Journal of Geochemical Exploration 197 (2019) 199–211

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

journal homepage: www.elsevier.com/locate/gexplo

PCA of Fe-oxides MLA data as an advanced tool in provenance discrimination and indicator mineral exploration: Case study from bedrock and till from the Kiggavik U deposits area (Nunavut, Canada)

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ARTICLE INFO

Keywords:
Fe-oxide
Kiggavik
Till
MLA
PCA
Grain size
Mineral association

ABSTRACT

Magnetite and hematite grains from the 0.25–0.5 mm and 0.5–2.0 mm ferromagnetic fractions of ten till samples collected up-ice, overlying and down-ice of the Kiggavik U deposits (Nunavut, Canada), as well as eight bedrock samples from Kiggavik igneous and metasedimentary basement and overlying sedimentary rocks were characterized for their grain size and mineral association using optical microscopy, scanning electron microscopy (SEM) and mineral liberation analysis (MLA). Principal component analysis (PCA) was used to evaluate the MLA data for Fe-oxide mineral association and grain size distribution. PCA shows that mineralogical and granulometric differences in Fe-oxides from Kiggavik igneous rocks distinguish them from that of Kiggavik metasedimentary and sedimentary rocks. In addition, The PCA results indicate that the composition and abundance of minerals associated/intergrown with Fe-oxides are not only different in various till samples, but also in different size fractions of the same sample. Higher proportions of hornblende, quartz, gahnite, grunerite, apatite, chromite and sulfides are intergrown with Fe-oxides in the 0.5–2.0 mm till fraction, as compared to the 0.25–0.5 mm fraction in which Fe-oxides are mostly associated with pyroxene, titanite, rutile, feldspars, calcite and zircon. The mineral associations and grain sizes of proximal bedrocks are reflected in smaller size fractions of Kiggavik till, whereas detrital grains in the 0.5–2.0 mm fraction of Kiggavik till may have originated from distal sources. PCA also shows that Fe-oxides from the Kiggavik bedrock and till can be discriminated from those of volcanogenic massive sulfide (VMS) deposits because of smaller grain sizes and higher abundances of sulfides, gahnite, axinite, corundum, hypersthene and pyroxene intergrown with VMS Fe-oxides. This study emphasizes the importance of selecting suitable representative grain size fractions of till, or other sediments, when using indicator minerals for exploration. The results of PCA of Fe-oxides MLA data are consistent with the results of using Fe-oxides geochemical data in provenance discrimination of Kiggavik till.

1. Introduction

In the past 30 years, breakthroughs have been achieved in the use of indicator minerals in the exploration for Au, Cu, Ni, PGE, Pb-Zn, and diamonds (e.g. Averill, 2001; McClenaghan and Kjarsgaard, 2007; Kaminsky and Belousova, 2009; McClenaghan et al., 2015; McClenaghan and Paulen, 2017). A great advantage of indicator mineral methods is the ability to trace the dispersion of eroded mineral deposits in surficial sediments. The presence of some minerals (e.g., omphacite, Cr-rich pyrope, and manganiferous ilmenite) in sediments indicates the potential to find specific deposits (e.g. fertile kimberlitic bodies). In the case of ubiquitous indicator heavy minerals such as Fe-oxides, their trace elements and isotope geochemistry can be used as a provenance discrimination and/or mineral exploration tool (Dupuis and Beaudoin, 2011; Boutroy et al., 2014; Dare et al., 2014; Nadoll et al., 2014; Makvandi et al., 2016a, 2016c, 2017). The extent of elemental substitution and the type of substituting elements in Fe-oxides are strongly controlled by the environment in which they formed. Given that Fe-oxides are major to accessory minerals in many types of mineral deposits/geologic settings, their composition has widely been used to

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https://doi.org/10.1016/j.gexplo.2018.11.013
Received 5 July 2018; Received in revised form 1 September 2018; Accepted 26 November 2018

distinguish various mineral deposit types including Ni-Cu, Fe-Ti, volcanogenic massive sulfide (VMS), porphyry Cu, iron oxide copper gold (IOCG), iron oxide-apatite (IOA), banded iron formation (BIF), skarn, and unconformity-related U deposits (Dupuis and Beaudoin, 2011; Nadoll et al., 2014; Dare et al., 2014; Makvandi et al., 2016a, 2016c, 2017). In contrast, the use of Fe-oxide mineral associations and grain size distribution in the identification of host mineral deposits is not well understood. Makvandi et al. (2015, 2016b) showed that the abundance of some minerals in association with magnetite helps to distinguish the composition of host rocks. They concluded that detrital Fe-oxides intergrown with gahnite, sillimanite and ilmenite were most likely derived from metamorphosed VMS deposits. Makvandi et al. (2015, 2016b) also reported that the shape and grain size of the Fe-oxides in till are fundamentally controlled by the grain's original shape and size (≤ 0.25 mm to ≥1.0 mm) in host rocks, whereas the mode and duration of transport are secondary. Thus, they suggested that the study of Fe-oxides shape and grain size can provide supplementary information to indicator mineral exploration programs.

This study aims to show the use of Fe-oxide mineral association and grain size distribution, obtained through mineral liberation analysis (MLA,) in provenance discrimination of till covering the Kiggavik U deposits area. To meet this objective, samples collected from various host rock compositions and from till collected at different distances from the Kiggavik deposits were studied using optical and electronic microscopy, as well as through mineral liberation analysis (MLA), an automated SEM-based mineralogy method. This study investigated the 0.25–0.5 and 0.5–2.0 mm fractions of Kiggavik till and will elaborate whether these size fractions of till are representative of Fe-oxides in Kiggavik host rocks, and thus, if they are suitable for further U exploration in the Kiggavik region.

1.1. Geologic setting

1.1.1. Regional and local geology

The Kiggavik camp is located in the northeast corner of the Thelon Basin (Nunavut, Canada; Fig. 1A-B), approximately 80 km west of Baker Lake (Hoffman, 1988). The Paleoproterozoic to Mesoproterozoic Thelon Basin is situated within the Rae Subprovince of the Western Churchill tectonic province of the Canadian Shield (Fig. 1B). The crystalline basement lithologies underlying the Kiggavik deposits comprise Archean granitoid gneiss, Neoarchean supracrustal rocks of the Woodburn Lake Group, metasedimentary and metavolcanic rocks of the Marjorie Hills Assemblage, the ~2.6 Ga Snow Island Suite (SIS), and the early Paleoproterozoic Ketyet River Group (Fig. 2A-B; Pehrsson et al., 2013; Tschirhart et al., 2013). These rocks have been variably metamorphosed from greenschist to amphibolite facies with common retrogression to greenschist facies (LeCheminant et al., 1979; Zaleski et al., 2000). Paleoproterozoic quartz arenites of the Amarook Formation and the Thelon Formation of the Dubawndt Supergroup occurs several kilometers north of the Kiggavik deposits.

In the Kiggavik area, the quartzofeldspathic metagreywacke of the Pipedream Assemblage is structurally overlain by a sequence of Snow Island Suite quartz-feldspar porphyritic rhyolite (Pukiq Lake Formation), schist, and epiclastic metavolcanic phyllite, and Ketyet River Group metaquartzite (Fig. 2A-B; Scott et al., 2015; Sharpe et al., 2015; Johnstone et al., 2016, 2017). The uranium mineralization that characterizes the Kiggavik deposits is located at the gently-dipping interface between the overlying epiclastic-rhyolite-quartzite imbricate panel and the underlying Pipedream metagreywacke (Johnstone et al., 2017; Grare et al., 2018).

The western portion of the Kiggavik camp consists of the 1.83 Ga Hudson Igneous Suite (HIS) that comprises Hudson granite and Martell syenite formed as a result of mingling between lamprophyre and Hudson granite magmas (Tschirhart et al., 2013; Miller and Peterson, 2015). The Neoarchean to Paleoproterozoic basement rocks under the Thelon Basin were intruded by Paleo- to Mesoproterozoic, late-orogenic granite to ultrapotassic mafic to felsic dykes, laccoliths, and localized plugs of the Hudson and Kivalliq Igneous Suites (Fig. 2A-B; Rainbird and Davis, 2007).

The Dubawnt Supergroup comprises three sedimentary sequences: the Baker Lake Group (1845–1785 Ma), Wharton Group (~1750 Ma), and Barrensland Group (< 1720–1540 Ma; Rainbird et al., 2003). The crystalline basement rocks were deeply weathered and overlain by the aeolian to alluvial sandstone and conglomerate of the Amarook Formation, which forms the lower part of the Wharton Group. The Wharton Group is overlain by the Barrensland Group composed of fluvial, variably hematitic, quartz arenite, conglomerate and red mudstone of the Thelon Formation. The Thelon Formation is the dominant basin-filling unit of the Thelon Basin, and comprises three dominantly alluvial siliciclastic sequences (Hiatt et al., 2003; Tschirhart et al., 2014). The Thelon Formation was deposited on a paleo-regolith suggesting a significant depositional pause (Hiatt et al., 2010), and is locally capped by ultrapotassic basaltic flows of the Kuungmi Formation overlain by siliceous stromatolitic dolostone of the Lookout Point Formation (Gall et al., 1992; Chamberlain et al., 2010). All lithologies in this region are cut by NW-trending 1.27 Ga Mackenzie dykes.

The Kiggavik area has been explored for uranium since the 1970s because the geology of the area is similar to that of the eastern part of the Athabasca Basin (Fuchs et al., 1985). The uranium deposits (Kiggavik, End, and Andrew Lake) and prospects (Bong, Granite, and Contact) in the Kiggavik region may be unconformity-related (Kiggavik Main and Central Zone deposits: Farkas, 1984; Shabaga et al., 2017; Bong deposit: Riegler et al., 2016a, 2016b; Sharpe et al., 2015; Quirt, 2017; End deposit: Chi et al., 2017; Fayek et al., 2017), and are associated with multiple fault systems trending ENE–WSW (Thelon, Judge Sissons), NE–SW (Andrew Lake), and S-SE (Grare et al., 2018). These fault systems are sites of intense brittle deformation and alteration associated with hydrothermal activity. The Kiggavik deposit comprises three separate ore zones (Fig. 2A): (Main (MZ), Centre (CZ), and East zones (EZ), with resources estimated at approximately 50,000 t U at an average grade of 0.5 wt% (Jefferson et al., 2007). Fuchs and Hilger (1989) recognized that the mineralization at the Kiggavik deposits is intimately associated with intense clay mineral alteration halos that are hosted by mica-rich quartzofeldspathic metasediments (Pipedream Assemblage metagreywacke) and locally in Hudsonian granite. Uranium mineralization at the Kiggavik, Andrew Lake, and End deposits was originally described as uraninite altering to coffinite that indicates these deposits have experienced U remobilization (Fuchs et al., 1986; Sharpe et al., 2015; Shabaga et al., 2017). The U mineralization at the Bong deposit is also composed of uraninite, coffinite and paragenetically late uranyl minerals (e.g., uranophane; Riegler et al., 2014; Sharpe et al., 2015). Host-rock alteration related to the Kiggavik mineralization is generally characterized by strong bleaching of the host rock, chloritization, illitization, and hematitization extending over tens of meters (Fuchs and Hilger, 1989; Riegler et al., 2014; Sharpe et al., 2015; Shabaga et al., 2017). The typical alteration mineral assemblage includes clay minerals (illite ± sudoite) ± hematite ± aluminum phosphates sulfates (APS), and quartz veining (Riegler et al., 2014; Sharpe et al., 2015).

1.1.2. Surficial geology

The Kiggavik region was covered by the Laurentide Ice Sheet from the beginning of the Wisconsinan through the Late Wisconsinan Maximum (18–13 Ka; Aylsworth and Shilts, 1989; Dyke et al., 2002; Dyke, 2004; McMartin and Henderson, 2004). The area was completely deglaciated between 7.2 and 6.0 Ka. Blocking of the Thelon River drainage by the retreating ice mass resulted in deposition of lake sediments in the Thelon River valley and Princess Mary Lake basin, approximately 60 km southeast of the Kiggavik deposits (McMartin and Dredge, 2005). No evidence of glaciofluvial sediments is recorded in the Schultz Lake area. In absence of eskers and ribbed moraines, a ubiquitous cover of till characterizes the surficial geology of the Kiggavik

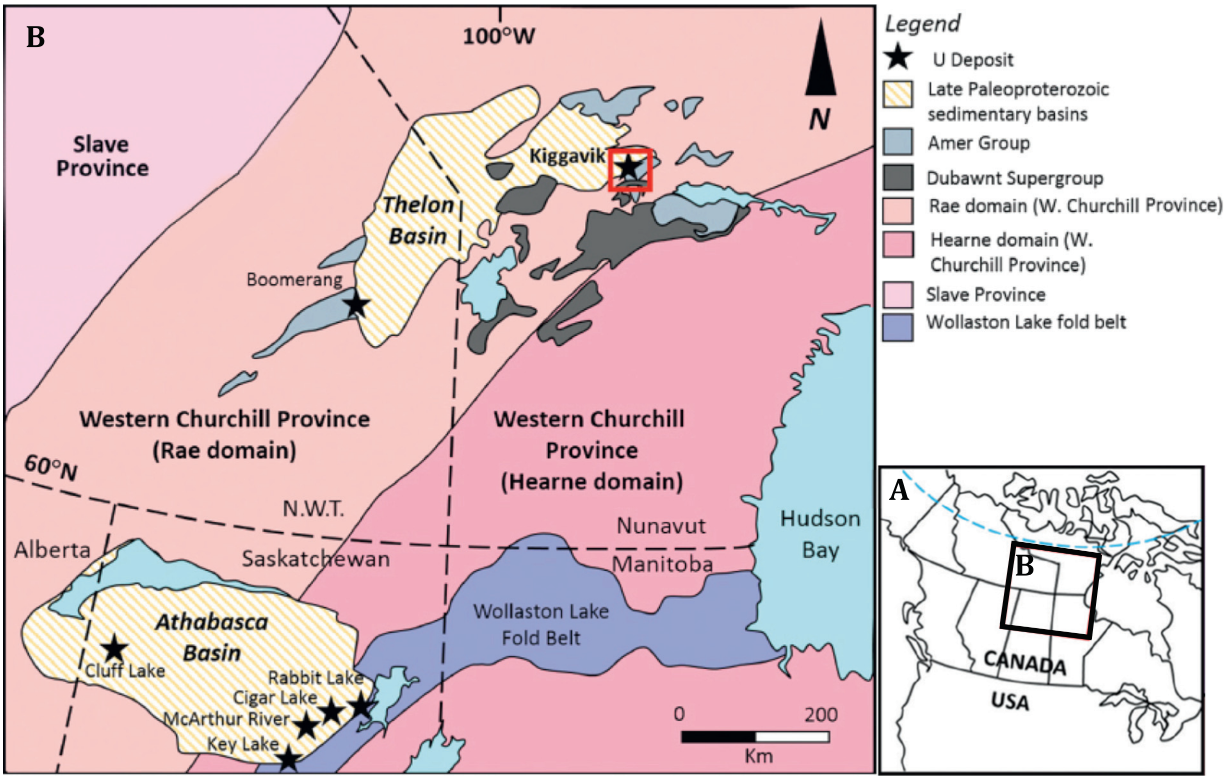

Fig. 1. A) The location of **B** in Canada. **B)** Simplified regional geology of the western Churchill Province and surrounding area around the Athabasca and Thelon basins, and location of the Kiggavik camp in the north east of the Thelon Basin, Nunavut, Canada (modified after Renac et al., 2002). Red box represents location of Fig. 2 (studied area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

camp (Aylsworth and Shilts, 1989; McMartin et al., 2006; Robinson et al., 2014).

In the Kiggavik deposit area, bedrock highs are covered by thin layers of till, whereas lower lying areas, and less-resistant metasedimentary rocks are covered by hummocky till (Robinson et al., 2016). There is only 5% bedrock exposure, mainly in gentle hills that consist of Ketyet River Group quartzite, Neoarchean basement granitic gneiss, or Hudson granitic rocks (Robinson et al., 2016). The Proterozoic quartzite exposures, situated north of the Kiggavik deposits, preserve faceted and striated surfaces that record multiple ice-flow trajectories (Robinson et al., 2016). Surficial mapping indicates that the Schultz Lake area has been affected by multiple phases of ice flows from which the Kiggavik area was dominantly affected by northwest and westnorthwest ice flows (Aylsworth and Shilts, 1989; Aylsworth et al., 1990; McMartin et al., 2006; Fig. 2C).

1.2. Fe-oxides in Kiggavik bedrock and till

1.2.1. Kiggavik bedrock

Makvandi et al. (2017) studied petrographic characteristics and trace element compositions of magnetite and hematite grains in unmineralized bedrock and till samples collected in the vicinity of the Kiggavik MZ deposit. The composition of these minerals from local bedrock lithologies was used to construct discriminant models that serve to classify the sources of Fe-oxides grains in Kiggavik till. Petrography and geochemical data suggest a magmatic origin for magnetite, the predominant Fe-oxide phase (Fig. 3A-C), in Kiggavik igneous basement rocks. Magnetite grains from the late-orogenic leucogranite, granite and Martell syenite samples of the Hudson and Kivalliq (Nueltin) Suites are hosted by the magmatic assemblage of feldspar, biotite, muscovite and hornblende (Fig. 3B), and are partly replaced by ilmenite. Cobalt, V, Cr, Pb and Ni are discriminant elements for the magmatic magnetite (Makvandi et al., 2017). In the Kiggavik igneous basement, hematite formed by replacing magnetite. Fig. 3C shows a hematite pseudomorph after magnetite from the Hudson and Kivalliq Suites granite. Higher concentrations of Mg, Al, Ti, and Zr in the hematite relative to the parent magnetite suggests that hematite crystallized from high-temperature hydrothermal fluids. Zircon (Fig. 3C) and apatite are abundant accessory minerals in association with Fe-oxides in the Kiggavik igneous basement rocks.

In contrast to Kiggavik igneous basement, hematite is the dominant Fe-oxide, assumed to be mainly a result of in situ replacement of magnetite and ilmenite (Fig. 3D, E). Specular hematite occurs in the Lower Ketyet River Group quartzite (Fig. 3D) filling vugs after dissolution of the host rock, suggesting that this hematite is hydrothermal, whereas, the SIS rocks contain detrital hematite grains (Fig. 3E). The Thelon Formation quartz arenite also contains detrital hematite grains (Fig. 3F) that are associated with different phases of quartz mineralization (host rock silicification). Makvandi et al. (2017) suggested that part of detrital hematite grains from the quartz arenite originate from the Kiggavik igneous basement as their trace element compositions resemble that of Fe-oxides from the Hudson and Kivalliq (Nueltin) Suites leucogranite and granite.

1.2.2. Kiggavik till

Petrography and geochemical data suggest that Kiggavik till contains Fe-oxides from various host bedrock lithologies. Although magnetite is abundant in Kiggavik till, hematite is the dominant Fe-oxide. Magnetite is commonly granular and/or it occurs as altered material in different mineral assemblages, such as intergrowths with quartz and hematite (Fig. 4A). The assemblage of quartz, platy hematite, and almandine garnet replacing euhedral magnetite (Fig. 4A) suggests that the host rock underwent metamorphism. Some magnetite grains in Kiggavik till that might originate from igneous rocks are intergrown with ilmenite and mafic minerals, such as clinopyroxene and orthopyroxene (Fig. 4B), or occur in association with quartz and apatite

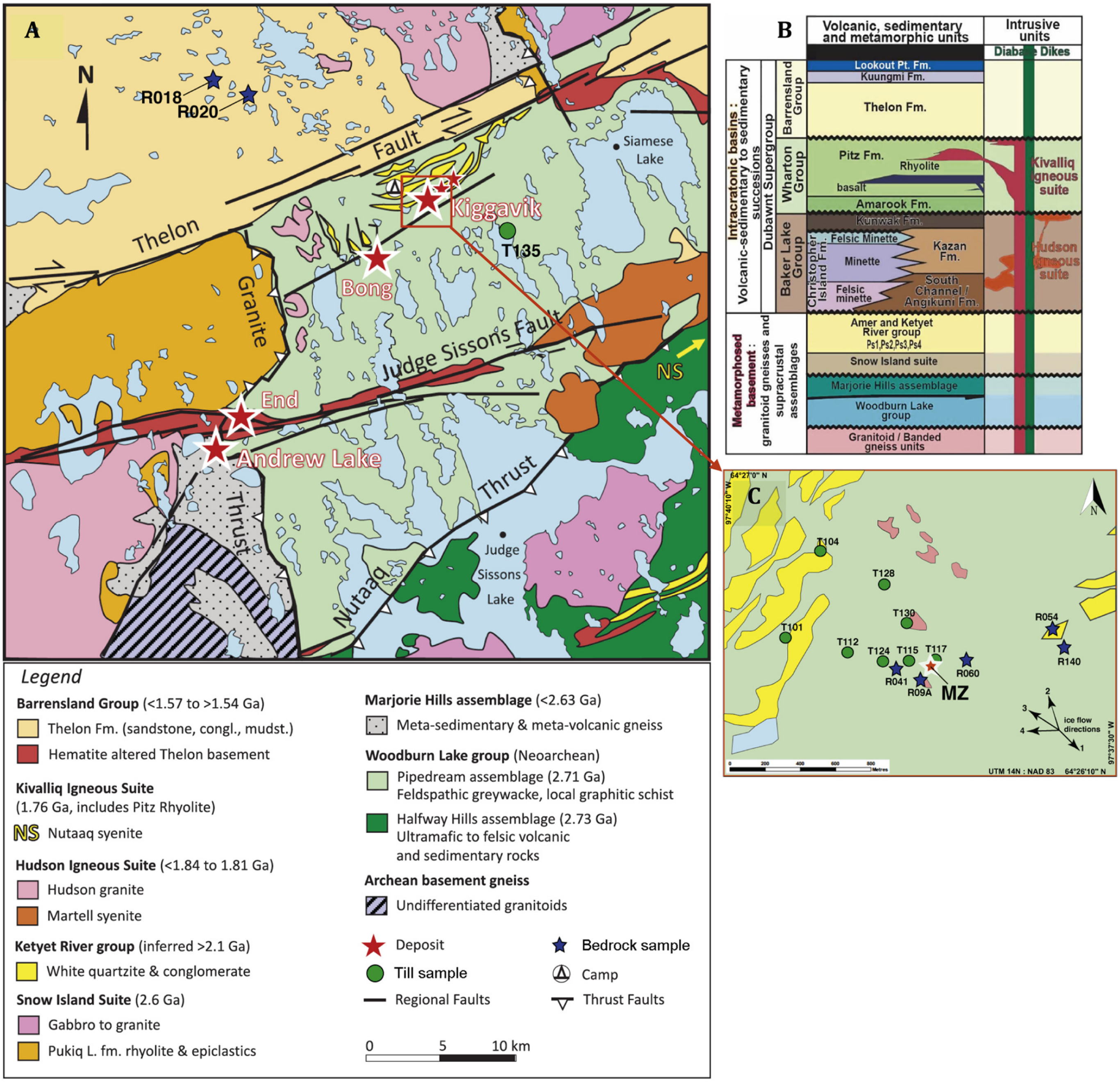

Fig. 2. A) Regional bedrock geology map of the Kiggavik area (modified from Riegler et al., 2014; Scott et al., 2015; Sharpe et al., 2015, Shabaga et al., 2017) showing the location of the Kiggavik deposits. B) Simplified stratigraphic column of lithological and intrusive units in the Western Churchill Province (modified after Peterson et al., 2015; Grare et al., 2018). C) Kiggavik Bedrock and till samples location. Note all rock sample numbers have the prefix 10-PTA- (e.g., R018 refers to sample 10-PTA-R018). In till sample numbers, T replaced the prefix (e.g., T128 refers to sample 10-PTA-128).

(Fig. 4C). Fig. 4D illustrates a polymineralic aggregate from Kiggavik till composed of subhedral magnetite grains as well as magnetite-rutile symplectite and Mn-rich ilmenite islands filling dissolution pits. The Fe-Ti oxides intergrowths are partly replaced by titanite (Fig. 4D). In Kiggavik till, hematite occurs as veinlets or disseminated grains in quartz aggregates as well as specular or botryoidal hematite in polymineralic particles. Occurrence of specular hematite in association with quartz resembles the mineralogy and textures of hematite in Ketyet River Group quartzite (Robinson et al., 2016). Hematite pseudomorphs after magnetite that are associated with clay minerals (Fig. 4E) suggest Kiggavik metasedimentary basement rocks as the potential source of the till grains. In contrast, sulfide inclusions in hematite pseudomorphs (Fig. 4F) resemble the mineralogy of the HIS mafic syenite (Makvandi et al., 2017). Although many studies showed the close association between Fe-oxides and U-bearing minerals in the Kiggavik deposits and prospects (e.g., Chi et al., 2017; Shabaga et al., 2017; Grare et al., 2018), petrography indicates that U-bearing minerals are absent in the 0.25–2.0 mm F-HMC of Kiggavik till. Makvandi et al. (2018) showed that U-bearing minerals (mostly uraninite and coffinite) are not intergrown with hematite and/or goethite in mineralized bedrock samples from the Kiggavik-Andrew Lake structural trend deposits.

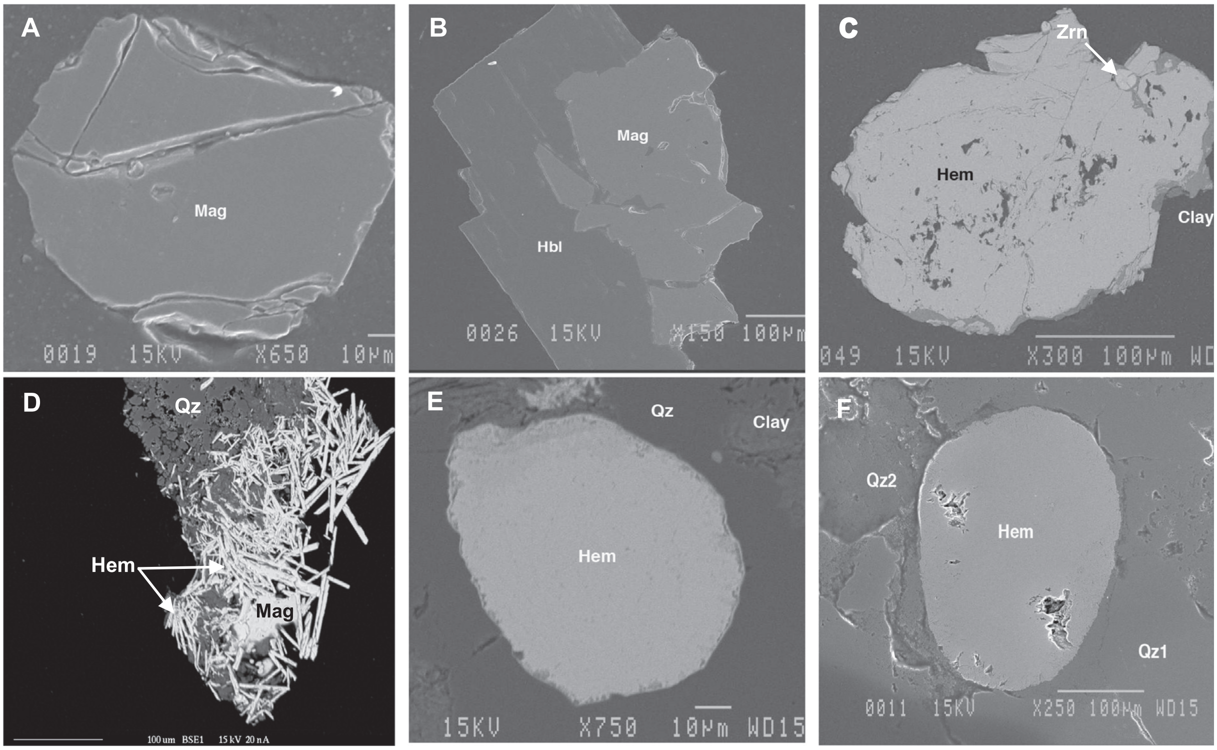

Fig. 3. A selection of SEM backscatter images showing mineral aggregates from the Kiggavik igneous, metasedimentary, and sedimentary bedrock lithologies. **A)** A fractured magnetite (Mag) grain from the Hudson and Kivalliq Suites granite. **B)** A mineral aggregate from the Hudson Igneous Suite (HIS) mafic syenite consisting of magnetite and hornblende (Hbl). Hornblende replaced magnetite along edges and fractures. **C)** Pseudomorph hematite (Hem) after magnetite from the Hudson and Kivalliq Suites granite associated with clay alteration. Zircon (Zrn) occurs as inclusions in Fe oxides. **D)** Specular hematite from Ketyet River Group quartzite is associated with quartz and partly replaced magnetite. **E)** Detrital hematite in association with quartz (Qz) and clay from Snow Island Suite (SIS) epiclastic rocks. **F)** Round hematite grain from Thelon Formation quartz arenite intergrown with two quartz phases (Qz1 & Qz2).

2. Methods

2.1. Sample selection and preparation

The Geological Survey of Canada (GSC) collected a total of forty-two bedrock and seventy-one bulk till samples in the Kiggavik area during the summer of 2010; a portion of the bedrock and till samples was sent to the Overburden Drilling Management Limited (ODM; Ottawa, Canada) to produce heavy mineral concentrates (HMC; Robinson et al., 2016). Bedrock samples were disaggregated using electric pulse disaggregation (EPD). The morphology of the liberated minerals is expected to reflect their original shape and grain size in the bedrock (Rudashevsky et al., 2002; Cabri et al., 2008). The preparation of ferromagnetic heavy mineral fractions (F-HMC) from disaggregated bedrock and till samples is described in McClenaghan et al. (2012). The F-HMC of till samples were sieved to produced 0.25–0.5 mm and 0.5–2.0 mm fractions, and the < 0.25 mm fraction was archived. From the GSC Kiggavik samples, the 0.25–0.5 mm and 0.5–2.0 mm fractions of ten F-HMC till samples, the 0.25–2.0 mm fractions of four F-HMC bedrock samples as well as offcuts of four other bedrock samples were sent to the Université Laval to study geochemical and mineralogical characteristics of Fe-oxides. Descriptions of the studied bedrock and till samples are in Table 1. The eight Kiggavik bedrock samples are from Snow Island Suite (SIS) epiclastic rocks ($n = 1$), Lower Ketyet River Group quartzite ($n = 1$), Hudson and Kivalliq Suites leucogranite ($n = 1$) and granite ($n = 1$), Martell syenite ($n = 1$), Hudson Igneous Suite (HIS) mafic syenite ($n = 1$), and Thelon Formation quartz arenite ($n = 2$). The location of studied bedrock and till samples is shown in Fig. 2A and C. The Kiggavik till samples are from locations up-ice, overlying, and down-ice (NW and WNW directions) of the Kiggavik MZ. Twenty-five polished grain mounts and four polished thin sections were made of the given bedrock and till samples.

2.2. Analytical methods

The Kiggavik bedrock and till samples were investigated using MLA that was carried out on a FEI Quanta 400 W instrument at Memorial University (Newfoundland, Canada) with a Bruker EDX and the Esprit software. Instrument parameters were 25 kV, spot size 7.94 µm, 1.5 mm HFW (horizontal field width), and working distance of 12 mm. The beam current was 13 nA, 16 microseconds BSE (back-scattered electron) dwell time, 500 dpi frame resolution, and 20 ms spectral dwell time. Prior to MLA, magnetite and hematite grains from the Kiggavik bedrock and till samples were studied and photographed using optical microscopy and were analyzed by scanning electron microscopy (SEM) to determine their textural relationships with mineral associations. The petrographic and SEM results were used to develop the library of reference spectra before MLA and also to validate MLA results.

2.3. Multivariate statistical approaches to MLA data analysis

The MLA grain size distribution and mineral association data for the Fe-oxides from the Kiggavik bedrock and till samples were analyzed by principal component analysis (PCA). Traditionally, MLA data are analyzed by conventional data presentation methods, such as box and whisker diagrams, histograms, pie charts and/or cumulative passing plots (Sylvester, 2012; Makvandi et al., 2015). In contrast, PCA is a mathematical procedure that is used to reduce a large set of possibly correlated variables to a smaller number of uncorrelated variables called principal components that still contains important information from the original dataset (Wishart, 2013). A principal component (PC) factor is a linear combination of the original variables that is weighted

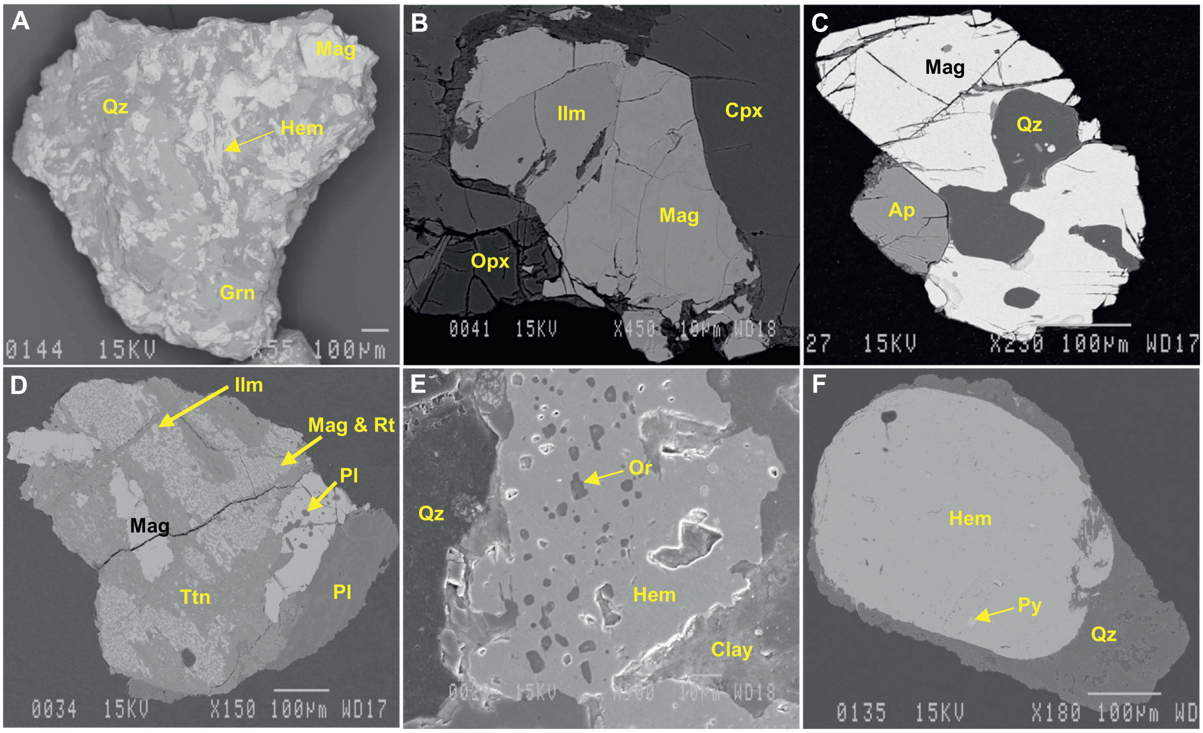

Fig. 4. A selection of SEM backscatter images showing mineral aggregates including Fe oxides from Kiggavik till. **A)** Polymineralic aggregate from the 0.25–0.5 mm fraction of till sample 10-PTA-130 including magnetite, quartz and garnet (Grn) altered by needles of hematite. **B)** Polymineralic aggregate from the 0.5–2.0 mm fraction of till sample 10-PTA-101 including magnetite interlocked with ilmenite (Ilm) and mafic minerals such orthopyroxene (Opx) and clinopyroxene (Cpx). **C)** Polymineralic aggregate from the 0.25–0.5 mm fraction of till sample 10-PTA-096, consisting of magnetite, quartz, and apatite (Ap). **D)** Polymineralic aggregate from the 0.5–2.0 mm fraction of till sample 10-PTA-096 including disseminated magnetite with plagioclase (Pl) inclusions, and slightly replaced by titanite (Ttn). **E)** Hematite pseudomorph consisting of orthoclase (Or) micro-inclusions and altered by clays from the 0.5–2.0 mm fraction of till sample 10-PTA-104. **F)** Round shape hematite from the 0.25–0.5 mm fraction of till sample 10-PTA-096 characterized by pyrite (Py) inclusions and altered by quartz from edges.

by their contribution to explaining the variance in a particular orthogonal dimension (Geladi et al., 1989; Geladi and Grahn, 1996). The first factor (PC1) explains the greatest possible portion of the variance within the dataset, whereas the second factor (PC2) captures the second largest variance orthogonal to the first, and so on. PCA factor loadings are the correlation coefficients between the original variables and the PC and represent the percent of variance in a given variable that is explained by the PC. Factor loadings provide information on the impact of a particular variable (e.g., the abundance of a mineral of interest) on a given factor (Geladi et al., 1989; Geladi and Grahn, 1996). The sign of loadings (positive or negative) is used to interpret the correlation between variables (e.g., Fe-oxide grain size and/or the abundance of mineral associations). Loadings are depicted on factor plots (PC1 versus PC2, PC1 versus PC3, etc.). PCA scores are composite values for each observation on each factor extracted in the factor analysis. Factor weights are used in conjunction with the original variable values to calculate each observation's score which are standardized to reflect a z-score (Geladi et al., 1989; Geladi and Grahn, 1996). Factor scores place each variable in a plane of multivariate variability and are depicted on score plots (t_1 versus t_2, t_1 versus t_3, etc.). In fact, the score plot is a scatter plot, and involves the projection of the data onto the PCs in two dimensions. The x axis contains a user-selected PC (e.g., PC1), while the y axis contains another user-selected PC (e.g., PC2). In this study, PCA was applied to reduce the dimensionality of the large MLA datasets, to reveal hidden correlations among variables, and to identify variables potentially useful in classifying sources of Fe-oxides in the till samples.

3. Results

MLA produces datasets that include modal mineralogy, particle (polymineralic aggregate) size distribution and particle properties (containing values of particles angularity, area, perimeter, aspect ratio and form factor) that can be viewed using the DataView software (Fandrich et al., 2007). In addition, to characterize a mineral (assemblage) of interest, respective data subsets of grain size and/or grain properties and mineral associations can be generated. Fig. 5 is a MLA false-colour image of Fe-oxide grains from Kiggavik till illustrating that Fe-oxides in F-HMC of Kiggavik till may occur as liberated grains (Fig. 5A) or they may be intergrown with other minerals (Fig. 5B-C). Fig. 5B shows an Fe-oxide aggregate containing micro-inclusions of quartz, chlorite, spinel, amphibole, gahnite and zeolite, whereas in Fig. 5C, Fe-oxides are fine-grained (< 0.02 mm) components of a polymineralic aggregate formed by quartz, almandine garnet and clay intergrowths. The Fe-oxides have been replaced by clay minerals along their edges and also contain apatite inclusions (Fig. 5C).

MLA computes values for the maximum length of mineral grains and the grain size distribution for classes based on physical sieve sizes (Sylvester, 2012). Grain size data for the Kiggavik bedrock and till samples are cumulative percentages of values obtained from Fe-oxide grains in each sample passing different sieve sizes. The grain size data are subject to the constant-sum constraint (Aitchison, 1986), so the data were centered log-ratio (clr) transformed prior to PCA to overcome the closure effect (Aitchison, 1986; Flood et al., 2015).

In this study, the data subsets of Fe-oxide grain size and mineral associations from different bedrock and till samples were integrated and then investigated by PCA to demonstrate the use of indicator minerals MLA data analysis in provenance discrimination and in mineral exploration, (Figs. 6–8). Grain size was considered to be an important variable because the MLA results showed that the size of Fe-oxides in each size fraction (0.25–0.5 mm and 0.5–2.0 mm) of the till samples also varies over a wide range depending on the form of minerals occurrence (e.g., liberated grains or inclusions in other minerals

Table 1
A) Bedrock and B) till samples description.

A

Sample ID	Rock type	Easting*	Northing	Lithology	Mineralogy
10-PTA-R018**	Quartz arenite	553,695	7,152,777	Thelon formation	Quartz (83%), alkaline feldspar (15%), hematite (2%)
10-PTA-R020**	Quartz arenite	555,263	7,151,994	Thelon formation	Quartz (90%), pseudomorphs feldspar (6%), hematite (3%), goethite (< 1%), ilmenite (tr.)
10-PTA-R009**	Martell syenite	565,130	7,146,834	Hudson suite intrusive	Alkaline feldspar (45%), quartz (5%), plagioclase (25%), biotite (5%), phologopite (5%), muscovite (2%), chlorite (7%), pyrite (1%), hematite (1%), magnetite (1%), ilmenite (< 1%), apatite (1%), zircon (< 1%)
10-PTA-R060	Leucogranite	565,340	7,146,959	Hudson granite and possibly Nueltin granite	Alkalie feldspar (43%), quartz (40%), hornblende (5%), biotite (5%), muscovite (3%), magnetite (1%), hematite (< 1%), ilmenite and sphene (1%), zircon and apatite (1%), pyrite (tr.)
10-PTA-R041	Granite	564,968	7,146,879	Lone gull plug: Hudson + Nueltin	Alkali feldspar (40%), quartz (30%), plagioclase (20%), muscovite (7%), chlorite (1%), magnetite (1%), zircon (tr), pyrite (tr.), molybdenite (tr.)
10-PTA-R026a	Mafic syenite	552,112	7,142,563	Hudson igneous suite	Alkaline feldspar (28%), amphibole (20%; more horblende and less actinolite), plagioclase (15%), clinopyroxene (15%), biotite (10%), quartz (5%), magnetite (3%), hematite (1%), apatite (1%), pyrite (1%), chalcopyrite (1%)
10-PTA-R054	Quartzite	564,877	7,146,889	Lower Ketyet river group	Quartz (93%), muscovite (5%), hematite (< 2%), magnetite (tr.)
10-PTA-R140**	Epiclastic	565,807	7,147,336	Pukiq lake formation	Quartz (45%), clay alteration (25%), alkaline feldspar (15%), muscovite and sericite (15%), hematite (5%)

B

Sample name	Easting	Northing	Location & direction from the main zone	Distance from main zone
10-PTA-135	570,008	7,147,566	up ice, NE	5 km
10-PTA-117	565,154	7,146,913	overlying	10 m
10-PTA-096	563,729	7,147,964	down ice, NW	2 km
10-PTA-101	564,338	7,147,064	down ice, WNW	1 km
10-PTA-104	564,796	7,147,744	down ice, NW	1 km
10-PTA-112	564,694	7,146,983	down ice, WNW	500 m
10-PTA-115	565,045	7,146,933	down ice, WNW	50 m
10-PTA-124	564,899	7,146,933	down ice, WNW	250 m
10-PTA-128	564,900	7,147,365	down ice, NW	500 m
10-PTA-130	565,024	7,147,155	down ice, NW	250 m

* For all bedrock and till samples: DATUM 83, Zone 14 N.

** Fe oxide grains in the polished thin sections made of these samples' offcuts were investigated in this study.

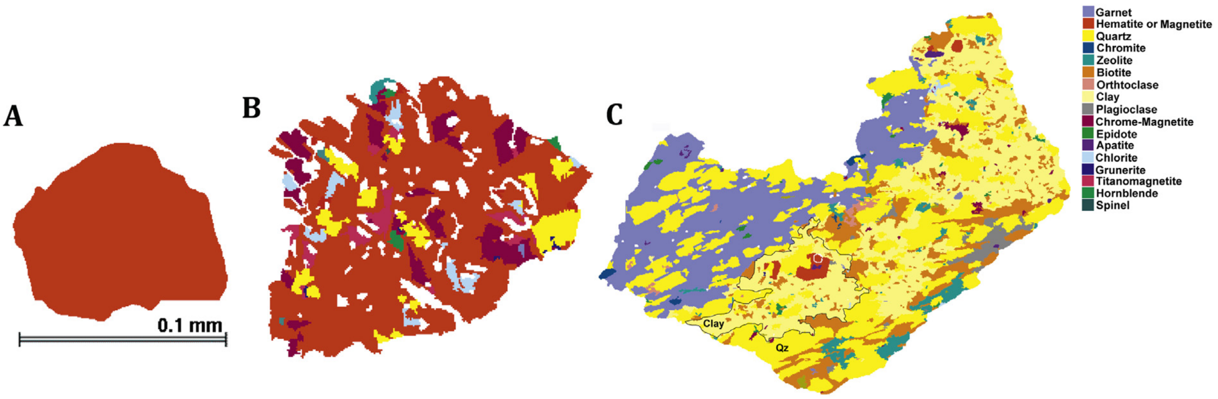

Fig. 5. Mineral liberation analysis (MLA) false colour images. **A)** Liberated Fe oxide grain from the 0.25–0.5 mm fraction of till sample 10-PTA-101. **B)** Magnetite aggregate from the 0.5–2.0 mm fraction of till sample 10-PTA-117 composed of different mineral inclusions such as titanomagnetite (TitanoMag), spinel (Spl), chlorite (Chl), quartz (Qz), zeolite (Zeo), hornblende (Hbl), gahnite (Ghn), and grunerite (Gru). **C)** Fine-grained mineral components of a polymineralic aggregate from the 0.5–2.0 mm fraction of till sample 10-PTA-135. The aggregate is composed of Fe oxides (Hem/Mag), clay minerals, quartz, zeolite, chromite (Chr), biotite (Bi), hornblende, chlorite, orthoclase (Or), plagioclase (Pl), Cr-rich magnetite (Cr-Mag), epidote (Ep), and apatite (Ap). In this aggregate, Fe oxides occur as inclusions in clay minerals.

aggregates). However, the MLA results revealed that liberated Fe-oxide grains are mostly present in the smaller size fraction of tills, whereas in the larger size fraction, Fe-oxides occur in polymineralic aggregates.

3.1. Mineral associations and grain size of Fe-oxides from Kiggavik bedrock

An integrated dataset of mineral associations and grain size of Fe-oxides from the bedrock samples were investigated by PCA. Only the results of analysis of the first and second PCs are depicted in Fig. 6 because they explain 42 and 15% of the total variance within the MLA dataset, respectively. Smaller portions of the 45% remaining variance were captured by the succeeding factors (e.g., 8% by PC3). In Fig. 6A, factor loadings in the PC1-PC2 space illustrate the correlations between variables (Fe-oxide grain size, and the abundance of mineral associations). Grain sizes and/or minerals plotted in the vicinity of each other in this factor space show strong positive correlations, and they are negatively correlated to grain sizes and/or minerals plotted in the opposite quadrant. In Fig. 6A, grain sizes of 425 to ≥1000 μm plot with orthopyroxene, chromite, Cr-rich magnetite and spinel in the low PC1 and PC2 values region, that means coarse Fe-oxides from the Kiggavik bedrock samples are mostly interlocked with the given minerals. In contrast, biotite, muscovite, chlorite and zeolite that plot in high PC1 values region are dominant in association with fine-grained Fe-oxides (9.6 to 250 μm).

Fig. 6B illustrates the distribution of the Kiggavik bedrock samples in t_1-t_2 scores space. In the PCA scores plot, samples that plot in the vicinity of each other share similar grain size distributions and mineralogy. As a result, PC1 separates Fe-oxides from the igneous basement samples (granite, leucogranite, mafic syenite and Martell syenite) and those from the metasedimentary basement samples (quartzite and epiclastic rocks) and Thelon Formation quartz arenites because of distinct differences in mineralogy and grain size distribution (Fig. 6A-B). The igneous basement rocks are mainly characterized by small grain sizes (≤5.7 to 350 μm) and are associated with minerals such as Ti-bearing minerals (e.g., ilmenite, rutile, titanite), feldspars (anorthite, albite, orthoclase), garnet, apatite and zircon (Fig. 6A-B). Fig. 6A indicates that clay minerals, gahnite, clinopyroxene and staurolite have no impact on the sample distribution in Fig. 6B.

3.2. Mineral associations and grain size of Fe-oxides from Kiggavik till

In Fig. 7A-B, PCA shows the relationships between grain size

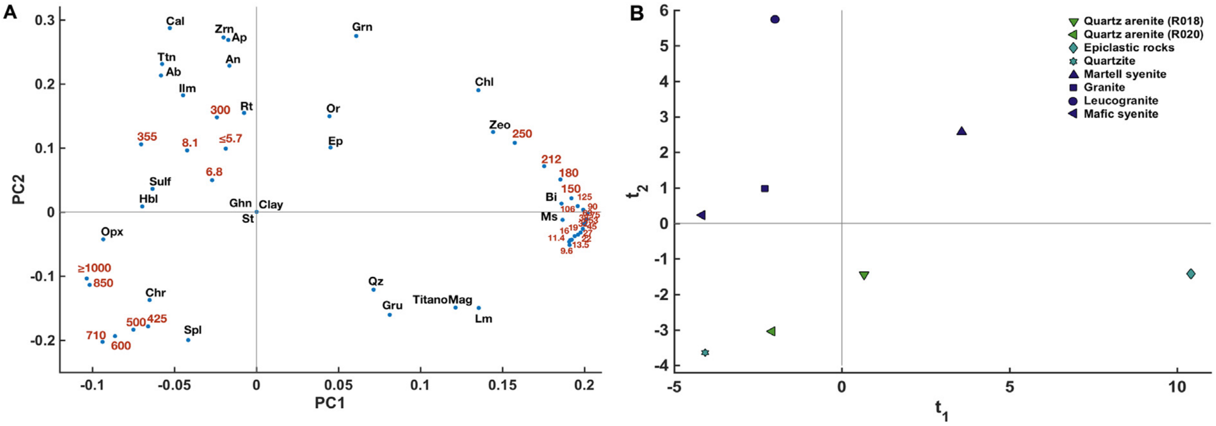

Fig. 6. Principal component analysis (PCA) of integrated data of grain size and mineral association of Fe oxides from the Kiggavik bedrock samples. Loadings (PC1-PC2) and scores (t_1-t_2) of the first and second principal components are shown in **A** and **B**, respectively. PCA loadings show correlations among different variables and the impact of these correlations on the distribution/classification of the Kiggavik bedrock samples in the scores scatter plot. The red numbers in **A** represent different grain size classes. ***Abbreviations-*** St: staurolite; Grn: garnet; Opx: orthopyroxene; Chl: chlorite; Bi: biotite; Or: orthoclase; Zeo: zeolite; Ms.: muscovite; Cpx: clinopyroxene; Cal: calcite; Rt: rutile; Ttn: titanite; Spl: spinel; Zrn: zircon; Ab: albite; An: anorthite; Lm: limonite; TitanoMag: titano-magnetite; Ilm: ilmenite; Qz: quartz; Ep: epidote; Ap: apatite; Hbl: hornblende; Gru: grunerite; Sulf: sulfides; Ghn: gahnite; Chr: chromite; Cr-Mag: Cr-rich magnetite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

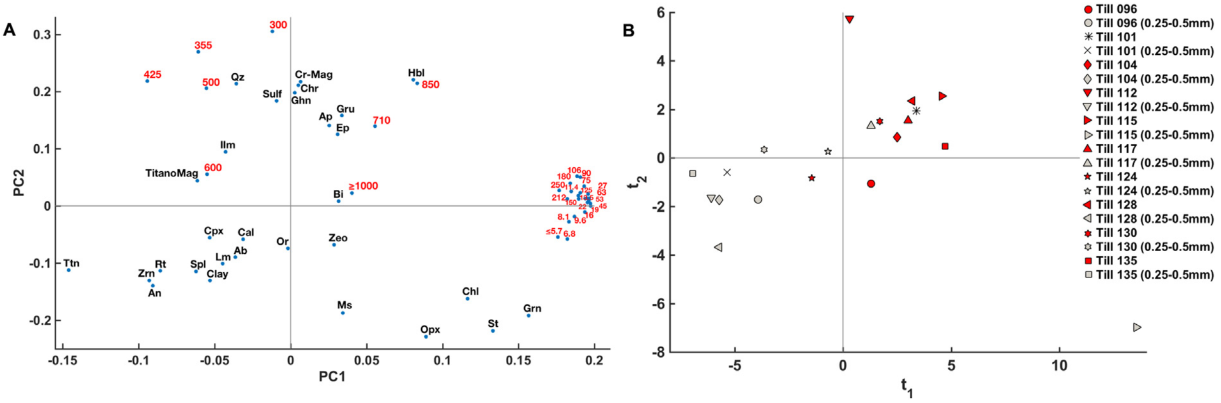

Fig. 7. Principal component analysis (PCA) of integrated data of grain size and mineral association of Fe oxides from the 0.25–0.5 mm and 0.5–2.0 mm fractions of the Kiggavik till samples. Loadings (PC1-PC2) and scores (t_1-t_2) of the first and second principal components are shown in **A** and **B**, respectively. PCA loadings show correlations among different variables and the impact of these correlations on the distribution/classification of different fractions of the Kiggavik till samples in the scores scatter plot. The red numbers in **A** represent different grain size classes. Abbreviations for mineral names are the same as in Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distribution and abundance of mineral associations of Fe-oxides from the till samples. In this analysis, 55% of the total variance within the MLA dataset analyzed was captured by the first and second principal components. The PC1-PC2 factor loadings plot (Fig. 7A) demonstrates the close spatial association between quartz and 300–500 μm grain size on the upper left quadrant that means quartz is the dominant mineral association of 300–500 μm Fe-oxide grains. In contrast, Fig. 7A indicates that ilmenite and titanomagnetite are mostly intergrown with 600 μm grains. The PCA scores (Fig. 7B) also show that the abundance of mineral associations and variable grain sizes differentiate between Fe-oxides from different fractions of the Kiggavik till samples. As a result, the smaller size fraction (0.25–0.5 mm) of Kiggavik till, except for sample 10-PTA-115 (Till 115), are clustered in the low t_1 region mostly because of their smaller grain size, and higher abundance of Ti-bearing minerals, clays, calcite, zircon and feldspars. In contrast, higher abundance of hornblende, biotite, apatite, gahnite, chromite and sulfides in association with coarse Fe-oxide grains (710–≥1000 μm) discriminates the 0.5–2.0 mm fraction of Kiggavik till.

PCA separates the 0.25–0.5 mm fraction of Till 115 from the other till samples in the high t_1 value region in Fig. 7B. Fig. 7A indicates that the separation of small fraction size of Till 115 is due to the very fine-grained nature (≤5.7 to 250 μm) of Fe-oxides and higher abundance of garnet, chlorite, orthopyroxene, staurolite and muscovite associated with Fe-oxides in this samples. The 0.25–0.5 mm fraction of sample 10-PTA-128 (Till 128) is isolated in the low t_1, t_2 region of Fig. 7B because of the higher abundance of titanite, rutile, clays, zircon, feldspars and spinel intergrown with Fe-oxides, whereas the 0.5–2.0 mm fraction of sample 10-PTA-112 (Till 112) is mainly separated by PC2 in the high t_2 region due to the distinct grain size distribution of Fe-oxides (300, 710 and 850 μm) and the higher abundance of hornblende, grunerite, gahnite, sulfides and chromite.

A data subset of mineral associations and grain size of Fe-oxides from the bedrock and till samples was investigated by PCA to determine whether the Kiggavik till shares similar mineralogy and grain size distribution as the local bedrock. In Fig. 8, the first and second PC factors represent 50% of the total variance in the MLA dataset. As shown in Fig. 8A, the larger grain sizes (710 to ≥1000 μm) plot in the vicinity of hornblende, apatite, epidote, Cr-rich magnetite, chromite and gahnite in the high PC2 values region (Fig. 8A), whereas the 9.6 to 250 μm grain sizes are isolated in the higher PC1 values region and show a close association with chlorite, biotite and muscovite. The correlation among Fe-oxides grain sizes and the abundance different minerals in association with them in Fig. 8A resulted in discrimination the 0.25–0.5 mm and 0.5–2.0 mm fractions of Kiggavik till in Fig. 8B as the coarser size fraction of the till samples mostly plot in the high t_1 region, whereas the smaller size fraction of the till samples are mostly clustered in the low t_1 region. In addition, quartz arenite (R020), quartzite and mafic syenite plot in the vicinity of the smaller size fraction of Kiggavik tills (Fig. 8B). Higher abundance of titanite, sulfides, zircon, rutile and calcite in association with 300 μm Fe-oxide grains (in the low PC1, PC2 region of Fig. 8A) differentiate granite, leucogranite, quartz arenite (R018) and Martell syenite (in the low t_1, t_2 region of Fig. 8B) from the Kiggavik till

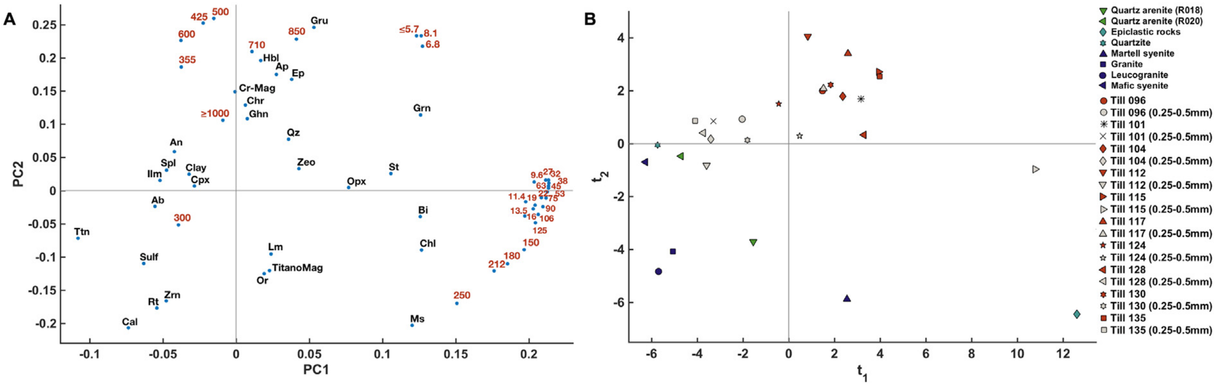

Fig. 8. Principal component analysis (PCA) of integrated data of grain size and mineral association of Fe oxides from the Kiggavik bedrock and till samples. Loadings (PC1-PC2) and scores (t_1-t_2) of the first and second principal components are shown in **A** and **B**, respectively. The red numbers in **A** represent different grain size classes. Abbreviations for mineral names are the same as in Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

samples. Whereas PC1 separates the epiclastic bedrock and the small size fraction of Till 115 (in the high t_1 region) from the other till and bedrock samples (Fig. 8B), different PC2 values differentiate them in the t_1-t_2 space (Fig. 8B).

4. Discussion

The petrographic and MLA results show that Fe-oxides from the Kiggavik bedrock and till samples are characterized by variable grain size distributions and mineral associations (Figs. 3–5). However, some Fe-oxides from the till samples show mineralogical and granulometric characteristics similar to those from studied bedrock suggesting that they may originate from proximal sources. For example, the replacement of magnetite by hematite and/or quartz (Fig. 4A-B) is similar to the alteration history of Kiggavik bedrock (Riegler et al., 2014; Robinson et al., 2014; Makvandi et al., 2017). Veins or disseminated hematite associated with widespread quartz ± clay minerals are also characteristic signatures of Kiggavik metasedimentary basement rocks (Robinson et al., 2016). The replacement of magnetite by titanite (Fig. 4D) may indicate the igneous basement as the bedrock source of the grain (Robinson et al., 2014; Makvandi et al., 2017).

Despite the focus being on the 0.25–0.5 mm and 0.5–2.0 mm F-HMC of the Kiggavik tills, the MLA revealed that $> 1.5\%$ of Fe-oxide grains in the till are $\leq 5.7\,\mu m$ in size and form parts of larger multi-mineralic grains. These Fe-oxides occur either as liberated grains (5A) or as inclusions in other minerals (Fig. 5C), thus, their grain size in each fraction size is also variable, as grains < 0.25 mm and < 0.5 mm are observed in the 0.25–0.5 mm and 0.5–2.0 mm fractions of Kiggavik tills, respectively.

4.1. Bedrock sample discrimination using PCA of Fe-oxides MLA data

Fig. 6A-B show that PCA can differentiate between Fe-oxides from different Kiggavik bedrock lithologies due to their different mineral association and grain size. PCA indicates that higher abundances of orthoclase, ilmenite, titanite, apatite, zircon, grunerite, albite, chlorite, calcite, and the 300 μm grain size are discriminant variables for Fe-oxides from the Kiggavik igneous basement, whereas higher abundance of grunerite, quartz, spinel, titanomagnetite and ilmenite, and the 425, 500, 600, and 710 μm grain sizes separate quartz arenite from the igneous and metasedimentary basement rocks (Fig. 6A-B). Makvandi et al. (2017) showed that in Kiggavik granite, leucogranite, and Martell syenite, ilmenite partly formed at the expense of magnetite grains and the disequilibrium textural relationship between the Fe-Ti oxides in given rocks is consistent with the complex history of formation and emplacement of the Nueltin granites and associated Kivalliq Suite mafic rocks (Scott et al., 2015; Peterson et al., 2015). Fe-oxides from the Kiggavik igneous rocks contain zircon inclusions that were most likely inherited from Archean to Early Paleoproterozoic basement rocks. Although Fe-oxides from Kiggavik igneous basement are separated by PC2 from that of sedimentary and metasedimentary rocks, they also show distinct mineralogical and granulometric signatures. For example, leucogranite plots in the high t_2 scores region, making an impact on the classification model mainly due to the higher proportion of 355 μm Fe-oxide grains, and the greater abundance of ilmenite, rutile, titanite, apatite, zircon, grunerite, anorthite and calcite intergrown with Fe-oxides (Fig. 6A-B). Robinson et al. (2016) showed the close association of magnetite and hematite grains with plagioclase, amphiboles and Ti-bearing minerals in the leucogranite. They also indicated that fine-grain pyrite (< 0.1 mm) occurs in trace amounts ($< 1\%$) in leucogranite, consistent with the results in Fig. 6A that suggest sulfides are not important in discrimination of leucogranite Fe-oxides from that of the other bedrock samples. In contrast, PCA shows that Fe-oxides from the mafic syenite sample are mainly discriminated from other rock types because of intergrowths with sulfides and hornblende (Fig. 3B), consistent with the earlier suggestion that magmatic magnetite from the HIS mafic syenite was formed partly by replacement of early crystallized sulfides (e.g., pyrite and chalcopyrite) and silicates (Makvandi et al., 2017).

4.2. Provenance discrimination of Fe-oxides from Kiggavik till using PCA of MLA data

PCA of integrated mineral association and grain size of Fe-oxides discriminates different samples and size fractions of till samples (Fig. 7A-B). This suggests that Fe-oxides from the finer size fraction of the Kiggavik till samples represent different host rock lithologies than Fe-oxides from the coarser size fraction. In the PCA t_1–t_2 scores space (Fig. 7B), Till 115 (0.25–0.5 mm), collected 50 m down-ice (WNW) of the Kiggavik MZ (Fig. 2), is well discriminated from the other till samples because of the fine-grained nature of its Fe-oxides as well as high abundance of garnet (mostly almandine), staurolite, chlorite, orthopyroxene, and muscovite intergrown with Fe-oxides. This mineral assemblage is typical for metamorphic rocks such as metamorphosed schists, greywacke and/or pelitic rocks (Bucher and Frey, 2002; Suk, 2013), and consistent with the mineral composition of metasedimentary rocks of the Woodburn Lake Group hosting the Kiggavik deposits (Jefferson et al., 2007; Scott et al., 2015; Sharpe et al., 2015). PCA scores also plot Till 128 (0.25–0.5 mm), collected 500 m down-ice (NW) of the Kiggavik MZ (Fig. 2), in the low t_1, low t_2 region because of the higher abundance of rutile, spinel, titanite, clay minerals and zircon intergrown/associated with Fe-oxides (Fig. 7A-B). The rutile-spinel-titanite-clay-zircon assemblage observed in Till 128 (0.25–0.5 mm) is representative of the Kiggavik deposits (Makvandi et al., 2018) as well as sandstone/basement hosted U deposits in the Athabasca Basin (Campbell, 2009). In contrast, the 0.5–2.0 mm fraction of till sample 10-PTA-112, collected 500 m down-ice (WNW) of the Kiggavik MZ (Fig. 2), contains greater abundances of coarse Fe-oxide grains intergrown with gahnite, sulfides, chromite, grunerite and hornblende (Fig. 7A-B). This mineral assemblage suggests that these till Fe-oxide grains were likely derived from distal bedrock source(s) potentially associated with metamorphosed VMS mineralization. Gahnite occurs in and around moderate to high grade metamorphosed massive sulfides and VMS deposits, and it is used as an indicator mineral in till for these deposit types (O'Brien et al., 2015; McClenaghan et al., 2015). Makvandi et al. (2017) also suggested VMS-related banded iron formations (BIF) as the potential source for part of Fe-oxide grains in Kiggavik till because trace element compositions of these Fe-oxides resemble that of the Izok Lake BIF. In addition, the mineral exploration program undertaken by Aura Silver Resources Inc. in 2009 in the area of Greyhound Lake detected the signature of VMS mineralization about 60 km north of Baker Lake (Boaz, 2009).

PCA results of the integrated MLA data of Fe-oxides from the Kiggavik bedrock and till samples, show that the bedrock samples plot in the same factor space as the smaller size fraction of Kiggavik tills (Fig. 8A-B). This result is consistent with the results shown in Fig. 7A-B that detected the signature of the Kiggavik deposits and local metamorphic bedrock in the smaller size fraction of Till 128 and Till 115, respectively, but identified the signature of distal sources in the larger fraction of Till 112. Given the proximity of the HIS mafic syenite, quartzite and quartz arenite (R020) to the 0.25–0.5 mm fraction of Kiggavik tills in the PCA t_1–t_2 space (Fig. 8B) that is practically resulted from similar mineral association and grain size of Fe-oxides, these bedrock lithologies might be the source of higher proportion of Fe-oxide grains in the smaller size fraction of the tills. The PCA results in Fig. 8A-B also suggest that the contribution of the other studied bedrock samples such as granite, leucogranite, Martell syenite and quartz arenite (R018) in feeding Fe-oxides to the local till might be much less than the previous bedrock samples. However, trace element geochemistry of Fe-oxides indicated that part of detrital Fe-oxides in Thelon Formation quartz arenite are the product of weathering, erosion and local transportation of Kiggavik igneous basement (Makvandi et al., 2017). The

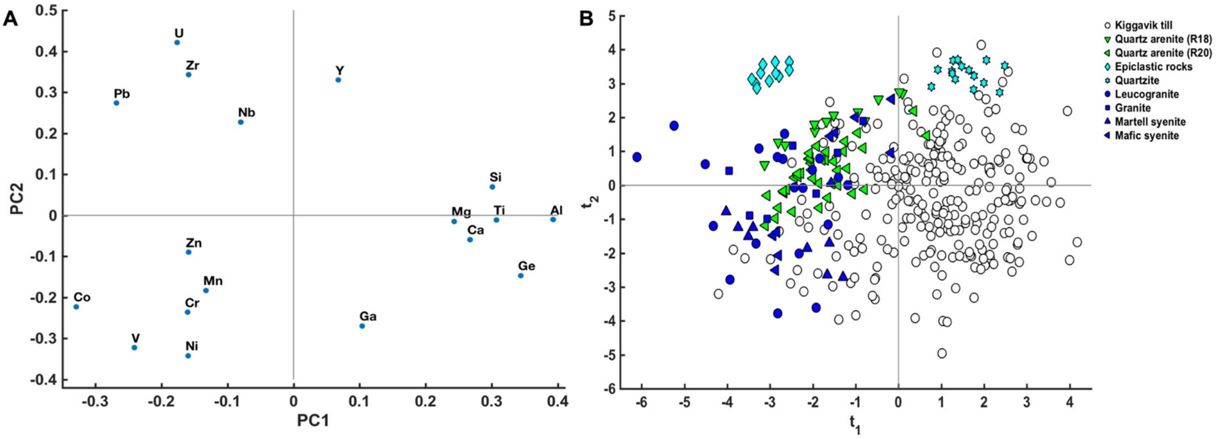

Fig. 9. Principal component analysis (PCA) of trace elements concentration in Fe oxides from the Kiggavik bedrock and till samples. Loadings (PC1-PC2) and scores (t_1-t_2) of the first and second principal components are shown in **A** and **B**, respectively.

isolation of Till 115 (0.25–0.5 mm) in the high t_2 scores region of Fig. 8B indicates that the source of Fe-oxide grains in this sample not only differs from that of Fe-oxides from the other till samples, but that also none of studied bedrock lithologies is the potential source of the grains.

Unlike quartzite, mafic syenite and quartz arenite (R020), PCA plots the SIS epiclastic rocks in the high t_1, low t_2 scores region in Fig. 8B mainly because of higher proportions of fine-grained (≤ 250 μm) Fe-oxides in this sample (Fig. 8A). The large difference between the grain size distribution of Fe-oxides from the SIS epiclastic rocks and that of till Fe-oxides suggests that the signature of this lithology is misrepresented in both fractions of Kiggavik till analyzed in this study.

To evaluate the utility of PCA of MLA data in provenance discrimination of the Kiggavik till Fe-oxides, the results were compared to the results of PCA of trace element compositions of Fe-oxides from the same bedrock and till samples (Makvandi et al., 2017; Fig. 9A-B). As shown in Fig. 9B, the fields occupied by all Kiggavik bedrock samples other than the fine-grained (≤ 250 μm) hematite from the epiclastic rocks are occupied by Kiggavik till Fe-oxides that means the geochemical signatures of Fe-oxides from these bedrocks can be detected in the till. Makvandi et al. (2017) measured 370 to 600 ppm U in hematite from the epiclastic rocks. This emphasizes on the importance of missing the signature of this lithologie in till. Robinson et al. (2016) showed that the < 0.063 mm fractions of Till 115 and Till 128 (representing till matrix) contain anomalous concentrations of U, Ti, Ag, Co, Mo, Ni, and Cu. This geochemical signature of Kiggavik mineralization in the till matrix, and small sizes of U-rich hematite from the SIS epiclastic rocks (≤ 250 μm) suggest that Fe-oxides associated with U mineralization might occur in the < 0.063 mm fraction of the Kiggavik tills. Fig. 9A-B shows that some till Fe-oxides that could originate from distal bedrock sources, plotting in the high t_1, low t_2 region of Fig. 9B, contain higher Mg, Si, Ca, Al, Ti, Ge and Ga. Makvandi et al. (2016c) also identified Si, Ca, Al, Ga, Mg, and Ti as discriminant elements for Fe-oxides from VMS mineralization and respective alteration zones.

4.3. *Application of Fe-oxides MLA data to mineral exploration*

PCA was initiated to compare mineral association and grain size MLA data of Fe-oxides from the bedrock and till samples with Fe-oxides MLA data from bedrock and till collected from the vicinity of the Halfmile Lake (New Brunswick, Canada; Makvandi and Beaudoin, 2012) and Izok Lake VMS deposits (Makvandi et al., 2015; Fig. 10A-B). PCA shows that the Izok Lake and Halfmile Lake bedrock and till samples form a distinct cluster in the low t_1, t_2 scores region because of the higher proportions of coarse Fe-oxide grains (425– ≥ 1000 μm), and greater abundance of muscovite, sulfides, orthopyroxene, gahnite, axinite and corundum in association with the Fe-oxides (Fig. 10A-B). Unlike the tight field formed by the VMS samples, Fe-oxides from the Kiggavik bedrock and till samples plot over a larger area in the t_1-t_2 scores space because of the diversity in mineralogy and grain size of the Fe-oxides (Fig. 10A-B). The classification model formed by PCA of Fe-oxide MLA data from the Kiggavik, Izok Lake, and Halfmile Lake areas is significantly affected by very small grain sizes of Fe-oxides from the SIS epiclastic rocks relative to that of the other samples (Fig. 10A-B). The results in Fig. 10A-B indicate that different geologic settings can be differentiated based on specific mineral association and grain size of Fe-oxides. In addition, these results demonstrate that the success of indicator mineral exploration programs very much depends on selecting suitable size fractions of till or other sediments to sample and study.

5. Conclusions

This study demonstrates the potential of using Fe-oxides mineral association and grain size data in provenance discrimination of unconsolidated sediments. The analysis of Fe-oxides MLA data indicates that mineralogical signatures of Kiggavik bedrock lithologies are reflected mostly in the 0.25–0.5 mm fraction of Kiggavik till. In till samples that reflect the metasedimentary basement rocks, 0.25–0.5 mm Fe-oxide grains mainly occur integrown with almandine, staurolite, chlorite and orthopyroxene. The results suggest that Fe oxides in the larger size fraction of till might originate from distal bedrock sources, potentially associated with VMS mineralization. PCA of Fe-oxides bedrock and till MLA data differentiates between the Kiggavik samples from that of the Halfmile Lake and Izok Lake VMS deposits. This study shows that the MLA results agree with the till Fe-oxides geochemical results. The latter suggests that a combination of MLA and geochemical data may improve indicator mineral exploration programs using Fe-oxides. PCA of MLA data also demonstrated that the signature of certain bedrocks of interest, such as Snow Island Suite epiclastic rocks, are misrepresented in the 0.25 to 2.0 mm fraction of Kiggavik till due to small grain sizes of Fe-oxides in these rocks. Thus, characterizing the grain size distribution of indicator minerals in deposits and/or lithologies is critical for selecting representative particle-size fractions of till or stream sediments for application of indicator mineral analysis in exploration.

Acknowledgements

This research was funded by the NSERC-Agnico Eagle Industrial Research Chair in Mineral Exploration. We acknowledge the earlier field work and research by S. Robinson (University of Queen's) on the Kiggavik area rocks and till samples and his sharing of data for the

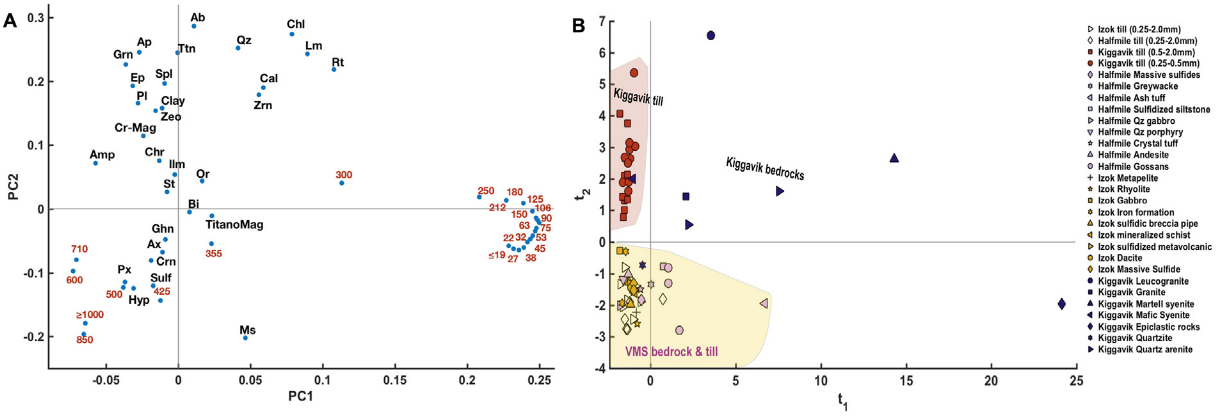

Fig. 10. Principal component analysis (PCA) compares the grain size, and the abundance of minerals in association with Fe oxides from the Kiggavik bedrock and till samples with Fe oxides MLA data from bedrocks and till from the Izok Lake and Halfmile VMS deposits areas. Loadings (PC1-PC2) and scores (t_1-t_2) of the first and second principal components are shown in **A** and **B**, respectively. The red numbers in **A** represent different grain size classes. ***Abbreviations-*** Zrn: zircon; Cal: calcite; Rt: rutile; Ttn: titanite; Ab: albite; Ilm: imenite; TitanoMag: titano-magnetite; Or: orthoclase; Ms.: muscovite; Sulf: suflides: Px: Pyroxene; Ax: axinite; Ghn: gahnite; Crn: corundum; Bi: biotite; St: staurolie; An: anorthite; Zeo: zeolite; Amp: amphiboles; Chr: chromite; Cr-Mag: Cr-rich magnetite; Ep: epidote; Grn: garnet; Spl: spinel; Ap: apatite; Qz: quartzite; Lm: limonite; Chl: chlorite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

current study. We would like to thank all who collaborated on this project including M. Ghasemzadeh-Barvarz (Ingredion Incorporated), M. Choquette (ULaval), A. Ferland (ULaval), E. Rousseau (ULaval), D. Grant (MUN) and D.J. Goudie (MUN). John Robbins and Craig Cutts (Orano Canada) are also thanked for their insightful reviews of this manuscript.

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