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GEOLOGICAL SURVEY OF CANADA
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The National Mineral Reference Collection (NMC) digital spectral (VIS-NIR-SWIR) library, part III: background REE-Nb-U-Th-bearing mineral databases

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The National Mineral Reference Collection (NMC) digital spectral (VIS-NIR-SWIR) library, part III: background REE-Nb-U-Th-bearing mineral databases

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INTRODUCTION

In 2016, a study on the National (Reference) Mineral Collection (NMC) was initiated to collect reflectance spectra from minerals containing rare earth elements (REE), niobium (Nb), uranium (U), and thorium (Th). The elements selected were based on the on-going GSC-NRCAN Environmental Geoscience projects examining REE-, U- and Th-bearing minerals in granites (Bancroft, Ontario) (Desbarats et al., 2016) and Nb-, REE-, U- and Th bearing minerals in carbonatites (Oka, QC) (Desbarats and Percival, 2020; Desbarats *et al.*, 2020; Percival et al., 2017, 2019b). The objective of these projects was to develop a geo-environmental ore deposit model to predict and possibly mitigate any downstream problems before, during, and after mining. The purpose of the Spectral Library was to determine if infrared spectra (VIS-NIR-SWIR) could be used to target minerals in core or outcrop in support of GSC programs.

To develop the Spectral Library, identifying potential minerals in the NMC was paramount. To do this, a database was developed using online sites including the International Mineralogical Association (IMA; www.ima-mineralogy.org), mindat.org (https://www.mindat.org), and webmineral.com (http://www.webmineral.com) to determine what minerals exist that contain these elements of interest. The database grew and once all species were identified, searching and matching to the NMC catalogue was enabled. This Open File report provides the two databases that support the Spectral Library published in 2019 (see Percival *et al*., 2019a). In 2021, new minerals added to the lexicon of IMA were added to the overall database (Appendix A), and minerals containing scandium (Sc) and yttrium (Y), elements commonly associated with REEs, were included.

MINERAL DATABASES

Two databases are presented. Appendix A is an MS-Excel™ Workbook listing all minerals that may contain REEs (+ Sc and Y), Nb, U and/or Th. Minerals include silicates (classified via Dana (Gaines *et al.,* 1997) and Nickel-Strunz (www.webmineral.com.strunz.shtml) systems), oxides, carbonates, phosphates+arsenates+vanadates, and miscellaneous (ordered via Dana). IMA status is indicated with a corresponding legend found on the notes page. Minerals in RED have been discredited by the IMA. Minerals not present in the IMA are *italicized*. Minerals not present in the IMA and pending approval are ***italicized and bolded***. The information captured for each worksheet includes:

Column A:	Nickel-Strunz Classification
Column B:	Dana Classification
Column C:	Mineral Supergroup
Column D:	Mineral Group
Column E:	Mineral Name
Column F:	Mineral Formula
Column G:	Crystal System
Column H:	Crystal Class (Hermann–Mauguin notation)
Column I:	Type of REE’s Present

Column J: Presence of Nb, Th, or U
Column K: Other Associated Elements
Column L: Deposit Type
Column M: If mineral fluoresces in UV light
Column N: If mineral is radioactive
Column O: Sources for mineral data
Column P: If mineral is present in the National Mineral Collection (NMC)
Column Q: Comments
Column R: If mineral was added since 2016 by the Commission on New Minerals, Nomenclature and Classification (CNMNC) of IMA
Column S: Major Mineral Type (Miscellaneous worksheet only)

Additional information is provided regarding the old pyrochlore group of Hogarth (1977) showing minerals renamed according to Atencio *et al*. (2010, 2017) with updates in Atencio (2021):

Column A: Dana Classification
Column B: Mineral Subgroup
Column C Mineral Name
Column D: Mineral Formula
Column E: If mineral is present in the National Mineral Collection
Column F: If the mineral is radioactive
Column G: Updated Pyrochlore Name
Column H: Status
Column I: Sources of mineral data

Appendix B is an MS-Excel™ Workbook listing all the REE-, Nb-, U- and Th-bearing minerals contained in the National (Reference) Mineral Collection currently hosted at the GSC. The "List of Minerals" worksheet includes all minerals initially examined; a subset was analysed to develop the Spectral Library (Percival *et al*., 2019a). The other two worksheets include data on Silicate Minerals and Non-Silicate minerals, both Dana-ordered classifications. The information captured in the Silicate Dana-ordered worksheet includes:

Column A: Dana Classification
Column B: Nickel-Strunz Classification
Column C: Species Name
Column D: Varietal Name
Column E: NMC Catalogue Number
Column F: Sample Description from NMC Card
Column G: Sample Source

The information captured in the Non-Silicate worksheet includes:

Column A:	Dana Classification
Column B:	Species Name
Column C:	Variety Name
Column D:	Type of Mineral
Column E:	NMC Catalogue Number
Column F:	Sample Description from NMC Card
Column G:	Sample Source

APPLICATIONS

In March 2021, Canada released the list of minerals deemed critical to transition towards a low-emissions global economy (Fig. 1). These 31 minerals (mix of minerals, metals and elements) are deemed essential to meet the global demands for modern technology and development of green and defence technologies. Although Canada is a prime source of some of these critical minerals including cobalt, graphite, lithium, and nickel, it is important to secure a sustainable supply chain for the others (https://www.nrcan.gc.ca/criticalminerals).

Each of the elements of interest are described in brief to provide an overview as to why these are considered important. Table 1 lists the critical metals and their main applications. Note that although thorium is not on the list, it is included in this report as it was a focus of the Spectral Library.

Rare Earth Elements (REE)

The Rare Earth Elements (REE) include the 15 Lanthanide Group minerals plus scandium (Sc) and yttrium (Y) (Table 2). They are subdivided into Light (lanthanum to europium or lanthanum to gadolinium) and Heavy (gadolinium to lutetium or terbium to lutetium), with Y considered as a Heavy REE (Chakhmouradian and Wall, 2012; Mariano and Mariano, 2012). Although Sc is not always included due to its small ionic size, it is included in Canada's list (Fig. 1). The main reason for targeting REEs is their industrial application in permanent magnets, aerospace guidance, lasers, fibre optics, batteries and various electronics (Tables 1 and 2). The main target minerals containing REEs are summarized in Table 3; however, only a few of these major phases are targeted for exploration.

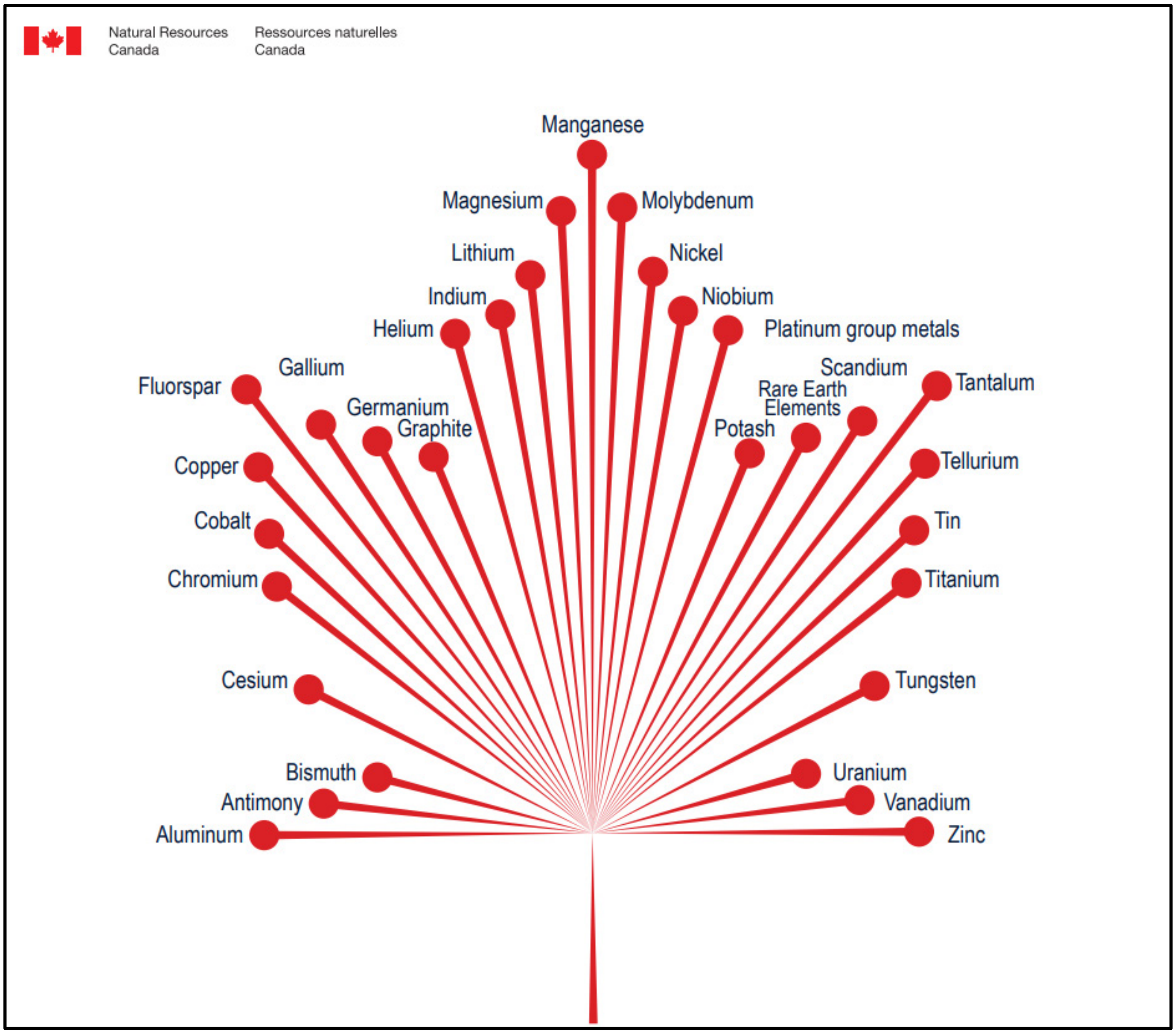

Fig. 1. List of critical minerals for Canada announced in March 2021 essential to Canada's economic security and transition to a low-carbon economy (https://nrcan.gc.ca/criticalminerals).

Niobium

This grey, ductile transition element is used in alloys, superalloys, and in welding applications. Its low density enables it to be used in aerospace applications (jet and rocket engines) and its high melting and boiling point allow it to strengthen steel and superalloys. It is a component of superconducting materials when mixed with titanium or tin. Niobium is found in pyrochlore but is also present in perovskite and other minor minerals (niocalite, britholite, etc.) (Table 3). Niobium is processed through smelting with iron oxide and aluminum in an aluminothermic reaction to form a ferroniobium alloy (Gupta and Suri, 1994; Desbarats and Percival, 2020). This alloy is added to molten steel to provide strength.

Uranium

This white, silvery-white lithophile actinide-group element is used in nuclear fuel and medical applications due to its radioactive properties. It has also been used in glass, ship ballasts and as a counterweight in planes (Reimann and de Caritat, 1998). It is the heaviest naturally-occurring element which tends to be enriched in the upper crust.

Thorium

This weakly radioactive actinide element is more abundant in the earth's crust than U. As thorium is considered a fertile element, it is used in a limited way in the nuclear industry in conjunction with fissile elements such as recycled plutonium (World Nuclear Association, accessed March 2022). Due to its high melting point, it can be used as coatings on tungsten wires, in portable gas lamps, optical lenses and in Mg-Ni alloys (Reimann and de Caritat, 1998).

Table 1. List of critical minerals identified by Canada ((https://nrcan.gc.ca/criticalminerals) and their main use (Fortier *et al*., 2018; Conca, 2019).

Critical Mineral	**Applications**
Aluminum	Aircraft, power transmission lines, lightweight alloys, packaging
Antimony	Lead-acid batteries, flame retardants
Bismuth	Pharmaceuticals, lead-free solders
Cesium	Medical applications, night vision devices, R&D
Chromium	Stainless steel, superalloys
Cobalt	Rechargeable batteries, superalloys
Copper	Electrical wires, cables, plumbing, emerging clean technologies-solar cells, electric vehicles
Fluorspar	Aluminum and steel production, uranium processing
Gallium	Radar, LEDs, cellular phones
Germanium	Fibre optics, infrared devices
Graphite	Rechargeable batteries, body armor
Helium	Semiconductor manufacturing, cryogenic applications, magnetic resonance imaging: MRI, R&D
Indium	LED screens, special alloys
Lithium	Rechargeable batteries, aerospace alloys
Magnesium	Furnace linings manufacturing steel and ceramics, incendiary countermeasure for aerospace
Manganese	Aluminum and steel production, lightweight alloys
Molybdenum	Alloys, high-strength steel
Nickel	Batteries, stainless steel, electroplating
Niobium	High-strength steel
Platinum Group Elements	Catalysts, superalloys for jet engines
Potash	Fertilizer
Rare Earth Elements	Aerospace guidance, lasers, fibre optics, batteries, electronics
Scandium	Lightweight alloys, fuel cells
Tantalum	Capacitors, electronic components, super alloys
Tellurium	Infrared devices, solar cells, steelmaking
Tin	Solder, protective coatings, alloys for steel, flat panel displays
Titanium	Superalloys, airframes, armor, white pigment
Tungsten	Cutting and drilling tools, catalysts, superalloys
Uranium	Nuclear fuel, medical applications
Vanadium	Superalloys, airframes, high-strength steel
Zinc	Alloys, galvanizing processes

Table 2. Common, but not exhaustive, uses for REE (rare earth elements) plus scandium and yttrium (from Reimann and de Caritat, 1998; Kilbourn, 2011; Hatch, 2012; Seredin and Dai, 2012; Haque *et al.*, 2014; Innocenzi *et al.*, 2014; Van Gosen *et al.*, 2014; Castano *et al.*, 2015; Dahle and Arai, 2015; Grandell *et al.* 2016; Do *et al.*, 2020; Los Alamos National Laboratory, 2021).

REE Group	**Applications**
Scandium	Lightweight alloys, catalysts, ceramics, electronics, lasers, fuel cells, pyrotechnics
Yttrium	Thermal coatings, energy efficient compact fluorescent lamps, superconducting power lines, cubic zirconia jewels, industrial lasers, medical, graphic technologies, missile defense systems
Light Rare Earth Elements	Permanent magnets, battery cells, glass treatments, energy efficient fluorescent lamps, fluid-cracking catalysts in petroleum industry
Lanthanum	Fluid-cracking catalysts in petroleum industry, battery cells, carbon lighting, alkali resistance of glass
Cerium	Fluid-cracking catalysts in petroleum industry, automotive catalytic converters, pollutant emission reduction, polishing media of glass and various electronics, mischmetal for metallurgy, catalyst in Friedel-Crafts alkylation reactions, scintillation counters, fuel cells, battery cells, glass (de)pigmentations, corrosion prevention, UV absorbers, biomaterials, microelectronics, optical devices, thermal coatings, fluorescent lighting phosphors, alloy in lighter Flints, radiation resistant glass
Praseodymium	Permanent magnets
Neodymium	Permanent magnets
Promethium	Nuclear transformations
Samarium	Permanent magnets
Europium	Energy efficient compact fluorescent lamps
Heavy Rare Earth Elements	Permanent magnets
Gadolinium	Magnetic resonance imaging
Terbium	Energy efficient compact fluorescent lamps, permanent magnets
Dysprosium	Permanent magnets
Holmium	Superconductor magnets
Erbium	Nuclear, metallurgy, colorant in glasses and porcelain glaze
Thulium	Fluorescent materials, lasers
Ytterbium	Stainless steel, substitute for portable X-ray machine
Lutetium	Catalysts in cracking, alkylation, hydrogenation and polymerization, research, geochronology

Table 3. Common minerals explored for some of the REEs plus scandium, yttrium, niobium, uranium, and thorium.

Element	Major Minerals	Minor Minerals	References
La	Bastnäsite, Monazite	Cerite, Allanite	Los Alamos National Laboratory, 2021
Ce	Bastnäsite-(Ce), Monazite-(Ce)	Allanite-(Ce), Ancylite-(Ce), Cerite, Euxenite	Kilbourn, 2011; Mariano and Mariano, 2012; Williams-Jones *et al.,* 2012; Dahle and Arai, 2015
Pr	Bastnäsite, Monazite		Los Alamos National Laboratory, 2021
Nd	Bastnäsite, Monazite		Stuckman *et al.,* 2018; Los Alamos National Laboratory, 2021
Sm	Bastnäsite, Monazite		Los Alamos National Laboratory, 2021
Eu	Bastnäsite, Monazite		Maestro, 2004
Gd	Monazite	Gadolonite	Los Alamos National Laboratory, 2021
Tb	Monazite, Xenotime, Euxenite	Cerite, Gadolinite	Los Alamos National Laboratory, 2021
Dy	Xenotime		Mariano and Mariano, 2012
Ho	Bastnäsite, Monazite		Los Alamos National Laboratory, 2021
Er	Xenotime		Mariano and Mariano, 2012
Tm	Monazite		Los Alamos National Laboratory, 2021
Yb	Xenotime, Monazite		Mariano and Mariano, 2012; Los Alamos National Laboratory, 2021
Lu	Xenotime		Mariano and Mariano, 2012
Sc	Thortveitite, Bazzite, Kolbeckite, Ixiolite, Perrierite, Magbasite		Schock, 1975
Y	Xenotime, Gadolinite, Samarskite, Euxenite, Fergusonite, Yttrotantalite, Yttrotungstite, Yttrialite, Monazite		Mariano and Mariano, 2012 ; Haque *et al.,* 2014; Innocenzi *et al.,* 2014,
Nb	Rutile, Columbite, Aeschynite, Bariopyrochlore, Ceriopyrochlore, Kalipyrochlore, Pyrochlore, Plumbopyrochlore, Strontiopyrochlore, Uranopyrochlore, Perovskite, Latrappite, Loparite, Lueshite, Tausonite, Fergusonite–(Ce), Ferrocolumbite, Fersmite, Zirconolite	Niocalite, Wöhlerite, Marianoite, Niobian Titanite	Kynicky *et al.,* 2012; Mitchell, 2015; Schulz *et al.,* 2017
U	Uraninite, uranophane, carnotite, coffinite, autunite, tyuyamunite, meta-tyuyamunite	Betafite (Now known as Oxycalciobetafite or Oxyuranobetafite)	Page et al., 1955; Ulmer-Scholle, 2021
Th	Thorite, monazite		Parker and Baroch, 1970

NEXT STEPS

The Spectral Library for REE-, Nb, U- and Th-bearing minerals is being converted into a Database more suitable for hyperspectral studies. This will be released as Part IV in the series of GSC Open File Reports.

As part of a new project in the TGI (Targeted Geoscience Initiative) Program, twenty-nine reference minerals from the National Reference Mineral Collection were selected for detailed analyses as these minerals exhibit the best spectral signatures. Follow-up analytical work will include infrared spectroscopy of solid and pulverized samples with complementary portable X-ray fluorescence analyses, whole rock X-ray diffraction analyses, scanning electron microscopy, and electron probe microanalyses. From this suite, a set of minerals deemed essential for exploration will be used to develop a field guide for explorationists. During the summers of 2022 and 2023, the Terraspec Halo will be deployed in the field to collect equivalent data from highly prospective critical mineral sites.

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