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The Tectonic, Thermal, and Temporal Controls on the Production of Lithium-Enriched Melts

Alex Copley[1] and **Owen Weller**[1]

[1]Department of Earth Sciences, University of Cambridge, Cambridge, UK

Key Points:

- The tectonic filters controlling the production of lithium-enriched melts
- The importance of crustal thickness, radiogenic heating, and convergence rate
- Explanations for the known distribution of lithium deposits, and a means for range-scale assessments of mineralization potential

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. Copley,
acc41@cam.ac.uk

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Author Contributions:

Conceptualization: Alex Copley
Funding acquisition: Alex Copley, Owen Weller
Investigation: Alex Copley, Owen Weller
Methodology: Alex Copley
Writing – original draft: Alex Copley
Writing – review & editing: Alex Copley, Owen Weller

Abstract We present a new tectonically-based method for understanding the mountain-belt-scale controls on the distribution of critical metals, applied to lithium ores. Lithium-rich melts in collisional zones are produced by biotite-breakdown reactions, so we analyze the tectonic "filters" that control whether underthrusting (meta-)sediments reach sufficiently high temperatures for these reactions. Such conditions are most readily achieved with large crustal thicknesses, high radiogenic heating rates, and slow convergence. The first two factors indicate an important role for geological history, in terms of creating a strong foreland and assembling sufficiently radiogenic lithologies. Slow convergence is generally incompatible with uplift outpacing erosion to develop thick mountain belts, but this paradox is resolved by, and explains, most lithium deposits being formed late in the history of mountain belts, at times of slowing convergence rates. Our results explain why lithium deposits are more prevalent in preserved Precambrian mountain belts, formed during times of higher radiogenic heating.

Plain Language Summary The energy transition is driving increasing demand for a variety of metals, including lithium. The controls on the large-scale distribution of lithium, and other critical metals, are not yet established. In this paper we use a model for the thermal structure of continental mountain belts to establish the tectonic conditions that are able to generate lithium-rich melts. Our results highlight the most important factors (crustal thickness, rate of radiogenic heating, rate of convergence), and by doing to provide an explanation for the documented distribution of economically-viable lithium deposits. Our approach therefore provides a means to undertake range-scale assessments of mineralization potential. This method can be applied to other critical metals (e.g., Sn, W) whose distributions are also controlled by temperature-dependent melt processes in mountain belts.

1. Introduction

Increasing demand for lithium-ion batteries, coupled to the desire for diversified supply chains, has driven ongoing attention into the formation of, and exploration for, lithium (Li) ores (Gardiner, Jowitt, & Sykes, 2024). The formation of ore deposits requires a source of the element in question, an enrichment process, and a scenario for emplacement in economically-viable concentrations and tonnages (e.g., Robb, 2020). Many of the world's important hard-rock lithium deposits are pegmatites and granites derived from partial melting of sedimentary protoliths, often in continent-continent collision zones (e.g., Bowell et al., 2020; Bradley et al., 2017; Gardiner, Palin, et al., 2024; Goodenough et al., 2025). Partial melting of metasedimentary rocks is dominated by muscovite-and/or biotite-breakdown reactions, with the abundance of the phase at the solidus a rough guide to the volume of melt produced (White et al., 2001). Muscovite is only stable in appreciable quantities for pelitic (mud-dominated) compositions, whereas biotite is a major phase across a wide range of metasedimentary compositions (Text S1 in Supporting Information S1). Furthermore, biotite has been documented to be the most important host of lithium in metasedimentary rocks (Kunz et al., 2022), consistent with most estimates of its mineral-melt partitioning value being higher than for other potentially important lithium hosts, such as cordierite and muscovite (Icenhower & London, 1995; Pichavant et al., 2024). Therefore, biotite breakdown reactions represent the most important source for the generation of lithium-rich melts, either directly (e.g., Gardiner, Palin, et al., 2024; Kunz et al., 2022), or via re-melting of granitoids produced by biotite-breakdown melting (Koopmans et al., 2023). Fractionation of that melt can then lead to the saturation of minerals in which lithium is an integral part of the crustal lattice (e.g., spodumene; $LiAlSi_2O_6$), and the generation of economically-viable deposits (e.g., Bradley et al., 2017), provided that lithium does not first become sequestered in other phases (e.g. peritectic cordierite during partial melting at low pressures; Text S1 in Supporting Information S1).

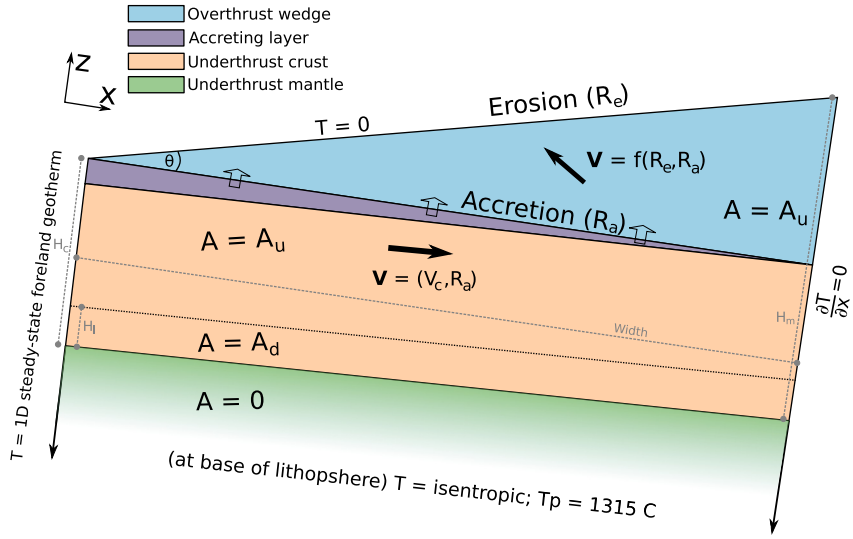

Figure 1. Model setup. Symbols are defined in Table 1, with the exception of the three most important parameters, which we vary in this study: the convergence rate (V_c); the rate of radiogenic heating in undepleted crust (A_u); and the crustal thickness in the mountain belt (H_m).

This paper examines the tectonic controls on the temperatures achieved in mountain belts, as a means to understand the conditions required for biotite-breakdown melting reactions in metasedimentary rocks (derived from sediment underthrusting on the range margin), and therefore the range-scale patterns of lithium mineralization. We do not consider the other controls on the production of lithium ores, such as the presence of suitable source rocks and the role of extensive fractionation of the resulting melt, which are beyond the scope of this study, and which will operate in addition to the concepts discussed here. We note that despite our focus on the temperature conditions required for biotite breakdown, if future developments reveal additional, or alternative, processes to be important (e.g., water-fluxed or muscovite-dehydration melting), then as described below the patterns described in this paper will still apply in the event of those processes also being temperature-controlled. In this sense, the only requirement for our models to be applicable is the melting of metasedimentary rocks within a continental mountain belt at a temperature range that can be estimated. The general approach we outline can also be applied to other critical metals provided that melting in continental mountain belts is an important factor in their distributions, regardless of the lithologies involved and the temperature range of importance (e.g., tin, tungsten, tantalum, and others).

2. Model Description

We model the thermal structure of collisional mountain belts, using an approach that has been successfully applied to understand a variety of temperature-dependent observations from present-day mountain belts, such as the distribution of earthquakes, the locations and timings of igneous activity, and the conditions experienced by exhumed metamorphic rocks (e.g., Craig et al., 2012, 2020). We construct the models in a reference frame attached to the topographic range-front. Molnar and England (1990) and Royden (1993) demonstrated that such a reference frame results in a steady-state temperature distribution within the belt, which we exploit here, the characteristics of which are controlled by the imposed geometry and thermal parameters. We use the geometry and boundary conditions shown in Figure 1, and take into account horizontal and vertical advection and diffusion, radiogenic heating, and the temperature-dependence of the thermal conductivity and specific heat capacity (McKenzie et al., 2005; Nabelek et al., 2010). The radiogenic heating is initially characterized by different values in the depleted lower crust and the undepleted remainder of the crust. The distribution of radiogenic heating is taken to be static in time, due to the steady-state nature of the models. However, in models where a sufficient temperature is attained, that model is re-run with a different distribution of radiogenic heating in order to simulate radiogenic isotopes having been transported by melts (see Text S2 in Supporting Information S1 for details). We do not include shear heating, because of this effect being negligible in continental mountain belts due to the low levels of differential stress involved in the deformation (e.g., see discussion in Copley & Weller, 2022). The

Table 1
Parameters Specified in the Models

Parameter	Value	Notes
Crust thickness in lowlands (H_c)	40 km	Laske et al. (2013), Hacker et al. (2015); 30 km shown in Text S2 of Supporting Information S1
Thickness of lower crust (H_l)	10 km	McKenzie et al. (2005), Hacker et al. (2015); 20 km shown in Text S2 of Supporting Information S1
T for re-distribution of radiogenic heating	850 °C	Copley and Weller (2024); 750 °C and 950 °C shown in Text S2 of Supporting Information S1
Radiogenic heating in lower/depleted crust (A_d)	0.4 μW/m^3	Jaupart et al. (1998), Hasterok et al. (2018)
Radiogenic heating in mantle	0	Rudnick et al. (1998), McKenzie et al. (2005)
Thermal conductivity and heat capacity of crust	T-dependent	Nabelek et al. (2010)
Thermal conductivity and heat capacity of mantle	T-dependent	McKenzie et al. (2005)
Erosion rate (R_e)	1 mm/yr	Perron (2017), Wittmann et al. (2020), Brown et al. (2022); 0.5 and 2 mm/yr in Text S2 of Supporting Information S1
Accretion rate (R_a)	V_c-dependent	10 km accretion over width of model
Model width	300 km	Weller et al. (2021)
Lithosphere thickness in lowlands	200 km	Priestley et al. (2024)

Note. See Text S2 in Supporting Information S1 for additional details.

velocity field in the model domain is controlled by the rate of convergence (V_c), the rate of accretion of underthrusting material into the overlying mountain belt (R_a) and the rate of erosion at the surface (R_e) (Royden, 1993). Because we are concerned with the temperatures achieved in the underthrusting metasedimentary layer, we only model the part of a mountain belt adjacent to the margin, where the sedimentary parts of the foreland are underthrust, and accreted into the overlying deforming wedge of material. In that region, we model the full thickness of the lithosphere. Our boundary condition on the right-hand side of the model domain ($\partial T/\partial x = 0$) is equivalent to there being a range interior with a similar variation of temperature with depth as at the boundary of our model domain. Previous models show this boundary condition is an acceptable approximation that has limited effect on the model behavior, due to the lateral dimensions of mountain belts being considerably greater than their thickness (Craig et al., 2012; Molnar & England, 1990; Royden, 1993). We use a model width of 300 km, based upon the commonly-observed distances between range-front thrusts and the locations of suture zones (e.g., Weller et al., 2021). Based upon the characteristics of modern-day mountain belts, we take the thickness of foreland material accreted to the mountain belt to be 10 km (Barke & Lamb, 2006; Blanc et al., 2003; Yin, 2006). A detailed description of the model methodology is provided in Text S2 of Supporting Information S1.

To explore the controls on the thermal structure, and so the generation of lithium-enriched melts, we discuss the effects of varying the three most important parameters: the convergence rate (V_c), the crustal thickness in the mountain belt (H_m), and the rate of radiogenic heating in undepleted crustal material (A_u). Other parameters have more minor effects on the resulting models, are kept constant at the values shown in Table 1, and Text S3 in Supporting Information S1 shows the limited variation in our results if other geologically-viable values are used.

Given the previous results discussed above, we examine where in our models a layer of underthrusting metasedimentary rock achieves the temperatures required for the breakdown of biotite and therefore the release of lithium into the melt. The temperature range over which biotite is consumed by dehydration melt reactions in metasedimentary rocks depends on pressure and composition, and is commonly ≥800 °C at pressures relevant to partial melting in continent-continent collision zones (e.g., Holland et al., 2018; Spear et al., 1999; Weller et al., 2025). The presence of significant levels of fluorine in numerous lithium-rich granite-pegmatite systems (e.g., Bradley et al., 2017) implies that some regions of partial melting may include high concentrations of fluorine, likely hosted in biotite. Experimental (Peterson et al., 1991) and observational (Finch & Tomkins, 2017; Hacker et al., 2000) studies show that fluorine stabilizes biotite to temperatures above the fluorine-absent temperature range of melting, with the magnitude of displacement dependent on the extent of F-OH substitution, but of order 100–200 °C at crustal pressures. Given the substitution mechanisms of lithium in mica solid solution series, lithium is likely enriched in fluorine-rich biotite (Tischendorf et al., 2007), but as yet a composition-

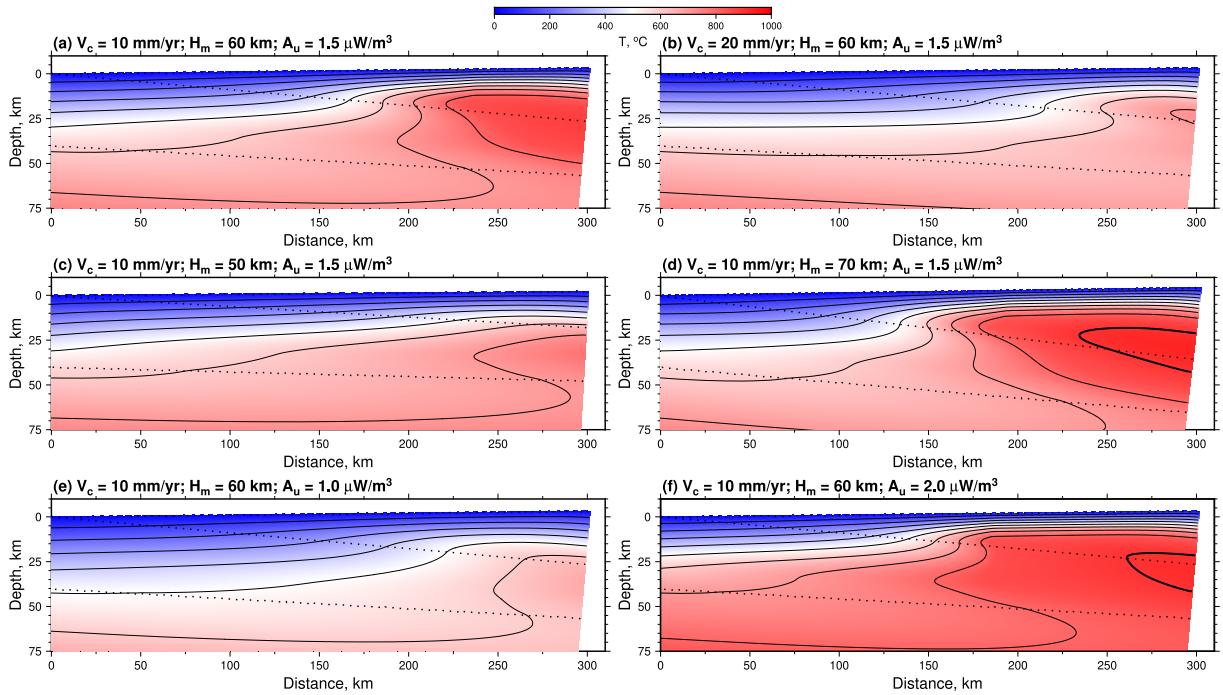

Figure 2. Examples of steady-state temperature distributions calculated by our model. All models were produced using the parameters given in Table 1. Each figure is labeled with the values used for the crustal thickness in the mountain belt (H_m), the rate of radiogenic heating (A_u), and the convergence rate relative to the range-front (V_c) Temperature contours are at 100 °C intervals, and where present the 900 °C contour is shown in bold. The dotted lines show the interface between the overthrust wedge and the accreting layer (upper; Figure 1), and the Moho (lower).

dependent partition coefficient is not available for biotite. We expect that future results regarding experimentally-derived partition coefficients (e.g., Icenhower & London, 1995), and analysis of natural samples (e.g., Kunz et al., 2022; Neukampf et al., 2023), will reveal which compositions of biotite are most important for hosting lithium, and under what conditions it is released into the melt. Due to these current uncertainties, and to capture the range of possible conditions that may be important, we here examine a range of melting temperatures in our models (800–1000 °C), and also note that the patterns revealed by our analysis will hold true if alternative temperatures are used. We neglect the pressure-dependence of biotite breakdown temperatures, because in our models the underthrusting metasedimentary rocks reach relevant temperatures over a narrow range of pressures, the relevant melt reactions have a steep slope in pressure–temperature space (i.e., they are relatively pressure-insensitive; Text S1 in Supporting Information S1), and because the models described below show that isotherms cut the metasedimentary layer at high angles. These features mean that the temperature, rather than pressure, of biotite breakdown dominates the results.

3. Controls on Thermal Structures

Figures 2a–2d show examples of thermal models in which the rate of underthrusting (V_c), and the crustal thickness in the mountain belt (H_m), have been varied. These calculations reveal two straightforward effects: (a) Mountain belts with thicker crust become hotter than thin ones, because of radiogenic heating in the thick crust (e.g., as previously discussed by Copley & Weller, 2022; McKenzie and Priestley, 2008); and (b) Mountain belts with faster convergence rates are cooler at a given location, due to the increased importance of advection of cool foreland material into the mountain belt (i.e., the thermal Peclet number is higher; Jamieson et al., 2002; Molnar & England, 1990; Royden, 1993).

Over Earth history, the rate of heat production by the decay of unstable isotopes has decreased, dominantly due to the decay of ^{40}K and ^{235}U (e.g., O'Neill et al., 2020). To explore the temporal variation in the production of lithium-enriched magmas, we therefore vary the rate of radiogenic heating in the models, although we note that the spatial distribution of heat-producing isotopes in the distant past is not well known. The comparison of

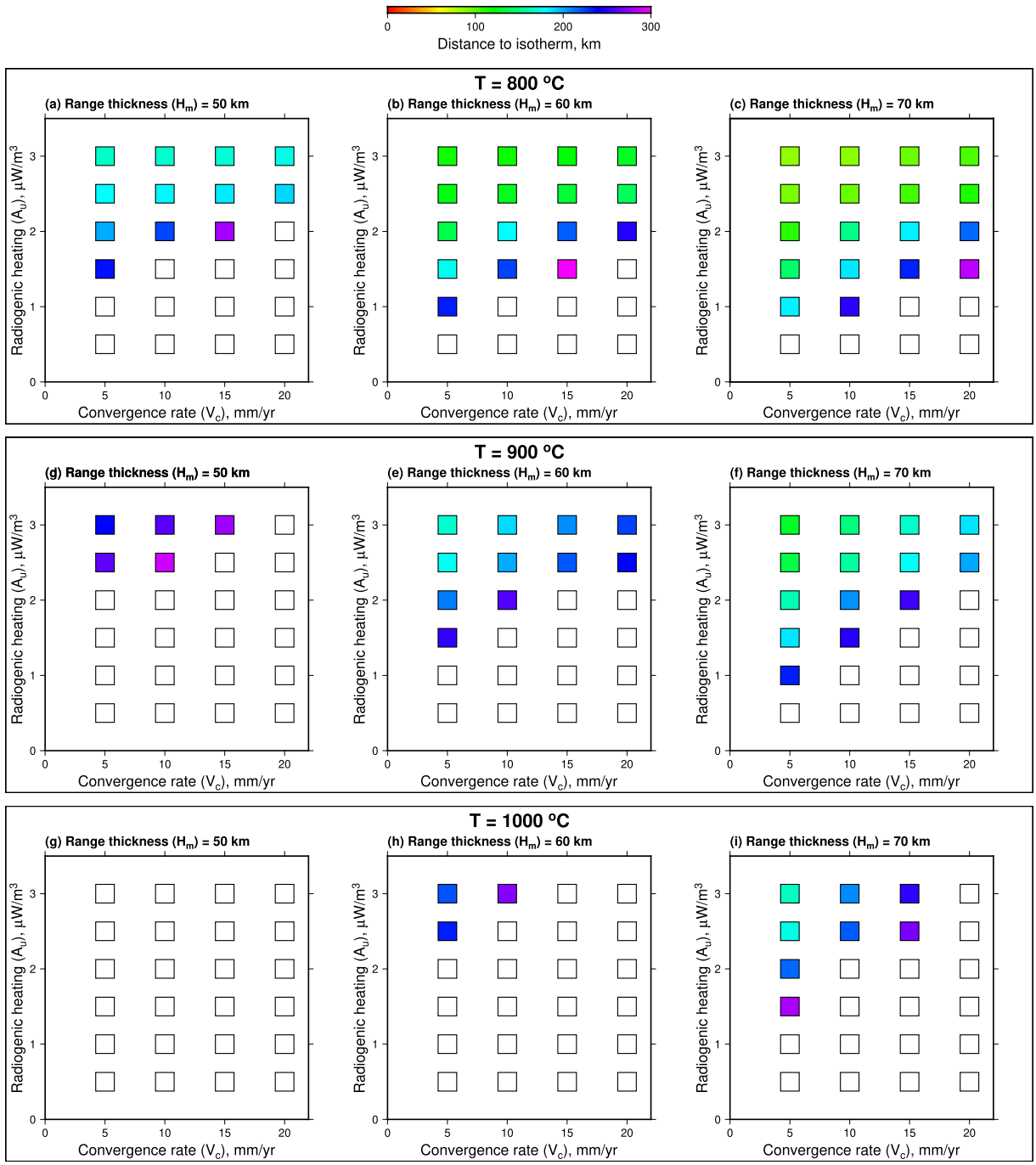

Figure 3. The distance between the range-front and the location where the underthrusting sediment layer intersects the 800 °C (panels a–c), 900 °C (d–f) and 1000 °C (g–i) isotherms (colored squares), as a function of the crustal thickness in the mountain belt (H_m), the convergence rate (V_c), and the rate of radiogenic heat production in undepleted crust (A_u). White squares show models in which the isotherm in question is not intersected by the underthrusting sediment layer.

Figures 2a, 2e, and 2f shows the intuitive result that increasing the rate of radiogenic heating leads to hotter mountain-building events.

We have varied all of the above three parameters within wide and geologically-feasible limits, and computed temperature structures for all their combinations. Figure 3 shows, as a function of each of those three parameters, at what distance from the topographic front the 800, 900, and 1000 °C isotherms intersect the underthrusting metasedimentary rocks, if at all. These results highlight the three key range-scale tectonic controls on the

production of lithium-enriched magmas: mountain belts with thick crust, slow convergence, and high rates of radiogenic heating. Not all conditions need to be met, provided that the other parameters have sufficiently extreme values. Because all three governing parameters influence the temperatures achieved, they trade-off against each other when determining whether lithium-bearing melts are likely to be produced, and no single mountain belt characteristic can be used as a proxy for the likelihood of ores being produced: all three factors must be considered. As shown in Text S3 of Supporting Information S1, varying the other model parameters, shown in Table 1, has limited effects on the results, and does not change these overall patterns.

4. Why Is Lithium 'Critical'?

The results presented in Figures 2 and 3 provide insights into some of the reasons why many nations regard lithium as a "critical" resource, due to the scarcity of economically-viable deposits. Few mountain belts reach high crustal thicknesses (≥60 km), due to this situation requiring both unusually strong foreland lithosphere able to support such high lateral gradients in gravitational potential energy (Jackson et al., 2008; Molnar & Lyon-Caen, 1988; Weller et al., 2021), and sufficient convergence rates to reach such thicknesses despite the highly erosive nature of high-relief mountain belts (e.g., Perron, 2017; Wittmann et al., 2020). The first point typically requires a geological history involving previous partial melting and dehydration, to leave a strong and relatively anhydrous residue (e.g., Jackson et al., 2008). The second point implies rapid convergence, which decreases the likelihood of sufficiently high temperatures for biotite breakdown being experienced by an underthrusting layer of metasedimentary rocks (Figure 3). This dichotomy may explain why lithium-bearing pegmatites are often emplaced in the late stages of orogenic events (Bradley et al., 2017; Goodenough et al., 2025), when the convergence rate slows. For example, Goodenough et al. (2025) noted that lithium-rich pegmatites are widespread in Africa, and although formed in numerous different orogenic events, are thought to be related to the waning stages of those events. Our model results suggest that these patterns may result from high-temperature melting of the underthrusting metasedimentary rocks enabled by reduced convergence rates in the late stages of mountain-building events. This concept is schematically illustrated in Figure 4.

As a specific example of the above concept, the Variscan-aged Cornubian batholith is unusual in the UK for being lithium-rich, and this intrusion formed late in the life of the mountain belt (e.g., Searle et al., 2024). At that time, the rate of convergence on the northern margin of the Variscan mountain belt had decreased to a level at which erosion was keeping pace with tectonic uplift, as indicated by the range-front remaining stationary with respect to the foreland for >10 Myr (Burgess & Gayer, 2000; Hecht, 1992). In other words, lithium-enriched intrusion only occurred once the value of V_c had decreased. The reason why this intrusion suite is significantly enriched, but not to the extent of producing world-class lithium ore bodies, is beyond the scope of this paper. However, this feature highlights that other conditions need to be met to form an economically-important deposit (e.g., related to source composition, melt fractionation, and emplacement depth relative to the present-day erosion level), in addition to just the tectonic effects discussed here.

Although lithium pegmatites have been found with a wide range of ages, many of the world's important deposits are Precambrian in age (Bradley et al., 2017; Figure 4a), which is as expected from our analysis. Due to higher rates of radiogenic heating in Earth's past (O'Neill et al., 2020), mountain belts with thinner crust and faster convergence rates would have been able to reach the temperatures for biotite breakdown, whereas an equivalent range at the present day would not (Figure 3). It is therefore unsurprising that Precambrian lithium pegmatites are more prominent in the geological record than other rocks of that age (either observed in outcrop, or in proxy by the detrital zircon record; Bradley et al., 2017; Figure 4a).

The required rates of radiogenic heating also place limits on the lithologies that can make up the bulk of a mountain belt and it still become hot enough for biotite breakdown. Mud-rich clastic sedimentary rocks and felsic igneous rocks (and their low-to mid-grade metamorphosed equivalents) in general host sufficient radiogenic isotopes for the required rates of heating (e.g., Hasterok et al., 2018). In contrast, carbonates, highly-mature clastic sediments, mafic igneous rocks, and high-grade metamorphic rocks that have experienced prior melt extraction events (at high enough temperatures to transport radiogenic isotopes), generally have insufficient levels of radiogenic heating (e.g., Hasterok et al., 2018). There is therefore an important role for the geological history of, and so lithologies within, the accreted terranes and fragments of ocean basins that form mountain belts in controlling the potential for lithium deposits.

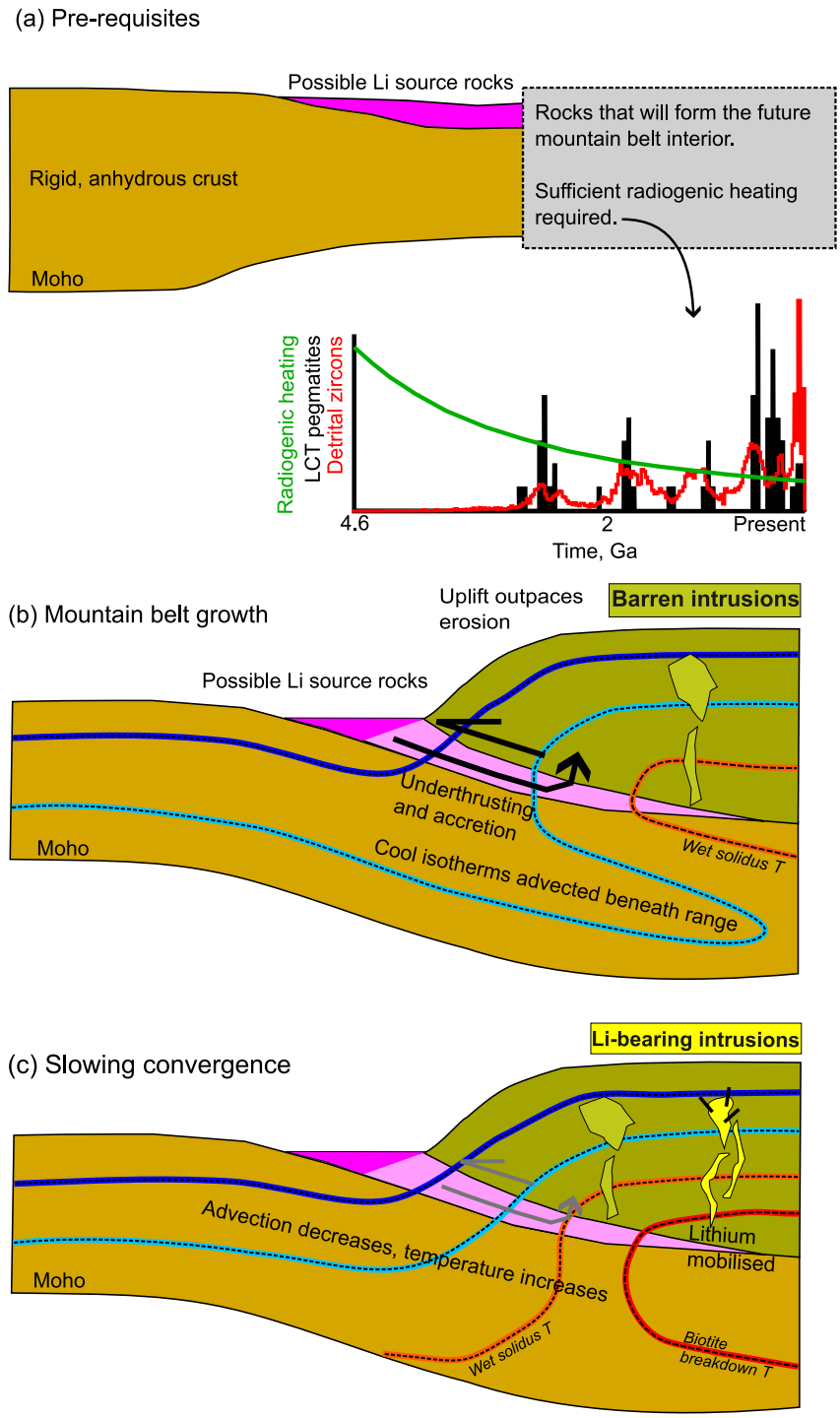

Figure 4. Schematic illustration of the conditions required for lithium ore production. The graph illustrates the concept that the overall rate of radiogenic heating was higher when the Earth was younger (green line), possibly explaining the prevalence of LCT pegmatites (black bars) relative to a proxy for the abundance of rocks (red line). The histograms of lithium-cesium-tantalum (LCT) pegmatite ages, and detrital zircon ages in modern sands, are from Bradley et al. (2017). The isotherms corresponding to the wet solidus and biotite-breakdown temperatures are indicated, which for average pelite and greywacke compositions and mid-crustal pressures are 650–700 °C and 800–900 °C, respectively (Text S1 in Supporting Information S1).

The importance of lithology is highlighted by the paucity of lithium-rich bodies associated with the widespread Caledonian-aged granitic intrusions in the meta-sandstone-dominated Grampian and Highland terranes of Scotland (e.g., Deady et al., 2023; Krabbendam et al., 2021; Prave, 1999). Caledonian-aged metamorphic temperatures of mostly ≤700 °C are recorded by the mid-crustal levels now exposed at the surface over large areas (e.g., Friend et al., 2000; Mako et al., 2019; Vorhies & Ague, 2011). Summing the present-day crustal thickness (e.g., Davis et al., 2012) and the metamorphic pressure estimates implies a total thickness during deformation that was likely to be ≥60 km, implying that the crustal thickness during the Caledonian orogeny was not the limiting factor for the production of lithium-enriched melts. The sandstone-dominated country rock lithology would, however, have reduced the temperatures that could be achieved (due to their generally low levels of radiogenic heating), and limited lithium-bearing source rocks (e.g., mica-bearing) would likely have been present in melt source regions. In contrast, along the structural strike of the Scottish Caledonides in the Appalachian belt of North America, there are more varied protoliths, including significant volumes of mudrocks (e.g., Peters et al., 2018), and lithium-bearing pegmatites were formed (e.g., Bradley et al., 2016). This comparison implies an important lithological control on the temperatures attained at depth, the lithium content of the source rocks, or both.

When combined with the additional requirements of a lithium-rich source rock, and high degrees of fractionation of the extracted partial melts, the tectonic "filters" discussed in this section (in terms of convergence rate, mountain belt thickness, and rate of radiogenic heating) mean that economic hard-rock lithium deposits are expected to be scarce. If the required melting temperatures to generate lithium-enriched melts were significantly lower, geologists would commonly visit their local spodumene quarry as part of their education, and other metals would be the subject of papers such as this one. The comparison of the different temperatures of interest on Figure 3 reveals the importance of the temperature range over which biotite melts, which part of that temperature range releases lithium into the melt, and whether specific compositions (e.g., fluorinated biotite) play a role. Such factors have a strong control over the breadth of the parameter space that is capable reaching the required temperatures, and therefore represents an important avenue for future research.

The utility of the approach described in this paper stems from being able to assess the patterns of temperature within mountain belts, and highlight which regions are potential hosts for lithium deposits. Although this paper has focused on lithium, the same principles apply for any element in which the temperature of partial melting plays an important role in determining the viability of economic deposits. Although such a method becomes more difficult to apply in the distant past, where the geometries and rates of motion in mountain belts become progressively more difficult to estimate, the Variscan example described above demonstrates that it can be applied wherever there is a record of foreland basin sedimentation and of metamorphic conditions in the range interior.

5. Conclusions

The concepts previously used to analyze the distributions and characteristics of earthquakes, and metamorphic and igneous rocks, in continental mountain belts have been used to investigate the controls on the distribution of lithium ores. Our analysis reveals an important set of tectonic filters that govern whether temperatures are attained that result in biotite-breakdown reactions, and by inference potentially generate lithium-rich melts, which accompany the requirements related to source-rock compositions and melt fractionation extent. We find that a strong foreland, able to support a thick mountain belt, is a requirement. The rate of underthrusting of this foreland must be initially rapid enough to build a thick mountain belt, but then decrease sufficiently to allow high temperatures to be produced in the underthrusting metasedimentary rocks. The requirement for significant rates of radiogenic heating means that the pre-mountain-building geological history plays an important role, as this controls the lithologies, and therefore heating rates, in the rocks that form a mountain belt. A quantitative understanding of the tectonic history and configuration of a region can therefore enable the assessment of range-scale mineralization potential.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No new data was produced by this work. The calculations were performed using existing methods, documented by Craig et al. (2012, 2020).

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