main lithologies: an arfvedsonite granite core that is surrounded by an outer ring of mostly aegerine granite (Dostal et al., 2013). The granite has a 2- to 3-km-wide aureole of albitized country rocks (MacKevett, 1963; Staatz, 1978; Philpotts et al., 1996). The albitized aureole around the pluton is the location of many U-Th-REE prospects and has been interpreted to be related to either hydrothermal activity or magmatic activity associated with the peralkaline granite (MacKevett, 1963). The granites and surrounding country rocks have been overprinted by a hydrothermal event, which Dostal et al. (2011) believe led to metasomatic remobilization and concentration of the uranium, thorium, and rare earth minerals. Alteration types that have been noted within the pluton include hematization, albitization, and silicification (Thompson et al., 1980; Collot, 1981).

The BMC intrudes Silurian/Ordovician plutonic rocks and lower Paleozoic metasedimentary and metavolcanic rocks (Gehrels and Saleeby, 1987). The plutonic country rock comprises primarily quartz monzonite and quartz diorite (Figure 1). The monzonitic rocks are in contact

with the Bokan Mountain pluton around its northern and eastern margins. Metasedimentary rocks including argillites and carbonaceous slates form a semicircular ring around the south and west edge of the pluton. The monzonite is albitized and the slates are hornfelsed at their contacts with the pluton (Dostal et al., 2011). Quartz diorite crops out around the West Arm of Kendrick Bay and to a lesser extent along the South Arm of Moira Sound, where it is in contact with the oldest rocks in the study area, which are lower Paleozoic basalts and andesitic metavolcanic rocks (MacKevett, 1959).

### Mineralization

A significant amount of research has been conducted on the uranium and REE mineralization at Bokan Mountain since the late 1950s (MacKevett, 1959, 1963; Staatz, 1978; Thompson et al., 1982; Thompson, 1988; Warner and Barker, 1989; Philpotts et al., 1996; UCore Rare Metals Inc., 2011; Dostal et al., 2011, 2013, 2014; Barker and Van Gosen, 2012). Uranium mineralization was recognized in the mid-1950s at the Ross-Adams deposit, which brought more interest and scrutiny to the geology at Bokan Mountain, eventually leading to the recognition of rare earth mineralization. As part of MacKevett's (1959) research to characterize the Ross-Adams uranium deposit, REE deposits were first identified in the BMC and in pegmatites and aplite dikes that intrude the granitic complex. The uranium deposit is hosted in veins, pods, and pipelike ore bodies with the dominant ore minerals being uranothorite and uranoan thorianite (MacKevett, 1963).

Rare earth mineralization is hosted in four types of deposits at Bokan Mountain: (1) shear zones and faults that cross the BMC; (2) pegmatites within and along the margins of the BMC; (3) within structurally controlled, northwest-trending sets of thin dikes (vein-dikes) that extend outward from the granite; and (4) in subeconomic placer deposits in postglacial sediments (Staatz, 1978; Warner and Barker, 1989).

To date, the most REE-enriched of these deposits are the northwest-trending REE-bearing mineralized vein-dike systems associated with shear-fault zones (UCore Rare Metals Inc., 2011). At least four REE-bearing dike systems have been mapped: Dotson Ridge, which is the largest extending outward from the BMC more than 2 km; the Geoduck; Geiger; and the I&L (Figure 1).

### Geophysical data

#### Previous airborne geophysical surveys

One of the earliest airborne magnetic surveys flown in the United States for nonmilitary purposes occurred over the area that includes Bokan Mountain in 1945. The survey was flown by the U.S. Geological Survey (USGS) in cooperation with the U.S. Navy and was initiated to evaluate the utility of magnetic surveys for copper and iron ore deposits (Rossman et al., 1956). In 1955, spurred by a boom in uranium exploration in the western United States, Ketchikan, Alaska bush

pilot Don Ross flew over Bokan Mountain with a portable scintillation counter. He measured a total count anomaly high over an area on the southeastern flank of the mountain. The high was subsequently ground checked by Ross and geologist Kelly Adams. These efforts led to the development of the Ross-Adams uranium mine, which began production in 1957 (MacKevett, 1963).

In 1976, the U.S. Department of Energy flew a reconnaissance helicopter radiometric and magnetic survey over the Craig 1° by 3° quadrangle, which encompasses the entire Bokan Mountain study area, as part of the National Uranium Resource Evaluation program (LKB Resources Inc., 1979). The data, which are available digitally, were collected along very coarsely spaced (10 km) east–west flight lines and 40-km spaced north–south tie lines at a nominal altitude of 122 m above ground. Only one tie line and one flight line crossed the Bokan Mountain study area. In 1978, the U.S. Department of Energy funded a subsequent helicopter radiometric survey over Bokan Mountain (Burgett and Krause, 1979). Data for this survey are only available on microfiche as contour maps in counts per second and are not useful for studies at deposit scales.

In 1982, as part of a federal mandate to survey certain Alaskan federal lands for mineral potential, the USGS flew a magnetic survey over the southern Prince of Wales Island (U.S. Geological Survey, 1984). Data were collected along north–south flight lines spaced every 1.6 km at a mean terrain clearance of 305 m above ground. Wynn et al. (1999) provide a regional interpretation for the causes of major magnetic anomalies. Seven north–south flight lines that cross the study area are available digitally, and provide a regional magnetic anomaly field that is used here to determine the coarse subsurface geometry of the Bokan Mountain Granite pluton.

### **High-resolution helicopter magnetic and gamma-ray survey data**

During 2009 and 2010, magnetic and gamma-ray spectrometric data were collected simultaneously by helicopter by Precision GeoSurveys over Bokan Mountain and the surrounding area (Figure 1). Aerial gamma-ray surveys measure the naturally emitted gamma radiation derived from three radioelement K, U, and Th, via daughter radionuclides for the latter two, hence the prefix “e” for eU and eTh. The area was flown in four parts with varying flight-line directions for each block. Technical specifications on the survey design, equipment, reduction procedures, and corrections for the gamma-ray and magnetic data are described in UCore Rare Metals, Inc. (2011). Radioelement data were provided in relative concentrations. Flight lines for all blocks were spaced at 100 m with tie lines flown every 1 km perpendicular to the flight-line direction. A total of 410 line-kilometers of magnetic and gamma-ray data were collected at terrain clearances ranging from

35 to 59 m above the ground surface. The ave. sampling interval along the flight lines for the magnetic data is 2 to 2.5 m and 25 m for the gamma-ray data (UCore Rare Metals Inc., 2011).

Relative concentrations of eU, eTh, and %K were gridded at 30 m for each survey block using an inverse distance weighted gridding algorithm. A scaling factor and constant were determined from the overlap between grids and applied to individual grids to level the blocks to a common datum. The four blocks were merged to create composite grids of %K, eU, and eTh (Figure 2a, 2b, and 2c, respectively).

Minimum to maximum values range from –0.53 to 19.9% for the potassium grid, from –0.06 to 186.6 ppm for the uranium grid, and from –0.75 to 594 ppm for the thorium grid (Table 1). The negative values that are present in all three gamma-ray grids occur mostly over water where the signal is shielded. Negative values over land areas are assumed to correspond to rocks and soils with very low radioactivity or may be water saturated.

Gamma-ray anomaly highs in all three channels that correspond to cultural features are noted on the maps (Figure 2a–2c). These include linear anomaly highs related to spillage of ore along the haul roads from the Ross-Adams mine (UCore Rare Metals Inc., 2011), elongate highs over the Ross-Adams open pit, and bull’s-eye highs located over an ore pile located at the load-out dock at the shore of Kendrick Bay.

Grids of the magnetic anomaly flight-line data (corrected for the International Geomagnetic Reference Field), were calculated using a 25-m cell size for each survey block. A constant was added or subtracted as necessary to level one block to another. The four survey blocks were combined into a single grid, and a reduced-to-pole (RTP) algorithm was applied (Phillips, 1997) to correct for any positional shift and anomaly distortion at this geomagnetic latitude using a declination = 26.6° and an inclination = 73° (Figure 3a).

The magnetic data from the older 1982 USGS survey (U.S. Geological Survey, 1984) were also gridded at one-fourth the flight-line spacing using a 400-m interval, and RTP (Figure 3b). The WGS84 datum and UTM Zone 8 projection was used for all geophysical, geochemical, and geologic data.

## **Geophysical analyses**

### **Subsurface geometry of the Bokan Mountain pluton**

The boundary of the helicopter geophysical survey truncates the pluton on its southwest and northeast sides and so, unfortunately, is limited in its use to map the pluton in its entirety. However, although the low-resolution (1.6-km-spaced) magnetic anomaly data over the BMC are coarse — only four north–south flight lines cross the pluton (Figure 3b) — the data cover the entire pluton and extend into the surrounding area and, hence, are useful to evaluate the overall geometry and potential subsurface extent of the pluton.

The regional magnetic data from the older survey shows that the BMC coincides with a north–north-east-trending ovoid anomaly low. Edges for the source of the anomaly low were inferred by applying the horizontal gradient magnitude (HGM) method (Cordell and Grauch, 1985) to the gridded regional RTP data. A contour that traces the HGM maximum values (Figure 3b)

suggests that the pluton may be larger at depth, with dimensions roughly  $3.6 \times 2.1$  km in size. Tighter gradients on the southeast and northwest suggest a steeper dip along these boundaries. Less steep gradients on the north edge suggest that the pluton dips shallowly beyond and under the edge of the exposed Silurian–Ordovician granitic rocks.

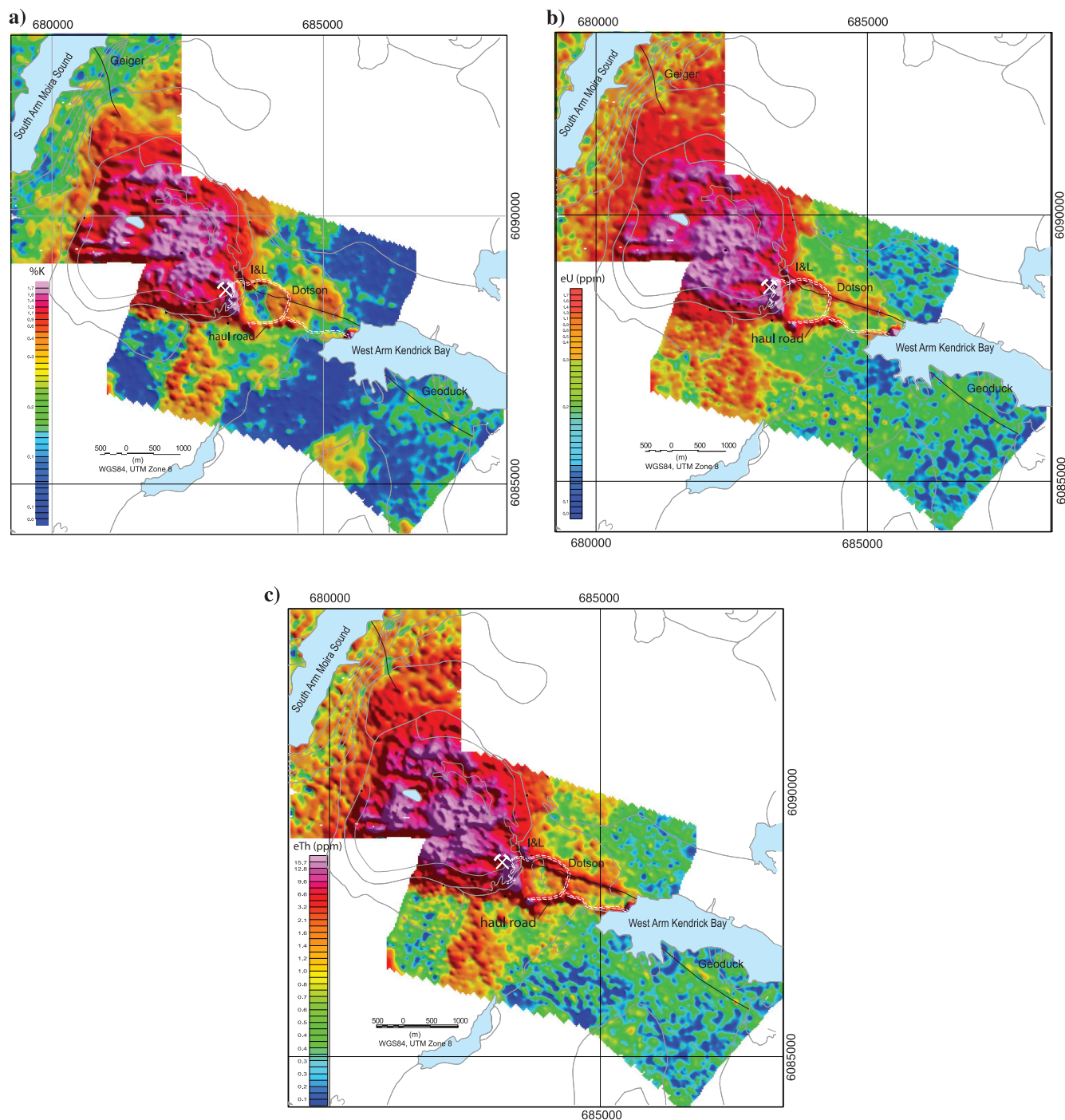


**Figure 2.** Airborne gamma-ray maps over Bokan Mountain and vicinity. Flight-line data provided by Precision GeoSurveys in cooperation with UCore Rare Metals, Inc. (2011) (a) %K, (b) eU (ppm), and (c) eTh (ppm). Major REE-bearing vein-dike systems are shown as well as the geologic contacts.

### Calculation of REE- and U-mineralization prospectivity maps from gamma-ray data

The data from the airborne radiometric survey are used to examine the K, U, and Th signals over shallow exposures of the Dotson vein-dike system to determine whether similar radioelement abundances are in some way indicative of rare earth mineralization in other parts of the survey area. Gamma-ray maps are essentially geochemical maps of K, U, and Th, so variations in the concentration of these elements are primarily related to the mineralogy and geochemistry of rock and soil within the uppermost 30 to 40 cm of the surface (International Atomic Energy Agency, 2003). Because the gamma-ray method maps radioelement concentrations within very shallow depths, we assume that mineralization deeper than approximately 40 cm or located within this depth range, but covered, will not be detected by this approach.

Specifically, our approach involved three steps, which included (1) define a training area based on known mineralization, (2) determine the radioelement signature over the training area, and (3) combine the characteristic radioelement signatures into a prospectivity map. The training area was defined along a length of the Dotson zone, approximately 1300- to 1500-m long, with a mostly continuous airborne gamma-ray signature. The felsic vein-dikes within the Dotson trend are best exposed along either side of the Camp Creek fault, which bisects the Dotson zone (Figure 1). The gamma-ray signal is lost at the extreme east and west ends of the Dotson because the vein-dikes are covered with alluvial material and thick vegetation (UCore Rare Metals Inc., 2011, 2013).

To determine the radioelement signature spatially associated with the trace of the best exposed parts of the Dotson system, the three airborne gamma-ray grids were input into an red-green-blue algorithm as individual bands using the ERDAS ER Mapper image processing system (Intergraph, 2014) with K concentrations displayed in red, eU in blue, and eTh in green. In general, each image is comprised of an array of pixels. In any one of the radioelement images, the color of a pixel represents the concentration of the band represented by that color. The brightest colors represent the highest concentration values, and dark hues represent areas of lowest concentrations. The horizontal axis on the histo-

grams shows the signal concentration versus number of pixels with a given concentration on the vertical axis (Figure 4).

A step transform was applied to the histogram of each element channel (shown as the dashed lines on the histograms in Figure 4). The step transform served to bin concentrations into values of either 0 or 255. Values of 255 represent concentrations that occur over the Dotson vein-dikes and are the brightest color in each channel. A value of zero (darkest color or black) corresponds to K, eU, and eTh concentrations that fell outside those ranges. Specifically, a value of 255 denotes K values between 0.8% and 2.15%; eU concentrations between 3.1 and 11.8 ppm; and eTh concentrations between 12 and 38.2 ppm (Table 1). The binary images for each channel were then combined into a ternary image (Figure 4) where the white areas show where the K (red), eU (blue), and eTh (green) pixels overlap.

The REE-prospectivity map was created by converting the brightest (white) areas of the ternary image to polygons. The gamma-ray expression from spillage of uranium ore (UCore Rare Metals Inc., 2011) along the Ross-Adam's haul road falls within the range of %K, eTh, and eU for the REE-dominant mineralization. However, because the road signature is not geologic, it was not included in the final REE prospectivity map (Figure 5).

The ternary image shows a total of seven classes represented in the REE prospectivity map (Figure 4). Classes are indicated by different colors that correspond to one or combinations of two or three radioelements with gamma-ray signatures consistent with that over the Dotson zone. For example, the red areas represent rocks that share the same K signature as Dotson but have eU and eTh concentrations that fall outside the range mapped over the Dotson zone. Areas that are mapped as light blue have an eU and eTh signature similar to that over the Dotson zone but have K concentrations not found along the Dotson structure.

The same process was used to determine a prospectivity map for U-mineralization using the area over the Ross-Adams open pit and mine workings as a training area for the gamma-ray data. Results for the uranium mineralization (Table 1) are only presented here in a cursory form for comparison purposes because the focus of our study resides primarily on the REE mineralization.

**Table 1. Airborne gamma-ray concentrations for the Bokan Mountain survey (land areas only), the Dotson REE prospectivity areas, and Ross-Adams U prospectivity areas.**

|         | K (%)       |            |              | eU (ppm)    |            |              | eTh (ppm)   |            |              |
|---------|-------------|------------|--------------|-------------|------------|--------------|-------------|------------|--------------|
|         | Survey area | Dotson REE | Ross-Adams U | Survey area | Dotson REE | Ross-Adams U | Survey area | Dotson REE | Ross-Adams U |
| Minimum | -0.53       | 0.8        | 3.2          | -0.02       | 3.1        | 13.8         | -0.7        | 12         | 40.2         |
| Maximum | 19.9        | 2.15       | 19.9         | 186.6       | 11.8       | 186.6        | 594         | 38.2       | 594          |
| Median  | 0.4         | 1.6        | 4.5          | 1.8         | 6.6        | 17.7         | 3.5         | 18.2       | 50.2         |

### Prospectivity map results

Because the prospective tracts are derived from gamma-ray measurements, sources for the radioele-

ments must be located within the upper 30–40 cm of the surface material ([International Atomic Energy Agency, 2003](#)) to be traceable. In many cases,

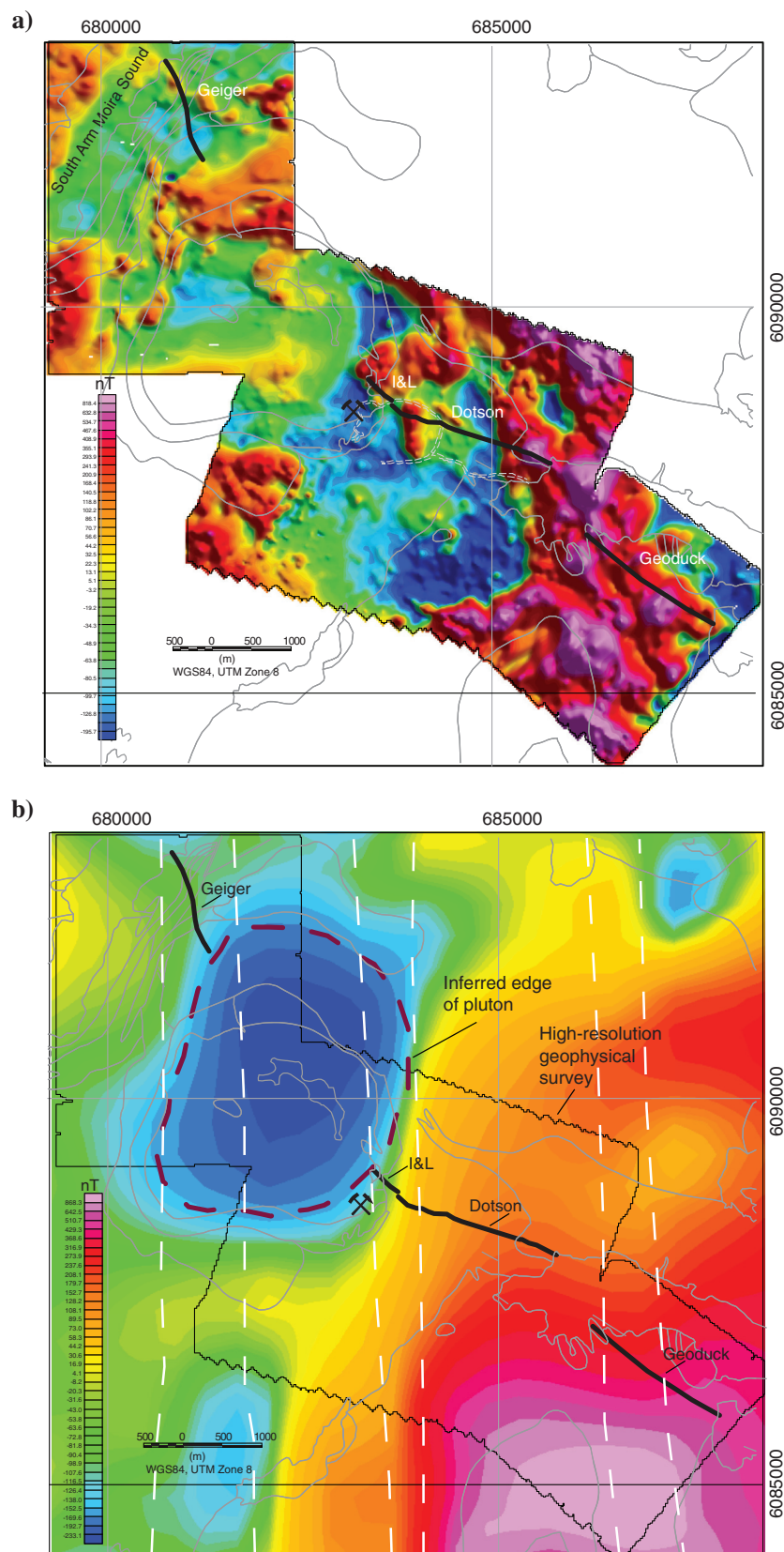


**Figure 3.** (a) High-resolution magnetic anomaly. Data provided by Precision GeoSurveys in cooperation with UCore Rare Metals Inc. (2011) and (b) low-resolution regional magnetic anomaly (U.S. Geological Survey, 1984). Both magnetic fields are RTP. Dashed line shows the trace of the horizontal gradient maxima of the RTP data, which infers the extent of the Bokan Mountain pluton. Major REE-bearing vein-dike systems are shown as well as the geologic contacts.

known mineralized prospects are missed because they are covered. Cover types along the Dotson zone and within the survey area overall are extensive and

include fresh and seawater, alluvium, colluvium, muskeg soil, forest, and thick mattes of ground vegetation.

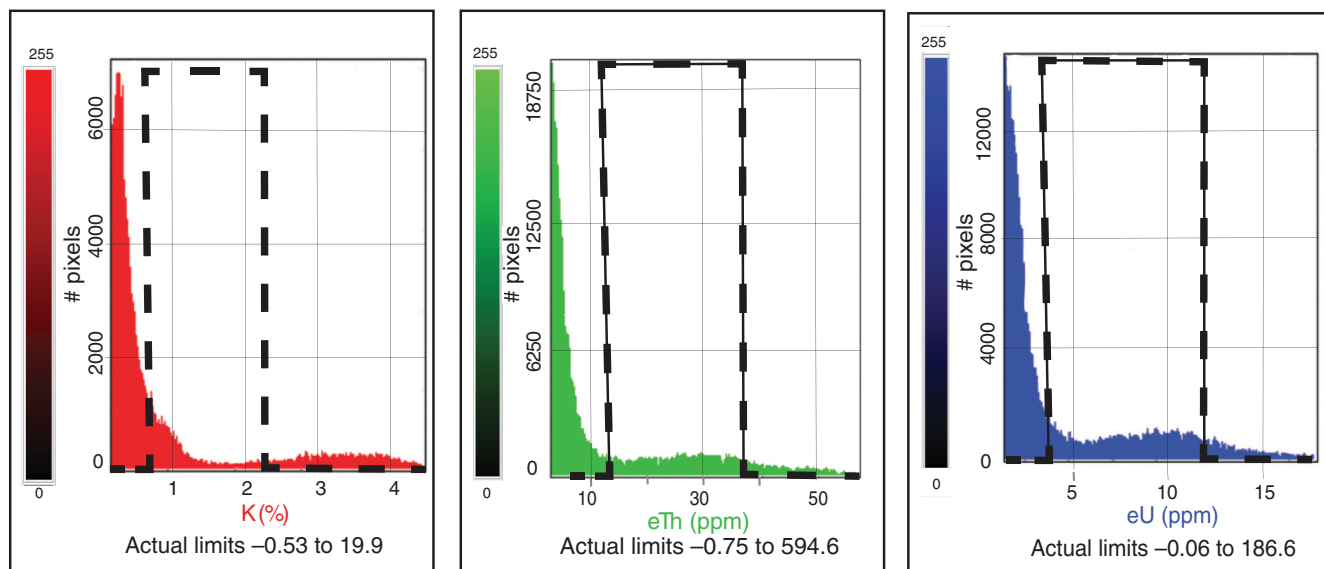
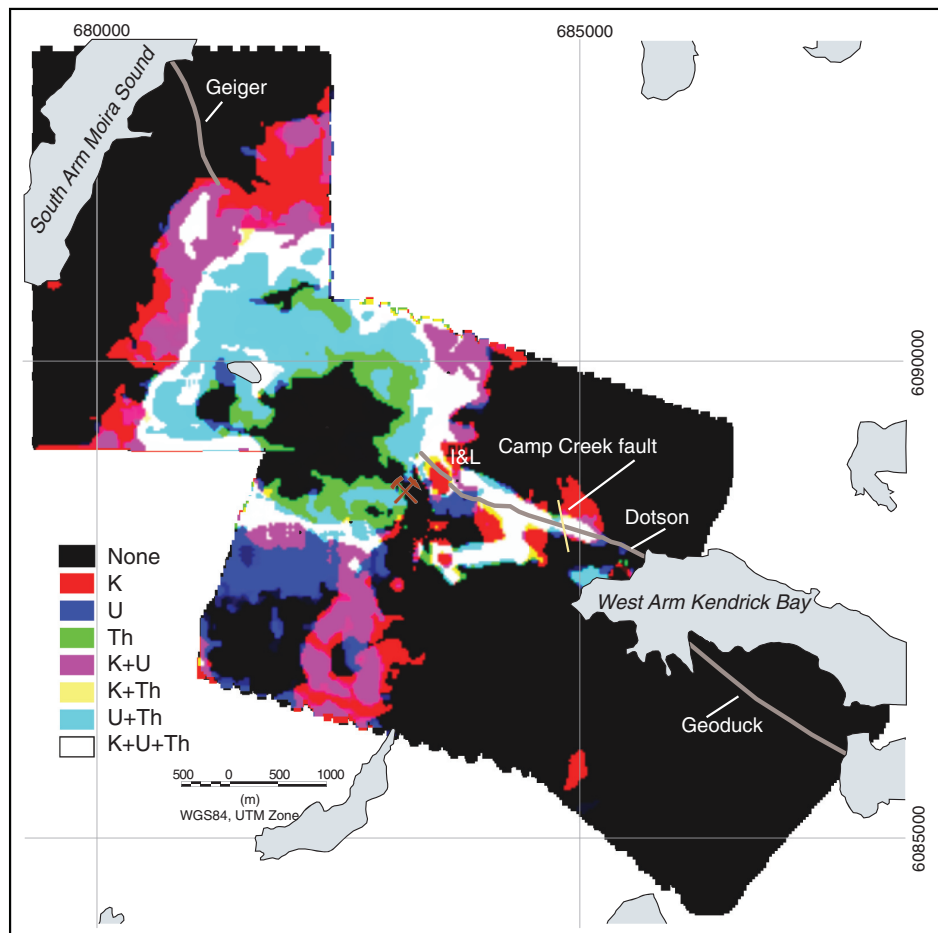


**Figure 4.** Ternary map of gamma-ray data: %K (red), eU (blue), and eTh (green). Areas in white map the range of the three radioelements that correspond to Dotson-type REE mineralization. Histograms show the range of radioelement concentrations. The step transform used to create the ternary map is shown as a dashed line.

To gauge how much of the bedrock within the study area is covered and exposed, a vegetation cover map was calculated from a Landsat scene collected in August of 2001 (R. McDougal, personal communication, 2014). A vegetation map was generated using ENVI 5.1 and the included spectral processing exploitation and analysis routine, vegetation delineation option. The program produces a vegetation cover map using two main steps. First, an image correction was performed using a “dark target subtraction” to minimize the effects of atmospheric scattering. Second, a normalized difference vegetation index (NDVI) was calculated using the red (band 3) and near-infrared (band 4) to map reflectance values of vegetation. Finally, the NDVI reflectance values were classified, based on their digital number (0–255), and binned into classes of no cover, sparse, moderated, and dense. The class thresholds were then adjusted using true-color and false-color infrared imagery to visually inspect the final output map. Results show that within the geophysical survey area, 94% of the study is covered with some level of vegetation. Only the granite, located at the uppermost elevations of Bokan Mountain, is exposed. Most of the REE prospectivity tracts occur in areas with sparse to moderate vegetation. We assume that the airborne concentrations are proportional to, but less than, the rock exposure concentrations, mainly due to the effect of overburden.

The REE prospectivity map delineates the central part of the Dotson vein-dike system for approximately 1300 m of its total length of 2140 m (UCore Rare Metals Inc., 2011). The lack of an REE prospectivity signal on the east and west ends of the zone is attributed to a loss of radioelement signal due to cover. The west end of the vein-dike system, near the BMC pluton boundary, is covered by forest and boulder till, and the east end is covered by recent alluvial deposits and is sparsely to moderately vegetated (UCore Rare Metals Inc., 2011, 2013).

Beyond the Dotson zone, prospective REE mineralization correlates spatially with the locations of several known REE prospects that occur mostly within the outer aegerine granite phase of the Bokan Mountain pluton, including the Sunday Lake, Wennie, Pieper’s Purple, and Irene D prospects (Figure 5). Some of the prospective areas that occur along the pluton border overlap into the surrounding country rock. One of the largest contiguous areas is located on the east side of the pluton near the Irene D prospect, which Warner and Barker (1989) describe as a small (10- to 15-m-wide × 900-m-long) zone of radioactive and magnetic pegmatite dikes. Based on the prospectivity map, the

Irene D may be part of a larger radioactive zone, which is approximately 625 m across at its widest point where it overlaps into quartz monzonite and then narrows toward the north and south where it is mostly within the aegerine granite annular rim. This prospective area also overlaps a triangular-shaped magnetic low (825 × 670 × 810 m). Although Warner and Barker (1989) note that the Irene D pegmatites are magnetite rich, the magnetic low here suggests that the volume of pegmatites is small compared to a significantly larger volume of less magnetic rock.

Another notable REE prospective area occurs northwest of the pluton just to the east of the Boots REE prospect, which is hosted in aplitic dikes and pegmatites (MacKevett, 1963). The map shows a north-south-trending elongate area, approximately 630 × 270 m, although Warner and Barker (1989) mapped only a narrow north-south-trending zone approximately 30 m across. Sampling of Warner and Barker (1989) revealed moderately high concentrations of REEs.

Only a few relatively small areas occur as prospective entirely within the pluton, with the largest being around the lake northwest of the Bokan Mountain summit (Figure 5). The prospective area wraps around the north and east part of the lake with a northwest-trending projection. The strike of this projection is subparallel with the major REE-bearing shear structures in the study.

The REE prospectivity map did not indicate any aerial gamma-ray expression on the Geoduck, Geiger, and I&L REE-bearing felsic dikes, and so they are not depicted on the final prospectivity map (Figure 5). The vein-dike structures are not readily apparent in the

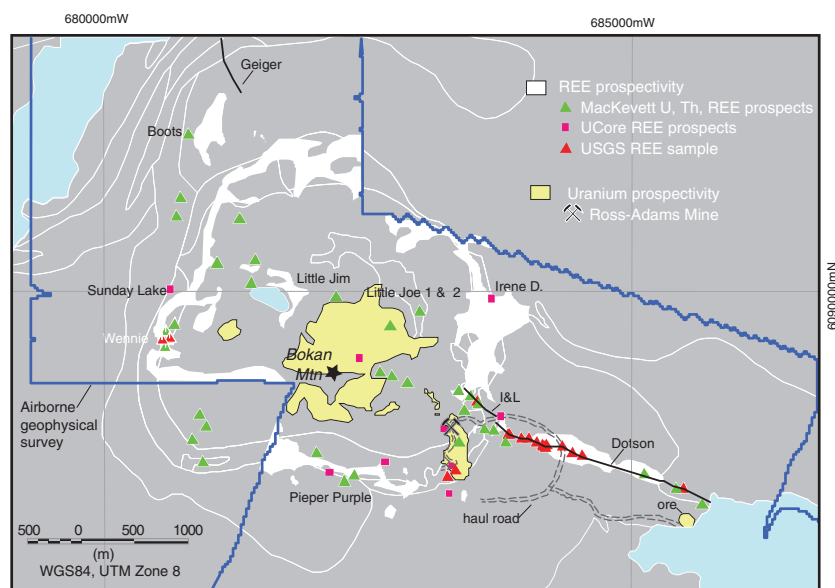


**Figure 5.** REE prospectivity (white) and uranium (yellow) prospectivity maps calculated from the high-resolution gamma-ray data. Locations of REE, U, and Th prospects are shown and include data from MacKevett (1964), U.S. Geological Survey (B. S. Van Gosen, personal communication, 2014; UCore Rare Metals Inc., 2011).

individual airborne gamma-ray maps (Figure 2a–2c). However, they have been mapped as linear but discontinuous total count anomalies with ground gamma-spectrometer surveying (Warner and Barker, 1989; UCore Rare Metals Inc., 2011).

The map for uranium prospectivity identifies rocks that share similar signatures with those measured over the Ross-Adams mine. With the exception of the ore pile near Kendrick Bay, U-dominant areas are entirely within the pluton and exhibit maximum radioactivity. Geographically, the U-dominant areas occur over parts of the pluton that are well exposed, so there is little dampening of the gamma-ray signal due to overburden, forest, or vegetation cover. Such exposure likely accentuates the high radioelement signal observed over these areas. The largest area of prospective U-dominant mineralization is mostly within the arfvendsonite granite core and contains the IL&M, Little Jim, and Little Joe #1 pegmatite deposits. However, the large size and shape of the U-prospective area is more suggestive of a U-, Th-, and K-rich granite phase within the arfvendsonite granite rather than an area of pervasive mineralization, which would likely have been noted by previous exploration efforts.

MacKevett (1959) and Thompson (1988) note a near-complete lack of potassium in association with the uranium-thorium ore at the Ross-Adams deposit. The very high %K over the mine area from the airborne survey is in contrast to the ore chemistry, and it is likely due to the small volume of ore compared with the volume and enriched potassic nature of the surrounding alkaline granite host.

## U and Th mineralogy and chemistry of the Dotson zone

### Mineralogical analyses of the Dotson vein-dike system

A detailed mineralogical characterization was conducted on samples collected along the Dotson vein-dike system (USGS samples in Figure 5). This aspect of the study was motivated by a desire to better understand the influence of thorium and uranium minerals on the airborne gamma-ray signature over the Dotson zone and to evaluate whether U and Th minerals were carriers of REEs. Eighteen samples from the Dotson zone were examined by scanning electron microscope (SEM). Elemental mineralogical analyses were performed on a Joel 8900 Superprobe electron microprobe (EMP) with a 20 Kev accelerating voltage and 30  $\mu$ amp beam current and a Joel JSM-5800LV SEM with a 20-Kev accelerating voltage. All analyses on both instruments were obtained using a focused beam of approximately 1  $\mu$ m. EMP data reduction was done using the Probe EMPA software package of John Donovan and SEM energy dispersive spectral analyses using the Noran 7 software package of Thermo Fisher Scientific, Inc. Oxide values were obtained in a similar manner.

Minerals containing thorium and uranium were recorded. Five additional samples from three bulk sample

pits were also studied in more detail. The pits were used by UCore Rare Metals Inc., to obtain a 20-ton metallurgical sample of the ore body near the eastern end of the Dotson zone and the West Arm of Kendrick Bay.

Thorium and uranium in the Dotson zone are dominantly sited in thorite with some of the thorites significantly enriched in uranium. Thorium and uranium are also present in a complex suite of  $\pm$ Ti  $\pm$  Nb  $\pm$  Y oxide minerals, of which the most abundant are the fergusonite-(Y) group minerals ( $\text{YNbO}_4$ ) and Ti-Nb-Y-oxides, of which polycrase-(Y) ( $\text{Y}(\text{Ti}, \text{Nb})_2(\text{O}, \text{OH})_6$ ) and aeschynite-(Y) ( $\text{Y}, \text{Ln}, \text{Ca}, \text{Th}(\text{Ti}, \text{Nb})_2(\text{O}, \text{OH})_6$ ) are the most important.

The U-oxides, which include fergusonite and the Ti-Nb-Y-oxides, along with Y-silicates (devoid of Th and U), are the main carriers of HREE-bearing minerals of the Dotson REE deposit (Stoeser and Lowers, 2013). In some samples, the dominant HREE carrier is the Y-silicates, in others, the U-oxides. Thus, eU anomalies from the airborne survey may be a potential indicator of the location of similar mineralization related to HREE-bearing U-oxides within the Bokan Mountain area.

Although hydrothermal xenotime and monazite are locally abundant within the Dotson zone, they rarely have detectable Th and thus are not significant contributors to the airborne gamma-ray Th signal in the presented maps.

Thorite is widespread throughout the Dotson vein system, but its distribution is very inhomogeneous, with some samples having only trace amounts whereas in other samples thorite occurs as significant member of the minor mineral suite (<1%). Thorite is often partially altered to Y-P-U-enriched phases as well as complex late-stage Th-rich carbonates. U-dominant minerals are extremely rare, and only several grains of U-oxide (>5  $\mu$ m diameter) were observed in the 18 Dotson samples examined by SEM.

Fergusonite from three samples showed distinct differences in  $\text{ThO}_2/(\text{ThO}_2 + \text{U}_2\text{O}_8)$  values. Two fergusonite grains ave. 57% and the second ave. 18%; thus, some fergusonites are slightly Th-dominant and some are very U-dominant. The Th-U content of fergusonite from the Dotson zone is highly variable, ranging from 0.5 to 3.5 weight percent (wt%)  $\text{ThO}_2$  and 0.5 to 4.5  $\text{U}_3\text{O}_8$  (all U-oxide computed as  $\text{U}_3\text{O}_8$ ) with an ave. of 1.4 wt%  $\text{ThO}_2$  and 2.7 wt%  $\text{U}_3\text{O}_8$ . Fergusonite is typically partially to completely hydrothermally altered to a Nb-Y  $\pm$  Ca  $\pm$  Fe-siliceous mineral. Whether this is a proper silicate mineral or a silica-rich oxide material has not been determined. It typically has a highly variable silica content, which supports the latter interpretation. The U and Th content of the hydrothermal alteration is approximately the same as the parent fergusonite.

Polycrase and aeschynite are compositionally very similar but can be distinguished by their U and Th content because polycrase is U-dominant whereas aeschynite is Th dominant (Tomašić et al., 2004; Škoda and

Novák, 2007). Based on their Th/U ratios, the bulk of the Ti-Nb-Y-oxide minerals in the Dotson is polycrase although some aeschynite also is present. Polycrase has 0.5–3.0 wt% ThO<sub>2</sub> and 6–8.5 wt% U<sub>3</sub>O<sub>8</sub> with an ave. of 2.1 wt% ThO<sub>2</sub> and 6.1 wt% U<sub>3</sub>O<sub>8</sub>. As with the fergusonites, the Ti-Nb-Y-oxides are typically partially to completely replaced by a Ti-Nb-Y ± Ca-siliceous mineral with a highly variable silica content. Unlike the fergusonite alteration, the siliceous replacement material has a significantly lower U content (3.5–6.2 wt% U<sub>3</sub>O<sub>8</sub>) but the Th content remains about the same.

Potassium in the Dotson vein-dike rocks is primarily sited in phlogopite and potassium feldspar. The phlogopite ranges from less than 1% to as much as several modal percent in places. Relic potassium feldspar occurs in the western part of the Dotson zone. Neither of the primary K minerals within the Dotson rocks hosts REEs.

### U, Th, and REE chemistry of the Dotson vein-dike system

In addition to determining the U and Th mineralogy of the Dotson zone, channel and rock sample chemistry from pegmatite dikes, aplitic dikes, and veins of the Dotson zone along its 2140-m length were examined from Warner and Barker's study (1989). Uranium, Th, and REE concentrations were determined by neutron activation with a detection limit of 0.5 ppm for U and Th, varying between 0.2 and 5 ppm for the REEs depending on the element. The data show that the U, Th, and REE chemistry of the western side of the zone is distinctly different from the eastern 800 m (Figure 6). The difference is marked by the inferred north–northwest-trending Camp Creek fault, which appears to bisect the Dotson zone (Figures 1 and 6). The fault has not been confirmed due to poor bedrock exposure in the creek but is inferred based on changes in the strike of the veins from west to east and the fault gouge encountered in a drill core (UCore Rare Metals Inc., 2011). Ave. U and total REE (TREE) concentrations are lower on the western part of the Dotson zone (ave. = 83 and 1592 ppm, respectively) compared to higher ave. concentrations east of the Camp Creek fault (ave. = 256 and 9732 ppm, respectively). The change in ave. Th concentrations from west to east is not as extreme, but Th concentrations are slightly higher in the west (ave. = 585 ppm) compared to ave. concentrations in the east (458 ppm). The area of REE prospectivity is continuous across the Camp Creek fault (Figure 6) and does not show any significant change from one side of the fault to the other.

The chemistry suggests that the western section may be slightly thorite dominant, whereas the elevated U content of the eastern section may indicate the presence of significantly more fergusonite and Ti-Nb-Y-oxide minerals. The change in U and REE chemistry values along the Dotson zone at the Camp Creek fault (Figure 1) suggests the possibility that displacement on

the fault may be juxtaposing two different parts of the mineralized system.

### Discussion

Worldwide, peralkaline igneous complexes have been targeted by recent exploration, in particular because of their enrichments in the HREEs (i.e., Alkane Resources Ltd., 2011; Greenland Minerals and Energy Ltd., 2012; Srivastava et al., 2012; Avalon Rare Metals Inc., 2013; Quest Rare Minerals Ltd., 2014). Within peralkaline complexes, REE concentrations occur in two general geologic forms — deposits that occur in layered peralkaline complexes or deposits that are associated with peralkaline intrusions as veins/dikes or disseminated within the intrusion (Verplank et al., 2014). At present, there are at least 16 peralkaline complexes in 11 countries with advanced exploration efforts to develop rare earth deposits (Hatch, 2012, 2014; Mariano and Mariano, 2012). The only operating

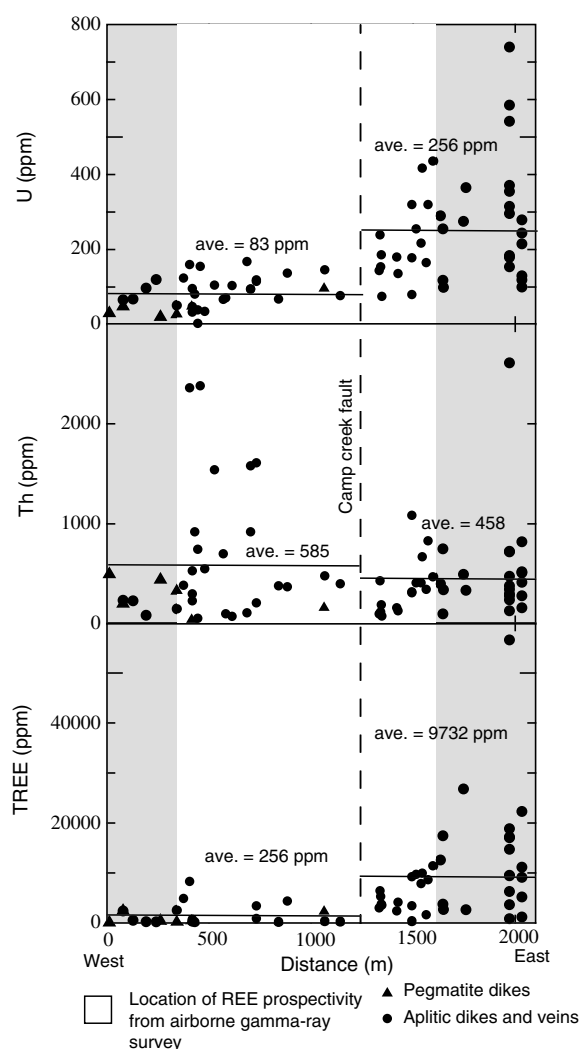


**Figure 6.** Chemistry of TREES, Th, and U along the Dotson zone (after Warner and Barker, 1989). REE prospectivity is shown in white relative to the chemistry profiles ave.

mine in a peralkaline complex that is extracting rare earths as a by-product is in Russia at the Lovozero Nb-REE deposit (U.S. Geological Survey, 2011; Chakhmouradian and Zaitsev, 2012).

Orris and Grauch (2002) note in their report on rare earth occurrences that many REE deposits have not been well studied. More than a decade later, published literature, especially related to the geophysical signatures of peralkaline-hosted REE deposits, remains scarce. An overview of the state of airborne geophysics over the 16 peralkaline complexes with advanced ex-

ploration efforts was compiled from publications, information on mining company web sites, and reports on standards of disclosure for mineral projects (NI 43-101 and JORC Code) (Table 2). Results show some type of airborne geophysical survey has been flown over most of the deposits. Magnetic and radiometric surveys are, by far, the most common geophysical data collected over peralkaline complexes. More recent geophysical surveys have included airborne gravity gradiometry (AGG) technology. Two magnetic and AGG surveys, funded by the GSC were flown over the

**Table 2. Types of geologic host and airborne geophysical data available over peralkaline rocks host to REE deposits with advanced exploration programs (Hatch, 2014).**

| Peralkaline host type  | Name                   | Airborne geophysical survey type       | Flight-line spacing | Year flown | Location                      | Reference                                                            |
|------------------------|------------------------|----------------------------------------|---------------------|------------|-------------------------------|----------------------------------------------------------------------|
| Layered complex        | Kipawa                 | Magnetic, radiometric, TDEM            | Not specified       | 2011       | Quebec, Canada                | Matamec Explorations Inc. (2010); Desaulniers (2011)                 |
|                        | Strange Lake           | Magnetic, radiometric                  | 400 m               | 2008–2009  | Quebec/Labrador, Canada       | Quest Rare Metals Ltd. (2014)                                        |
|                        |                        | Magnetic, gravity gradiometry          | 100 m               | 2012       |                               | Dumont and Jones (2012)                                              |
|                        | Nechalacho (Thor Lake) | Magnetic                               | not specified       | 2009       | Northwest Territories, Canada | Avalon Rare Metals Ltd. (2013)                                       |
|                        |                        | Magnetic, gravity gradiometry          | 250 m               | 2011       |                               | Dumont and Hefford (2011)                                            |
|                        | Kutessay II project    | None found                             | N/A                 | N/A        | Chuy Oblusu, Kyrgyzstan       | Stans Energy Corp. (2011)                                            |
|                        | TRE project            | Magnetic, radiometric                  | 100 m               | 2008–2009  | Northern Madagascar           | Tantalus Rare Earths (2014); Earthmaps Consulting (2009)             |
|                        | Lovozero               | None — only ground gravity and seismic | N/A                 | N/A        | Murmanskaya Oblast', Russia   | Glaznev et al. (2008)                                                |
| Dikes/veins or plutons | Ilmaussaq complex      | Magnetic                               | 500 m               | 1995–1996  | Kommune Kujalleq, Greenland   | Greenland Minerals and Energy Ltd. (2012); Thorning and Stemp (1997) |
|                        | Bokan Mountain         | Magnetic, radiometric                  | 100 m               | 2009–2010  | Southeast Alaska              | UCore Rare Metals Inc. (2011)                                        |
|                        | Foxtrot                | Magnetic, radiometric                  | not specified       | 2009       | Labrador, Canada              | Srivastava (2012)                                                    |
|                        | Hastings project       | Regional magnetic, radiometric         | not specified       | 1954       | Western Australia             | Hastings Rare Metals (2014)                                          |
|                        | Hoidas Lake            | Radiometric, electromagnetic           | not specified       | 1961       | Saskatchewan, Canada          | Great Western Mining Group (2009)                                    |
|                        | Norra Kärr             | None found                             | N/A                 | N/A        | Jönköpings län, Sweden        | Tasman Metals Limited (2011)                                         |
|                        | Dubbo (Toongi)         | None found                             | N/A                 | N/A        | New South Wales, Australia    | Alkane Resources Ltd. (2011)                                         |
|                        | Two Tom                | Magnetic gradiometry, radiometric      | 100 m               | 2010–2011  | Labrador, Canada              | Medallion Resources (2010)                                           |
|                        | Ghurayyah              | None found                             | N/A                 | N/A        | Saudi Arabia                  | Tertiary Minerals (2014)                                             |
|                        | Khaldzan-Buregtey      | None found                             | N/A                 | N/A        | Hovd Aymag, Mongolia          | Kovalendo et al. (1995)                                              |

Strange Lake (Dumont and Jones, 2012) and Thor Lake (Dumont and Hefford, 2011) deposits.

Lack of higher quality data (or no data at all) over some of the advanced exploration projects and scarcity in the published literature may be attributed to the proprietary nature of mining exploration. Given that most of these peralkaline deposits are partly to mostly exposed, they would be suitable targets for radiometric surveying. The prospectivity approach used here for the Bokan REE deposit could easily be applied to these deposits if surveys are, or would become, available. The approach could also be applied to older gamma-ray survey data. In general, research to describe the radioelement signatures of peralkaline-hosted REE deposits using airborne gamma-ray data is almost entirely missing. At present, most of the published geophysical interpretations using modern geophysical survey data come from Canada (Satterly, 1970; Thomas et al., 2011; Pilkington et al., 2012) and provide good overviews on the general magnetic, gravity, and radiometric characteristics of REE deposits.

To properly interpret the airborne gamma-ray signature at the Bokan deposit, it is important to understand the relation between the REEs, the radioelements, and how they got there. The REEs, U, and Th that occur in these deposits are part of a group of incompatible elements, also called high-field-strength elements (HFSEs), which tend to concentrate in differentiated magmas, such as melts that form peralkaline intrusions. HFSEs tend to not participate in the early mineral formation processes but tend to preferentially remain in the coexisting melt. Successive generations of this process, referred to as crystal fractionation, increase concentrations of REEs, Th, and U until individual REE-, Th-, and U-rich minerals crystallize.

An understanding of the magmatic and hydrothermal processes of HFSEs transport and enrichment within these systems remains under debate (Chakhmouradian and Zaitsev, 2012). However, Dostal et al. (2014) attribute the REE mineralization at Bokan to a two-stage process: a late stage of magma emplacement along shear zones, which relates to the felsic dikes (i.e., the Dotson vein-dike system), followed by an influx of hydrothermal fluids enriched in REEs, U, and Th. Both processes served to concentrate the REE deposits hosted in the dikes and within various phases within the peralkaline granite complex. Other deposits in which fractional crystallization and hydrothermal alteration had been interpreted to concentrate REEs and other HFSEs are within the Strange Lake and Thor Lake peralkaline intrusions in Canada. Geochemical analyses comparing REE and HFSE concentrations in the hydrothermally altered granites versus the unaltered granites show REE enrichment from 7 to 22 times at Strange Lake and 25 to 85 times more at Thor Lake in the hydrothermally altered granites (Salvi and Williams-Jones, 2006).

At Bokan Mountain, Barker and Van Gosen (2012) note differences in concentrations of LREE versus

HREEs in deposits that have undergone more extensive hydrothermal alteration. They note significantly higher HREE content in the more evolved hydrothermal deposits, which include the Boots, Ross-Adams, Pieper's Purple, Sunday Lake, and Wennie deposits. All these deposits occur very near or within REE prospective areas (Figure 5). For these deposits, greater than 80% of the total REE is ascribed to the HREEs. In contrast, the vein-dike systems (Dotson, Geiger, and Geoduck) have a lower proportion of HREEs (40% of the total REEs). Hence, it appears that determining where more extensive hydrothermal alteration has occurred will have direct implication to determining where the more valuable HREEs may exist.

The replacement of arfvedsonite by aegerine has also been ascribed to hydrothermal alteration at many peralkaline intrusions (Marks et al., 2003; Salvi and Williams-Jones, 2006), although Dostal et al. (2011, 2014) attribute the compositional differences of the granites at Bokan Mountain to late phase crystallization of the parent magma.

Defining areas with a low potential for mineralization is as important as defining where there might be mineralization. We interpret that granite phases within the BMC with little to no radioactivity would have little to no potential for rare earth or uranium mineralization. Likewise, areas of low radioactivity within the Silurian and Ordovician country rocks would be unlikely targets for shallow REE deposits.

## Conclusions

Data from an airborne gamma-ray survey flown at Bokan Mountain provide insight into known and prospective areas of rare earth mineralization. A REE mineralization prospectivity map calculated from the airborne gamma-ray data shows that rare earth mineralization is characterized by moderate to moderately high eU, eTh, and %K. In contrast, the uranium mineralization at Ross-Adams mine is characterized by the highest radioelement values. Highest radiometric values also occur over a large area mostly internal to the pluton and are interpreted to represent a U-, Th-, and K-rich granite phase rather than mineralized rock. Prospective areas for REE mineralization include most of the Dotson vein-dike system, several known occurrences around the outer edge of the BMC pluton, and discrete regions outside the BMC boundary. The prospective areas may highlight where more extensive hydrothermal alteration may have occurred, potentially concentrating REEs. If so, results may have direct implication to determining where more valuable deposits concentrated with HREEs may exist. Known REE-bearing vein-dike systems that were not mapped in the REE prospectivity map include the Geiger, I&L, and Geoduck structures. These structures are too narrow to be imaged in the airborne data but can be mapped at ground level with field gamma spectrometers. The airborne magnetic data show no expression of the REE mineralized felsic dikes or other REE prospects but

instead map magnetic variation related to the major lithological units in the study area. Regional magnetic data indicate that the Bokan Mountain Granite pluton may be underlain by a larger pluton at depth.

The detailed mineralogical study of samples along the Dotson vein-dike system showed that thorium and uranium are dominantly sited in thorite and a complex suite of  $\pm\text{Ti} \pm \text{Nb} \pm \text{Y}$  oxide minerals including fergusonite, polycrase, and aeschynite. These oxide minerals, along with Y-silicates, are the chief HREE-bearing minerals of the Dotson REE deposit. Thorium and uranium chemistry along the Dotson zone shows trends that suggest that the western section may be slightly more thorite-dominant (high Th, low U), whereas the elevated U content of the eastern section may indicate the presence of significantly more fergusonite and Ti-Nb-Y-oxide minerals (high Th, high U). This suggests that the eastern end of the Dotson zone may be more enriched in the HREEs.

The REE prospectivity map provides a methodology resulting in a field guide to identify target areas for future sampling and evaluation for similar REE mineralization. The approach offers a viable and simple approach that can be extended to a wide range of geophysical image data (i.e., gravity, electromagnetic, and magnetic data) to identify potential mineralized rock. Few published studies exist regarding the airborne geophysical expression of peralkaline rocks that host REE mineralization. Many of these REE projects have airborne geophysical survey data available that would be suitable for the analyses presented here.

## Acknowledgments

Data were provided to the USGS by UCore Rare Metals Inc., and Precision GeoSurveys. The authors thank H. Keyser with Precision GeoSurveys, for the opportunity to work with the high-resolution airborne geophysical data over Bokan Mountain. The authors also thank D. V. Smith (USGS), Cliff Taylor (USGS), James Austin (CSIRO), Mike Thomas (GSC), and Bill Morris for helpful reviews and discussions of ideas presented in this manuscript. R. McDougal, USGS Denver, is thanked for the analyses of Landsat data. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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