Journal of Geochemical Exploration 183 (2017) 1–21

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

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

Geochemistry of magnetite and hematite from unmineralized bedrock and local till at the Kiggavik uranium deposit: Implications for sediment provenance

Sheida Makvandi[a,*], Georges Beaudoin[a], M. Beth McClenaghan[b], David Quirt[c]

[a] Département de Géologie et de Génie Géologique, Université Laval, Quebec (QC) G1V 0A6, Canada
[b] Geological Survey of Canada, Ottawa (ON) K1A 0E8, Canada
[c] AREVA Resources Canada Inc., P.O. Box 9204, Saskatoon, SK S7K3X5, Canada

ARTICLE INFO

Keywords:
Magnetite
Hematite
Indicator mineral exploration
Kiggavik uranium deposit
Till
Partial least squares discriminant analysis

ABSTRACT

The petrography and mineral chemistry of magnetite and hematite from igneous, metasedimentary, and sedimentary bedrock in the area of the Kiggavik unconformity-related uranium deposit, and from till covering the deposit were investigated using optical microscopy, scanning electron microscopy (SEM), electron probe microanalyzer (EPMA), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The R-package rob-Compositions method was used to treat censored values in the EPMA and LA-ICP-MS geochemical data, and the results were transformed using a centered log-ratio transformation prior to data analysis using partial least squares-discriminant analysis (PLS-DA). The Kiggavik rock samples are from a wide range of lithologies including granite, leucogranite, syenite, metagreywacke, quartzite, and quartz arenite. The integration of petrography and mineral chemistry identifies four origins for iron oxides in the Kiggavik bedrocks: magmatic, hydrothermal, diagenetic, and weathering. The igneous bedrocks mainly contain magmatic magnetite replaced by mostly hydrothermal and rarely by weathering related hematite. Higher concentrations of trace elements such as Mg, Al, Ti, and Zr in hydrothermal hematite from leucogranite, granite and Martell syenite relative to parent magnetite suggest that hematite crystallized from high-temperatures hydrothermal fluids. By contrast, relative trace elements depletion in hematite replacing V-Cr-rich magnetite from Schultz Lake Intrusive Complex syenite may indicate hematite precipitation from low-temperature oxidizing fluids.

The high U content (450 ppm averagely), rounded shape, and altered edges of hematite grains from metagreywacke indicate that the iron oxide is detrital, originally precipitated from U-rich hydrothermal fluids. Quartzite also contains hydrothermal hematite. Distinct chemical compositions of hydrothermal hematite from Kiggavik metasedimentary and igneous basement demonstrate different compositions and temperatures of parental hydrothermal fluids, as well as different compositions of replaced minerals/host rocks.

Magnetite rarely occurs in the Kiggavik sedimentary bedrocks as it has been partly or entirely replaced by hematite. The Thelon Formation quartz arenite contains detrital hematite mainly sourced from weathering of the Kiggavik igneous basement, and also diagenetic hematite that formed in situ replacing detrital magnetite, ilmenite, sulfides and/or Fe-bearing silicates.

PLS-DA distinguishes different compositions of magnetite and hematite characterizing the various Kiggavik rock samples. The PLS-DA latent variable subspaces defined by the bedrock samples were used to classify the sources of iron oxides in Kiggavik till. The results show that magnetite and hematite from the till are mainly derived from local rocks, with a small proportion from unknown host rocks. PLS-DA identifies Si, Ca, Pb, Zr, Al, Ge, Nb, Ga, Mn, Mg, Ti, Co, Y U, V, Ni, and Cr as main discriminator elements. Their variable concentrations in iron oxides can be used to separate different Kiggavik rocks. PLS-DA also demonstrates that lower concentrations of Si, Ca, Al, Mn, Mg, Ti, Zn, Co and Ni discriminate Kiggavik iron oxides from magnetite from porphyry, iron oxide copper gold ore deposits (IOCG), Iron Oxide-Apatite (IOA), and Bayan Obo Fe-Nb-REE deposit types. Nickel enrichment and higher Ca values also differentiate magnetite from Ni-Cu, and from VMS deposits and VMS-related BIF, respectively, from Kiggavik iron oxides. The PLS-DA discrimination models suggest that volcanogenic massive sulfide (VMS)-related banded iron formations (BIF) are the potential source for some of the unclassified iron oxide grains in Kiggavik till.

* Corresponding author at: Département de Géologie et de Génie Géologique, Université Laval, Pavillon Adrien-Pouliot, 1065 avenue de la Medecine, Québec (QC) G1V 0A6, Canada.
E-mail addresses: sh.makvandi@gmail.com, sheida.makvandi.1@ulaval.ca (S. Makvandi), Georges.Beaudoin@ggl.ulaval.ca (G. Beaudoin), beth.mcclenaghan@canada.ca (M. Beth McClenaghan), David.Quirt@areva.com (D. Quirt).

http://dx.doi.org/10.1016/j.gexplo.2017.09.010
Received 17 November 2016; Received in revised form 8 June 2017; Accepted 21 September 2017
Available online 23 September 2017
0375-6742/

Retention of U contents by iron oxides during phase transformation or in detrital hematite indicates the ability of iron oxides to act as a long term repository of U. Overall, this study shows that magnetite and hematite are efficient minerals for provenance studies and mineral exploration in uranium rich environments, and also indicates that robust models for classification of indicator minerals origins in unconsolidated sediments can be established from PLS-DA of LA-ICP-MS data.

1. Introduction

Magnetite and hematite are common minerals found in a wide variety of igneous, metamorphic, and sedimentary rocks (Dupuis and Beaudoin, 2011). Iron oxides occur in many magmatic-hydrothermal ore deposits as major (e.g., iron oxide copper gold ore deposits, banded iron formations) or as accessory minerals (e.g., volcanogenic massive sulfide deposits). Magnetite (Fe_3O_4) belongs to the spinel group minerals with the general stoichiometry **XY2O4** (Fleet, 1981), where **X** is divalent cations such as Mg, Fe^{2+}, Ni, Mn, Co, or Zn, and **Y** can be trivalent or tetravalent cations such as Al, Ti, Fe^{3+}, Cr, V, Mn, or Ga (Lindsley, 1976; Wechsler et al., 1984). Spinel group minerals display a wide range of chemical compositions owing to several solid-solution substitutions of these divalent and trivalent cations (Deer et al., 1992). Magnetite can form complete or partial solid solutions with other spinel group minerals such as spinel ($MgAl_2O_4$), ulvöspinel (Fe_2TiO_4), ilmenite ($FeTiO_3$), chromite (FeCr2O4), and gahnite ($ZnAl_2O_4$). Hematite (Fe_2O_3) crystallizes in the rhombohedral lattice system, forming the same crystal structure as ilmenite and corundum. Hematite forms a complete solid solution with ilmenite at temperatures above 1050 °C, whereas it can form a limited solid solution with magnetite, corundum (Al_2O_3), or bixbyite (Mn_2O_3; Dupuis and Beaudoin, 2011). In the

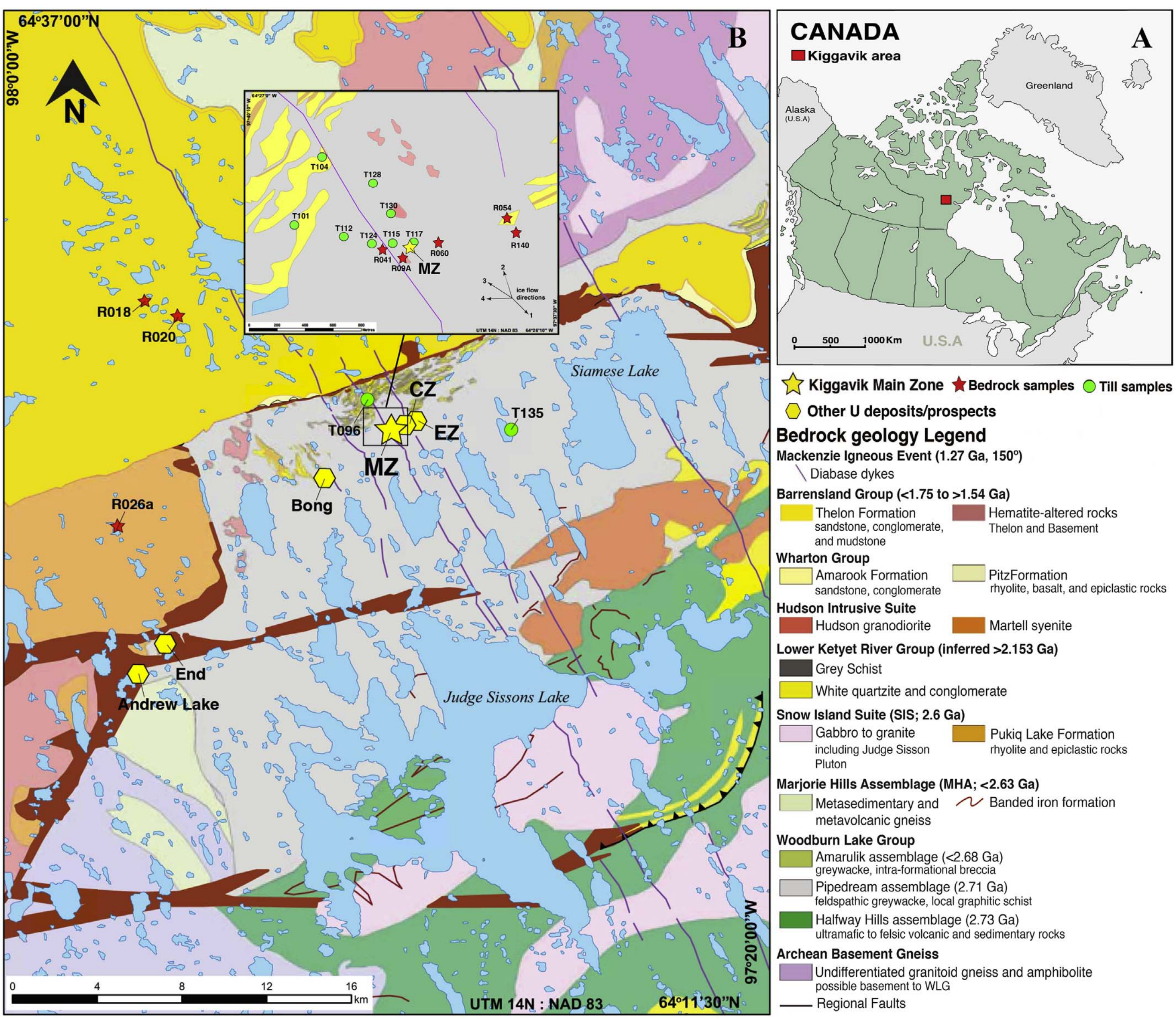

Fig. 1. A) The location of the Kiggavik project area in Canada. B) Regional bedrock geology map (modified from Robinson et al., 2016) including the location of the Kiggavik Main, Center, and East ore zones (MZ, CZ, EZ), other U deposits/prospects (e.g., Bong, End, Andrew Lake), and studied bedrock and till samples. Note all rock sample numbers have the prefix 10-PTA- (e.g., R020 refers to sample 10-PTA-R020). In till sample numbers, T replaced the prefix (e.g., T135 refers to sample 10-PTA-135).