Geoenergy

https://doi.org/10.1144/geoenergy2023-045 | Vol. 2 | 2024 | geoenergy2023-045

Lithium: critical, or not so critical?

Nicholas J. Gardiner[1]*, Simon M. Jowitt[2] and John P. Sykes[3]

[1] School of Earth & Environmental Sciences, University of St Andrews, Bute Building, Queen's Terrace, St Andrews KY16 9TS, UK

[2] Ralph J. Roberts Center for Research in Economic Geology, Department of Geological Sciences and Engineering, University of Nevada, Reno, USA

[3] Business School and Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Crawley, Perth, Australia

NJG, 0000-0003-3465-9295

* Correspondence: nick.gardiner@st-andrews.ac.uk

Abstract: Some metals necessary to deliver renewable energy are considered critical. Metal criticality is a major factor in achieving energy decarbonization, leading to efforts to make metals *uncritical*. Among the most critical is lithium which, like many critical metals, represents a small-scale market experiencing significant demand increase causing price and supply volatility, thereby hindering necessary transformative investment. Global lithium demand is soaring, with current supply now dominated by pegmatite-sourced lithium hydroxide. Clay extraction has yet to be industrially proven, thus there remains uncertainty from where and in what quantity future lithium supply will come, and whether lithium remains critical, however geoscience research is best focused on pegmatite and clay-sourced lithium to improve discovery and extraction. Of five lithium criticality scenarios (business as usual; clays onstream; everything plus recycling; shift away from lithium; black swan event), only two project a longer-term criticality reduction. However, few metals will be critical over the very long term as techno-economic and environmental, social, and governance challenges can be overcome and/or metal demand will be structurally adjusted by substitution. Although criticality may be a short to medium term barrier to the energy transition, effective research and overall market forces will reduce the majority of mineral criticality over the longer term.

Thematic collection: This article is part of The energy-critical metals for a low carbon transition collection available at: https://www.lyellcollection.org/topic/collections/critical-metals

Received 29 October 2023; **revised** 19 December 2023; **accepted** 21 December 2023

Criticality of battery metals

Some of the metals necessary to deliver renewable energy and other transformative technologies are considered critical, in that they have both economic and industrial importance resulting in growing demand combined with insecure supply chains (Eggert *et al.* 2008; McNulty and Jowitt 2021; Jowitt 2023). This criticality, and approaches to increase their security of supply, will be major factors in achieving (or failing to achieve) the metal supplies required for global decarbonization (Gardiner *et al.* 2023*a* and refs therein), a development that has led to a new focus on the shoring up of their value (supply) chains (Porter 1985; Graedel *et al.* 2015; Gardiner *et al.* 2023*b*). In essence, this is a global drive to make critical metals *uncritical* by the removal of 'bottlenecks' (Goldratt and Cox 1984; Sykes *et al.* 2023) in individual or grouped critical metal and mineral value chains.

The drivers and degree of criticality vary significantly between different metals, reflecting uncertainties in supply and/or demand, and include: (i) technological importance and potential; (ii) whether they are mined as a primary or by-product; (iii) resource geopolitics; (iv) their market size, maturity, and structure; (v) our understanding of their deposit formation; (vi) our ability to prospect for and process them; and (vii) their recyclability (Graedel *et al.* 2015; Redlinger and Eggert 2016; Sykes *et al.* 2016; McNulty and Jowitt 2021). Some metals may only be temporarily critical for short-term geopolitical reasons (e.g. recent example of gallium and gadolinium; Liu and Bradshaw 2023), whereas others may be 'structurally critical' where supply may ultimately never be sufficient to meet demand, leading to both shortfall and substitution efforts. All of this has led to significant variations in what different governmental groups, bodies and other organizations consider critical (e.g. McNulty and Jowitt 2021).

The battery metals lithium, cobalt, graphite, manganese, and nickel, are among those metals and minerals that are considered the most critical, both in terms of their overall criticality and by the number of countries and other bodies that consider these metals critical (e.g. McNulty and Jowitt 2021). With the exception of nickel and perhaps manganese, these commodities represent small sectors of the global minerals industry with low overall values compared to major metals such as iron and aluminium – for example mined tonnages of lithium are typically 100× less than copper (US Geological Survey 2023*a*). The small-scale of these sectors reflects the fact that historically these commodities have immature markets that are now experiencing a significant demand uptick primarily due to their use in Li-ion batteries, reflected in such metal price increases that raw materials now account for three quarters of battery costs (IEA 2022).

Crucially, small-scale metals suffer from volatility in supply and hence price (Gardiner *et al.* 2015; Redlinger and Eggert 2016; Mudd *et al.* 2017) – especially when considering the often long lead-in times for a mining project to translate discovery into production (e.g. IEA 2022). Small-scale metals can therefore represent an unattractive long-term investment risk (despite predicted demand), at all parts of the value chain. These factors all combine to produce insecure supply chains for battery metals, with strong dependencies on a small number of countries and/or companies as dominant producers, on a limited number of intermediaries (processors, refiners, separators, semi-manufacturers etc.), with weak relationships between demand and price, and hence low economic stimuli for new exploration (Frenzel *et al.* 2017; Lee *et al.* 2020; Jowitt and McNulty 2021; McNulty and Jowitt 2022).

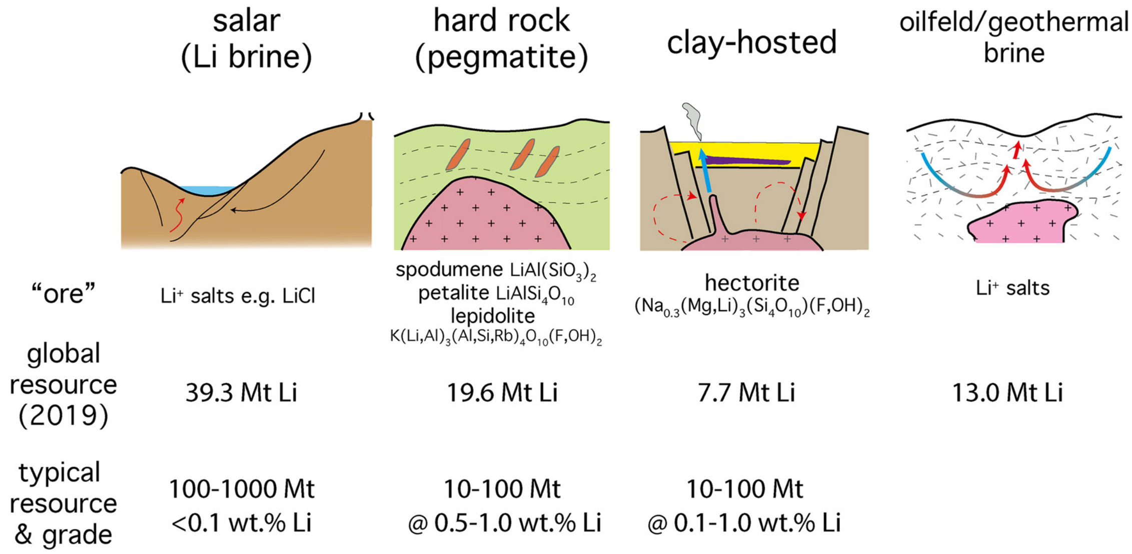

Fig. 1. Outline of the main Li deposit types and estimated global resource by type; 2019 global resource estimates from MinEx consulting (Sykes 2021, p. 20), with resource grades and tonnages from Bowell *et al.* (2020) and Kesler and Simon (2021).

This contribution focuses on lithium, a commodity considered among the most crucial for the energy transition as well as one of the most critical of the battery metals (IEA 2022). We provide an outline of the geological aspects of lithium deposits, the demand and likely supply of lithium over the next few decades, the significant uncertainties within this sector, and explore possible scenarios where lithium may eventually become an uncritical metal.

Lithium: geological background and current supply

Lithium deposits fall into three main types (Fig. 1): (a) salar deposits, formed from lithium-bearing continental brines; (b) hard-rock deposits, mainly from Li-rich pegmatites; and (c) (volcano)-sedimentary clay-hosted deposits (Bowell *et al.* 2020). The first two types have provided the vast majority of lithium supply to date (Fig. 2), whereas the processing and extraction of lithium from clay-rich sedimentary deposits has yet to be economically proven at an industrial scale. Other potential sources such as oilfield brines, and the processing of lithium-bearing geothermal fluids, have also been the focus of recent research but with zero industrial scale production to date.

In Li-ion batteries the lithium is used in both the electrolyte, typically a lithium salt solution (e.g. $LiPF_6$), and in the cathode, usually a lithium oxide compound. In traditional LCO type batteries the cathode is $LiCoO_2$ (Scrosati and Garche 2010) – for which Li_2CO_3 is the preferred input feedstock. However, there are a number of different Li-ion batteries with different performance characteristics and metal compositions – see Table 1.

Until 2018, supply from *lithium brines* in salar-type environments – primarily exploited in South America – dominated lithium supply, with easy production of Li_2CO_3 (Mohr *et al.* 2012; Bradley *et al.* 2017; Fig. 2). However, more recently hard rock supply has increasingly dominated the lithium production sector (US Geological Survey 2023*b*) – a transition referred to as the 'rise of the pegmatites'. This switch from brine-sourced lithium was driven by: (a) the generally superior quality of pegmatite-sourced Li_2CO_3 which typically contain fewer deleterious elements (Hao *et al.* 2017); (b) a shift towards LiOH as the preferred

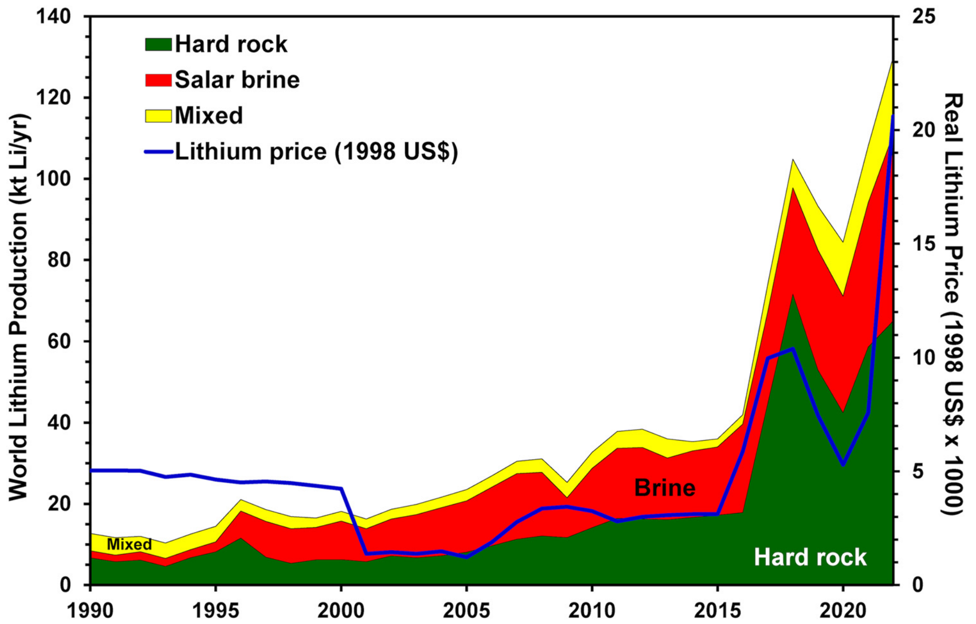

Fig. 2. Lithium production from 1990–2022 by deposit type, and Li concentrate price; adapted from Mudd (2021). This highlights the increasing importance of pegmatite-sources lithium from 2018.

Table 1. Estimated metal (Li, Co, Ni, Mn) and graphite (C) requirements for the production of lithium-ion battery cathodes; adapted from Jowitt (2023)

Battery composition	Li (kg/kWh)	Mn (kg/kWh)	Co (kg/kWh)	Ni (kg/kWh)	C (kg/kWh)	Gravimetric energy density (Wh/kg)	Cycles per life of battery
LCO	0.113	0	0.959	0	~1.2	200	500–1000
NCA	0.112	0	0.143	0.759		225	500–1000
NMC-111	0.139	0.367	0.394	0.392		419–498	1000+
NMC-622	0.126	0.200	0.214	0.641			
NMC-811	0.111	0.088	0.094	0.750			

LCO, lithium cobalt oxide; NCA, lithium nickel cobalt aluminum oxide; NMC, lithium nickel manganese cobalt oxide (numbers denote ratio of Ni, Co, and Mn on a mole fraction basis).

battery feedstock (Hao *et al.* 2017; Azevedo *et al.* 2018) which can be directly produced from pegmatites, unlike that from brines which requires a second conversion step from Li_2CO_3; and (c) a general rise in lithium prices that have changed the economic calculations of some lithium pegmatite operations (compared to the relatively cheap brines) (e.g. Bradley *et al.* 2017), leading to a refocusing of existing pegmatite mining operations towards lithium. LiOH is the primary input for both nickel-cobalt-aluminium (NCA) and nickel-manganese-cobalt (NMC) Li-ion batteries, which are more energy intensive than LCO and are increasingly used for the longest-range electric vehicles (EVs) (Azevedo *et al.* 2018); Table 1. A switch towards LiOH also serves to diversify battery feedstock supply chains.

Lithium-rich pegmatites are typically so-called ‘LCT-type’ pegmatites (London 2016) with ore minerals the aluminosilicates petalite and spodumene, although Li-rich micas such as zinnwaldite and lepidolite occur and represent potential lithium sources. Pegmatites vary in overall character, metallogenic endowment (Sn, W, Ta, Nb, REE-Zr, etc.), and form from highly-evolved volatile-rich melts, of which some result from extreme fractionation of a source granite, whilst others represent the product of low degree anatexis of source rocks (Černý 1991; Müller *et al.* 2017; Koopmans *et al.* 2023). Many of the largest lithium pegmatites are found within the Archean terranes of Western Australia and southern Africa (Dittrich *et al.* 2019). Pegmatite resource sizes range between 10–100 Mt contained ore at average grades of 0.5–1.0 wt% Li (Bowell *et al.* 2020; Kesler and Simon 2021). Sourcing lithium from pegmatites has challenges in that many are small deposits with only limited mining life expectancies, with strong mineralogical and chemical zonation that can present complex mining operations with difficult grade control, and given their robust nature, they require much energy to process. Hard-rock lithium sources can suffer from challenging processing, and typical spodumene-derived concentrates sent to refineries contain about 2.8% Li (6% Li_2O) (Ebensperger *et al.* 2005). Lithium concentrations are possibly even less for petalite or lepidolite-derived Li concentrates where the extremely low grades mean significant transportation costs are often incurred. A lack of historic demand also means lithium pegmatite exploration is still in its infancy: many ‘new’ projects are in fact brownfields tin and/or tantalum deposits, or represent deposits where economics were formerly dominated by tantalum or other elements but are now increasingly dominated by lithium (e.g. Greenbushes in Western Australia; Partington 2017). However, there have also been new developments in lithium pegmatite discovery that suggests we are now moving into a new phase of lithium exploration (Phelps-Barber *et al.* 2022). Regardless of the overall nature of the pegmatite being mined or explored for, there is an urgent drive to improve both geological models and processing technology for hard-rock sourced lithium.

Lithium clay deposits are typically associated with rhyolitic volcanism – the presumed source of the metals (Evans 2014). They are broadly defined either as those with lithium-bearing clay minerals such as hectorite, or those where Li is ion-adsorbed onto clay minerals (Bowell *et al.* 2020). An example of a modern project is Thacker Pass in Nevada, located in the extinct McDermott caldera, which contains lithium-rich illite (Benson *et al.* 2023). The Thacker Pass project includes 217.3 Mt of proven and probable reserves at a grade of 3160 ppm Li, yielding 3.7 Mt contained lithium carbonate equivalent (LCE) within some 19.1 Mt of contained LCE in measured, indicated and inferred resources and a stated aim of 40 000 t of LCE production per year during the main phases of mining. The main uncertainty associated with lithium clay deposits such as Thacker Pass, Rhyolite Ridge (also Nevada), and Jadar (Serbia) is that they have significant potential but uncertain processing that has not been economically proven at an industrial scale, one of the reasons that clay-derived lithium is not currently a significant source of lithium (Fig. 2). Reported resources tend to be in the 10’s of Mt of contained Li in LCE terms (Bowell *et al.* 2020; Kesler and Simon 2021), but determining the accessible grade of clay deposits, where lithium is a trace element in clay/micaceous minerals is difficult, especially as they tend to be large, low grade, and sometimes heterogeneous deposits.

There are also a number of other potential sources of lithium, including geothermal fluids that are often Li-enriched (e.g. Simmons *et al.* 2018) and oilfield brines that can be similarly enriched in Li (e.g. Vera *et al.* 2023). However, neither of these fluids can be processed in the same evaporative way as lithium (salar) brines, meaning that direct lithium extraction technology will be required to make any potential lithium extraction from these sources a reality. Couple this with the energy generation-focused nature of geothermal system development, the low grade of these deposits compared to both pegmatite and clay lithium resources, and the potential challenges around direct lithium extraction (e.g. Vera *et al.* 2023), and all of this indicates these alternative sources have a significant amount of uncertainty over the timescales and viability of their development. The advantage salar brines have over these alternative sources is that they are in equilibrium with the present-day atmosphere and hence lithium can be concentrated by evaporation (e.g. Bradley *et al.* 2017). The lack of availability of this cheap and proven approach to processing indicates a significant amount of work remains in both assessing and potentially eventually developing alternative sources such as geothermal and oilfield brines to provide reliable lithium supply.

Lithium demand and supply volatility

The overall rapid global increase in refined lithium demand is being primarily driven by EV demand, which is expected to grow annually by 26% through to 2030 (Bibienne *et al.* 2020). In response, the development of new hard-rock supply from Western Australia and other areas has been accelerating, and lithium prices have increased significantly in real terms since the mid-2010s, from under \$20/t to close to \$120/t (Fig. 2). However, prices remain volatile, as demonstrated by changes in price during 2022 and 2023 despite the fact that lithium production and reserves have both significantly increased since the mid-2010s, with the ratios of reserves to production (i.e. ‘years left’) decreasing over time but still remaining at 162 or so times reserves, significantly higher than for a number of other key commodities such as the base metals (Jowitt *et al.* 2020).

The uncertainty over supply and demand balances for critical metals with small sized sectors such as lithium can be demonstrated by considering that a number of lithium projects are under development globally, including those at Thacker Pass and Rhyolite Ridge. These projects are focused on untested (in industrial-scale production terms) lithium clays, but if processing challenges can be overcome, these projects alone are likely to add ~45–50 kt/yr contained lithium to global supply, equivalent to the increase from 2019 to 2022 (Fig. 2). The rapid addition of three lithium mines of this scale would potentially cause significant oversupply to the current market, with the possibility that an additional ~90–100 kt/yr of lithium production could cause short-term (1–2 year) oversupply, resulting in severe economic issues for current lithium producers as a result of potential price depression, before the overall lithium demand driven by the energy transition moves the sector back into possible undersupply (e.g. Goldman Sachs 2023). Crucially, this could cause a scenario where lithium miners are subjected to 1–2 years of poor economics, leading to a possible longer-term impact where depressed prices and the potential failure of lithium projects means that the overarching required increase in lithium supply for the enablement of the energy transition is not met, with significant economic and climate change-related impacts. The scenario becomes even more uncertain if other forms of supply are eventually realized, including direct lithium extraction from oilfield brines or geothermal fluids, or the extraction of previously unrecovered lithium from mine waste in brownfield operations.

Pathways to lithium decriticality

In the light of the above example, to explore the future of lithium as a critical metal, we consider several possible scenarios for lithium supply over the next decade – say to 2035 – and their impacts on the medium- and long-term criticality of lithium, all of which can potentially be applied to a range of other critical metals and minerals:

(1) **Business as usual**. Hard-rock sourced LiOH continues to grow in importance and the bulk of lithium supply increasingly comes from pegmatites, initially in Western Australia and southern Africa. Industrial clay production proves to be problematic, with the focus increasingly on exploring and processing hard rock lithium. Assuming an ongoing shortfall in supply, the result will be that that lithium continues to be on most critical metals lists.

(2) **Clays come onstream**. Clay processing technology is proven to be economic at an industrial scale, and the potential of deposits such as Thacker Pass is realized. This causes a potential short-term lithium glut and the scenario outlined earlier, with oversupply perhaps leading to undersupply after 1–2 years and with an overall negative impact on smaller producers with the risk of longer-term lithium shortages. A further twist is that Thacker Pass and Rhyolite Ridge and other domestic resources could make the US lithium self-sufficient, enabling it to decouple from the global lithium supply chain, and reducing criticality for the US compared to other jurisdictions globally.

(3) **Everything plus recycling**. As well as clays, novel lithium sources such as oilfield and geothermal brines come onstream, and recycling processes of lithium products is industrialzed. This causes a significant oversupply of lithium and moves it towards being a 'normal' major metal with a mature market; there are a range of potential sources in both deposit type and jurisdiction, which can ensure a more steady supply, and a significant reduction in lithium supply criticality. This also may open up further uses for lithium in other areas beyond batteries as a result of the increase in supply.

(4) **Shift away from lithium**. Although predictions assume long-term take up of Li-ion batteries, it is possible that restricted lithium supply, elevated lithium prices, and/or alternative technological advancement, might see a longer-term reduction in lithium demand. In general, when the usage for a metal is narrowly focused on a key strategic purpose, e.g. for EV batteries, the metal becomes unusually vital for that specific purpose and any changes to the market are highly disruptive to that use (Sykes *et al.* 2016; IEA 2022). There is the risk that lithium demand will structurally outstrip supply, leading to efforts to find suitable substitutions and/or different technologies relying upon different raw materials. The development of suitable batteries which are less dependent on lithium (e.g. sodium ion) and/or other technologies for grid storage would depress lithium demand in the long term, serve to reduce its criticality, and means lithium would remain a risky investment.

(5) **A lithium black swan event**. By definition unpredictable, a number of events may occur that negatively disrupt either supply or demand. The deteriorating trade relations between the USA and China, the Covid-19 pandemic, the Russian invasion of the Ukraine, and the re-start of the war between Israel and Palestine are a reminder that global geopolitics are always subject to unexpected and significant changes that could drive the reshaping of current supply chains. Some current lithium pegmatite projects are in the global South (e.g. Zimbabwe, Rwanda, Namibia), representing a geopolitical resource race in areas where lithium mining often has significant artisanal/small scale mining operations with the associated societal, environmental and transparency issues, in the same way as for some other metals and minerals (e.g. diamonds, gold, tantalum, tungsten, tin, and cobalt). A technological paradigm shift might also serve to change lithium demand profile, for example the commercialisation of so-called 'solid state' EV Li-ion batteries could change EV economics and

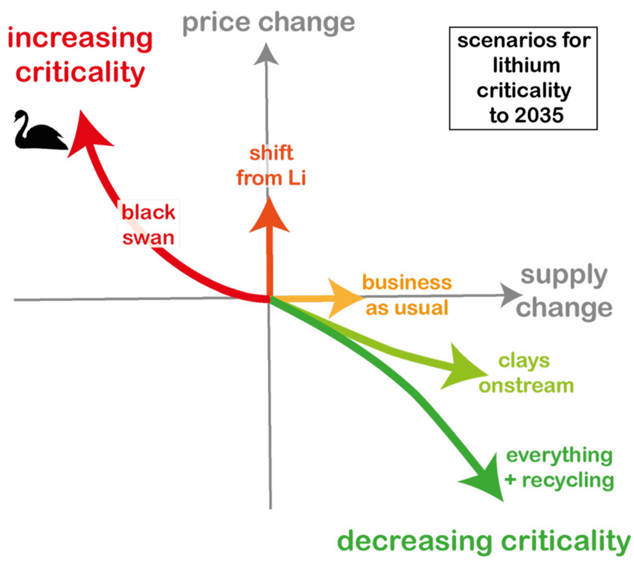

Fig. 3. Plotting conceptual lithium scenarios over the next decade as changes in price and supply changes, and how they might affect lithium criticality. We assume an increase in supply and decrease in price serves to make critical metals less critical.

commercial attractiveness. The effect on lithium supply and hence price of these black swan events are thus near-impossible to predict.

Given than a reduction in metal criticality can be conceptually achieved with combined price reductions and supply increases, Figure 3 figuratively plots price v. production changes for each of these scenarios to demonstrate how they might ultimately affect longer term lithium criticality. Two of our scenarios ('clays come onboard' and 'everything plus recycling') project a longer-term reduction in lithium criticality, although the net effects of the other scenarios mean that lithium would still be generally considered a critical metal.

The tin market in the early 2000s has many similarities to lithium in the 2020s, where a new use for tin in the form of industrial solder drove a demand surge, whereas the supply pipeline, which had languished since the 1986 collapse of the International Tin Council, was unable to meet demand (Gardiner *et al.* 2015). Initially, tin was supply-constrained as a result of a lack of mine supply, leading to a significant rise in the tin price. More recently, the price has remained high due to the essential use of tin in decarbonization and beyond, although the tin price was temporarily disrupted in the early 2010's by the addition of previously unknown mine supply from Myanmar (Gardiner *et al.* 2015), putting new tin projects in jeopardy. However, tin has been historically mined and processed and tin deposit formation models and processing technology are significantly better developed than the often-nascent models available for lithium. Furthermore, tin mining has a significant alluvial and artisanal footprint, and such resources can more quickly meet rapid increases in demand – although struggle to scale to meet demand requirements over the long-term.

With lithium, there remains uncertainty over whether sufficient supply will meet demand estimates, and further where that supply may ultimately come from. It is likely that in the longer term, lithium mine supply will be derived mainly from the three principal deposit types: continental brines from salars, hard-rock pegmatite, and clay-based sources. However, the fact that pegmatite (and perhaps clay) deposits align more conventionally with industry business models – e.g. open-pit, with an operation that produces and sells mineral concentrate – means that that both hard-rock and (eventually) clay-sourced lithium may remain the stable of best bet for future lithium supply. Accordingly, geoscience research and development is likely best focused on improving metallogenic models for both pegmatite and clay deposits to better enable exploration to improve discovery rates and increasing extraction effectiveness. With pegmatite deposits in particular, there is a renewed interest in their genesis, driven principally by the rush for lithium; this is enabling a reassessment of pegmatite formation models in the light both of new analytical and modelling advances, and in application of recent research developments in other granite-related deposit types (e.g. tin granites and porphyry copper systems).

Our scenarios also demonstrate that the timing of potential supply v. increasing demand is crucial for lithium, as is the case for other small scale commodities such as cobalt, graphite, and tantalum. The relative timing of often slower-responding supply v. more dynamic but variable changes in demand, or rather supply and demand change mismatches, can lead to volatility in both the price and supply of such metals, factors that are not typically associated with major metals such as copper (Redlinger and Eggert 2016). Although criticality is a short-term issue in itself, the vulnerability of a metal to criticality is a longer-term, structural issue. Small-scale critical metals thus are likely to remain somewhat risky investments for the short to medium term at least, which can serve to hamper the maturation of associated markets. The fundamental issue small-scale critical metals face is that they require investment to create a tipping point into being a major metal, but paradoxically the small-scale nature and typical producer profile tends to deter investment which would 'industrialze' these metals. Minor metal deposits tend to be explored and mined for by mid-tier and junior producers, who in some cases operate vertically-integrated oligopolies owning both extraction and processing, and who may have limited appetite for transformative investment which would be required to turn lithium into a major 'uncritical' metal. However, very few metals beyond the most geologically rare are likely to remain critical. The assumption is that techno-economic challenges and even environmental, social, and governance (ESG) challenges can be overcome, and if not, the demand for the given metal is structurally adjusted by substitution, thrifting, or other correctives. Ultimately, this will be the pathway that determines whether lithium remains a critical metal, or becomes a major metal in the way that the aluminium and copper sectors have developed over time. Although criticality may be a barrier to the global energy transition over the short to medium term, effective research and development allied to overall market and other forces will ultimately move to reduce criticality for the majority of minerals over the longer term.

Acknowledgements We thank Kathryn Moore for the invitation to submit this perspective and an anonymous reviewer for constructive comments that improved this manuscript.

Author contributions **NJG**: investigation (equal), methodology (equal), writing – original draft (equal), writing – review & editing (equal); **SJ**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **JPS**: conceptualization (equal), methodology (equal), writing – original draft (equal), writing – review & editing (equal)

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

Azevedo, M., Campagnol, N., Hagenbruch, T., Hoffman, K., Lala, A. and Ramsbottom, O. 2018. *Lithium and Cobalt – A Tale of Two Commodities*. McKinsey & Company.

Benson, T., Coble, M. and Dilles, J. 2023. Hydrothermal enrichment of lithium in intracaldera illite-bearing claystones. *Science Advances*, **9**, https://doi.org/10.1126/sciadv.adh8183

Bibienne, T., Magnan, J.-F., Rupp, A. and Laroche, N. 2020. From Mine to mind and mobiles: society's increasing dependence on lithium. *Elements*, **16**, 265–270, https://doi.org/10.2138/gselements.16.4.265

Bowell, R.J., Lagos, L., De Los Hoyos, C.R. and Declercq, J. 2020. Classification and characteristics of natural lithium resources. *Elements*, **16**, 259–264, https://doi.org/10.2138/gselements.16.4.259

Bradley, D., Stillings, L., Jaskula, B., Munk, L. and McCauley, A. 2017. *Lithium (No. 1802), USGS Numbered Series*. United States Geological Survey.

Černý, P. 1991. *Rare-element Granitic Pegmatites. Part II: Regional to Global Environments and Petrogenesis*. GSA Today.

Dittrich, T., Seifert, T., Schulz, B., Hagemann, S., Gerdes, A. and Pfänder, J. 2019. Introduction to Archean rare-metal pegmatites. *Archean Rare-Metal Pegmatites in Zimbabwe and Western Australia*. Springer, 1–21.

Ebensperger, A., Maxwell, P. and Moscoso, C. 2005. The lithium industry: its recent evolution and future prospects. *Resources Policy*, **30**, 218–231, https://doi.org/10.1016/j.resourpol.2005.09.001

Eggert, R.D., Carpenter, A.S. *et al.* 2008. *Minerals, Critical Minerals, and the U.S. Economy*. National Academies Press.

Evans, K. 2014. Lithium. *In*: Gunn, G. (ed.) *Critical Metals Handbook*. American Geophysical Union, 230–260.

Frenzel, M., Mikolajczak, C., Reuter, M.A. and Gutzmer, J. 2017. Quantifying the relative availability of high-tech by-product metals – the cases of gallium, germanium and indium. *Resources Policy*, **52**, 327–335, https://doi.org/10.1016/j.resourpol.2017.04.008

Gardiner, N.J., Sykes, J.P., Trench, A. and Robb, L.J. 2015. Tin mining in Myanmar: production and potential. *Resources Policy*, **46**, 219–233, https://doi.org/10.1016/j.resourpol.2015.10.002

Gardiner, N.J., Roberts, J.J. *et al.* 2023*a*. Geosciences and the energy transition. *Earth Science, Systems and Society*, **3**, 10072, https://doi.org/10.3389/esss.2023.10072

Gardiner, N., Sykes, J. and Jowitt, S. 2023*b*. Critical metals – a matter of confidence? Presented at the AusIMM Critical Minerals Conference 2023, AusIMM, Perth, Australia.

Goldman Sachs 2023. *Direct Lithium Extraction: A Potential Game Changing Technology*.

Goldratt, E. and Cox, J. 1984. *The Goal*. North River Press, Great Barrington, MA.

Graedel, T.E., Harper, E., Nassar, N., Nuss, P. and Reck, B. 2015. Criticality of metals and metalloids. *Proceedings of the National Academy of Sciences*, **112**, 4257–4262, https://doi.org/10.1073/pnas.1500415112

Hao, H., Liu, Z., Zhao, F., Geng, Y. and Sarkis, J. 2017. Materials flow analysis of lithium in China. *Resources Policy*, **51**, 100–106, https://doi.org/10.1016/j.resourpol.2016.12.005

IEA 2022. *The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report*. International Energy Agency (IEA), Paris.

Jowitt, S. 2023. Renewable energy and associated technologies and the scarcity of metal. *In:* Letcher, T. (ed.) *Living With Climate Change*. Elsevier, Amsterdam, 618.

Jowitt, S. and McNulty, B. 2021. Battery and energy metals: future drivers of the minerals industry? *SEG Discovery*, **127**, 11–18, https://doi.org/10.5382/2021-127.fea-01

Jowitt, S.M., Mudd, G.M. and Thompson, J.F.H. 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Communications Earth & Environment*, **1**, 13, https://doi.org/10.1038/s43247-020-0011-0

Kesler, S.E. and Simon, A.C. 2021. Lithium deposits: from magmas to playas. *Characterizing and Prioritizing Critical Mineral Supply Chain Risks and Potential Abatement Strategies. Critical Minerals From Discovery to Supply Chain, GeoFile*. British Columbia Geological Survey, 9–10.

Koopmans, L., Martins, T. *et al.* 2023. The formation of lithium-rich pegmatites through multi-stage melting. *Geology*, **52**, 7–11, https://doi.org/10.1130/G51633.1

Lee, J., Bazilian, M. *et al.* 2020. Reviewing the material and metal security of low-carbon energy transitions. *Renewable and Sustainable Energy Reviews*, **124**, 109789, https://doi.org/10.1016/j.rser.2020.109789

Liu, Q. and Bradshaw, T. 2023. China imposes export curbs on chipmaking metals. *Financial Times*.

London, D. 2016. Rare-element granitic pegmatites. *In:* Verplanck, P.L. and Hitzman, M.W. (eds) *Rare Earth and Critical Elements in Ore Deposits*. *Reviews in Economic Geology*. Society of Economic Geologists, **18**, 165–193, https://doi.org/10.5382/Rev.18.08

McNulty, B. and Jowitt, S. 2021. Barriers to and uncertainties in understanding and quantifying global critical mineral and element supply. *iScience*, **23**, 102809, https://doi.org/10.1016/j.isci.2021.102809

McNulty, B.A. and Jowitt, S.M. 2022. Byproduct critical metal supply and demand and implications for the energy transition: a case study of tellurium supply and CdTe PV demand. *Renewable and Sustainable Energy Reviews*, **168**, 112838, https://doi.org/10.1016/j.rser.2022.112838

Mohr, S., Mudd, G. and Giurco, D. 2012. Lithium resources and production: critical assessment and global projections. *Minerals*, **2**, 65–84, https://doi.org/10.3390/min2010065

Mudd, G. 2021. Assessing the availability of global metals and minerals for the sustainable century: from aluminium to zirconium. *Sustainability*, **13**, 10855, https://doi.org/10.3390/su131910855

Mudd, G., Jowitt, S. and Werner, T. 2017. The world's by-product and critical metal resources part I: uncertainties, current reporting practices, implications and grounds for optimism. *Ore Geology Reviews*, **86**, 924–938, https://doi.org/10.1016/j.oregeorev.2016.05.001

Müller, A., Romer, R. and Pederson, R. 2017. The sveconorwegian pegmatite province -thousands of pegmatites without parental granites. *Canadian Mineralogist*, **55**, 283–315, https://doi.org/10.3749/canmin.1600075

Partington, G.A. 2017. Greenbushes tin, tantalum and lithium deposit. *In:* Phillips, G.N. (ed.) *Australian Ore Deposits*. The Australian Institute of Mining and Metallurgy (AusIMM), Melbourne, Australia, 153–157.

Phelps-Barber, Z., Trench, A. and Groves, D. 2022. Recent pegmatite-hosted spodumene discoveries in Western Australia: insights for lithium exploration in Australia and globally. *Applied Earth Science*, **131**, 100–113, https://doi.org/10.1080/25726838.2022.2065450

Porter, M.E. 1985. *Competitive Advantage: Creating and Sustaining Superior Performance: With a New Introduction*. The Free Press, New York.

Redlinger, M. and Eggert, R.D. 2016. Volatility of by-product metal and mineral prices. *Resources Policy*, **47**, 69–77, https://doi.org/10.1016/j.resourpol.2015.12.002

Scrosati, B. and Garche, J. 2010. Lithium batteries: Status, prospects and future. *Journal of Power Sources*, **195**, 2419–2430, https://doi.org/10.1016/j.jpowsour.2009.11.048

Simmons, S., Kirby, S., Verplanck, P. and Kelley, K. 2018. Strategic and critical metals in produced geothermal fluids from Nevada and Utah. Presented at the 43rd Workshop on Geothermal Reservoir Engineering, Stanford, California, 1–12.

Sykes, J.P. 2021. The MinEx Consulting lithium deposit database and research.

Sykes, J.P., Wright, J.P., Trench, A. and Miller, P. 2016. An assessment of the potential for transformational market growth amongst the critical metals. *Applied Earth Science*, **125**, 21–56, https://doi.org/10.1080/03717453.2015.1104055

Sykes, J., Trench, A., McCuaig, T.C. and Jessel, M. 2023. 'Novel scenarios' on the energy transition for 2023 onwards. Presented at the AusIMM Critical Minerals Conference 2023, AusIMM, Perth, Australia.

US Geological Survey 2023*a*. *Mineral Commodity Summaries 2023*. United States Geological Survey.

US Geological Survey 2023*b*. *Lithium (Mineral Commodity Summaries)*.

Vera, M., Torres, W., Galli, C., Chagnes, A. and Flexer, V. 2023. Environmental impact of direct lithium extraction from brines. *Nature Reviews Earth & Environment*, **4**, 149–165, https://doi.org/10.1038/s43017-022-00387-5