Public geoscience solutions for diversifying Canada’s critical mineral production

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Abstract: Achieving net-zero carbon emissions goals will increasingly rely on critical mineral resources while simultaneously decreasing the extraction, processing and use of hydrocarbons as the primary provider of energy. Canada is well positioned to contribute to this effort through a series of innovative policy and research initiatives, and it is Canada’s goal to be a stable supplier of critical minerals into the future. To this end, Natural Resources Canada and the Geological Survey of Canada invest financial resources into critical mineral research initiatives. This research aims to generate precompetitive baseline geological, geochemical and geophysical data for large, underexplored regions within Canada, whereas targeted studies focus on mineral systems science and improved exploration models for the large variety of critical mineral resources distributed throughout Canada. These research approaches can be combined, digitally, to generate mineral potential models. These ongoing efforts by the Geological Survey of Canada enhance the viability of Canada being (or maintaining its status as) a hub for critical mineral resource development and processing well into the future.

Canada has committed to net-zero carbon emissions by 2050 (Government of Canada 2021a). To achieve this goal, it must reduce significantly the extraction, processing, and use of hydrocarbons. One of the most visible and significant contributors to greenhouse gas emissions in Canada is road transportation; from 2011 to 2019, this sector accounted for approximately 20% of the total greenhouse gases emitted in Canada (Environment Climate Change Canada 2021). The transition from fossil fuels to clean energy has begun with gains being made in battery and hybrid electric vehicles (about 6% of total passenger vehicle registrations in 2020; StatCan 2021b) and a plan for 100% zero emission light-vehicle sales by 2035 (Transport Canada 2021). Electric vehicles typically require six times the mineral inputs (Cu, Li, Ni, Mn, Co, graphite) of conventional light vehicles (IEA 2021) and in order to meet net-zero carbon emission targets electric vehicle sales must increase by about 16-fold. More broadly, the shift towards green energy production will become increasingly material-intensive as internal combustion engines are phased out of use. Critical minerals are the building blocks for the electric and other technologies that are instrumental for the energy required for a low-carbon future, which will likely emerge as the main driver for growth in critical mineral demand (IEA 2021).

Natural Resources Canada (NRCan) has developed a list of 31 critical minerals (Fig. 1) that is built on a criteria-based approach that recognizes export opportunities and security requirements, while highlighting the potential to build valuable domestic manufacturing (e.g. battery supply chains). The list consists of a range of primary, co-product and by-product mineral commodities; these comprise chemical elements and/or compounds, metals, metalloids, and minerals (hereafter referred to as ‘minerals’ for simplicity). Criteria for inclusion on the list are: (1) essential to Canada’s economic security; (2) required for Canada’s transition to a low-carbon economy; and/or (3) a sustainable source of critical minerals for our partners (NRCan 2021b). The following are included on Canada’s critical mineral list: Al, Bi, Co, Cr, Cs, Cu, fluorospar, Ga, Ge, graphite, He, In, Li, Mg, Mn, Mo, Nb, Ni, platinum group elements (PGE), potash, rare earth elements (REE), Sb, Sc, Sn, Ta, Te, Ti, W, U, V, Zn. Many of these critical minerals are essential for batteries (e.g. Al, graphite, Mn, Ni, Co, Li), car components (e.g. PGE), solar panels (e.g. Ga, Ge, In, Se, Te), magnets (e.g. REE), alloys (e.g. Zn, Mn, Co, Cr, V, Mo, Sn,
Nb, fluorspar), fibre optics (e.g. Ge), electronics (e.g. Cu, Ga, In, Ta), and fertilizers (e.g. potash).

Several of the critical minerals on Canada’s list are currently being mined, or have been in the past. These include major (e.g. U and base metals such as Cu and Zn) and specialty (e.g. Nb) metals (for definitions, see Simandl et al. 2021). Others are co-products with, or by-products of, primary commodities. The inclusion of several base metals (Ni, Cu, Zn) in the Canadian list is because the high importance of the minerals to the Canadian economy. Their inclusion was also driven by inclusion of these minerals in the lists of Canada’s major trading partners (e.g. US, UK, Japan, South Korea, EU) and Canada’s potential to supply them. Some critical base metals (i.e. Ni and Zn) have experienced more volatility on the supply-side (Fig. 2). For example, Canadian zinc production has dropped by about 80% since its zenith in the late 1980s and zinc reserves have declined by nearly 90% since the mid-1990s (Fig. 2). The drops in production are driven in large part by the closures of major zinc mines (e.g. Sullivan, British Columbia) and reserves have not been replenished by development of new mines. Canada contains an estimated 12.5% of global unexploited zinc resources (resource category is different from reserve category; Mudd et al. 2017), which bodes well for future development of all the critical minerals known to be associated with zinc ores (see below). Nickel is similarly abundant in Canada, with about 7.5% of global resources (Mudd and Jowitt 2014; Lawley et al. 2021).

Thus, large and undeveloped critical mineral resources are available and likely will be into the future. The development of such resources may be technically viable; however, contemporary environmental, societal and governance requirements may preclude their development (or market availability) and the resulting lack of access represents a supply risk (Arndt et al. 2017; Jowitt et al. 2020). Availability issues are compounded when considering that several critical raw materials are by-products of primary production. The potential to extract critical minerals as by-products (e.g. Co, In, Ge, Ga) from base metal production has the potential to enhance the viability of previously sub-economic deposits, whereas critical minerals that occur as by-products are inaccessible if undeveloped base metal projects fail to go into production.

Some by-products were once considered deleterious, commonly denoting inferior mill feed (Salomonde-Friedberg and Robinson 2015). Many of these materials are now seen as critical for their role in the advanced technologies that drive green economies. Indium recovery, for example, is proportional to sphalerite recovery, and the range of indium in the tailings of zinc mines (where waste consists of 5–35% of unrecovered zinc ore, depending on processing efficiency) is a reflection of the efficiency of sphalerite recovery (Werner et al. 2017). This indicates that a large proportion of this critical mineral remains untapped – especially in mines (or former mines) that had extremely high abundances of indium (hundreds of ppm) contained with the zinc concentrate (e.g. Heath Steele; Chen and Petruk 1980).

Reprocessing tailings and/or smelter slags presents additional benefits beyond the potentially economic recovery of critical minerals. Mine waste is typically a significant proportion of the material removed during the mining process and the amount of mine waste increases as lower grade ores are produced and processed. Mine waste represents major short- and long-term environmental hazards (e.g. acid rock drainage; impoundment dam breaches and associated damages). The ability to re-integrate mine waste into a circular economy may therefore mitigate some of the potential environmental issues (Tayebi-Khorami et al. 2019). Although some mine waste is currently being reprocessed from some Canadian (e.g. True North Gold Mine; Puritch et al. 2016) and South African deposits (e.g. Witwatersrand; Nwaila et al. 2021), obstacles remain in sustainably developing mines wastes. Mostly these are related to the sub-economic and refractory nature of potentially economic materials. New technologies may allow renewed exploitation of tailings and CANMET Mining (i.e. the research organization within Natural Resources Canada that focuses on mineral extraction, processing, and environment) is currently investigating methods to do this (i.e. Mining Value from Waste; Žinck et al. 2019).

**Government initiatives**

Specific federal, provincial and territorial policy frameworks have been introduced (NRCan 2021b;
Government of Ontario 2022; Government of Quebec 2022) or are under development (e.g. Northwest Territories) as per the critical minerals list. The Canadian Minerals and Metals Plan (NRCan 2020b) provides a roadmap over the entire lifecycle of the mineral extractive process, from the production of geoscience data that leads to deposit discovery through to reclamation of exhausted deposits. The critical minerals list aligns with the Canadian Minerals and Metals Plan to improve competitiveness in all aspects of the minerals and metals industry and to position Canada to thrive when economies look to grow following the COVID-19 pandemic. Other work includes developing a Pan-Canadian Geoscience Strategy, which focuses on critical minerals and developing made-in-Canada supply chains for critical minerals and clean technologies. Canada aims to provide $9.6 million over three years, starting in 2021–22, to Natural Resources Canada to create a Critical Minerals Centre of Excellence. This centre aims to coordinate federal policy and programmes, as well as work with provincial and territorial

Fig. 2. Historical (a) production and (b) reserves of Ni and Zn (BGS 2021; StatCan 2021a).
governments, Canadian industry, Indigenous groups and with allied foreign governments to stimulate the development of Canadian critical mineral value chains (Government of Canada 2021b). An additional $36.8M is proposed over three years, starting in 2021–22, to support targeted R&D for upstream critical minerals processing and battery precursors as well as related materials engineering (Government of Canada 2021b). Moreover, the Government of Canada announced in April 2022, that it intends to invest $3.7B over eight years through a new Critical Mineral Strategy that will focus on priority critical mineral deposits, while working closely with affected Indigenous groups and through established regulatory processes. Among other specific initiatives linked to this strategy, $79.2M over five years has been announced for Natural Resources Canada to provide public access to integrated data sets to inform critical mineral exploration and development (Government of Canada 2022).

Indigenous initiatives and the need for infrastructure

Management of natural resources is a provincial jurisdiction in Canada and exploration and mining are taking place across traditional indigenous lands. Hence, all federal initiatives are accomplished in partnership with provincial, territorial and indigenous governments, and in close collaborations with local and indigenous communities and industry. In some cases, indigenous governments have sought mineral wealth within their traditional and owned lands (Cree Nation Government 2010; Scales 2016). For example, the Denendeh Exploration and Mining Company (DEMCo) is owned and operated by the 27 Dene First Nations of Northwest Territories through the Denendeh Investment Corporation. Amongst DEMCo’s holdings are the past-producing districts of Camsell River (Ag) and the Port Radium–Echo Bay (U–Ag), Northwest Territories (Fig. 3). The exploration opportunities and challenges faced by the company are shared broadly. Since mining ceased in these districts decades ago, new public geoscience and on-going exploration has enhanced their mineral prospectivity (e.g. polymetallic iron oxide–copper gold [IOCG], Fe-rich Au–Co–Bi–Cu, iron oxide–apatite–rare-earth and albitite-hosted U) (Corriveau et al. 2010). A vast collection of historic drill cores (e.g. 200 km valued at $40M) is available to test new exploration models; core preservation programmes are essential to renewed exploration and are locally supported by government programmes (e.g. Mining Incentive Program of the Government of the Northwest Territories in 2015) (Bowdidge and Dunford 2015; Grinstead 2015).

A major risk to further mineral development in the Camsell River area is a lack of essential infrastructure (e.g. transportation, energy transmission lines, communications, etc.). Indeed, much of northern and near-northern Canada lack the requisite infrastructure to realize the economic potential. Indigenous peoples stand to benefit greatly from coordinated infrastructure development in the north, as would all Canadians (Beaulieu 2018). Indigenous governments that lead the planning and development process can coordinate and leverage public and private investments. Indigenous groups can also be included in mineral resources projects from the development of precompetitive data to exploration, environmental assessment, mining, and remediation. Some major infrastructure and exploration projects are being initiated jointly with indigenous groups. The new Tḻı̨cẖo Highway from Behchokǫ to Whátì (NWT) serves aboriginal communities and increases feasibility of the NICO Au–Co–Bi–Cu project (Fig. 3), itself within a few kilometres from a hydroelectric plant (Tḻı̨cẖo Highway: http://www.inf.gov.nt.ca/en/map). The proposed pan-Canadian infrastructure project (Canadian Northern Corridor) could potentially link widespread and disparate portions of the north with the south for shared mineral resources development, increased economic and social opportunity, prosperity, and national security (Fellows et al. 2020).

Public geoscience to support exploration across Canada’s critical mineral frontiers

The Geological Survey of Canada (GSC) responds to society’s mineral needs in the context of global climate change through extensive research on critical minerals (Simandl et al. 2015; Lebel 2020). Investing in public geoscience research is a significant economic driver and economic assessments suggest that the benefit of these investments is seven times greater than the original government expenditure (NRCan 2020a). Additionally, thousands of employment opportunities are generated from new mining operations that are essential for the economic development of Canada’s North (Duke 2010; NRCan 2020b). At the GSC, there are two main geoscience programmes focusing on critical minerals: Geo-mapping for Energy and Minerals (GEM-GeoNorth) and the Targeted Geoscience Initiative (TGI).

Geo-mapping for Energy and Minerals

Critical mineral deposits are geographically widespread across Canada (Fig. 3). Whereas most easily recognized deposits at- or near-surface will have been discovered, there remains significant potential for new discoveries. Buried deposits in existing
mining districts and at (or near) surface deposits in under-explored regions may be targeted through the development of new exploration techniques. Indeed, the Government of Canada is investing (e.g. $200M over 12 years in GEM-GeoNorth) in geoscience research, systematic bedrock geological mapping, and regional geophysical and geochemical surveys. Research under GEM-GeoNorth focuses on regions with high mineral potential across Canada’s north and provides precompetitive data and derivative products to the public (NRCan 2020). The impetus for this research is due, in part, to the ever-increasing cost of exploration, particularly as the quality (in terms of grade and tonnage) of discoveries diminish. Public geoscience programmes support the mineral industry by providing datasets in frontier exploration settings that are either high-risk or too costly to acquire large-scale systematic surveys and by synthesizing knowledge from multiple researchers and companies over time (Hayward et al. 2016; Skulski et al. 2018; Ielpi et al. 2021; Lawley et al. 2021; Regis et al. 2021).

**Targeted Geoscience Initiative**

The GSC is conducting the sixth phase of TGI on Critical Minerals with Canadian provincial and territorial surveys and extensive collaborations with academia, surveys and industry (NRCan 2021a). Targeted geoscience research at the GSC is focused on many of Canada’s major deposits and districts. The TGI programme is designed to provide industry stakeholders with cutting-edge geoscience knowledge and innovative exploration tools. Results also inform public geoscience, academia, policy and environmental stakeholders, Indigenous peoples, and the general public.

Some of the main goals for the TGI programme include: (1) reducing risk and cost for industry stakeholders; (2) developing new knowledge to enhance

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**Fig. 3.** Map of Canada showing geological provinces and highlighting key mineral localities discussed in the text. 1, Casino Cu–Au–Mo–Ag deposit; 2, Windy Craggy Cu–Zn–(Co) deposit; 3, Nick Ni–Zn–Mo–PGE–Re–Au prospect; 4, MacMillan Pass Pb–Ag–Zn–(Ba) district; 5, Howard’s Pass Pb–Zn district; 6, Mount Polley Cu–Au mine; 7, Highland Valley Cu–Au mine; 8, New Afton Cu–Au mine; 9, Sue Dianne Cu–Au–Ag deposit; 10, NICO Au–Co–Bi–Cu deposit; 11, Monarch and Kicking Horse Pb–Zn mine; 12, Sullivan Pb–Zn–Ag–(Sn) mine; 13, Muskox intrusion Ni–Cu–Cr–PGE prospect; 14, Pine Point Pb–Zn mine; 15, Izok Lake Cu–Ag–Zn deposit; 16, Nechalacho REE deposit; 17, Patterson Lake U district; 18, MacArthur River U deposit; 19, Cigar Lake U deposit; 20, Lynn Lake Ni–Cu–Co–PGE deposit; 21, Thompson Ni–Cu–Co–PGE mine; 22, Polaris Pb–Zn mine 23, Marathon PGE–Cu deposit; 24, Ring of Fire Cr–PGE district; 25, Côté Au deposit; 26, Fostung W deposit; 27, Kidd Creek Cu–Ag–Zn mine; 28, Sudbury Ni–Cu–Co–PGE–Au–Ag mine; 29, Cape Smith Ni–Cu–Co–PGE belt; 30, Niobe Nb deposit; 31, Heath Steele Cu–Pb–Zn district; 32, Josette REE deposit; 33, Lac Tio Fe–Ti deposit; 34, Gays River Pb–Zn deposit; 35, Voisey’s Bay Ni–Cu–Co deposit; 36, Moran Lake U–V deposit; 37, Cocheath Cu–Mo–Au deposit; 38, Michelin U deposit.
modelling and detection of Canada’s major mineral systems; and (3) training students to increase the highly qualified personnel available to industry. The examples presented below are highlights of research results completed during recent investigations into Canada’s most economically important mineral systems. Additional information can be found in the series of syntheses and special volumes of TGI research: Bleeker and Houlé (2020), Mercier-Langevin et al. (2020), Potter et al. (2020), Plouffe and Schetselaar (2021), Corriveau et al. (in press-a), Peter and Gadd (2022).

Mineral systems

Targeted Geoscience Initiative research has become increasingly focused on the geological processes that intersect in space and time to form ore deposits—that is, the economically viable part of a mineral system (e.g. Wyborn et al. 1994; McCuaig and Hronsky 2014; Hagemann et al. 2016). Various authors have grouped some of the key ore-forming processes and their conceptual targeting criteria into a series of distinct components, including: (1) drivers; (2) sources; (3) pathways; and (4) traps. Drivers are the processes that drive fluid or magma flow, and are essentially the energy source for mineralization. Sources refer to regions in which metals and ligands are enriched, typically by geochemical or tectonic processes, and subsequently released into an ore fluid. Metal- and ligand-bearing fluids travel via pathways; structures, surfaces capable of transmitting fluids, or as metasomatic coupled-dissolution and reprecipitation mechanisms. Once the fluids are trapped, the ores precipitate. Traps may be geochemical (e.g. redox-controlled, fractional crystallization, wall-rock interaction, etc.) or physical (density separation, temperature drop) and result in accumulation of ore. Each component must be present and converge in space and time to form a mineral deposit and many of these geological processes operate at spatial and temporal scales that are considerably greater than the relatively small-scale and short-lived mineralizing events. Primary metal endowment can be subsequently enriched through renewed fluid circulation induced by magmatism or tectonism, or through metamorphic and sedimentary processes. Further, deposits must be preserved in their primary depositional zones (typically defined as the upper 10 km of Earth’s crust) and deposits may be preserved by geological processes such as tectonism or magmatism (McCuaig and Hronsky 2014). The mineral system concept can thus be used to focus mineral exploration targeting across a range of spatial scales and in areas without any known critical mineral deposits.

Magmatic mineral systems

Mafic to ultramafic mineral systems (Co, Cr, Cu, Ni, PGE, Sc, Te, Ti, V)

Most of the largest and most economic magmatic Ni–Cu–PGE–Co mineral systems are associated with mafic to ultramafic igneous rocks (Fig. 4a), and occur in rift-related tectonic settings (Eckstrand and Hulbert 2007). Canada contains a wide variety of prospective geology for these types of mineral systems of varying age (e.g. Neoarchean to Cretaceous) and is the fifth largest producer of Ni globally. Bulk historic and current production is mainly from five major mining districts (Sudbury, Ontario; Thompson, Manitoba; Lynn Lake, Manitoba; Voisey’s Bay, Labrador; Cape Smith, Quebec). These were formed during the Paleoproterozoic (Thompson, Lynn Lake, and Cape Smith: c. 1.8 Ga; Eckstrand and Hulbert 2007; Bleeker and Kamo 2020) to

![Fig. 4. Representative photographs from some mineral systems described in the text, including: (a) leopard net-textured sulfides from the Katinniq Ni–Cu–Co–PGE deposit in the Raglan Mining Camp (Quebec); (b) eudyalite (pink mineral) in pegmatic syenite of the Kipawa alkaline complex (Quebec); (c) chrysocolla (hydrated Cu silicate) exposed on the pit wall of the Gibraltar Cu–Mo mine (British Columbia); (d) chalcopyrite and molybdenite within the mine phase tonalite from the Gibraltar mine (British Columbia) (Plouffe and Schetselaar 2021); (e) amphibole–magnetite–biotite alteration and sulfide mineralization from the NICO deposit (Northwest Territories); (f) feeder zone stratigraphically beneath the north sulfide body at the Windy Craggy Cu–Zn–(Co) deposit (British Columbia).](http://sp.lyellcollection.org/)
Mesoproterozoic (Voisey’s Bay: c. 1.3 Ga; Eckstrand and Hubert 2007), and three of these districts (i.e. Sudbury, Thompson, and Cape Smith) are located along the periphery of the Archean Superior craton (Fig. 3).

There are two main types of Cr–PGE mineral systems: (1) podiform and (2) stratiform chromite deposits. There is no current production from the podiform type, although there was some historic mining during the early part of the twentieth century (mainly Phanerozoic mines in Quebec, Newfoundland, and British Columbia) (Duke 1996). Until the discovery of chromite deposits in the Ring of Fire region of northern Ontario (Fig. 3), the Bird River sill (Manitoba) and the Muskox layered intrusion (Nunavut) were the most significant deposits of this type in the Canadian Shield. However, with the future development of the Ring of Fire chromite deposits, Canada is poised to become a significant chromite producer.

Iron–Ti–V–P deposits occur as large ilmenite and titaniferous magnetite deposits hosted mainly in massive and layered Proterozoic anorogenic complexes and Archean to Proterozoic gabbro–anorogenicitric complexes. The Lac Tio mine in Quebec is the only Fe–Ti deposit currently being mined. However, despite the lack of production for V and P in Canada, numerous advanced mineral exploration projects are currently underway such as the Fe–Ti–V deposits within the Lac Dør complex and the Lac à Paul P–Ti deposits within the Lac St-Jean anorogenicitic complex, Quebec.

Extensive work has been conducted in the past on orthomagmatic Ni–Cu–(PGE), Cr–(PGE), and Fe–Ti–V deposits worldwide (e.g. Barnes and Lightfoot 2005; Cawthorn et al. 2005; Naldrett 2011; Charlier et al. 2015) which have identified the key processes to generate mafic to ultramafic mineral systems: (1) a large flux of mantle-derived melts produced by high degree of partial melting to release most critical metals from the mantle; (2) presence of lithospheric structures to allow the ascent of the magmas through the crust; (3) achieving saturation in sulfides, chromite, and Fe-oxides by various mechanisms (e.g. crustal contamination, magma mixing, etc.) as a driver to generate Ni–Cu–PGE, Cr, and Fe–Ti–V mineralization, respectively, and (4) ultimately concentration of these ore minerals into physical traps (e.g. depression in the floor of the magma chamber, shape of a magmatic conduit) or specific layers to form economic accumulation of critical minerals. As most of the Canadian mafic to ultramafic mineral systems were emplaced into Precambrian terranes and may have experienced numerous post-depositional processes, such as deformation and metamorphism, it is also essential that the orebodies were sufficiently preserved in order to be discovered.

Although the source, the pathway, the driver, and the trap frameworks of mafic to ultramafic mineral systems are generally well characterized and their associated exploration techniques are fairly well understood (Barnes et al. 2016), a number of scientific questions remain. In particular, the main drivers responsible for the spatial and temporal distribution of these large, well-endowed systems remain enigmatic. Other questions include how the mode of emplacement and the role of the magmatic architecture influence metal endowment. Deformation and metamorphism play an important role in the degree of preservation and the likelihood of finding new discoveries, but a major challenge (in Canada) is the burial of these mineral systems under thick cover of unconsolidated deposits (e.g. glacial till) and/or sedimentary rocks, which complicates their detection (e.g. Ring of Fire Ni–Cu–[PGE] and Cr deposits).

Research conducted in recent years as part of the TGI programme has made significant progress to advance the understanding of mafic to ultramafic mineral systems in terms of their spatial and temporal distribution (Bleeker et al. 2020; Bleeker and Kamo 2020; Houlé et al. 2020a), their magmatic architecture (Zuccarelli et al. 2020; Houlé et al. 2020b) and the compositions of ore-forming minerals (Smith et al. 2020) to develop targeting criteria. These advances may be used to determine the potential for different magmatic suites to develop a mineral system and/or vector towards mineralization (Sappin and Houlé 2020). For example, TGI research has shown the largest mafic to ultramafic mineral systems are characterized by large magmatic events with evidence of dynamic multi-phase intrusive or extrusive history emplaced over a relatively short time period (Bleeker et al. 2020; Bleeker and Kamo 2020; Houlé et al. 2020b). In addition, TGI work has demonstrated the usefulness of Fe-oxide minerals as an indicator of the Ni–Cu–PGE and Fe–Ti–V–P prospectivity of mafic to ultramafic systems even within structurally deformed and metamorphosed Archean and Proterozoic terranes (Dare et al. 2015; Sappin and Houlé 2020).

**Magmatic felsic to alkaline mineral systems**

(Li, Nb, REE, Ta)

Felsic, alkaline, and carbonatite magmatic systems occur in a wide range of tectonic settings (e.g. intracontinental anorogenic, post-orogenic extensional, and continental orogenic) that host a variety of critical (REE–Nb–Ta–Li) and other (Zr–Hf–Be) mineral systems. They range in age from Archean to Mesozoic, although the majority are in Neoarchean to Neoproterozoic cratonic regions (Sappin and Beaudoin 2015; Simandl and Paradis 2018; Easton...
2020). Substantial critical mineral resources related to these magmatic systems are currently in production (Niobec Nb mine, Quebec; Nechalacho REE–Nb–Ta mine, Northwest Territories) (USGS 2021). There are also past operating mines (Tanco Cs and Ta mine, Manitoba) and advanced-stage exploration projects (e.g. Strange Lake REE deposit, Quebec; Ashram REE deposit, Quebec; Whabouchi Li deposit, Quebec; Aley Nb deposit, British Columbia) (Fig. 3).

The critical processes controlling the formation of carbonatite to alkaline mineral systems (e.g. Dostal 2016; Goodenough et al. 2021; Yaxley et al. 2022) and pegmatite mineral systems (e.g. Cerný and Ercit 2005; Dill 2015) are relatively well known. The source of the carbonatite to alkaline mineral systems is compatible with volatile-enriched alkaline and carbonatite parental magmas generated by low degrees of partial melting of a metasomatized or crustally contaminated lithospheric mantle source. Their magmatic pathways are generally controlled by the presence of major crustal-scale weakness zones, such as continental rifts or translithospheric structures. Fractional crystallization, immiscibility of melts ± hydrothermal fluids, and metasomatism are the main processes that drive the critical metal enrichment and deposition in these mineral systems (Goodenough et al. 2021; Yaxley et al. 2022). Fertile fluids and melts are trapped at shallow crustal levels in the host rocks, where critical minerals precipitate (Dostal 2016).

In contrast, pegmatite mineral systems require highly differentiated and volatile-enriched granitic magmas as a source for fluids and metals. These magmas are generated by various processes, which involve crustal or mantle contribution (e.g. Cerný and Ercit 2005). Similar to mafic to ultramafic mineral systems, regional-scale structures (e.g. faults, shear zones) are essential pathways through the crust. Cooling and chemical diffusion in strongly fractionating granitic magmas are the main drivers leading to the formation of mineralized pegmatites. Their traps involve some structures providing the accommodation space necessary for their emplacement (Dill 2015).

Many geological features of the felsic to alkaline magmatic systems have been documented, but their integration into the mineral system framework is relatively recent (e.g. Banks et al. 2019). Thus, it is essential to improve our understanding of these magmatic mineral systems and the available exploration methods for effective detection of these deposit types. Targeting the source(s) of the carbonatite to alkaline mineral systems via prospectivity mapping is difficult in Canada because of a limited knowledge of the spatial and temporal distribution of their host rocks. In addition, the identification of new felsic to alkaline-related ore deposits remains a challenge in Canada due to extensive overburden cover. To resolve this issue, development of new techniques directly applied to exploration for these specific mineral systems in those conditions is a research priority.

Recent TGI and GEM research on felsic and alkaline igneous rocks and their associated critical mineral resources aims to overcome these challenges. Reviews on carbonatite complex- and pegmatite-associated deposits (Simandl et al. 2018; Simandl and Paradis 2018) summarized key criteria (e.g. temporal distribution, tectonic setting, morphology and geometry, rock association, alteration, and mineral resources) and new advances in exploration methods (e.g. radiometric and magnetic geophysical surveys, soil and till geochemical surveys, and biogeophysical surveys) for effective deposit detection. Furthermore, new indicator mineral surveys coupled to automated mineralogical analyses (e.g. QEMS-CAN®) have proven to be an effective mineral exploration approach for carbonatite-related ore deposits (Simandl et al. 2017). These studies demonstrate that uncommon REE minerals (e.g. eudialyte; Fig. 4b) should be included in lists of indicator minerals used during exploration for critical mineral resources (McClenaghan et al. 2019).

A comprehensive digital database on the spatial and temporal distribution of these magmatic ore systems throughout Canada is also in progress and a new synthesis of the critical mineral resources hosted within Canadian carbonatite and peralkaline igneous rocks (e.g. Kipawa REE deposits, Quebec; Fig. 4b) will be updated from Simandl and Paradis (2018). This compilation will be beneficial to identifying the most permissive areas to find these critical minerals. Experimental laboratory work will be implemented to provide a better understanding of the physical and chemical magmatic processes responsible for the formation of critical mineral deposits. In addition, promising research on indicator mineral methods applied to the exploration of such deposits will be pursued (e.g. study of the chemical composition of REE indicator minerals to fingerprint critical mineral deposits) to improve the detection of prospective carbonatite and peralkaline igneous rocks.

Magmatic-hydrothermal mineral systems
Porphyry mineral systems (Bi, Cu, In, Mo, PGE, Sn, Te, W, Zn)

Porphyry deposits are a primary (or emerging) source of several critical minerals, accounting for about 40% of the Cu and all of the Mo produced in Canada (Sinclair 2007). These systems also contain several by-product critical minerals (Bi, In, PGE, Sn, W, and Zn; Sinclair 2007) and potentially unrecognized resources of Co and REE, some of which
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could be present in the waste rocks of existing or past-producing mines (Velasquez et al. 2020). Potential for undiscovered porphyry Cu mineralization remains high in Canada, and particularly in the Canadian Cordillera; however, exploration in some regions is difficult due to thick accumulations of glacial overburden (e.g. Quesnel terrane; Montsion et al. 2019).

Porphyry mineral systems form in convergent plate margins, typically during late- to post-orogenic extension. Indeed, the Cordilleran region of western Canada is characterized by this tectonic setting and is well endowed with porphyry Cu mineralization (Figs 3, 4c and d). The mineral systems formed in response to exotic terrane accretion to the Laurentian cratonic landmass during the Mesozoic era (Sharman to exotic terrane accretion to the Laurentian cratonic landmass during the Mesozoic era (Sharman et al. 2007)). A number of keystone publications have provided an overview of porphyry and porphyry-style mineralization in various regions of Canada (Sutherland-Brown 1976; Schroeter 1995; Sinclair 2007; van Staal 2007; Sharman and van Staal 2007). The preservation potential of porphyry systems is low due to the relatively shallow crustal setting (typically <5 km; Sinclair 2007), thus older and fewer porphyry-style or intrusion-related deposits are also found in the Appalachians of eastern Canada (van Staal 2007). A number of keystone publications have provided an overview of porphyry and porphyry-style mineralization in various regions of Canada (Sutherland-Brown 1976; Schroeter 1995; Sinclair 2007; van Staal 2007; Sharman and van Staal 2007). To better understand porphyry mineralization and improve exploration methods, Plouffe and Schetselaar (2021) present the most recent research conducted on porphyry deposits by the GSC during its fifth phase of TGI. The contributions are summarized below.

Recent research conducted under the TGI programme on porphyry mineral systems and their critical mineral resources contributed to improved exploration models and development of new methodologies to support the mineral exploration industry. Kellett et al. (2021) examine the spatial and temporal distribution of porphyry-style mineralization in the Canadian Appalachians, including an assessment of the potential for structurally controlled Sn–W–Mo mineralization in Middle to Late Devonian granitoids. Their investigation is supported by a compilation of new and previously published U–Pb zircon crystallization ages. For the Canadian Cordillera, Rogers (2021) provides an alternative to the widely accepted model of eastward migration of east-dipping subduction in the Quesnel terrane of British Columbia (Logan and Mihalynuk 2014). Instead, Rogers (2021) suggests that post-depositional structural re-alignments can explain the eastward-younging plutonic belts in the southern part of British Columbia. If correct, his model raises the possibility of undiscovered porphyry mineralization in central and eastern Quesnel terrane.

Other developments include new geophysical methods for interpreting data at the Iron Mask batholith and the associated New Afton porphyry Cu–Au deposit in south-central British Columbia. Bellefleur et al. (2021) present vertical seismic profiling to image the deeper part of the deposits. They report seismic reflectors along alteration zones, in numerous structures and in different metavolcanic rocks that improve the imaging of a mineralized system. Such information may be applied during a drilling campaign of an advanced mineral exploration programme. Roots et al. (2021) conducted a magnetotelluric survey over the New Afton deposit to demonstrate that these data are capable of imaging deep-seated, structurally controlled mineralization. For a regional evaluation of porphyry mineralization potential, Thomas (2021) combined airborne magnetic and gamma-ray spectrometry data (cf. Shives et al. 1995). Thomas (2021) notes that numerous porphyry occurrences in the region of the Iron Mask batholith are characterized by overlapping magnetic highs and low Th/K ratios, suggesting the spatial relationship between magnetic and radiometric data may narrow the search area and delineate prospective rocks.

Mineralogical and geochemical footprints of porphyry mineralization are evident in the overlying surficial sediment cover (Plouffe et al. 2016; McClenaghan et al. 2017). High abundances of ore and alteration minerals (i.e. porphyry indicator minerals, PIM; Cooke et al. 2020a) in detrital sediments and high contents of ore and pathfinder elements contained therein are mineral exploration targets that can extend over large areas (tens to hundreds of square kilometres) (Plouffe et al. 2022). These minerals may be recovered and traced in the cover sediments (Plouffe and Ferbey 2017) and traced up-ice to the bedrock source of porphyry mineralization (Wilkinson et al. 2020; Cooke et al. 2020b). Mineralogy and mineral chemistry are valuable tools, especially in glaciated (and unglaciated) landscapes of the Canadian Cordillera (Plouffe et al. 2016, 2022; McClenaghan et al. 2021). Glacial sediments in the vicinity of porphyry mineralization may host PIM that can be identified using automated mineralogy that combines a scanning electron microscope and a Mineral Liberation Analysis database (Plouffe et al. 2021a). Tourmaline and epidote are two additional PIM commonly observed in the alteration zones of porphyry mineralization, and may thus also be useful in exploration (Beckett-Brown et al. 2021; Plouffe et al. 2021b). Continued research aims at better defining the geochemical discriminators of porphyry fertility in specific indicator minerals (Lee et al. 2021) or providing new constraints on ore formation (Percival et al. 2021). A concept of
mineral exploration in regions of poor bedrock exposure could thus include the following: (1) regional investigation(s) of surficial sediment geochemistry and mineralogy to define anomalies; (2) geophysical survey(s) in targeted area(s); (3) exploratory drilling and PIM studies in drill core samples. Development and refinement of exploration methods for porphyry mineral systems within the Canadian Cordillera is motivated by mineral potential assessments (e.g., Mihalasky et al. 2011) that estimate approximately 49 Mt Cu remain in undiscovered deposits in British Columbia and Yukon.

**Metasomatic iron and alkali-calcic mineral systems (Al, Bi, Co, Cu, F, Mo, Nb, Ni, PGE, REE, Sb, Sn, Ta, Te, U, V, W, Zn)**

Regional metasomatic iron and alkali-calcic (MIAC) mineral systems generate a range of economic deposit types with base, precious and critical metals as primary commodities such as IOCG, iron-rich Au–Co–Bi ± Cu, iron oxide–apatite–REE (IOA), albitite-hosted U or Au–Co, and W-skarn deposits (Corriveau et al. in press-a, b, c, d). These districts are spread across Canada (Fig. 3), mostly within Paleoproterozoic rocks. In Canadian deposits, critical mineral grades reach values of 0.14 wt% Bi (NICO), 2.7% REE2O3 (Josette), 0.098 wt% U3O8 (Michelin), 0.078 wt% V2O5 (Moran), and 0.2 wt% WO3 (Fostung) (Corriveau et al. 2021). Enrichments in other critical minerals (including global examples) include Al2O3 (17–35 wt%), Co (up to 0.7 wt%), Cu (up to 1.1 wt%), Mo (up to 1.5 wt%), Ni (up to 0.96 wt%), Sb (100–910 ppm), Sc (14–325 ppm), Sn (68–256 ppm), Ta (3–30 ppm), Te (500–2000 ppm), Y (1377–710 ppm), and Zn (up to 0.3 wt%) (Corriveau et al. in press-d). Overall, MIAC systems have the potential to source 19 of the 31 critical minerals on the Canadian list (NRCan 2021b).

Establishing robust case examples and tools to identify, map, and explore these mineral systems is fundamental in securing critical metal resources for Canada and its economic partners. To this effect, the GSC and its collaborators from the academic, private and public sectors are conducting research on the geological, geophysical and geochemical signatures, genetic framework, and spatial distribution of MIAC systems in Canada and globally (Corriveau et al. in press-a). There is also extensive collaboration with the Denendeh Exploration and Mining Company to optimize current and future MIAC-related resource development in Canada with and among First Nations (Beaulieu 2018).

Mapping across MIAC systems highlights how the ascent of highly reactive, high-temperature (c. 400 to 900°C), saline to hypersaline fluid plumes generate consecutive hydrothermal alteration facies at regional scales (hundreds of square kilometres). Each facies has a distinctive suite of mineral assemblages and compositional ranges and precipitates distinct metal associations, leading to a predictable suite of mineralization types and ultimately deposit characteristics (Fig. 5) (Corriveau et al. in press-b, d).

The onset of hydrothermal activity (based on available field exposures) consists of intense albitization along regional fault networks (or above subvolcanic intrusions). The intense leaching of upper crustal rocks to form albitite leads to addition of metals to the main fluid plume. In the presence of carbonate units, skarns also form prior to, during, or after albitization without the requirement of proximal intrusions.

As the fluid plume evolves, amphibole- to magnetite-dominant mineral assemblages become stable under the high-temperature Ca–Fe alteration facies and can precipitate iron skarn, IOA, IOA–REE and metasomatic Fe-rich Ni deposits (Fig. 5). Iron-rich Au–Co–Bi deposits (e.g. NICO deposit; Fig. 4e) and some Ni mineralization are cogenetic with the subsequent high-temperature Ca–K–Fe alteration facies. Amphibole to magnetite to biotite-dominant assemblages are stable, precipitate with arsenide, sulfosalt and iron sulfide minerals, and occur primarily within sedimentary successions. Magnetite- to hematite-group IOCG (e.g. Sue Diane Cu–Au–Ag deposit) and iron-sulfide copper–gold deposits form at the K–Fe alteration facies with mineral assemblages precipitating Cu-sulfides in oxidized or reduced environments, respectively. The apical parts of MIAC systems commonly consist of extensive epithermal caps. Examples are known to be preserved from the Cenozoic in the Andes as well as in Proterozoic non-metamorphosed (Great Bear magmatic zone) to metamorphosed (Bodny gneiss complex) systems (Corriveau et al. in press-a, b, c, d).

Systems that form IOCG and affiliated deposits form in tectonically active environments. Extensive syn-metasomatic thrusting, uplift and down-faulting, and addition of external high- or low-temperature fluids result in the telescoping, and repetition of alteration facies and metal precipitation. These processes remobilize and reconcentrate metals, increasing the potential for ore deposition in the deposit types discussed above. They can also form additional deposit types during the later stage of the systems (Fig. 5). Overprinting by lower temperature facies can form albitite-hosted U and Au–Co deposits (e.g. Michelin U and Moran U–V; Acosta-Góngora et al. 2022). Renewed fluid circulation within systems can result in metasomatic or metamorphic remobilization of primary metal endowments into ores such as the REE-rich vein-type ore within the Josette IOA.
deposit (Fig. 3; Gauthier et al. 2004; Sappin and Perreault 2021), and the addition of metals (e.g. basal fluids; Corriveau et al. in press-b). Systems metamorphosed to high-grade conditions (e.g. upper amphibolite and granulite facies) preserve metamorphosed IOA and IOCG mineralization. Host MIAC alteration facies (e.g. Na, high-temperature Ca–Fe, and high-temperature to low-temperature K–Fe), associated tourmaline alteration of albite and epithetical caps with advanced argillic alteration are known to preserve their diagnostic compositions forming plagioclase-, amphibole-, magnetite-, garnet-, biotite-, K-feldspar-, sillimanite- or tourmaline-rich gneisses (Corriveau and Spry 2014). Many such rocks are mapped as metasedimentary and exhalative rocks which hampers effective mineral exploration of metamorphosed MIAC systems (Corriveau and Spry 2014).

Disruption of systems through syn- to post-metasomatic tectonic activities, magma emplacement and fluid ingress, and the formation of iron oxide-poor to iron-poor variants in certain systems, lead to a highly varied spatial distribution of alteration facies and mineralization that preclude a one-size-fits-all conceptual depth-to-surface deposit model. System evolution is best reported as alteration facies, including where the evolution is disrupted or systems are metamorphosed (Fig. 5).

Cogenetic relationships between alteration facies, metal associations and mineralization types provide a robust exploration tool (Fig. 5) (Corriveau et al. in press-b, d). The distinctive mineral assemblages and mineral contents of each alteration facies produce distinctive geochemical and geophysical footprints (Enkin et al. 2016; Corriveau et al. in press-c). Multiple sources of fluids and metals contribute to the mineralizing fluid plumes (e.g. magmatic, basinal or evaporite-derived, potential salt melts) to form metal lodes (Williams et al. 2005; Zhao et al. in press). Through time, cratonic edges facilitate the formation of fault networks that enable the collection and the ascent of the voluminous, high-temperature saline-hypersaline fluid plumes. These conditions can also generate voluminous batholiths with A-type granites (Wade et al. 2019), alkaline ultrapotassic to carbonatite intrusions (Corriveau and Gorton 1993) and comeging maflf-felsic dyke swarms (Corriveau 2007), and sedimentary basins hosting base metal and U deposits (Hoggard et al. 2020).

The MIAC fluid pathways have diagnostic geological (Potter et al. 2019a, b; Corriveau et al. in press-c), mineralogical (McMartin et al. 2011; Normandeau et al. 2018; Kelly et al. 2020), petrophysical (Enkin et al. 2016), and geophysical (e.g. magnetic and gravimetric anomalies; Hayward et al. 2017).
et al. 2016) footprints. The footprints are distinct from those of unmineralized sedimentary, igneous and metamorphic rocks. In the field, some MIAC footprint attributes resemble common rocks and may be overlooked during mapping and exploration. Once recognized and mapped, each of the consecutive alteration facies, or combination thereof, can be used to vector toward its associated deposit type and variants (Fig. 5). The presence, repetition, telescoping or absence of a facies and their spatial distribution inform on the simple prograding or complexly disrupted nature of the systems (e.g. disruption through voluminous influx of low-temperature fluids, magma ascent, faulting; Corriveau et al. in press-b, c) as well as on potential exploration targets. Novel alteration mapping and lithogeochemical discrimination methods, global case examples of geological and geophysical footprints, and refined exploration tools are provided in Corriveau et al. (in press-a) and preparation of an extensive lexicon of field attributes and series of geochemical datasets are in progress.

Submarine volcanic mineral systems (Bi, Co, Cu, Ge, In, Sb, Sn, Te, Zn)

Volcanogenic massive sulfides (VMS), also referred to as volcanic-hosted massive sulfides, are well studied and fairly well understood in terms of genesis (e.g. Hannington 2014). The mineral system forms in extensional geodynamic regimes and includes a heat source (driver) that typically consists of an intrusive complex that enables circulation and convection of modified seawater and magmatic-derived fluids towards the seafloor, through synvolcanic faults (conduits). At or near the seafloor, the hot, metal-enriched fluids undergo physico-chemical changes due to interactions with cold seawater. This leads to precipitation of stratiform lenses of massive to semi-massive sulfides and discordant stockworks of sulfide veins (i.e. the feeder zone). This process induces precipitation of a range of sulfides and associated metals and minerals (Franklin et al. 2005). These mineral systems are relatively common in Canada and span a range of ages, from Archean to Paleozoic (Fig. 3), and some mines have been in production for decades (e.g. Kidd Creek).

Whereas the overall mechanisms for mineralization are well understood, key aspects of VMS formation remain enigmatic, such as the process(es) responsible for critical mineral (e.g. Bi, Co, Ge, In, Sb, Sn, Te) and other trace metal/metalloid (e.g. As, Cd, Hg, Se) enrichments in some deposits (Leybourne et al. 2022); the possible role of magmatic fluids and vapours in these enrichments (Fayard et al. 2020; Schmidt et al. 2021; Leybourne et al. 2022); and the effects of metamorphism and deformation on these primary distributions. The Windy Craggy Cu–Co VMS deposit (Fig. 4f), NW British Columbia, is hosted by mafic alkalic rocks and siliciclastic sediments. Enrichments of Sb, Sn, and Bi in primary fluid inclusions in the feeder zone are related to magmatic contributions, rather than leaching by circulating fluids (modified seawater) from host rocks (Schmidt et al. 2021). Leybourne et al. (2022) studied the geochemistry of the mineralization at Windy Craggy and noted that Co, Bi, Mo, Te, Au, As, and Sb enrichments are also consistent with a direct magmatic contribution, perhaps by magmatic degassing. The distributions and origins of critical metals within VMS systems (and seafloor massive sulfides, their modern analogues) are a focus of current research at the GSC. The goal is to tailor exploration models for deposits with specific critical mineral enrichments, such as Co (e.g. Windy Craggy), In (e.g. Brunswick No. 12, New Brunswick), and Sn (e.g. Kidd Creek, Ontario) that can be recovered as by-products or co-products.

Targeted Geoscience Initiative research has also advanced exploration methods and methodologies for VMS deposit. A recent study by Pilote et al. (2020) on diagenetic pyrite nodules in argillites enclosed in massive sulfide lenses at the LaRonde Penna VMS deposit aimed at establishing the timing of trace element uptake in the pyrite and their link to the VMS formation. Laser ablation-ICP-MS of pyrite has shown that elements such as Sn, Cu, Zn, Pb, and Bi are enriched in some parts of the nodules, and these parts contain inclusions such as stannite, sphalerite and galena. These elements are also present in the adjacent massive sulfides, which suggests that the elements were introduced in the sediments during the onset of the ore-forming hydrothermal system. Although the data suggest a link between the trace element chemistry of nodules and the massive sulfides, the trace element geochemistry of diagenetic pyrite is an equivocal vector to VMS-style mineralization that remains to be tested on the camp-scale.

Lougheed et al. (2022) investigated the potential of the fine-grained fraction (<250 µm) of till heavy mineral concentrates (HMC) to serve as a vector towards mineralization. This fraction has rarely been used previously due to the difficulty and time consuming nature of optical characterization of mineral phases in very small grains. This problem is being tackled by employing automated mineralogical identification methods (mineral liberation analysis). These authors studied till samples from the highly metamorphosed Izok Lake Zn–Cu–Pb–Ag VMS deposit (Nunavut) and recovered HMC from till samples down-ice of the deposit. The HMC in the fine-fraction consist of sulfide ore indicator minerals (chalcopyrite, galena, pyrite, sphalerite, and
pyrrhotite) and associated hydrothermal alteration minerals (gahnite, corundum, epidote, and iron oxide) typical of metamorphosed VMS deposits. These indicator minerals were detected in till farther down ice within the fine-fraction than is typically found in coarser fractions (>250 µm) recovered from the same samples. The fine fraction, therefore, delineates a larger (longer) dispersal train than the coarse fraction, enhancing deposit detectability. The workflow developed by this project can be scaled to broader regional surveys to increase the likelihood of detecting indicator mineral footprint(s) and provide more detailed mineralogical information from till samples.

Basin-hosted mineral systems

Sediment-hosted mineral systems (Co, Cu, Cr, Mo, Ni, PGE, REE, Se, U, V, Zn)

Sedimentary basins are repositories for terrigenous clastic and chemical sedimentary detritus and they host a variety of mineral systems, many of which are well endowed with critical minerals as primary, by-product, and co-product commodities. These different mineral systems form in response to different geodynamic triggers throughout the history of a basin, from rifting to drifting and passive margin development, through to basin inversion and closure.

Research on these deposits has aimed at elucidating the processes responsible for mineralization. Mineral systems in sedimentary basinal settings that have been recently studied by the GSC include: hyper-enriched black shale (HEBS) polymetallic deposits, clastic-dominated (CD) Zn–Pb–Ag deposits, carbonate-hosted Mississippi Valley-type (MVT) Zn–Pb deposits, and unconformity U deposits. Some highlights and implications of recently completed research studies are presented below.

Hyper-enriched black shale, also referred to as highly metalliferous black shales (Johnson et al. 2017), is an important global repository for Zn, Ni, Cu, Mo, Se, U, V, Cr, Co, Ag, Au, Re, PGE and REE (Jowitt and Keays 2011). Johnson et al. (2017) defined HEBS as having Mo + Ni + Zn + Se + V greater than 1500 ppm, which is more than three times higher than the United States Geological Survey black shale standard SDO-1 (Kane 1993). The best-known example of HEBS in Canada is the Nick Ni–Zn–Mo–PGE–Re–Au prospect, Yukon (Hulbert et al. 1992). The mineralization is widespread throughout the northern Cordillera of northern Yukon and northeastern British Columbia (Fig. 3), where it occurs at the same regional stratigraphic contact at all known localities (Gadd et al. 2022).

Recent TGI research has greatly increased our understanding of the genesis of HEBS in the northern Canadian Cordillera, clarifying the following: the sedimentary environment of formation (Crawford et al. 2021; Gadd et al. 2022), the age of and timing of mineralization (Gadd et al. 2020), the PGE mineralogy (Gadd et al. 2019) and establishing new genetic and exploration models (Crawford et al. 2021; Gadd et al. 2022). In summary, myriad models had previously been proposed for the northern Cordilleran examples (e.g. seafloor hydrothermal, meteorite impact-related), but the most recent GSC and partner research showed a clear hydrogenetic (direct precipitation from seawater) origin, within a redox trap and triggered by eustatic sea-level rise. This has implications for the exploration model, as there will be no associated hydrothermal alteration zones that would signify the presence of a nearby deposit in the seafloor hydrothermal model. Further, there should be no expected primary thick (several meters or more) sulfide intersections, and any thick intervals would be due to tectonic and deformational modifications. Finally, exploration should be focused at a key stratigraphic contact (i.e. the terminal Road River Group in the Northern Canadian Cordillera).

Clastic-dominated Zn–Pb–Ag (+ barite) deposits, also referred to as sedimentary exhalative (SEDEX) deposits, are also hosted in fine-grained, carbonaceous, siliciclastic rocks. The primary commodities are Pb and Zn, and they commonly contain Ag and barite. Canada is well-endowed with CD deposits (Fig. 3), such as the past-producing Sullivan Pb–Zn–Ag mine in British Columbia and the world-class (but undeveloped) Howard’s Pass and MacMillan Pass Pb–Zn–(Ag) districts in Yukon. The GSC has made several research contributions to CD deposits, including major advances in understanding of how CD deposits form and improved exploration methodologies. Traditional models envisaged hydrothermal, metalliferous fluids escaping from synsedimentary structures into the ambient waters, wherein quenching and mixing resulted in the precipitation and chemical sedimentation of sphalerite and galena (Goodfellow et al. 1993). Newer TGI-funded research indicates that mineralization largely formed within the un lithified (reducing) muds from ponding and/or infiltrating hydrothermal fluids that precipitated base metal sulfides within them (Gadd et al. 2017), or hydrothermal fluids traveling along fractures within the semi-lithified to lithified muds (Magnall et al. 2020). This finding has exploration implications that utilize metals, and other elements and ratios thereof, that were originally considered to be dispersed in the water column overlying mineralization when it formed, to vector lithogeochemically toward concealed mineralization (Leighton et al. 2021). Rather, hydrothermal fluids (dense brines) emanating from a point source (e.g. growth
fault) and then flowing down topography along (on top of) and/or within wet sediments, and cooling along the way (Sangster 2018), might impart unidirectional lithgeochemical vectors in the case of vent-distal CD deposits, and 360° ‘bullseye’ vectors in the case of vent-proximal CD deposits.

Mississippi Valley-type carbonate-hosted deposits are a significant source of the World’s Pb and Zn (Mudd et al. 2017). These deposits are epigenetic and stratabound sulfide bodies that comprise sphalerite, galena, pyrite, calcite, and dolomite. These carbonate-hosted systems are also a potential resource for selected critical minerals, such as Ge, because sphalerite in these deposits is generally enriched in Ge (surmised to be due to precipitation from low-temperature, oxidized fluids) (e.g. Huston and Brauhart 2017). Canada has a large number of past producers (e.g. Pine Point, Nanisivik, Polaris) (Paradis et al. 2007), with some receiving strong consideration for further mining (e.g. Pine Point).

Recently completed TGI research has consisted of targeted studies of select MVT deposits in southeastern British Columbia. Paradis et al. (2022) present $^{87}$Sr/$^{86}$Sr isotope ratio data for MVT deposits (0.71076–0.71484) that are similar to, or higher than, host carbonate minerals (0.70964–0.71044). Oxygen and carbon isotope values in ore-stage dolomite, together with the trapping temperatures for fluid inclusions in sphalerite (c. 100–200°C; Kontak et al. 2022) support interaction of relatively high-temperature fluids with siliciclastic source rocks (i.e. the source of radiogenic Sr), and precipitation of sulfide minerals in the carbonate host rocks. Simandl et al. (2022) present compositional data of carbonate minerals in MVT deposits of the Canadian Rocky Mountains (Munroe, Shag, Kicking Horse, Monarch, Coral, and Robb Lake deposits) and Kootenay Arc (Pend Oreille, Reeves MacDonald, Jersey-Emerald, HB, and Duncan deposits). Rare-earth element patterns for these carbonates (including recrystallized dolomite and sparry dolomite) are varied, but most do not display the light REE depletion and strongly negative Ce anomalies typical of oxygenated seawater. All calcite and dolomite samples from the Kootenay Arc (except dolomites from the Pend Oreille mine) have positive Eu anomalies, suggesting that they precipitated from, or interacted with, different fluids than the carbonate minerals that formed the Rocky Mountains MVT deposits.

Unconformity-related uranium systems (Co, Cu, Ni, REE, U)

Uranium continues to rank amongst Canada’s top 10 metal commodities. Production from three high-grade deposits (Cigar Lake, Eagle Point and McArthur River) in the eastern Athabasca Basin of Saskatchewan yields c. 13% of the annual global production (NEA-IAEA 2020). In addition to uranium, which fuels nuclear reactors around the world, unconformity-related uranium deposits contain potential critical mineral by-products such as: Ni, Co, Cu, REE, Sc and Y (Normand 2014).

The high-grade unconformity-related uranium deposits in Canada remain prime exploration targets given the global trend toward lower ore grades, greater mining depths, and higher production costs. However, the McArthur River and Cigar Lake deposits represent the last of the ‘first generation’ of deposits mined in the Athabasca Basin, a Paleo-proterozoic intracratonic basin (Jefferson et al. 2007). These deposits were discovered using the classic Rabbit Lake unconformity-related model in which graphite-rich metapelite in underlying basement rocks was directly involved in ore precipitation (Hoeve and Sibbald 1978). However, recent discoveries of deposits in deeper and other geological settings, such as the basement-hosted Triple R and Arrow deposits (Cox et al. 2017) and sandstone-hosted Centennial deposit, are not directly associated with graphitic metapelite basement units (Jiricka 2010; Alexandre et al. 2012; Reid et al. 2014).

These discoveries have driven re-evaluation of the unconformity-related U mineral system model within the Athabasca basin. In response to this need, the GSC led a multidisciplinary, collaborative study of the Patterson Lake corridor (Potter et al. 2020) (Fig. 3) that hosts the Triple R and Arrow deposits as well as numerous occurrences (e.g. Spitfire, Harpoon, Cannon). Regional structural studies indicate ore formation occurred during episodic brittle reactivation of high-strain ductile to brittle-ductile structures, in particular late west- and NNW-striking brittle conjugate faults that crosscut the Athabasca sandstone (Johnstone et al. 2021). New airborne magnetic, gravity and magnetotelluric surveys (NRCan 2017, 2019; Tschirhart et al. 2019) permitted three-dimensional geophysical modelling of the Patterson Lake corridor deposits (Tschirhart et al. accepted). This modelling illustrates linkages between the surface architecture and lower crust/mantle, in particular the influence of a buried magmatic belt (Clearwater Domain granitic intrusions) key thermal drivers and developing architecture conducive to fluid flow, respectively (Potter et al. 2020; Tschirhart et al. 2020). Although the Clearwater intrusions were emplaced at least 300 myr before the mineralization event at c. 1840 Ma (Stern et al. 2003), preliminary geochemistry and geochronology indicate that radiogenic heat was produced from these intrusions and other c. 1.8 Ga felsic intrusions beneath the basin (e.g. the Hudson suite, Trans-Hudson Orogen pegmatites and plutons; Powell et al. 2019a). Insulating sedimentary successions trapped this heat, resulting in elevated geothermal gradients.
Public geoscience and critical minerals

Despite being hosted by rocks that do not align with the classic genetic models (i.e. altered and metamorphosed granite, granodiorite, and ultramafic to mafic basement rocks; Card 2020), the new discoveries have similar mineralogical, chemical, geophysical, and structural characteristics of the typical Athabasca Basin deposits (Powell et al. 2018, 2019a, b; Potter et al. 2020; Tschirhart et al. 2020; Johnstone et al. 2021; Rabiei et al. 2021). These results support a revised genetic model in which hydrothermal mineralization was emplaced at shallower depths (Chi et al. 2018) than was originally proposed for unconformity-related deposits (Hoeve and Sibbald 1978), as a result of the buried, high heat-producing intrusions. Brittle fault reactivations focused oxidized basinal brines into the basement rocks, where fault-valve behaviour (Sibson 1990) facilitated fluid–rock interactions, pressure-induced fluid boiling, and precipitation of the metals. Although the host rock lithologies and the extension of mineralization up to 1 km below the unconformity surface differ from the classic genetic models, these results support expansion of the unconformity-related mineral system models to include the Patterson Lake corridor deposits. The basement-hosted deposits are challenging exploration targets because the diagnostic low temperature clay alteration that occurs at the unconformity is rare or difficult to detect within the metamorphosed host rocks (Potter and Wright 2015). However, the spatial association with buried, high heat-producing intrusions defines a prospective corridor that extends from Saskatchewan to Nunavut where metamorphic basement rocks were previously covered by the Athabasca, Thelon, and Western Canada sedimentary basins (Potter et al. 2020).

Mineral potential modelling

The results presented above provide a number of examples of how public geoscience research can lead to a new or improved understanding of the drivers, sources, pathways, and traps of mineral systems (Wyborn et al. 1994; McCuaig et al. 2010; McCuaig and Hronsky 2014). Each of these components need to converge in space and time to form a mineral deposit (Wyborn et al. 1994; McCuaig et al. 2010; McCuaig and Hronsky 2014). However, to assess mineral potential and support mineral exploration targeting, mineral system components must be translated to geological, geophysical, and geochemical proxies that can be mapped at the surface or subsurface. Regions with multiple overlapping proxies, with at least one mappable proxy for each of the required mineral system components, are generally considered to be more prospective (McCuaig and Hronsky 2014). For example, magmas and/or hydrothermal fluids that transport critical minerals typically reactivate pre-existing crustal boundaries and/or contacts between rocks of different density, magnetic susceptibility, electrical resistivity, and/or seismic velocity. These rock properties can be mapped on land and water, in the air, and by satellites and the resulting geophysical datasets can be processed to highlight some of the most likely pathways that transported ore-forming fluids and magmas from their source to their depositional traps. Recent research on Canada’s magmatic Ni (Cu–Co–PGE) mineral systems has demonstrated that public geophysical datasets pre-processed to remove near-surface anomalies and/or to emphasize the edges of gravity or magnetic anomalies (i.e. high horizontal gradient magnitude) are effective at mapping mineral system pathways at multiple spatial scales to support mineral exploration targeting (Lawley et al. 2021).

Other datasets (e.g. geological, isotopic, and/or geochemical) are better suited for mapping the drivers, sources, and traps of minerals, as demonstrated for several of the critical mineral systems described above. For example, temperature changes occurring during MIAC ore-formation can be mapped from the rock record using a combination of mineralogy (i.e. alteration facies) and element associations (Fig. 5). Mapping the presence of these different mineral alteration facies and their geological timing relative to faults thus provides some indication as to whether the drivers (e.g. magmatic and mantle heat) and pathways (e.g. ore transport by saline fluid plumes along major faults) required to form a MIAC deposit occurred together at the same time. Similarly, bedrock geological maps and/or systematic geochemical surveys can be used to map the sources (e.g. mafic, ultramafic, or alkaline rocks in magmatic mineral systems) and depositional traps (e.g. black shales for basin-hosted mineral systems) for several of the magmatic and basin-hosted mineral systems described above. Although some of these host intrusions are too small to be depicted on regional geological maps, mapping these different mineral system components directly from the rock record and their application as indicators of mineral potential represents an important focus area for bedrock mapping programmes.

There are two broad approaches to assess mineral potential based on mineral systems science: (1) knowledge-driven models that are based on manually selected combinations of mappable proxies (An et al. 1991; Montsion et al. 2019); and (2) data-driven models that are based on the statistical association between mappable proxies and areas of known mineralization (Bonham-Carter et al. 1988; Agterberg 1992; Harris et al. 2015). The advantage of knowledge-driven methods is that the mappable proxies for each mineral system component are
explicitly weighted by experts, which can then be combined with simple Boolean operators (i.e. AND, OR, NOT) and/or more complex functions that can accommodate some measure of uncertainty. Knowledge-driven modelling has historically been performed in a GIS software environment and/or mineral potential modelling ‘plugins’ that offer more advanced functionality (e.g. ArcDSM). More recently, geospatial data packages have become available in high-level programming languages such as python (e.g. GeoPandas) and R (e.g. sf) that allow for reproducible data-processing workflows and/or deployed as web-based portals with built-in modelling functions (e.g. Geoscience Australia Portal; https://portal.ga.gov.au/). In the absence of training data, the knowledge-driven approach is the only available option for assessing the potential of mineral systems. For example, orogenic graphite, Li-bearing pegmatite, and some REE mineral deposits (discussed above) represent important primary sources for critical minerals but relatively few examples are known and/or are available in public databases across Canada. Critical mineral deposits in the deep-sea (discussed above), unconventional black shale-hosted deposits (discussed above), and/or brines associated with Canada’s oil fields are other examples of emerging sources that lend themselves to knowledge-driven modelling methods.

Data-driven models are better suited for mineral systems that are associated with thousands of showings, deposits, or operating mines to look for the best combination of mappable mineral system proxies (Bonham-Carter et al. 1988; Agterberg 1992). In Canada, relatively large numbers of training data are available for conventional base-metal deposits, which supply a significant proportion of the world’s Ni, Cu, and Zn. Critical minerals that occur as co- and by-products in association with base-metal deposits are best suited for data-driven modelling. Several recent pan-Canadian prospectivity models have been developed, including (1) magmatic Ni-Cu (Lawley et al. 2021); (2) MVT Zn–Pb (Lawley et al. 2022), and (3) CD Zn–Pb (Fig. 6; Lawley et al. 2022). Each of these prospectivity models is based on machine learning methods (e.g. deep neural networks, gradient boosting machine, random forest) and a large number of training deposits to digitally integrate public geophysical, geochemical, and geological datasets. The vast majority of the national datasets are compilations of much smaller-scale surveys conducted over many decades. Data-driven models, such as those presented in Figure 6, outperform knowledge-driven methods at classifying the presence or absence of known deposits, thus

Fig. 6. Data-driven prospectivity models for Magmatic Ni–Cu (± Co ± PGE), Mississippi Valley-type (MVT) Zn–Pb, and clastic-dominated (CD) Zn–Pb mineral systems. Prospectivity values are colour-coded using quantiles and the methods are described in Lawley et al. (2021). Model results highlight the variable potential for different mineral system across Canada and are based on public geological and geophysical datasets.
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Reducing the search for mineral exploration targeting as long as there are sufficient data available for training (Bonham-Carter 1994; Harris et al. 2005; Lawley et al. 2021). The statistical association between each input dataset and the training data can also be used to refine the conceptual targeting criteria identified through thematic research and to prioritize the most important supporting datasets for future acquisition. As a result, data-driven prospectivity modelling is an iterative process whereby models are constructed, validated, and then repeated to improve results. New spatial data packages that are available in high-level programming languages (e.g. python and R), coupled with open-source artificial intelligence platforms and high-performance cloud computing, are making it easier, faster, and cheaper to iterate over this data-driven prospectivity modelling process (Lawley et al. 2021).

International collaboration

Exploration, discovery and development of critical mineral resources are inherently international endeavors. Indeed, establishing and maintaining global supply chains of critical minerals requires agreements and partnerships. To this end, Canada is joined in a research partnership with Australia (Geoscience Australia) and United States (US Geological Survey), called the Critical Mineral Mapping Initiative (CMMI), that aims to promote the understanding of critical mineral science (Kelley 2020). Key goals for this initiative are: (1) to undertake research to develop a better understanding of critical mineral resources in known deposits; (2) to determine the geological controls on critical mineral distribution for deposits currently producing by-products; and, (3) to identify new sources of supply through mineral prospectivity mapping and resource assessment (Kelley 2020).

This collaboration has produced a web portal (https://criticalminerals.org) that hosts a database of critical minerals in ores and their chemical compositions (CMMI 2021). The first version of this website consists of archival and legacy data from each of the three countries (representing global critical mineral deposits), and it is anticipated that nationally produced geochemical datasets will be incorporated into versions to produce seamless maps (Emsho et al. 2021). As part of the effort to construct this global database, CMMI designed a deposit classification scheme using the mineral systems approach that can be used to group similar deposits (Hofstra et al. 2021). The classification scheme provides internal consistency to the geochemistry database, such that it can be queried and analysed. Thus, it can be used to predict critical mineral abundances of different deposit types, and this will be useful to industry in identifying exploration and development opportunities. Ongoing efforts are now focused on using the deposit classification scheme as the basis for a tectono-metallogenic classification scheme that can be used to link diverse, disparate mineral systems to tectonic environment and plate tectonic evolution. Another key future goal is to gain a fundamental understanding of the myriad controls on critical mineral distributions within various mineral deposit types.

Conclusions

Mineral exploration and mining are important to Canada’s economic development. However, to achieve net-zero carbon emission goals and transform Canada’s electrical grid and transportation networks to renewable energy, new domestic sources of critical minerals will be required. From a trade perspective, Canada is well positioned to become a lead supplier because of its critical mineral endowment and the strengths of its existing mineral exploration and mining industries. The new critical mineral list (Al, Bi, Co, Cr, Cs, Cu, fluor spar, Ga, Ge, graphite, He, In, Li, Mg, Mn, Mo, Nb, Ni, PGE, potash, REE, Sb, Sc, Sn, Ta, Te, Ti, W, U, V, Zn) reflects Canada’s geological potential and is intended to re-focus industry, investors, government policy, and geoscience research to the most important raw materials for the green economy of the future.

New research results from the TGI programme are providing public geoscience data, genetic and exploration models, and methodologies to support mineral exploration in the search for the next generation of critical mineral deposits. Some of these new discoveries will occur within and around established mining districts (e.g. Kamloops, Athabasca Basin, Flin Flon, Sudbury, Abitibi, Bathurst, Labrador Trough); whereas other critical minerals will be sourced from frontier areas across Canada’s north or entirely new deposit types that are at the very earliest stages of exploration and research (e.g. mine waste, oil-field brines, coal ash). Improving discovery rates for new sources of critical minerals will also generate new public geoscience, including prospectivity models that are based on the latest advances in artificial intelligence. Indeed, digital geoscience is one of the core pillars of the renewed TGI programme and has the potential to impact every step of the scientific process. Finally, critical mineral research within the GSC represents only a small fraction of the other supply chain initiatives that are currently underway across the federal, provincial, and territorial governments and in close collaboration with local and indigenous communities and industry. To this end, Canada has announced...
significant new funding to develop and support a Critical Minerals Strategy. Such public solutions are required for securing critical mineral supply chains and addressing the global challenges presented by climate change.

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