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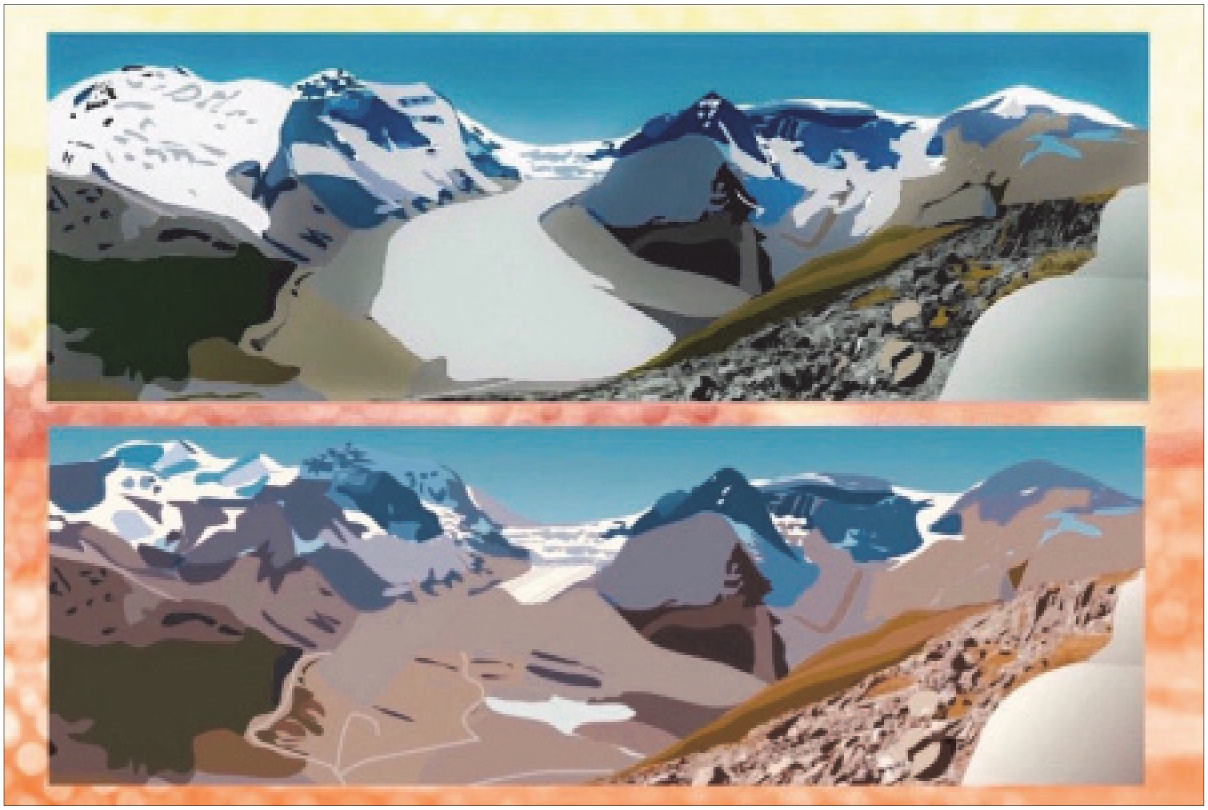

Our Deepening Climate Crisis: Canadian Geoscience Moves Past Predictions into a Proactive Statement

Resources for the Green Economy: Rewards, Risks and Realistic Analysis

From Badlands with Dinosaurs to Mountains of Folds and Faults: A Guidebook to Alberta's Scenic Geology

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Cover Image: An artistic rendition of the receding Athabasca Glacier from Wilcox Pass, Alberta, between 1917 (top image) and 2011 (bottom). For further information, read the Canadian Federation of Earth Sciences Scientific Statement on Climate Change article in this issue by Burn et al. Image Credit: Artwork by the Journal's Peter Russell, recipient of the 2021 GAC Distinguished Service Award.

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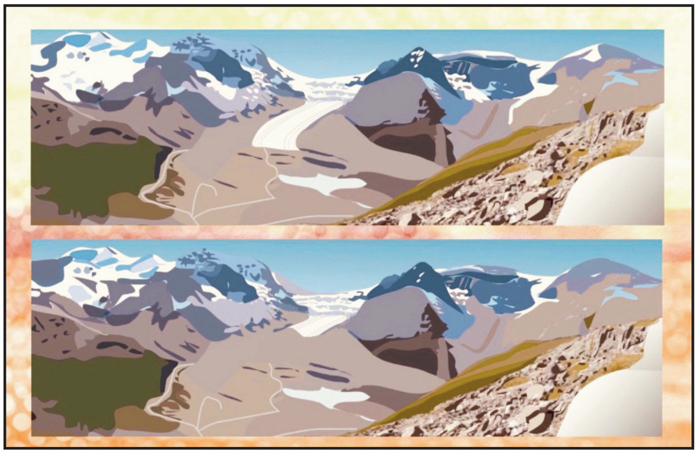

The Canadian Federation of Earth Sciences Scientific Statement on Climate Change – Its Impacts in Canada, and the Critical Role of Earth Scientists in Mitigation and Adaptation

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SUMMARY

The Canadian Federation of Earth Sciences (CFES) has issued this statement to summarize the science, effects, and implications of climate change. We highlight the role of Earth scientists in documenting and mitigating climate change, and in managing and adapting to its consequences in Canada. CFES is the coordinated voice of Canada's Earth Sciences community with 14 member organizations representing some 15,000 geoscientists. Our members are drawn from academia, industry, education, and government. The mission of CFES is to ensure decision makers and the public understand the contributions of Earth Science to Canadian society and the economy.

Climate change has become a national and global priority for all levels of government. The geological record shows us that the global climate has changed throughout Earth's history, but the current rates of change are almost unprecedented. Over the last 70 years, levels of common greenhouse gases (GHGs) in the atmosphere have steadily increased. Carbon dioxide (CO_2) concentration is now 418 parts per million — its highest of the last three million years. The chemical (isotopic) composition of carbon in the atmosphere indicates the increase in GHGs is due to burning fossil fuels. GHGs absorb energy emitted from Earth's surface and re-radiate it back, warming the lower levels of the atmosphere. Climatic adjustments that have recently occurred are, in practical terms, irreversible, but further change can be mitigated by lowering emissions of GHGs.

Climate change is amplified by three important Earth system processes and effects. First, as the climate warms evaporation increases, raising atmospheric concentrations of water vapour, itself a GHG — and adding to warming. Second, loss of ice cover from the polar ice sheets and glaciers exposes larger areas of land and open water — leading to greater absorption of heat from the sun. Third, thawing of near-surface permafrost releases additional GHGs (primarily CO_2 and methane) during decay of organic matter previously preserved frozen in the ground. Some impacts of climate change are incremental and steadily occurring, such as melting of glaciers and ice sheets, with consequent sea level rise. Others are intermittent, such as extreme weather events, like hurricanes — but are becoming more frequent. Summer water shortages are increasingly common in western Canada as mountain snowpacks melt earlier and summer river flows decline. In northern Canada, warming and thawing of near-surface permafrost has led to deterioration of infrastructure and increased costs for

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buildings that now require chilled foundations. Other consequences of unchecked climate change include increased coastal erosion, increases in the number and size of wildfires, and reduction in winter road access to isolated northern communities. Reductions in net GHG emissions are urgently required to mitigate the many effects of further climate change. Industrial and public works development projects must now assess the effects of climate change in their planning, design, and management. Cities, municipalities, and rural communities need to plan new residential development carefully to avoid enhanced risk of flooding, coastal erosion, or wildfire.

Earth Science knowledge and expertise is integral to exploration and development of new metals and Earth materials required for a carbon-neutral future, and in the capture and storage of CO_2 within the Earth. Earth Science is also central to society's adaptation to new climatic regimes and reduction of risks. This includes anticipation, assessment, and management of extreme events, development of new standards and guidelines for geotechnical and engineering practice, and revision to regulations that consider climate change. Geoscientists also have an important role in the education of students and the public on the reasons for necessary action. Canada is uniquely positioned with its strong global geoscientific leadership, its vast landmass, and its northern terrain to effectively leverage research activities around climate change. Geoscience tools and geoscientists' skills will be integral to Canada's preparation for climate change.

RÉSUMÉ

La Fédération canadienne des sciences de la Terre (FCST) a publié ce communiqué pour résumer la science, les effets et les implications des changements climatiques. Nous soulignons le rôle des scientifiques en science de la Terre dans la documentation et l'atténuation des changements climatiques, ainsi que dans la gestion de leurs conséquences et la création de mesures d'adaptation au Canada. La FCST est la voix coordonnée de la communauté canadienne des sciences de la Terre avec 14 organisations membres représentant environ 15 000 géoscientifiques. Nos membres sont issus du milieu universitaire, de l'industrie, de l'éducation et du gouvernement. La mission de la FCST est de s'assurer que les décideurs et le public comprennent les contributions des sciences de la Terre à la société canadienne et à l'économie.

Les changements climatiques sont devenus une priorité nationale et mondiale à tous les niveaux de gouvernement. Les archives géologiques nous montrent que le climat mondial a changé tout au long de l'histoire de la Terre, mais les taux de changement actuels sont presque sans précédent. Au cours des 70 dernières années, les niveaux de gaz à effet de serre (GES) communs dans l'atmosphère n'ont cessé d'augmenter. La concentration de dioxyde de carbone (CO_2) est maintenant de 418 parties par million - son plus haut niveau des trois derniers millions d'années. La composition chimique (isotopique) du carbone dans l'atmosphère indique que l'augmentation des GES est due à la combustion de combustibles fossiles. Les GES absorbent l'énergie émise par la surface de la Terre et la réfléchissent, réchauffant les niveaux inférieurs de l'atmosphère. Les modifications climatiques qui se sont produits récemment sont, concrètement, irréversibles, mais les changements additionnels peuvent être atténués en réduisant les émissions de GES.

Les changements climatiques sont amplifiés par trois processus et effets importants du système terrestre. Premièrement, à mesure que le climat se réchauffe, l'évaporation augmente, ce qui augmente les concentrations atmosphériques de vapeur d'eau, elle-même un GES, et contribue au réchauffement. Deuxièmement, la perte de la couverture de glace des calottes glaciaires polaires et des glaciers expose de plus grandes superficies de terre et d'eau libre, ce qui entraîne une plus grande absorption de la chaleur du soleil. Troisièmement, le dégel du pergélisol proche de la surface libère des GES supplémentaires (principalement du CO_2 et du méthane) lors de la décomposition de la matière organique jusqu'alors préservée gelée dans le sol. Certains impacts des changements climatiques sont progressifs et se produisent régulièrement, comme la fonte des glaciers et des calottes glaciaires, avec pour conséquence une élévation du niveau de la mer. D'autres sont intermittents, comme les événements météorologiques extrêmes, tels que les ouragans, mais deviennent de plus en plus fréquents. Les pénuries d'eau en été sont de plus en plus courantes dans l'ouest du Canada, car le manteau neigeux des montagnes fond plus tôt et le débit des rivières en été diminue. Dans le nord du Canada, le réchauffement et le dégel du pergélisol proche de la surface ont entraîné une détérioration des infrastructures et une augmentation des coûts des bâtiments qui nécessitent maintenant des fondations réfrigérées. Les autres conséquences des changements climatiques incontrôlés comprennent l'augmentation de l'érosion côtière, l'augmentation du nombre et de la taille des incendies de forêt et la réduction de l'accès aux routes d'hiver aux collectivités isolées du Nord. Des réductions des émissions nettes de GES sont nécessaires de toute urgence pour atténuer les nombreux effets de nouveaux changements climatiques. Les projets de développement industriel et de travaux publics doivent désormais évaluer les effets des changements climatiques dans leur planification, leur conception et leur gestion. Les villes, les municipalités et les communautés rurales doivent planifier soigneusement les nouveaux développements résidentiels pour éviter les risques accrus d'inondation, d'érosion côtière ou d'incendie de forêt.

Les connaissances et l'expertise en sciences de la Terre font partie intégrante de l'exploration et du développement de nouveaux métaux et matériaux terrestres requis pour un avenir neutre en carbone, ainsi que dans la capture et la séquestration du CO_2 dans la Terre. Les sciences de la Terre sont également au cœur de l'adaptation de la société aux nouveaux régimes climatiques et de la réduction des risques. Cela comprend l'anticipation, l'évaluation et la gestion des événements extrêmes, l'élaboration de nouvelles normes et directives pour les pratiques géotechniques et d'ingénierie, et la révision des réglementations qui tient compte des changements climatiques. Les géoscientifiques ont également un rôle important dans l'éducation des étudiants et du public sur le fondement des mesures

nécessaires. Le Canada occupe une position unique grâce à son solide leadership géoscientifique mondial, sa vaste étendue et son territoire nordique pour tirer efficacement parti des activités de recherche sur les changements climatiques. Les outils géoscientifiques et les compétences des géoscientifiques feront partie intégrante de la préparation du Canada aux changements climatiques.

Traduit par la Traductrice

INTRODUCTION

The evidence for climate change in Canada is compelling (Vincent et al. 2015, 2018). Northern Canada has experienced some of the most rapid climate warming on Earth. For example, mean annual air temperatures at Inuvik, NT, climbed from -9.7°C in 1961–70 to -6.1°C in 2011–20 (Burn and Kokelj 2009; Figs. 1, 2). The rates of change in southern Canada are lower, but just as definitive. At Ottawa, ON, for instance, the mean annual air temperatures for 1961–70 and 2011– 20 were 5.5 and 6.5°C, respectively (Fig. 2). The geological record shows us that global climate has changed throughout Earth's history, but the current and anticipated rates of change are almost unprecedented. The only known exception occurred after the meteorite impact 66 million years ago when most dinosaurs became extinct (Henehan et al. 2019; Lear et al. 2020).

The Canadian Federation of Earth Sciences has published this statement to summarize the scientific basis for some of the distinct challenges that Canada faces from climate change. We highlight the critical role of Earth scientists in documenting rates of change and variability in the climate, and in mitigating, managing, and adapting to the effects of climate change in Canada.

Simultaneously, Earth scientists will support a strong economy, including the exploration and development of natural resources needed to foster a carbon-neutral society. The scientific data, interpretations, and actions presented below are derived largely from the work of many geoscientists over decades of research.

UNDERSTANDING THE SCIENCE OF CLIMATE CHANGE

Climate change is caused by four fundamental factors: (1) changes in the energy Earth receives from the Sun; (2) changes at the surface of the Earth, including deforestation, that affect how solar energy is absorbed or redistributed; (3) changes in the composition of the atmosphere influenced by natural processes and human activity; and (4) changes in the circulation of the oceans (e.g. Broecker 2001; Veizer 2005; Stocker et al. 2013). Over the last 70 years, the greatest adjustment to these factors has been in the composition of the atmosphere, particularly the concentrations of several common gases that have been present for hundreds of millions of years. These include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In addition, new fluorinated industrial gases (F-gases), such as the hydrofluorocarbons, have been introduced since 1950 (Lacis et al. 2010; Tans et al. 2020). All these gases absorb energy emitted from Earth's surface and re-radiate it, thereby further warming the lower levels of the atmosphere

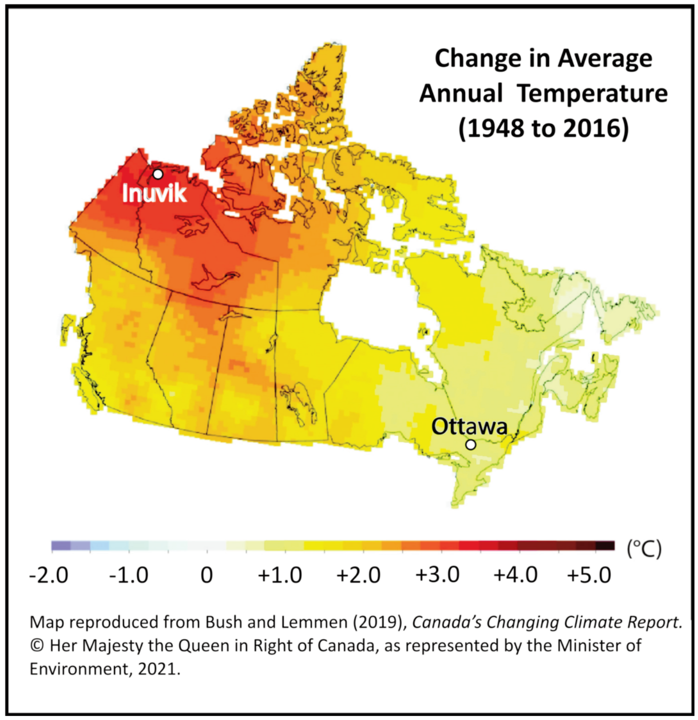

Figure 1. Observed changes in annual temperature between 1948 and 2016 across Canada. From figure 4.3 in Bush and Lemmen (2019).

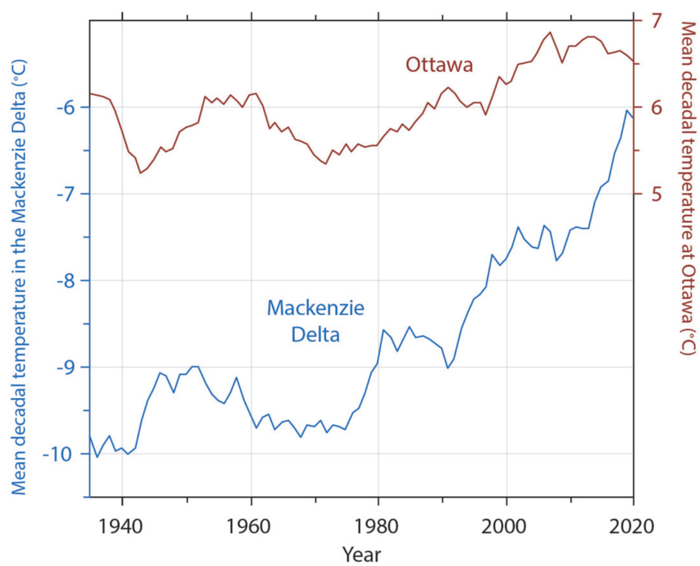

Figure 2. Change in mean decadal air temperature from 1926–35 to 2011–20 in the Mackenzie Delta area, Northwest Territories, and Ottawa, Ontario. For the Mackenzie Delta area, data are from Inuvik, Northwest Territories, (1958–2020) and nearby stations (1926–1957) (Burn and Kokelj 2009). Data are for the decade preceding the date on the horizontal axis.

(Fig. 3). The warming imitates heating in a greenhouse, hence the terms *greenhouse gases* (GHGs), and the *greenhouse effect*. As the concentration of GHGs increases, so does the greenhouse effect. Of all GHGs, CO_2 has had the most influence on climate recently (Fig. 4). The anthropogenic greenhouse effect reached an energy equivalent to 1.37% of Earth's absorbed solar radiation in 2019 (Tans et al. 2020).

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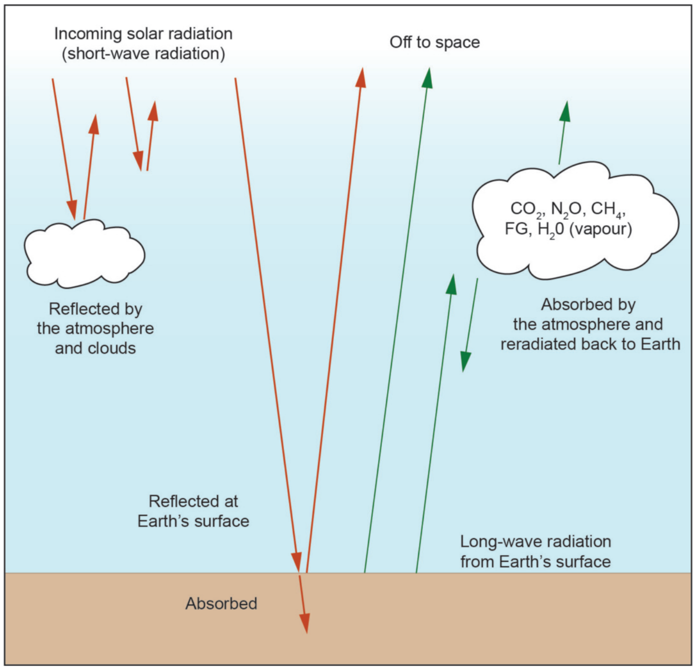

Figure 3. The distribution of solar (short-wave; red) and terrestrial (long-wave; green) radiation within the atmosphere and at Earth's surface.

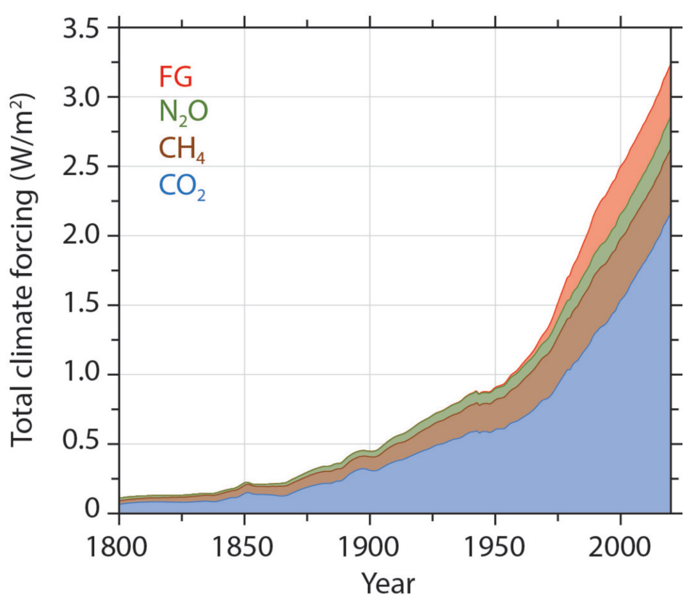

Figure 4. Climate forcing, i.e. the greenhouse effect, from CO_2, CH_4, N_2O, and fluorinated gases (FG), 1800–2019. In 2019, 66% of the anthropogenic climate forcing was from CO_2, 16% from CH_4, 6% from N_2O and 12% from the industrial gases. In comparison, 11-year average solar irradiance has declined by 0.5 W/m^2 since the late 1980s (NASA 2019). Data from Tans et al. (2020), used with permission.

We have known about the thermal impact of the atmospheric greenhouse effect for nearly 200 years. Life as we know it could not exist without the atmospheric greenhouse. The atmosphere's role in maintaining Earth's habitable surface temperatures was first proposed by Joseph Fourier in 1824. The radiative properties of CO_2 and their implications for climate were discovered independently by the American scientist Eunice Foote in 1856 and the Irish scientist John Tyndall in 1859. For more than 160 years we have known that CO_2 is one of the principal agents responsible for our climate. Now we simulate the climate using vast and detailed computer models, tested against decades of weather observations. These independent models each use slightly different sets of algorithms to represent physical interactions between the atmosphere, the oceans, landmasses, and the biosphere. They create consistent projections of the extent and direction of future climate change, which vary by region (e.g. Stocker et al. 2013).

The results primarily depend on the range of anticipated future atmospheric concentrations of greenhouse gases and characterization of energy exchanges between the atmosphere and the oceans. All models clearly point to a warming of the climate and shifting precipitation patterns as GHG emissions and other human activities further enhance the greenhouse effect (Stocker et al. 2013; Maslin 2014).

VALIDATION OF THE GREENHOUSE EFFECT BY THE GEOLOGICAL RECORD

The history of Earth's climate is best preserved in the sedimentary deposits laid down at the bottom of our lakes and oceans and in the annual layers of ice formed from compressed snow such as in the ice sheets of Greenland and Antarctica (e.g. Stuiver and Grootes 2000; Gajewski 2015). The annual growth rings of trees also document recent conditions (e.g. Porter et al. 2009). These sources give precise records of global climate change over the past thousand to even millions of years. For example, ocean sediments have preserved a record of successive glaciations determined by the chemical or isotopic composition of marine shells (Shackleton 1995; Wright 2000; Fig. 5), whereas the record in the ice sheets is determined by the isotopes of oxygen and hydrogen in the H_2O molecules of the ice (EPICA community members 2004). The glacial record from Antarctica provides a record of successive glaciations over the last 2.8 million years (Yan et al. 2019).

Layers of Antarctic ice provide a *continuous* record of climate change going back over 800,000 years (Fig. 6). Atmospheric gases were trapped as the snow fell and were subsequently compressed and sealed in the ice layers. The gas bubbles directly record the composition of the atmosphere when the ice formed. Analysis of these ancient atmospheric samples shows the CO_2 concentration varying cyclically, in step with the climate, over periods of 100,000 years, 41,000 years, and down to 500 and 100 years (Fig. 6). During climate fluctuations, CO_2 and methane concentrations correlate closely with temperature. This pattern continues during the present climate warming.

The geological record also reveals the profound effect of living organisms on atmospheric composition, greenhouse gases, and climate. Proliferation of the first trees and forests in the Devonian and Carboniferous periods, 419 to 299 million years ago, drew down atmospheric carbon, reducing the greenhouse effect and cooling the climate (e.g. Berner 2006). A southern polar ice cap developed toward the end of this time as CO_2 levels fell to about 320 parts per million by volume

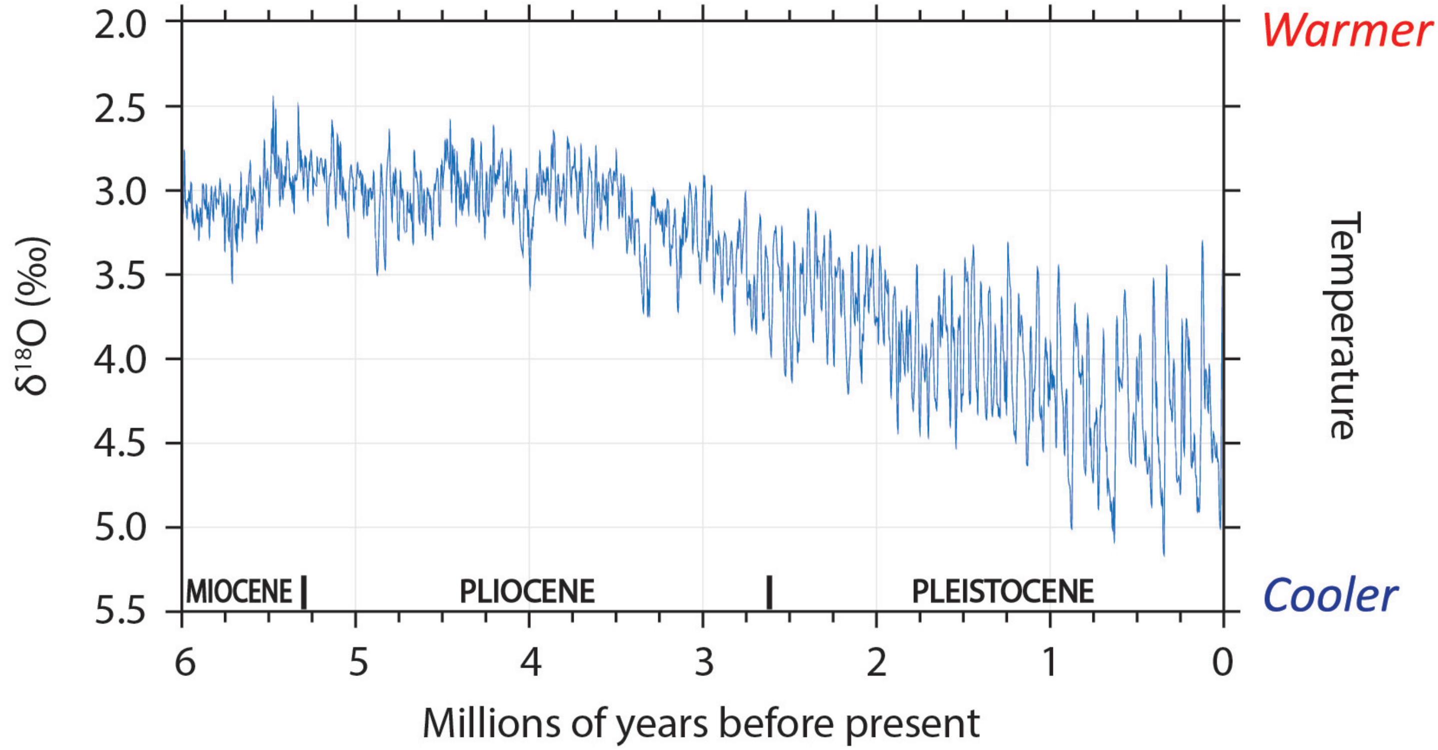

Figure 5. Climate record over 6 million years determined from the concentration of ^{18}O relative to ^{16}O ($\delta^{18}O$) in shells of ocean-bottom organisms recovered from depths up to 120 m beneath the ocean floor several hundred kilometres off the coasts of Ecuador and Peru (Shackleton 1995). The graph shows the beginning of the ice ages about 3 million years ago and the oscillation of climate between the glaciations, especially in the last million years. $\delta^{18}O$ in the ocean increases as the climate cools and water from the oceans is transferred to ice sheets.

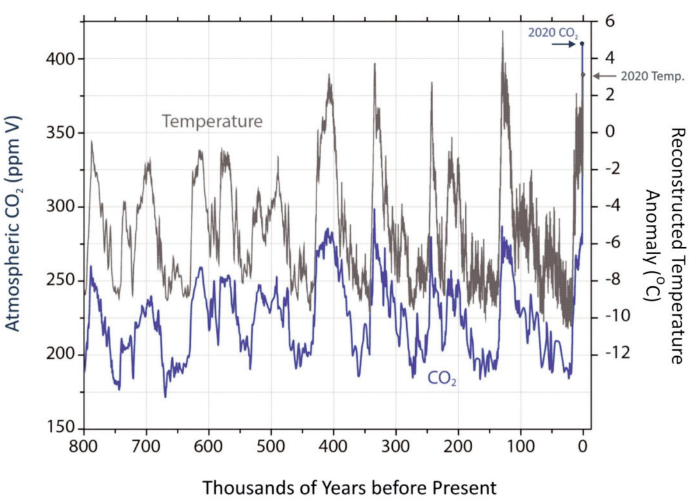

Figure 6. Co-variation of atmospheric CO_2 concentration and climate over the last 800,000 years, as determined from deep ice cores collected in Antarctica. CO_2 is in parts per million by volume measured from gases in bubbles in the ice and is presented in blue (Lüthi et al. 2008). Climatic fluctuations are inferred from the relative concentration of ^2H to ^1H in the ice and are shown in grey (Jouzel et al. 2007). Diagram after Pisaric and Smol (2021, figure 2.4).

(ppm), just higher than the atmospheric concentration of 280 ppm that preceded the Industrial Revolution (1760–1840).

ANTHROPOGENIC CO_2 EMISSIONS AND CLIMATE

Society's use of fossil fuels as its primary source of energy since the beginning of the Industrial Revolution has added CO_2 and other gases to the atmosphere. These fuels are used in all sectors of manufacturing, forestry, agriculture, construction, and transportation, and for domestic heating. Fossil fuel, or hydrocarbon resources were created by the entrapment of plants and micro-organisms over time, from at least 1.6 billion years ago right up to the present (Craig et al. 2013). Peat accumulation is one example of such storage taking place now (Robinson and Moore 1999). After burial, heat and pressure converted these vast quantities of carbon-rich organic matter to coal, oil, natural gas, and other reservoirs of stored carbon.

The return of the fossilized carbon to the atmosphere through the burning of fuel in the past 250 years accounts for about 80% of the increase in atmospheric CO_2 concentration. Deforestation, wildfires, cement manufacturing, and agriculture contribute the remainder (Fig. 7). About 75% of all CO_2 emissions from fossil fuel combustion have occurred since 1970 (Tans et al. 2020). Half of the CO_2 emissions remain in the atmosphere, whereas the oceans and plants on land each absorb about a quarter (Maslin 2014). The atmospheric CO_2 concentration is now 418 ppm (CO_2 Earth 2021), having risen steadily over the period of continuous measurement from about 315 ppm in 1958 (Fig. 8). The concentration at present is higher than it has been in the last 3 million years.

The current rate of anthropogenic emission, about 10 billion tonnes of carbon per year (EPA 2021), is the highest documented in the geological record (Gingerich 2019; Lear et al. 2020). It leads to an annual change in atmospheric CO_2 concentration of 2.4 ppm. The relative concentration of anthro-

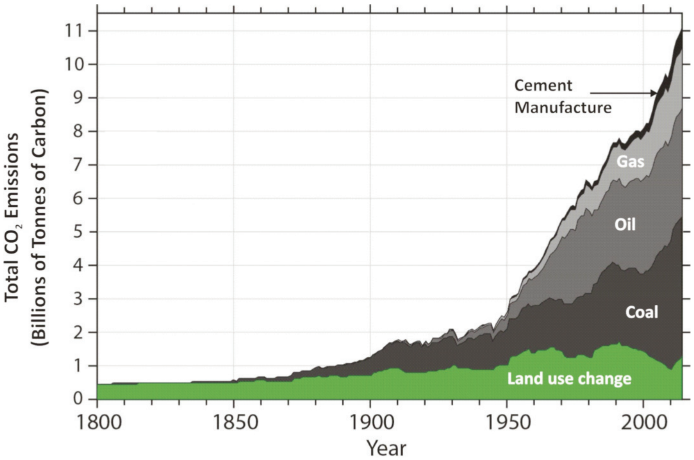

Figure 7. Anthropogenic carbon emitted as CO_2 in billions of tonnes per year from land use change, fossil fuel consumption, and cement manufacturing, 1800–2014. Data from Boden et al. (2017), Houghton (2008), and Houghton and Nassikas (2017). Diagram after Stocker et al. (2013, figure TS.4).

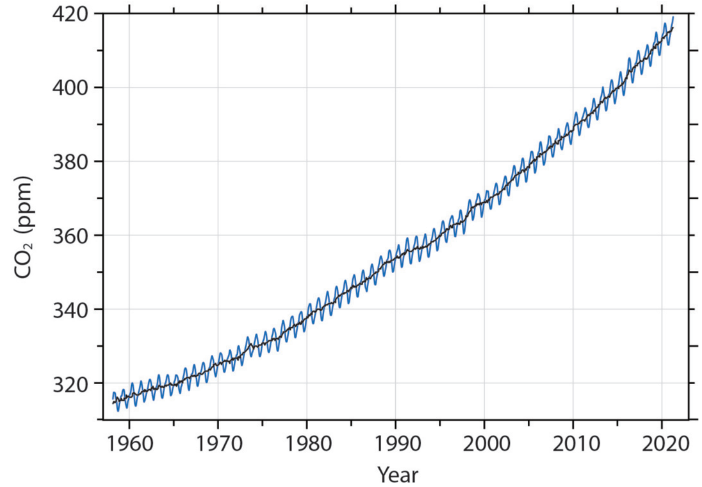

Figure 8. Increase in atmospheric concentration of CO_2 in parts per million by volume at Mauna Loa, Hawaii, 1958–2021. The annual fluctuation in concentration is due to absorption of CO_2 by plant growth in the Northern Hemisphere's growing season and release of CO_2 while burning fuels for heating in winter. Data from National Oceanic and Atmospheric Administration/Global Monitoring Laboratory May 1974 to present and C. David Keeling, Scripps Institution of Oceanography, from March 1958 to April 1974 (GML 2021), reproduced with permission.

pogenic carbon in the atmosphere can be determined by examining its chemical (isotopic) composition. The atmospheric concentration of the radioactive carbon isotope ^{14}C was diluted after the Industrial Revolution by burning fossil fuels which do not contain ^{14}C (Suess 1955). ^{14}C is manufactured in the atmosphere and is included in organic materials as they grow. It decays radioactively over about 60,000 years and is absent from organic materials that are millions of years old. Similarly, the isotopic concentration of ^{13}C has been diluted in the atmosphere by burning fossil fuels with their low concentrations of this isotope (Keeling et al. 2017).

Atmospheric CO_2 and methane concentrations have been much higher in the past, particularly 400 and 200 million years ago — a time when the Earth's overall climatic regime was very different. However, human activities today generate greenhouse gases at a rate far exceeding the capacity of vegetation or oceans to absorb them and hence the atmospheric concentration is increasing (Foster et al. 2017). Natural absorption of CO_2 occurs gradually. For the present atmospheric concentration, about 1000 years will be needed for the atmosphere and oceans to reach a new chemical equilibrium. After this equilibrium is reached, several more thousand years will be required for the oceans to absorb the excess CO_2 and return the atmosphere to pre-industrial concentrations (Archer et al. 2009). The climate change we have already experienced is, in practical terms, irreversible. Given our continued population growth and the time needed to move global society away from fossil fuels, atmospheric concentrations of greenhouse gases will most likely continue to increase over the next few decades and will drive ongoing climate change and its multiple effects (Stocker et al. 2013).

AMPLIFICATION OF GHG EFFECTS BY OTHER EARTH PROCESSES

Anthropogenic greenhouse gas emissions warm the climate, but the resulting adjustments in temperature, evaporation, and precipitation cause additional modifications at the Earth's surface that amplify or exacerbate climate change. An immediate amplifying effect is that evaporation and the potential amount of atmospheric water vapour, also a greenhouse gas, increases with temperature. Since water vapour cycles quickly through the atmosphere, its concentration is a response to temperature and its effect is not to drive climate change but to amplify it (Maslin 2014).

A second effect of global warming is the wasting of ice sheets in Greenland and Antarctica and of ice caps and glaciers in mountains worldwide (Hugonnet et al. 2021). This is apparent in the western mountains and Arctic islands of Canada, where glaciers are shrinking and ice shelves are collapsing (Marshall et al. 2011; Fig. 9). The loss of ice cover lowers surface reflectivity, so that more solar radiation is absorbed and the surface warms further. Reduction in the Arctic Ocean ice cover also reduces reflection of solar radiation from the polar regions and, in turn, contributes to the greater warming observed and expected in the North (Serreze et al. 2007). A similar reduction in reflectivity and enhanced warming occurs in the spring when seasonal snow cover melts earlier or is less extensive across Canada (Zhang et al. 2019).

A third effect follows the thawing of near-surface permafrost, with emissions of CO_2 and methane from the decay of soil organic matter formerly entombed in frozen ground (Schuur et al. 2015; Fig. 10). It is particularly relevant for Canada because, after Russia, we have the largest area of permafrost enriched in carbon, particularly in the Mackenzie River valley, NT, and the Hudson Bay Lowlands of Manitoba, Ontario, and Quebec (Fig. 11). Canada has about 400 billion tonnes of soil organic carbon in the uppermost 3 m of the ground in the permafrost regions (Hugelius et al. 2014). Worldwide, the quantity of carbon in the top 3 m of permafrost terrain, some 1000 billion tonnes (Tarnocai et al. 2009), is about 100 times greater than annual industrial emissions (EPA 2021), so the release of even a small fraction of the permafrost carbon will counteract

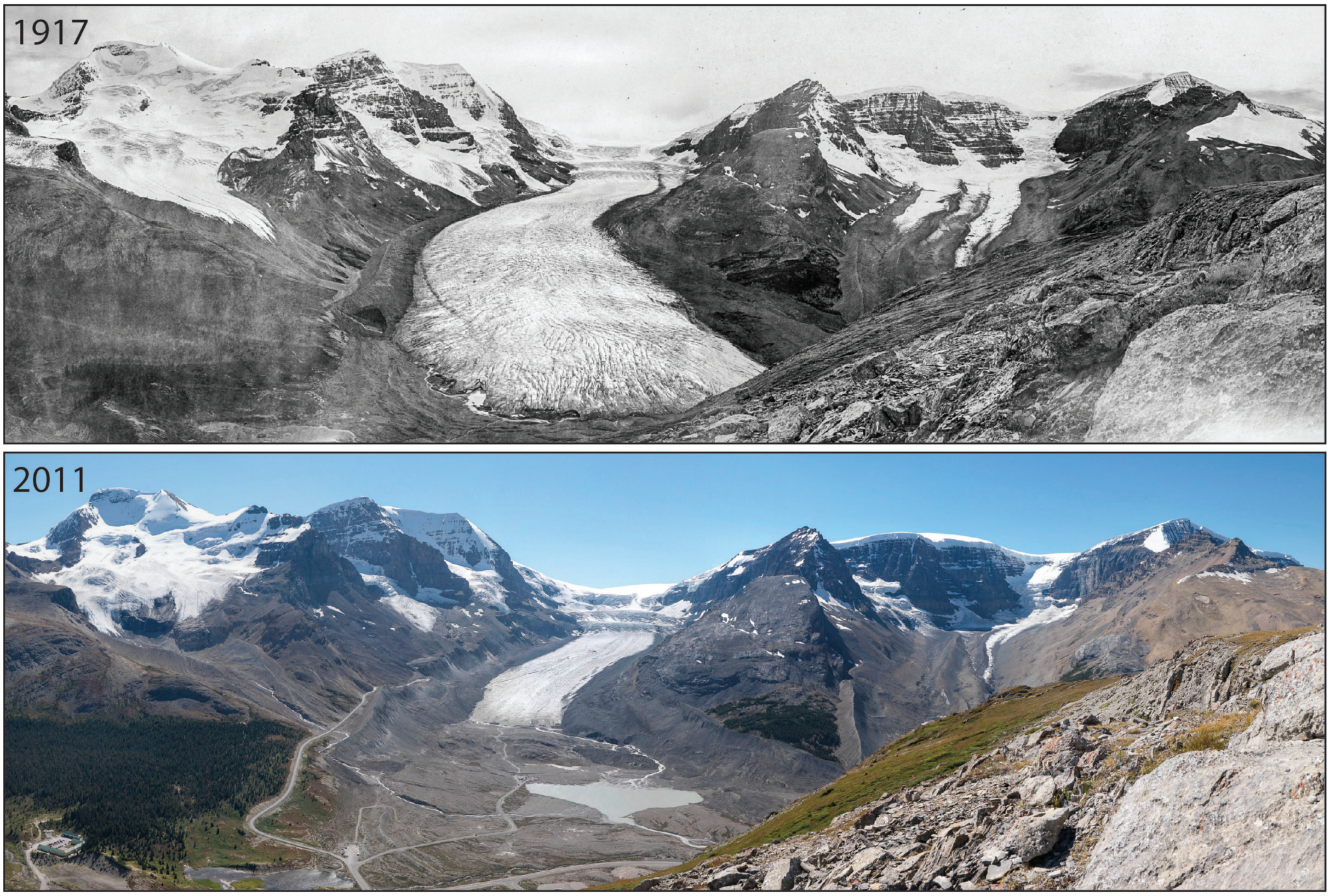

Figure 9. View of Athabasca Glacier from Wilcox Pass, Alberta, showing its reduction in size between 1917 and 2011. The distance from the road in the foreground to the head of the glacier is 6.25 km. 1917 photo reproduced courtesy of Library and Archives Canada / Bibliothèque et Archives Canada, photos e010675607 to e010675610. The 2011 photo courtesy of the Mountain Legacy Project, School of Environmental Studies, University of Victoria, Victoria, British Columbia (http://mountainlegacy.ca/).

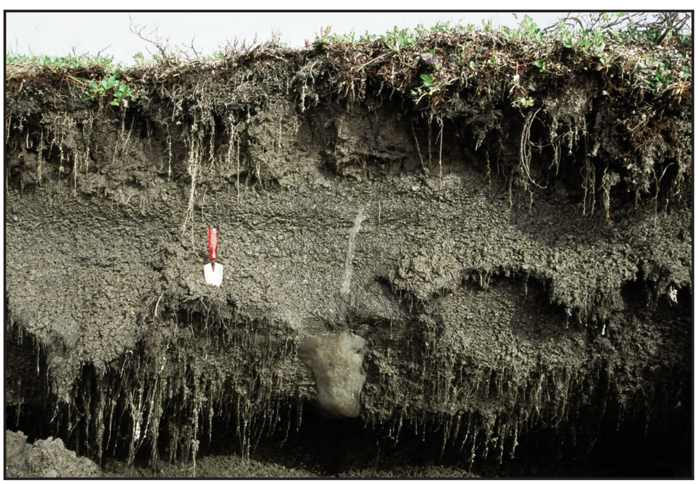

Figure 10. Organic matter (rootlets alongside ice) in near-surface permafrost at Herschel Island, Yukon. Decay of this formerly frozen matter emits CO_2 and methane to the atmosphere. The trowel is 22 cm long. Photo copyright © C.R. Burn.

governments' efforts to limit emissions (Natali et al. 2021). Methane emissions from permafrost sources are of particular concern because CH_4 has greater warming potential, about 30 times higher per tonne than CO_2 over 100 years (EPA 2020). Thawing of permafrost beneath lakes and in the continental shelves of the Arctic Ocean also leads to release of deeply stored geological methane (Walter Anthony et al. 2012; Kohnert et al. 2017).

Two further amplifying effects stem from the increase in area burned by wildfires as summers become drier in a warming climate (Wang et al. 2017). First, a reduction of forest cover reduces evapotranspiration and more of the available solar energy warms the soil and atmosphere. Second, tundra and peatland fires add to atmospheric concentrations of greenhouse gases. These fires have more net emissions than forest fires because burned forests commonly regrow and recapture their lost carbon over a few decades whereas peat takes hundreds to thousands of years to reaccumulate (Zoltai 1993).

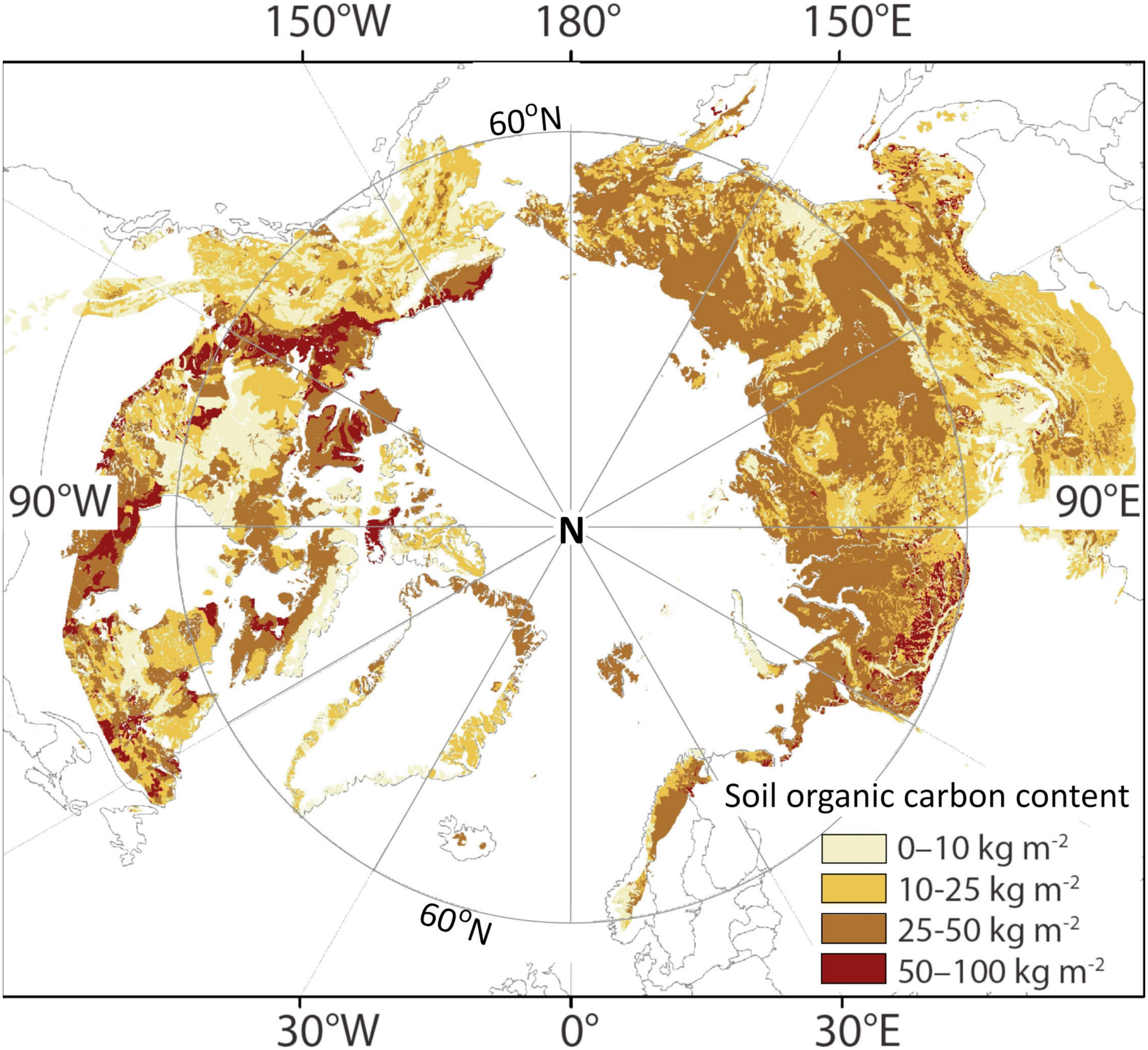

Figure 11. Soil organic carbon content in the uppermost 1 m of the ground throughout thecircumpolar permafrost region. Data from Hugelius et al. (2013); map after Bolin Centre for Climate Change (https://bolin.su.se/data/ncscd/), reproduced with permission.

Significant policy issues arise with such amplification for the responsibility of governments, under international climate protocols, to limit human-sourced emissions. Adjustments in 'natural' carbon sources, resulting from amplifying effects such as permafrost thawing or tundra fires, are not included in a country's emissions totals. Increases from these sources may outstrip actions currently being proposed by governments (Natali et al. 2021).

CONSEQUENCES OF CLIMATE CHANGE FOR CANADIAN SOCIETY

Some of the immediate consequences of climate change stem from the increasing frequency and intensity of unusual and, at times, extreme weather events (Vincent et al. 2018). These lead to flooding, especially in spring, as in Calgary (2013), Saskatchewan (2014 and 2016), eastern Ontario and Quebec (2017), and New Brunswick (2018 and 2019) (e.g. Pomeroy et

Figure 12. The 2013 flood at Heritage Drive, Calgary, Alberta. The flooding in 2013 caused $7.8 billion in insurance losses and direct costs in Alberta (CESD 2016). Photo copyright © The City of Calgary. All rights reserved. Reprinted with permission.

al. 2016; Fig. 12). In addition, the frequency of hurricanes and other major storms making landfall has increased, with 16 of these events battering Canada in the 45 years between 1950 and 1994, and, more recently, 25 hurricanes in the 25 years since 1995. Excessive precipitation and thawing permafrost also promote the conditions for landslides (Patton et al. 2019). Data published by both the federal Climate Disaster Database and the Insurance Bureau of Canada track increasing numbers of weather-related disasters over the last 50 years: the federal data show a doubling of events in 1970–2019, and the Insurance Bureau a tripling in 1983–2019 (Sawyer et al. 2020).

More frequent drought is anticipated with climate change. Many rivers of western Canada depend on runoff from glaciers in the mountains and are now facing reduced flow or drought in the summer as these ice fields melt away and snowmelt occurs earlier in the year (Dierauer et al. 2019). Acute summer drought in the interior of British Columbia is already a regular occurrence due to shifts in timing of spring melt of mountain snowpacks and high water use for irrigation. These factors lead to increased water shortages for municipal use and affect stream flows (Polar Geoscience Ltd. 2012). Reductions in the thickness of mountain snowpacks are leading to reduced replenishment of surface water reservoirs during spring melt, exacerbating water shortages (Schindler and Donahue 2006). Drought in the Prairies, like that in 1999–2004, is similarly expected to increase. However, in areas where recharge of aquifers mainly occurs in summer, more extreme rainstorms may benefit the water supply (Bonsal et al. 2019).

Sea level has risen and fallen over the last few million years, largely in response to glaciation. Current melting of ice sheets and glaciers and warming of the oceans is causing sea level to rise between 3 and 4 mm per year (Dangendorf et al. 2017), increasing the risk of flooding and destructive storm surges for communities near sea level. About 40% of the increase is due to expansion of the oceans as their temperature rises and most of the rest from melting of ice on land. The increase in sea level by the end of this century is projected to be between 0.5 and 1 m, with a further metre possible if melt of the Greenland ice sheet accelerates (Maslin 2014). In the long term, losses from the Greenland and West Antarctic ice sheets are expected to raise sea level significantly, because the level was 6–20 m higher the last time atmospheric greenhouse gas concentrations were similar to present values (Foster and Rohling 2013). Cities such as Charlottetown, PE, and Richmond, BC, will eventually become submerged if the ice caps respond fully to climate warming, but the time at which this may happen is not clear. Sea level also depends on long-term effects associated with movement of Earth's crust, especially continuing relaxation from the loss of the ice that formed during the last glaciation. The east coasts of Canada may experience over 1.5 m of sea level rise before 2100, but less is anticipated on the west coast (James et al. 2021). This century, the near-sea-level transportation corridor between New Brunswick and Nova Scotia, which includes the Trans-Canada Highway and the CN Railway, will become increasingly vulnerable and need protection by dykes or to be relocated (Fig. 13).

Figure 13. CN railway at Tantramar marshes on the New Brunswick–Nova Scotia border during high tide with storm surge of 60 cm, November 2015. Wave splash reached the rails. Photo by Mike Johnson, Cumberland Regional Emergency Management, reproduced with permission.

The effects of sea-level rise will be exacerbated by increased storm damage due to the loss of protective winter ice along shorelines of the Great Lakes, the coasts of eastern Canada, and in the Arctic (Lemmen et al. 2016). The longer open water season and greater area of open water increasing storm wave power has already led to more rapid coastal erosion, threatening Arctic settlements such as Hall Beach, NU, and Tuktoyaktuk, NT (Lim et al. 2020; Fig. 14). Erosion is prevalent along the coast of Prince Edward Island and the depositional shorelines of the Great Lakes (Genest and Joseph 1989; Keillor 2003).

The steady climate warming also has immediate consequences for the inhabitants, infrastructure, and environment of the North. The serviceability of winter roads to northern communities and mines and of infrastructure built upon permafrost will deteriorate. Chilled foundations are now needed for some new buildings with proposed service lives of 30–50 years (Hoeve and Zhang 2019), while roads and airport runways deteriorating through thaw settlement need new, similarly costly construction. Hundreds of waste disposal sites, or sumps, created by military (DEW Line) and resource exploration operations in 1950–2010 were designed to use the surrounding permafrost as a secure containment field but now

https://doi.org/10.12789/geocanj.2021.48.173

Figure 14. Waves breaking at Tuktoyaktuk, Northwest Territories, during a storm in August 2019. Coastal erosion at Tuktoyaktuk has forced relocation of houses such as these. Photo by Weronika Murray, courtesy of Natural Resources Canada.

Figure 15. Failed drilling waste disposal sump at Parsons Lake, Tuktoyaktuk Coastlands, Northwest Territories, June 2004. Photo copyright © C.R. Burn.

may fail (Kokelj et al. 2010; Fig. 15). Natural contaminants, such as mercury released by thawing permafrost, are already being detected in northern rivers but thawing of permafrost around sumps will lead to the release of other wastes (Thienpont et al. 2013; St. Pierre et al. 2018; Mu et al. 2019).

Ocean acidification, due to uptake of CO_2 and its combination with water to form carbonic acid, is a global consequence that will negatively affect marine biodiversity and production (Godbold and Calosi 2013). Climate change also has numerous biological effects; two such recorded examples are the proliferation of shrubs north of the treeline and adjustments in the ranges of various plant and animal species (Wilcox et al. 2019; Aronsson et al. 2021).

The problems that stem from large-magnitude precipitation events are commonly managed through emergency measures, but the gradual effects of climate change may require resources to be diverted from other government programs. There will be higher insurance costs for Canadians as forest fires and floods damage property. Insured losses in Canada from catastrophic weather events exceeded $20 billion in 2010–19, compared with $12.7 billion in the three previous decades (Sawyer et al. 2020). Many Canadians may appreciate the milder winters that climate change brings (Vincent et al. 2018) but not the higher coastal waters, lengthened forest fire seasons, and associated poor air quality in the elevated heat of summer.

CLIMATE CHALLENGES AND SOCIAL RESPONSIBILITY

Environment and Climate Change Canada has estimated that in 2016 Canada's anthropogenic emissions of greenhouse gases were about 1.5% of the global total (ECCC 2021a). We have 0.5% of the global population, and our per-capita emissions are amongst the highest in the world, currently at 19.5 tonnes of CO_2 equivalent per capita (ECCC 2021b). Our national annual emissions have been more than 700 million tonnes of CO_2 almost every year since 1999, even though they have declined on a per capita basis by about 10% since 2005. As of 2019, Canada had 10% of the world's proven oil reserves, the vast majority being in the Athabasca Oil Sands. About half of the world's total reserves that are open to private sector investment are contained in the Oil Sands (NRCan 2019). About 7% of our electricity was produced using coal in 2018, with the tonnage burned declining by 49% since 2008 to 26 million tonnes (NRCan 2021).

Emissions reduction is now recognized as imperative to limit climate change. Society is rapidly developing alternative energy sources and different technologies for a post-fossil-fuel economy. New technologies for power generation, heat storage, electric vehicles, and batteries all require new supplies of critical metals and materials, whose exploration and development must accelerate if we are to transform society away from dependence on carbon in the next 30 years. Earth scientists are involved directly in these initiatives as well as in helping to reduce emissions from operating mines and energy development projects. Direct reduction of atmospheric carbon may be achieved through capture and sequestration facilities that will need to proliferate at sites where the geology facilitates and ensures successful underground storage of CO_2. Government policy plays an essential role in supporting such activities, from research through to development.

There is widespread recognition that the climate is warming. Its anticipated effects are unprecedented in recent human history. The transition to a low-carbon economy must come quickly to mitigate the long-term consequences for future generations of Canadians. However, continued population growth, the amount of time required to transform the global economy, and long-term responses of the atmosphere-ocean-land system, including the time required for the oceans to adjust to atmospheric warming, all mean that climate change and its effects will continue for millennia partly because the rate of absorption of CO_2 by the oceans will decline as the temperature rises (Maslin 2014). Even if the causes could be remedied immediately, adaptation to these consequences will be necessary. Along with rapid reduction of emissions, society requires technical adaptations, better land-use planning, and new standards and regulations driven by sound understanding of the current and predicted environmental effects from climate change. These initiatives will take time to develop and need effective implementation.

CRITICAL ROLE OF THE EARTH SCIENCES

Canada is uniquely positioned with its strong global geoscientific leadership, its vast landmass, and its northern terrain to effectively leverage research activities around climate change. Practical measures, such as improved environmental assessment techniques that include and mitigate effects of climate change on all municipal and industrial development, are also needed. For example, climate change issues such as water availability, forest-fire potential, flooding, and use of cement should be rigorously assessed prior to new housing development and other construction within cities and smaller municipalities. Building codes, strict zoning, and other standards should protect Canadians from climate change effects especially in areas prone to forest fire, flooding, coastal erosion, and/or permafrost thaw (e.g. CSA 2019). Accurate prediction of extreme events by Earth scientists both statistically and in real time will be a key part of climate-change management. Education of students and the public in Earth Science aspects of climate change, as summarized in this statement, will explain the reasons why national action on climate change is necessary. Geoscientists, engineers, and their professional associations will be in the forefront of the activity to identify, mitigate, and adapt to the inevitable effects of climate change (CAPSG 2021).

The scientific knowledge of climate change and its impacts is physically robust. We cannot predict our climate precisely decades from now because we do not know how emissions will change, but we can trust the scientific knowledge regarding climate change because it has stood the test of historical examination of CO_2 and global conditions through the geological record. Our simulations of future climate are based on validated physical understanding of the atmosphere-ocean-land system (Stocker et al. 2013). Legislation, regulation, and policy development all need such knowledge and a long-term commitment to mitigate climate change and manage its effects, while creating opportunities for nation building through innovative and aligned research and development.

ABOUT THE CANADIAN FEDERATION OF EARTH SCIENCES (CFES)

CFES (www.cfes-fcst.ca) is the national organization for Canada's learned, technical, and educational societies in the Earth Sciences. With 14 member organizations, representing 15,000 geoscientists, the mission of CFES is to serve as the coordinated voice of Canada's Earth Science community, ensuring that decision makers and the public understand the contributions of Earth Science to Canadian society and the economy.

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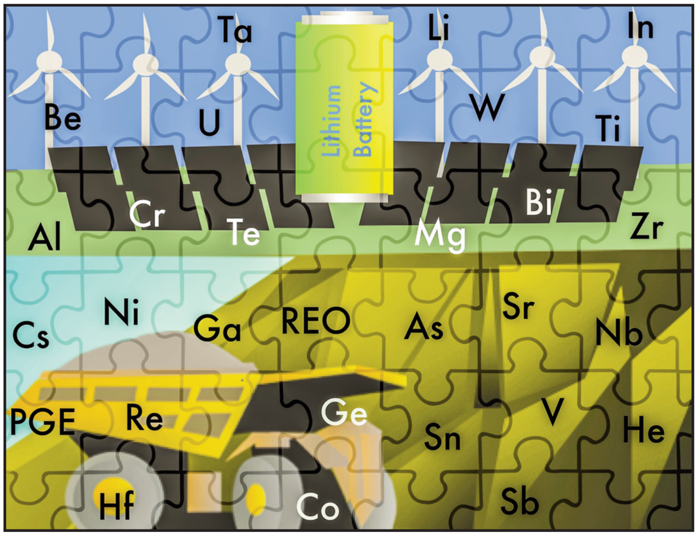

Economic Geology Models 5. Specialty, Critical, Battery, Magnet and Photovoltaic Materials: Market Facts, Projections and Implications for Exploration and Development

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SUMMARY

Many exploration companies are now focusing on specialty materials that are associated with so-called 'green technology'. These include 'battery materials', 'magnet materials' and 'photovoltaic materials', and many such commodities are also broadly labelled as 'critical materials' because they are seen as vital for industrial development, societal needs or national security. The definitions used for such materials are not always consistent among jurisdictions or across industry, and this paper attempts to clarify the criteria and address some common misconceptions. The distinction between major minerals (e.g. base metals) and 'specialty materials' (i.e. those mined or produced in much smaller amounts) is particularly important.

The markets for many specialty materials are growing faster than those for traditional ferrous, precious and base metals and they are often portrayed as excellent long-term investment opportunities. However, the small market bases for specialty materials and considerable uncertainty around growth projections (especially related to material substitutions and rapid technological change) need to be taken into consideration for objective assessment of the development potential of any proposed project, establishment of new supply chains by major corporations, and responsible decision-making (mineral policy) by government. In the short-term, projects aimed at specialty materials (materials with a small market base) cannot benefit from economy of scale, and their development hinges on commercially proven metallurgical processes, unless they are supported by governments or end-users.

Several specialty metals (e.g. germanium, indium, cadmium, and cobalt) are commonly obtained as by-products of base metal extraction. In such cases, systematic testing of base metal ores for their specialty metal content may justify the addition of relevant recovery circuits to existing smelters. If positive results are obtained, the need for targeting new sources of such specialty metals as primary exploration targets may be reduced or eliminated.

Where market conditions permit and concerns about the future availability of materials seem reliable, grass-roots exploration for specialty materials is warranted, and pre-competitive government involvement may be justified to promote such development efforts.

RÉSUMÉ

De nombreuses sociétés d'exploration se concentrent désormais sur les matériaux spécialisés associés à ce que l'on appelle la « technologie verte ». Ceux-ci incluent les « matériaux pour batterie », les « matériaux magnétiques » et les « matériaux photovoltaïques », et de nombreux produits de ce type sont aussi largement étiquetés comme « matériaux critiques » car ils sont

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considérés comme vitaux pour le développement industriel, les besoins sociétaux ou la sécurité nationale. Les définitions utilisées pour ces matériaux ne sont pas toujours cohérentes entre les juridictions ou dans l'industrie, et ce document tente de clarifier les critères et de répondre à certaines idées fausses courantes. La distinction entre les principaux minéraux (par exemple les métaux de base) et les « matériaux spécialisés » (c'est-à-dire ceux extraits ou produits en quantités beaucoup plus faibles) est particulièrement importante.

Les marchés de nombreux matériaux spécialisés croissent plus rapidement que ceux des métaux ferreux, précieux et de base traditionnels et ils sont souvent présentés comme d'excellentes opportunités d'investissement à long terme. Cependant, le marché restreint des matériaux spécialisés et l'incertitude considérable entourant les projections de croissance (en particulier liées aux substitutions de matériaux et aux changements technologiques rapides) doivent être prises en considération pour une évaluation objective du potentiel de développement de tout projet proposé, l'établissement de nouvelles chaînes d'approvisionnement par les grandes entreprises et une prise de décisions responsable par le gouvernement (politique minière). À court terme, les projets visant des matériaux spécialisés (matériaux ayant un marché restreint) ne peuvent pas bénéficier d'économies d'échelle et leur développement repose sur des procédés métallurgiques commercialement éprouvés, à moins qu'ils ne soient soutenus par les gouvernements ou les utilisateurs finaux.

Plusieurs métaux spécialisés (par exemple le germanium, l'indium, le cadmium et le cobalt) sont couramment obtenus comme sous-produits de l'extraction des métaux de base. Dans de tels cas, l'analyse systématique des minerais de métaux de base pour leur teneur en métaux spécialisés peut justifier l'ajout de circuits de récupération adéquats aux fonderies existantes. Si des résultats positifs sont obtenus, la nécessité de cibler de nouvelles sources de ces métaux spécialisés en tant que cibles d'exploration primaires peut être réduite ou éliminée.

Lorsque les conditions du marché le permettent et que les craintes quant à la disponibilité future des matériaux semblent fiables, l'exploration primaire de matériaux spécialisés est justifiée, et la participation préconcurrentielle du gouvernement peut être justifiée pour promouvoir de tels efforts de développement.

Traduit par la Traductrice

INTRODUCTION

The Context of Critical Materials

Future growth in 'green technologies' is largely dependent on the anticipated increase in the use of electric vehicles, and the development of renewable energy operations and energy storage capacities in electricity grids. These visions of a 'green energy future' are indicated in recent studies by the World Bank Group (2017), Hund et al. (2020), the European Commission (2018, 2020), and Küpper et al. (2018). Green technologies are increasingly dependent on reliable supply chains of so-called 'battery', 'magnet', and 'photovoltaic' raw materials. Many of these raw materials are part of a broader category of materials commonly labelled as 'critical', although the criteria for this label are not always rigorous (see below). Efforts by major corporations and governments are underway to secure adequate supplies of several 'critical' raw materials, such as lithium (Li), cobalt (Co), nickel (Ni), graphite, vanadium (V), and manganese (Mn) to meet future demands. At the same time, there is growing public pressure to assess supply chains for such materials in terms of their human and/or environmental impacts, and to ensure that they meet ethical expectations held by western industrialized countries. The U.S., Japan, and many European countries have historically relied on materials sourced from Africa, China, South America, or other countries that have less stringent environmental regulations and lower production costs compared to those of western industrialized nations (European Commission 2017, 2020; World Bank 2017; U.S. Department of the Interior 2018; Hund et al. 2020; Fortier et al. 2020). This is one reason why traditional suppliers of raw materials such as Canada and Australia were finding it hard to compete with African, Chinese, and South American sources producing some of these materials.

The critical materials concept, which western countries relied upon during past military conflicts, was viewed as redundant by some western military powers after World War II and the Cold War, and their stockpiles of critical materials were eliminated or reduced. The rush for 'magnet' materials was reignited around 2010 by disruptions and insecurities around the availability of rare earth elements (REE), following the real or perceived threats by China to reduce or cut its REE exports to western-style industrialized countries as a bargaining strategy in geopolitical and economic negotiations (e.g. Simandl 2014; Goodenough et al. 2018). At that time, China controlled more than 95% of global REE production. Some REE are essential for the manufacturing of high-performance magnets used in wind turbines and electric-car drive trains, and they are widely used in portable computing and communication equipment (e.g. laptops, tablets, smart phones, etc.). These technologies are all considered essential for the economies and national security of developed countries, for efforts to reduce greenhouse gas emissions, and for the transition to low-carbon societies (European Commission 2017, 2020; World Bank 2017; Brainard et al. 2018; U.S. Department of the Interior 2018; Fortier et al. 2020; Hund et al. 2020). The rush to identify new REE resources quickly spilled over to other materials, including 'battery' and 'photovoltaic' materials, and a wide selection of so-called 'critical materials' are now attracting unprecedented exploration interest. The efforts to rely on responsible sourcing and the ongoing global coronavirus pandemic have not diminished this activity, because in many respects, they have highlighted the vulnerability of international supply chains for commodities of all types.

What Are Critical and Specialty Materials?

Numerous companies now focus and explore for materials that are deemed 'critical' by major industrialized nations or nation blocs (European Commission 2017, 2020; U.S. Department of the Interior 2018; Fortier et al. 2020). A full list of these materials is provided in Table 1, which shows that designations vary among jurisdictions. In recent years, emphasis has shifted towards critical materials used in batteries and permanent magnets needed by electric vehicles, for electrical generation and for energy storage associated with alternative (renewable) sources (e.g. solar and wind energy). Most of these so-called 'battery', 'magnet', and 'photovoltaic' materials are designated as critical (Table 1), but many are also termed 'specialty materials' because their global production does not exceed 200,000 tonnes per year.

It is also important to remember that the usage of a given material in battery, magnet, or photovoltaic applications accounts for only a *portion* of its global annual production. For example, global natural graphite production for 2020 was reported at 1.1 million metric tonnes (Olson 2021), but only some of this is used in battery applications. Natural graphite is also used for applications such as refractory bricks, crucibles and crucible linings, brake linings, lubricants, and in electric arc furnaces. Similarly, most of the 86,000 metric tonnes of vanadium produced was used as an alloying agent in iron and steelmaking (Polyak 2021), and almost all the 18.5 million tonnes of manganese produced was used in the steel industry. Other uses of manganese include fertilizers, animal feed, and as a brick colourant, so its actual consumption for battery applications is a trivial part of the global production (Schnebele 2021). The low ratio between total global reserves for a given material and its yearly global production has been used for many years as a general indicator of potential future short-term resource shortages and related price hike forecasts, and as justification for increasing exploration efforts and expenses. This ratio is provided in Table 2. In interpreting data in this way, it is important to remember that ongoing exploration and mining activities continually define new reserves and upgrade resources to reserves, so these apparent 'resource lifetimes' are changing continuously. In a 1999 article for the 'Economist' (Anonymous 1999), Don Huberts (the head of Hydrogen division of Royal Dutch Shell) is quoted: "*The stone age did not end because the world ran out of stones, and the oil age will not end because we run out of oil.*" His prophecy is becoming a reality, and the same will probably apply to materials that we currently consider as essential for a green economy.

The first purpose of this paper is to define and describe the terms 'critical', 'specialty', 'battery', 'magnet', and 'photovoltaic' materials as used today. We then highlight the importance of understanding the current market bases, various market projections, and the possible influences of technological change on future demand. It is especially important to separate hard data (including the current market base) from market projections subject to uncertainties. Both should be considered differently from documents containing more speculative or potentially inflated expectations regarding the commercialization of early laboratory research, non-technical documents emphasizing the potential future importance of a given material, and promotional documents aiming to attract speculative investment. We also stress the need to consider the effects of potential material substitutions and future technological developments on market projections of all types. A full appreciation of all these concepts is essential for the selection of exploration targets, the design of exploration programs, and the timing of mineral development projects or property acquisitions. These issues are important beyond the corporate world, as they should also influence responsible government-level decision making.

Definitions of key terms

Some key terms used in this paper require definition because they also have wider common usage that is less restrictive. Our definitions are provided below:

> *Material:* the element, constituent, or substance (solid, liquid, or gas) of which something is composed of, or can be made of (may be organic, mineral, metal, etc.). Consequently, 'material' is a more general term than 'mineral' or 'metal' (see below).
>
> *Mineral:* a solid, homogeneous crystalline chemical element or compound that results from the inorganic processes of nature (e.g. quartz, feldspar, fluorite, native gold, etc.). This term also includes industrial minerals.
>
> *Industrial Mineral:* a geological material, which is mined for its commercial value, but is not used for its energetic value or as a metal ore. Industrial minerals are valued for their physical and/or chemical properties (e.g. graphite, fluorite, barite). This term also includes 'industrial rocks' (e.g. marble, quartzite, and phosphate rock).
>
> *Metal:* any of various opaque, fusible, ductile, and typically lustrous substances that is a good conductor of electricity and heat, forms cations by loss of electrons, and yields basic oxides and hydroxides (e.g. Cu, PGE, Au). For the purposes of this paper, it also includes some elements that are technically labelled as semi-metals (metalloids) by chemists (e.g. silicon, boron, germanium, and arsenic). For example, silicon has most of the metallic properties, aside from ductility; however, the term 'silicon metal' is used in many publications.

Some materials (e.g. magnesite) have dual allegiance. Magnesite can be considered as an industrial mineral if it is used in the production of Mg-bearing compounds valued for their physical and chemical properties. However, it is considered a metal ore when it is used as a raw material for the production of Mg metal.

MAJOR COMMODITIES AND SPECIALTY MATERIALS: IMPLICATIONS OF CONTRASTING MARKET SIZES

Example of Major Commodities: Base and Precious Metals

Exploration companies typically target major commodities such as ferrous metals (e.g. Fe and Mn), precious metals (e.g. Au and Ag), and base metals (e.g. Al, Pb, Ni, and Zn). These major commodities have well-established global market bases with relatively predictable growth rates related to global eco-

Table 1. 'Critical', 'specialty', 'battery', 'magnet', and 'photovoltaic' materials. A material is designated as a 'specialty' material if its global production is less than 200,000 tonnes per year (global production estimates are provided in Table 2). A material is classified as a 'U.S. Critical Material' if it was included in the U.S. Department of the Interior (2018) Critical Material List. Similarly, a material is classified as 'EU Critical Material' if included in the European Commission (2020) Critical Materials List. Materials are referred to as 'battery', 'magnet', and 'photovoltaic' based on prevalent use in trade journals, company reports, and government publications (by consumers, exploration companies, banks, general public, and governments). Note that individual platinum group elements (PGE) and rare earth elements (REE) are not listed individually.

Material	Specialty Material	U.S. Critical Material	EU Critical Material	Battery Material	Photovoltaic Material	Magnet Material
Sb	x	x	x			
As	x	x				
Barite		x	x			
Bauxite (Al)		x	x			
Be	x	x	x			
Bi	x	x	x			
Borate			x			
Cs	x	x				
Cr		x				
Co	x	x	x	x		x
Coking coal			x			
Fluorspar		x	x			
Ga	x	x	x		x	
Ge	x	x	x		x	
Graphite (natural)		x	x	x		
Hf	x	x	x			
He	x	x				
In	x	x	x		x	
Li	x	x	x	x		
Mg		x	x			
Mn		x		x		
Nb	x	x	x			
Phosphate rock			x			
P			x			
Platinum Group Elements (PGE)	x	x	x			
Potash		x				
Rare Earth Elements (REE)	x	x	x			x
Rhenium (Re)	x	x				
Rb	x	x				
Sc	x	x	x			
Silicon			x		x	
Sr		x	x			
Ta	x	x	x			
Te	x	x			x	
Sn		x				
Ti		x	x			
W	x	x	x			
U		x				
V	x	x	x	x		
Zr	x	x				

nomic cycles. Production of major commodities is not severely geographically restricted and overall, their markets are subject to the law of supply and demand. The prices of these major commodities fluctuate, but there are always markets for the production of most of them, with 'spot prices' available through metal exchange(s).

For these major commodity materials, assuming that technical aspects (e.g. geological, geotechnical, mineralogical, metallurgical factors) are favourable, and that societal and economic conditions permit, a given deposit can generally be developed. It is also normally the case that if we consider two hypothetical and technically identical deposits having the same ore-grade, the deposit having greater tonnage is more likely to be developed than the smaller deposit. This is because economy of scale leads to cost efficiency, as the cost per unit of output generally decreases with the increasing scale and lifespan of the operation.

The positive effects of the economy of scale for many industrial commodities with well-established market bases (e.g. Cu and Fe) are demonstrated by currently profitable high-tonnage, low-grade deposits that are exploited at high production rates.

An example of a mining operation benefiting from economy of scale is the Highland Valley porphyry copper–molybdenum mine in British Columbia, with proven and probable reserves of 484 Mt at 0.31% Cu and 0.007% Mo, respectively. Resource estimates are as follows; measured: 552.3 million tonnes at 0.29% Cu and 0.008% Mo; indicated: 861.6 million tonnes at 0.23% Cu and 0.009% Mo, and inferred: 270.5 million tonnes at 0.20% Cu and 0.008% Mo. The forecasted 2020 production from Highland Valley was 120,000–125,000 tonnes of Cu, and 1500–1800 tonnes of Mo (Clarke et al. 2021). The Highland Valley operation will be used in the next section as a benchmark in discussion of importance of the market base constraint on development of specialty metal deposits.

Examples of Specialty Materials

In contrast to the major commodities and construction materials, many other materials, including some perceived as 'critical,' are produced in much smaller quantities. Materials that have global production below 200,000 tonnes/year are commonly referred to as 'specialty' materials (Tables 1 and 2).

The size of the global market for a typical specialty material, in terms of tonnage, is less than the annual Cu production of two deposits comparable in size to the Highland Valley mine summarized above. Consequently, mining operations supplying specialty materials do not benefit from economy of scale in the manner that large deposits of major commodities enjoy. An example is tantalum (Ta; global production of 1700 tonnes; Table 2), for which some medium-sized operations may be mechanized, whereas smaller and higher-grade deposits, especially if located in developing countries, are artisanal enterprises, worked by hand (Mackay and Simandl 2014; Simandl et al. 2018). Tantalum is a material of great importance in high-technology applications, but its small market base and current prices provide limited incentive for the development of new high tonnage, low-grade deposits that would have to rely on the economy of scale to be profitable. However, there are exceptions, such as pegmatite mining operations in Australia where Ta is co-produced with Li, and where companies are vertically integrated or have long-term contracts for their output.

The REE provide another example. In the medium- and long-term, there is high expected market growth for some of the REE, especially for Nd and Dy, and the market conditions appear very promising. However, let us put this into the context of the *current* market situation. If the law of supply and demand applies and no punitive import tariffs or export restrictions exist, one or two hypothetical, newly developed deposits each producing 50,000 tonnes/year of rare earth oxides (REO) would result in a short-term market oversupply. This is because the world REO demand, including yttrium (Y), was estimated at only 250,000 tonnes in 2020 (Gambogi 2021a, b). It is not surprising that most of the REE deposits that were investigated as potential non-Chinese sources of REE in the early 2000s never made it to the production stage. The price of a specialty material can be severely impacted by oversupply from a single potential new source.

In contrast, a hypothetical new Cu mine equivalent to the Highland Valley example would represent only a small fraction (approximately 0.6%) of the global 2020 Cu production, estimated at 20 million metric tonnes (Flanagan 2021; Table 2). The impact of a new Cu mine on the global supply of Cu would be minimal, and no short-term oversupply of Cu would emerge.

Examples of specialty metals that are considered critical by the U.S. Department of the Interior (Fortier et al. 2020) and the European Commission (2020) include both Ta (used in capacitors), and certain REE, mainly Nd and Dy (used in high-intensity permanent magnets). Other critical specialty materials include minor alloying agents for steel alloys (e.g. Nb, Ta, W, and Be), and other metal alloys (e.g. Sc).

To summarize, we can say that under normal (free market) conditions, projects targeting specialty materials cannot be assessed in the same way as those targeting major commodities. At least in the short-term, because of the small market bases, potential specialty material producers cannot compensate for lower grades by mining and processing larger tonnages of ore (i.e. relying on economies of scale) unless the specialty material is a by-product or a co-product of another commodity. However, if the specialty material is also considered critical, as discussed in the next section, free market conditions may not apply, because in some cases financial incentives may be provided by governments or major corporations.

CRITICAL MATERIALS

Concepts and Definitions

The concept of critical materials is familiar to most people in the resource sector, and there are several examples and reviews of how materials are assessed and ranked in terms of criticality (e.g. U.S. Department of Defense 2013; European Commission 2014, 2017; Simandl et al. 2015; Hayes and McCullough 2018).

Raw materials are essential to the global economy and society. Availability of some materials at competitive prices is now important for the high technology industry and the development of clean emission-free energy. During World War II and the subsequent Cold War, most western countries identified critical materials and maintained stockpiles of them. 'Critical material lists' were considered to be obsolete following the disintegration of the Soviet Union in the late 1980s, and stockpiles were reduced. However, since the early 2010s, relationships between the United States and other western countries with China and Russia have deteriorated, so many western industrialized countries re-established lists of materials

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Table 2. Global production, price, reserves, and years of supply of selected materials. Emphasis is on materials designated as 'critical' by the European Commission (2020) and the U.S. Department of the Interior (2018) and those commonly referred to as 'battery', 'magnet', and 'photovoltaic' by industry, exploration companies, banks, and government users. Source: U.S. Geological Survey (2021). Helium production was converted from cubic metres to tonnes assuming the density was at standard temperature and pressure conditions. Dashes indicate that information was not available. Unless otherwise indicated, production values represent those produced from mining operations, and prices reported are for North American markets. Lifetimes of reserves (years of supply) were estimated by dividing USGS global reserve estimates by 2020 production values (for simplicity, market growth-rate was not considered, see text for details).

		Material	2020 World Production (tonnes)	2020 Price (U.S.$/tonne)[1]	Reserves (tonnes)	Lifetime of Reserves (years)	Main Producing Countries
Examples of Major Commodities and Non-Critical Precious Metals		Au	3,200	56,906,739	53,000	17	China (12%), Australia (10%), Russia (9%)
		Ag	25,000	643,014	500,000	20	Mexico (22%), Peru (14%), China (13%)
		Cu[2]	20,000,000	6,173	870,000,000	44	Chile (29%), Peru (11%), China (9%)
		Zn	12,000,000	2,403	250,000,000	21	China (35%), Australia (12%), Peru (10%)
		Pb	4,400,000	1,982	88,000,000	20	China (43%), Australia (11%), U.S. (7%)
		Fe (usable ore)[3]	2,400,000,000	119	180,000,000,000	75	Australia (38%), Brazil (17%), China (14%)
		Al (metal)[4]	65,200,000	1,962	-	-	China (57%), India (6%), Russia (6%)
Critical Materials		Ni[5]	2,500,000	14,000	94,000,000	38	Indonesia (30%), Philippines (13%), Russia (10%)
		As[6]	32,000	420	-	-	China (75%), Morocco (17%), Russia (5%)
		Barite[7]	7,500,000	198	390,000,000	52	China (33%), India (27%), Morocco (11%)
		Bauxite[7]	371,000,000	30	30,000,000,000	81	Australia (30%), Guinea (22%), China (16%)
		Be[8]	240	620,000	-	-	U.S. (63%), China (30%), Mozambique (6%)
		Bi[29]	17,000	5,952	-	-	China (82%), Laos (6%), Korea (5%)
		Borate[9]	-	-	-	-	U.S.(?), Turkey, Chile
		Co[10]	140,000	35,274	7,100,000	51	D.R. Congo (68%), Russia (5%), Australia (4%)
		Coking coal	-	-	-	-	-
		Cr[11]	40,000,000	198	570,000,000	14	South Africa (40%), Turkey (16%), India (10%)
		Cs	-	-	< 200,000	-	No primary production, except China
		Fluorspar[12]	7,600,000	353	320,000,000	42	China (57%), Mexico (16%), Mongolia (9%)
		Ga1[3, 29]	300	170,000–570,000	-	-	China (97%), Russia (1%), Korea (1%), Japan (1%)
		Ge[7, 29]	130	1,000,000	-	-	China (66%), Russia (4%)
		Graphite (natural)[14]	1,100,000	1,400	320,000,000	291	China (59%), Mozambique (11%), Brazil (9%)
		He[15]	140	4.29	-	-	U.S. (53%), Qatar (32%), Algeria (10%)
		Hf	-	750,000	-	-	-
		In[29]	900	400,000	-	-	China (56%), Korea (22%), Japan (7%)
		Li[7]	82,000	8,000	21,000,000	256	Australia (49%), Chile (22%), China (17%)
		Mg Metal[7, 29]	1,000,000	5,512	-	-	China (90%), Russia (6%), Brazil (2%)
		Mn[16]	18,500,000	4.72	1,300,000,000	70	South Africa (28%), Australia (19%), Gabon (15%)
		Nb[17]	78,000	24,000	> 17,000,000	> 218	Brazil (91%), Canada (8%)
		Phosphate rock	223,000,000	77	71,000,000,000	318	China (40%), Morocco (17%), U.S. (11%)
		Potash[18]	43,000,000	500	3,700,000,000	86	Canada (33%), Russia (18%), Belarus (17%)
	PGE[19]	Iridium	-	51,441,156		-	
		Palladium	210	67,516,517	PGE	-	Russia (43%), South Africa (33%), Canada (10%)
		Platinum	170	27,328,114	combined	-	South Africa (71%), Russia (12%), Zimbabwe (8%)
		Rhodium	-	295,786,648	69,000	-	
		Ruthenium	-	8,359,188		-	
		Osmium	-	-		-	

(continued)

Table 2. *Concluded*

		Material	2020 World Production (tonnes)	2020 Price (U.S.$/tonne)[1]	Reserves (tonnes)	Lifetime of Reserves (years)	Main Producing Countries
Critical Materials	Rare Earth Oxides (REO)	Cerium oxide		2,000			
		Dysprosium oxide		258,000		-	
		Europium oxide	240,000	31,000	120,000,000	-	
		Lanthanum oxide	(REO, except	2,000	(REO, except	-	China (58%), U.S. (16%), Myanmar (13%),
		Mischmetal	Yttrium oxide)	5,000	Yttrium oxide)	-	Australia (7%); Yttrium oxide not considered
		Neodymium oxide		47,000		-	
		Terbium oxide		628,000		-	
		Yttrium oxide	10,000	3,000	500,000		China and Myanmar (qualitative)
		Rb	-	-	-	-	No reliable data
		Rhenium (Re)[20]	53	1,000,000	2,400	45	Chile (57%), Poland (16%), U.S. (15%)
		Sb	153,000	8,774	1,900,000	12	China (52%), Russia (20%), Tajikistan (18%)
		Sc[21]	15	134,000,000	-	-	Canada (20%), China (?), Kazakhstan (?)
		Silicon[22, 29]	8,000,000	2,116	-	-	China (68%), Russia (7%), Brazil (4%)
		Sn	270,000	17,417	4,300,000	16	China (30%), Indonesia (24%), Myanmar (12%)
		Sr[23] (Celestite)	210,000	66	-	-	Spain (41%), China (24%), Mexico (18%)
		Ta[24]	1,700	158,000	> 140,000	> 82	D.R. Congo (39%), Brazil (22%), Rwanda (16%)
		Te[29]	490	55,000	31,000	63	China (61%), Russia (10%), Japan (10%)
		Ti[7, 25]	> 210,000	6,900	1,440,000,000	-	China (52%), Japan (24%), Russia (16%)
		U	-	-	-	-	
		V[26]	86,000	14,771	22,000,000	256	China (63%), Russia (21%), South Africa (10%)
		W[27]	84,000	270	3,400,000	40	China (82%), Vietnam (5%), Russia (3%)
		Zr[28]	1,400,000	6,000	64,000,000	46	Australia (34%), South Africa (23%), China (10%)

[1]Prices in U.S. $ per metric tonne unless otherwise indicated;
[2]Price for U.S. producer (COMEX price + premium);
[3]Production values are for usable ore, and reserve estimates are for crude ore;
[4]Price for ingot;
[5]Prices from London Metal Exchange (LME);
[6]Production values and price estimates are for arsenic trioxide. Prices are for imports from China;
[7]World production estimates exclude U.S. production;
[8]Be-Cu master alloy; beryllium content estimated to be 4%. Kazakhstan and Portugal may have also produced beryl ore but information available was inadequate for estimates;
[9]Boron from Commodity Metals Summary;
[10]Price estimates are for average U.S. spot prices for cobalt cathode (refined cobalt metal produced by an electrolytic process);
[11]Mine production units are tonnes, gross weight, of marketable chromite ore;
[12]Production quantities and price values are for acid grade fluorspar. Reserve estimates are measured as 100% calcium fluoride;
[13]Price range indicates prices for low and high purity gallium;
[14]Prices reported for flake graphite;
[15]Price for Helium in $/cubic metre for nongovernment users. Estimated global production value in units of million cubic metres;
[16]Price, average, 46% to 48% Mn metallurgical ore; cost, insurance, and freight (c.i.f.), U.S. ports;
[17]Prices are for ferroniobium. Reserves exceed 17 million tonnes;
[18]Price, dollars per ton of K_2O, average, muriate, f.o.b. min;
[19]Total PGE reserves are estimated at 69,000 tonnes;
[20]Metal pellets, 99.99% pure;
[21]For ingot, per gram, 5 gram sample size;
[22]Production quantities are the silicon content of combined totals for ferrosilicon and silicon metal;
[23]Prices are for celestite imports into the US World production estimates are also for celestite;
[24]Price are for tantalite concentrate, US$/tonne of Ta_2O_5 content;
[25]Price and production figures are for Ti sponge; resource as TiO_2 content of rutile and ilmenite concentrates;
[26]Prices are for vanadium pentoxide;
[27]Prices are for tungsten trioxide;
[28]Price for imported, unwrought Zr (from China); Production estimate: weigth of Zr ores and zircon concentrates; reserves: tonnes of contained ZrO_2;
[29]Production values represent smelter or refinery production.

deemed as critical for economic, environmental, or national security reasons.

Since 2010, critical materials lists of western industrialized countries have been updated and expanded. For example, the 2018 list commissioned by the U.S. Department of the Interior contains 35 materials (Table 1). The lists of critical materials become substantially longer if the PGE and REE are considered as discrete chemical elements, rather than as groups of elements that commonly occur together. Depending on the interests of the organization that commissions the study (e.g. European Commission, U.S. Departments of Defense and of the Interior and Energy; see reference list for sources), the list of critical materials will vary significantly (Simandl et al. 2015; Hayes and McCullough 2018; see Tables 1 and 2).

The methods used to establish critical materials lists also vary (Simandl at al. 2015) and are not always exclusively based on usage and demand. The methodology used in several well-known criticality studies was compared by Simandl et al. (2015) and thirty-two criticality studies were discussed and summarized by Hayes and McCullough (2018).

Figure 1 demonstrates the principle behind a traditional criticality study, as applied by the European Commission (2014). The vertical axis represents the increasing risk of supply disruption, and the horizontal axis represents the increasing economic importance of a given material. The vertical and horizontal dotted lines represent acceptable 'economic' and 'supply risk' thresholds. For simplicity, we selected two industrial minerals (barite and graphite), one metal (Cu), and one construction material (aggregate). Barite exceeded the supply risk threshold of the study, but its economic importance was low. Copper and aggregate exceeded the economic threshold but were considered at low risk of supply disruption. However, natural graphite exceeded both thresholds and is thus defined as a critical material. The European Commission's critical material study emphasized the importance of materials to their economy, but other studies may employ different criteria. For example, the horizontal axis could represent importance to national security or other specific policy objectives.

Several nations that are major exporters of raw materials have produced their own critical materials lists, which may not always follow the reasoning outlined above, and may reflect internal or regional political pressures. These lists commonly combine the EU and U.S. critical material lists, which reflects the desire to export to the EU and/or the U.S., and to support development of their own non-critical resources. For example, on March 11, 2021, Canada released its own list, which includes 31 materials (Government of Canada 2021). This list of 31 materials includes Cu, which is excluded from U.S. and EU critical material lists, and also includes Nb, U and potash. Canada is itself a major producer of these four commodities, so it is not vulnerable to high supply risks for any of these materials. There is nothing legally wrong with the creation of such 'expanded criticality lists', but the original meaning of the term 'critical' is lost or distorted. The inclusion of Nb, Cu, U, and potash simply reflects the importance of these commodities to Canada's resource-based economy and Canada's desire to supply its trading partners and allies.

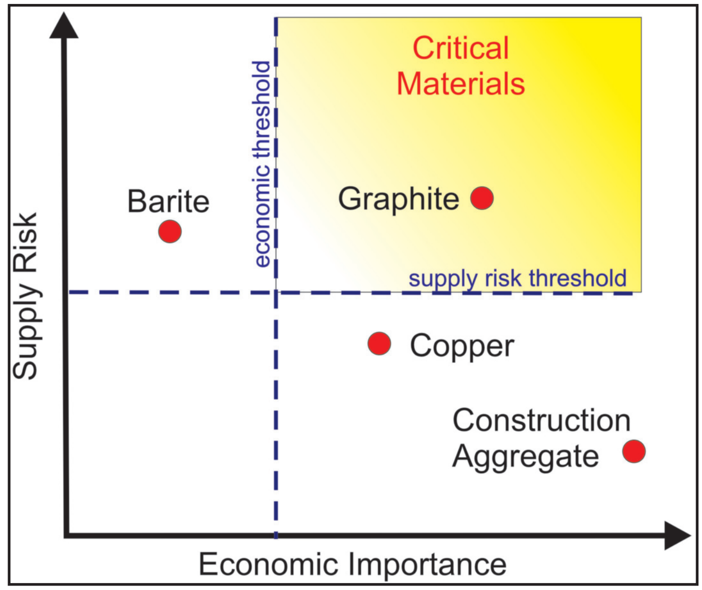

Figure 1. Criticality concept. The vertical axis represents the increasing risk of supply disruption and the horizontal axis represents the increasing economic importance of a given material. The vertical and horizontal dotted lines represent acceptable 'economic' and 'supply risk' thresholds. For simplicity, and to highlight the versatility of this approach, we selected two industrial minerals (barite and graphite), one metal (copper), and one construction material (aggregate). Barite exceeded the supply risk threshold of the European Commission (2014) critical material study; however, its economic importance was low. Copper and construction aggregate exceeded the economic threshold but were considered at low risk of supply disruption. Only natural graphite exceeded both thresholds and plotted in the critical materials field. The horizontal axis of the 2014 European Commission's critical material study represented importance to the economy.

Any critical mineral list that lacks description of the methodology on which it is based should be examined closely to avoid misinterpretation, because some critical mineral list entries may be motivated more by domestic efforts to preferentially support mineral production than by true risk of supply disruption.

To reduce the supply risk, some governments are encouraging the development of domestic critical material-bearing deposits and related supply chains via financial or other incentives. This approach may result in the development of deposits that would not otherwise be developed in a free trade environment. Governments in industrialized countries may also mitigate the level of supply risk by expanding strategic stockpiles of critical materials to limit the impact of potential supply disruptions. This would represent a shorter-term solution but might in some cases be more convenient and cheaper than encouraging development of a domestic supply.

Resources, Reserves and Supply Chains

The concept of a 'circular economy' (defined as a regenerative approach benefiting industries, society, and the environment through ethical mining and recycling) was recently embraced by most industrialized nations and major corporations (e.g. Nassar 2017; Merli et al. 2018). It is expected to influence the classification of critical materials by improving or fortifying existing supply chains. Industry, investors, and the general public are acutely aware that potential shortages in critical materials may materialize in the short to medium terms. However, they seldom realize that the supply chain beginning with an exploration project and leading to end-use of any material (Fig. 2) is complex and not easy to quantify. The supply chain involves exploration, development, mining, processing, concentration, refining, and end-product manufacturing. It extends beyond the production period as end-of-chain activities (by-product recovery, recycling, and mine rehabilitation) must now also be considered for any project.

If all critical material projects currently in the exploration and development stages targeting materials belonging simultaneously to the critical and specialty material categories were brought to production as scheduled, there would be a short-term oversupply, which would inevitably affect prices. The problem that most exploration companies and investors struggle with is how to screen and rank critical material projects according to their true merit.

In general, after the discovery of a major commodity deposit, the development of mining infrastructure, milling facilities and concentration circuits is routine and rarely technically insurmountable. However, for many critical materials (e.g. REE, graphite, Ta, Co, and Li) varied and complex mineralogy can present metallurgical challenges in processing, which can impede the development of a deposit (Fig. 2). This is especially problematic if the critical material *also* belongs to the specialty materials category, because the research investment and financing of new or complex extraction circuits is not justified for such a small market base.

If we consider the simple ratio of global reserves to yearly commodity production (lifetime of reserves; Table 2), shortages of critical materials appear unlikely. This ratio is only an indicator of order of magnitude, but Table 2 shows that at the 2020 production rates, the present global reserves (*sensu* USGS) for most critical materials would last from 12 to more than 100 years. Global reserves will also grow with continued exploration to replace mined-out deposits and upgrade subeconomic resources to reserves. The most likely causes of critical materials shortages would be weaknesses (e.g. bottlenecks) in other links of the supply chain (Fig. 2), time lags in reaching production, or the unwillingness of consumers to accept higher prices. The resistance of consumers to the use of materials sourced from jurisdictions or operations with questionable environmental or human rights records may also become more important in the 21st century.

BATTERY MATERIALS

Transportation Applications

With recent positive forecasts for electric vehicle market growth, the term ‘battery materials’ has emerged as a strong promotional label in the exploration industry. The term generally refers to Li, Co, Mn, V, Ni, and graphite. It disregards several materials used in lead–acid, nickel–cadmium (NiCd), nickel–metal hydride (NiMH), and other older battery technologies. The term also disregards materials used in batteries that are currently in research development, and/or were recently introduced. Examples of excluded materials are Pb, Cd, sulphuric acid and certain REE (mainly La, Ce, and Y), which may account for 4 to 18 wt.% of NiMH batteries (Lin et al. 2016). The 2020 global production of these materials is provided in Table 2.

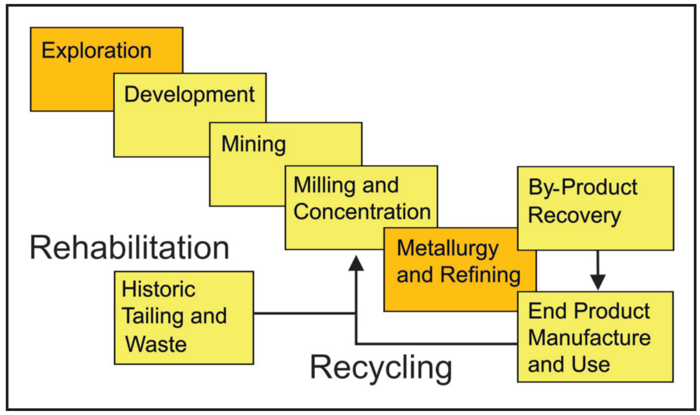

Figure 2. The supply chain from deposit exploration to manufacturing of the end-product and its use. The orange boxes are particularly relevant to this paper and for the early technical ranking of the deposit according to their development potential. In the early stages, only the general market base and growth projections, conceptual and early exploration data, and preliminary metallurgical/refining (geometallurgical) information are available.

Battery technologies are rapidly evolving, but the current emphasis in transportation-related applications is on lithium-ion batteries. A typical modern Li-ion battery consists of an anode, a cathode, an electrolyte, a polymer separator, Cu and Al current collectors, and a casing. The anode electrode consists mainly of graphite and/or other carbon-based materials. The most common type of cathode electrode belongs to a ‘layered category’ of $LiMO_2$, where M consists of a combination of Co, Ni, Al, and/or Mn. ‘Non-layered categories’ of cathodes (e.g. lithium iron phosphate, $LiFePO_4$, also referred to as LFP) are less common. LFP-type batteries were used mainly in China for bus propulsion, grid stabilization, and in some electric vehicles. Until recently, it was believed that LFP batteries would be replaced by batteries relying on layered cathodes, mainly nickel–manganese–cobalt (NMC) and nickel–cobalt–aluminum oxide (NCA) types that possess higher energy densities (e.g. Olivetti et al. 2017). A high energy density battery is favoured in transportation applications because it provides a longer travel range for the electric vehicle between two consecutive charges for the same weight of battery. Surprisingly, since October 2020, lower energy density LFP batteries are finding their way into Tesla Model 3 vehicles produced in China and into lower-cost electric vehicles produced elsewhere. Research and development objectives specific to Li-ion batteries for the automotive industry are summarized in Figure 3. This figure, modified from Bresser et al. (2018), combines views of representatives from China, Germany, Japan, and the U.S. who participated in the Advanced Lithium Batteries for Automobile Applications 10 Conference held in Chicago, U.S. in 2017. It is essentially a survey summary and it provides a comprehensive overview of the research and development strategies in several industrialized countries. The details vary by jurisdiction, but the long-term objectives are similar, i.e. manufacturers aspire

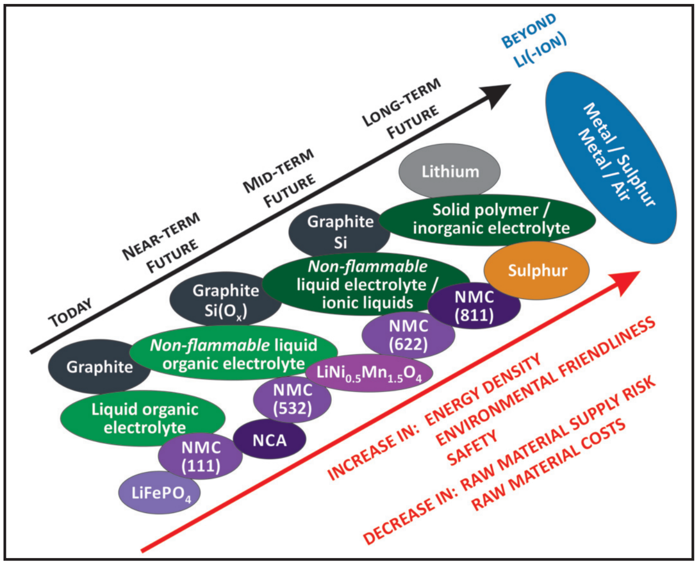

Figure 3. Summary of research and development objectives specific to batteries for the automotive industry; covering anode, electrolyte and cathode materials. The anticipated progression in anode materials (black) leads from graphite to lithium in the long term. Similarly, in terms of electrolyte progression (green), the expected path will lead from liquid organic electrolytes to solid polymer/inorganic electrolytes. The expected cathode evolution trend (purple) leads from current lithium–iron–phosphate ($LiFePO_4$; i.e. LFP) and NMC to sulphur (orange) in the long term. Post-lithium–ion battery era shown in blue will be dominated by metal–sulphur and metal–air batteries. The proportions of metals, in respective order, are indicated numbers in parenthesis. NMC = nickel–manganese–cobalt (for example, NMC 111 has Ni–Mn–Co in ratios of 1:1:1). NCA = nickel–cobalt–aluminum (Ni–Co–Al) oxide. This figure is based on selected presentations from the annual International Conference on Advanced Lithium Batteries for Automotive Applications held in Chicago in October 2017 and is modified from Bresser et al. (2018).

to reach the post-Li-ion battery era through the commercialization of new battery chemistries. During this process they wish to increase the safety and energy density of batteries and reduce the use of costly cobalt. Inevitably, such successes would change the material requirements for the industry.

Substitutions are being routinely explored to reduce the use of high-cost raw materials in batteries (Leader et al. 2019), and especially those listed on EU and U.S. critical material lists. These efforts aim to protect industrial end-users against the impact of supply disruptions and keep the prices of batteries as low as possible without sacrificing quality or efficiency. The requirements for Li, Co, Ni, Mn, and C materials to produce lithium–cobalt oxide ($LiCoO_2$; LCO), lithium–nickel–cobalt–aluminum oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}$; NCA), and nickel–manganese–cobalt oxide (NMC) battery cathodes are listed in Table 3, in units that reflect their energy density (kg of material per kilowatt-hour). The lower requirement for Co in NCA and NMC cathode types is quite evident, as is the implied sensitivity of different types to changes in the prices of individual battery materials. Conversely, the variety in compositional proportions allows some flexibility of cathode choice, depending on commodity prices.

As an example, the direct impact of a hypothetical 100% increase in the price of Li, Co, Mn, and Ni on the overall cost of Li-ion batteries is shown in Figure 4. In the case of Mn, doubling the price has a limited impact, regardless of the battery type. In the case of Ni, the impact would be low to moderate for NCA and NMC 811 types. On the other hand, Co price increases would be severe for LCO and NMC 111 types but would not affect lithium–manganese oxide ($LiMn_2O_4$, LMO) or LFP systems. Lithium price increases would have the most significant effect on LFP and LMO batteries but would affect all types to some extent (Fig. 4).

Table 3. The main materials required for production of five prototypical cathodes used in Li-ion batteries in kg/kWh (Olivetti et al. 2017). LCO = lithium–cobalt oxide; NCA = lithium–nickel–aluminum oxide; NMC = lithium–nickel–manganese–cobalt oxide (where numbers following 'NMC' designation represent Ni:Mn:Co ratios on a mole fraction basis; for example, NMC 622 has a 6:2:2 Ni:Mn:Co ratio).

	Li	Co	Ni	Mn	C
LCO	0.113	0.959	0	0	~1.2
NCA	0.112	0.143	0.759	0	
NMC 111	0.139	0.394	0.392	0.367	
NMC 622	0.126	0.214	0.641	0.200	
NMC 811	0.11	0.094	0.750	0.088	

Nevertheless, the cost of raw materials is only one of many factors that need to be considered in this sector. For example, NMC 811 batteries show great promise in efforts to increase the driving range of electric vehicles and reduce the use of Co. However, technical problems and especially safety concerns around thermal runaway (leading to fires) have impeded the penetration of NMC 811 batteries into North American and European markets. Adamas Intelligence estimated that between January and September 2019, the market share of new passenger electric vehicles equipped with NMC 811 batteries increased from less than 1% to 18% in China but reached only 7% globally (Green Car Congress 2019).

In theory, solid-state batteries will be less expensive, will benefit from higher energy densities, and will provide higher safety than 'traditional' liquid electrolyte-based batteries currently used in plug-in electric vehicles. However, the potential impact of specific future battery chemistries for electric vehicles (Fig. 3) is difficult to evaluate because many of these are in the early research stage and have yet to demonstrate commercial viability. Expectations of usage remain speculative, and some predictions may be overly optimistic (Sapunkov et al. 2015; Walker 2018).

Energy Storage Applications

Stationary energy storage systems are required to maintain the stability of the electric power grids during transient peak demands and to accommodate the intermittent nature of renewable energy generating power systems (e.g. wind and solar). They are also important for backup power generation in a carbon-neutral future. The requirements for these uses are different from those that apply to transportation applications (Guney and Tepe 2017; Mendoza-Vizcaino et al. 2019). Low energy density is not a major issue for stationary energy storage systems, but safety, reliability and durability are important (Chediak 2018). Although there is a perception that Li-ion batteries will be more important in transportation rather than in

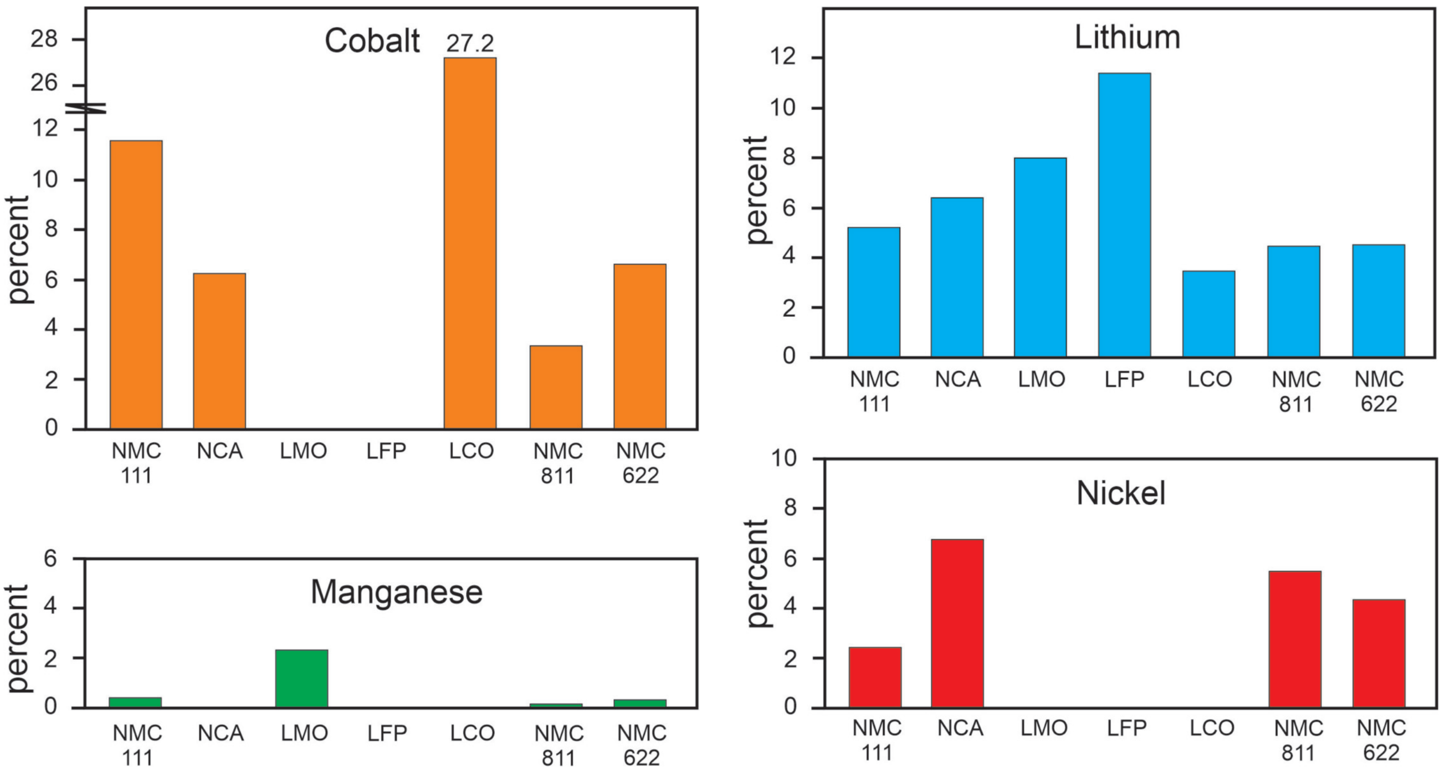

Figure 4. Impact of 100% price increase in Li, Co, Mn, and Ni on the cost of selected Li–ion battery systems (from Leader et al. 2019).

energy storage, this may not be the case. Bloomberg's predictions suggest that by 2030 the U.S. energy power grid storage capacity will approach 80 GWh (Fig. 5) and that Li-ion batteries will play a major role in this achievement (Chediak 2018).

Examples of non-Li energy-storage systems that already have reached the market or have the potential to do so include vanadium redox flow (VRFB), lead–acid, nickel–cadmium (NiCd), nickel–metal hydride (NiMH) types, and high-temperature batteries such as sodium–sulphur (NaS) and sodium–nickel–chloride (NaNiCl) types (Luo et al. 2015). Vanadium redox flow batteries appear particularly promising, but require an ion exchange membrane made from *Nafion*, which is an expensive product from DuPont (Vanýsek and Novák 2017).

In recent years, VRFBs have been considered as front-runners in grid-scale energy storage and to be on the verge of commercialization (Sánchez-Díez et al. 2021). However, a lifetime cost analysis of nine electricity storage technologies in twelve different system applications suggests that this is far from certain (Schmidt et al. 2019). Large-scale repurposing of used batteries from electric vehicles or traditional batteries displaced by solid-state batteries in other sectors could represent alternatives to VRFB deployment (Miao et al. 2019). Batteries operating at temperatures around 300°C, such as sodium–sulphur (NaS) and sodium–nickel–chloride (NaNiCl) are effective for energy storage, but the need to maintain a high temperature and related safety concerns currently present obstacles to commercialization.

The U.S. Department of Energy's Global Energy Storage Database (Sandia National Laboratories 2021) currently contains 1697 energy storage projects (proposed, under construction, operational or decommissioned). Battery technologies included as operational or future operations in this database include Li-ion (e.g. lithium iron phosphate, lithium titanate, lithium manganese dioxide, lithium nickel cobalt aluminum oxide), Na-ion batteries (e.g. sodium nickel chloride), redox flow batteries (e.g. vanadium), hybrid flow batteries (e.g. zinc bromine), and Ni-ion batteries (e.g. nickel iron, nickel metal hydride, nickel cadmium). Consequently, many materials that are currently not considered to belong to the 'battery' category may become more important in the future, and the demand for some materials of current interest could diminish. The potential for technological developments in the energy storage sector resembles the situation in the transportation sector (Fig. 3) and the long-term directions of both are hard to predict.

MAGNET MATERIALS

The term 'magnet materials' presently refers largely to the REE, specifically neodymium (Nd), praseodymium (Pr), samarium (Sm), dysprosium (Dy), and terbium (Tb). It also includes Co, but omits materials used in older magnet technologies such as ferrite-type magnets. Developments in permanent magnet technologies were slow and steady over more than 50 years (Baker 2018). Aluminum–nickel–cobalt (AlNiCo) magnets were first developed in the 1940s. In the 1950s, inexpensive, easy-to-process, relatively demagnetization-resistant ferrite or ceramic magnets (e.g. $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$) were introduced. More powerful REE-based magnets started with the development of YCo_5 magnets and later $SmCo_5$ and Sm_2Co_{17} magnets then captured most of the market in high-performance motors. Sm_2Co_{17} magnets were then

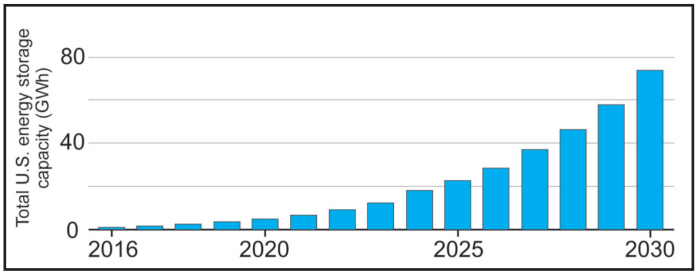

Figure 5. Expected growth in the total U.S. energy storage capacity in gigawatt-hours according to Chediak (2018). Values are forecasts from 2018 onwards.

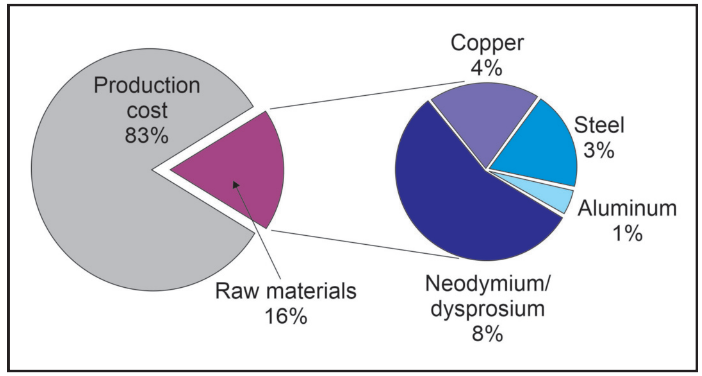

Figure 6. Cost breakdown of an electric motor for an electric vehicle; specifically, a Chevrolet Bolt E-Motor. Cost of motor reported to be U.S. $1200–1550. Source: Hummel et al. (2017). Note that values in left pie chart do not sum to 100% likely due to rounding.

largely replaced by $Nd_2Fe_{14}B$ magnets, due in part to research following the eightfold increase in Co prices caused by civil unrest in the Democratic Republic of the Congo (then called Zaire) in 1978 (Baker 2018). This is a prime example of how material price instability can drive technology research.

Neodymium–iron–boron (NdFeB) magnets contain approximately 30% REE, mostly Nd and to a lesser extent Dy (the latter is added to widen the operating temperature range), and small concentrations of other REE (e.g. Pr). Today, they are highly publicized because of their use in motors for electric vehicles, wind turbines and a variety of portable electronic equipment, and are considered to have the greatest potential market growth. Currently, REE (mainly Nd and Dy) represent 8% of the total cost and 50% of the raw materials cost for a typical electric vehicle motor (Fig. 6; Hummel et al. 2017; Delfeld 2018). According to Roskill (2018), a typical electric vehicle now requires around 1 to 2 kg of Nd–Pr alloy.

Price variations of Nd and Dy have a much higher impact than comparable price variations of Cu, steel, or Al, and will affect the total cost of a typical electric vehicle motor module (Fig. 6; Hummel et al. 2017). If we assume that the price of an electric motor used in the Chevrolet Bolt vehicles produced in 2017 was U.S. $1375 (middle of the range estimate provided in Fig. 6), the price of Nd and Dy raw materials would have been approximately U.S. $110, or about 8%. If the cost of Nd and Dy doubles, the total price of the motor would increase from U.S. $1375 to U.S. $1595. The REE would then account for 13.8% of the electric motor costs for the vehicle.

In 2018 and 2019, approximately 30% of the world's wind turbines relied on direct drive NdFeB magnet-based technology. The construction of these turbines accounted for 8–9% of estimated global NdFeB magnet production. In the future, proposed offshore wind farms are expected to compete head-on against the growing demand for NdFeB magnets for use in electric vehicles (Roskill 2019). To achieve the U.S. Department of Energy's objective of generating 86 GW of electric power from U.S. offshore wind farms by 2050, approximately 15,500 tonnes of Nd would be required. If the average Nd requirement for an electric vehicle motor is conservatively assumed to be 0.75 kg per vehicle, the amount needed for offshore wind energy purposes equates to nearly 21 million hybrid or electric vehicles (Fishman and Graedel 2019).

For these reasons, and because of perceived risks in global REE supply, research is seeking substitutes for NdFeB magnets (Widmer et al. 2015; Pavel et al. 2017a, b) and methods to recycle REE from waste (Schulze and Buchert 2016; Auerbach et al. 2019; Swain and Mishra 2019). If the REE cannot be eliminated, the REE content of magnets could also be reduced through better design and use of nanocomposites (Geuss 2018). Over the past decade, lots of research was directed towards improving the microstructure and physical properties of non-REE-based permanent magnets. Those with the best potential for replacing REE-based permanent magnets (or at least filling the gap between ferrite and REE-based magnets) were covered in detail by Cui et al. (2018). These details are well beyond the scope of this paper; however, as is the case for the battery industry, future technological innovations leading to commercialization results of this research could significantly alter the market conditions for materials currently belonging to this category.

Selecting the best choice among permanent magnet technologies is not straightforward if costs, performance, energy use, environmental impact and other aspects are all taken into consideration (Grunditz et al. 2018). The SmCo-type magnets are weaker and more costly (at current prices) than their NdFeB counterparts, but they can operate at higher temperatures than NdFeB magnets. Despite their shortcomings, unheralded old-technology ferrite magnets still account for the largest portion of the permanent magnet market by volume. Permanent magnets are also not an *absolute* requirement for electric vehicles, as some use so-called induction motors. The latter rely on current flowing through the stator windings to induce a magnetic field, and thus require no permanent magnets. However, motors using permanent magnets are lighter and smaller than induction motors and provide faster acceleration and longer driving ranges. Tesla, a premium North American electric car manufacturer, employs both permanent magnets and induction motors. In the past, its Model S and Model X vehicles used induction motors, whereas its Model 3 motor relied on permanent magnets (Geuss 2018). However, since 2019, all three Tesla models use motors with permanent magnets rather than induction motors to increase their range and performance.

PHOTOVOLTAIC MATERIALS

Theoretically, solar energy could provide more than enough energy for Earth's population (Solar Energy Industries Association 2018). Recent improvements in photovoltaic (PV) technology have reduced the cost of solar energy relative to traditional energy sources. The power capacity of installed PV panels in the U.S. reached 60 GW in 2018, and it is expected to double by 2023. China's total PV capacity recently increased by 60 GW in only one year (Solar Energy Industries Association 2018), and the cumulative global capacity of photovoltaic installations reached an energy generating capacity of 518 GW in 2018 (Heath et al. 2020). Thus, photovoltaic technology is a major contributor to efforts to combat climate change through green energy, and materials used in these applications are attracting wide interest.

Before the early 1970s oil crisis, most of the efforts to recover energy from solar radiation were focussed on aerospace applications (Braga et al. 2008). The oil crisis first ignited interest in the terrestrial application of photovoltaic technology. Silicon-based and 'thin-film' photovoltaic technologies are described separately below, but both are expected to remain important in the quest to optimize efficiency in converting solar energy into electricity. Ultimately, both technologies may be combined in the production of highly efficient multi-junction cells. However, currently this gain in efficiency is counterbalanced by a significant increase in manufacturing complexity and production cost.

Silicon-based Photovoltaic Technology

Until 1996, production of silicon-based photovoltaic (PV) technology was focused on panels using monocrystalline silicon (where the crystal lattice of a given photovoltaic cell is continuous, unbroken, and free of grain junctions and boundaries). Since then, there has been a shift to so-called 'polycrystalline panels' (where individual cells consist of multiple small crystals or grains of silicon in contact with each other and having varied crystallographic orientations). Both types are silicon-based, and raw materials used in their production until around 1997 largely came from rejects provided by the microelectronics industry (Braga et al. 2008). Today, most commercial PV modules based on first-generation silicon wafer technology convert 17% of incoming solar energy into electricity (Green et al. 2015; Fraunhofer Institute for Solar Energy Systems 2020). The theoretical efficiency of a crystalline silicon solar cell is around 29% (Richter et al. 2013), and efficiencies approaching these limits are reported for prototype designs (Oberbeck et al. 2020).

The raw materials used to produce metallurgical grade and chemical grade silicon metal are readily available, but these cannot be used directly in the production of solar grade silicon because of impurities or unfavourable physical properties. Silica raw material generally contains less than 99.8% SiO_2 and must be upgraded. The transformation involves carbothermic reduction (Xakalashe and Tangstad 2011; Maldonado 2020) followed by chemical or metallurgical processing to yield silicon metal at ≥ 99.9999% Si. The latter has a price of U.S. $10/kg or more, compared to less than 5 cents/kg for raw silica. Processing is energy-intensive and without government interventions, solar grade silicon prices would likely be U.S. $70/kg (Louwen et al. 2016; Chigondo 2018). There is much ongoing research to find lower-cost methods to produce solar-grade silicon (e.g. Marchal et al. 2015; Darghouth et al. 2021; Nagahata et al. 2021).

Thin-film Photovoltaic Technology

The relatively high prices of crystalline silicon also motivated research into 'thin-film-technology' solar cells that require one or more specialty metals. These are widely regarded as having a promising role in future PV technology.

These thin-film PV cells commonly involve cadmium–tellurium (CdTe), copper indium gallium selenide (CIGS), or other materials such as zinc oxide (ZnO) and cadmium–sulphur (CdS). Since about 2010, the conversion efficiency of these thin-film modules has increased significantly (Green et al. 2015; Fraunhofer Institute for Solar Energy Systems 2020). For example, the conversion efficiency of CdTe modules has increased from 9% to 19% since 2010. The future of the photovoltaic industry appears bright because modern high concentration multi-junction thin-film photovoltaic cells achieve conversion efficiencies of up to 47.1% in laboratory tests (Fraunhofer Institute for Solar Energy Systems 2020). This is considerably above the theoretical limits for silicon-based PV cells.

Many of the raw materials involved in thin-film PV technology are largely co-products of base metal smelting, so they are not ideal primary exploration targets. Many believe that material shortages or potential future supply disruptions could slow down commercialization of new technologies for energy production, and the availability of each metal should be considered individually (Davidsson and Höök 2017; Frenzel et al. 2017; Zhou et al. 2020).

Research in the thin-film technology domain is as intensive (if not more intensive) than in the field of crystalline silicon cells. The future of thin-film-based panels is very promising from a technological standpoint. However, some of them contain materials considered toxic (e.g. Cd), so questions linger regarding environmental impacts during production and later recycling and/or disposal.

In summary, if we consider that the need for renewable energy will continue to rise rapidly and that, based on the laboratory tests, the modern multi-junction photovoltaic cells can achieve conversion efficiencies exceeding 47%, the future of the photovoltaic industry appears bright.

RELATIONSHIPS BETWEEN SPECIALTY, BATTERY, MAGNET, AND PHOTOVOLTAIC MATERIALS

Up until this point, we have presented definitions and examples of critical, battery, magnet, photovoltaic, and specialty materials. Some of these materials belong to more than one of these five material categories; the complex relationship between these categories is depicted in Figure 7 and it shows many overlaps. For example, Co belongs to all categories except for photovoltaic materials. Cobalt can be promoted as a critical battery and/or magnet material depending on the available fundraising opportunities, or the availability of government stimuli. In contrast, barite only belongs in the wider critical materials category, so promotional opportunities for barite are far more limited. Figure 7 also shows that many critical materials fit into the specialty materials category. Projects that target critical specialty materials are severely constrained by the limited market base. As discussed earlier in the paper, such projects are unlikely to benefit from the economy of scale that commonly applies to the production of major commodities. In the final section of the paper, we examine some of the specific challenges and problems that must be considered in the assessment of projects targeting critical specialty materials.

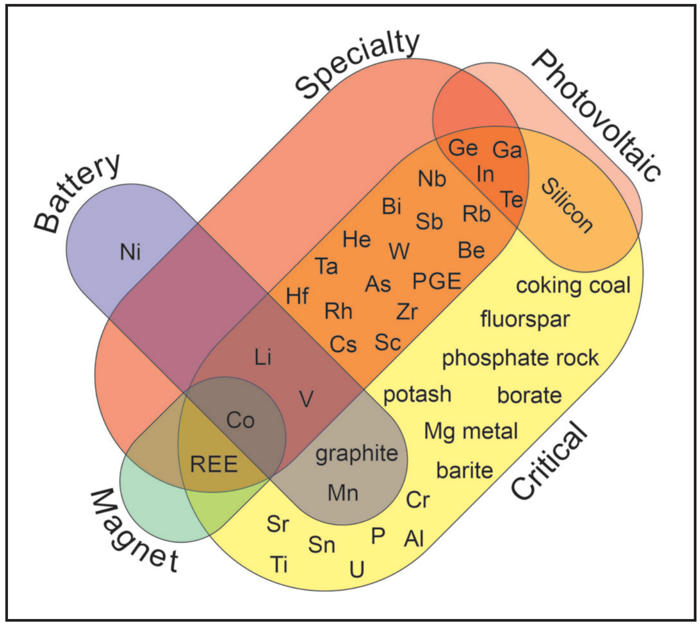

Figure 7. Examples of overlapping material categories. Terms 'battery', 'magnet', and 'photovoltaics' are used here in *sensu lato* (as used by industrial users, exploration companies, banks, and government organizations). For example, cobalt (Co) is currently considered as one of the specialty materials but may be referred to as a 'critical', 'battery', or 'magnet' metal.

FUTURE EXPLORATION AND DEVELOPMENT OF SPECIALTY MATERIALS

The Distinction Between Market Base and Market Projections

Larger exploration companies and vertically integrated mining companies have the luxury to consider medium- and long-term investments, but many junior mining and exploration companies are more concerned with short-term survival. Regardless of the company's size and financial situation, the market base (i.e. tonnes of material used per year) must be reflected in the design of exploration programs, and in the selection of a viable target. For example, in the short-term, compensating for low-grade ore in a specialty material(s) deposit by attempting to define much larger reserves is probably not a viable strategy because the current market base cannot support a large operation with a high production rate. However, if projections of the future demand for the material are enticing, lower grade–higher tonnage deposits may be appropriate targets for long-term development planning. This would be particularly true for an established specialty material producer with an existing market share.

Assessing Long-term Projections in Relative and Absolute Terms

In the long term, the markets for battery, magnet, and photovoltaic specialty materials are expected to grow at much faster rates than markets for typical industrial metals, such as Al and Cu. We are all bombarded by market projections and development proposals for battery, magnet, and photovoltaic materials, but most of the better studies are proprietary in nature. For the purpose of this paper, we use projections from the World Bank Group study authored by Hund et al. (2020). These projections predict the potential magnitude of the energy material requirements for the year 2050, assuming the "2-degree scenario" from the International Energy Agency (2017) report on energy technology perspectives. This scenario is considered to have at least a 50% chance of limiting the average global temperature increase to 2°C by the year 2100. The market growth projections for 17 materials considered in this scenario can be presented in two contrasting ways (Fig. 8a, b). Essentially, materials historically targeted by exploration companies because of their significant market base, such as Mn, Cu, Zn, Al, Mo, Pb, and Ni, are forecast to benefit from modest growth. This contrasts with the predictions for other materials belonging to the specialty material category, which are expected to benefit from spectacular growth. For example, Li, Co, and In have 2050 annual demand forecasts for energy technologies that are at least double their total production estimated for 2018 (Fig. 8a; Table 2).

Any promoter trying to raise money for critical materials, battery materials, or photovoltaic materials exploration projects will be thrilled by the approach used in Figure 8a, because the projected 2050 market for graphite, Li, Co, In, V, Ni and Nd appears spectacular relative to the corresponding 2018 global productions. Such long-term market growth projections, presented alone, or briefly as presentation slides, could impress explorationists, investors and developers, and might alarm politicians and end-users of such critical materials. However, if the same data are presented in a more traditional way, i.e. in terms of absolute yearly consumption (Fig. 8b), investor enthusiasm might subside, as the projected energy industry consumption (tonnage/year) for most materials with substantial market bases (e.g. Al, Cu, Zn, and Mn) is relatively unappealing, and usage projections for specialty materials (e.g. Ti, Nd, V, Li, and Co.) appear small in absolute terms. The only material that stands out regardless of the way in which the data are presented is graphite, although the projections for Ni also indicate significant market growth. The most balanced view of these long-term projections is achieved if both approaches (Fig. 8a, b) are presented simultaneously to allow comparison.

The Accuracy of Market Projections

Market projections are available for most specialty materials, but such projections have often proved inaccurate. For example, a projection for 2014, made in 2010, estimated a total

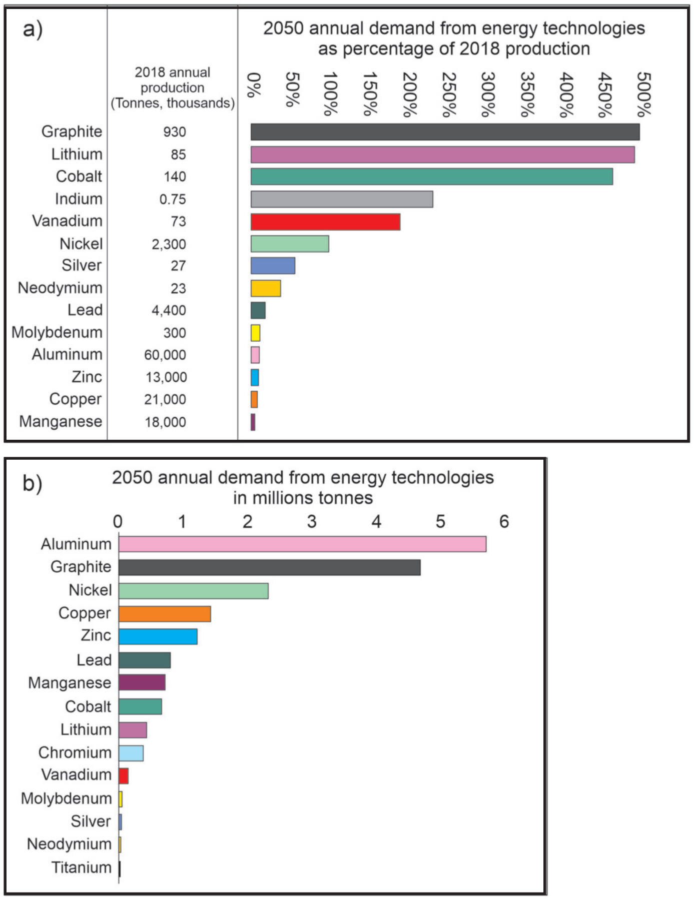

Figure 8. Expected material demands based on projections for ten energy technologies in 2050, assuming a 2 degrees scenario as defined in the International Energy Agency (2017) report; a) shown as a percentage of 2018 global production; b) shown in millions of tonnes. The 2018 global production data is from USGS Mineral Commodity Summaries (U.S. Geological Survey 2021). Figure modified from Hund et al. (2020).

demand of 197,000 tonnes/year for Rare Earth Oxides (REO) (Watts 2010) and even higher estimates were given by several renowned mineral economists. However, in 2018 the REO demand was still only 190,000 tonnes/year (Gambogi 2020). Only in 2019 did market growth exceed the 2014 projection made by Watts (2010), and 2019 production was estimated at 220,000 tonnes/year (Gambogi 2021a). The accuracy of the current market projections will probably be much better than that of historical projections. This is largely because government stimuli, if and when enacted, will support the development of dependent technologies and supply chains, which will provide a greater sense of security for potential explorationists and developers.

Direct Impact of Market Base on the Design of Exploration Programs

Some specialty metals (e.g. REE, Nb, Ta and Li), are commonly considered to be primary exploration targets. Projects targeting these materials should be compared and ranked in the early stages because only a small fraction of projects that seem to satisfy development requirements will actually achieve production. Projects may meet most requirements related to mining, metallurgy, infrastructure, and societal license, but they are unlikely to be economically viable under open-market conditions if the market base is small.

Several specialty metals projects were explored for many years before the mineralogical and metallurgical constraints on development were fully appreciated. It is economically difficult for specialty metal operations to justify the development and use of complex custom-designed metallurgical circuits instead of established systems that are commercially available. Thus, REE-bearing ionic clays, REE-fluorocarbonates, and REE-phosphates will continue to be favoured as REE ore minerals because commercial metallurgical circuits for them already exist (Mariano and Mariano 2012; Simandl 2014). This is not the case for unusual minerals such as REE-bearing silicates, which are present in many such exploration projects, including some that are enriched in more desirable heavy REE. Essentially, high-grade, metallurgically simple, near-surface deposits will be favoured because of the lower associated development and mining costs relative to larger deeply buried, metallurgically complex, or lower-grade deposits. The costs to bring large tonnage, low-grade deposits into production cannot be justified for materials with a small market base, and high research and development costs to tackle metallurgical complexities are difficult to justify for small operations.

The limited market base for specialty materials restricts the short-term interest of major mining companies in these commodities. However, there are some exceptions. Most of them are related to potential by-products that can be recovered in smelting. For example, Ge, In, and Cd are recovered at Teck Resources' integrated Zn and Pb smelting and refining complex in Trail, British Columbia, as by-products. In 2021, the Rio Tinto Fer et Titan (RTFT) complex in Sorel (Quebec) started operating a small plant aiming to produce 20% of the global demand for scandium (Sc) oxide, which is presently approximately 15 tonnes/year. This initiative was supported with financial contribution from the Quebec government. Other large companies are aware of upcoming opportunities, and many may pre-emptively attempt to establish themselves in promising specialty materials markets.

Some major companies are now showing long-term interest in materials that currently have a modest market base but have relatively well-constrained market projections – for instance, Li. Regardless of which battery technologies eventually dominate the electric automotive industry, Li demand is expected to grow substantially over the next few decades. However, as with most specialty metals, early screening of the project is necessary to determine if it really has a future. Lithium projects currently in production or reaching an advanced stage of exploration or development can be subdivided into 3 main categories: (1) evaporite/brine derived; (2) hard-rock pegmatite deposits consisting predominantly of spodumene ($LiAlSi_2O_6$); and (3) unconventional sources such as jadarite [($LiNaSiB_3O_7(OH)$)] and related Li- and B-bearing clays (Kesler et al. 2012; Evans 2014). Possible development of jadarite deposits in the Jadar Basin of Serbia is currently being investigated by Rio Tinto as a source of both Li and B (Gourcerol et al. 2019), and if successful, could significantly impact the global Li market.

Industry's Ability to Ensure Availability of Critical Materials

Great progress is being made in developing exploration models and in customizing existing exploration methods for the discovery and development of most of the critical materials listed in Tables 1 and 2, including those associated with batteries, magnets, and photovoltaic technologies. Traditional geochemical and geophysical surveys, as well as remote sensing methods used for other target types, can be applied in the exploration for most primary critical materials. However, these well-established methods must be modified and their applications customized to maximize their effectiveness. Detailed discussion covering new developments in exploration methods for individual critical materials is outside the scope of this paper, but progress in exploration methods specific for carbonatite-related deposits (including critical materials such as REE, Nb, and fluorite) illustrate some of the trends (Simandl and Paradis 2018).

Similar efforts are also taking place to develop methods for the extraction of complex, difficult to decompose minerals. For instance, examples of numerous flow sheets for REE projects are tabulated in Verbaan et al. (2015). Most of REE are currently derived from REE-bearing fluorocarbonates (e.g. bastnaesite and synchysite) and REE-bearing phosphates (e.g. monazite and xenotime); however, these minerals contain dominantly light REE. Most heavy REE are obtained from ion-adsorption clay deposits and this is expected to continue in the near future (Simandl 2014; Borst et al. 2020). The ability to extract REE from complex zirconosilicates (e.g. eudialyte) and other heavy REE-enriched minerals commercially at competitive cost would be a major breakthrough. It could permit production of heavy REE from large deposits hosted by alkaline intrusions whose development is presently impeded by metallurgical challenges.

Some specialty material(s) are present in high concentrations in small and/or uncommon deposits. For example, Ge is enriched in Kipushi-type polymetallic deposits in the Democratic Republic of Congo (Höll et al. 2007) and In-bearing polymetallic veins exist at the Akenobe deposit in Japan (Schwarz-Schampera 2014). However, exploration for such 'unusual' deposits as the primary target is not recommended if these metals can instead be recovered as by-products of other metal extraction operations. For example, Ga, Ge, and In are all by-products of Zn smelting (Schwarz-Schampera 2014; Paradis 2015), and rhenium (Re) is recovered from molybdenite concentrates produced from porphyry Cu–Mo type deposits (Millensifer et al. 2014). Cobalt has diverse associations as a co-product from the Katanga Copperbelt Cu ores (central Africa) and is present in many magmatic Ni and Cu deposits, and in Ni–Co laterites (Roberts and Gunn 2014).

Current Cu, Pb, Zn, and Ni mines and waste piles from historical operations may contain significant resources of these metals. Analyzing and evaluating these potential sources of critical materials is recommended over any attempt to generate material-specific exploration projects. Should shortages of these by-product specialty metals develop, adding appropriate extraction circuits to operating smelters that currently do not recover these elements may be the most straightforward solution, assuming that suitable economics and grades prevail. Higher-than-normal concentrations of a desired specialty metal (e.g. Ge in a Zn deposit) may also positively affect the development potential of such a deposit by subsidizing the production of its primary commodity.

SYNOPSIS

Projects involving 'battery', 'magnet', photovoltaic, and/or 'critical' materials currently have favourable public, government, and shareholder perceptions that make them easier to promote than projects aimed at more traditional major commodities. They are commonly seen as essential in the quest for a future carbon-neutral society. However, the assessment of projects involving specialty materials is far more complex and uncertain than the evaluation of projects involving major commodities that exploration and mining industries are accustomed to.

The influence of the market base is the most important parameter in the assessment of specialty materials exploration programs by industry, but it is also the most commonly overlooked or disregarded aspect. Careful consideration of the market base is also crucial for informed decision-making by government agencies seeking to support or encourage such projects. In the case of a given specialty material, only the best exploration and development projects will be economically successful without government or end-user stimuli. Early ranking of projects with an emphasis on grade and tonnage, geometallurgy, and infrastructure is recommended so that exploration budgets can be assigned to the best projects, and potential government stimuli responsibly allocated. In the short term, the economy of scale should not be expected to play an important role in the development of any projects targeting specialty materials because of their limited market base. However, in the medium and long term, the concept of economy of scale might become applicable to some of these projects because of fast market growth projections for some commodities. The reliability and accuracy of such growth projections are uncertain, especially in the light of rapid technological change.

Clearly distinguishing between current market data, legitimate market projections, and inflated expectations of new technologies by scientists and engineers is essential in order to separate factual information from more speculative or promotionally oriented viewpoints, and to make wise investment decisions. There are many uncertainties to consider in the rapidly changing world of modern technology. The greatest of these are the potential impact of future technological innovations (which are virtually unpredictable), future material substitutions initiated to reduce costs, and unwise assumptions regarding the ability of engineers to solve key technical problems that prevent commercialization of experimental technologies. The detailed discussion of battery, market and photovoltaic materials provides examples of these and other uncertainties.

Currently, efforts to reduce greenhouse gas emissions direct considerable research funding towards electrification of industries. In the short-term, specialty materials used in Nd(Dy)FeB-type magnets are benefiting from rapid market growth due to the increasing popularity of electric vehicles. In the medium- to long-term, the demand for these materials is expected to expand beyond electric vehicles to renewable electricity generation (e.g. turbines for offshore wind farms or tidal/wave energy). The projected demand for electric vehicles will also benefit various materials currently required for the production of Li-ion type batteries. However, the driver for market growth of battery materials will expand to include large-scale stationary electricity storage systems used to balance energy supply and demand, and to provide stability for power grids. These energy storage applications do not require batteries with a high energy density so other types of batteries (e.g. vanadium redox flow) may come to dominate this sector, and these will generate different material requirements.

It is difficult to determine which battery types will become commercially dominant in the long-term or if economically viable substitutes for Nd(Dy)FeB-type magnets will be discovered and commercialized. A single technological breakthrough could abruptly change the situation in both battery and magnet material domains and could significantly alter society's raw material requirements.

The global demand for several specialty materials important in photovoltaic applications is presently satisfied by their recovery as by-products of base metal or other mineral extraction. However, not all smelters have circuits in place to recover materials currently considered as critical. If deficiencies in supplies for materials such as Ge, In, Ga, and other specialty metals develop, adding the appropriate circuits to existing smelting operations may be the most effective way to meet demand.

In the short and medium term, shortages of battery, magnet, and photovoltaic raw materials due to lack of resources are highly unlikely. More likely causes for shortages are supply disruptions linked to civil unrest, military conflicts, supply chain bottlenecks, and delays in permitting future mines and processing facilities for production. Events and uncertainties since early 2020 also provide an illustration of the potential for disruptions from largely unforeseen events such as the Covid-19 pandemic.

CONCLUSION

In the long term, the ongoing transition from fossil fuels to renewable (alternative) energy sources provides opportunities and potential rewards comparable to the industrial revolution of 1760–1840 in Europe. However, caution is required because (at least in the short term) many critical materials are also specialty materials, used in small quantities compared to major industrial metals such as Fe, Cu, Al, and Zn. This aspect, and the uncertainty related to market projections, must be considered during the planning of exploration and development programs, efforts to secure new supply chains, and in corporate and governmental decision-making.

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Aley niobium-bearing carbonatite, British Columbia

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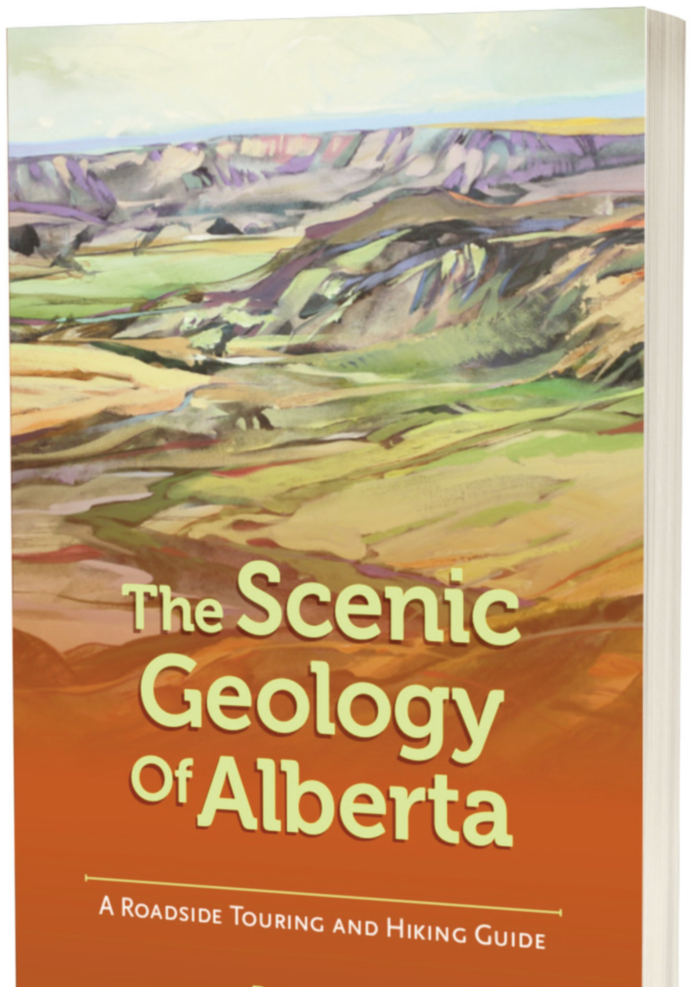
REVIEW



The Scenic Geology of Alberta: A Roadside Touring and Hiking Guide

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Many of us have signed up for and enjoyed geological field trips associated with Earth Science conferences. And the field trip guidebook is usually taken home - a treasured keepsake and a source of data and insights that often are unavailable elsewhere. In writing their guidebook, the trip leaders can assume that: 1) it is okay to use geological jargon (indeed, it is an expectation); 2) they have an interested audience (after all, we have already paid to come on the field trip); 3) geological maps and cross-sections will be (for the most part) readily understood by the field trip participants; and 4) everyone will happily pretend that they can grasp the concept of deep time. However, none of these assumptions are valid for the brave soul who pens a geological guidebook for a 'lay' audience, for the public. The immediate challenge in writing such a guidebook is to induce in people the idea that it might be fun (?) to purchase a field trip guidebook and to commit to spending time travelling around looking at and learning about rocks. This is the trick that Dale Leckie is attempting.

His first attempt, published in 2017, was "Rocks, Ridges and Rivers: Geological Wonders of Banff, Yoho, and Jasper National Parks. A Roadside Tour Guide" (a book which was favourably reviewed in these pages by Andy Kerr). I have a copy of that book. Indeed, I attended the Edmonton book release (at Audrey's Books - a wonderful place to get lost browsing for books) where I got to meet Dale. I purchased several copies of his book, and they have proven to be excellent gifts. And I have put my copy (signed by Dale) to good use, having had it along with me for hikes in and adjacent to Banff, Yoho, and Jasper parks.

But then, I am a geologist, not the audience that Dale was thinking about when he wrote *Rocks, Ridges and Rivers*. As Dale stated in the book's preface, his goal was to "share my curiosity for natural history", and to share it as broadly as possible. Toward that goal, he teamed up with an artist, Heather Pant, and filled the book with her artistic renderings of many of the scenic stops described in the book. This was Dale's stroke of brilliance! Geology isn't all science or just science. Most everyone recognizes the intrinsic beauty of the mountains and landscapes of Alberta. Heather's paintings provide implicit recognition of that beauty and allow Dale to then share widely the geological basis for that beauty. This is the recipe Dale has employed: 1) look at how beautiful this vista is, and now 2) listen to the incredible geological backstory to this vista.

Dale's recently published second book, "The Scenic Geology of Alberta: A roadside touring and hiking guide" (hereafter *Scenic Alberta*) follows the same recipe. It is targeted, just as was *Rocks, Ridges and Rivers*, at as broad an audience as possible. And instead of one artist, Dale has now teamed up with two (L.C. Cariou and Brent R. Laycock). It is Brent's work 'Landforms Coulee' that adorns the front cover and it sends a clear message - the foundation of this beautiful landscape is a wonderful geological story that spans millennia; come let me share that story with you. And sharing those stories is something that Dale is very good at.

Rocks, Ridges and Rivers focused on the geology in and immediately adjacent to Banff, Yoho, and Jasper national parks. This was low hanging fruit. These parks are home to some of the most beautiful and accessible mountains on Earth. *Scenic Alberta* is in many ways a more ambitious work in that Dale asks the reader to appreciate not just the mountains, but the far more subtle beauty and geology of the Prairies. Dale organizes about 80 (depending upon how you count them) 'geological stops' and hikes into 7 different 'subregions' including 1) Southern Alberta (including Waterton Park), 2) Calgary and Kananaskis area, 3) Red Deer River Valley, 4) Dinosaur Provincial Park, 5) Disruption in the Prairies, 6) Crossing Central Alberta, and 7) Checking out the North. In addition to the use of art to help convey the message, *Scenic Alberta* sticks with many of the same things that made *Rocks, Rivers and Ridges* a success: high-quality paper and binding (this is a guidebook that will last and which is ready for a bit of rain or snow); lots of excellent graphics and photographs; plenty of space for making annotations; a mixture of accessible and somewhat more adventuresome stops; a full stratigraphic column with notes printed on the inside of the front cover; and the use of sidebars to provide more information on select topics. It is an all-around excellent guidebook that could be the basis for several extended trips exploring the geology of the mountains and prairies of Alberta. And because this book addresses geological stops within and adjacent to both Calgary and Edmonton (which between the two cities accounts for 60% of the population of Alberta), it is a book that can be left in the car for whenever you have the opportunity or desire to get out for a short, informative stroll. Finally, it is such a beautiful book that, left on the coffee table, no one can resist picking it up and having a look. Indeed, there is so much to enjoy about this book that it would be a lovely gift even for someone who is never likely to set foot in Alberta.

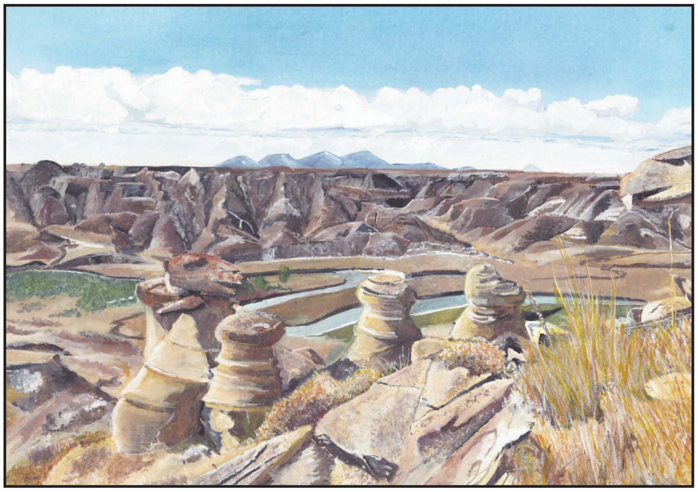
But it could be better. In terms of outreach, this is an excellent guidebook. And taken together with his previous effort, *Rocks, Ridges and Rivers*, it can be argued that between these two guidebooks, no one has done more than Dale Leckie in terms of geological outreach and public Earth Science education over the past 4 years. So, my comments and criticisms offered here are provided in the hope that Dale is not finished publishing guidebooks and that his next effort might be even better. There are errors but they are few and far between (mislocating

Painting of Cameron Falls descending over Precambrian strata of the Purcell Supergroup in Waterton Park, Alberta. Artist - Brent R. Laycock, *Morning Sun on Cameron Falls*, acrylic, 2020; used with permission.

Mt Kidd on the map on page 132 being the most notable that I found). The quality of the editing is quite good. No, the two main problems, as minor as they are, can be described as 1) unnecessary confusion, and 2) missed opportunities.

Unnecessary Confusion - The geological stops are organized into "seven subregions", and the subregions are described sequentially. Each starts with a list of the stops within that subregion accompanied by a map showing all the stops. The stops are numbered, and a list is provided showing the page on which the detailed stop description is provided. In addition, the introduction to each subregion features a numbered list describing the main attraction at each location. EXCEPT that the numbers of these short descriptions don't match the numbers on the map. For example, the Southern Alberta subregion includes 16 stops, whereas there are 19 entries in the numbered list of attractions. The map and the attraction list correspond up to number 6, but then diverge with a couple of attractions described that are not listed as stops. Attractions 10 through 13 correspond to stops 8 through 11. Attractions 14 and 15 correspond to stop 12. … why??

And the subregion designations are at best difficult to understand. Subregion 1 - Southern Alberta, works best. It is an E-W transect consisting of 16 stops that extend from the Crowsnest Pass - Waterton Park region in the west to Cypress Hills in the east. Travelling from west to east we get to experience the wonders of the Rocky Mountains, their foothills, and the Prairies that extend out in front of them. Great stuff, and very logical. And subregion 2, Calgary - Kananaskis, makes sense in that a great many users of this guidebook undoubtedly will be Calgarians. But the organization of the subsequent



Painting of the Milk River Canyon incised into Upper Cretaceous foreland basin strata of the Western Canadian Sedimentary Basin giving rise to the distinct erosional 'hoodoos'. Artist - L.C. Cariou, *Milk River Canyon Hoodoos*, watercolour, 2019; used with permission.

subregions defies explanation. Subregion 3 - A Dinosaur Road Trip - consists of a series of 6 stops along the Red Deer River valley, but for some reason, Dinosaur Provincial Park, which lies just downstream along the Red Deer River from subregion 3, is broken out as its own subregion despite it having only a single described stop (admittedly there are 5 sub-stops, but then why were these not listed as individual stops?). Even stranger, Dinosaur Provincial Park is included in the list of attractions provided for subregion 3. The logic behind subregions 5, 6 and 7 is equally difficult to figure out, which I am not going to belabour. I do, however, want to comment on the Buffalo Head Hills stop in subregion 7 - Checking out the North. I had to read this stop description several times before I understood that there is no stop in the Buffalo Head Hills. Instead, what the reader is asked to do is to stand at the Sagiwata Lookout in the town of Peace River (which happens to be stop 2 of subregion 7, but that isn't mentioned in the description of the Buffalo Head Hills stop) and look 130 km to the northeast. One hundred and thirty kilometres. I have never been to the Sagiwata Lookout, but I very much doubt that you can see the Buffalo Head Hills from there. This then isn't really a stop at all. It would make more sense to pick a viewpoint in Calgary as a 'stop' in the Rocky Mountains which lie 80 km to the west. At least you can see the Rockies from Calgary. So, if you happen to find yourself at Sagiwata Lookout someday and you see some very confused looking people, you can probably guess at the source of their confusion.

Missed Opportunities - Earth Science outreach involves informing the public about what we know and don't know about Earth history. What we don't know is just as important as, and can be very much more inspiring than, what we know. No one ever became a geologist or chemist or biologist because everything in those fields had already been figured out. No, people choose to become scientists because they are motivated to explain what hasn't yet been explained, to find answers to outstanding questions, to expand our field of knowledge. From that perspective *Scenic Alberta* too often depicts our current state of knowledge as being more thorough and detailed than it really is. I provide a couple of examples from the introductory 'Setting the Stage' section. The mountains of Waterton Park owe their existence to the Lewis thrust sheet, which consists of a thick section of the Precambrian Purcell Supergroup emplaced to the east over Cretaceous strata. The amount of slip across the Lewis thrust is difficult to constrain in part because, unlike most thrust faults, the hangingwall strata (Purcell Supergroup) is nowhere to be found in the fault's immediate footwall. Most estimates of the maximum amount of slip across the Lewis thrust are around 80 to 90 km. However, in the Setting the Stage section (and in several other places in the guidebook) the Purcell Supergroup is said to have moved "at about 6 cm a year for about 23 million years" during thrust emplacement. There are two problems with this statement: 1 - it implies a detailed knowledge of geological rates and time spans that is not supported by data, and 2 - these numbers are demonstrably wrong. A rate of translation of 5 cm/a for 20 million years yields a total slip of 1000 km. Ironically, I am one of the few people studying Cordilleran geology who would find the suggestion of there having been >1000 km of slip across the Lewis thrust as being interesting as opposed to absurd. The real point here is that we simply don't know the specific rates of translation, we don't know the time span over which slip occurred across the Lewis thrust, and we don't know how much slip has occurred across the fault. So why portray our state of knowledge as being so detailed? Similarly, the Crowsnest Volcanics are said to have originated "92 km" to the southwest before being transported eastward during thrust belt formation. While this estimate of the distance the Crowsnest Volcanics were translated eastward is reasonable, there is no justification for such a specific number. The Fernie 'basin', which lies just west of the Crowsnest Volcanics has been referred to as "a black hole of thrust faults" (I think Kevin Root was responsible for that quote) and there are significant disagreements over how to palinspastically unravel the Fernie - Crowsnest region. Not only that, but there are paleomagnetic data from the Crowsnest Volcanics that can be interpreted as suggesting that these rocks were deposited more than an order of magnitude farther away from their current location relative to cratonic North America. Providing people with the impression that we have an incredibly detailed understanding of geological processes that took place tens and hundreds of millions of years ago is a missed opportunity.

The other missed opportunity pertains to the use of maps. Geological maps are what make the Earth Sciences unique. They are not strictly data or exclusively interpretation, neither fish n'or fowl. And they are the basis for most all of the fascinating geological stories wedged into this book. And yet geological maps figure sparsely if at all in the stop descriptions. The Waterton Park stop descriptions are provided without a single map showing the trace of the Lewis thrust. And the Waterton Park stops, as well as the Police Outpost Provincial Park and Crowsnest Mountain stops are all about the Lewis thrust sheet. A decent geology map showing the Lewis thrust is subsequently provided (in reference to the Pincher Creek Viewpoint stop), more than 60 pages after the last page con-

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cerning Waterton Park. But even then, the map fails to depict Crowsnest Mountain (a klippe of the Lewis thrust) despite showing the geology of Crowsnest Pass. And because the figures are not numbered or even mentioned in the accompanying text there is no way for a family out using the guidebook to explore Waterton Park to know that there is a useful map of the Lewis thrust sheet to be found on page 131.

Another frustrating lack of map support pertains to the Foothills Erratic Train (FET), a linear train of boulders of Cambrian quartzite that extend from near Hinton in the north, south all the way to and beyond the 49th parallel. The boulder train marks the line of confluence between the Laurentide ice sheet to the east and the Cordilleran ice sheet to the west and is attributed to a landslide from the flanks of Mt Edith Cavell that covered the adjacent Cordilleran glacier with quartzite debris. The FET is featured and described and explained on pages 129, 133, 140 and 141 (which features a breakout sidebar on the topic). All of this without a map showing the boulder train, or Mt Edith Cavell, or the extent of the Cordilleran and Laurentide ice sheets. But we are finally provided with such a map on pages 156–157 where the Okotoks Big Rock, the most famous of the FET's boulders, is described. Unfortunately, given the way people use field guides (only looking at the pages pertinent to their current stop) and the lack of numbered figures, it means that only those reviewing this guide or those visiting the Okotoks Big Rock are going to see the map that beautifully explains the origins of the FET.

These criticisms in no way diminish what Dale Leckie has accomplished. He has more than adequately achieved his goal of sharing his obvious "curiosity for natural history". *Scenic Alberta* is a beautiful guidebook that seamlessly combines art and science in a highly successful effort to explain the geological processes and deep time involved in the development some of Alberta's most picturesque landscapes. We in the Earth Science community owe a huge debt of gratitude to Dale because, as I wrote in a 2011 *Geoscience Canada* article (Johnston 2011), "a public ignorant of the basic workings of the Earth and of the depth of Earth history, will never be able to imagine the substantial challenge that humanity currently faces."

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