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Rare Metal indicator minerals in bedrock and till at the Strange Lake peralkaline complex, Quebec and Labrador, Canada

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Abstract
A study of rare metal indicator minerals and glacial dispersal was carried out at the Strange Lake Zr-Y-heavy rare earth element deposit in northern Quebec and Labrador, Canada. The heavy mineral (>3.2 SG) and mid-density (3.0 – 3.2 SG) non-ferromagnetic fractions of mineralized bedrock from the deposit and till up to 50 km down ice of the deposit were examined to determine the potential of using REE and HFSE indicator minerals for exploration. The deposit contains oxide, silicate, phosphate, and carbonate indicator minerals, some of which (cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite, and aeschynite) have not been reported in previous bedrock studies of Strange Lake. Indicator minerals that could be useful in the exploration for similar deposits include: Zr-silicates (zircon, secondary gittinsite [CaZrSi$_2$O$_7$] and other hydrated Zr±Y±Ca-silicates), pyrochlore [(Na,Ca)$_2$Nb$_2$O$_6$(OH,F)], thorite [Th(SiO$_4$)]/thorianite [ThO$_2$], as well as REE-minerals monazite [(La,Ce,Y,Th)PO$_4$], chevkinite [(Ce,La,Ca,Th)$_4$(Fe,Mg)$_2$(Ti,Fe)$_3$Si$_4$O$_{22}$], parisite [Ca(Ce,La)$_2$(CO$_3$)$_3$F$_2$], bastnaesite [Ce(CO$_3$)F], kainosite [Ca$_2$(Y,Ce)$_2$Si$_4$O$_{12}$(CO$_3$)$\cdot$H$_2$O], and allanite [(Ce,Ca,Y)$_2$(Al,Fe)$_3$(SiO$_4$)$_3$(OH)]. Rare metal indicator minerals can be added to the expanding list of indicator minerals that can be recovered from surficial sediments and used to explore for a broad range of deposit types and commodities that already includes diamonds, and precious, base, and strategic metals.

Key words: indicator minerals, rare metals, glacial dispersal, glaciated terrain
Introduction
Rare metals are used in a variety of applications including consumer electronics, green technology, and defense systems (Hatch 2012). Interest in rare metal exploration in Canada has increased in recent years because of these technologies and supply challenges (Verplanck and Van Gosen 2011; Chakhmouradian and Wall 2012; Hatch 2012; Simandl 2014; Goodenough et al. 2018). Currently, rare metal deposits are neither mined nor processed within Canada, however, significant rare metal resource potential exists (Sinclair et al. 1992; Simandl et al. 2012; Sappin and Beaudoin 2015). In Canada, rare metals are hosted in peralkaline intrusions, carbonatites, pegmatites, and peraluminous granites (Mackay and Simandl 2015; Simandl et al. 2015; Sappin and Beaudoin 2015). With Canada being a glaciated landscape, till geochemistry and mineralogy have the potential to be useful exploration tools for rare metals deposits.

Indicator mineral methods are used in exploration programs and government heavy mineral surveys to evaluate the potential of a region or large property to host a variety of commodities, including diamonds (McClenaghan and Kjarsgaard 2007, and references therein), gold (McClenaghan and Cabri 2011; Averill 2013, 2017), Ni-Cu-PGE (Averill 2001, 2011; McClenaghan and Cabri 2011), porphyry Cu (Averill 2011; Kelley et al. 2011; Plouffe et al. 2016), Mississippi Valley-Type Pb-Zn (Paulen et al. 2011; McClenaghan et al. 2018), VMS hosted Cu-Pb-Zn (McClenaghan et al. 2015a,b), and granite-hosted Sn and W (McClenaghan et al. 2016, 2017a). However, indicator mineral methods have not been widely studied or applied to rare metal exploration in glaciated terrain.

The undeveloped Strange Lake peralkaline complex in eastern Canada is one of the world’s largest deposits of the Zr, Y, and heavy rare earth elements (HREE) (Zajac 2015). The complex was sampled by the Geological Survey of Canada to
demonstrate that rare metal indicator minerals can be recovered from till and used for exploration. This site was chosen because: (1) the bedrock and surficial geology are now well known; (2) it has a well known radioactive boulder and till geochemical dispersal train down ice; and, 3) rare metal-rich till was readily available for sampling. The purpose of this study was not to redefine the known dispersal train using indicator minerals but use the well documented train to optimize the collection of rare metal-bearing till and identify rare metal indicator minerals.

**Location and access**

The Strange Lake intrusive complex is in eastern Canada, on the border between the provinces of Quebec and Newfoundland and Labrador (Fig. 1), centred on latitude 56°18' N and longitude 64°07'W, and is accessible only by air. The deposit is just southeast of Lac Brisson, approximately 240 km northeast of Schefferville, Quebec, and 125 km west of the world class Voisey’s Bay Ni-Cu-Co mine in Labrador. The area is north of the tree line in the zone of discontinuous permafrost (Heginbottom et al. 1995) and is situated within the George Plateau physiographic region of the Canadian Shield (Bostock 2014). A large lake 15 km to the northeast of the deposit was informally named Strange Lake after the discovery of the intrusive complex.

**Geology**

**Bedrock geology**

The bedrock geology of the area, first delineated by the Iron Ore Company of Canada (IOC), is summarized from Zajac et al. (1984), Miller (1985, 1986, 1988, 1990, 1996), Kerr (2013), Gowans et al. (2014), and Zajac (2015). The Strange Lake intrusion is a peralkaline granite within the Paleoproterozoic Churchill Structural Province in the northeastern part of the Canadian Shield. The granite, dated at 1240±2 Ma (Miller 1990), intrudes along the contact between Late Archean to Early Proterozoic metasedimentary and metagabbroic rocks to the north and Middle Proterozoic quartz monzonite to the south (Fig. 1). The intrusion, approximately 7 km in diameter, consists of at least three varieties of
peralkaline granite that have been divided into four granitic subunits by Miller (1986, 1990) on the basis of mineralogy and the presence of inclusions (Fig. 2). The highest-grade mineralization is in the pegmatitic exotic-rich granites in the upper parts of the peralkaline intrusion, particularly in the Main Zone (also known as the A Zone) and the B Zone (Fig. 2). Mineral paragenesis and alteration assemblages at Strange Lake have been described by several researchers, including Boily and Williams-Jones (1994), Miller (1986), Salvi and Williams-Jones (1990, 1995, 1996, 2006), Gysi and Williams-Jones (2013), Vasyukova and Williams-Jones (2014, 2018) and Vasyukova et al. (2016).

The intrusion contains many rare minerals that are composed of incompatible elements that, at the time of the intrusion’s discovery, were unnamed. A list of potential indicator minerals contained in the intrusion and the elements they host are summarized from Jambor et al. (1996, 1998), Birkett et al. (1992, 1996), Miller et al. (1997), Oyediran et al. (2014), and Zajac (2015) in Table 1. The deposit is relatively enriched in heavy rare earth elements (HREE, Eu to Lu) and Y as compared to light rare earth elements (LREE).

The intrusion was discovered by the IOC in 1979 during the investigation of a lake sediment geochemical anomaly first reported by the Canada-Newfoundland Uranium Reconnaissance Program (Hornbrook et al. 1979; McConnell and Batterson 1987; Zajac et al. 1984; Zajac 2015). To date, the intrusion and its REE deposits have been explored and evaluated almost exclusively by IOC (1979 – 1984) and Quest Rare Minerals Limited. IOC exploration delineated the outline and main geological characteristics of the peralkaline complex and its best mineralization: the Main Zone (known to IOC as the A Zone) in the central part of the intrusion, and the B Zone (Zajac 2015; Fig. 4) in the northwest part of the intrusion. The B Zone was explored in detail by Quest Rare Minerals Limited (Oyediran et al. 2014) and is larger than the Main Zone, with indicated mineral resources of 278 Mt at 0.93% total rare earth element oxide (TREO) and inferred mineral resources of 214 Mt at 0.85% TREO (Gowans et al. 2014). The resource
for the smaller Main Zone has been estimated at 55.8 Mt with a grade of 2.99\% ZrO\textsubscript{2}, 0.38\% Y\textsubscript{2}O\textsubscript{3}, 0.29\% Nb\textsubscript{2}O\textsubscript{5}, 0.08\% BeO (Kerr and Rafuse 2012; Kerr 2013). Due to its grade and large size, the B Zone may be mined in the future (Gowans et al. 2014).

The complex has a strong gamma-ray signature that was identified in 1980s (Geological Survey of Canada 1980). Cumulative values for eTh (Fig. 3) and eU reflect the presence of the intrusion as well as the presence of radioactive boulders and minerals in till that have been glacially dispersed down ice to the northeast (Miller 1985; Batterson 1989; Zajac 2015). The upper part of the Main Zone was removed by erosion, which Zajac (2015) attributed largely to glacial erosion. It is likely that preglacial erosion also removed some of the Main Zone prior to glaciation. Because of the highly-altered nature of the minerals in the Strange Lake intrusion, it is likely that preglacial weathering formed a regolith in the upper part of the intrusion that was the source of a significant volume of REE-rich debris that was glacially eroded and dispersed down ice. In contrast, the B Zone is largely intact because it only suffered only minimal glacial erosion (Zajac 2015).

**Surficial geology**

The Strange Lake intrusion was strongly scoured by the Laurentide Ice Sheet throughout the Wisconsin glaciation by ice that flowed outward from a large ice dome over central Quebec (Dyke and Prest 1987; Vincent 1989). Bedrock outcrops in the region are uncommon and most of the landscape is covered by till of variable thickness, from veneers (<2 m) to several metres (Batterson et al. 1985). The landscape is characterized by streamlined glacial landforms consisting of mega-flutings and mega-lineations that were formed by fast flow of the Kogaluk River ice stream (IS #187; Margold et al. 2015; Paulen et al. 2017). Measurements of striations and landforms indicate that the ice stream flowed east-northeast towards the Labrador coast. The till (Fig. 4) in the region is very sandy (average 58\% sand, 37\% silt and 5\% clay) (McClenaghan et al. 2017b).
having been derived mainly from local rapakivi granite and the Strange Lake intrusion.

The Laurentide Ice Sheet eroded the Strange Lake intrusion and distributed boulders, cobbles, and glacial sediment in a ribbon-shaped glacial dispersal train that was traced more than 40 km down ice to the northeast using boulder mapping (Batterson et al. 1985; Batterson 1989) and matrix till geochemistry, most notably Be (Fig. 5), Ce, La, Nb, Pb, Rb, Th, U, Y, and Zr (McConnell and Batterson 1987; Batterson 1989; Batterson and Taylor 2009). Airborne gamma-ray spectrometry data (Fig. 3) reveal that the dispersal train can be detected in excess of 50 km down ice to the northeast (Geological Survey of Canada 1980; Batterson 1989; Zajac 2015; Paulen et al. 2017; McClenaghan et al. 2017b,c).

**Previous work**

McConnell and Batterson (1987) collected till, lake, and stream sediment and water around and down ice (northeast) of the deposit. The northeast-trending glacial dispersal train is most apparent in their till and stream sediment data sets. Bell (1984) and DiLabio (1988, 1990, 1995) examined the areal distribution of, and size fractions enriched in rare metals in till at Strange Lake. They noted that the abundance of Be, Nb, Th, and Zr is greatest in the 2.0 – 4.0 mm and 0.063 – 0.037 mm fractions of metal-rich till immediately down ice of the deposit. Bolduc (1990) reported that clasts from the Strange Lake complex were also transported to the northeast in glaciofluvial sediments.

**METHODS**

**Bedrock sample collection**

Six bedrock samples were collected from the Strange Lake Main Zone (08-MPB-027 to -031) in 2008 (Fig. 5). In 2015, four bedrock samples and one mineralized float sample were collected: sample 15-MPB-003 was collected on the south side of Lac Brisson, just south of the B Zone; samples 15-MPB-004A-2 and 15-MPB-004B were collected from stripped outcrop at the B Zone, 86 m to the northwest.
of sample 15-MPB-003 (Fig. 5); sample 15-MPB-006 was collected from a bedrock outcrop at a high point of land in the central part of the intrusion and one km south of the Main Zone (Fig. 5); sample 15-MPB-010 is a cobble that was collected 30 km down ice (east) of the deposit and suspected to be from the Strange Lake intrusion because of its similar appearance and high radioactivity determined using a portable gamma-ray spectrometer. Colour photographs of sample sites and polished bedrock sample slabs, hand sample descriptions, and petrographic descriptions are reported in McClenaghan et al. (2017b).

Till sample collection

Till samples were collected by the GSC around the Strange Lake deposit in 1981 and 1983 between 0.1 to 0.7 m depth in mud boils developed in the till. For our study, unprocessed dried archived splits (~700 g) of five to nine till samples in close proximity (within 100 m) to one another in 1981 or 1983 were composited to make five new till samples and relabeled with new sample numbers (08-MPB-022 to -026). These composited samples were 4 to 7 kg prior to processing to recover indicator minerals. The original GSC sample numbers and locations, from 1981 and 1983, and resulting composited GSC sample numbers are listed in McClenaghan et al. (2017b). The centroid of each cluster of composited till samples are shown in Figure 5.

In 2015, six large (15 kg) till samples (samples 15-MPB-002, -005, -007 to -010) (Fig. 5) were collected along the known dispersal train using a handheld portable gamma-ray spectrometer as a guide to the location of metal-rich till. Samples were collected between 0.5 to 0.7 m depth from mud boils developed in till using modern GSC protocols (Spirito et al. 2011; McClenaghan et al. 2013). Site and sample information and photos are reported in McClenaghan et al. (2017b). Sample 15-MPB-002 was collected 2 km up ice of the intrusion to determine background contents of indicator minerals. Samples 15-MPB-005 and -007 were collected overlying the Strange Lake complex and south of the Main Zone, and
samples 15-MPB-008 to -010 were collected between 11 and 50 km down ice (east-northeast) of the intrusion.

Sample processing and indicator mineral selection

Bedrock and till samples were processed at Overburden Drilling Management Limited, Ottawa, Canada to produce heavy mineral concentrates (HMC) and visually examined to identify and count indicator minerals. Flow charts, masses of each sample split produced during processing, and grain count data reported by the laboratory are included in McClenaghan et al. (2017b). Bedrock samples were disaggregated prior to heavy mineral recovery using a CNT Spark-2 electric pulse disaggregator (EPD), instead of a conventional rock crusher, in order to preserve natural mineral grain sizes, textures, and shapes (Rudashevsky et al. 1995; Cabri et al. 2008). The material was disaggregated until most fragments were <2 mm in diameter.

The <2.0 mm material from each bedrock and till sample was processed at ODM to produce a non-ferromagnetic HMC (>3.2 specific gravity (SG)) and mid-density (3.0 – 3.2 SG) mineral concentrate for examination of indicator minerals, using tabling and heavy liquid methods described by McClenaghan (2011) and McClenaghan et al. (2017b). The non-ferromagnetic HMC (SG >3.2) of bedrock and till samples was sieved and the 0.25 – 0.5, 0.5 – 1.0, and 1.0 – 2.0 mm size fractions examined. The 0.25 – 0.5 mm portion of the mid-density (SG 3.0-3.2) fraction of bedrock and till samples was also examined. Mineral grains were identified using a binocular microscope and potential rare metal indicator minerals, as well as other indicator minerals, were counted. The visual identification of some mineral grains was verified using a scanning electron microscope (Cambridge Stereoscan S250 with EDS) on grains mounted on SEM stubs.

A separate split of each bedrock sample was examined in polished thin section (PTS). Quantitative mineral analyses of selected indicator minerals PTS and
selected bedrock HMC grains in 25 mm epoxy grain mounts were carried out with an automated four-spectrometer Cameca Camebax MBX electron microprobe (EMP) by wavelength dispersive x-ray analysis method (WDX) at the Earth Sciences Department, Carleton University, Ottawa, Canada using a 20 kV accelerating voltage, 22 nA current, focused (2 µm diameter) electron beam. Counting times were 20 seconds or 40,000 accumulated counts. A detailed description of EMP operating conditions and the mineral chemistry data are reported in McClenaghan et al. (2017b).

RESULTS

Indicator minerals in bedrock

Petrographic examination of the PTS revealed that various stages of hydrothermal alteration involving aggressive F-rich fluids that had altered many of the primary minerals in the mineralized rock samples, introduced fluorite and generated quartz, titanite, rhabdophane, and several secondary Zr-, Y-, Nb-, Ti- and REE-minerals after the primary Zr- and Ti-silicates. These secondary minerals in places have dendritic, plumose, acicular to almost fibrous and globular habits. They are intergrown with other minerals such as quartz, fluorite, and hematite. Some minerals occur predominantly in pseudomorphs after primary Zr-minerals (elpidite, armstrongite).

Indicator minerals that were observed in bedrock PTS and HMC in this study are listed in Table 1. Some indicator minerals in bedrock HMC were difficult to visually differentiate because of: a) their small size; b) tendency to be intergrown with other minerals; and c) discoloration from hematite staining. The following minerals were particularly difficult to differentiate: 1) thorite and thorianite; 2) rhabdophane and monazite, and 3) zircon and gittinsite. Minerals observed in bedrock samples but not reported in previous studies of the Strange Lake complex include: cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite, molybdenite, and aeschynite. Colour photographs of some of the minerals recovered from bedrock samples are shown in Figure 6.
**Indicator minerals in till**

Indicator minerals identified till HMC in this study are listed in Table 1 and abundances for selected indicator minerals in the 0.25 – 0.5 mm mid-density and heavy mineral fractions are listed in Table 2. Minerals observed in till but not reported in previous bedrock studies of the Strange Lake deposit include chevkinite, thorianite, and rhabdophane. Colour photographs of selected minerals recovered from till samples are shown in Figure 6. The most abundant indicator minerals recovered from till are discussed below, starting with the major minerals arfvedsonite, aegirine and fluorite, and then the rare metal (Zr-, Nb-, Y-, Th-, and REE) minerals.

**Arfvedsonite**

Arfvedsonite (Table 1) was recognized in HMC by its dark reddish brown to black colour and fibrous crystal habit (Fig. 6a). The SEM was used to establish the visual differences between arfvedsonite and hornblende at the start of the examination of all till and bedrock HMC. It was abundant in till; samples ≤5 km down ice contained up to tens of thousands of grains and samples >5 km contained thousands of grains. No arfvedsonite was recovered from background till sample 15-MPB-002, collected up-ice of the intrusion.

**Aegirine**

Aegirine (Table 1) was recognized in HMC by its dark green colour and acicular crystals (Fig. 6b). It was present in most till samples. Till contained tens to thousands of grains in samples ≤3 km down ice and tens of grains in samples >3 km (Table 2). No aegirine was recovered from background sample 15-MPB-002 up ice.

**Fluorite**

Fluorite (Table 1) abundance in both the 3.0 – 3.2 SG and >3.2 SG fractions of till samples is reported in Table 2. It was easily identified by its deep purple colour
(Fig. 6c) and was consistently more abundant in the 3.0 – 3.2 SG fraction of both bedrock and till samples. Fluorite was present in sample 08-MPB-22, overlying mineralization (42 grains), and sample 08-MPB-023, 5 km down ice (Table 2).

**Gittinsite and zircon**

Despite the use of SEM to assist with mineral identification, Ca-free zircon \((\text{ZrSi}_2\text{O}_4)\) was difficult to distinguish from Ca-rich gittinsite \((\text{CaZrSi}_2\text{O}_7)\) if the zircon was intergrown with calcite or a REE carbonate mineral such as parisite. Table 2 lists the number of gittinsite grains recovered from the >3.2 SG and 3.0-3.2 SG fractions.

Till samples that overlie the intrusion contain hundreds of gittinsite (Table 1) grains and till samples between 2 and 5 km down ice contain thousands of grains. Despite being 35 km down ice from the deposit, till sample 15-MPB-010 was found to contain eight grains. A significant portion of the gittinsite grains were intergrown with allanite and these grains are reported in a separate column in Table 2. Gittinsite was more abundant in the 3.0 – 3.2 SG fraction than in the heavy mineral (>3.2 SG) fraction (Table 2), likely because the gittinsite was intergrown with quartz, which would lower the overall SG of the intergrown grains from that of gittinsite (SG 3.62). No grains were found in the one till sample up ice.

Zircon is more abundant than gittinsite in the till samples, with concentrations ranging from 100s to 1000s of grains per sample. The maximum count in till down ice was 9259 grains. More zircon was recovered from till samples two to five km down ice (100s of grains) than those directly overlying the deposit. Till sample 15-MPB-010, collected 35 km down ice, contained a couple of hundred grains. No zircon was recovered from background sample 15-MPB-002.

**Pyrochlore**
Pyrochlore (Table 1) was recognized in HMC by its orange-brown colour and octahedral crystal habit (Fig. 6d). Tens of grains were present in till between two to five km down ice. The maximum count in till down ice was 100 grains.

Kainosite
Kainosite (Table 1) was identified in HMC by its earthy white colour and with assistance from the SEM because they looked similar to barite. It was most abundant in the 0.25 – 0.5 mm HMC of sample 08-MPB-24 (~1100 grains), 3 km down ice but a few grains were also recovered from sample 08-MPB-22 overlying the intrusion. A few grains were recovered from the coarser 0.5 – 1.0 mm HMC fraction of till samples 08-MPB-22, -24, -25, and -26 that overlie the deposit.

Thorite/thorianite
Thorite and thorianite (Table 1) grains were often intergrown and difficult to differentiate, therefore their abundances were reported as a combined total in Table 2. Three samples overlying and up to 3 km down ice of the intrusion contained ones to tens of grains and one sample at 50 km down ice contained 14 grains. Background sample 15-MPB-002 collected up ice did not contain thorite or thorianite grains.

Monazite/Rhabdophane
Rhabdophane [(Ce,La)PO₄•(H₂O)] was sometimes difficult to visually distinguish from monazite [(Ce,La,Nd)PO₄] thus the lab combined counts for rhabdophane and/or monazite. Tens to hundreds of REE-phosphate grains were present in till overlying and just down ice of the deposit. A few grains were recovered from the one till sample up ice (background) as well as till samples between five and 50 km down ice. The highest abundances (56 to 250 grains) are in till samples between two to five km down ice. Orange monazite grains from bedrock sample 15-MPB-006 are shown in Figure 6e.

Bastnaesite
A few grains of bastnaesite (Table 1) were recovered from the HMC of till samples overlying the deposit, however, the greatest number of grains were in till samples between two to five km down ice, with a maximum of 18 grains. Background content was zero grains. It was identified in heavy mineral concentrates by its white colour (Fig. 6f) and use of SEM-EDS.

Chevkinite
Chevkinite (Table 1) was visually identified in HMC by its resinous, brownish black colour, massive habit, and conchoidal fracture (Fig. 6g). Between 1 and 10 grains were recovered from seven till samples, both overlying and down ice of the intrusion, including sample 15-MPB-010, 35 km down ice. Chevkinite was not recovered from the background till sample.

Allanite
Allanite (Table 1) was visually identified in HMC by its brownish black colour, massive habit, conchoidal fracture, and with assistance from the SEM. Till samples contained numerous grains of allanite and allanite intergrown with gittinsite (Fig. 6h) (Table 2). Till samples between 16 and 50 km down ice contained 100s to 1000s of both types of allanite grains. In contrast, till samples overlying and a few km down ice, contained only 0 to 2 grains. It was not recovered from background sample 15-MPB-002.

Parisite
Parisite (Table 1) was visually identified in till HMC by its greyish white color and with assistance from the SEM. Till sample 08-MPB-022 overlying the intrusion, and samples 08-MPB-023 (5 km down ice) and 15-MPB-09 (50 km down ice) contained a few grains, the rest of the till samples contained none (Table 2).

DISCUSSION
The mineralogy of the Strange Lake granite complex is unusual due to the variety and abundance of primary and secondary Zr-, Y-, RE- and other high field
strength-minerals. Major and minor minerals observed in bedrock samples in this study include quartz, feldspar, arfvedsonite, aegirine, fluorite, Zr-silicates (primary elpidite, secondary gittinsite, zircon, and many other hydrated Zr±Y±Ca-silicates), and pyrochlore.

Minerals that were recovered from bedrock and/or in till down-ice from the deposit and that are indicative of rare metal mineralization and could be considered as potential indicator minerals for this deposit include: thorite/thorianite, pyrochlore, monazite/rhabdophane, chevkinite, parisite, gittinsite, zircon, allanite, bastnaesite, kainosite, and komarovite. This list of indicator minerals identified for the Strange Lake deposit reflects the ability of indicator mineral methods to recover and recognize a broad range of minerals in the >0.25 mm non-ferromagnetic HMC. Colour photographs of some of these minerals are published here for the first time to demonstrate their physical characteristics that better allow them to be visually identified (e.g., colour, cleavage, crystal habit, hardness, luster).

Arfvedsonite and aegirine are common major minerals in alkaline rocks and hence good indicators of the presence of such rocks. However, these minerals reveal little about the rare metal content of their host rocks which are naturally enriched in REE and HFSE. Fluorite is another common mineral that occurs in F-rich igneous rocks and in hydrothermal deposits. At Strange Lake, it is commonly associated with REE mineralization. It is present in the rapakivi granite (Currie 1985) up ice as well in the Strange Lake intrusion; thus its mere presence in till samples is of limited value. Its distinct dark violet colour in Strange Lake rocks may be due to irradiation from K-, Th-, or U radiation. It was only recovered from two Strange Lake till samples down ice. However, in the lake sediment survey of Strange Lake region, fluorine stood out as a prominent anomaly and was one of the inducements for selecting the area for exploration (McConnell and Batterson 1987).
Gittinsite is a common post magmatic mineral phase in the Strange Lake intrusion and is a potentially valuable ore mineral for Zr. It can be difficult to visually distinguish from zircon when the two minerals are intergrown. It was recognized in HMC when it was intergrown with allanite, as seen in Figure 6h. It was present in both bedrock and till samples.

Pyrochlore occurs as a common primary euhedral phase in the Strange Lake granite. It is very dense and easy to recognize in HMC due to its characteristic octahedral habit and orange-brown colour (Fig. 6d). Pyrochlore is also known to occur in Nb-rich silica-undersaturated alkaline rocks and carbonatites, where it is also an indicator of possibly high Nb and REE contents in the host rocks.

Monazite and rhabdophane are both RE-phosphates with very similar compositions which makes it difficult to reliably distinguish between the two based on electron microprobe analysis or SEM-energy dispersive spectroscopy data alone (O and H cannot be analyzed by these methods). Their high REE-contents makes them useful indicators of the presence of REE-rich rocks.

Bastnaesite is one source of Ce and La in the deposit and kainosite is one mineral source of Y. Both minerals are rare in till samples but their presence is a strong indication of the presence of REE mineralization up ice. Chevkinite is a REE-silicate that is visually distinct and sufficiently abundant in the till at Strange Lake to be considered a useful indicator of REE mineralization.

Allanite is a REE-silicate that is visually distinct and sufficiently abundant in the till at Strange Lake to be considered an indicator mineral of REE mineralization. Parisite is an indicator mineral for REE-rich rocks such as NYF-granites and certain REE-carbonatites. A few grains were observed in till samples up to 50 km down ice indicating it may be a useful indicator mineral.
Thorite and thorianite are heavy dark brown minerals found in pegmatites. In bedrock and till HMC in this study, they were difficult to distinguish between. They were observed in the HMC of four of the bedrock samples and a few grains were recovered from the till up to 50 km down ice.

According to earlier studies, most REEs in the deposit are hosted by gerenite, kainosite, and gadolinite (Kerr 2013). However, these minerals were not observed in bedrock PTS or HMC and only kainosite was recovered from till. The absence of these minerals in bedrock samples is likely due to the limited samples available for study combined with the fact that their visual appearance is similar to other minerals in the HMC and that the grain size may be smaller than the size fraction examined (<0.25 mm). Gerenite, in particular, was found to be submicroscopic in size and intimately intergrown with quartz at Strange Lake (Jambor et al. 1998) and hence probably not detected during petrographic examination in our study. Gadolinite may not have been observed in till samples for the reasons stated above as well as possible destruction due to post glacial weathering.

**Relation to till geochemistry**

Batterson (1989) and Batterson and Taylor (2009) reported the key elements in the till matrix that define the glacial dispersal train include the LREEs as well as Be, Nb, Pb, Rb, Th, U, Y, and Zr. Most REEs in the deposit are hosted by gerenite, kainosite, and gadolinite and these are the likely sources of REEs in the till.

Specific Ce- and La-bearing minerals recovered from till that are likely the sources of elevated Ce and La contents in till include monazite, rhabodophane, basnaestite, kainosite, chevkinite, parsite, and allanite. The main host of Be in the deposit and in the till is gadolinite-group minerals, as well as milarite (SG ≤ 2.63) and helvite (Oyediran et al. 2014), although these minerals were not observed in any samples in this study.
Zirconium in the deposit is hosted mainly by gittinsite, elpidite, armstrongite, and minor zircon in the deposit. Zr-bearing heavy minerals recovered from till include gittinsite and zircon. Thorite, thorianite and cerianite are the likely sources of most Th in till, although only thorite and thorianite were recovered from till in this study. Pyrochlore is likely the main source of Nb in the till, although Nb-bearing komarovite may also be a source. The Y-bearing minerals recovered from till include kainosite, xenotime, monazite, and allanite. Although not recovered from till samples, elevated Pb contents in the till matrix are likely derived from galena which Miller (1996) reported to be present in local pegmatite veins and was recovered from rock samples from the B Zone (15-MPB-003, -004). Elevated concentrations of Rb in till are likely derived from K-feldspar and muscovite, minerals not examined in this study.

**Distance of glacial transport**

A glacial dispersal train trending east-northeast from the Strange Lake deposit for at least 50 km was previously defined using airborne gamma-ray spectrometry data, radioactive boulders, lake and stream sediment geochemistry, and till geochemistry. This study has shown that indicator mineral methods can also detect the distal parts of the dispersal train. Pyrochlore, gittinsite, bastnaesite, and chevkinite were recovered from till up to 35 km down ice, and rhabdophane, parisite and allanite were recovered from till 50 km down ice.

The Strange Lake train likely extends more than 50 km down ice. Wilton et al. (2017) recovered gittinsite in till collected 100 km down ice (east-northeast) of the deposit, which may have been eroded from the Strange Lake pluton. Distribution patterns for elevated Be, Nb, Pb, Y and Zr contents in organic lake sediments (Friske et al. 1996a,b; McConnell and Batterson 1987; McConnell and Finch 2012; McCurdy et al. 2018) suggest that glacial dispersal from Strange Lake may have extended up to 150 km down ice.
Comparisons to other till dispersal studies

The results reported here greatly expand on the earliest observations of indicator minerals (pyrochlore, altered hornblende) in till at Strange Lake by Bell (1984) and DiLabio (1988, 1995). The REE suite of indicator minerals identified here includes some of those reported by Lehtonen et al. (2011) in two areas in eastern and northern Finland where REE-bearing minerals were recovered from till with no known bedrock source. They observed varying combinations of pyrochlore, columbite-tantalite, monazite, xenotime, allanite, and rhabdophane in the <0.063 mm fraction of till in two studies. Both, Lehtonen et al. (2011) and Wilton et al. (2017) used specialized techniques to examine smaller heavy minerals (<0.25 mm) in till and employed rapid SEM scanning methods to identify the indicator minerals in grain mounts. In our study, sand-sized unmounted 0.25 – 2.0 mm grains were visually examined using routine heavy mineral methods used in base and precious metal exploration programs and with a minor amount of assistance from an SEM.

Advantages of indicator mineral methods

The advantages of REE indicator mineral methods over geochemical analysis of till matrix samples are that the indicator mineral grains: (1) are visible and can be examined with a binocular or scanning electron microscope; (2) may be chemically analyzed to provide information about the nature of the mineralizing system; (3) provide physical evidence of the presence or absence of mineralization or alteration; and (4) may be present in very low abundances (few grains in a 10 kg till sample) in till that does not have a matrix geochemical signature (Averill 2001; McClenaghan 2011). The fourth advantage can be especially important in reconnaissance to regional scale surveys, where the mere presence of a few indicator grains in a sample may indicate that a region is worth more detailed examination/sampling.

The advantages of visually examining the >0.25 mm HMC fraction to identify indicator minerals are: 1) the method described here is well established and been
used for more than 30 years by industry and governments and thus results can
be compared between surveys conducted during different years or by different
organizations; 2) the method is routine, fast, and moderately priced; 3)
identification of REE-minerals can be conducted as part of any indicator mineral
survey conducted for other purposes (i.e., precious and base metal exploration);
4) the grains are sufficiently large and most remain unmounted so that they can
be manipulated and their morphology and surface textures can be examined.

REE indicator minerals may now be added to the expanding list of commodities
that can be targeted in mineral resource evaluations of large regions. When
focused on property scale targets, indicator mineral methods should be used in
combination with till geochemistry to explore properties and/or follow up
anomalies. Archived HMC from previous indicator mineral surveys (i.e., diamond
exploration) can be re-examined to detect the presence of REE minerals.

The large number (n=570) of closely-spaced (500 m spacing) till samples
collected by Batterson (1989) to define the Strange Lake glacial dispersal train
was unusually dense as compared to routine regional-scale till geochemical
surveys carried out in present times (cf., McClenaghan and Paulen 2018). For
example, if Batterson’s sample spacing had been 10 to 20 km, a common
spacing used in reconnaissance or regional surveys (Levson 2001; McClenaghan
and Paulen 2018), the dispersal train would not have been as obvious.

**FUTURE RESEARCH**

Automated SEM-based methods (MLA, QEMSCAN, etc.) are also useful for
detecting unusual rare metal minerals in till heavy mineral concentrates
(Lehtonen et al. 2015; Layton-Matthews et al. 2017). The advantage of
automated methods is the constant quality and speed of mineral observing.
However, such methods are statistically relevant only to finer grain size
fractions of till and other sample media (M. Lehtonen, personal communication,
2018). These methods are expensive to prepare and analyze, and thus
not yet routinely applied to every heavy mineral sample. Future research
should include analysis of the <0.25 mm HMC and mid-density fractions of
bedrock and till from Strange Lake using automated SEM-based methods to
determine the rare metal minerals present, how the indicator mineral population
correlates with the grain size, and why gerenite and gadolinite were not visually
observed in the >0.25 mm HMC. Future research will also include
characterization of the mineral chemistry of selected indicator minerals in
bedrock and till down ice to test recently developed discrimination criteria (e.g. for
pyrochlore, fluorite, titanite, zircon and apatite; Mackay and Simandl 2015; Mao
et al. 2015; Simandl et al. 2015) that could aid in the exploration for a deposit
such as Strange Lake.

CONCLUSIONS

The Strange Lake study is the first detailed investigation of the indicator mineral
signature of a major rare metal deposit in glaciated terrain. The deposit contains
a large number of oxide, silicate, phosphate, and carbonate indicator minerals,
some of which were recovered from till overlying the deposit and up to 50 km
down ice. Several minerals were observed in bedrock and or till samples in this
study that had not been previously reported for the Strange Lake HREE deposit
(chevkinite, cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite,
and aeschynite). The most useful indicators of the Zr-REE mineralization in the
Strange Lake area include Zr-silicates (zircon, secondary gittinsite and other
hydrated Zr±Y±Ca-silicates), pyrochlore, thorite/thorianite,
monazite/rhabdophane, chevkinite, parisite, bastnaesite, kainosite, and allanite.
Minerals such as aegirine, arfvedsonite, and fluorite are indicators of highly
alkaline host rocks that could potentially be HFSE- and REE-bearing.

The Strange Lake test site is exceptional for two reasons. First, a large volume of
REE-rich debris was glacially eroded from the deposit and second, the debris
was glacially transported a long distance (>50 km) by a palaeo-ice stream. The
net result is a long ribbon-shaped dispersal train formed by unidirectional ice
flow. This remarkable dispersal train was ideal for the study of metal-rich till at varying distances down ice to test rare metal indicator mineral methods. The indicator mineral abundances for till reported here offer a guide to contents in till that might be expected down ice of rare metal mineralization within ice streams. These indicator minerals can be used to explore for similar rare metal mineralization in the region, and elsewhere in glaciated terrain.

This case study demonstrates that indicator mineral methods have a broader application that includes rare metal exploration, a fact that is not well known for till sampling. The suites of minerals that may now be recovered from the same till or stream sediment sample is broad and includes diamonds, precious, base, strategic, and rare metals.

ACKNOWLEDGEMENTS

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References


Bell, J.E. 1984. Mineralogy of till in a dispersal train derived from a peralkaline granite, Lac Bisson, Quebec-Newfoundland. B.Sc. thesis, Department of Geology, Queen’s University, Kingston, ON.


Jambor, J.L., Roberts, A.C., Grice, J.D., Birkett, T.C., Groat, L., and Zajac, S. 1998. Gerenite-(Y), (CaNa)$_2$(Y,REE)$_3$Si$_6$O$_{18}$$\cdot$2H$_2$O, a new mineral species and an associated Y-bearing gadolinite-group mineral, from the Strange Lake peralkaline complex, Quebec-Labrador. The Canadian Mineralogist, 36; 793-800.


McClenaghan, M.B., Paulen, R.C., and Oviatt, N.M. 2018. Geometry of indicator mineral and till geochemistry dispersal fans from the Pine Point Mississippi


**Tables**

Table 1. List of potential indicator minerals (>2.8 specific gravity) in the Strange Lake deposit compiled from Birkett et al. (1992), Miller (1996), Jambor et al. (1998), Gowans et al. (2014), Oyediran et al. (2014), and Zajac (2015) as well as indicator minerals that were recovered from the >2.8 specific gravity non-ferromagnetic fractions of bedrock and till samples in this study.
Table 2. Number of indicator mineral grains in the 0.25 – 0.5 mm non-ferromagnetic heavy mineral fraction (specific gravity >3.2) and mid-density fraction (specific gravity 3.0 – 3.2) of bedrock, cobble, and till samples examined in this study. Bedrock samples normalized to a 1 kg sample mass of <2 mm (table feed) material and till samples normalized to a 10 kg mass of the <2 mm (table feed) material.

**Figures**

Figure 1. Location of the study area in eastern Canada (inset) and regional bedrock geology map of the Strange Lake area (geology summarized from Miller et al. 1997).

Figure 2. Simplified bedrock geology map of the Strange Lake intrusion, modified from Kerr (2013).

Figure 3. Equivalent Th (ppm) from airborne gamma-ray spectrometry data for the Strange Lake area. The area similar Th values outlined in white and trending northeast is the signature of the Strange Lake glacial dispersal train. The Strange Lake intrusion is outlined with a black line. Data from Geological Survey of Canada (1980).

Figure 4. Sandy till sampled at site 15-MPB-009, 50 km down ice of the Strange Lake intrusion.

Figure 5. Distribution of Be (ppm) in the <0.063 mm fraction of till (total digestion/ICP-ES) overlying and down ice of the Strange Lake intrusion (data
from Batterson and Taylor, 2009). Location of GSC bedrock and till samples are shown as red dots; red arrows indicate samples are just off the edge of the map.

Figure 6. Colour photographs of selected indicator minerals from bedrock or from till samples overlying and down ice of the Strange Lake deposit: a) reddish brown to black fibrous arfvedsonite grains from till sample 15-MPB-010; b) dark green acicular aegirine from till sample 15-MPB-008; c) dark purple fluorite grains from bedrock sample 15-MPB-004A02; d) orange-brown octahedral pyrochlore grains from bedrock sample 15-MPB-004A; e) orange monazite grains from till sample 15-MPB-006; f) white bastnaesite grains from till sample 15-MPB-009; and, g) black chevkinite from till sample 15-MPB-010; h) dark brown allanite intergrown with white gittinsite from till sample 15-MPB-009. Digital photography by Michael J. Bainbridge Photography.
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Hardness*</th>
<th>Density*</th>
<th>Presence of mineral at Strange Lake first reported by others</th>
<th>Seen in bedrock PTS in this study</th>
<th>Seen in bedrock HMC in this study</th>
<th>Seen in Till HMC in this study</th>
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<td><strong>U, Th Minerals</strong></td>
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<td>no</td>
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<td>no</td>
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<td>Th(SiO₄)</td>
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<td>4 - 6.7</td>
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<td>thorianite</td>
<td>ThO₂</td>
<td>6.0</td>
<td>10.0</td>
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<td>yes</td>
<td>yes</td>
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<td>uraninite</td>
<td>UO₂</td>
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<td>6.5 - 10.95</td>
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<td>yes</td>
<td>yes</td>
<td>no</td>
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<td>aeschynite</td>
<td>(Y,Ca,Fe)(Ti,Nb)₂(O,OH)₆</td>
<td>5.5 - 6</td>
<td>4.85 - 5.13</td>
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<td>yes</td>
<td>no</td>
<td>no</td>
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<td>pyrochlore</td>
<td>(Na, Ca)₂Nb₂O₅(OH,F)</td>
<td>5.5 - 5.5</td>
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<td>Zajac et al. (1984)</td>
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<td>fersmite</td>
<td>(Ca,Ce,Na)(Nb,Ti,Ta)₂(O,OH,F)₆</td>
<td>4.4 - 5</td>
<td>4.69 - 4.79</td>
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<td>aegirine</td>
<td>NaFe(Si₂O₆)</td>
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<td>3.5 - 3.6</td>
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<td>yes</td>
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<td>allanite</td>
<td>(Ca₄, Ce, Y, La)₃(Al, Fe)₃(SiO₄)₂(OH)</td>
<td>5.5</td>
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<td>yes</td>
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<tr>
<td>aenigmatite</td>
<td>(Na, Ca)₂(Fe, Ti, Mg)₁₂Si₁₂O₄₀</td>
<td>5 - 6</td>
<td>3.7 - 3.9</td>
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<td>arvedsonite</td>
<td>Na₃Fe₂Fe(Si₆O₂₂)(OH)₂</td>
<td>5.5 - 6</td>
<td>3.44 - 3.45</td>
<td>Miller (1996)</td>
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<td>britholite</td>
<td>(Ca₄, Ce, Th, La, Nd)₃(SiO₄, PO₄)₂(OH,F)</td>
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<td>cerite</td>
<td>Ce₅Fe(SiO₄)₃(SiO₃)(OH)₄</td>
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<td>4.86</td>
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<td>chevkinite</td>
<td>(Ce₄, La, Ca, Th)ₙ(Fe, Mg)₂(Ti, Fe)ₙSi₄O₂₂</td>
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<td>danburite</td>
<td>Ca₆Si₃O₈</td>
<td>7.0</td>
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<td>no</td>
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<td>flurobritholite-(Ce)</td>
<td>(LREE)₃(SiO₄, PO₄)₂(OH,F)</td>
<td>5.0</td>
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<td>gadolinite group</td>
<td>Be₃(Ca, REE, Fe)Si₃O₁₀</td>
<td>6.5 - 7</td>
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<td>gerenite</td>
<td>(Ca₄, Na)₂(Y, REE)₃Si₆O₁₈·2(H₂O)</td>
<td>5</td>
<td>3.3 - 3.52</td>
<td>Jambor et al. (1998)</td>
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<td>helvite</td>
<td>Mn₄Be₃(SiO₄)₂S</td>
<td>6-6.5</td>
<td>3.16 - 3.36</td>
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<td>no</td>
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<td>kainosite</td>
<td>Ca₃(Y, Ce)₂Si₄O₁₂(CO₃)•H₂O</td>
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<td>Zajac et al. (1984)</td>
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<td>komarovite</td>
<td>(Ca, Mn)₂(Nb, Ti)₂Si₅O₇(O, F)•3.5(H₂O)</td>
<td>4</td>
<td>3.61 - 3.76</td>
<td>Oyedirian et al. (2014)</td>
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<td>malayaite</td>
<td>CaSnSiO₅</td>
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<td>4.3 - 4.55</td>
<td>Oyedirian et al. (2014)</td>
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**Zirconosilicates**

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<th>Reference</th>
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<td>gittinsite</td>
<td>CaZrSiO₇</td>
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<td>ZrSiO₄</td>
<td>7.5</td>
<td>4.6 - 4.7</td>
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<td>Ca₀.₉ZrSiO₉•2(H₂O)</td>
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<td>Birkett et al. (1992)</td>
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**Titanosilicates**

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<td>astrophyllite</td>
<td>K₂Na(Fe, Mn)₇Ti₂Si₈O₂₆(OH)₄</td>
<td>3-3.5</td>
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<td>bafertisite</td>
<td>Ba(Fe, Mn)₂TiSi₂O₅(O, OH)₂</td>
<td>5</td>
<td>3.96 - 4.25</td>
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<td>neptunite</td>
<td>KNa₂Li(Fe, Mn)₂Ti₂Si₈O₂₄</td>
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<td>K₂Na(Fe, Mn)₇(Nb, Ti)₂Si₈O₂₆(OH)₄(F, O)</td>
<td>3-4</td>
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<td>CaTiSiO₅</td>
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<td>3.4 - 3.56</td>
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<td>apatite</td>
<td>Ca₅(PO₄)₃(OH, F, Cl)</td>
<td>5.0</td>
<td>3.2</td>
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**REE-F minerals**

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**Sulphides**

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*source of information [www.webmineral.com](http://www.webmineral.com)*

Table 1. List of potential indicator minerals (>2.8 specific gravity) in the Strange Lake deposit compiled from Birkett et al. (1992), Miller (1996), Jambor et al. (1998), Gowans et al. (2014), Oyediran et al. (2014), and Zajac (2015) as well as indicator minerals that were recovered from the >2.8 specific gravity nonferromagnetic fractions of bedrock and till samples in this study.
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<th>Pyro</th>
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<th>Kain</th>
<th>Chevk / Thorite</th>
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* allanite+gittinsite in >3.2 SG fraction

Table 2. Number of indicator mineral grains in the 0.25 – 0.5 mm non-ferromagnetic heavy mineral fraction (specific gravity >3.2) and mid-density fraction (specific gravity 3.0 – 3.2) of bedrock, cobble, and till samples examined in this study. Bedrock samples normalized to a 1 kg sample mass of <2 mm (table feed) material and till samples normalized to a 10 kg mass of the <2mm (table feed) material.
Figure 2. Simplified bedrock geology map of the Strange Lake intrusion, modified from Kerr, 2013, after Miller (1986) and Miller et al. (1997).
Figure 3. Equivalent Th (ppm) from airborne gamma-ray spectrometry data for the Strange Lake area. The area similar Th values outlined in white and trending northeast is the signature of the Strange Lake glacial dispersal train. The Strange Lake intrusion is outlined with a black line. Data from Geological Survey of Canada (1980). Modified from McClenaghan et al. (2017b)
Figure 4. Sandy till sampled at site 15-MPB-009, 50 km down ice of the Strange Lake intrusion.
Figure 6. Colour photographs of selected indicator minerals from bedrock or from till samples overlying and down ice of the Strange Lake deposit: a) reddish brown to black /fibrond arfvedsonite grains from till sample 15-MPB-010; b) dark green acicular aegirine from till sample 15-MPB-008; c) dark purple /fluorite grains from bedrock sample 15-MPB-004A02; d) orange-brown octahedral pyrochlore grains from bedrock sample 15-MPB-004A; e) orange monazite grains from till sample 15-MPB-006; f) white bastnaesite grains from till sample 15-MPB-009; and, g) black chevkinite from till sample 15-MPB-010; h) dark brown allanite intergrown with white gittinsite from till sample 15-MPB-009. Digital photography by Michael J. Bainbridge Photography.