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Article

Transforming LCT Pegmatite Targeting Models into AI-Powered Predictive Maps of Lithium Potential for Western Australia and Ontario: Approach, Results and Implications

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Abstract: Lithium-cesium-tantalum (LCT) pegmatites account for circa one-third of global lithium resources and two-thirds of global lithium production. Western Australia, the world's largest supplier of hardrock lithium ores, and Ontario, an emerging lithium mining jurisdiction, have significant endowments that will be critical to the 'green revolution' given the predicted transition to lithium-based electromobility. In addition, both jurisdictions show excellent potential for future lithium discoveries given they cover large areas of favorable geology that, by and large, have recorded only limited lithium exploration. Here, we developed holistic LCT pegmatite targeting models for these important jurisdictions, informed by a detailed review of this deposit type and framed in the context of a mineral systems approach. Artificial intelligence (AI)-powered mineral potential modelling (MPM), using multiple, complimentary techniques and guided by the mappable elements of the LCT pegmatite genetic model, not only delivered the first regional scale views of lithium potential across the Archean to Proterozoic terrains of Western Australia and Ontario but also delivered compelling targets for future exploration and thought-provoking insights, such as the statistically verifiable proximity relationship between lithium, gold and nickel occurrences. Overall, this study also served to demonstrate the power of precompetitive, high-quality geoscience data, not only for regional scale targeting but also the development of camp-scale targets that are concise enough to be investigated using conventional prospecting techniques.

Keywords: exploration targeting; LCT pegmatites; lithium; artificial intelligence (AI); mineral potential modelling (MPM); mineral systems approach; Western Australia; Ontario

1. Introduction

Lithium deposits can be grouped into three principal types: Brine-, clay-, and hardrock-hosted. Lithium-cesium-tantalum (LCT) pegmatites, which fall into the hardrock category, are formed by orogenic processes at convergent plate boundaries. More specifically, they are products of extreme crystal-melt fractionation whereby the fractional crystallization of a parental granitic melt leads to enrichment in lithium, cesium and tantalum $\pm$ boron, beryllium, fluorine, gallium, hafnium, manganese, niobium, phosphorous, rubidium and tin in the residual pegmatitic facies. From a commercial perspective, the most important lithium mineral in LCT pegmatites is spodumene [1-3].

LCT pegmatites constitute a major economic resource of lithium. For example, in 2022, this deposit type accounted for almost 30% of global lithium resources and 60% of global lithium production [4]. LCT pegmatites in the Precambrian terrains of Western Australia (Australia) and Ontario (Canada), the subject of this study, are very well endowed with regards to lithium:

- Western Australia ranks fourth in terms of global lithium resource endowment and is the world’s largest lithium supplier. Total resources amount to ~2,000 Mt of ore for 26 Mt of contained lithium oxide (Li₂O), or lithia, contained in 19 LCT pegmatite deposit clusters (Figure 1; Table 1) [5]. The lithium mined in Western Australia to date has come entirely from LCT pegmatites of the Archean Pilbara and Yilgarn cratons. These two cratons host almost the entire Western Australian lithium endowment except for the Malinda lithium resource, which is hosted in LCT pegmatites of the Proterozoic Gascoyne Orogen. Greenbushes, located in the southwestern Yilgarn Craton, is not only the largest LCT pegmatite deposit in Western Australia but also the largest operating hard-rock lithium mine in the world [5-6].

Table 1. LCT pegmatite lithium resources, Western Australia.

Project	Province	Ore (Mt)	Grade (% Li ₂ O)	Li ₂ O (kt)	Status	Owner
Greenbushes	YC	445.5	1.48	6,547	Operating	Albemarle / Tianqi / IGO
Pilgangoora	PC	413.9	1.16	4,802	Operating	Pilbara Minerals
Andover	PC	240.0	1.50	3,600	Exploration	SQM / Hancock Prospecting)
Mt Holland	YC	186.0	1.53	2,846	Operating	SQM / Wesfarmers
Wodgina	PC	217.4	1.16	2,517	Operating	Albemarle / Mineral Resources
Kathleen Valley	YC	156.0	1.35	2,100	Operating	Liontown Resources
Mt Marion	YC	64.8	1.43	924	Operating	Ganfeng / Mineral Resources
Tabba Tappa	PC	74.1	1.00	740	Pre-feasibility	Wildcat Resources
Manna	YC	51.6	1.00	515	Pre-feasibility	Global Lithium Resources
Bald Hill	YC	26.5	0.97	256	Operating	Lithco No. 2
Malinda	GO	24.7	0.98	243	Exploration	Delta Lithium
Marble Bar	PC	18.0	1.00	180	Exploration	Global Lithium Resources
Mt Ida	YC	14.6	1.22	178	Exploration	Delta Lithium
Mt Cattlin	YC	13.3	1.29	172	Operating	Arcadium Lithium
Buldanina	YC	15.0	0.97	145	Exploration	Liontown Resources
Dome North	YC	11.1	1.15	128	Scoping	Develop Global
Split Rocks	YC	11.9	0.72	86	Exploration	Zenith Minerals
Mt Edwards	YC	2.0	0.69	13	Exploration	WIN Metals
Niobe	YC	4.6	0.07	3	Exploration	Aldoro Resources
King Tamba	YC	5.0	0.05	3	Exploration	Krakatoa Resources
Totals		1,996		25,998		

All figures are rounded. All projects are LCT pegmatite-hosted. All resources are JORC 2012 compliant except for Mt Holland, which is CRIRSCO compliant. Tappa Tappa resource compiled from [7]. Manna resource compiled from [8]. Andover is a pre-resource stage discovery with a JORC 2012 compliant exploration target range of 100 to 240 Mt @ 1.0 to 1.5% Li₂O for 1,000 to 3,600 kt Li₂O [9] that was included here given its very significant size potential and exploration upside. All other resource figures compiled from [5]. Key to abbreviations: GO = Gascoyne Orogen (Proterozoic); PC = Pilbara Craton (Archean); YC = Yilgarn Craton (Archean).

- Ontario, on the other hand, does not have any producing lithium mines although it is host to a number of advanced projects [10-11], some of which are moving towards production. Total resources are estimated at just under 120 Mt of ore for ~1.5 Mt Li₂O contained in seven LCT pegmatite deposit clusters (Figure 2; Table 2), all located in the Archean Superior Craton.

Table 2. LCT pegmatite lithium resources, Ontario.

Project	Province	Ore (Mt)	Grade (% Li ₂ O)	Li ₂ O (kt)	Status	Owner
PAK	SC	58.5	1.49	871	Feasibility	Frontier Lithium / Mitsubishi
Separation Rapids	SC	12.9	1.36	175	Exploration	Avalon / SCR-Sibelco
Georgia Lake	SC	14.8	0.91	93	Pre-Feasibility	RockTech Lithium
Root Bay	SC	10.1	1.29	130	Exploration	Green Technology Metals
Seymour Lake	SC	10.3	1.03	106	Feasibility	Green Technology Metals
Mavis Lake	SC	8.0	1.07	86	Exploration	Critical Resources

McCombe	SC	4.5	1.01	45	Exploration	Green Technology Metals
Totals		119		1,549		

All figures are rounded. All resources are LCT pegmatite-hosted and either JORC 2012 or NI 43-101 compliant. Mineral resources compiled from [12] for PAK, [13] for Separation Rapids, [14] for Root Bay, Seymour Lake and McCombe, [15] for Georgie Lake, and [16] for Mavis Lake. Key to abbreviations: Avalon = Avalon Advanced Materials; SC = Superior Craton (Archean).

In addition to their existing lithium resource endowments, both Western Australia and Ontario show excellent potential for future discoveries given they host large areas of favorable geology, which, by and large, have recorded only limited historic lithium exploration activity, and keep attracting significant lithium exploration spent, which, in the last couple of years alone, has resulted in a series of demonstrably and potentially significant finds such as Andover (Azure Minerals) and Tabba Tabba (Wildcat Resources) in Western Australia as well as Case Lake (Power Metals) and Falcon Lake (Battery Age Minerals) in Ontario. Recent, more speculative and yet to be drilled, or more comprehensively drill tested, finds include, for example, Big Red (Future Battery Metals), Kobe (Greentech Metals), Farson (WIN Metals), Andover South (Raiden Resources) and Andover West (Errawarra Resources) in Western Australia as well as Despard (Green Technology Metals), Victory (Beyond Lithium), Gorman (Patriot Lithium), Livyatan (Blaze Minerals), and SBC (Libra Lithium) in Ontario.

Whilst the LCT pegmatite systems of Western Australia and Ontario have featured in several government reports and journal publications [e.g., 17-24], no formal assessments exist in the public domain of the lithium prospectivity of these important jurisdictions, both of which have significant lithium endowment and undiscovered resource potential and, thus, are vital in meeting future lithium demand.

This study set out to generate artificial intelligence (AI)-driven mineral potential models, conveying the prospectivity for LCT pegmatite-hosted lithium mineralisation across the entire state of Western Australia and province of Ontario. The approach taken here was broadly similar to those employed by [25-26]:

- A detailed review was undertaken of the underlying mineral deposit model, in this case of LCT pegmatite-hosted lithium deposits;
- A mineral systems approach [27-29] was used to frame the preparation of a targeting model with an emphasis on the critical processes of LCT pegmatite genesis and their mappable expressions; and
- A multi-technique approach to mineral potential mapping (MPM) was adopted, using continuous as well as data- and knowledge-driven mathematical techniques, thereby facilitating cross-validation and comparing of the resulting prospectivity maps.

The study results, which include the first lithium prospectivity maps of Western Australia and Ontario, served:

- To capture the current understanding of the genesis of and controls on LCT pegmatite mineralizing systems as well as their mappable expressions;
- To delineate both the known as well as new areas lithium prospectivity, including extensions to the existing lithium occurrences clusters and greenfield areas not previously explored for lithium;
- As a basis for discussion, for example, on what work may be required to improve exploration targeting of LCT pegmatite systems, in particular with regards to the publicly available and missing datasets;
- To compare geological, data and exploration aspects unique to Western Australia and Ontario;
- To determine the most effective spatial proxies for targeting LCT pegmatite mineralizing systems; and
- To compare the results obtained from continuous, knowledge-driven and data-driven MPM.

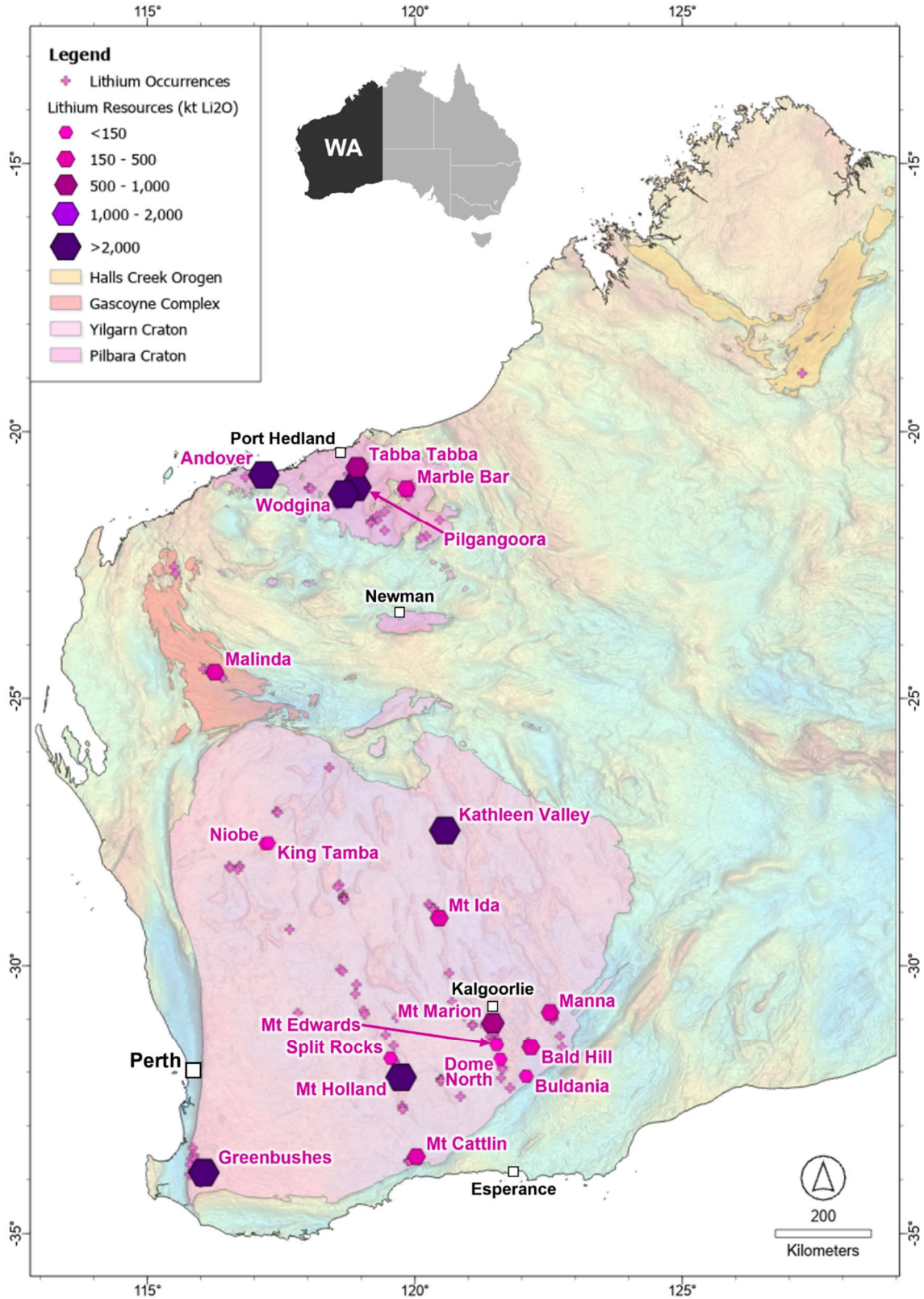


Figure 1. Map of LCT pegmatite-hosted lithium occurrences and deposits of Western Australia. See Table 1 for grade-tonnage estimates. The map also shows the outlines of the geological regions that host these lithium pegmatites: The Archean Yilgarn and Pilbara cratons and the Proterozoic Gascoyne Complex and Halls Creek Orogen. Background image: Bouguer gravity of Western Australia (<https://catalogue.data.wa.gov.au/>).

Figure 2. Map of LCT pegmatite-hosted lithium occurrences and deposits of Ontario. See Table 2 for grade-tonnage estimates. The map also shows the outline of the Superior Craton, the geological region that hosts these

lithium pegmatites. Background image: Bouguer gravity of Ontario (<https://www.geologyontario.mines.gov.on.ca>).

2. About Lithium: Discovery, Applications & Markets

Lithium, a member of the alkali metals group, was first discovered in 1817 by Swedish chemist Johan August Arfvedson, who isolated the element from the mineral petalite, a lithium aluminum phyllosilicate found in certain pegmatites [1]. However, demand for lithium, initially a relatively obscure mineral commodity with limited industrial uses, remained modest until the 1950s to 1960s, when new healthcare and defense sector applications gave rise to surging demand. A second boom in the 1980s to 1990s was underpinned by the rise of portable electronic devices powered by lithium-ion batteries. However, these earlier booms pale in comparison to the latest, which is underpinned by lithium’s critical role in the green energy revolution. This latest boom, which gathered momentum in the mid-2010s, has seen dramatic rises (and falls) in lithium demand and product prices, largely driven by the rapid expansion of the global electric vehicle market [1,30].

What makes lithium such an attractive battery material is that it is lightweight, able to store large amounts of energy and an excellent electrical conductor. Whilst lithium is a relatively abundant metallic element, commercially exploitable lithium deposits are relatively rare. Hardrock-hosted lithium deposits, in particular spodumene-bearing LCT pegmatites, are currently the best and most sought-after deposit type for commercial production [31]. Spodumene, due to its relative abundance and high lithium content, is the principal economic hardrock lithium mineral mined [32]. In addition, lithium extraction from spodumene typically offers lower capital costs and a shorter time from discovery to production in comparison to brine operations whilst commercial lithium production from clay-hosted deposits is yet to be achieved [31,33]. Other lithium minerals that are mined from LCT pegmatites include lepidolite, petalite, eucryptite and amblygonite. Whilst the latter is widespread, it is rarely of economic significance. The former are typically much less common in LCT pegmatites compared to spodumene or amblygonite [34].

3. Materials and Methods

3.1. Data Sources

The geoscience and exploration data used in this study were almost entirely sourced from open-access repositories maintained by the Geological Survey of Western Australia (GSWA) and the Ontario Geological Survey (OGS) (Table 3).

In addition to their proven lithium endowment and potential, it was the excellent quality and broad coverage of the publicly available geoscience data provided by the state of Western Australia and the province of Ontario that made these jurisdictions highly attractive and amenable to a mineral prospectivity study such as presented in this contribution.

Table 3. Data sources.

Repository	Datasets	Website URL
<i>Geological Survey of Western Australia (GSWA)</i>		
Data and Software Centre	Mines and mineral deposits (MINEDEX)	https://dasc.dmirs.wa.gov.au/
	Mineral exploration reports (WAMEX)	
	Mineral systems atlas: Rare-element pegmatite systems	
	Open-file mineral exploration drillholes	
	Geochronology	
	Surface geochemistry	
	Field observations (WAROX)	
	Regolith, surface and interpreted bedrock geology	
	Tectonic units	

	Airborne geophysics (gravity, magnetics, radiometrics) Multiscale edges from gravity and magnetics Tenements	
eBookshop	Books, reports and maps	https://dmpbookshop.eruditetechnologies.com.au/
	<i>Ontario Geological Survey (OGS)</i>	
OGSEarth	Mines and mineral deposits (OMI) Mineral exploration activity reports (OAFD) Open-file mineral exploration drillholes (ODHD) Geochronology Surface geochemistry Surface and interpreted bedrock geology Airborne geophysics (gravity, magnetics) Tenements Books, reports and maps	https://www.geologyontario.mndm.gov.on.ca/ogsearch.html

3.2. Mineral Systems Concept

The targeting model developed in this study was generated in the framework of a mineral systems approach [27-29,35-36] and in a manner described in more detail by [37-40]. Briefly, the mineral systems concept views mineral deposits as small-scale expressions of a series of geological processes operating at different temporal and spatial scales:

- Source processes extract the essential mineral deposit components (i.e., melts and/or fluids, metals and ligands) from their crustal or mantle sources;
- Transport processes drive the transfer of the essential components from source to trap regions via melts and/or fluids;
- Trap processes focus melt and/or fluid flow into physically and/or chemically responsive, deposit-scale sites;
- Deposition processes drive the efficient extraction of metals from melts and/or fluids passing through the traps; and
- Preservation processes act to preserve the accumulated metals through time.

In situations where one or more of these processes fail to operate, a mineral deposit cannot form or will not be preserved. The probabilistic principle at the core of this concept is one of the key strengths of the mineral systems approach, and one that works well in combination with a mathematical method such as MPM [37-38,40]. An additional key strength of the mineral systems approach is that it provides a robust yet flexible framework for formulating a holistic, process-based targeting model, and observing, mapping and/or querying in the available geoscience data the expressions of the critical processes of mineral deposit formation [35,41].

3.3. Mineral Potential Modelling (MPM)

MPM, first developed and applied in the late 1980s in conjunction with the arrival of geographic information systems (GIS) [42,43], has since evolved into a powerful, time- and cost-effective targeting tool capable of big data analytics. In other words. MPM is capable of simultaneously handling, integrating, processing and modelling the typically diverse and often very substantial geological, geochemical, geophysical, remote sensing and drilling data generated and used in mineral exploration. It is also a tool that is well-suited for efficient screening of and target generation within large search areas, be it a mineral district or belt, or an entire country or continent. In summary, MPM is a multi-stage process that includes the following steps [29,41,44-47]:

- Genetic model stage: Identification of the geological processes that are essential in the formation of the targeted deposit type to build a conceptual deposit model.
- Targeting model stage: Translation of the genetic model into a targeting model in which the essential processes are reflected by mappable targeting criteria (also referred to as targeting elements, predictors, predictor maps or spatial proxies).
- Mathematical model stage: Allocation of weights to combine the various spatial proxies using mathematical algorithms.

- Target identification and prioritized stage: Mapping and prioritization of the most prospective areas.

Concerning the mathematical modelling, the prevailing methods can be broadly subdivided into data-driven, knowledge-driven, hybrid knowledge- and data-driven and continuous approaches employing logistic functions [44, 48-49]. The selection as to which weighting technique should be used is strongly guided by data availability, specifically the number of known mineral occurrences in support of the targeting model, commonly referred to as prospect locations (PL). For example, un- or underexplored 'greenfields', 'grassroots' or 'frontier' regions are typically data poor and may contain only few, if any, mineral occurrences of the target type. In such search spaces, a knowledge-driven approach is often a must with MPM reliant on expert opinion. 'Brownfields' regions, on the other hand, are typically well explored, at least in places, and, thus, data-rich, in particular in the vicinity of known mineral deposits. For such regions, the weighting is commonly data-driven [44,48]. In contrast, continuous weighting methods require neither expert opinion nor PLs with continuous spatial evidence offering superior predictive capability compared to discretized evidence [49].

Here, we adopted a multi-technique approach to MPM [26] comprised of continuous (data-driven index overlay [50], fuzzy gamma [51], geometric average [52]), knowledge-driven BWM-MARCOS [47] and data-driven random forest [53] approaches.

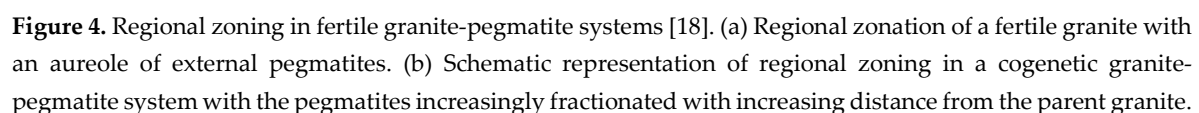
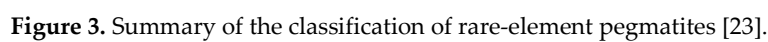
4. Lithium-Cesium-Tantalum (LCT) Pegmatites

4.1. Descriptive LCT Pegmatite Deposit Model

The Collins Dictionary of Geology [54] defines pegmatite as *"very coarse-grained igneous rock, typically found around the margins of large, deep-seated plutons, usually extending from the pluton itself into the surrounding country rocks"* and *"a volatile-rich, late stage in the crystallization of a magma"* that is typically granitic in composition.

Only ~0.1% of all granitic pegmatites on Earth classify as rare-element pegmatites [23], distinguishable from common pegmatites by their typically more complex mineralogy and compositional zoning and variably anomalous contents of beryllium, cesium, lithium, niobium, rare earth elements, rubidium, tantalum, tin, and uranium, yttrium and zirconium [55]. The class of rare-element granitic pegmatites has two end-members: LCT pegmatites, and niobium-yttrium-fluorine (NYF) pegmatites [55-56] (Figure 3). In contrast to LCT pegmatites, which can host significant deposits of beryllium, cesium, lithium, tantalum and/or tin, NYF pegmatites are, by and large, of little consequence to the global economy with only few representatives of this pegmatite family known to contain any mineable resources; in these cases small- to modest-sized deposits of niobium, uranium and/or rare earth elements [55].

LCT pegmatites can be found on all continents and range in age from Meso-Archean (Pilgangoora, Western Australia: ~2,879 Ma) to Cenozoic (Fonte del Prete, Italy: ~7 Ma). Most pegmatites are hosted by belts of sedimentary and igneous rocks that have been deformed and metamorphosed to upper greenschist to amphibolite facies grades. Whilst it is common to observe LCT pegmatites that lack any apparent source granite, there are many belts worldwide where a continuum can be observed from 'parental' granites to their pegmatite 'offspring' (Figure 4), or a genetic link can be inferred between the two based on textural, mineralogical, geochemical, isotopic, and geochronological evidence. The interpreted source intrusions are commonly relatively small, chemically and texturally evolved, and spatially and genetically associated with the waning stages of much more voluminous felsic magmatism. In addition, in many cases, the pegmatite offspring shows a district-scale zoning pattern with respect to the parental granite, with the greatest enrichment in incompatible elements characteristically recorded in the more distal pegmatites [2,57-58]. Overall, the geological features and spatial and temporal distribution of LCT pegmatites are consistent with their genesis in zones of crustal thickening along convergent plate boundaries, triggered by subduction or continental collision but most likely contemporaneous with post-tectonic crustal relaxation of the thickened crust [2,21,59]. However, according to [59], LCT pegmatites can



LCT pegmatites can be very large in size as exemplified by Western Australia's Greenbushes lithium-tantalum-tin deposit, which is centered upon a group of pegmatites that are traceable along

strike for up to 3,500 m, have maximum widths of up to 300 m and are interpreted to persist to vertical depths of at least 600 m [60]. In terms of their geometries, LCT pegmatites can take the form of flat-lying tabular sills, variably dipping tabular dykes, lenticular bodies or oddly shaped masses that commonly occur in groups (i.e., pegmatite swarms, fields or districts). Dykes are often vertically stacked [2] (Figures 5-7).

The degree of internal compositional zoning in LCT pegmatites ranges from relatively homogeneous types with relatively simple mineral assemblages (e.g., Pilgangoora, Western Australia) to distinctly zoned types with complex mineralogical assemblages (e.g., Greenbushes, Western Australia) (Figure 3). Mineralogically, LCT pegmatites comprise mostly of quartz, potassium feldspar, albite, and muscovite. Biotite, garnet, tourmaline and apatite are typical accessories. The principal components of economic interest are the lithium-bearing minerals spodumene, petalite, and/or lepidolite, the cesium-bearing mineral pollucite, the tantalum-bearing columbite-tantalite group of minerals, the tin-bearing mineral cassiterite and the beryllium-bearing mineral beryl [2].

Global examples of prominent LCT pegmatite systems are Greenbushes (Australia), Tanco (Canada), King's Mountain (USA), Manono-Kitotolo (DRC) and Jiajika (China) [2].

4.2. LCT Pegmatites of Western Australia

4.2.1. Geological Background and Distribution of Endowment

Western Australia records a greater four-billion-year history of assembly and breakup of cratonic elements, tied to global supercontinent cycles, that shaped the Australian continent and its mineral resources [61].

The oldest crustal elements of Western Australia, the Archean-age Yilgarn (~3,730 to 2,660 Ma) and Pilbara (~3,530 to 2,930 Ma) cratons (Figures 1, 8-9), comprised of extensive granite-greenstone and high-grade metamorphic gneiss terrains, are thought to have formed by either crustal overturn, sagduction or tectonic processes more analogous to modern plate tectonics. During early Proterozoic times, these Archean nuclei were amalgamated and incorporated into the broader Western Australian Craton, driven by a series of orogenies between ~2,215 and 1,950 Ma. The subsequent collision of the West Australian Craton with the North Australian Craton, a previously formed amalgamation of several Archean to Paleoproterozoic (pre-1,840 Ma) tectonic elements, lead to a complex series of tectono-thermal events concurrent with the final assembly of the Columbia/Nuna Supercontinent between 1,950 and 1,770 Ma [62-65].

The entire Western Australian lithium endowment and all but one of the known lithium occurrences are contained within the West Australian Craton, particularly its Archean nuclei, the Yilgarn and Pilbara cratons (Figures 1, 8-9). The Paleoproterozoic Gascoyne Block (Figures 1, 8), also located in the West Australian Craton, represents an emerging lithium province. The only known lithium occurrence outside of the West Australian Craton is found in the Paleoproterozoic Halls Creek Orogen (Figure 1) of the North Australian Craton. No lithium occurrences have been identified thus far in any of the other Proterozoic orogenic belts of Western Australia. Many of the Phanerozoic geological regions in the state are composed of unmetamorphosed basin sequences and, consequently, would have little to no LCT pegmatite potential (cf. [2]).

4.2.2. LCT Pegmatites of the Archean Yilgarn Craton

Eastern Yilgarn Craton LCT pegmatites are hosted in greenstone belts close to granite-greenstone contacts. They typically occur no more than 10 km from major faults or lineaments, often substantial structures marking domain or terrane boundaries, and generally show a preference for mafic or ultramafic host rocks metamorphosed at greenschist to amphibolite grade [66] (Figure 8; Table 4). Whilst the LCT pegmatites in the Eastern Goldfields Superterrane tend to cluster along first-order faults that separate individual terranes or lithostructural domains, those in the Murchison and Southern Cross terranes tend to be associated with less substantial second- or third-order faults. They also tend to be smaller in size compared to those in the Eastern Goldfields Superterrane.

Age-wise, the eastern Yilgarn Craton LCT pegmatites fall within a relatively narrow bracket of ~2,650 to 2,600 Ma, contemporaneous with a major period of global pegmatite emplacement [2,66-67]. No S-type granites exist in the Yilgarn Craton that would indicate the melting of sedimentary crustal sources [68], a key ingredient in the widely accepted LCT pegmatite deposit model (cf. [2]). However, in the Yilgarn Craton, the 2,650 to 2,600 Ma interval correlates with the formation of voluminous low-Ca granite melts of I-type affinity and with chemistries indicative of crustal melting. Granites of this igneous suite are potassic in composition, with high LILE and HFSE contents, and illustrate features indicative of late-magmatic fluid movements, such as miarolitic cavities and common pegmatites [66-67,69]. Witt [70] documented a plausible genetic link between some low-Ca granites and LCT pegmatites in the Kalgoorlie Terrane of the eastern Yilgarn Craton. More specifically, the author demonstrated that the geochemical and petrographic characteristics of the inferred parental granites are comparable to those of demonstrated lithium source granites in pegmatite provinces elsewhere on Earth. Recent work by [68] and [71] demonstrated that the low-Ca granites are progressively more radiogenic and enriched in lithium close to granite-greenstone contacts, typically marked by fault systems. The enrichment was interpreted as the signature of a preconditioned crust, which, at the time, was primed for biotite-dehydration melting at relatively shallow greenstone-root levels [68,71].

Compositionally and mineralogically, most eastern Yilgarn Craton LCT pegmatites classify as albite-spodumene pegmatites (Figure 3; Table 4), a category that is reserved for homogenous, unzoned LCT pegmatites, predominantly comprised of spodumene crystals in a quartz-albite matrix. If present, other lithium minerals, such as petalite, amblygonite, eucryptite, lepidolite or zinnwaldite, are not abundant enough in these pegmatites to be of economic interest. Albite-spodumene LCT pegmatites commonly take the form of subhorizontal to gently-dipping, sheet-like bodies [23,66], which, in the eastern Yilgarn Craton, can have strike lengths of >3 km (Manna) and maximum thicknesses of up to 100 m (Mt Holland). With proven distances of >2 km (Mt Holland), down-dip extents can be equally impressive.

The giant Greenbushes LCT pegmatite in the southwestern Yilgarn Craton (Figure 8; Table 1) does not fit the general mold. Rather, it is dated at ~2,527 Ma and, therefore, postdates the period of eastern Yilgarn Craton LCT pegmatite emplacement by about 75 to 100 m.y. Moreover, Greenbushes lacks an apparent causative parental intrusion, was emplaced syntectonically into a 150 km-long, regional-scale shear zone and is extensively deformed. It crystallized at upper amphibolite facies temperature and pressure conditions, which are higher than those recorded for its eastern Yilgarn Craton counterparts and displays an atypical, complex mineralogical zonation pattern [66,72] (Table 4).

4.2.3. LCT Pegmatites of the Archean Pilbara Craton

Pilbara Craton LCT pegmatites (Figure 9) are in many respects like those found in the eastern Yilgarn, including their preference for mafic-ultramafic, greenschist to amphibolite facies grade host rocks, proximity to granite-greenstone contacts and major faults and lineaments, and prevalence of albite-spodumene LCT pegmatites. Yet, the Pilbara Craton LCT pegmatites are older (~2,880 to 2,830 Ma) and, by and large, illustrate stronger spatial, geochemical, geochronological and, thus, genetic links to their inferred source intrusions: Highly fractionated, high silica monzogranites, with high LILE and HFSE contents and low K/Rb ratios, of the ~2,850 to 2,830 Ma post-tectonic Split Rock Supersuite (Figure 9; Table 4) [66].

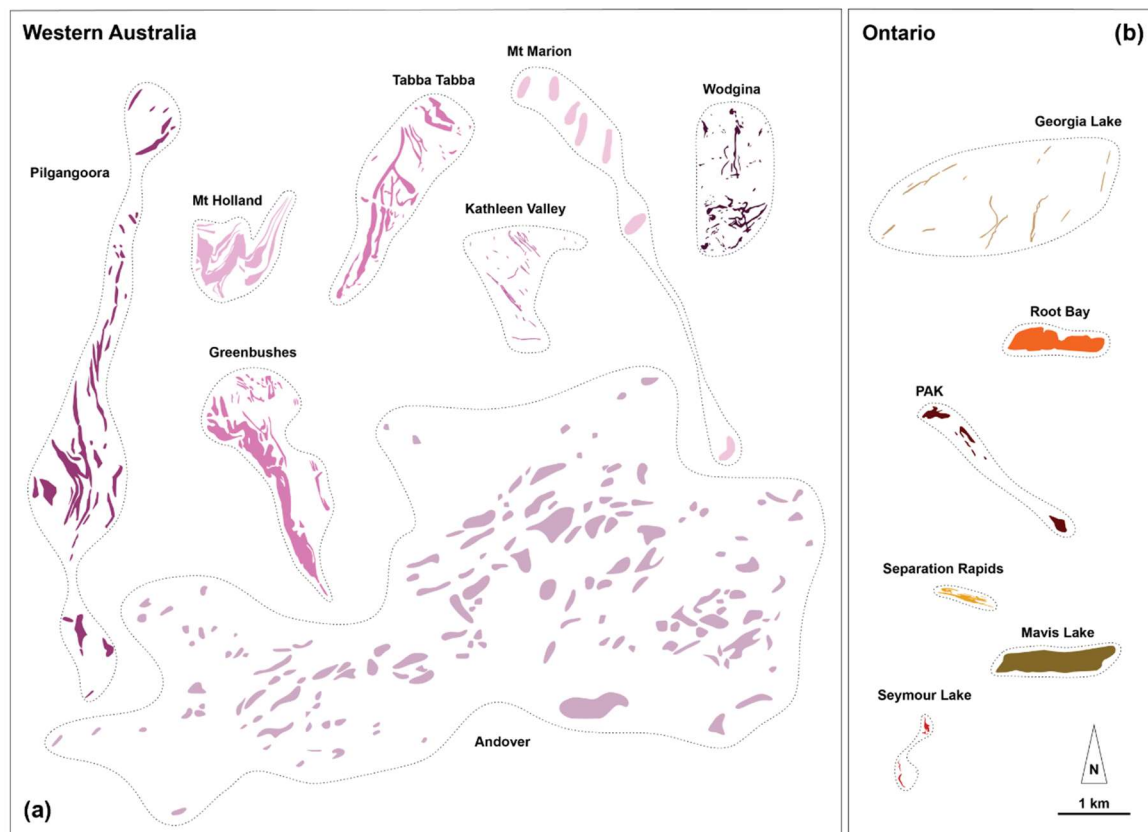


Figure 5. Two-dimensional (2D) footprints of the best-endowed LCT pegmatite camps in (a) Western Australia and (b) Ontario. The footprints are presented at the same scale, in plan view and orientated according to geographic north. Stippled lines provide approximate camp boundaries although, in many cases, the true extent of the LCT pegmatite systems has not been defined yet. Grade-tonnage and geological information as well as source references are provided in Tables 1-2 and 4-5.

4.2.4. LCT Pegmatites in Proterozoic Terrain

Little information exists in the public domain about LCT pegmatites in the Proterozoic terrains of Western Australia, and few such occurrences have been identified to date. The largest known system occurs at Malinda in the Yinnetharra LCT pegmatite district of the Paleoproterozoic Gascoyne Complex (Figure 8; Table 4). Here, multiple gently south- and north-dipping pegmatites cut a Paleoproterozoic basement of folded amphibolite and sedimentary schist, metamorphosed at upper greenschist to lower amphibolite facies conditions. The pegmatites are located along a greater 200 km-long, mantle tapping fault system and immediately adjacent to a composite intrusive body dominated by porphyritic monzogranite and leucocratic tourmaline-bearing granite of the Neoproterozoic (995 to 939 Ma) Thirty-Three Supersuite. This igneous suite, which was emplaced during and immediately after the Edmundian Orogeny (1,030 to 955 Ma), is interpreted as a possible causative intrusion [73-74]. The Malinda LCT pegmatites are sheet-like bodies that pinch and swell with the thicker parts of the pegmatites mineralised. Over 5 km of combined strike length of pegmatites has been defined to date. Individual pegmatites are up to 1.8 km long and have maximum widths up to >100 m and down-dip extents of >400 m. Lithium minerals within the pegmatites are predominantly spodumene, with subordinate lepidolite and trilithionite. Gangue minerals are mainly quartz and albite, with some microcline and muscovite [74].

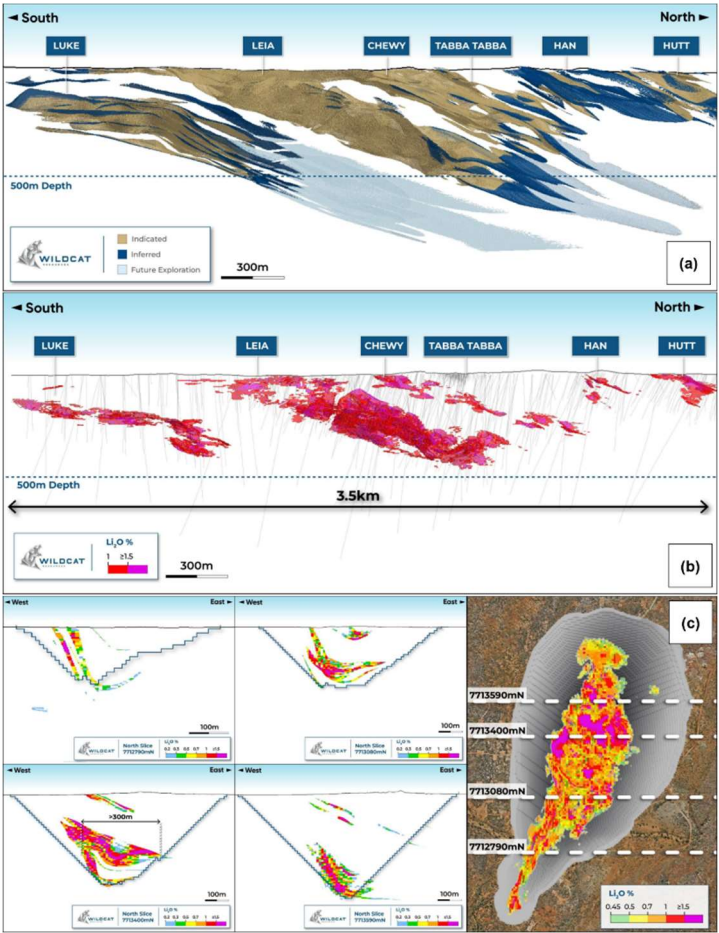


Figure 6. Geological and lithium block models of the Tabbatabba LCT pegmatite system, Pilbara Craton, Western Australia [8], illustrating, in 3D, the stacked nature and gently-dipping geometries that are typical of many Archean LCT pegmatites in Western Australian. (a) Isometric view of the current lithium resource envelope with plunge extents identified as targets for future exploration drilling. (b) Long section of the block model showing individual mineralised pegmatite domains. Mineralised blocks <1.0% Li₂O are not shown to demonstrate continuity of thick high-grade mineralisation. (c) Cross Sections (>0.2% Li₂O) through a plan view of a conceptual open pit at Leia (>0.45% Li₂O).

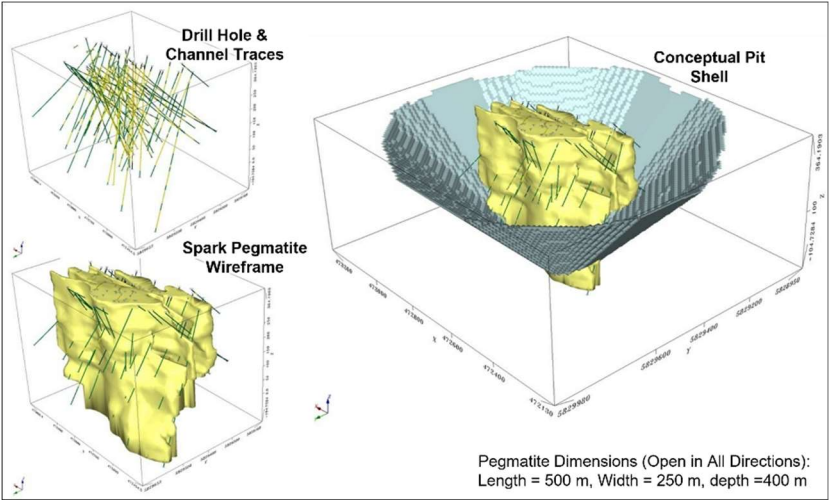


Figure 7. Wireframe model of the lithium mineralised Spark pegmatite, which forms part of the PAK LCT pegmatite system, Superior Craton, Ontario (see Table 5 for references). The 3D model serves to illustrate the vertical geometry of this pegmatite, which is typical of several of the well-mineralised Archean LCT pegmatites in Ontario, such as PAK and Separation Rapids.

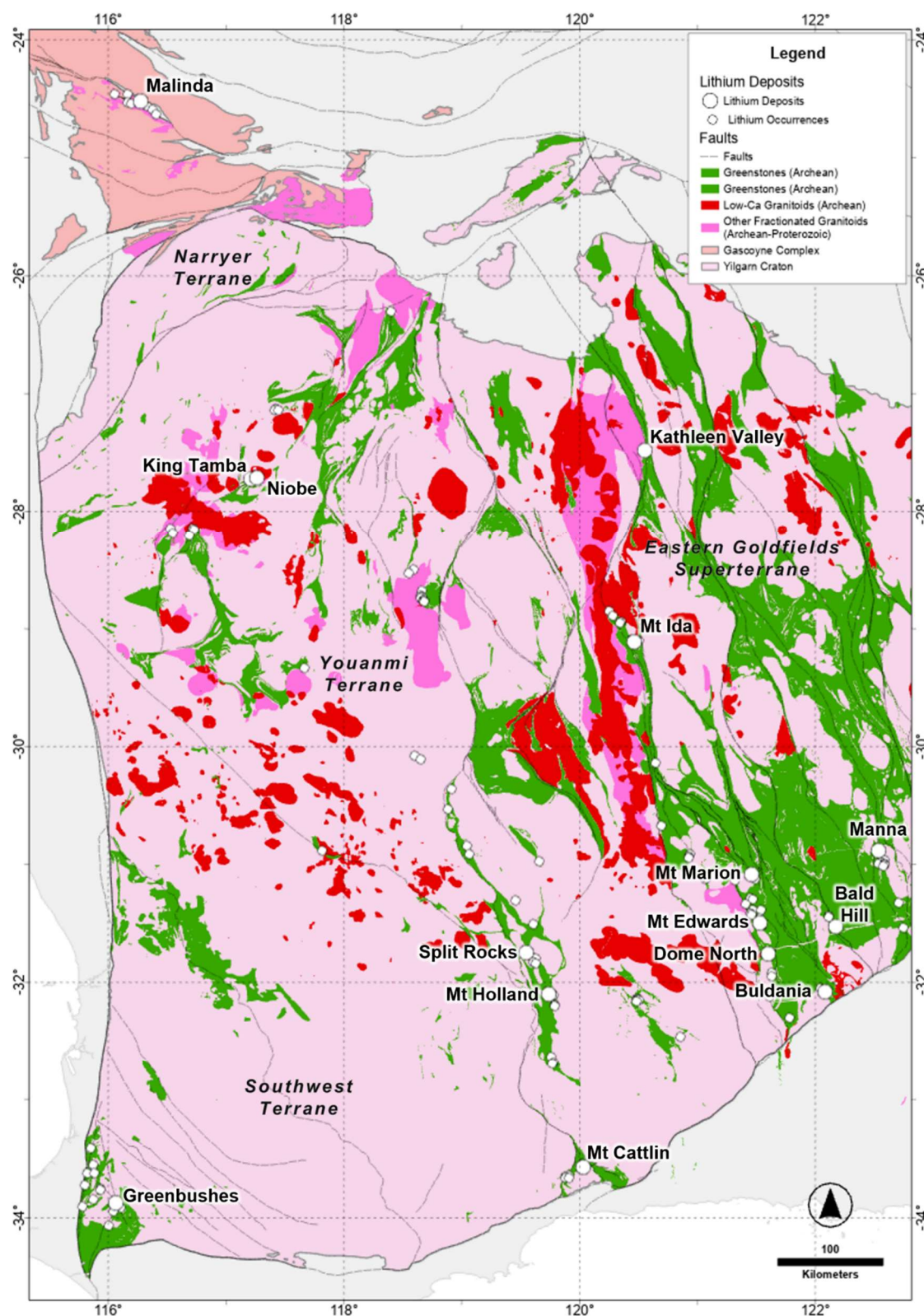


Figure 8. Map of lithium deposits and occurrences in the western and central Archean Yilgarn Craton and southern Proterozoic Gascoyne Complex, Western Australia. The map also shows the spatial distribution of potentially lithium fertile, fractionated felsic intrusions and greenstone host sequences. Most LCT pegmatites in the Yilgarn Craton were emplaced at ~2,650 to 2,600 Ma, contemporaneous with the low-Ca granites. The giant Greenbushes LCT pegmatite in the Southwest Terrane is dated at ~2,527 Ma and, therefore, postdates the low-Ca felsic igneous event. It lacks an apparent causative parental intrusion, was emplaced syntectonically into a regional-scale shear zone and is extensively deformed.

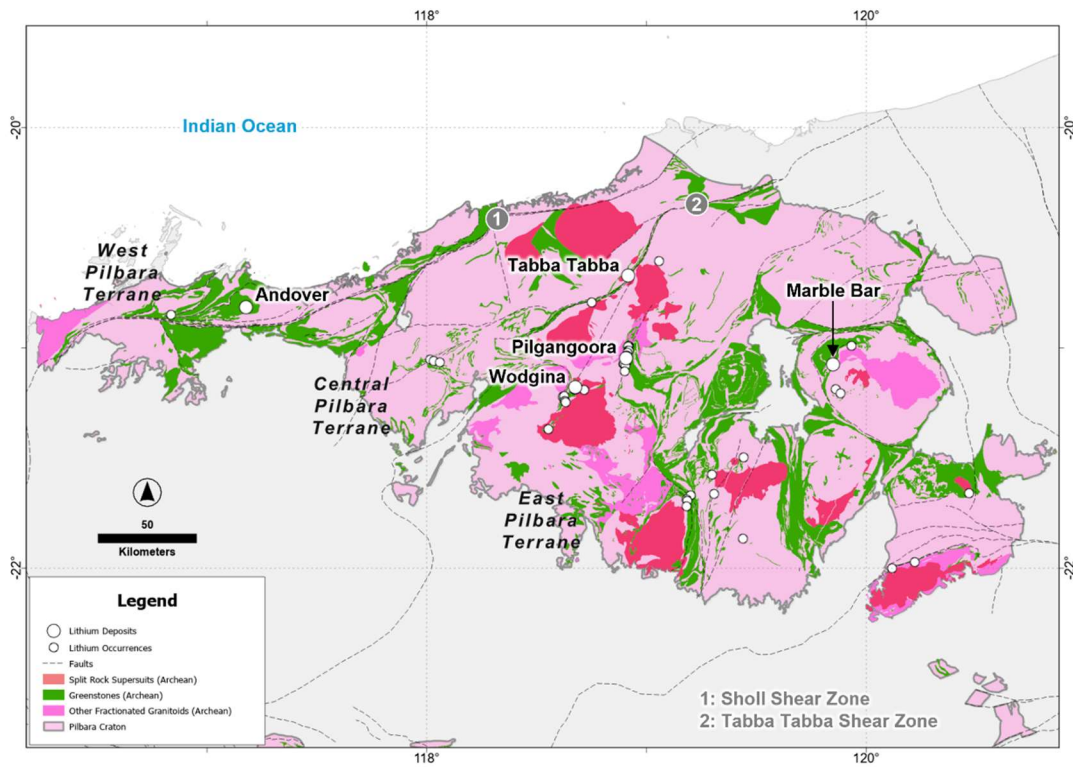


Figure 9. Map of lithium deposits and occurrences in the Archean Pilbara Craton, Western Australia. The map also shows the spatial distribution of potentially lithium fertile, fractionated felsic intrusions and greenstone host sequences. Most of the fractionated intrusions form part of the ~2,850 to 2,830 Ma Split Rock Supersuite, which aligns along a broad north-northwest trend. Split Rock Supersuite intrusive rocks are believed to be genetically associated with the ~2,880 to 2,830 Ma LCT pegmatites at Wodgina, Pilgangoora and Tappa Tappa as well as other LCT pegmatite occurrences. No fractionated intrusions are known within a radius of 55 km from the Andover deposit, a highly significant, relatively recent discovery. However, Andover is located proximal to the Sholl Shear Zone, a regionally extensive, terrane-bounding fault zone.

Table 4. LCT pegmatite systems, Western Australia.

System	Sub-Type	Province	Age	Geology & Structure	Mineralogy	References
Pilgangoora	LCT-AS	PC	Mesoarchean (~2,879 Ma)	<u>HR</u> : basalt, dolerite, undifferentiated ultramafic rock; <u>SC</u> : shear zone corridor; <u>SR</u> : Kadgewarrina & Poocatche Monzogranite, Split Rock Supersuite; <u>MG</u> : upper greenschist to lower amphibolite facies	spd, lpd, cot, cst, tlt, tap, brl	[2,24,75]
Andover	LCT-AS	PC	Mesoarchean	<u>HR</u> : peridotite, dunite; <u>SC</u> : poorly defined and/or described but proximal to shear zone corridor; <u>SR</u> : no obvious causative intrusion; <u>MG</u> : upper greenschist to lower amphibolite facies	spd, lpd, brl, cot, cst	[9]
Wodgina	LCT-A + LCT-AS	PC	Mesoarchean (~2,829 Ma)	<u>HR</u> : komatiite (Wodgina), metasedimentary sequence (Mt Cassiterite); <u>SC</u> : shear zone corridor; <u>SR</u> : Numbana Monzogranite, Split Rock Supersuite; <u>MG</u> : upper greenschist to lower amphibolite facies	cot, wod, Cs-brl, Li-mica, lit	[2,24,67]
Tappa Tappa	LCT-AS	PC	Mesoarchean (~2,877 Ma)	<u>HR</u> : dolerite sill, siliciclastic rocks; <u>SC</u> : shear zone corridor, schistosity; <u>SR</u> : Split Rock Supersuite; <u>MG</u> : upper greenschist to lower amphibolite facies(?)	spd, pet, Li-mica, brl, cot, cst, tlt	[7,76]
Marble Bar	LCT-AS(?)	PC	Mesoarchean	<u>HR</u> : amphibolite, dolerite, basalt; <u>SC</u> : shear zone corridor; <u>SR</u> : Moolyella Monzogranite–Mt Edgar Batholith (Split Rock Supersuite); <u>MG</u> : upper greenschist to lower amphibolite facies(?)	spd	[77]

Greenbushes	LCT-C-spd	YC	Neoproterozoic (~2,527 Ma)	<u>HR</u> : amphibolite, ultramafic schist, granofels; <u>SC</u> : shear zone corridor; <u>SR</u> : no obvious causative intrusion; <u>MG</u> : upper amphibolite facies	spd, brl, cot, cst, wod	[2,24,60]
Mt Holland	LCT-AS	YC	Neoproterozoic	<u>HR</u> : komatiite, dolerite, basalt, andesite; <u>SC</u> : shear zone corridor, folding; <u>SR</u> : post-tectonic, low-Ca granite; <u>MG</u> : upper greenschist to lower amphibolite facies	spd, pet	[78]
Kathleen Valley	LCT-C-spd	YC	Neoproterozoic	<u>HR</u> : gabbro, basalt, conglomerate; <u>SC</u> : shear zone corridor; <u>SR</u> : post-tectonic, low-Ca granite(?); <u>MG</u> : upper greenschist to lower amphibolite facies	spd, tlt, lpd	[79,80]
Mt Marion	LCT-AS + LCT-C-spd	YC	Neoproterozoic	<u>HR</u> : amphibolite, serpentinite, ultramafic schist, basalt, carbonaceous black shale; <u>SC</u> : folding, shear zone corridor; <u>SR</u> : Depot Granodiorite; <u>MG</u> : lower amphibolite facies	spd, cot, cst, brl, lpd	[81-82]
Manna	LCT-AS(?)	YC	Neoproterozoic	<u>HR</u> : gabbro, basalt; <u>SC</u> : shear zone corridor; <u>SR</u> : Cardunia Granite; <u>MG</u> : lower to middle amphibolite facies(?)	spd, lpd	[83-84]
Bald Hill	LCT-AS	YC	Neoproterozoic	<u>HR</u> : schist, greywacke, granite; <u>SC</u> : schistosity, shear zone corridor; <u>SR</u> : post-tectonic, low-Ca granite(?); <u>MG</u> : upper greenschist to lower amphibolite facies	spd, lpd, tlt	[23]
Mt Ida	LCT-AS(?)	YC	Neoproterozoic	<u>HR</u> : anorthosite-leucogabbro; <u>SC</u> : shear zone corridor, folding; <u>SR</u> : post-tectonic, low-Ca Oberwyl Granite; <u>MG</u> : upper greenschist to lower amphibolite facies	spd, lpd	[85]
Mt Cattlin	LCT-AS	YC	Neoproterozoic (~2,625 Ma)	<u>HR</u> : intermediate to mafic volcanic rocks, dolerite, tonalite; <u>SC</u> : shear zone corridor; <u>SR</u> : post-tectonic, fractionated, low-Ca granite; <u>MG</u> : greenschist to amphibolite facies	spd, cot, lpd, tlt, cst, tap, brl	[23,86]
Buldania	LCT-C-spd(?)	YC	Neoproterozoic	<u>HR</u> : komatiite, basalt, dolerite, carbonaceous shale; <u>SC</u> : shear zone corridor; <u>SR</u> : post-tectonic, fractionated, low-Ca granite; <u>MG</u> : upper greenschist to middle amphibolite facies	spd	[87]
Dome North	LCT-C-pet	YC	Neoproterozoic	<u>HR</u> : komatiite, basalt, sedimentary rock sequence; <u>SC</u> : shear zone corridor; <u>SR</u> : Pioneer Monzogranite; <u>MG</u> : upper greenschist to lower amphibolite facies	pol, pet, lpd, spd, lpd	[88]
Split Rocks	LCT-C-pet(?)	YC	Neoproterozoic	<u>HR</u> : undifferentiated mafic rock; <u>SC</u> : shear zone corridor; <u>SR</u> : post-tectonic, fractionated, low-Ca granite(?); <u>MG</u> : lower amphibolite facies(?)	euc, spd, pet, lpd	[89]
Mt Edwards	LCT-AS(?)	YC	Neoproterozoic	<u>HR</u> : komatiite, basalt; <u>SC</u> : shear zone corridor; <u>SR</u> : post-tectonic, fractionated, low-Ca granite(?); <u>MG</u> : middle to upper amphibolite facies	spd	[90]
Niobe	LCT-C-lpd(?)	YC	Neoproterozoic	<u>HR</u> : gabbro; <u>SC</u> : poorly defined and/or described; <u>SR</u> : post-tectonic, fractionated, low-Ca Walganna Suite granite(?); <u>MG</u> : greenschist to amphibolite facies	lpd, zwd, mic, brl, spd(?)	[91]
King Tamba	LCT-C-lpd(?)	YC	Neoproterozoic	<u>HR</u> : dolerite, sedimentary schist; <u>SC</u> : shear zone corridor, folding; <u>SR</u> : post-tectonic, fractionated low-Ca Walganna Suite granite(?); <u>MG</u> : greenschist to amphibolite facies	tap, tlt, cst, lpd, mic, zwd, brl	[92]

Malinda	LCT-AS(?)	GO	Neoproterozoic	HR: volcano (mafic)-sedimentary sequence; SC: shear zone corridor, folding; SR: Thirty-Three Supersuite granite; MG: upper greenschist to lower amphibolite facies	spd, lpd, pet, tlt, cst	[74]
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Key to abbreviations. *Sub-Types*: LCT-A = LCT albite pegmatite, LCT-AS = LCT albite-spodumene pegmatite, LCT-C-lpd = LCT complex pegmatite, lepidolite-type, LCT-C-pet = LCT complex pegmatite, petalite-type, LCT-C-spd = LCT complex pegmatite, spodumene-type. *Province*: GO = Gascoyne Orogen, PC = Pilbara Craton, YC = Yilgarn Craton. *Geology & Structure*: HR = host rock, MG = metamorphic grade, SC = structural control, SR = source rock. *Mineralogy*: brl = beryl; cot = columbite-tantalite; Cs = cesium; cst = cassiterite; euc = eucryptite; Li = lithium; lit = lithiophilite; lpd = lepidolite; mic = microlite; pet = petalite; pol = pollucite; spd = spodumene; tap = tapiolite; tlt = tantalite; wod = wodginite; zwd = zinnwaldite.

4.3. LCT Pegmatite Systems of Ontario

4.3.1. Geological Background and Distribution of Endowment

The Superior Craton of eastern Canada and the north-central United States consists of extensive granite-greenstone, clastic sediment-dominated and high-grade metamorphic gneiss terrains. It represents the world's largest preserved piece of Archean crust, which forms the core of the much larger Canadian Shield. The craton was assembled between 2,720 and 2,680 Ma by amalgamation of continental blocks with rocks as old as ~3,800 Ma and intervening tracts of oceanic crust, most likely by tectonic processes analogous to modern plate tectonics. By and large, the Superior Craton has been tectonically stable since 2,600 Ma, following progressive north to south assembly of its terranes into a coherent craton during the Kenoran Orogeny [93-96].

Ontario's entire lithium endowment, including all known lithium occurrences, is contained within the Archean Superior Craton (Figure 10; Tables 1, 5). No lithium occurrences have been identified thus far in the Proterozoic orogenic belts of Ontario (i.e., 2,200 to 1,850 Ma Penokean and 1,300 to 1,000 Ma Grenville orogens) although discovery potential may exist. Widespread Paleozoic to Mesozoic basin sequences in northern and southern Ontario are unmetamorphosed [97-98] and, consequently, would have little to no LCT pegmatite potential [2].

4.3.2. LCT Pegmatites of the Archean Superior Craton

Like in the Western Australian Yilgarn and Pilbara cratons, LCT pegmatites in the Superior Craton are hosted in greenstone belts close to granite-greenstone contacts and typically occur no more than 10 km from prominent faults or lineaments. These are often substantial structures marking domain or terrane boundaries. They also display a similar preference for mafic or ultramafic host rocks metamorphosed at greenschist to amphibolite grade and fall into a broadly similar Neoproterozoic age bracket as the eastern Yilgarn LCT pegmatites of ~2,670 to 2,640 Ma [18-19] (Figure 10; Table 5). Where most of the Archean LCT pegmatite systems in Ontario differ from those in Western Australia is in the following aspects:

- There is good evidence in the Superior Craton of Ontario of a genetic link between fertile parental granites and spatially associated LCT pegmatites. The fertile, peraluminous, Neoproterozoic-age (2,680 to 2,640 Ma) S-type granites, derived from the partial melting of a thickened sedimentary crustal source, are most abundant in the metasediment-dominated English River and Quetico terranes. Well documented examples of lithium source granites and their related pegmatites are the Ghost Lake Batholith and Mavis Lake pegmatites and the Separation Rapids Pluton and Separation Rapids pegmatites, which typically occur no more than 15 km from the margins of their parental intrusions [18-19,99]. Terranes that lack these S-type granites are largely devoid of LCT pegmatites (Figure 10).
- Most LCT pegmatites in the Superior Craton of Ontario classify as complex pegmatites, whereas this subtype is less common in the Archean cratons of Western Australia. Interestingly, the two largest lithium resources in Ontario, hosted by the PAK and Separation Rapids LCT pegmatite systems, both classify as complex petalite types, a category of LCT pegmatite that is rare in Western Australia. On the other hand, Ontario has few known LCT pegmatites of the albite-

- spodumene type, which is a common type in Western Australia where pegmatites of this type can host substantial lithium resources.
- LCT pegmatites in Ontario have a preponderance for steep to subvertical dip angles (e.g., PAK, Separation Rapids) whilst their Western Australian counterparts are typically gently-dipping to subhorizontal in nature. There also appear to be more examples of LCT pegmatites in Ontario that (i) are tectonically deformed or strongly deformed (e.g., PAK is schistose [100], Separation rapids is complexly folded, strongly schistose and locally mylonitized [101]), and (ii) have lenticular or prolate (e.g., PAK, Separation Rapids) rather than sheet-like geometries, which is more common in Western Australia. Pegmatite footprints are commonly more modest than in Western Australia with the larger Ontarian systems (i.e., PAK, Separations Rapids) characterized by strike lengths of between 1.5 and 2.3 km, maximum widths of between 70 and 125 m and proven down-dip extents of between 275 to 400 m. The smaller systems have strike lengths in the range from 0.2 to 1.3 km, maximum thicknesses of 10 to 25 m and proven down-dip extents of 300 to 950 m. As in Western Australia, stacked pegmatite systems are common.
 - Ontario’s known LCT pegmatites have a combined lithium resource endowment of 1,549 kt Li₂O, which amounts to only 6% of the combined Western Australian lithium resource endowment of 25,998 kt Li₂O (Table 1). Even at the craton level, the Superior Craton in Ontario hosts significantly less lithium than the Yilgarn (13,916 kt Li₂O) or Pilbara (11,839 kt Li₂O) cratons of Western Australia despite its size of ~595,000 km² (the entire Superior Craton has a size of 1 572 000 km², comprising almost a quarter of the Earth’s exposed Archean crust [93]), which is comparable to that of the Yilgarn Craton (~609,000 km²) and several times larger than that of the Pilbara Craton (~57,000 km²). Looking at individual deposits, PAK, the largest lithium resource in Ontario would only rank at number eight amongst the Western Australian lithium resources. To a certain degree, this discrepancy may be a function of exploration maturity but the latter is unlikely to account for the large variability . Rather, it is more likely that the specific conjunction of critical geological factors, including some of those mentioned above, had an important role to play.

Table 5. LCT pegmatite systems, Ontario.

System	Sub-Type	Province	Age	Geology & Structure	Mineralogy	References
PAK	LCT-C-pet	SC	Neoarchean (~2,670 Ma)	HR: felsic to ultramafic volcano-sedimentary rocks, granite; SC: shear zone corridor; SR: peraluminous two-mica granite; MG: amphibolite facies	pet, spd, cot, wod, csd	[2,24,100, 102]
Separation Rapids	LCT-C-pet	SC	Neoarchean (~2,644 Ma)	HR: basalt (± pillowed); SC: shear zone corridor; SR: Separation Rapids Pluton; MG: lower to middle amphibolite facies	pet, spd, euc, cot, wod, lpd, cst, brl	[2,24,101]
Root Bay	LCT-C-spd	SC	Neoarchean	HR: basalt (± pillowed); SC: shear zone corridor; SR: genetic linkage not well established, possible linkage with Allison Lake Batholith; MG: upper greenschist to lower amphibolite facies(?)	spd	[103]
Seymour Lake	LCT-C-spd	SC	Neoarchean (~2,666 Ma)	HR: pillow basalt ± amphibolite, dolerite, gabbro; SC: poorly defined and described; SR: no obvious causative intrusion; MG: upper greenschist to lower amphibolite facies(?)	spd; pol, lpd, Cs-brl, cot	[2,24,103]
Georgia Lake	LCT-AS	SC	Neoarchean	HR: sedimentary rocks, granite; SC: poorly defined and described; SR: Glacier Lake and Barbara Lake batholiths; MG: upper greenschist to lower amphibolite facies(?)	spd, brl, cot, cst	[104]
Mavis Lake	LCT-AS	SC	Neoarchean (~2,665 Ma)	HR: mafic volcanic rock; SC: shear zone corridor; SR: Ghost Lake Batholith; MG: upper greenschist to lower amphibolite facies(?)	spd, tri, cot	[2,24,105]
McCombe	LCT-C-spd	SC	Neoarchean	HR: basalt (± pillowed); SC: shear zone corridor; SR: peraluminous two-mica granite; MG: upper greenschist to lower amphibolite facies(?)	spd, lpd, tlt, col, pet, mic, brl	[103]

Key to abbreviations: Sub-Types: LCT-AS = LCT albite-spodumene pegmatite, LCT-C-pet = LCT complex pegmatite, petalite-type, LCT-C-spd = LCT complex pegmatite, spodumene-type. Province: SC = Superior Craton. Geology & Structure: HR = host rock, MG = metamorphic grade, SC = structural control, SR = source rock. Mineralogy: brl = beryl; col = columbite; cot =

columbite-tantalite; Cs = cesium; cst = cassiterite; euc = eucryptite; lpd = lepidolite; mic = microlite; pet = petalite; pol = pollucite; spd = spodumene; tlt = tantalite; tri = triphylite; wod = wodginite.

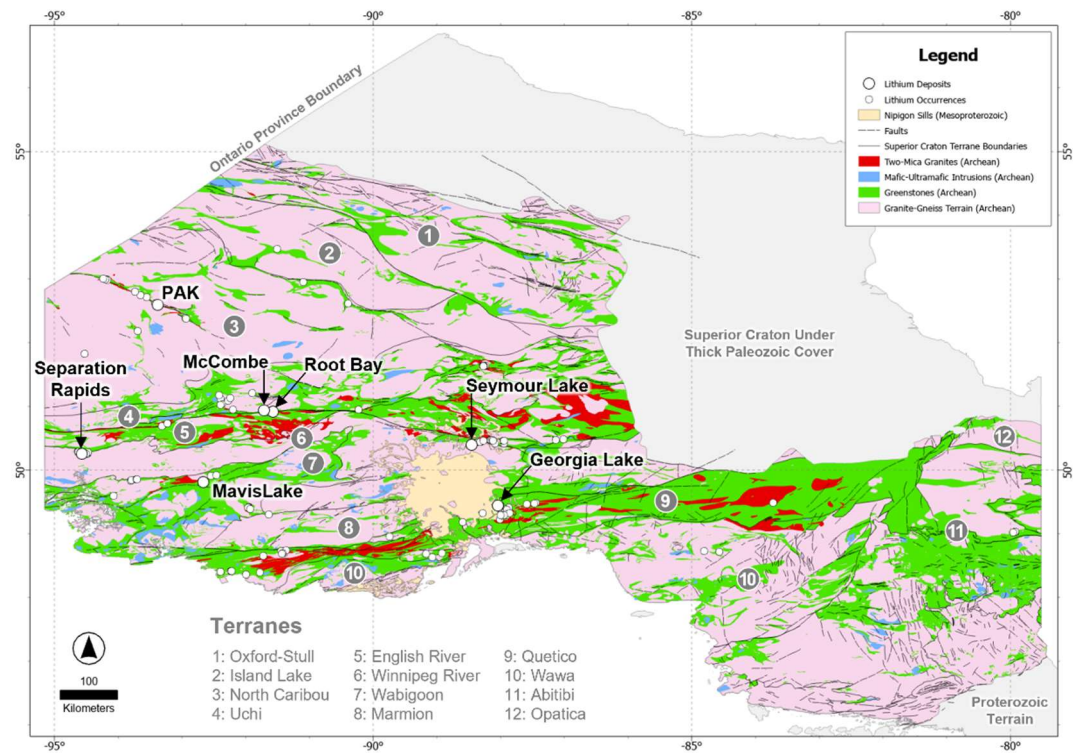


Figure 10. Map of lithium deposits and occurrences in the Archean Superior Craton of Ontario. There is good evidence in this part of the Superior Craton of a strong genetic link between peraluminous S-type magmas, represented by a suite of 2,680 to 2,640 Ma two-mica granites, and LCT pegmatite formation between ~2,670 and 2,640 Ma. Spatially, both two-mica granites and associated LCT pegmatites are concentrated within two broad, approximately east-west-trending lithostructural zones: The metasediment-dominant English River, Quetico and some of their adjacent terranes.

4.2. LCT Pegmatite Targeting Model

Table 6 provides a summary of the processes deemed critical in the genesis of the LCT pegmatite-hosted lithium deposits using the information summarized above and succinctly presented in [1-2,20-21].

Here, we followed the approach of [29], according to which the critical processes of a mineral system are translated into targeting criteria. In essence, this is done by (i) breaking down the critical processes into their constituent processes, (ii) gathering the geological evidence that reflects the constituent processes, and (iii) developing targeting criteria that can be used to detect the targeting elements, either directly or by proxy.

Importantly, any expressions of a mineral system that cannot be mapped in the obtainable exploration geoscience data cannot be honored in MPM. And, ideally, the datasets that reflect the predictors should have relatively uniform, unbiased coverage of the target area [106].

Table 6. LCT pegmatite targeting model adopted in this study.

Critical Processes	Constituent Processes	Targeting Criteria	Targeting Elements (Predictor Maps)
Source	LCT pegmatites are products of extreme fractionation of granitic magmas and acquire most of their compositional attributes at source.	Convergent plate margin settings. Granite stocks, plutons or batholiths of S-type or evolved I-type affinity.	Proximity to fractionated granitic rock units. Proximity to pegmatitic or pegmatite-bearing rock units.
	Their genesis requires a high degree of crustal melting to form fertile granitic magmas as a source for fluids, metals and energy to drive the mineral system.		
	The genetic link between LCT pegmatites and S-type or evolved I-type granitic magmas and their tectonic settings is well established.		
Transport	Granitic melts ascent into the upper crust along zones of structural weakness.	First- and second-order fault systems. High degree of crustal permeability.	Domains of greater density of Bouguer gravity breaks.
	Upper crustal fault-fracture systems act as conduits for focusing large volumes of melts and fluids over short periods of time		Proximity to Bouguer gravity breaks.
			Domains of greater density of RTP magnetic breaks. Domains of greater density of major crustal boundaries. Proximity to faults and lineaments.
Trap	Given their affinity with convergent plate margin settings and emplacement of source granites at midcrustal levels, LCT pegmatites cut and solidify in metamorphosed supra-crustal rocks.	Metamorphosed terrains at greenschist to amphibolite facies grade.	Proximity to metamorphic rocks.
	LCT pegmatites have a distinct preference for mafic or ultramafic host rocks; likely a function of favorable physico-chemical parameters that serve to enhance trap and depositional processes.	Mafic and ultramafic rock sequences.	Proximity to mafic-ultramafic rocks.
	LCT pegmatites have statistically valid abundance and proximity relationships with gold and nickel occurrences; likely a function of loosely comparable transport and trap processes (this study).	Clusters of gold and/or nickel occurrences.	Proximity to Au occurrences. Proximity to Ni occurrences.
Deposition	Extreme fractional crystallization of parental granitic magmas.	Confirmed LCT pegmatites.	Proximity to mapped pegmatites. Proximity to LCT pegmatite indicator minerals.
	Concentration of incompatible rare elements and volatiles in residual LCT pegmatite melts.	Presence of indicator minerals (e.g., beryl, tourmaline or garnet in pegmatites or holmquistite in country rocks).	
	LCT pegmatite melt solidification, magmatic-hydrothermal transition and rare metals mineralisation.	Lithogeochemical dispersion halos (e.g., Li, Rb, Cs) in country rocks. Geochemical anomalism (e.g., Li, Cs, Ta). Fractionation indicators (e.g., very low K/Rb, K/Cs, Nb/Ta or Mg/Li ratios).	
Preservation	Metasomatic alteration processes can result in selective to complete replacement of primary spodumene	Sub-solidus hydrothermal alteration. Post-magmatic hydrothermal activity.	Not mappable at the scale of this investigation.

by secondary minerals (e.g., albite, cookeite or kaolinite).		
Tectonic and/or climatic and erosional forces can have positive (e.g., LCT pegmatite exhumation) or negative (e.g., complete destruction of LCT pegmatites) effects.	For example, topographic highs formed by outcropping, weathering-resistant LCT pegmatites.	

5. Mineral Potential Modelling (MPM)

5.1. Statistical Assessment of Spatial Proxies

The predictive capacity of each spatial proxy was statistically assessed against a set of prospect locations (PL) and non-prospect locations (NPL) with the Western Australian dataset comprising 208 PL and an equal number of NPL and the Ontarian dataset comprises 122 PL and an equal number of NPL. The PL data represent a mix of significant mineralized drillhole intersections as well as lithium deposits and occurrences whilst the NPL were selected according to the following rules: The must (i) be located outside of the lithium permissive tracts; (ii) not be located close to any of the PL; and (iii) have a random spatial distribution.

Two procedures were used in the statistical assessment of the spatial proxies, namely the (i) area under the receiver operating characteristic curve (*AUC*) (Figures A1-A2) [107-109], and (ii) index of normalized density (*N_d*) [110]. Prediction-area (P-A) plots (Figs. A3-A4) served to define the best-performing spatial proxies for targeting lithium mineralised systems in Western Australia and Ontario. Any spatial proxies that fulfilled the statistical requirements of *AUC* > 0.50 [107] and *N_d* > 1.00 [110] were considered adequate for use in MPM (Tables 7-8).

Table 7. Statistical parameters of the spatial proxies used in the Western Australian lithium MPM.

Spatial Proxy	<i>P_r</i> (%)	<i>O_a</i> (%)	<i>N_d</i>	<i>AUC</i>	<i>ln(N_d)</i>
Proximity to mapped pegmatites	86	14	6.14	0.95	1.82
Proximity to LCT pegmatite indicator minerals	84	16	5.25	0.92	1.66
Proximity to mafic-ultramafic rocks	78	22	3.55	0.94	1.27
Proximity to Au occurrences	76	24	3.17	0.84	1.15
Proximity to Ni occurrences	74	26	2.85	0.86	1.05
Proximity to fractionated granitic rock units	70	30	2.33	0.81	0.85
Proximity to pegmatitic or pegmatite-bearing rock units	69	31	2.23	0.84	0.80
Proximity to faults and lineaments	67	33	2.03	0.67	0.71
Domains of greater density of RTP magnetic breaks	65	35	1.86	0.66	0.62
Domains of greater density of Bouguer gravity breaks	63	37	1.70	0.66	0.53
Domains of greater density of major crustal boundaries	58	42	1.38	0.59	0.32
Proximity to metamorphic rocks	57	43	1.33	0.55	0.28

Key to abbreviations: *P_r* = prediction rate, *O_a* = prediction area, *N_d* = *P_r*/*O_a*, *AUC* = area under the receiver operating characteristic curve, *ln(N_d)* = weight.

Table 8. Statistical parameters of the spatial proxies used in the Ontarian lithium MPM.

Spatial Proxy	<i>P_r</i> (%)	<i>O_a</i> (%)	<i>N_d</i>	<i>AUC</i>	<i>ln(N_d)</i>
Proximity to LCT pegmatite indicator minerals	89	11	8.09	0.96	2.09
Proximity to mapped pegmatites	87	13	6.69	0.94	1.90
Proximity to fractionated granitic rock units	86	14	6.14	0.94	1.82
Proximity to Au occurrences	69	31	2.23	0.76	0.80
Domains of greater density of major crustal boundaries	68	32	2.13	0.73	0.75
Proximity to mafic-ultramafic rocks	65	35	1.86	0.90	0.62
Proximity to Ni occurrences	68	32	2.13	0.78	0.75

Proximity to Bouguer gravity breaks	51	49	1.04	0.54	0.04
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Key to abbreviations: See Table 7.

5.2. Continuous Data-Driven Index Overlay, Continuous Fuzzy Gamma, Geometric Average Approaches

Three continuous modelling functions, data-driven index overlay [50], fuzzy gamma [51] and geometric average [52], were utilized to model the lithium potential of Western Australia and Ontario. Large and small fuzzification functions [111-112] were utilized to assign weights to the spatial proxies with the resulting fuzzy scores of the evidential values in the range [0,1] (Figures A5-A24).

The MPM results for Western Australia and Ontario, as computed by these modelling functions are illustrated in Figures 11a-c and 12a-c.

5.2.1. Data-Driven Index Overlay

Mathematically, the data-driven index overlay approach can be expressed as follows [50]:

$$D_{IO} = \frac{\sum_i^n W_{vi} W_i}{\sum_i^n W_i} \quad (1)$$

where, for individual cells, W_i is the weight of the i^{th} individual spatial proxy computed utilizing P-A plots and D_{IO} is the resulting score from the data-driven index overlay procedure. In the same equation, W_{vi} indicates the cell value of the i^{th} spatial proxy assigned continuously through a fuzzification function. For the purpose of this study, Equation 1 was rewritten for Western Australia (WA) as Equation 2 and for Ontario (ON) as Equation 3:

$$D_{IO(WA)} = \frac{WV_1 W_1 + WV_2 W_2 + \dots + WV_{12} W_{12}}{W_1 + W_2 + \dots + W_{12}} \quad (2)$$

$$D_{IO(ON)} = \frac{WV_1 W_1 + WV_2 W_2 + \dots + WV_{10} W_{10}}{W_1 + W_2 + \dots + W_{10}} \quad (3)$$

where $W_1, W_2, \dots, W_{12}$ and $W_1, W_2, \dots, W_{10}$ represent the weights of the spatial proxies assigned pursuant to corresponding P-A plots (Figures A3-A4). The parameters $WV_1, WV_2, \dots, WV_{12}$ and $WV_1, WV_2, \dots, WV_{10}$ are the continuously assigned weights of evidential values of cells in the corresponding individual spatial proxies.

Statistically, proximity to mapped pegmatites is the most important predictor for targeting LCT pegmatites in both Western Australia and Ontario, while proximity to metamorphic rocks (Western Australia) and domains of greater density of Bouguer gravity breaks (Ontario) present the least significant predictors (Tables 7-8).

5.2.2. Continuous Fuzzy Gamma Approach

Continuously-weighted fuzzy spatial proxies can be synthesized utilizing fuzzy operators [48]. In this study, we utilized a fuzzy gamma operator that uses the *PRODUCT* and *SUM* operators, which provide delicate adjustment of the diverse input components [45]:

$$\mu_C = [1 - \prod_{i=1}^n (1 - \mu_i)]^\gamma \times [\prod_{i=1}^n \mu_i]^{1-\gamma} \quad (4)$$

where for each cell, μ_i is the i^{th} input spatial proxy's fuzzy score, μ_C is the potential score resulting from the combination process and $(0 \leq \gamma \leq 1)$. Here, we used a gamma value of 0.9.

5.2.3. Geometric Average

Geometric average is a multiple-criteria decision-making technique for synthesizing weighted spatial proxies in MPM. Pursuant to Equation 5, the geometric average, G_A , is calculated for each cell as the n^{th} root of the value products [52]:

$$G_A(F_1, F_2, \dots, F_n) = \sqrt[n]{\prod_{i=1}^n F_i} = \sqrt[n]{F_1 F_2 \dots F_n} \quad (5)$$

where for each cell, n is the number of spatial proxies and F_i is the fuzzy weight assigned for the i^{th} spatial proxy. Here, Equation 5 was rewritten for Western Australia (WA) as Equation 6 and for Ontario (ON) as Equation 7:

$$G_{Lithium(WA)}(F_1, F_2, \dots, F_{12}) = \sqrt[12]{\prod_{i=1}^{12} F_i} = \sqrt[12]{F_1 F_2 \dots F_{12}} \quad (6)$$

$$G_{Lithium(ON)}(F_1, F_2, \dots, F_{10}) = \sqrt[10]{\prod_{i=1}^{10} F_i} = \sqrt[10]{F_1 F_2 \dots F_{10}} \quad (7)$$

where $F_1, F_2, \dots, F_{12}$ and $F_1, F_2, \dots, F_{10}$ are fuzzy scores of evidential values in the corresponding spatial proxies. After computing the $G_{Lithium(WA)}$ and $G_{Lithium(ON)}$ values for each unit cell of the study areas, the cells were mapped to develop geometric average lithium potential models.

5.3. Knowledge-Driven BWM-MARCOS Approach

Among the various knowledge-driven approaches to MPM, multi-criteria decision-making (MCDM) techniques are highly regarded due to their effectiveness [113-116]. In the MCDM approach, the weighting of spatial proxies is either comparison- or matrix-based. Whilst novel, the best-worth method (BWM: [117]) and Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS: [118]) comparison- and matrix-based MCDM techniques have been successfully applied in MPM [47, 113-116]. Here, we used a hybrid MCDM approach known as BWM-MARCOS [47] in combination with the overall performance (O_p) index [119,120]. The latter is computed via an improved P-A plot incorporating three principal criteria: (i) PL prediction rate curve, (ii) occupied area curve and (iii) NPL prediction rate curve [119].

5.3.1. Western Australian BWM-MARCOS Model

Here, the BWM technique was applied to objectively delineate the weights of the decision criteria embodied by the spatial proxies (Table 7). The O_p index served to determine spatial proxy weights as well as the worst and best spatial proxies (Figure A25, Table 9). Following this initial step, others-to-worst (OW) and best-to-others (BO) vectors were defined according to the O_p values given in Table 9. According to these parameters, problem 3 of [47] can be formulated as shown in the following Equation 8:

$$\begin{aligned} & \min \xi \\ & \text{s.t.} \\ & |W_8 - 7W_1| \leq \xi, \text{for all } j \\ & |W_8 - 8W_2| \leq \xi, \text{for all } j \\ & |W_8 - 9W_3| \leq \xi, \text{for all } j \\ & \vdots \\ & |W_8 - 5W_{12}| \leq \xi, \text{for all } j \\ & |W_1 - 3W_3| \leq \xi, \text{for all } j \\ & |W_2 - 2W_3| \leq \xi, \text{for all } j \\ & |W_4 - 2W_3| \leq \xi, \text{for all } j \\ & \vdots \\ & |W_{12} - 5W_3| \leq \xi, \text{for all } j \\ & \sum_j W_j = 1 \\ & W_j \geq 0, \text{for all } j \end{aligned} \quad (8)$$

Next, optimal weights ($W_B^*, W_1^*, \dots, W_W^*$) and ξ^* were specified by solving Equation 8. For $a_{BW} = a_{83} = 9$, the obtained consistency index was 5.23 [47] whilst the consistency ratio was $0.062/5.23 = 0.011$, showing appropriate consistency. After allocating weights to the spatial proxies,

the MARCOS technique was applied to rank the alternatives. To achieve this, an initial decision matrix $B_{1758143 \times 12}$ was generated that contains 1,758,143 decision alternatives, each linked to an individual cell with a particular coordinate in the corresponding spatial proxies, and 12 decision criteria. The alternatives were then ranked via the MARCOS step-by-step process, previously described by [47].

The BWM-MARCOS lithium potential model for Western Australia is shown in Figure 11d.

Table 9. BWM-MARCOS efficiency statistics for competent spatial proxies, Western Australia MPM.

Competent Spatial Proxies	Parameters						
	P_m	P_n	$100-P_m$	$100-P_n$	TP_r	FP_r	O_p
Proximity to mapped pegmatites (DC_8)	86	49	14	51	0.86	0.49	0.37
Proximity to LCT pegmatite indicator minerals (DC_{10})	84	52	16	48	0.84	0.52	0.32
Proximity to mafic-ultramafic rocks (DC_9)	78	50	22	50	0.78	0.50	0.28
Proximity to Au occurrences (DC_{11})	76	52	24	48	0.76	0.52	0.24
Proximity to Ni occurrences (DC_{12})	74	50	26	50	0.74	0.50	0.24
Proximity to pegmatitic or pegmatite-bearing rock units (DC_7)	69	52	31	48	0.69	0.52	0.17
Proximity to fractionated granitic rock units (DC_1)	70	53	30	47	0.70	0.53	0.17
Domains of greater density of RTP magnetic breaks (DC_6)	65	50	35	50	0.65	0.50	0.15
Domains of greater density of Bouguer gravity breaks (DC_5)	63	50	37	50	0.63	0.50	0.13
Proximity to faults and lineaments (DC_4)	67	55	33	45	0.67	0.55	0.12
Proximity to metamorphic rocks (DC_2)	57	47	43	53	0.57	0.47	0.10
Domains of greater density of major crustal boundaries (DC_3)	58	49	42	51	0.58	0.49	0.09

Key to abbreviations: P_m = hits, P_n = false alarms, $100-P_m$ = misses, $100-P_n$ = correct rejections, TP_r = true positive rate, FP_r = false positive rate, O_p = overall performance, DC = decision criterion.

5.3.2. Ontarian BWM-MARCOS Model

For Ontario, the same approach was followed as for Western Australia with the relevant modelling information provided in Figure A26 and Table 8. As for Western Australia, problem 3 of [47] can be formulated as per the following Equation 9:

$$\begin{aligned} & \min \xi \\ & \text{s.t.} \\ & |W_8 - 2W_1| \leq \xi, \text{for all } j \\ & |W_8 - 9W_2| \leq \xi, \text{for all } j \\ & |W_8 - 4W_3| \leq \xi, \text{for all } j \\ & \vdots \\ & |W_8 - 5W_7| \leq \xi, \text{for all } j \\ & |W_1 - 8W_2| \leq \xi, \text{for all } j \\ & |W_3 - 6W_2| \leq \xi, \text{for all } j \\ & |W_4 - 8W_2| \leq \xi, \text{for all } j \\ & \vdots \\ & |W_7 - 5W_2| \leq \xi, \text{for all } j \\ & \sum_j W_j = 1 \\ & W_j \geq 0, \text{for all } j \end{aligned}$$

(9)

Subsequently, the optimal weights $(W_B^*, W_1^*, \dots, W_W^*)$ and ξ^* were defined by solving Equation 9. For $a_{BW} = a_{83} = 9$, the obtained consistency index was 5.23 [47] whilst the consistency ratio was $0.062/5.23 = 0.011$, showing suitable consistency. As for Western Australia, the MARCOS technique was applied to rank the alternatives using an initial decision matrix $B_{1526806 \times 8}$ with 1,526,806

decision alternatives linked to 8 decision criteria. The alternatives were again ranked by the MARCOS step-by-step process.

The BWM-MARCOS lithium potential model for Ontario is illustrated in Figure 12d.

Table 10. BWM-MARCOS efficiency statistics for competent spatial proxies, Ontario MPM.

Competent Spatial Proxies	Parameters						
	P_m	P_n	$100-P_m$	$100-P_n$	TP_r	FP_r	OP_r
Proximity to mapped pegmatites (DC8)	87	44	13	56	0.87	0.44	0.43
Proximity to LCT pegmatite indicator minerals (DC4)	89	47	11	53	0.89	0.47	0.42
Proximity to fractionated granitic rock units (DC1)	86	47	14	53	0.86	0.47	0.39
Proximity to mafic-ultramafic rocks (DC3)	65	38	35	62	0.65	0.38	0.27
Proximity to Au occurrences (DC5)	69	43	31	57	0.69	0.43	0.26
Proximity to Ni occurrences (DC6)	68	43	32	57	0.68	0.43	0.25
Domains of greater density of major crustal boundaries (DC7)	68	48	32	52	0.68	0.48	0.20
Proximity to Bouguer gravity breaks (DC2)	51	50	49	50	0.51	0.50	0.01

Key to abbreviations: See Table 9.

5.4. Data-Driven Random Forest (RF) Approach

A growing body of evidence [e.g., 26,40,121-126] has demonstrated that RF is more effective than and consistently outperforms other supervised machine learning algorithms applied to MPM. This is because the RF algorithm mitigates the problem of overfitting and improves model efficiency by way of a bagging procedure [53]. As an ensemble-based machine learning method [126], RF adopts a resampling strategy that generates each set of random training samples of an unpruned decision tree [53]. For MPM, a bootstrapping procedure is applied that collects sub-samples by resampling, with replacement, the spatial proxies for PL and NPL, referred to as labeled data. Decision trees are trained using in-bag samples, which include two-thirds of the labeled data. Decision tree impurity, termed out-of-bag (OOB) error, is measured by the remaining labeled data, termed OOB samples. As such, RF presents an aggregation of unpruned decision trees, each of which is developed in accordance with a distinct set of so-called existent patterns.

Executing RF requires (i) the number of trees (n) to be grown and (ii) the number of predictor variables (m) to be entered at each node [53]. These parameters should be tuned so that decision tree impurity is minimized. The mean decrease in the Gini impurity index (M_G) and accuracy (M_a) can be employed to assess the relative importance of the predictor variables. M_G is a measure of how each variable contributes to the homogeneity of the nodes and the final RF model, while M_a is defined by the computation of the OOB error. According to [53], the higher the values of M_a and M_G , the more important a predictor map.

5.4.1. Western Australian RF Model

As a first step, the original (non-transformed) spatial proxies (Figures A5a-A12a and A14a-A16a) were normalized via the following equation [127]:

$$X_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{10}$$

where X_i for per cell is the normalized score of the indicator value, x_i is the indicator value for the cell of the i^{th} spatial proxy and x_{max} and x_{min} are the largest and smallest indicator values pertaining to the i^{th} spatial proxy. Hence, spatial proxy indicator values fall within a range of [0, 1]. Next, an n value of 1,000 and m value of 4 were opted in accordance with the procedure provided by [122]. Figure A27 illustrates the significance of the predictor variables in the RF modelling according to the mean decrease in the accuracy and Gini impurity index. Pursuant to this figure, the proximity to metamorphic rocks is the least significant spatial proxy in the RF MPM of Western Australia’s lithium potential while the proximity to mapped pegmatites is the most significant one.

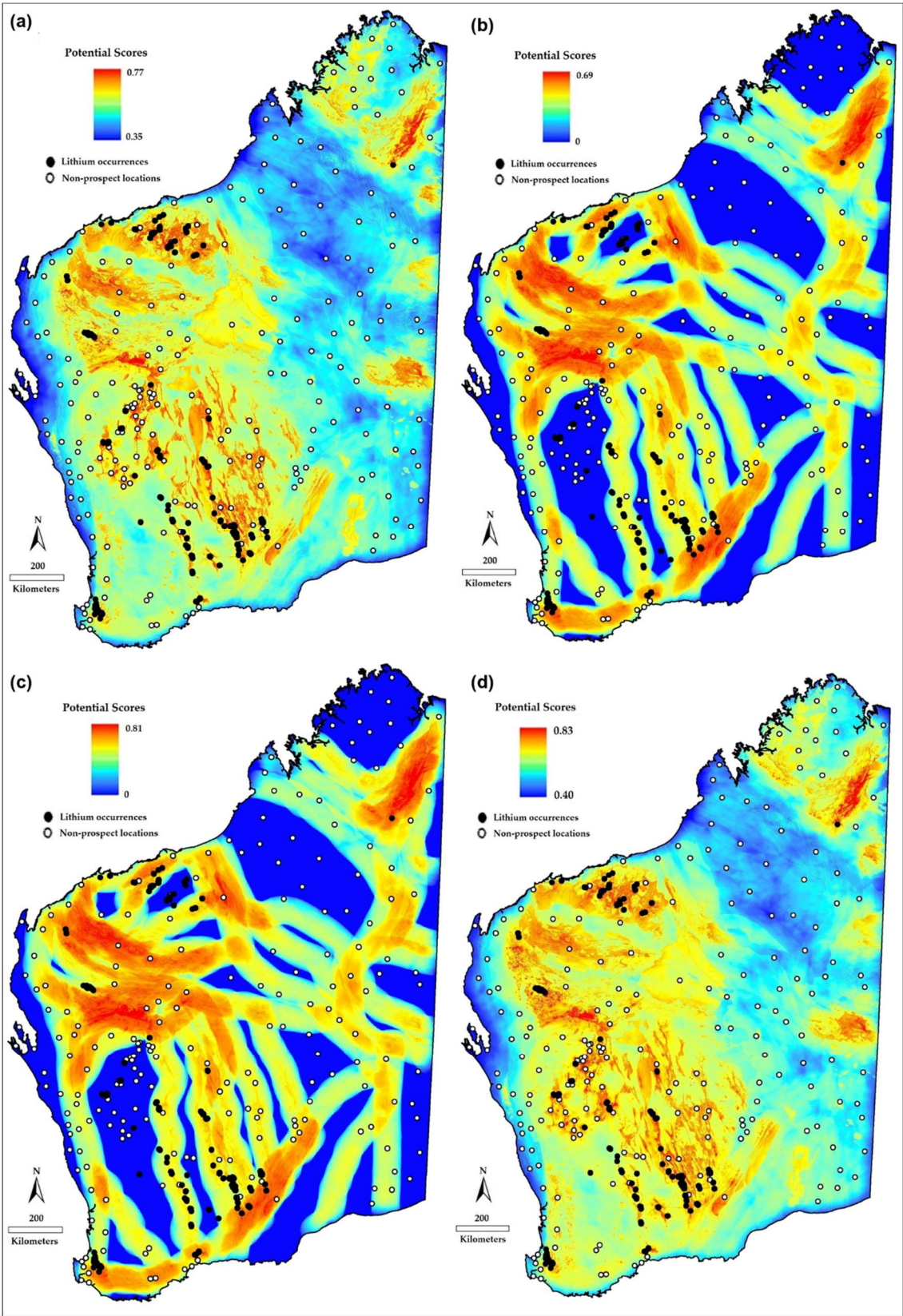


Figure 11. Lithium potential maps, Western Australia. (a) Data-driven index overlay. (b) Fuzzy gamma. (c) Geometric average. (d) BMW-MARCOS.

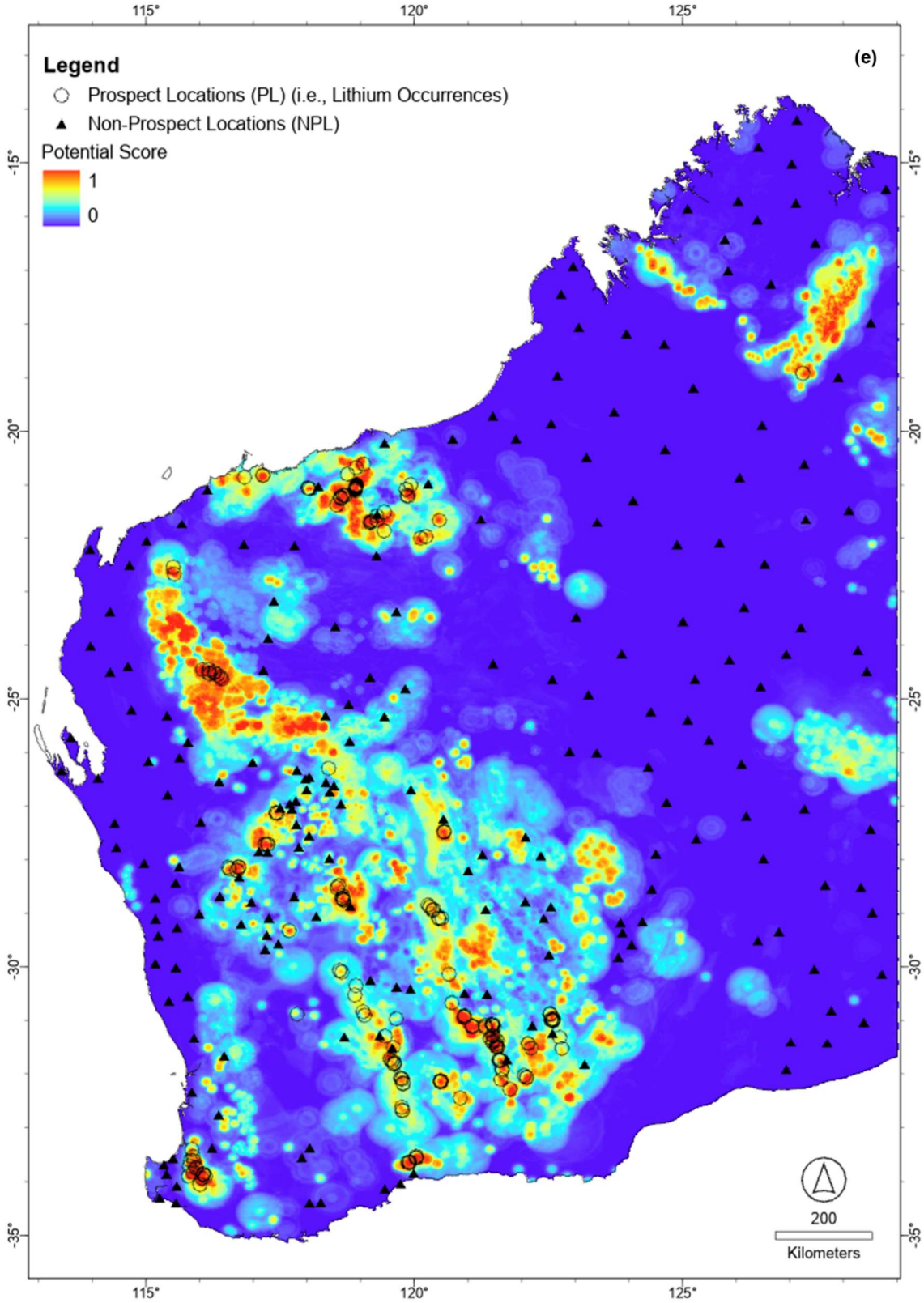


Figure 11. Lithium potential maps, Western Australia. (e) Random forest.

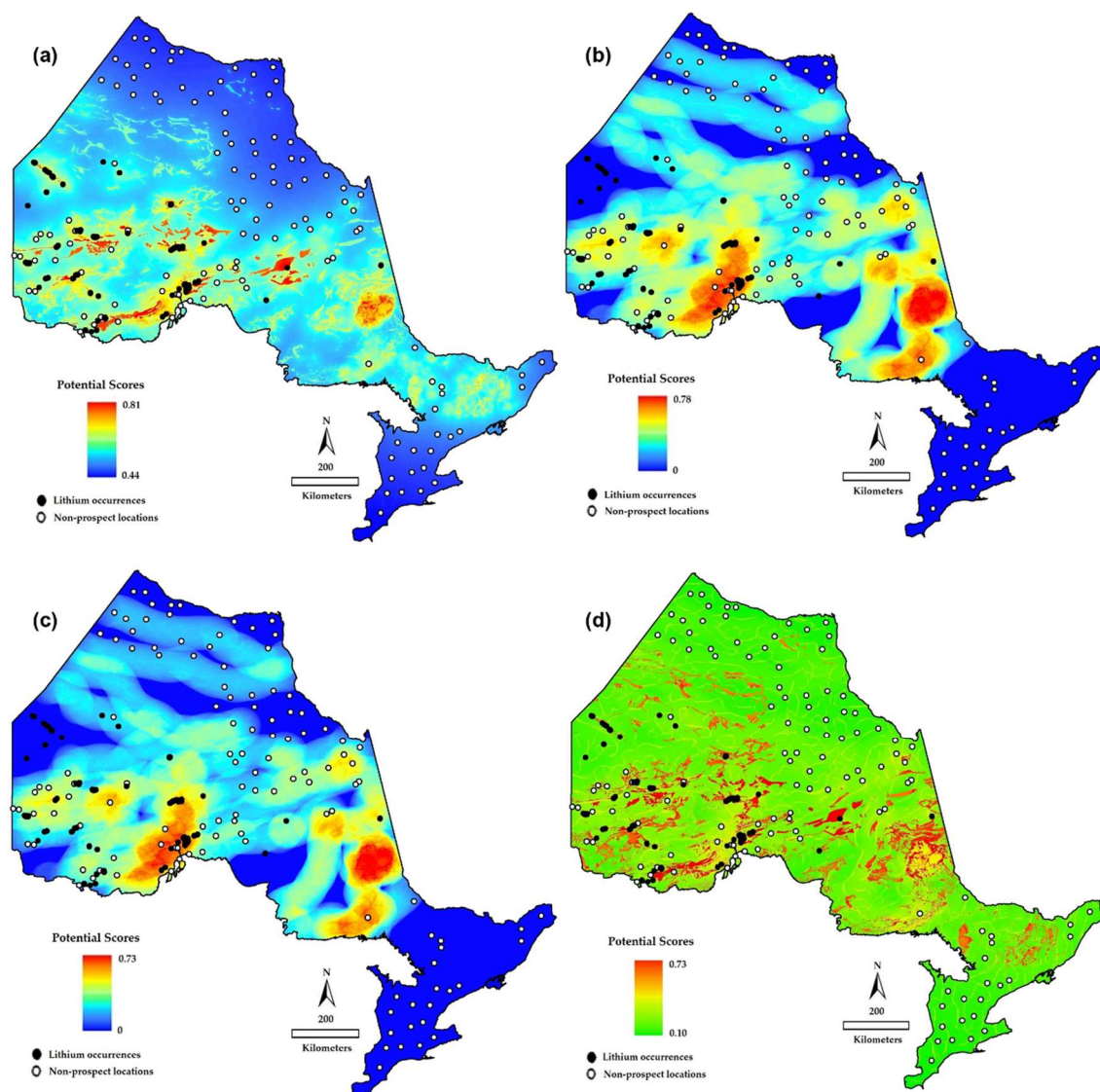


Figure 12. Lithium potential maps, Ontario. (a) Data-driven index overlay. (b) Fuzzy gamma. (c) Geometric average. (d) BMW-MARCOS.

Figure 11e illustrates the RF lithium potential model for Western Australia, which was developed with normalized spatial proxies and a training error curve as indicated in Figure A28. Pursuant to the latter, the error rate of modelling is progressively alleviated as the number of decision trees rises, with a mean squared error rate of ~ 0.115 for the first decision tree and 0.05 for the 1,000th iteration.

5.4.2. Ontarian RF Model

After normalizing the original spatial proxies (Figures A17a-21a, A23a-24a) by Equation (10), an m value of 3 and n value of 1,000 were chosen in accordance with [122]. Figure A29 illustrates the significance of the predictor variables in RF modelling according to the mean decrease in the accuracy and Gini impurity index with proximity to LCT pegmatite indicator minerals the most significant spatial proxy and proximity to Bouguer gravity breaks the least significant one.

Figure 12e illustrates the RF lithium potential model for Ontario which was developed with normalized spatial proxies and a training error curve as indicated in Figure A30. Pursuant to the latter, the error rate of modelling is progressively alleviated as the number of decision trees rises, with a mean squared error rate of ~ 0.09 for the first decision tree and 0.042 for the 1,000th iteration.

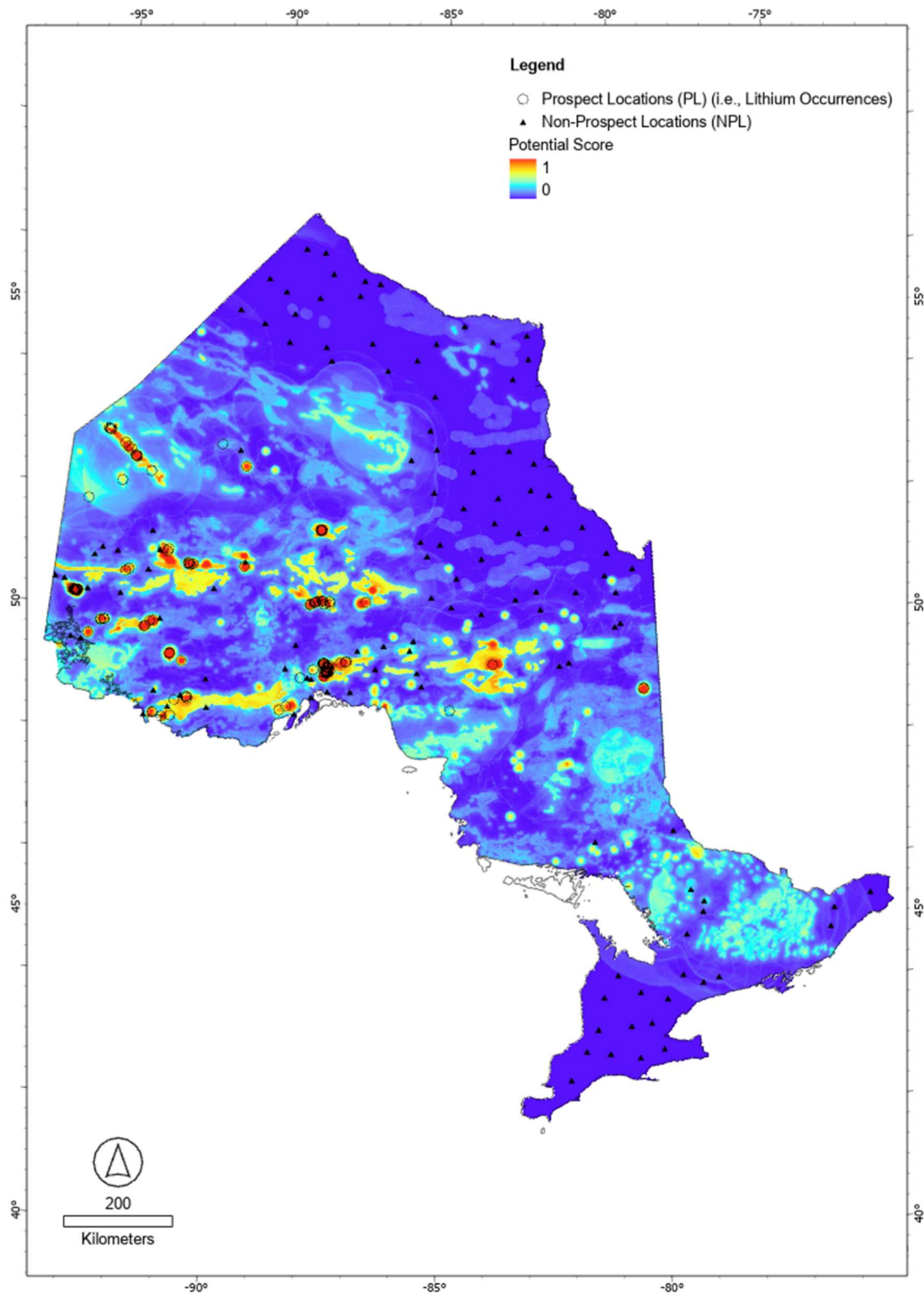


Figure 12. Lithium potential maps, Ontario. (e) Random forest.

6. Discussion

6.1. Mineral Potential Mapping (MPM)

6.1.1. Criticisms, Limitations & Opportunities

Mineral exploration is fundamentally a search problem, and an information problem associated with significant stochastic and systemic uncertainty in that our decision making is influenced by heuristics and biases and reliant on inferences, extrapolations and predictions revolving around sparse or heavily clustered data points. This is particularly true for mineral exploration targeting [128-129].

Modern computer systems, paired with AI approaches, are ideally suited to help tackle the many challenges in mineral exploration targeting. MPM offers such an approach [130-131]. Whilst often criticized for being biased toward mature, well-explored areas and tending toward the generation of excessively large areas of high prospectivity, these issues are not regarded as limitations in the MPM algorithms but shortcomings in the input data that, in many cases, could be easily avoided [106].

It would be unwise to treat MPM output as ‘treasure maps’ given MPM typically identifies more than a few areas of high potential. Rather, the output should be taken as the starting point for a ‘treasure hunt’ and regarded as just another tool in the ‘exploration toolbox’. That is to say, MPM results (i) should be regarded as decision-support tools for delineating, ranking, and prioritizing exploration targets based on the underlying modelled prospectivity and, (ii) present a snapshot in time of the conceptual understanding of the targeted mineral deposit type in combination with the quality, quantity and variety of the data available to map the deposit footprints, and (iii) form the starting point for additional analyses such as of previously unrecognized areas of modelled high potential [41,132]. It is also important to understand that neither MPM nor any alternative targeting approach can discriminate between targets that may host a small mineral occurrence and those that may host a world-class mineral deposit [133].

Given the current limitations, the most effective way of harnessing the power of advanced computer systems and AI in mineral exploration may be intelligence amplification (IA) rather than a sole reliance on AI. In other words, the best approach may be a hybrid of subjective human input and objective, machine-based analysis, informing and balancing each other [106]. In a practical sense and where targeting projects are industry-funded, this could be achieved by addressing shortcomings in the predictor maps through geological interpretation and/or manual targeting by individuals or teams to augment GIS-driven MPM [134]. In such a two-pronged IA approach, multiple scenarios can be investigated, and a range of decision aids can be generated in support of the final targeting decisions [45,129].

6.1.2. Spatial Proxy Performance

Stochastic and systemic errors present significant sources of uncertainty affecting MPM. The former is typically linked to the nature and quality of the input data and can manifest in inappropriate targeting criteria. The latter primarily pertains to spatial proxies and how they are integrated for MPM. Hence, appropriate, well-performing spatial proxies and robust, fit-for-purpose modelling tools are critical aids in minimizing systemic uncertainty in MPM [106].

In the same vein, utilizing only one statistical approach to appraise predictor maps is insufficient for a comprehensive analysis of their performance. Here, we used a combination of the *AUC* and *N_d* techniques to analyze and categorize the predictor maps and measure their performance. One of the key advantages of using a combination of statistical analysis tools is that such an approach provides a means for comparing predictor maps according to various performance metrics (Tables 7-8). For instance, whilst both the “proximity to LCT pegmatite indicator minerals” (spatial proxy E1) and “proximity to pegmatitic or pegmatite-bearing rock units” (spatial proxy E2) predictor maps achieved high *AUC* scores of 0.84, their *N_d* scores set them apart in that proxy E1 scored an *N_d* value that is ~1.4 times higher than that of spatial proxy E2. Moreover, proxy E1 demonstrated superior

statistical efficacy compared to E2 in that it achieved a greater prediction rate pertaining to a smaller area.

6.1.3. Comparative Model Performance

As demonstrated by the pertinent body of literature, modelers typically only use one modelling technique for MPM of their study areas. In contrast, examples of studies that used two or more different modelling techniques are rare [26]. However, there are several benefits to a multi-technique approach to MPM such as the ability to (i) better constrain exploration targets by integrating the results from different numerical models, (ii) compare, contrast and cross-validate MPM results, (iii) ensure optimal use of the available empirical and conceptual information, and (iv) recognize and reduce stochastic and systemic uncertainties [26,106]. As clearly illustrated in [26,40,47,135], a multi-technique approach to MPM can (i) generate more robust targets, (ii) deliver insights that cannot be derived from a single modelling technique, and even (iii) aid in the development and calibration of new tools and techniques.

In addition to the above benefits, employing a multi-technique approach and developing a variety of lithium potential models (Figures 11-12) also supports assessment of model performance. For this, we used the improved P-A plot procedure of [119]. According to the performance statistics listed in Tables 11 and 12, the RF approach to MPM delivered the best-performing lithium potential models for both Western Australia (overall performance, $O_p = 0.53$) and Ontario ($O_p = 0.63$) (Figures 11d, 12d). As the top ranked modelling technique and given the relatively high O_p values of the RF models, it is clear that RF-driven MPM presents the tool of choice for targeting new lithium discoveries in these jurisdictions, and likely elsewhere.

It is striking that the top-performing RF method produced a lithium prospectivity pattern that is unlike those generated by the other techniques (Figures. 11-12). The reason for this characteristic distinctive result is likely due to the specific mechanics of RF, a robust ensemble machine-learning algorithm that is ideally suited to modelling complex, multistage nonlinear systems, such as mineral systems.

Table 11. Improved P-A plot parameters for the Western Australian lithium potential models.

	Fuzzy Gamma	Geometric Average	Index Overlay	BWM- MARCOS	RF
P_m (Hits)	65	64	87	89	97
P_n (False Alarms)	48	48	50	48	44
100- P_m (Misses)	35	36	13	11	3
100- P_n (Correct Rejection)	52	52	50	52	56
True Positive Rate (TP_r)	0.65	0.64	0.87	0.89	0.97
False Positive Rate (FP_r)	0.48	0.48	0.50	0.48	0.44
Overall Performance (O_p)	0.17	0.16	0.37	0.41	0.53

Table 12. Improved P-A plot parameters for the Ontarian lithium potential models.

	Fuzzy Gamma	Geometric Average	Index Overlay	BWM- MARCOS	RF
P_m (Hits)	74	75	91	88	98
P_n (False Alarms)	49	49	43	49	35
100- P_m (Misses)	26	25	9	12	2
100- P_n (Correct Rejection)	51	51	57	51	65
True Positive Rate (TP_r)	0.74	0.75	0.91	0.88	0.98
False Positive Rate (FP_r)	0.49	0.49	0.43	0.49	0.35

Overall Performance (<i>O_p</i>)	0.25	0.26	0.48	0.39	0.63
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6.2. Geological Validity & Insights

The lithium potential models generated in this study delivered new, regional views of the lithium prospectivity of Western Australia and Ontario, two of the world’s best endowed jurisdictions with regards to LCT pegmatite hosted lithium deposits. The validity of the models, in particular the best-performing RF model (*TP_r*: Western Australia: 97%; *TP_r* Ontario: 98%), is demonstrated by the fact that most known lithium deposits, camps and districts plot within areas of elevated to very high lithium favorability. In addition, the models identified several areas that contain all ingredients for LCT pegmatite-hosted lithium mineralisation that are mappable at the regional scale of our investigation but which may have been overlooked by previous explorers.

Our study, which included a comprehensive review of LCT pegmatite systems in Western Australia and Ontario, also delivered insights worthy of further analysis, in particular the statistically verifiable proximity relationship between lithium, gold and nickel occurrences (Figure 13; Tables 7-8). At this stage, the underlying reason for this relationship is speculative in nature but it seems plausible that the clustering of lithium, gold and nickel occurrences is linked to common ingredients of the respective mineral systems models such as the presence of deep-seated faults and mafic-ultramafic rock sequences. Interestingly, [136] postulated a genetic link between the Goulamina LCT pegmatite system, a globally significant hardrock lithium deposit located in Mali, and gold mineralisation. The authors argued that albitization, elevated arsenic and magmatic loellingite in the Goulamina pegmatites are also prominent features of gold deposits in the region, such as Morila (8 Moz Au), both of which formed during a period of felsic magmatism at ~2,100 Ma.

Also worthy of closer investigation may be some of the geological regions that have few LCT pegmatite lithium occurrences, or none, but were identified by MPM as having moderate to very high lithium potential. In Western Australia, these include, for example, the Proterozoic-age Halls Creek, southern Capricorn and Paterson orogens as well as the eastern Archean-age Yilgarn Craton (Figure 14). Ontarian examples include the Kasabonika Lake-Ekwan River, Savant Lake-Crow Lake and Michipicoten greenstone belts of the Archean-age Superior Craton and the pegmatite belts of the Proterozoic Grenville Orogen in southern Ontario (Figure 15).

Another aspect to consider here are the differences in geological information collected from and available Western Australia and Ontario (Table 3). For example, the bedrock geology of Ontario, compiled at a scale of 1:250,000, includes a unit named ‘muscovite-bearing granitic rocks’, which captures all known Archean two-mica granites, many of which are recognized as parental lithium source intrusions and many more are likely lithium pegmatite sources. The Western Australian bedrock geology, on the other hand, is delivered at a scale of 1:500,000 and lacks a breakdown of Archean and Proterozoic granitoids according to their fractionation state. Hence, compiling a map of granitoids that may have lithium source potential is not a straightforward exercise. Having said that, Western Australia offers a pegmatite database (work in progress) and much more detailed structural and geophysical data than Ontario. These differences are reflected in the underlying MPM predictor maps, which differ somewhat between Western Australia and Ontario given certain spatial proxies are better supported by either the Western Australian or Ontarian datasets and, thus, more effective if backed by better quality data (Tables 9-10).

6.2. Mineral Exploration Implications

6.2.1. Exploration Search Space Concept

Given that lithium was a niche market up to the 2010s [137], most geoscientists have never had the opportunity to work in lithium exploration and only few resources companies had owned and operated lithium assets prior to this time. Hence, until recently, there has been a general lack of practical and theoretical know-how amongst explorationists when it comes to LCT pegmatites as well

as a lack of modern systematic exploration of this mineral deposit type. As such, the lithium exploration booms of the late 2010s and early 2020s opened an entirely new search space [138] because only very few districts worldwide had ever recorded any noteworthy lithium exploration. Even belts that had received significant previous exploration and, thus, were relatively mature with regards to other metals became highly attractive as lithium had never constituted a valid exploration target and, consequently, had been ignored or the mineralization not been recognized. The worldwide search efforts triggered by the recent lithium price booms of the late 2010s and early 2020s resulted in a 'golden period of discovery' with numerous, new and globally significant hardrock lithium (re-)discovered in short succession (e.g., Shaakichiuwaanaan, Quebec; Andover and Tappa Tappa, Western Australia; Ewoyaa, Ghana). A great example to illustrate the above is that of the world-class Mt Holland lithium deposit, which underlies the former Earl Grey gold mine and, locally, truncates the gold mineralisation. Prior to its discovery in 2016, the Mt Holland pegmatite system was not understood to be spodumene-bearing and, thus, was never assayed for lithium. A review of the historical drill core eventually confirmed the lithium potential as demonstrated by pegmatite occurrences with a combined strike length of >25 km with true widths up to 50 m and interval grades of up to 2.6% Li₂O. Subsequent drilling programs delivered one of the largest lithium hardrock resources in Australia [78,139].

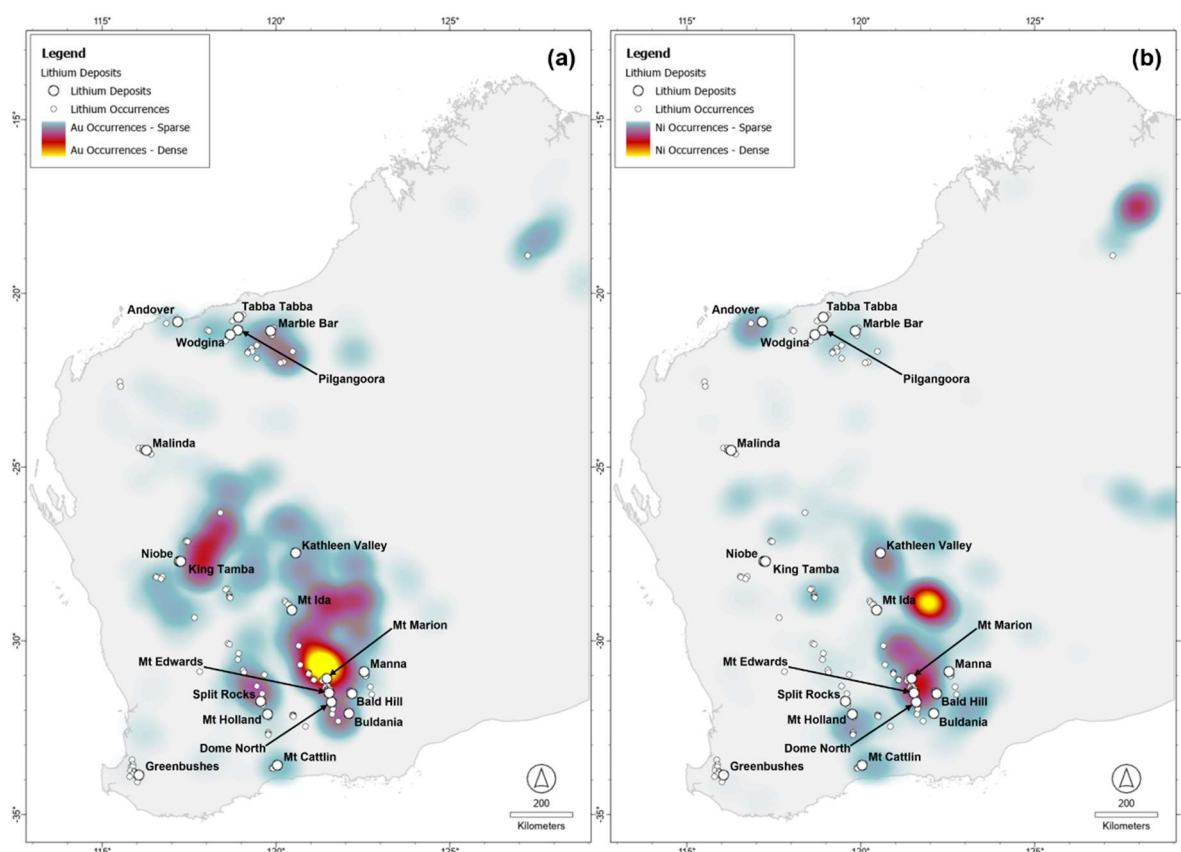


Figure 13. Maps illustrating the statistically verifiable proximity relationship between lithium and (a) gold and (b) nickel occurrences (Tables 7 and 8).

6.2.2. Exploration Maturity & Potential

Whilst both Western Australia and Ontario may both still be considered exploration frontiers in the search for LCT pegmatite hosted lithium deposits (see 6.2.1. above), Western Australia has, by and large, seen much more exploration drilling than Ontario, in particular when it comes to the highly lithium fertile and endowed Archean greenstone belts. In contrast to Western Australia, many of northern Ontario's greenstone belts remain significantly underexplored.

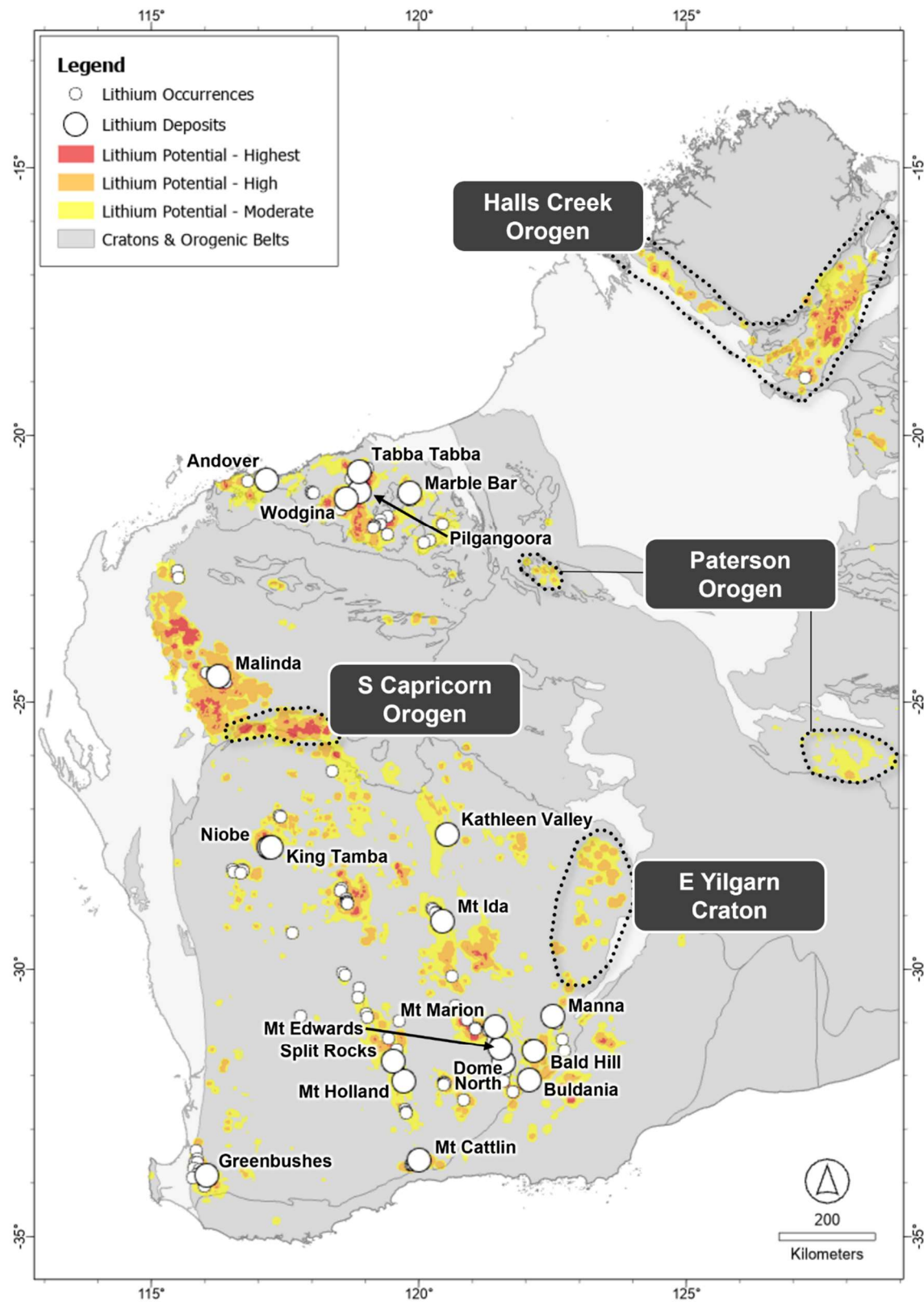


Figure 14. Map of the moderate to highest lithium potential of Western Australia (RF model), also illustrating newly identified lithium prospective domains in eastern Archean Yilgarn Craton and the Proterozoic southern Capricorn, Halls Creek and Paterson orogens.

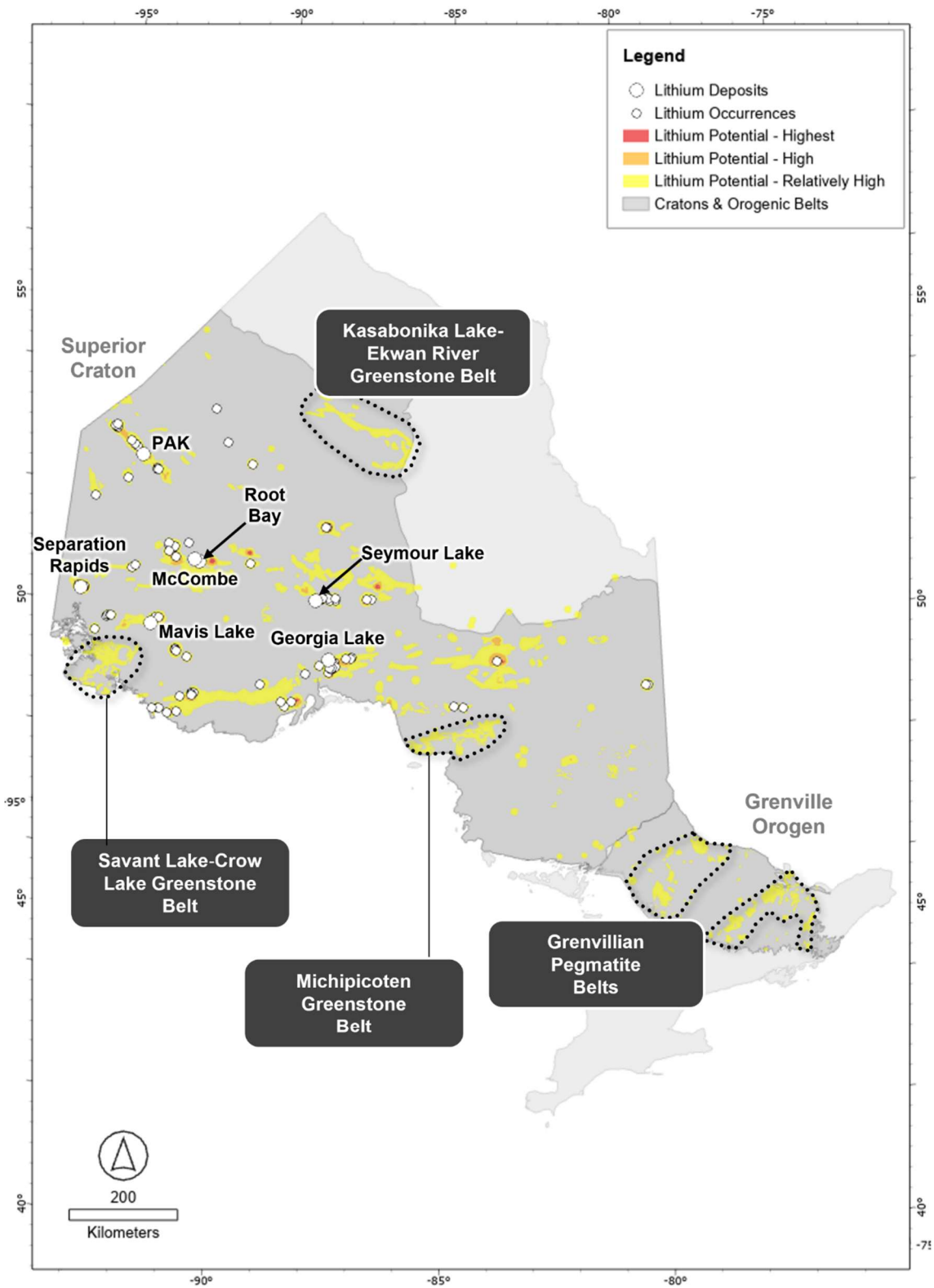


Figure 15. Map of the moderate to highest lithium potential of Ontario (RF model), also illustrating newly identified lithium prospective greenstone belts in the Archean Superior Craton and the Proterozoic Grenville Orogen.

For example, in the >300 km-long Southern Cross Greenstone Belt, Yilgarn Craton, Western Australia, which hosts Mount Holland, one of the world’s largest hard rock lithium deposits, there are >66,000 publicly recorded drillholes (Figure 16a). In comparison, there are only <610 publicly

recorded drillholes in the >230 km-long Favorable Lake Greenstone Belt of the Superior Craton of Ontario and neighboring Manitoba (Figure 16b). Large segments, up to 45 km long, of the Favorable Lake Greenstone Belt have never been drilled. That is despite the Favorable Lake Greenstone Belt hosting the PAK deposit cluster, one of the largest and highest-grade hardrock lithium resources in North America. LCT pegmatites have been identified over ~110 km-long sections of both the Southern Cross and Favorable Lake greenstone belts.

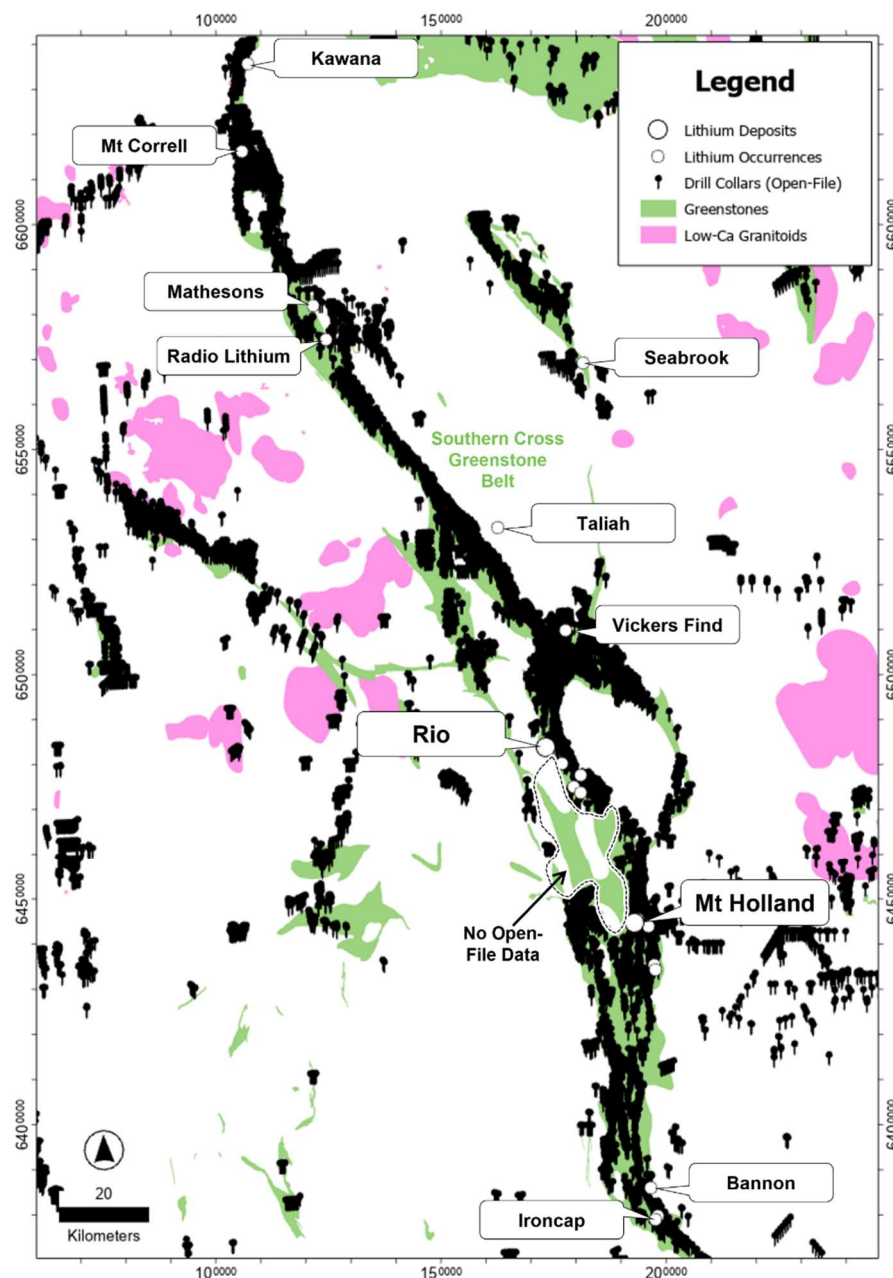


Figure 16a. Simplified map of part of the >300 km-long Southern Cross Greenstone Belt, Archean Yilgarn Craton, showing LCT pegmatite occurrences and deposits as well as >66,000 publicly recorded drillholes completed in the area, mostly focused on gold and nickel. The globally significant Mt Holland lithium deposit was only discovered in 2016, postdating most of the prior drilling. However, this drilling helped to quickly evaluate the deposit and district potential.

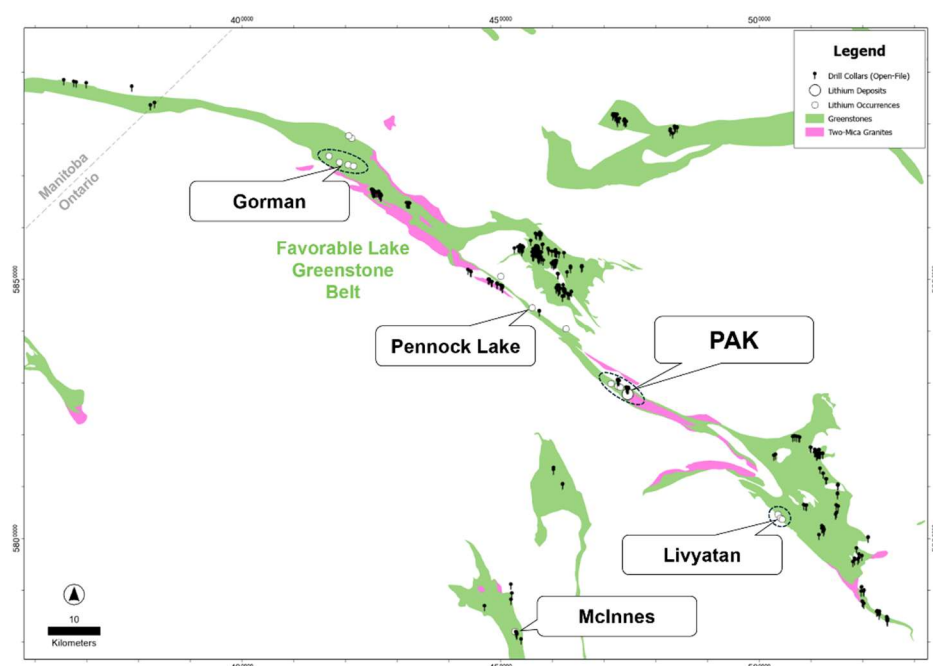


Figure 16b. Simplified map of part of the >230 km-long Favorable Lake Greenstone Belt, Archean Superior Craton, showing LCT pegmatite occurrences and deposits as well as the <610 publicly recorded drillholes. Large segments, up to 45 km long, of the Favorable Lake Greenstone Belt have never been drilled. That is despite the Favorable Lake Greenstone Belt hosting the PAK deposit cluster, one of the largest and highest-grade hardrock lithium resources in North America.

Whilst the PAK (or Pakeagama Lake) pegmatite was discovered in 1999 and has been subject to decades of intermittent lithium exploration, only <100 publicly recorded drillholes have been completed since the maiden drilling program in 2013. The adjacent Spark and Bolt lithium pegmatites were discovered in 2018 and 2020, respectively [100], whilst the Gorman and Livyatan lithium pegmatite clusters, ~70 km northwest and ~40 km southeast of PAK, respectively, were only located in 2023. The conduct of exploration programs and development of mining operations in the Favorable Lake Greenstone Belt are challenged, amongst other things, by the remote nature of the area, lack of infrastructure and long and harsh winters, all of which combine to create a high-cost environment. Added challenges are presented by widespread transported till cover, which may conceal the geochemical signals of the prospective bedrock, and thick brush, which may hide outcrops and make it difficult to get around other than by helicopter.

The lithium mineralised Bounty and Earl Grey pegmatites at Mt Holland, on the other hand, were brought into production in 2024, only eight years after their discovery given the existing gold mine infrastructure, a granted mining lease and access to an existing mining workforce. Another important aspect was the rapid conversion of the 2016 lithium pegmatite discovery to a world-class lithium resource in under five months [140], aided by the existence of 100s of previous gold-focused drillholes (<600 publicly recorded) that had intersected the pegmatites but had not been assayed for lithium and related pathfinder elements.

Overall, given the (i) results of our MPM, (ii) large size of the Superior Craton in Ontario compared to the Western Australian cratons (Superior Craton: ~595,000 km²; Yilgarn Craton: ~609,000 km²; Pilbara Craton: ~57,000 km²), (iii) occurrence of globally significant hardrock lithium deposits across the Canadian Superior Craton (e.g., Tanco in Manitoba, PAK in Ontario and Shaakichiuwaanaan in Quebec), and (iv) underexplored nature of the Ontarian greenstone belts, in particular those in northern Ontario, the province should be able to deliver additional lithium pegmatite discoveries in the future as should Western Australia.

6.2.3. Target Example

The following example of a target generated by this lithium MPM, the Pinderi Hills area in Western Australia (Figure 17), also serves to provide a more detailed look at the modelling results and how MPM can facilitate the rapid recognition of areas of high potential that lack any known mineral occurrences of the targeted type, in this case of potentially lithium mineralised LCT pegmatites.

The Pinderi Hills target is located in the western part of the Archean Pilbara Craton, ~40 km southwest of the globally significant Andover lithium deposit and ~32 km southwest of the recent Andover South discovery. The east-west-striking Scholl Shear Zone lies 17 km to the north whilst the north-northwest-east-southeast-striking Maitland Shear Zone runs straight through the target area. The project geology is dominated by the Munni Munni and Maitland intrusions, two adjoining mafic-ultramafic complexes, and felsic to mafic volcanic rocks of the Whundo Group. The mineral exploration tenure over Pinderi Hills is subject to an earn-in joint venture between Errawarra Resources and Alien Metals announced in April 2024. Exploration is at a very early stage. Nevertheless, work undertaken by Errawarra Resources to date delivered encouraging results: (i) Satellite imagery analysis identified a group of linear geomorphic features interpreted as pegmatites; and (ii) field reconnaissance and surface geochemistry surveys returned anomalous rock chips, including an assay of 288 ppm Li₂O (associated with elevated cesium, tantalum and niobium) from an outcropping pegmatite, and identified several up to >1 km-long, linear soil anomalies with peak anomalies of up to >100 ppm Li₂O [141]. Further investigation is required to demonstrate the lithium potential of the Pinderi Hills area but the limited work undertaken to date suggests that the MPM generated a valid target.

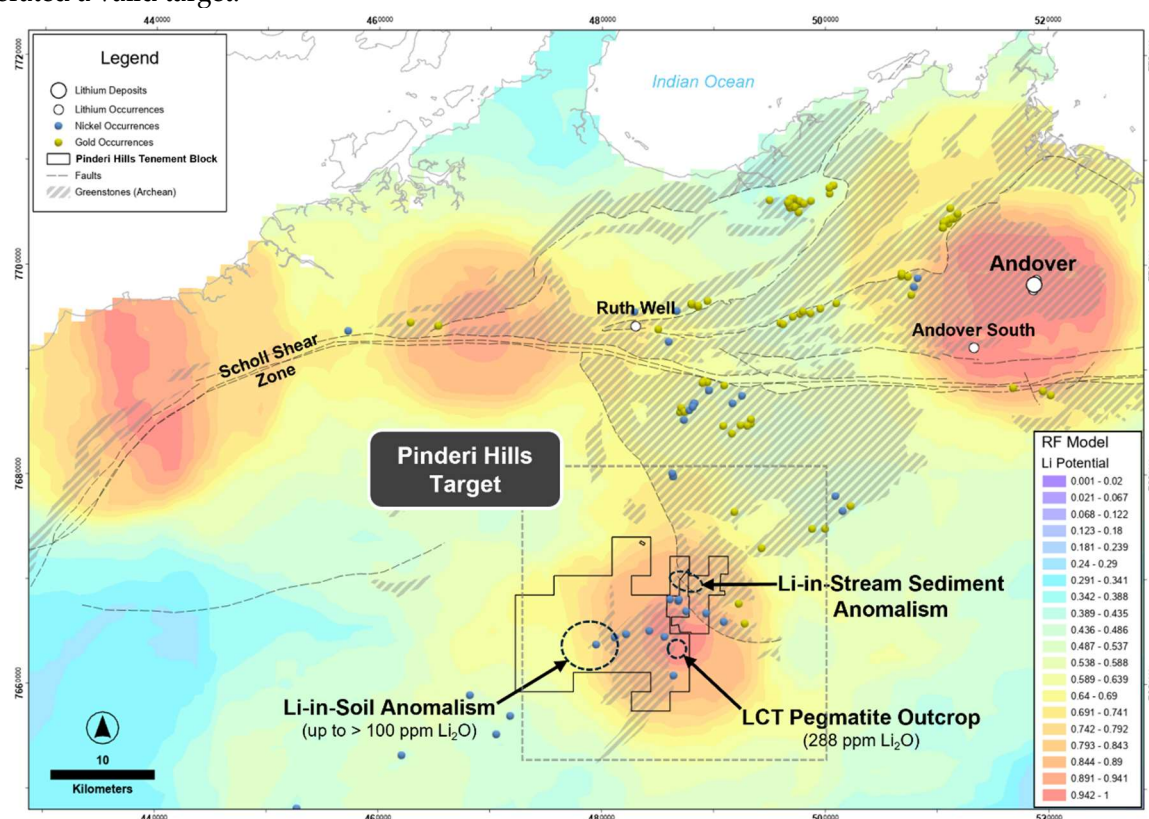


Figure 17. Example of a MPM (RF model) generated target in the Archean Pilbara Craton, referred to as Pinderi Hills. At the time of modelling, no LCT pegmatites were known to exist at Pinderi Hills, which is only ~32 km southwest of the globally significant Andover lithium deposit. Recent exploration work at Pinderi Hills has identified lithium and associated cesium, tantalum and niobium anomalism in rock chips, soils and stream sediments over large areas, which may point to the presence of a poorly outcropping LCT pegmatite swarm. Andover South is a recent LCT pegmatite discovery that postdates our MPM but falls within a domain of highest lithium potential.

7. Summary & Conclusions

In this study, we developed the first predictive models of hardrock lithium potential for two of the world's best-endowed jurisdictions, Western Australia and Ontario. The main conclusions and insights gained from this study can be summarized as follows:

- Western Australia has known resources of ~26 Mt Li₂O contained in 19 lithium-cesium-tantalum (LCT) pegmatite deposit clusters. One of these clusters is in the Gascoyne Complex and is Proterozoic in age. The remainder is hosted by the Yilgarn and Pilbara cratons and formed during Archean times. Ontario has a much smaller endowment of ~1.5 Mt Li₂O contained in seven LCT pegmatite deposit clusters, all of which are in the Superior Craton and Archean in age.
- Even the best-endowed lithium pegmatite system in Ontario, PAK, would only rank eighth among the Western Australian lithium pegmatite resources. This size discrepancy may be taken to imply that either the Ontarian LCT pegmatites have lesser endowments than their Western Australian counterparts or several very substantial pegmatite-hosted lithium resources are yet to be discovered in Ontario, or to be fully delineated by further drilling.
- As demonstrated for the Favorable Lake Greenstone Belt of northern Ontario, large tracts of the Archean Superior Craton are significantly underexplored compared to the Archean cratons of Western Australia. Government records indicate that <610 drillholes were completed along the >230 km-long Favorable Lake Greenstone Belt. That is despite the presence of the PAK pegmatite cluster, one of the largest and highest-grade hardrock lithium resources in North America. In contrast there are >66,000 publicly recorded drillholes that were completed along the >300 km-long Southern Cross Greenstone Belt, Yilgarn Craton, which hosts one of the world's largest hard rock lithium deposits at Mount Holland. Large segments, up to 45 km long, of the Favorable Lake Greenstone Belt have never been drilled. No such large undrilled search spaces exist near world-class mineralised systems in the Archean Yilgarn and Pilbara cratons of Western Australia.
- In contrast to the Western Australian LCT pegmatites, the Ontarian systems often illustrate clear genetic links to S-type parental granitoids. Terranes that lack S-type granitoids are typically devoid of LCT pegmatites. Given this perceived genetic link, it is not surprising that Ontarian LCT pegmatites are often complexly zoned whereas LCT complex pegmatite types are less common in the Archean cratons of Western Australia, which are dominated by more homogeneous LCT albite-spodumene pegmatite types.
- LCT pegmatites in Ontario have a preponderance for steep to subvertical dip angles and lenticular or prolate geometries (e.g., PAK, Separation Rapids) whilst their Western Australian counterparts are typically sheet-like and gently-dipping to subhorizontal in nature (e.g., Mt Holland, Mt Cattlin, Tabbatabba). To our knowledge, no previous studies have been undertaken, focusing on the likely structural and genetic controls on these architectures and their economic implications.
- Common expressions of LCT pegmatite systems and controls on lithium deposit formation include the following: (i) High degrees of melting of a fertile protolith, typically a sedimentary crustal source (as represented by the S-type, two-mica granitoids of the Superior Craton), or biotite dehydration melting at relatively shallow greenstone-root levels (as potentially represented by the evolved I-type, low-Ca granitoids of the Yilgarn Craton). In all cases investigated in this study, the crustal melting was spatially associated with convergent margin tectonic settings (ii) Extreme fractionation of the granitic melts that formed the pegmatites. (iii) A high degree of crustal permeability, typically associated with active deformation along first- and second-order fault systems, typically localized along belt margins. (iv) Presence of mafic to ultramafic rock sequences that have been metamorphosed at greenschist to amphibolite facies grade.
- We adopted a best-practice multi-technique approach to mineral potential mapping (MPM) of LCT pegmatite system in Western Australia and Ontario, which included the use of five different methods spanning the spectrum between traditional MPM algorithms and artificial intelligence (AI). The best-performing method, random forest (RF) machine-learning AI technique, achieved excellent overall performance (O_p) metrics (Western Australia: $O_p = 0.53$; Ontario: $O_p = 0.63$), outclassing all other methods by ~3.3 times for Western Australia and ~2.5 times for Ontario.

The validity of the RF model is also demonstrated by most of the known lithium deposits, camps and districts plotting within areas of elevated to very high lithium favorability as identified by this modelling approach.

- MPM also identified certain belts that have few LCT pegmatite lithium occurrences, or none, but have moderate to very high lithium potential. In Western Australia, these include, for example, the Proterozoic Halls Creek, southern Capricorn and Paterson orogens as well as the eastern Archean Yilgarn Craton. Ontarian examples include the Kasabonika Lake-Ekwan River, Savant Lake-Crow Lake and Michipicoten greenstone belts of the Archean Superior Craton and the pegmatite belts of the Proterozoic Grenville Orogen in southern Ontario. In our opinion, these belts warrant closer investigation as to their LCT pegmatite potential.
- In addition, our modelling revealed a statistically verifiable proximity relationship between lithium, gold and nickel occurrences. At this stage, the underlying reason for this relationship is speculative but it seems plausible that the clustering of these different mineral deposit types is linked to their common spatial association with deep-seated faults and mafic-ultramafic rock sequences.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Figure S1: title; Table S1: title; Video S1: title.

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