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Critical Minerals in the Context of Canada: Concepts, Challenges and Contradictions

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Article abstract

Increased use of renewable energy, coupled with electrification of the economy, is considered important in efforts to limit future climate change. This energy transition is predicted to increase demands for some commodities, many of which are now labelled as critical mineral. The quest for such commodities is now a persistent theme for the resource industry and emerging government policies. This review for non-specialists explains several key concepts but also explores some challenges and apparent contradictions in the context of Canada.

Canada now has a list of 31 critical minerals, but this includes some major commodities for which domestic production is significant and supply risk is low. The differences between our list and those of other jurisdictions reflect our more specific definitions. Most other commodities on Canada's list are also identified by other countries and some are specifically linked to the energy transition. These include cobalt, lithium, manganese, nickel, graphite and vanadium (used in electric vehicle batteries and static energy storage), rare earth elements (REE; used for magnets in EV motors and wind turbines) and some rarer elements (e.g. germanium, gallium, indium and tellurium) used in photovoltaic (solar) energy systems. Some of these are potential primary products (e.g. lithium, graphite and REE) but many others (e.g. cobalt, platinum group elements and the photovoltaic elements) are byproducts from the production of major commodities, notably nickel, copper and zinc. The REE represent coproducts that are closely associated in nature and very hard to separate from each other; they are produced as a group.

There are some specific challenges in exploring for and developing critical mineral resources. The end-use technology driving demand evolves on a timescale of years, but mineral exploration and development now typically take multiple decades. Material substitutions and unpredictable developments in technology complicate the exact prediction of future demands. The forecasts of overall relative demand growth are impressive, but for some key commodities global production will remain small in absolute terms, which may limit the potential for new discoveries. Simple measures of grade and tonnage are not always guarantees of viability, because deposits of some commodities (e.g. the REE) are mineralogically complex. Byproduct commodities cannot be produced in isolation, and many of these are only extracted in smelting and refining. Domestic production of these commodities is effectively lost if concentrates are exported for processing. The emissions and environmental impacts associated with production of critical mineral resources will also become important if such activity is to be linked to wider climate goals. This may present challenges in northern Canada, where renewable or low-carbon energy options are limited. Most draft Land Use Plans in the north presently emphasize large-scale land conservation, which could limit future exploration access before resource potential is fully assessed. Given the strong divisions of opinion about resource development, especially in the north, controversy and polarized debate will not easily be avoided.

There are no simple answers to challenges that are political or jurisdictional rather than technical, but there is definitely a need for more public geoscientific information. This will help to identify areas of greatest potential, evaluate known deposits and contribute to future sustainable development. For many of the commodities on our critical mineral resources list, data for Canada remains incomplete, especially in more remote regions that are generally considered to have the highest potential.

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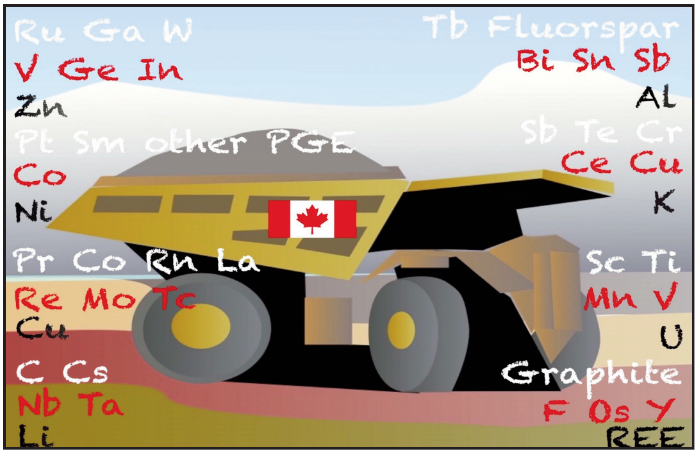

Critical Minerals in the Context of Canada: Concepts, Challenges and Contradictions

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SUMMARY
Increased use of renewable energy, coupled with electrification of the economy, is considered important in efforts to limit future climate change. This quest for such commodities is now a persistent theme for the resource industry and emerging government policies. This review for non-specialists explains several key concepts but also explores some challenges and apparent contradictions in the context of Canada.

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RÉSUMÉ
L'utilisation accrue des énergies renouvelables, associée à l'électrification de l'économie, est considérée comme étant

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essentielle dans les mesures visant à limiter les changements climatiques futurs. Cette transition énergétique devrait accroître la demande de certaines matières premières, dont bon nombre sont maintenant qualifiés de minéraux critiques. La quête de telles matières premières est désormais un thème persistant pour l'industrie des ressources et les politiques gouvernementales émergentes. Cette revue à l'intention des non-spécialistes explique plusieurs concepts clés, mais explore également certains défis et contradictions apparentes dans le contexte du Canada.

Le Canada dispose désormais d'une liste de 31 minéraux critiques, mais celle-ci inclut certaines matières premières majeures pour lesquelles la production nationale est importante et le risque d'approvisionnement est faible. Les différences entre notre liste et celles d'autres juridictions reflètent nos définitions plus spécifiques. La plupart des autres matières premières de la liste du Canada sont également identifiées par d'autres pays et certaines sont spécifiquement liées à la transition énergétique. Il s'agit notamment du cobalt, du lithium, du manganèse, du nickel, du graphite et du vanadium (utilisés dans les batteries de véhicules électriques et le stockage statique de l'énergie), des éléments des terres rares (ETR ; utilisés pour les aimants dans les moteurs de véhicules électriques et les éoliennes) et de certains éléments plus rares (comme le germanium, le gallium, l'indium et le tellure) utilisés dans les systèmes d'énergie photovoltaïque (solaire). Certains d'entre eux sont des produits primaires potentiels (comme le lithium, le graphite et les ETR), mais beaucoup d'autres (comme le cobalt, les éléments du groupe du platine et les éléments photovoltaïques) sont des sous-produits de la production de matières premières majeures, notamment le nickel, le cuivre et le zinc. Les ETR représentent des coproduits étroitement associés dans la nature et très difficiles à séparer les uns des autres; ils sont produits groupés.

L'exploration et le développement de ressources minérales critiques présentent des défis spécifiques. La technologie d'utilisation finale qui stimule la demande évolue sur une échelle de temps de quelques années, mais l'exploration et le développement miniers prennent désormais généralement plusieurs décennies. Les matériaux de substitution et les développements imprévisibles de la technologie compliquent la prévision exacte des demandes futures. Les prévisions de croissance relative globale de la demande sont impressionnantes, mais pour certaines matières premières clés, la production mondiale restera faible en termes absolus, ce qui pourrait limiter le potentiel de nouvelles découvertes. Les mesures simples de teneur et de tonnage ne garantissent pas toujours la viabilité car les gisements de certaines matières premières (comme les ETR) sont minéralogiquement complexes. Les matières premières secondaires ne peuvent pas être produites isolément, et bon nombre d'entre elles ne sont extraites que lors de la fusion et du raffinement. La production nationale de ces matières premières est effectivement perdue si les concentrés sont exportés pour être transformés. Les émissions et les impacts environnementaux associés à la production de ressources minérales critiques deviendront également importants si cette activité doit être liée à des objectifs climatiques plus larges. Cela peut présenter des défis dans le nord du Canada, où les options d'énergie renouvelable ou à faible émission de carbone sont limitées. La plupart des projets de plans d'utilisation des terres dans le Nord mettent actuellement l'accent sur la conservation à grande échelle des terres, ce qui pourrait limiter l'accès à de futures explorations avant que le potentiel en ressources n'y soit pleinement évalué. Étant donné les fortes divergences d'opinion concernant le développement des ressources, en particulier dans le Nord, la controverse et les débats polarisés ne seront pas facilement évités.

Il n'y a pas de réponses simples aux défis qui relèvent davantage de la politique ou de la juridiction que de la technique, mais il est certainement nécessaire de disposer de plus d'informations géoscientifiques publiques. Cela aidera à identifier les domaines à plus grand potentiel, à évaluer les gisements connus, et à contribuer au développement durable futur. Pour bon nombre des matières premières de notre liste de ressources minérales critiques, les données pour le Canada demeurent incomplètes, en particulier dans les régions plus éloignées qui sont généralement considérées comme ayant le potentiel le plus élevé.

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INTRODUCTION

The Context of the Modern Critical Minerals Discussion

The third decade of the 21st century began turbulently, with a disruptive global pandemic followed by disturbing armed conflicts. Disruptions to supply chains from such circumstances, including impacts on mineral resources availability, illustrated the vulnerability of integrated international economies to natural and human influences. The topic of so-called *critical minerals* is one small part of a much wider discussion about energy and resource futures. Critical minerals are in the media on almost a daily basis and addressed by formal documents from the federal government (Government of Canada 2022) and individual provinces (Government of Quebec 2020; Government of Ontario 2022a). These documents emphasize expanded and/or new mineral resource extraction and more efficient utilization of existing resources to meet demands anticipated as part of the so-called *energy transition*. Such needs are predicted by studies that attempt long-range predictions of supply and demand to 2100. The most widely quoted of these 'scoping studies' are by the World Bank (2017, 2020) and the International Energy Agency (IEA) in 2020 and 2022. The IEA released an updated report in July 2023 that analyzes the growth in demand and supply for such commodities. This review article outlines key critical minerals concepts in a general sense and explores present discussions in the context of Canada. It does not include detailed geological treatments of every commodity, although this is certainly needed. It also touches on some wider issues, including challenges and potential contradictions that are not always discussed in scientific papers. It is intended to inform readers who lack specialized knowledge, which include many in the geoscience community. There is no shortage of promotional corporate material related to exploration, and more nuanced policy documents from governments will inevitably be tabled, but widespread media misconceptions underline the need for jargon-free explanatory material. There is also a pressing need for systematic geoscientific information about many of these commodities on a national scale, but this is no small task.

What are Critical Minerals and Why Might They Prove Controversial?

As geoscientists, we know that non-renewable natural resources are a cornerstone of modern industrial society, although this is not always recognized by the public. Simplistic estimates of the annual per-capita usage of key commodities in current decades by the United States Geological Survey (USGS) illustrate this vividly (Fig. 1). If such consumption rates are sustained over human lifetimes, the demand for materials is truly immense. Such guesstimates apply to the USA and other industrialized countries, but most people on Planet Earth consume far less than this. However, the peoples of the world understandably aspire to enjoy living standards akin to those of industrialized countries, so resource usage will only grow, even if global populations stabilize or even diminish.

The concept of critical minerals arose long before this century, but some of its tenets are now altered. The first list of 'war minerals' was compiled by the USA during World War I (Nicholls 2022), and control of strategic resource supplies was certainly critical in World War II, as illustrated by uranium (Zoellner 2011). During the ensuing "Cold War" western nations worried about disruption of strategic resource supplies, so they prioritized such materials and some maintained physical stockpiles. Such policies lapsed for most commodities in the late 20th century, but returned in the early 21st century, in part because of China's increasing dominance in the minerals sector. Critical minerals are now foremost on the agenda of most industrialized countries in the form of 'critical minerals lists' and specific policies to reduce dependence on imports. However, this revival is not universally welcomed, as it amplifies divergence between advocates of resource extraction and those concerned with environmental impacts and land conservation (e.g. Lee et al. 2020; Lèbre et al. 2020; Crawford and Odell 2022). Linking potential new mining developments to global efforts to limit the impacts of climate change is controversial in this context, and some (e.g. Environmental Justice Atlas and MiningWatch Canada n.d.; see also Deniau et al. 2021) contend that it is a distraction from the greater need to reduce material usage and emissions. A recent analysis of media discussion around critical minerals extraction related to electric vehicles (EVs) by Agusdinata and Liu (2023) shows that issues related to environmental and social impacts receive far more coverage than any technical matters. The degree to which media coverage actually reflects the balance of opinion is of course subject to discussion, but there is no denying its potential influence.

The most common questions about critical minerals are as follows. First, what are they and how exactly are they defined? Second, why do the critical minerals lists of various jurisdictions differ in important respects? Third, how reliable are demand forecasts by the World Bank, IEA and other agencies

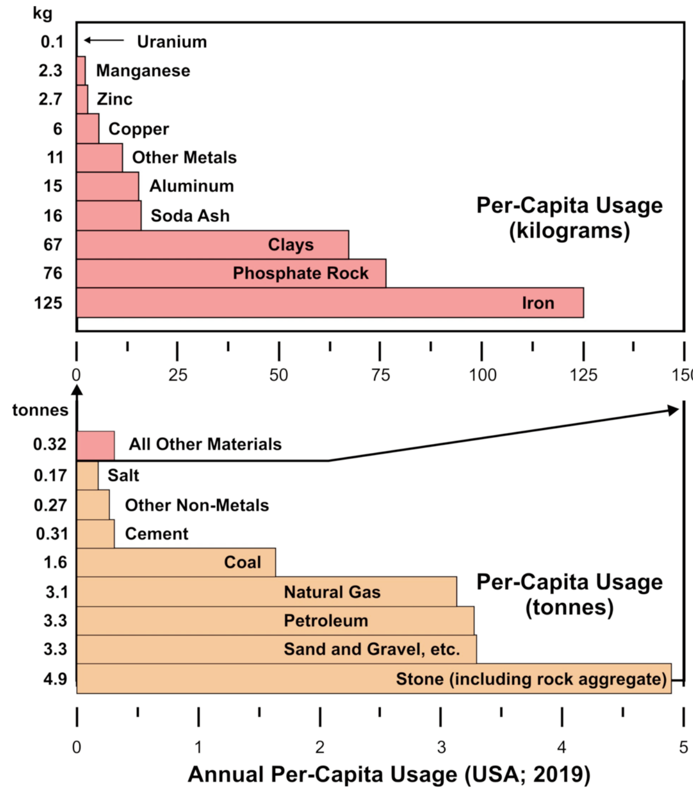

Figure 1. An illustration of per-capita annual resource demands for the United States in the early 21st century, as compiled by the United States Geological Survey in 2019. For the purposes of representation, petroleum products are recalculated into tonnes on the basis of an average density of 0.9 g/cc, and natural gas is converted from cubic feet assuming that a cubic foot weighs 0.15 kg (i.e. about 5 kg/m^3; or 0.005 g/cc). The horizontal scales for the upper and lower parts of the figure are adjusted to represent the wide range of values.

for such commodities? Fourth, are there substitutes for such materials, and could existing sources augmented by recycling instead suffice? A more complex question brings these themes together to ask if the purported criticality of a mineral deposit might justify its more rapid development, and/or setting aside some environmental concerns. Another closely linked question asks if emissions involved in developing and processing such resources discount or negate long-term climate benefits. Some of the commodities involved in this debate are now labelled as "green minerals" or referred to in phrases such as "*mining for clean energy*" (e.g. Clean Energy Canada 2017) or "*climate-smart mining*" (World Bank 2020). To phrase these questions in another way, are such labels truly accurate, or are some commodities being misrepresented or 'greenwashed' by those with a vested interest in their extraction?

Sources of Technical Information about Critical Mineral Resources

In Canada, public geoscientific information is presently incomplete for many commodities now labelled as critical minerals, especially those that lack previous exploration interest. Some entries on Canada's list are familiar major commodities (although the criteria for their inclusion are debatable; see later discussion) but existing resources may not suit new uses, so new technical information is still needed. Canada has a reputation as a resource-rich jurisdiction and a leader in minerals research and exploration financing, but other jurisdictions (e.g. the USA, UK, EU countries and Australia) have to date been more active in gathering, compiling and disseminating technical geoscience information.

A massive compilation of technical information by the USGS (Schulz et al. 2017) provides geological and geochemical data for more than 20 commodities, including information on markets, processing and environmental aspects. These provide useful background information on resources and environments in Canada. The British Geological Survey (BGS) provides excellent reports on multiple commodities with a wider scope, although with some focus on Africa, seen as a prospective region closest to Europe (e.g. Petavratsi et al. 2019; Mitchell and Deady 2021; Goodenough et al. 2021). Geoscience Australia also provides summary information and detailed accounts for specific commodities and more general analyses (e.g. Skirrow et al. 2013; Mudd et al. 2019, Huleatt 2019). Specific commodities in parts of Canada are discussed in reports issued by provincial geoscience agencies (e.g. Kerr et al. 2009, 2013; Simandl et al. 2012) but these lack national context and some are now outdated. The critical minerals strategies tabled by federal and provincial governments contain limited geoscientific data and focus more on the wider economic potential of these commodities, including the development of vertically integrated supply and production chains.

Broad statements that Canada is a *"storehouse of critical minerals"* (or words to that effect) abound in strategy documents and much corporate literature, but supporting data remain limited. Such statements partly reflect a modified definition of criticality adopted by Canada, through which several well-established commodities that we produce are included on our list, as discussed in the next section. A recent CBC news item (Panetta 2021) pointed out that our reserves of other critical mineral resources are actually small on a global scale even if there is perception of untapped wider potential. A more recent newspaper article (The Globe and Mail 2022) stated that *"Canada's ambitions are the right ones, at least on paper. The trick is moving beyond blueprints"*. One of few documents that are easily available on government websites is the report of the House of Commons Standing Committee on Natural Resources (Maloney 2021). An earlier document of this type (Anonymous 2014) is specifically related to rare earth elements (REE). Both include submissions from diverse industry experts, and the lack of technical information emerges as a common theme. These committee reports are not technical geoscience documents, although they contain opinions from geoscientists, but they provide interesting insights into political and ideological viewpoints that will likely influence geoscience research efforts. The Government of Ontario (2022b) provides information on specific commodities in that province, but only at a general level. The Ontario Mining Association (2022) provides more detailed information on production, markets and forecasts, outlining the concerns of industry, but their compilation is not geoscience oriented. The recent paper by Simandl et al. (2021) in *Geoscience Canada* discussed commodities linked specifically to energy applications in more detail, and was a useful source for this paper, but is not specifically Canadian in focus. A more recent summary by Simandl (2023) discusses more specific issues related to Canada's critical minerals list and strategy, and also touches upon some of the themes in this paper.

CRITICAL MINERALS AS VIEWED IN THE 21st CENTURY

Critical Minerals versus Critical Materials or Critical Mineral Resources

The term critical mineral(s) is established but inaccurate because it includes elements, groups of elements, minerals, gases, and other organic raw materials. The minerals that are processed to extract chemical elements, or used directly, are the real topic under discussion and some entries (e.g. helium) have no connection to minerals. Some treatments prefer *critical materials* as a term, but this might be construed to include synthetic substances. Although it is difficult to avoid 'critical mineral' entirely, the more precise definition should be kept in mind, and the term *critical mineral resources* is preferred here. Helium (He) is present on several lists, including Canada's, but this is excluded from discussion here.

Definitions and Modified Definitions

The term critical mineral first appeared following World War II, although the concept is much older. Nicholls (2022) mentions a terse anonymous quote that simply said, *"it's stuff you need that you can't get,"* and this is the essence of the concept. It is applied to mineral resources from geographic areas deemed vulnerable to natural disasters, military conflicts or political upheavals. In other words, mineral resources considered vulnerable to supply risk are deemed as critical. Consideration is also given to another loosely defined parameter termed economic importance (or similar wording) that measures industrial or strategic value. Criticality then becomes a combination of the two measures, such that a critical mineral resource is defined largely by high economic importance and elevated supply risk (e.g. Graedel et al. 2015). Usually, a numerical 'score' is assigned to supply risk and economic importance, as shown in Figure 2 (adapted from Skirrow et al. 2013). The criteria used to derive these scores are only partly quantitative, so some divergence among critical mineral resources lists should be expected, especially where countries also have some domestic production. It is also important to remember that the ranking of a given critical mineral resource is subject to change over time; for example, Figure 2 (which is 10 years old) did not categorize lithium (Li) as critical, but this would not apply today. Supply risk is also defined in different ways; for example, some jurisdictions (such as the USA) use 'single-point-of-failure' exclusions such that even if domestic production is significant, the commodity is considered at risk if the source is unique. The methods and reasoning used in definitions of criticality are discussed in much more detail elsewhere (e.g. Graedel et al. 2015; Simandl et al. 2021), but the key point is that there is no single rigorous definition, and the approaches of various jurisdictions may be inconsistent.

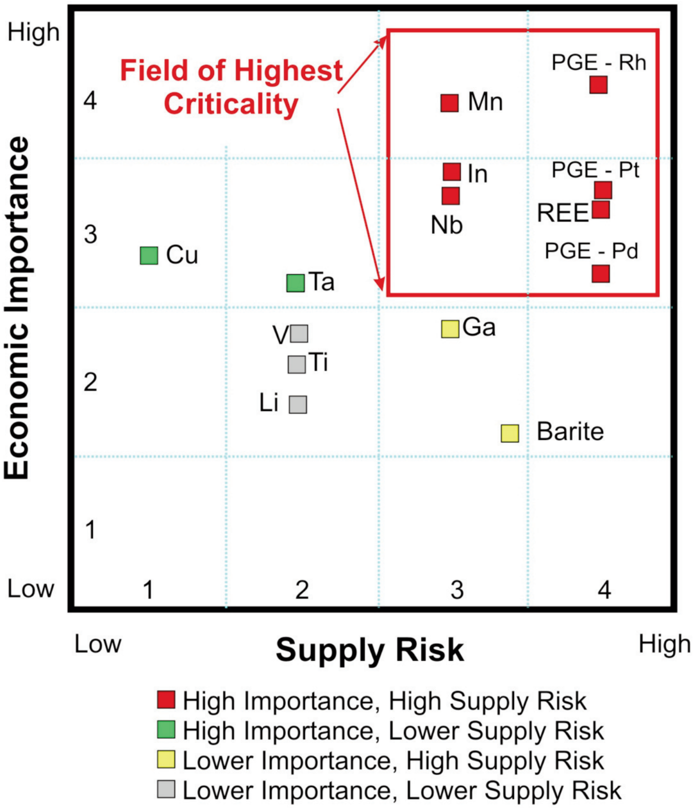

Figure 2. An illustration of how critical minerals are defined in terms of their perceived importance to industry and perceived risks to their supplies. Modified after Skirrow et al. (2013).

Some mineral resources are excluded even though they seem to have obvious relevance to the energy transition. For example, uranium (U) was removed in 2021 from the US critical mineral resources list because it was considered an "energy mineral". This decision proved politically controversial (e.g. Mining Newswire, November 2021). In other cases, mineral resources that lack obvious supply risk are defined as critical, as in the case of Canada's current critical minerals list, as discussed below, and also by Simandl (2023).

Lists and Changing Lists

The critical mineral resources lists maintained by Canada, USA, the EU and Australia are not identical, but they have much in common. They can be visually represented using the periodic table, even though some are not strictly chemical elements (Fig. 3; following Emsbo et al. 2021). Most commodities are found on two or more of these lists, and some are present on virtually all. Figure 3 also illustrates an important facet of Canada's list; it includes several major commodities (aluminium (Al), nickel (Ni), copper (Cu), zinc (Zn), potash (KCl)) and also U, which are generally not listed by the other jurisdictions. The Government of Canada strategy document (2022) tabulates a wider selection of such lists, including Japan, South Korea and the United Kingdom, but these are not incorporated in Figure 3. A patriotic 'Maple Leaf' graphic illustrates our list in strategy documents (Government of Canada 2022). This is included here to highlight differences from lists maintained by the USA, EU and Australia (Fig. 4a). As noted above, Canada's list includes some commodities that do not have obvious supply risk in our context. Nickel was added to the USA list at the same time as U was dropped. Canada was the world's largest source of potash and its second-largest source of U in 2022. Our production of copper, nickel and zinc is also significant over many decades, although our world share has declined. In 2022 we ranked sixth for Ni, eleventh for Zn and twelfth for Cu. We also produce many other commodities on our list, such as cobalt (Co), titanium (Ti), molybdenum (Mo), niobium (Nb) and platinum group elements (PGE). Canada does not mine any ores of Al, as raw materials (bauxite) are all imported, but aluminum production is important economically in Quebec and British Columbia. Simandl (2023) also pointed out that several entries on Canada's critical mineral resources list are not obviously subject to supply risks. This contrast between Canada's list and those of others reflects slightly different definitions of criticality. The Government of Canada (2022) also includes commodities that are *"....a sustainable source of highly strategic critical minerals for our partners and allies...."*.

Simandl et al. (2021) discussed this issue in general terms and suggested that it reflects the desire to promote domestic production and exports. Simandl (2023) provided additional discussion in a Canadian context and suggested that some commodities are included on the basis of their importance to the economies of provinces and territories, rather than according to supply risk. Among the commodities that contribute most of the more than $40 billion value of mineral production in Canada in 2021 (Natural Resources Canada 2022; excluding coal, iron ore and construction materials) only gold and diamonds are actually excluded from the critical mineral resources list. On the basis of the current list, close to one third of the total value of Canada's mineral production is represented by critical mineral resources.

The differences between our list and those of others illustrate the influence that the precise definition of criticality has upon which commodities are included on such lists. Although our inclusion of some major commodities is fully consistent with the reasoning employed, it could cause some complications. First, when references are made to total Canadian reserves and resources, these include (and are in fact dominated by) such commodities. Second, if the development of critical mineral resources is to be prioritized or financially encouraged in some way, proposals involving these commodities could be challenged by opponents of development, because they do not have obvious supply risk and are not classed as critical by others. Proposals to develop uranium deposits would probably be the most likely to awaken controversy on this basis, based on numerous historical precedents. Presently, only Canada and South Africa include uranium as a critical mineral.

However, it is important to note that commodities that lack obvious supply risk may indeed be important in the context of the energy transition (e.g. Cu, Ni and perhaps U), in efforts to reduce emissions (e.g. Zn) or for global food production (e.g. potash). Aluminum plays a vital role across all industries, including energy technology. Copper is important because

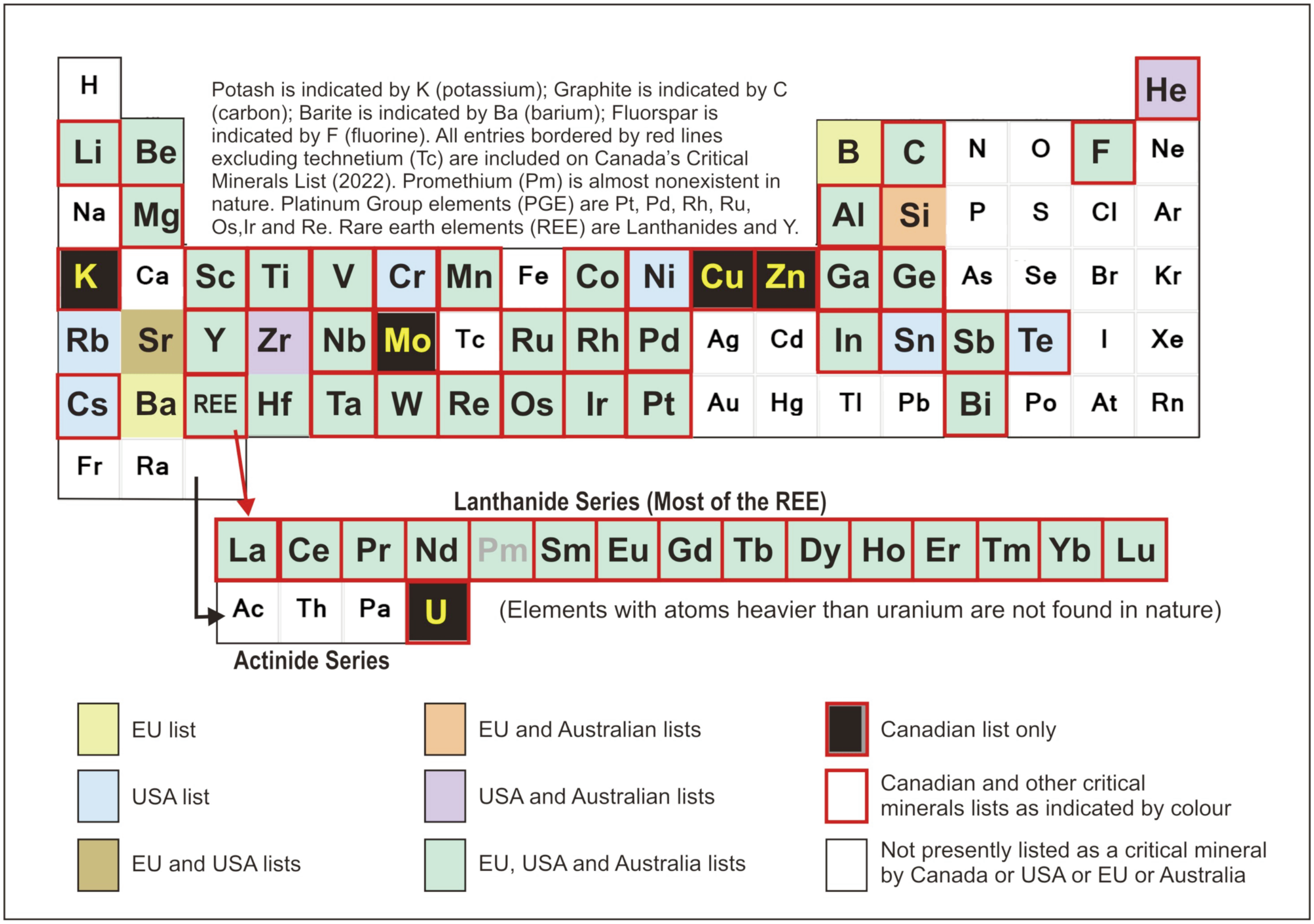

Figure 3. The periodic table of the elements, showing the critical minerals defined by four jurisdictions (USA, Canada, European Union and Australia) using a colour-coding system. Potash is illustrated using potassium (K), fluorspar is illustrated by fluorine (F) and graphite is illustrated by carbon (C). Elements denoted in negative format (black fill and yellow letters) are those categorized as critical by Canada, but not by most other jurisdictions. Modified after a similar diagram by Emsbo et al. (2021). Note that the critical minerals lists do change with time.

renewable energy generation requires much greater transmission capacity. Nickel and Zn also have existing and potential roles in energy technology, although this is not their most important usage.

Most other entries on Canada's critical mineral resources list (Figs. 3, 4a) have geographically restricted sources, although we do produce some. The supply risk for many has increased since 2000, and China now dominates some, to the extent of controlling most supply and downstream processing. This is most extreme for the rare earth elements (REE) but it applies to other commodities, such as antimony (Sb), graphite and tungsten (W). Whenever a single entity – be it a nation or a corporation – controls most sources and most availability, it effectively controls pricing, so this is part of the supply risk assessment. This aspect is downplayed in many critical minerals strategies (for example, Canada's document refers to "non-like-minded countries" and avoids any identification) but concern is more overt in documents that have a political context (e.g. Anonymous 2014; Maloney 2021) and in equivalent analyses from the USA (e.g. Humphries 2019). Russia's important reserves of some critical mineral resources (e.g. PGE, vanadium (V) and potash) are undoubtedly of more recent concern. As geoscientists, we naturally prefer to focus on technical information, but there are definite nationalistic and competitive dimensions to the current interest in critical mineral resources.

Groupings of Critical Minerals and their Importance

Canada's present list of 31 critical mineral resources (Figs. 3, 4) is also summarized in Table 1. Note that it includes two groups, REE and PGE, that comprise multiple chemical elements. The individual elements in each of these groups are not all critical in their own right, but rather occur together in nature, and may be difficult to separate.

The REE include 15 individual elements, comprising the lanthanide series (La to Lu in the periodic table; Fig. 3) and the chemically similar element yttrium (Y). Scandium (Sc) is also commonly grouped with the REE, although there is no geochemical basis for this. The PGE include iridium (Ir), platinum (Pt), palladium (Pd), osmium (Os), rhenium (Re), rhodium

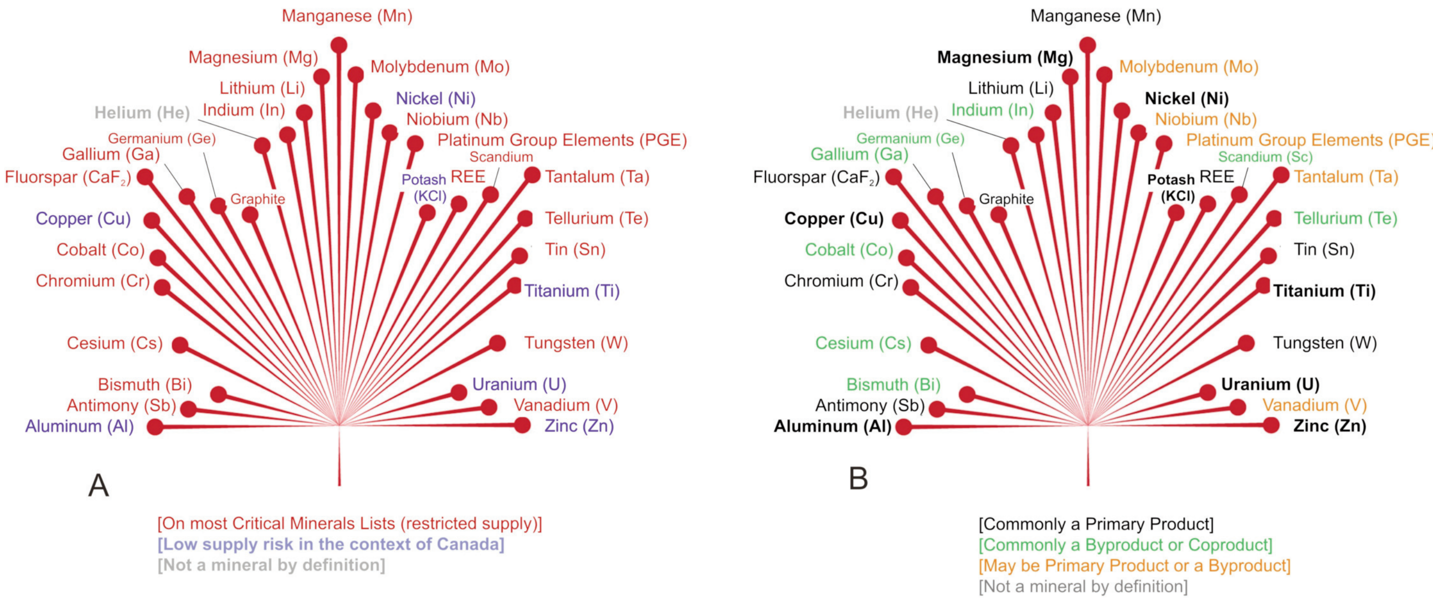

Figure 4. Canada's present list of critical minerals in graphical form, structured to provide the outline of a maple leaf, as in our flag, modified after Government of Canada (2022); (A) colour-coded version to highlight commodities for which Canada's definition of critical also includes factors other than supply risk; see text for discussion. (B) A colour-coded version to highlight primary products versus byproducts and coproducts. Note that the REE are mutual coproducts, but commonly are mined as a collective primary product.

(Rh), and ruthenium (Ru). The elements within the REE and PGE groups each exhibit similar geochemical behaviour and each element group occurs in distinct geological settings. The affinities between individual PGE are looser than those between individual REE; for example, it is possible to identify Pd-rich deposits that contain little Pt, or vice versa. In contrast, REE deposits dominated by only a single individual element simply do not exist. REE with lower atomic numbers ('light REE') are more abundant in absolute terms than those with higher atomic numbers ('heavy REE'). Note that the conventional scientific method of graphically representing REE patterns, by normalizing data to chondritic meteorite data, does not actually represent absolute abundances; the heavy REE are much rarer than the light REE. Weng et al. (2015), Goodenough et al. (2018) and Jowitt (2022) provided additional discussion around "REE Balance". The REE are effectively coproducts, at least at the mining and processing stages of supply chains, and this also generally (but not always) applies to the PGE.

Several commodities on Canada's list are important transition metals associated with the steel industry, such as Mo, V, W, chromium (Cr), and manganese (Mn). Chromium and Mn are major commodities based on their large annual global production, but Canada is presently dependent on imports. Other transition metals on Canada's list include Co, Nb, bismuth (Bi), and tantalum (Ta). Some of these (notably Co, Mn, Ta and V) have important applications in energy technology, as discussed below. Lithium and cesium (Cs) are alkali metals (Group 1 in the periodic table; Fig. 3) but have rather different geochemical properties and natural abundances. Lithium is especially important in modern battery technology (see later discussion).

Critical Mineral Resources and the Energy Transition

Current discussion about critical mineral resources focuses on materials that have roles in renewable energy (e.g. solar power, wind power and other innovations) and energy storage technology (i.e. batteries). Most industrialized countries now have policies to decarbonize transportation within the coming decades. Electric vehicles (EVs) need efficient motors and lightweight batteries with high energy densities, i.e. able to function for long periods before recharge. Wind power needs lightweight and efficient generators, which have much in common with EV motors. Photovoltaic technology (i.e. direct conversion of solar radiation to electricity) is moving from relatively inefficient silicon-based panels to so-called 'thin film' technology that is more efficient. Research in the energy sector is especially active and dynamic (see Simandl et al. 2021, 2023 for more details; also, Goodenough et al. 2018; Gunn and Petavratsi 2018; Bloodworth 2019; McNulty and Jowitt 2021). The treatment here is confined to a brief overview of essentials.

Important battery minerals include Co, graphite (a mineral formed of elemental carbon), Li, Mn, Ni and V. Although Ni is on Canada's list and is used in batteries, its main applications are in other sectors, such as steel. This is also true for Mn, which has many uses. Some of the REE (notably La, Ce and Y) and also lead (Pb) and cadmium (Cd) have battery sector applications, but the latter two elements are omitted from Canada's present list. Future V demand growth is projected if vanadium-redox batteries (VRBs) are extensively deployed (e.g. Simandl and Paradis 2022). Many other storage battery systems are in research stages, so the final shape of this sector is very hard to predict (Simandl et al. 2021, 2023). The greatest pres-

Table 1. Listing of critical minerals presently identified by Canada, with brief comments on their attributes.

Material	Symbol	Comments
Aluminum	Al	Important major commodity, but not mined in Canada. Produced from imported bauxite ores processed in QC and BC.
Antimony	Sb	Now supplied from China, but deposits in NB and NL have produced; resources remain in NL. Also associated with gold or base-metals veins, but generally at low grades. A pathfinder for gold.
Bismuth	Bi	Byproduct from some base-metal and gold deposits. Future production from NWT (NICO deposit) possible. Subeconomic deposits in NB associated with W, Mo and In (Mount Pleasant)
Cesium	Cs	Byproduct typically associated with Li- and Ta-Nb-bearing pegmatites. Produced in small amounts from Tanco, MB; largely used to make Cs-formate brines, but has other uses.
Chromium	Cr	Major commodity, typically found in layered mafic intrusions. Large undeveloped deposit (Black Thor) in the "Ring of Fire" area, northern ON. Smaller deposits associated with ophiolite suites (BC, QC, NL)
Cobalt	Co	Byproduct from some Ni-Cu sulphide deposits, but major global source is from Cu deposits in central Africa. Produced from several deposits in Canada, and associated with many undeveloped deposits.
Copper	Cu	Important major commodity mined from porphyry deposits (BC), in some cases with byproduct Mo. Also obtained from Ni-Cu sulphide deposits and VMS deposits all across Canada.
Fluorspar	CaF_2	Industrial mineral used in steel/chemical sectors. Mined in NL since the 1930s, Other Canadian deposits are minor, with limited past production. Usually in vein-type settings related to granite.
Gallium	Ga	Rare trace element, byproduct from smelting of some zinc ores, but also enriched in bauxite (aluminum) ores, although not easily extracted from these. Important photovoltaic applications.
Germanium	Ge	Rare trace metal element, byproduct from smelting of some zinc ores. Currently extracted at smelters in Canada and elsewhere. Semiconductor important in computer technology.
Graphite	C	Soft form of elemental carbon, in massive or microcrystalline form, usually found in metamorphic terranes. Supply dominated by China and Africa, but several deposits exist in QC and ON.
Helium	He	Inert gas extracted from hydrocarbons. Not a true mineral by definition, and absent from natural minerals. Not discussed in this article.
Indium	In	Rare trace element, byproduct from smelting of some zinc ores. Canada is an important producer. Associated with Cd and Ge, locally with Ga. Possible byproduct from Mt Pleasant deposit in NB
Lithium	Li	Critical in battery sector. Obtained from pegmatite deposits and salar brines in South America. Li-rich pegmatites are well-known in the Canadian Shield. Some production from Tanco (MB).
Magnesium	Mg	Not currently produced in Canada. Previous production from carbonate deposits in BC. Increasing usage in low-density alloys, with Al, other metals. Deposits in BC are being re-evaluated.
Manganese	Mn	Former byproduct from discrete zones in iron-ore deposits (QC, NL). Potentially large sedimentary Mn deposits known in NB and Maine (USA). Present supply is mostly from southern Africa.
Molybdenum	Mo	Byproduct from porphyry copper deposits (BC), but locally the primary commodity. Smaller granite-related deposits are known in NB and NL. Locally associated with U deposits.
Nickel	Ni	Important major commodity mined from Ni-Cu sulphide deposits in Canada, notably Thompson, Sudbury, Raglan and Voiseys Bay. Important for byproduct Co or PGE production from some.
Niobium	Nb	World supply largely from Brazil (90%), followed by Canada (10%). Associated with carbonatite in QC, but found locally in pegmatites (with Ta) and in various REE deposits.
*Platinum Group Elements	PGE	Trace elements associated with Ni-Cu sulphide deposits in Canada (Thompson, Sudbury, Raglan). Generally byproducts, but can also be a primary commodity, with byproduct Cu and Ni.
Potash	KCl	Industrial mineral used in fertilizers and chemicals. Canada is the world's largest producer, dominated by several mines in SK. Lesser intermittent production from southern NB.
*Rare Earth Elements	REE	Trace elements, associated with primary deposits in unusual granite and carbonatite bodies in Canada, but with diverse associations worldwide. Canada has significant resources, but limited production.
Scandium	Sc	Extraction and use limited by extreme rarity of deposits, but could have wide application in alloys. Byproduct from some REE mining in China, and recently from Ti deposits in QC.
Tantalum	Ta	Trace element associated with Nb in carbonatite and with Li, Cs in rare pegmatites. Previously mined in Tanco, MB. Important in electronics; varied supply includes aritisanal mining in Africa.
Tellurium	Te	Rare trace element, byproduct from smelting of zinc ores or refining of copper; also found as a byproduct in some Au-Ag deposits.
Tin	Sn	One of the very first critical minerals in the Bronze Age. Associated with hydrothermal deposits in high-level granite bodies. Low-grade deposits in NS and NB, locally enriched in VMS deposits.
Titanium	Ti	Important commodity produced from deposits in QC with very large ilmenite resources. Metallurgically suitable Ti deposits may yield byproduct vanadium, some are also enriched in Sc.
Tungsten	W	Similar geological habitat to tin, but also forms large skarn deposits, previously mined in YT/NWT area. Deposits known in NL and NB, including high-grade veins and large disseminated deposits.
Uranium	U	Energy mineral produced in Canada from several deposits in SK. Canada was once world's largest producer but now ranks sixth. Potential resources in NWT, NU and NL.
Vanadium	V	Generally a byproduct from steel industry or iron-ore mining, also extracted from heavy oil and coal ash. Primary deposits are associated with mafic intrusions, with resources in QC and ON.
Zinc	Zn	Major commodity mined across Canada, from sedimentary- and volcanic-hosted sulphide deposits. Increased usage in galvanization anticipated. Potentially important for byproduct Ga, Ge, In.

NOTES: Some entries (e.g., Al, Cu, potash, Ni, U and Zn) are generally not identified as "critical" by other jurisdictions, and Canadian production for these is significant, although raw material sources may be elsewhere, as for Al. Canada also produces cobalt, molybdenum, niobium, Platinum-Group Elements (PGE), titanium, indium, fluorite, germanium and REE, although for some of these production is minimal. Aside from niobium, fluorite, titanium and REE, Canadian production of these minor commodities is as byproducts.

* A group of related and chemically similar elements. PGE group includes Ru, Rh, Pd, Re, Os, Ir and Pt (ascending atomic number). REE group includes Y, La, Ce, Pr, Nd. Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu (ascending atomic number), and may include the unrelated element Sc (atomic number 21) in some discussions. See Figure 3 for periodic table information.

ent exploration interest is for Li, graphite and Co. There are numerous combinations of these (and other) materials used in electrodes, electrolytes and other battery components (see Bloodworth 2019 and Simandl et al. 2021). Although their performance varies, these recipes all fulfil the basic functional requirements, so there is wide scope for substitution in these applications if a given material is unavailable or prohibitively expensive.

Magnet materials contribute to high-strength, lightweight permanent magnets needed for wind turbines and many EV motors. However, not all EV motor designs require permanent magnets, although these offer performance advantages (Goodenough et al. 2018; Simandl et al. 2021). Interestingly, the German manufacturer BMW recently stated that their next generation of electric vehicles will be powered by motors that do not require REE (Banner 2022). There is considerable flexibility in proportions of component materials, as in the battery sector. The REE are very important, because the addition of REE to alloys (also involving iron, boron, cobalt and other elements) increases field intensity with minimal density increase. Neodymium, praseodymium (Pr), samarium (Sm), dysprosium (Dy) and terbium (Tb) are the most important and valuable of the REE, but others also have utility. The choice depends to some extent on the application and the operating environment. Simandl et al. (2021) provided a useful account of existing and potential magnet types and the wide variety of material requirements that might be anticipated from their use but cannot be accurately predicted.

Photovoltaic materials are those connected to direct solar power generation. Large-scale implementation of solar energy (of any type) also demands energy storage capacity (i.e. batteries) and extensive transmission networks. Thin-film photovoltaic systems are more efficient than silicon-based equivalents, but some have yet to demonstrate commercial feasibility. These involve several metals and semi-metals including Cd, gallium (Ga), germanium (Ge), indium (In) and tellurium (Te). Other elements, such as Mo and tin (Sn) may also have important future roles (e.g. Simandl et al. 2021, 2023). With the exception of Cd, all are listed as critical by Canada and other jurisdictions (Fig. 3; Table 1). All these commodities, with the local exception of Mo and Sn, are mined as byproducts or coproducts, most typically from zinc or copper deposits. They are recovered during smelting and refining operations, rather than being separated at sources. The byproduct status of these materials (and many others) adds significant complications in assessing possible sources, and for any efforts to increase production and recovery (see later discussion).

Primary Products, Coproducts and Byproducts

Only a few of the materials on Canada's critical minerals list are primary products from existing mining operations, and these are mostly the major commodities that lack obvious supply risk. Table 2 summarizes important relationships between byproducts and associated primary products. Figure 4b shows Canada's list in 'maple leaf' format and indicates primary products, byproducts and also a few entries that can come in either form. A visual representation of some of the links between commodities is provided in Figure 5, modified and simplified from the more comprehensive original by Mudd et al. (2019).

Some product–byproduct links are well known. For example, Mo is generally produced from large (porphyry-type) copper deposits although it may locally be the primary product in Mo-rich subtypes. As discussed earlier, the entire REE group are coproducts; they will commonly all occur in a single mineral or in a small selection of minerals. The PGE are mostly associated with magmatic Ni-Cu sulphide deposits (like Sudbury, Ontario) and extraction is usually dependent on Ni and (or) Cu production. But this is not always the case; in some instances PGE are the primary commodity, with Ni and Cu as byproducts. This is the case for the world's largest PGE producer, the deposits of the Bushveld Intrusion in South Africa.

Several important elements are linked to Cu and Zn, including many of those used in photovoltaic technology (Ga, Ge, In, Te and Cd). Cobalt was mined historically as a primary commodity in Ontario but is today largely a byproduct from Ni-Cu sulphide deposits (many areas worldwide) or sedimentary-hosted copper deposits in central Africa. These are all cases where a critical mineral resource is linked to another commodity that may have a different demand profile. Increasing the availability of Ga (which is enriched in some ores of aluminum) by processing more bauxite is obviously not feasible unless demand for aluminum grows hugely, but developing Ga recovery from existing operations may be. However, predictions of increased demand for Ni and possibly Zn (see later discussion) may be a route to increasing supplies of Co and the photovoltaic elements.

Niobium, Ta and Cs are all linked to pegmatites, which are late-stage segregations of fluid-enriched granitoid magmas, and this is also a noted geological environment for Li, which is generally a primary product in hard-rock mining. However, a large part of the global Li supply comes from brine extraction, notably in South America. Niobium and Ta are also enriched in many carbonatite bodies, and these represent the most important sources of present Nb supply (Simandl et al. 2018). Canada is the second largest global producer of Nb, but pales in comparison to Brazil, which accounts for nearly 90% of supply (Simandl et al. 2018; USGS sources).

In summary, if we exclude the major commodities included on Canada's critical mineral resources list (Al, Cu, Ni, Zn, potash) and also U, only a few other entries are likely to be primary products (Fig. 4). These are Cr, Li, graphite and fluorspar, although Mo and Nb may possibly have this status. Manganese is in some cases the primary product from Mn-enriched zones in larger iron ore deposits, but Mn extraction would not generally be viable without the infrastructure related to iron ore. The byproduct or coproduct status of many critical mineral resources holds significant implications for their exploration and development.

CHALLENGES IN EXPLORING FOR AND DEVELOPING NEW CRITICAL MINERAL RESOURCES

General Information

Strategies related to critical mineral resources from the Government of Canada (2022) and other jurisdictions all discuss

Table 2. Primary products, byproducts and coproducts as applied to Canada's critical minerals list. See also Figure 5 for visual representation of these relationships.

Primary Commodity	Commonly Associated Commodities	Less Commonly Associated Commodities	Comments and Qualifications
Copper (Cu)	Molybdenum (Mo) Tellurium (Te) Rhenium (Re) Gold (Au)	Cobalt (Co) Zinc (Zn) Selenium (Se) Silver (Ag)	Mo, Re, Te and Au are commonly (but not always) associated with porphyry-type settings, but may not be recoverable. Cobalt is found largely in sedimentary Cu deposits (Africa).
Nickel (Ni)	Cobalt (Co)	Platinum (Pt) Palladium (Pd) Other PGE (Ru, Rh, Ir, Os)	Cobalt is generally associated with deposits that also show Cu enrichment. Pt is more abundant in Ni-rich varieties compared to Pd but some deposits essentially lack PGE.
Zinc (Zn)	Cadmium (Cd) Indium (In) Germanium (Ge)	Tin (Sn) Gallium (Ga) Selenium (Se) Telluriun (Te)	Zn-rich sulphide deposits carry a wide variety of associated minor elements but their occurrence is hard to predict.
Lead (Pb)	Bismuth (Bi) Antimony (Sb)	Tellurium (Te) Fluorite (CaF_2)	Other base metals, e.g. Zn and Cu also occur sporadically in Pb-rich veins.
Iron (Fe)	Manganese (Mn) Vanadium (V)	Scandium (Sc)	Vanadium only found in iron-ores of igneous origin; Mn-rich zones are typically discrete.
Gold (Au)	Various base-metals (notably Cu)	Silver (Ag) Tellurium (Te) Arsenic (As) Antimony (Sb)	Byproducts are rarely recovered from Au deposits, aside from Ag, as their processing prioritizes Au recovery and byproducts add little value.
Aluminum (Al)	Gallium (Ga)	Vanadium (V)	Byproduct recovery is rare (and difficult).
Rare Earth Elements (REE)	Zirconium (Zr) Niobium (Nb) Thorium (Th)	Beryllium (Be) Uranium (U)	Byproducts may be difficult to recover without affecting REE recovery. Some elements (U, Th) are problematic.
Lithium	Tantalum (Ta) Niobium (Nb)	Cesium (Cs) Rubidium (Rb)	Spatial associations of Ta, Nb and Cs are commonly hard to predict in pegmatites.

exploration to define new resources. Northern regions are emphasized, because resource development has long been seen as a route to economic growth (e.g. Sherlock et al. 2003). Broader mineral strategies for Nunavut and the Northwest Territories (NWT) stress the economic impacts of mineral production and the need to maximize benefits from development (Government of Nunavut 2007; Government of Northwest Territories 2014). Government geoscience programs such as the *Targeted Geoscience Initiative and Geo-mapping for Energy and Minerals* by the Geological Survey of Canada provide mapping and other information, to complement work by provincial and territorial agencies. However, despite this widespread support from government and industry, opinions on mining developments in the North remain polarized. Strong voices advocate instead for a strategy of large-scale land conservation, reflected in draft land use plans, notably in the case of Nunavut (Nunavut Planning Commission 2021) and the NWT (Government of Northwest Territories 2022). Northern Canada is known as prospective for world-class gold, base metal and iron ore deposits but the information base for critical mineral resources remains incomplete. There are also wider challenges to the exploration and development of such resources, even in areas with better infrastructure or more plentiful geoscience data. Parts of the following discussion amplify points made previously by Goodenough et al. (2018) and Simandl et al. (2021, 2023) for the REE and other energy-related commodities, but the general considerations apply to all critical mineral resources, with the exception of some major commodities included on Canada's list.

The Timescales of Innovation and Resource Development

Critical minerals are widely labelled as "*vital resources for modern technology*", or words to this effect. Predictive studies (e.g. World

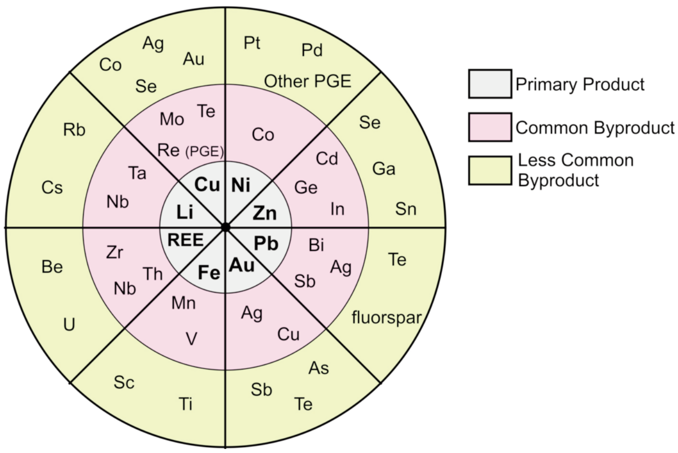

Figure 5. An illustration of the relationships between selected primary products or product groups (Cu, Zn, Ni, Pb, Fe, REE and Li) and the associated byproducts or coproducts, which include also some elements not presently ranked as critical. See also Table 2, as not all relationships can be indicated in this manner. Simplified from a more comprehensive graphic presented by Mudd et al. (2019).

Bank 2020; International Energy Agency 2022) build a persuasive narrative of unique attributes, immediate needs and strong growth potential. However, this view does not always consider order-of-magnitude contrasts in the timescales of technical innovation and resource development.

As anyone beyond middle age knows, the pace of technological innovation is fast and bewildering. Such changes can rapidly impact demands for commodities or change future expectations. Successful material substitutions can suddenly downgrade the importance of a given commodity, and research may create new demands for another commodity that may be hard to obtain. However, not all substitutions or innovations prove commercially feasible, so such changes are unpredictable. The timescale of technological innovation is typically measured in years, but the timescale for development of any mineral deposit (not including the preceding exploration effort) typically involves decades. It took only 5 years to advance Voisey's Bay (Labrador) from a gossan to a world-class Ni-Cu-Co discovery, but twice as long to finally break ground at the site (Goldie 2005). Most industry analysts would class Voisey's Bay as a rapid success in the context of northern development. Other discoveries took longer to develop, and some never completed their journey. The Kiggavik uranium deposit in Nunavut was first discovered over 30 years ago (Fuchs and Hilger 1989) but remains undeveloped following recent regulatory decisions. Development of Windy Craggy, a world-class volcanogenic Cu-Co-Ag-Au deposit in a remote area of British Columbia, was halted in 1993 following establishment of a provincial wilderness park. The present status of cobalt as a critical mineral has led to calls for this decision to be revisited (e.g. Downing and Van Nieuwenhuyse 2020) but there are few precedents for this.

This contrast in timescales has important implications. Established companies are hesitant to engage in any sudden exploration rush for materials that may have unpredictable futures. Those with greater capacity to apply expertise and knowledge may understandably conclude that it is better to let others take those risks. There is no obvious solution to this disconnect between timescales. Geoscience data that aid in exploration will help, but most research emphasis remains towards more familiar base metals and gold. The interval between research and the availability of integrated data is also often several years, which adds to the timescale contrasts. Industry groups advocate for simpler permitting and assessment procedures that could fast-track development (see Maloney et al. 2021 for many examples). Recent critical mineral resources strategies (e.g. Government of Canada 2022) make reference to this problem, and the wider idea of 'one project, one assessment' but this is not easily achieved when there are multiple stakeholders, each with defined rights. Such fast-tracking initiatives are seen in a different light by groups focused on large-scale land conservation, which is a prominent theme in draft land use plans for northern regions (e.g. Nunavut Planning Commission 2021; Government of Northwest Territories 2022). Land claims agreements with Indigenous peoples across Canada include strong provisions for consultation and environmental assessment. These principles are also strongly emphasized in critical mineral resources strategies (e.g. Government of Canada 2022), so there is presently some inconsistency in this area. It is unlikely that opposition to mining developments, and associated delays, will evaporate simply because a commodity is now labelled as 'critical'.

The Constraints of Small Markets

Huge amounts of raw materials are extracted every year to support industrial society, but most of this represents a small group of major commodities. We might think that we are well into the Space Age, but the Iron Age is alive and well. Figure 6, based on a graphic used by Bloodworth (2019) with updated data from Simandl et al. (2021) and USGS sources, illustrates the gross global annual 'balance of production', excluding energy minerals and construction materials.

Resource extraction is massively dominated by iron ore (~84%) followed distantly by phosphate (~8%) extracted for fertilizers (Fig. 6a). Among major commodities, Al, potash, Cr, Cu, Mn and Zn collectively amount to just over 7% of annual global extraction, or about 200 million tonnes. All other commodities, including most designated as critical mineral resources, add up to only 1.2%, or around 35 million tonnes (Fig. 6a). Figure 6b and 6c illustrate the total production of most of these in 2020, but the total amounts of some (e.g. Ta, In, PGE, Ga, Ge, and Sc) still cannot be shown on such a scale. Excluding the major commodities that lack significant supply risk (as discussed above) most of the entries on Canada's critical mineral resources list have global annual production below 1 million tonnes, and many qualify as 'specialty materials' (less than 0.25 Mt annually; Simandl et al. 2021, 2023).

The small absolute production of some well-known commodities (e.g. gold, and also PGE), is offset by extremely high unit prices, but other small-volume commodities do not benefit to the same extent. It is very difficult to constrain prices for minor commodities, as these reflect longer term supply contracts rather than spot prices on metal exchanges and are more

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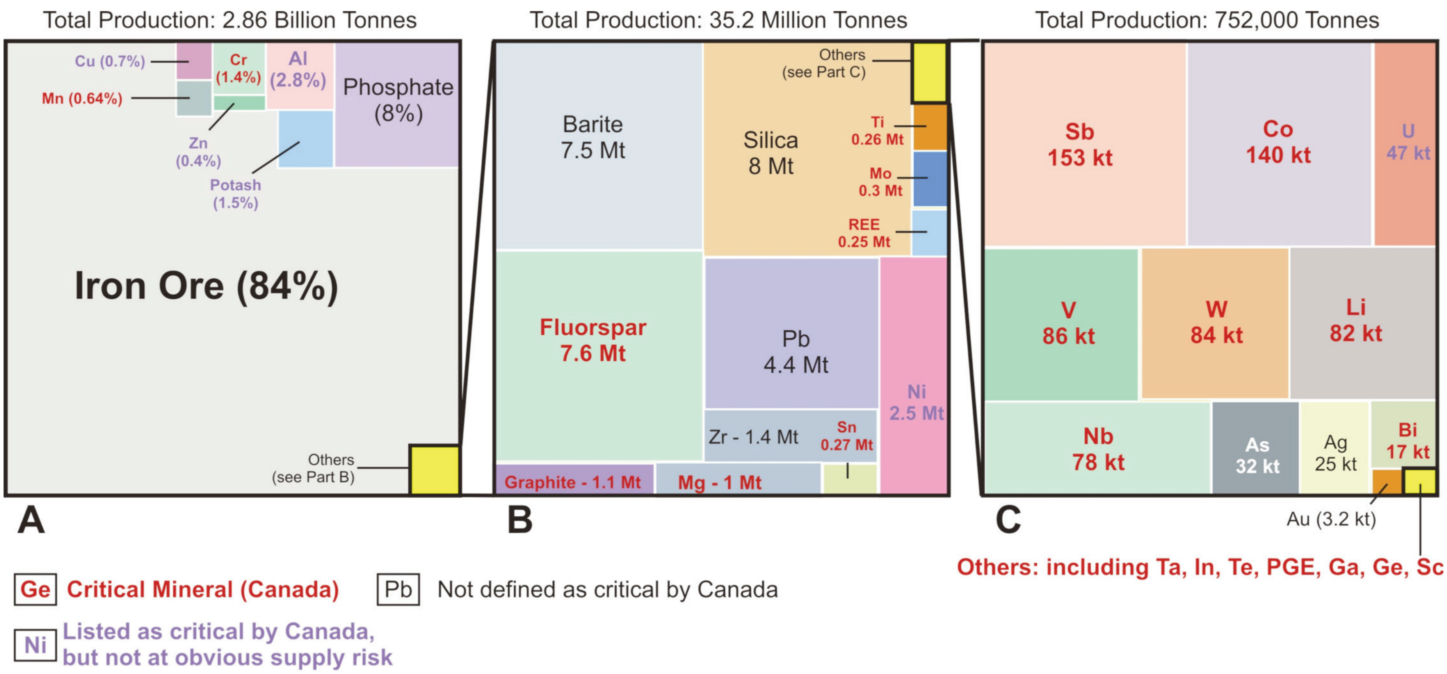

Figure 6. An illustration of global mineral resource production, based on a similar graphic used by Bloodworth (2019), with data from Simandl et al. (2021) and recent USGS sources for the same period. (A) major commodities, with global annual production greater than 12 million tonnes (Mt) (B) commodities with global annual production between 0.25 Mt and 12 Mt, including some classed as critical minerals; (C) commodities with global annual production less than 0.25 Mt, which includes many entries on critical minerals lists.

volatile on short time scales. A plot of production versus price estimates (Fig. 7a; data from Simandl et al. 2021 and USGS sources) shows that these are negatively correlated but also reveals considerable scatter. Crude estimates of total market values are better appreciated from Figure 7b, which shows them in order of increasing market size (i.e. value). This is a very crude method of assessment, but it shows that the total production values of most critical mineral resources are orders of magnitude less than those of major commodities. The difficulty of assigning price estimates lends considerable uncertainty to this, and different assumptions would likely alter the ranking, but would have little impact on the orders-of-magnitude differences. Similarly, large proportional increases in the production of minor commodities cannot erase such differences. Simandl et al. (2021) and Simandl (2023) also emphasized this point, and concluded that economies of scale, which favour larger low-grade deposits with lower per-unit production costs, generally will not apply. Simply defining a large resource at an attractive grade cannot guarantee its development, as any large-scale production would depress prices. Developing smaller deposits is hampered by the higher ratio of capital costs compared to total asset value, which increases the unit cost of long-term production. Increased output from already active deposits will generally be a more attractive option, especially given the time and effort needed to negotiate permitting and development. Simandl et al. (2021) discussed specific examples and concluded that incentives or subsidies may be important for successful development. These conclusions seem to be well founded, although they may not always apply where deposits have truly exceptional features. Critical mineral resources strategies (e.g. Government of Canada 2022) do indeed make reference to incentives aimed at encouraging development of domestic deposits or more efficient extraction of desired commodities.

Absolute and Proportional Measures of Demand Growth

Analyses of future demand for critical minerals (World Bank 2020; International Energy Agency 2022) emphasize percentage growth over absolute quantities. This makes data easier to comprehend but can also lead to misunderstanding. The World Bank (2020) predicts that requirements for graphite, Li and Co could quadruple by 2050, and those for other critical minerals (e.g. In, V and REE) could double by then. There are noted uncertainties in such forecasts, related largely to the scale and type of renewable energy infrastructure. But even if results exceed assumptions, the annual global production of many materials will remain small in absolute terms, and their market values may not grow proportionally if prices decline. An additional complication is that some forecasts of proportional demand growth express increased use of a commodity in the energy sector, rather than increased use across all sectors. For example, if demand for something from the energy sector is predicted to double, this does not necessarily mean that the total demand will double, because most commodities have other important end uses. This distinction is not always expressed clearly in graphs and tables.

Simandl et al. (2021) suggested that for new discoveries only those with the highest grades and lowest production costs will succeed in the long run. This is exactly what every explorationist wants to find, but also the least likely outcome for most exploration projects. Even if tonnage–grade statistics seem ideal, some other challenges remain.

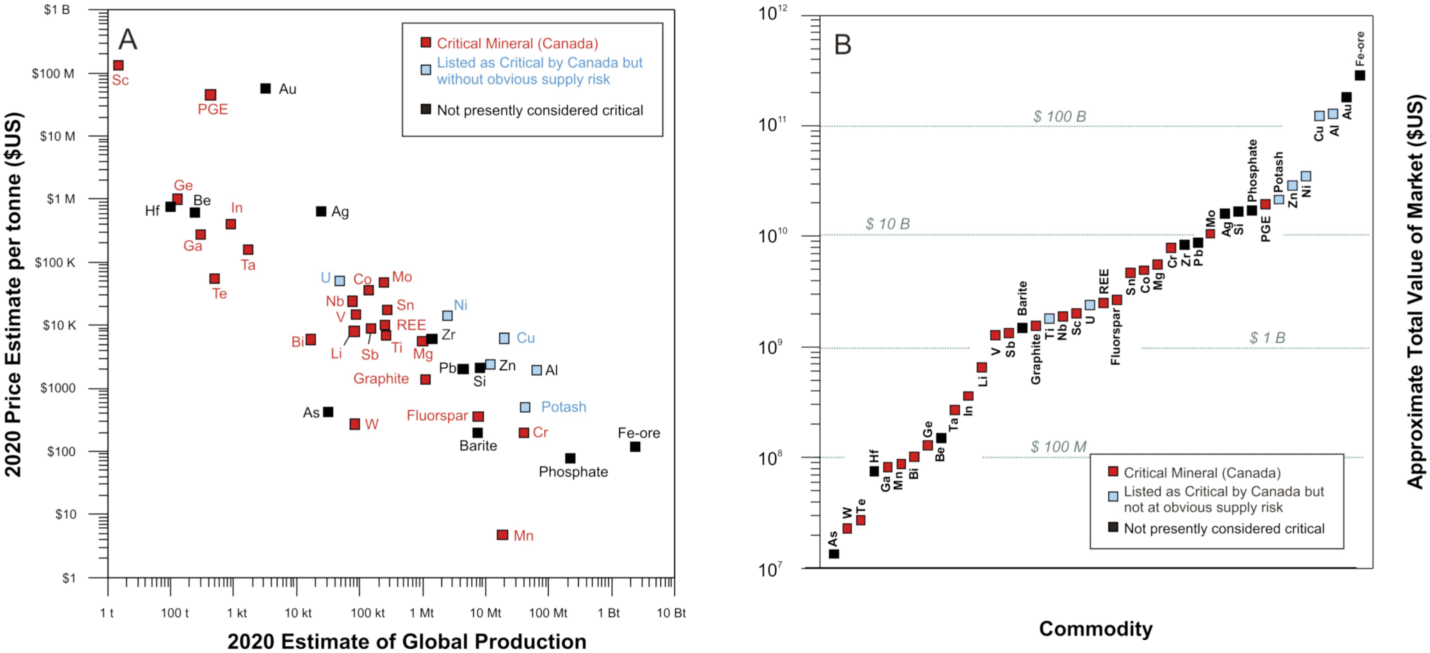

Figure 7. Relationships between global production, estimated average prices and total size of markets, as crudely indicated by multiplying production and price. Data are derived from Simandl et al. (2021) and recent USGS sources. Note that there is considerable uncertainty in assigning prices to many small-volume commodities, so these are general indications only. (A) logarithmic plot of annual production and average price, showing a general (but poor) inverse correlation of these measures. (B) total market values for commodities shown in ascending order from left to right, showing the orders-of-magnitude contrasts between major commodities and most of the commodities presently listed as critical. Although different price assumptions would affect individual calculations and would likely change the ranking of some, these shifts would not be significant in the bigger picture of contrasting markets.

Mineralogical and Metallurgical Complications

The chemical elements that dominate critical mineral resources lists must be extracted from true minerals (i.e. natural inorganic compounds that contain them), but details vary by commodity. For most major commodities, minerals of interest are separated from those of no value at the mining site (termed beneficiation), and then processed elsewhere by smelting and refining. Processing, smelting and refining are very energy-intensive, especially for low-grade high-tonnage operations. Every step in this process is influenced by the mineral assemblage, i.e. the nature, grain size, relative abundance and textural associations of minerals. This will often determine the viability of a deposit just as much as tonnage and grade. In a wider sense, we often depend on supergene (near-surface) processes to make some resources economically viable. For Al in bauxite, and for Ni from laterite deposits, we basically rely on Mother Nature to do most of the work over many thousands or millions of years.

For most major commodities, certain host minerals are favoured, and only a few minerals represent feasible sources. Sulphides are important for base metals because they are dense (easily concentrated) and easily decomposed at low and high temperatures, allowing supergene enrichment and ease of processing. Oxide and hydroxide minerals host most iron, Mn and Al resources and are also amenable to natural supergene processes. Mineralogical factors for deposits of major commodities vary little, and adaptation of existing extraction technology is routine. Some of the commodities on critical mineral resources lists are also like this. For example, molybdenite (MoS_2) is the most common host for Mo, and Cr comes almost exclusively from the oxide mineral chromite (Fe_2CrO_4); both are widely processed. There are also established processing routes for Li from the silicate minerals spodumene ($LiAlSi_2O_6$) and petalite ($LiAlSi_4O_{10}$) found in pegmatite deposits. Graphite processing is largely a matter of physical separation from associated silicate minerals. However, textural features and grain or flake size distributions are very important and the economic feasibility of a graphite deposit is as much a function of metallurgy as grade (e.g. Mitchell and Deady 2021).

Many of the other critical mineral resources (e.g. Table 1) have diverse and complex mineralogy. For example, the PGE may substitute in common sulphide minerals such as pentlandite and chalcopyrite, but can also form unusual sulphide, sulphosalt and telluride minerals, or tiny metal alloy grains. In most cases, the PGE are only actually extracted at the smelting and refining stage, so their production is not necessarily linked to the mine site or its host country. The REE occur in a seemingly endless list of diverse minerals, including oxide, hydroxide, phosphate, titanate, carbonate, fluorocarbonate and silicate phases (e.g. Weng et al. 2015; Van Gosen et al. 2017; Goodenough et al. 2018). Many REE deposits, especially in igneous rocks, contain several discrete REE-bearing minerals, some of which may be rare or unique. For example, the large Strange Lake deposit in Quebec and Labrador contains an unusual Ca-Y-REE silicate known as gerenite, known from only one other location in the world, but its REE inventory also includes other unusual minerals (e.g. Kerr 2011; Dostal 2016). Other REE deposits in Canada, such as Kipawa (Quebec) and Nechalacho (NWT) also have great mineralogical diversity (Currie and van Breemen 1996; Bakker et al. 2011). Extraction of REE from such varied minerals may be possible at a laboratory scale, but large-scale commercial feasibility is another matter.

The potential for REE deposits in Canada, especially in the Precambrian Shield, is well documented, and significant resources are defined. However, after decades of exploration, the only Canadian REE production comes from a small high-grade pod within the larger Nechalacho deposit (NWT). This limited area contains the REE-bearing carbonate bastnaesite (essentially $[REE]CO_3F$), which is easily processed. Deposits such as Strange Lake or the main Nechalacho deposit appear promising in terms of total resources (Kerr 2011; Bakker et al. 2011), but development, extraction and processing are not simple. Another complication related to REE is the extreme concentration of refining capacity in China. A small REE refinery facility now operating in Saskatchewan is an important factor in the viability of current small-scale production in the NWT (Connelly 2021, see also Vital Metals, https://vitalmetals.com/). Goodenough et al. (2018) noted that the industry 'demand profile' for REE closely matches the REE distribution of clay-rich surficial weathering deposits that currently account for much of Chinese (i.e. global) production. These deposits are another example of how we rely on very slow natural processes to initially process valuable minerals for our use.

Other materials contained in Canada's critical mineral resources list have specific mineralogical or metallurgical complications that relate to their coproduct or byproduct status. These affect Co, Sc, Cs and also elements linked to photovoltaic technology (Ga, Ge, Te, In). Cobalt typically occurs in low concentrations (< 0.3%) in magmatic Ni-Cu sulphide ores. Like the PGE, it is commonly extracted during smelting, rather than at mine sites. The photovoltaic elements (Ga, Ge, In, Te) are typically closely associated with common sulphide minerals as tiny discrete mineral inclusions or in solid solution, so the same constraints apply.

The Separation of Mine Production and Metal Extraction

As discussed above, many rarer elements are extracted during smelting and refining, rather than being concentrated at mining sites. Mineral concentrates have long been transported within Canada for smelting, but shipment distances are now greater and destinations are international. Smelting and refining capacity has also shifted away from Europe and North America over time, notably to Asia. The remaining smelting operations in Europe and North America are increasingly scrutinized for their environmental and human health impacts. Smelters are not generally seen as desirable neighbours by communities, but they are important for many of these commodities.

Outsourcing smelting and refining beyond Canada will effectively result in the loss of potentially valuable domestic resources of byproduct elements because concentrates from multiple sources are mixed, and some of these elements may not even be recovered. Maintaining or expanding existing domestic smelting and refining capacity is the most obvious solution, but such an effort would probably encounter opposition in most developed western countries, including Canada. Critical mineral resource strategies note this challenge, and financial assistance and incentives were important in establishing the REE refinery that aids in the exploitation of high-grade material from Nechalacho (Connelly 2021; Vital Metals, https://vitalmetals.com/). There is also an important geoscience question involved in this because there is presently limited information about the trace elements contained in ores of Cu, Pb or Zn distributed across Canada, especially for exploration-stage projects that might represent future production. These data were of limited interest in the past, but now assume greater importance.

The Climate Impacts of Critical Minerals Extraction

The connection between mineral resources and limiting climate change is by far the strongest theme in discussion of critical mineral resources. *Mining for Clean Energy* (Clean Energy Canada 2017) is just one of many documents that present this reasoning. If so-called climate-smart mining is to be validated and (more importantly) gain public acceptance, the emissions of increased extraction and processing need to be closely audited. This includes those associated with starting a mine and also the final stages of mineral resource developments (closure, rehabilitation, etc.). The studies by the World Bank (2020) and International Energy Agency (2022) concluded that associated emissions footprint would be only a small fraction of those from continued extraction and usage of fossil fuels. Such assessments always generate discussion about figures and exactly what is included or excluded, but this general premise seems sound.

The extraction and processing of mineral resources makes a significant contribution to CO_2 emissions, from 4 to 7% of global emissions and perhaps as much as 11%, depending on what is included (World Bank 2020). The crushing and grinding of raw materials are a big part of the energy budget for typical operations, especially for large-tonnage, low-grade deposits. Energy usage per unit of production has probably grown over time and will likely continue to do so. New or expanded operations will obviously benefit if their emissions footprint is low and (or) if they employ the same technology that extracted resources are claimed to support. It is suggested by some that assessment of resource developments in the 21st century must involve a much wider analysis where lifetime energy and environmental footprints are considered as much as tonnage, grade and metallurgy (e.g. Lee et al. 2020; Pell et al. 2021). This departs from conventional thinking, which emphasizes short-term economics, and such an approach will probably be seen as idealistic or at least unrealistic by the minerals industry. Nevertheless, questions about energy usage and emissions are bound to enter future debates concerning critical mineral resources.

In more remote parts of Canada where minerals are extracted, links to existing energy transmission networks are not feasible. Diesel power generation is the norm for many mines unless local hydroelectric potential exists. However, only larger developments could sustain the high costs of the latter, which is not entirely free of environmental consequences. Finding feasible renewable energy sources in northern regions with seasonal darkness is likely to provide challenges. Partially wind-based energy systems already exist, such as the hybrid wind-diesel system at the Diavik Mine in the NWT (Romero et al. 2016; Clean Energy Canada 2017), but wind cannot alone power a mine on a 24/7 basis. The use of modular nuclear reactors as power sources for remote mining was explored in a recent discussion paper (Government of Canada 2021) and was also assessed by Froese et al. (2020) but there is as yet no clear demonstration of feasibility and no regulatory framework. Ironically, the very regions of northern Canada that are generally identified in strategy documents as having the greatest future critical mineral resources potential are also those that will most challenge low-carbon energy technology.

Critical Mineral Resources and the Concept of a 'Just Transition'

In this article, the energy transition is discussed mostly from the perspective of natural resources development, where it is viewed in a generally positive light. However, this view is not shared by all, and advocates of environmental protection concerned with global inequity see it through a different lens. There are thus calls that any future energy transition must also be a 'just transition'. This term has multiple definitions, but a common theme is that nations with minimal historical carbon footprints (i.e. most of the Global South) are disproportionally affected by climate change and so should not pay a retroactive price for continued consumption and emissions by industrialized nations (the Global North). A related consideration is that benefits from any future 'green' economy should be more equally shared. There is some fear that the rush to develop critical mineral resources will result in rapid development and extraction from lower income countries that cannot maintain environmental standards, resulting in additional ecosystem damage. This outcome is not emphasized in documents advocating 'climate-smart mining' conducted with strict environmental standards, but it is certainly possible, and some think it very probable (e.g. Environmental Justice Atlas and MiningWatch Canada n.d.). This particular challenge is the most difficult to discuss because it is more ideological than technical.

The counterargument to the premise that increased mineral extraction is needed to limit climate change is that any energy transition should instead prioritize sustained reductions in energy and material usage, particularly in the developed industrial nations. This is linked to calls for a fully circular economy, in which recycling and reuse are emphasized. This view diverges from that of industry and most governments, which acknowledge the need for better use of existing resources but seek ways to maintain our energy-intensive society yet at the same time avoid consequences of emissions. There is an obvious philosophical divergence here, and the pages of *Geoscience Canada* are not the place for a lengthy discussion. When I started to write this article, I did not expect to include a quote from *MiningWatch Canada*, who stand firmly on one side of this divide. However, their short discourse entitled *Mining for the Energy Transition in the Americas* (Environmental Justice Atlas and MiningWatch Canada n.d.) includes a thought-provoking statement:

> *"A transition that heavily depends on mining new materials without considering materials and energy for what, for whom and at what socio-environmental costs will only reinforce the injustices and unsustainability that have led us to the climate crisis in the first place. Improved efficiency and recycling of materials are necessary components in the transition, but these strategies alone will not address the growing demand for these materials. Significant reductions in material and energy consumption, particularly in the Global North, are a key component to a just transition."*

This is a quote, and not necessarily my opinion, but it raises interesting points. A lengthier analysis from the same organization outlines this perspective in more detail (Deniau et al. 2021). These agree with the World Bank (2020) and the IEA (International Energy Agency 2022) that recycling alone cannot yet meet expected demands. The same World Bank study also stated that mining related to the energy transition could provide:

> *"...new economic benefits to resource-rich but poor countries that also hold significant solar energy potential to use in production"* and "*....contribute to efforts to combat climate change*".

This seems to imply that mineral resources needed for the energy transition should indeed be, in part, outsourced as a form of economic development. Canada's critical mineral resources strategy (Government of Canada 2022) similarly frames one of its purposes as reconciliation with Indigenous peoples by their participation in related economic development. This reads very much like the same concept, although admittedly within one nation. In the resource industries, we tend to interpret historical aspects of the mining industry as part of nation-building, in the broad sense of the word, but other treatments (e.g. Sandlos and Keeling 2021; Angus 2022) offer different interpretations. These aspects also lie well beyond the scope of this article, but their emergence in future discussions about critical mineral resources should be anticipated. They are already illustrated by some of the responses to the initial draft that preceded the release of the current Canadian strategy document late in 2022, by the Wildlife Conservation Society Canada (2022) and also by the International Council on Mining and Metals (2022) which is an industry-led group. These submissions, and others, emphasized the need to ensure a just transition. A recent article in the online journal *The Narwhal* (Struzik 2023) explores these issues in the specific context of Arctic Canada.

The point here is not one of a specific interpretation or world view being right or wrong, but rather that efforts to develop resources for the much-heralded energy transition will inevitably be discussed and judged within this concept of a just transition. This would certainly be the case if such developments are across the world in low-income countries, but very similar reasoning can be applied within Canada, where northern regions are economically disadvantaged, disproportionally affected by climate change and view much of their history in terms of sustained exploitation and injustice. We should be fully prepared for these less-tangible issues to become prominent in northern Canada wherever new resource developments are promoted as a vital part of the energy transition. Current strategies place great emphasis on sustainability and environmental protection, and more widely frame such efforts as part of reconciliation with Indigenous peoples and community development, but not all stakeholders will be convinced of such links. This is one of several challenges recently noted in a recent commentary by Tortell et al. (2023) on behalf of the *Institute for Research on Public Policy*, an independent Canadian research group.

SUMMARY AND DISCUSSION

Writing this article proved to be far more difficult than I ever expected at the outset. The topic of critical mineral resources is extraordinarily broad and does not only involve technical information. It inevitably spills over into politics, economics and divergent philosophical views about natural resources, which become hard to separate from geoscience in any discussion.

Canada's "storehouse of critical minerals", as it is often termed, still remains to be fully defined in detail. The modified definition that includes some major commodities that most other jurisdictions exclude supports such statements because we do indeed hold significant reserves and resources of Cu, Zn, potash, Ni and U. However, the inventory is less clear for many other commodities on Canada's critical mineral resources list, although significant resources of the REE are already defined. Northern Canada is widely regarded by the minerals industry as an underexplored region of significant potential, as shown by its important and diverse mineral deposits. It is equally well known as one of the largest remaining intact wilderness areas in the Northern Hemisphere, and as one of the Earth's great reservoirs of carbon storage. Developing mineral resources in this setting in the past was never simple, and it left some difficult environmental and social legacies. On the other hand, resource development provides important economic benefits and it employs many people in the North. Critical mineral resources may unlock this potential more in decades to come, as envisaged in various government strategies, but elements of past and present controversies will not disappear simply because a resource is designated 'critical'.

It is no surprise that the World Bank (2020) and the International Energy Agency (2022) concluded that the 21st century will see increased demand for familiar mineral resources and unconventional resources that have experienced relatively minor exploration interest in the past. The conclusions from the World Bank (2020) and the IEA (2022) seem well founded and in many respects represent common sense, given current per-capita resource consumption, growing populations, and increasing urbanization. The deployment of material-intensive renewable energy and electrification infrastructure will surely add to and change these demands, even if the exact details are hard to forecast. Finding these materials is one task in this greater challenge, but perhaps the easier part, as significant global resources already exist for most of them, even if presently defined reserves for some might seem sufficient for only a few decades (e.g. Simandl et al. 2021). The greater part of the challenge will be to extract and process such mineral resources without excessive ecosystem damage or increases in associated emissions, and also to gain acceptance for such increased activity.

I hope that this article illustrates that although many basic concepts around critical mineral resources seem straightforward, some aspects remain poorly defined, and the discussion becomes more complex and tangled when Canada's geography, history and geopolitics are considered. Some may consider parts of this article to have a discouraging tone, but I resist such judgment. It is intended to inform those without detailed geoscience knowledge but must also acknowledge some challenges that are beyond our control and others that are rooted in institutions and governance structures. If the energy transition is to unfold as envisioned, with Canada assuming a prominent role in supplying vital resources, and enjoying related economic benefits, these many linked challenges need to be recognized and addressed. The need for better geoscientific knowledge is an important part of this. Such information will better define the regional potential for specific commodities and assist future decisions about targets. Nevertheless, geoscience is only one part of this equation, as more significant challenges are linked to politics and jurisdiction. Critical mineral resources strategies so far released emphasize long-established policies for environmental protection, land conservation and recognition of Indigenous rights. These guiding principles are stressed in their pages just as much as the perceived need to expedite development pipelines and give proponents more confidence in successful outcomes. There is no overt conflict in this, but responses to initial strategy discussions (e.g. Wildlife Conservation Society Canada 2022; Kneen 2022; International Council on Mining and Metals 2022) imply that contradictions can be read between their lines. Strong provisions for impacts and benefits agreements and environmental assessment all across the North were not easily achieved and are highly valued. Although present geoscience data are incomplete, it is clear that many areas perceived as having significant potential for future critical mineral resources are already covered by such frameworks or await their formal definition. Land use plans for Nunatsiavut (Labrador), Nunavut and the NWT have yet to be finalized, despite years of discussion, but the drafts for all emphasize extensive protected areas where mineral exploration and mining would essentially be prohibited. Ambitious land conservation targets were also an important outcome of the recent UN Biodiversity Conference COP15 in Montreal aimed at protecting nature and biodiversity. If Canada's commitment to these initiatives is to be met, the extent of protected areas will need to at least double in coming decades. If difficult choices about lands are to be made in the years ahead, it is important to do so in the light of geoscientific information and systematic evaluation of mineral potential.

Canada is blessed with large tracts of underexplored Precambrian crust across much of its north, and global analogues suggest potential for a wide range of critical mineral resources.

Despite this broad perception, our geoscience knowledge remains incomplete, especially in the far north, where exploration over the last two decades focused largely on gold and diamonds. Aside from the REE, for which several significant but so far undeveloped concentrations are defined, we have limited information for many entries on the critical mineral resources list. Regional geological mapping and dissemination of broad-based geoscience data need to be emphasized for many regions that are labelled as "highly prospective" but in reality are poorly known. Some of these include defined base metal and gold deposits, so this provides some baseline information. However, some commodities (e.g. graphite and Li) are more likely to occur in plutonic rocks or high-grade metamorphic terranes that previously received less attention. The 'high science' aspects of economic geology research, such as theories of deposit genesis, detailed classifications, or links to plate tectonic evolution models may be useful in the long term (and they are certainly very interesting) but the greater short-term need is for descriptive, tangible, measured data that can assist exploration. For many areas, surficial exploration programs using geochemical or indicator mineral methods may be the first priority given the prevalence of thick glacial deposits. The mineralogical complexity of some critical minerals deposit types suggests that these aspects should also be stressed in examination of known mineralization. The success or failure of a project may ultimately rest with these parameters, rather than just its tonnage and grade. This technical knowledge side of the equation can be addressed, although the investment is large and will critically depend on finding highly qualified professionals, especially for field-based research. The latter is already known as a significant challenge for the mineral exploration sector.

New information and discussions concerning critical mineral resources appear constantly. When this article was in final revision for publication, the IEA released its first 'progress report' (International Energy Agency 2023) on global efforts to increase production and diversify supplies of key commodities. Some key points from their analysis are relevant to this discussion. The IEA reports that strong growth in deployment of clean energy technology since 2017 increased demand for Li, Co and Ni, and the total markets for these and other commodities grew significantly. Policy initiatives that seek to diversify supplies of critical minerals in industrialized countries were widely developed, of which Canada's strategy is just one example. However, over the same period many resource-rich countries introduced measures intended to restrict exports of such materials. Investment in development of and exploration for critical mineral resources grew by 30% and 20% respectively in 2022 alone, which illustrates strong interest in the sector and confidence in its future. The IEA expressed confidence that projected supplies could meet global demands to around 2030, but still predicts significant supply constraints in later decades. The efforts to diversify supplies over the last five years were judged to have had limited real-world success and, in some cases, the geographical concentration of supply (and processing capacity) actually worsened. The IEA's verdict on progress towards sustainable and environmentally responsible extraction of materials is similarly mixed, noting increased water usage and little change in associated emissions. It was also noted that China (already the principal source for many commodities) continues to invest heavily in securing supplies from elsewhere for its own import needs. For example, this investment in global Li projects since 2018 was twice as much as that from the USA, Canada and Australia combined. Overall, the new IEA report shows that critical mineral resources will retain a high profile in years to come and will likely continue to generate controversy. The need to address such challenges is presumably behind the IEA's initiative to hold the first-ever *International Summit on Critical Minerals*, projected for September 2023; see https://www.iea.org/events/iea-critical-minerals-and-clean-energy-summit for more details.

It is always easier to point out complications and obstacles than to formulate solutions, and I accept criticism of this article in such light. The questions raised in it, and in other specialized treatments such as the new IEA report, do not have simple answers, but hopefully practical and equitable solutions will be found. In closing, successfully meeting the mineral resource requirements of any successful and sustainable energy transition in Canada (or elsewhere) will require a great deal of reconciliation, but in its broadest possible sense, which is one of balance. I hope that this article might in some way assist in finding ways to overcome the challenges to what may be one of the most important tasks ever undertaken by the mineral resources industry.

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