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Geopolitical Sustainability of Lithium Supply Chain from European Perspective

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Abstract

Lithium supply security has become crucial for electric grid transition towards renewable energy sources and for automotive, electronics and military technology companies in Europe. In this paper we first discuss globally the swing producers who possess the capability to grow lithium production based on existing, already identified lithium resources. In the second part we discuss the possibility for developed nations to increase their self-sufficiency for engaging in the lithium supply chains through ensuring minimum-level long-term access to their own latent potential lithium resources. Europeans can discover their own potential lithium resources through systematic mineral systems modelling based on prospectivity analysis. We present a case study conducted in Northern Finland for identifying and mapping potential lithium-bearing pegmatites in prospectivity chart for lithium resources. It would be advisable for Europeans to build up scalable supply chain front-end for lithium, i.e. mining reserves, mining infrastructure, ore transport logistics, and refining capacity by research, development and taking into use smart mining technology. Scalable means that under business-as-usual conditions lithium supply chain front-end is hibernating with small costs, but under black-swan type abnormal conditions, the front-end could be activated rather quickly. As Europe aims to strengthen its military capabilities on the long run, military re-armament projects can provide a vehicle to provide a floor for demand upon which to build sustainable and reliable supply chain for lithium. Finally, increasing European cooperation with developing countries in geological exploration, transport infrastructure, mining and refining is recommended. Such cooperation has long-term potential to build resilient supply chains in developing countries for sourcing critical minerals and overcoming local lack of environmental protection, funding, infrastructure and knowhow. Combined, these measures provide long-term opportunities to reduce vulnerability to geopolitical supply chain risks in Europe.

Keywords: Lithium, Supply Chain, Decarbonization, Mineral Systems Model, Geopolitics

Introduction

The purpose of this analytical-empirical research is to assess theoretical lithium mineral systems models, found in the scientific geological literature, against the geological conditions and proxy data sources for economic lithium resource prospecting within the geographical area of Northern Finland in Europe. Additionally, a specially for Northern Finland developed contemporary tool for modeling geological conditions, its built-in proxy data sources, computational logic, and visualization capabilities are evaluated.

Battery grade lithium is produced from three different deposit types: pegmatite deposits, brine deposits, and sedimentary deposits.

Pegmatite deposits – Pegmatite is a coarse-grained intrusive igneous rock formed by fragmentation of magma deep below the Earth's crust and brought up by fluids through faults and cracks in the crust. Pegmatite lithium deposits are often titled also as hard-rock lithium deposits, can contain extractable amounts of several valuable elements, such as

lithium, tin, tantalum, beryllium and niobium [1]. Lithium in pegmatites is typically found in the mineral spodumene but also may appear in other minerals such as amblygonite, eucryptite, lepidolite and petalite. Extracting pegmatite lithium from hard-rock ore is expensive energy-wise, meaning that such deposits are at cost-disadvantage compared to brine deposits. However, a pegmatite lithium deposit can be economically viable if it has considerably higher lithium concentrations than typical brines. The production of side metals, such as tin and tantalum, may also help offset costs. This paper focuses on pegmatite deposits as introduced above. However, also other main types of lithium deposits are introduced for gaining better understanding for the geopolitical supply of lithium.

Lithium brine deposits are underground accumulations of saline groundwater enriched in lithium. Brines are high concentration salty waters containing lithium, sodium, potassium, magnesium, calcium, strontium as common cations and chlorine, sulfate, borate, and carbonate as common anions. The source of minerals in brines originates as volcanic material but over hundreds of millions of years, weathering processes cause them to dissolve in water, migrate, and concentrate in basins. Dissolved minerals and salts in brines are in liquid form, so that they can be pumped up to the surface for lithium extraction and for beneficiation processing. Lithium brine deposits currently represent about two thirds of global lithium resources and are located mainly in the salt flats of Argentina, Bolivia, Chile, and China. Geologically similar potential areas can be found also in southern slopes of Himalayas in northern parts of India and Pakistan although not yet sufficiently explored for mining, environmental and social feasibility. Currently most lithium production comes from continental brine deposits from Lithium Triangle -region of the Andes mountains that includes parts of Argentina, Bolivia and Chile. Brine type of deposits are lowest cost and generally most profitable lithium sources [1-3].

Sedimentary deposits constitute for less than 10 percent of known global lithium resources and are typically located in clay deposits and lacustrine evaporites in nonmarine basins. Sedimentary deposits are created when lithium is washed out of volcanic minerals by weathering processes and transported along water into basins where it accumulates in bottom sediments reacting with other minerals, creating chemical structures in which the lithium is captured in mineral form. Sediments typically have the form of clay, not hard rock, and potentially easily breaks into slurry when placed in water. Chemical leach methods can be used to extract the lithium from the sediment slurry. Every sediment deposit has different characteristic properties, and the chemistry of the sediments varies significantly and therefore for lithium beneficiation leaching reagents will need to be tailored. Major known lithium sediment deposits are in United States (U.S.) and Serbia [1].

The rest of this paper is organized as follows: review of global lithium production, bringing attention to fact that global supply chains of lithium for batteries currently are dominated by Australia, South America and China, with processing and manufacturing of the battery compounds, components and assemblies established in China, South Korea and Japan. Argumentation that limited geographical spatial distribution in the supply chain constitutes potential geopolitical and logistics risks for security of lithium supply. A possible black-swan scenario is presented that seriously undermines existing lithium supply chains for Europe. Finally, paper discusses the need for nations, especially European, to increase their lithium self-sufficiency, presenting a case study conducted in Northern Finland for identifying and mapping potential lithium-bearing pegmatites in prospectivity chart for lithium resources.

Literature Review

Worldwide Production and Reserves of Lithium

According to United States Geological Survey (USGS) report world-wide explored, measured and indicated lithium resources have increased substantially worldwide and total about 115 million tons (Table 1) [4].

Country	Measured and indicated lithium resources
[kilotons]	
Argentina	23 000
Bolivia	23 000
United States	19 000
Chile	11 000
Australia	8 900
China	6 800
Canada	5 700
Germany	4 000
Congo (Kinshasa)	3 000
Mexico	1 700
Brazil	1 300
Czechia	1 300
Mali	1 200

Serbia	1 200
Peru	1 000
Russia	1 000
Zimbabwe	860
Spain	320
Portugal	270
Namibia	230
Ghana	200
Austria	60
Finland	55
Kazakhstan	45

Table 1: Measured and Indicated Lithium Resources in Different Countries According to USGS [4]

Benson et al present types and relative sizes of lithium resource locations in global scale (Figure 1) [5].

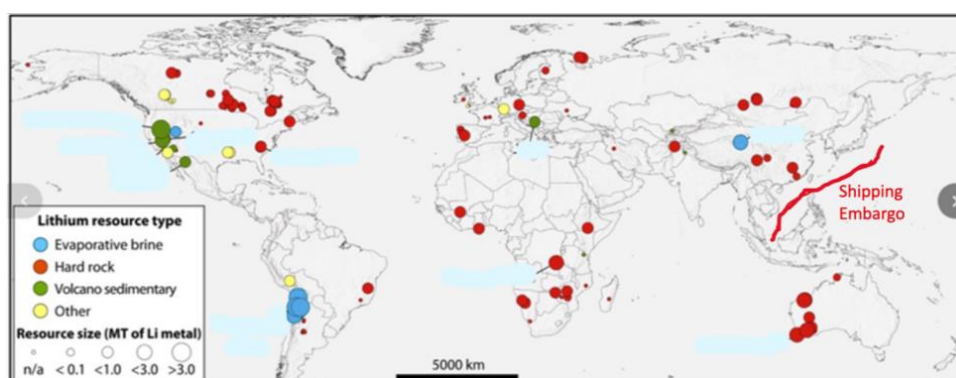


Figure 1: Map Showing Types and Relative Size of Global Lithium Resource locations. Modified from Benson et al [5]

There exist very large volcanic sedimentary deposits (Jadar, Serbia, Thacker Pass, Nevada, U.S.) which remain to be commercially developed, and their cost competitiveness remains to be seen [5]. Europe, U.S, and China all have in common that they are not self-sufficient, instead they are currently dependent on lithium imports. Australia is largest exporter of lithium together with South American countries (Argentina, Chile and Bolivia) who are the lowest cost producers. Africa has untapped potential for becoming large exporter for lithium provided it can develop lithium mining and supply chain. For that it needs geological expertise, financial help for mining operations and infrastructure investments, and connection linkage to supply chain channels. It remains interesting to see with whom the African nations select to cooperate with [6,7].

In Europe the largest untapped lithium resources are in Serbia (Jadar) and in Ukraine both of which are geopolitically problematic. In Russia there exist untapped large pegmatite type lithium resources in Kola region, and brine type resources associated with Siberian oil and gas fields. In Finland known lithium potential reserves have been estimated to be significant in European scale based on existing known discoveries [8-11].

In the following chapters we address key swing producers, i.e. producers who can develop lithium mining and production relatively quickly due to existing knowledge and availability of infrastructure and enterprises already established in the lithium supply chain.

Lithium Production and Reserves in Australia

Geoscience Australia's most recent report statistics show Australia's lithium ore reserves estimated to be 4.6 megatons lithium and annual mine production 55 kilotons of lithium. Figure 2 presents locations and relative sizes of lithium mineral resources in Australia. According to Benson et al they are all hard-rock pegmatite type deposits. According to Geoscience Australia was the source of more than 50% of global lithium supply in 2021 and has been able to expand production from Greenbushes, Western Australia because of relatively high price level due to demand for electric vehicles batteries worldwide [5,12].

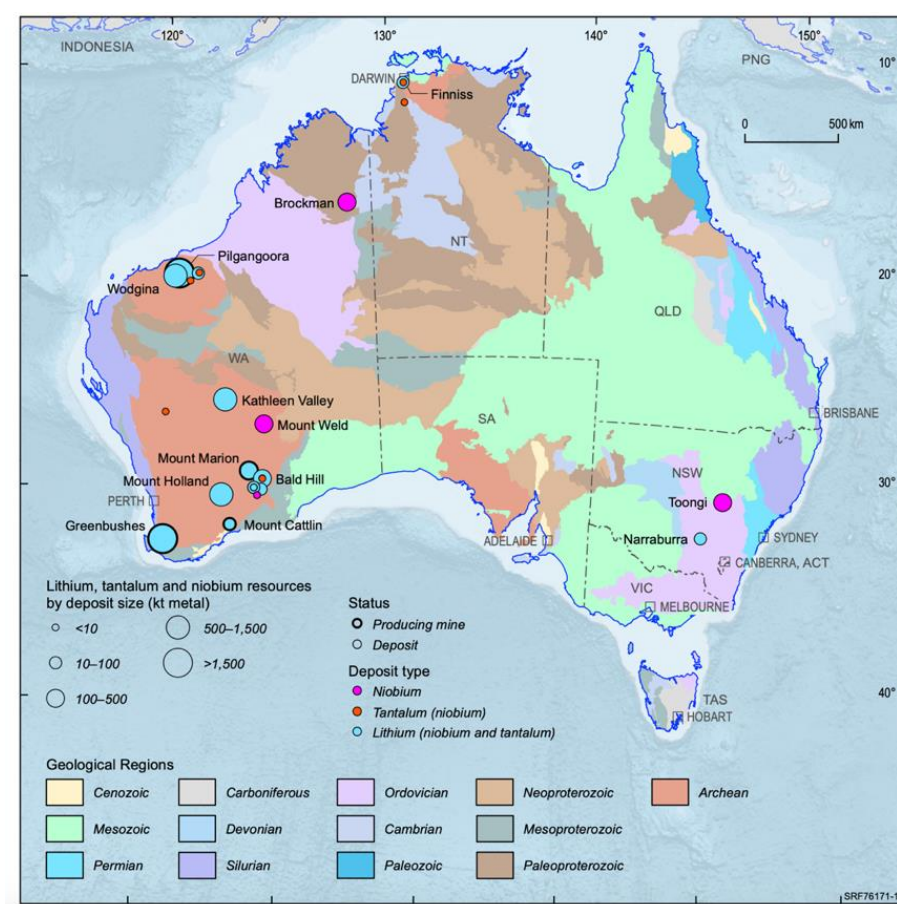


Figure 2: Australian Lithium Deposits and Operating Mines. Figure Courtesy [12]

Lithium Production and Reserves in China

Wang et al present map of major discovered lithium deposits in China, see Figure 3. Deposits are hard-rock (granitic pegmatites) and brines [3]. Wang et al state that brine-type deposits are generally more profitable due to lower cost of extracting lithium from brine salt lakes than hard-rock pegmatites, but current demand and prices are so high that also pegmatite extraction is profitable [3].

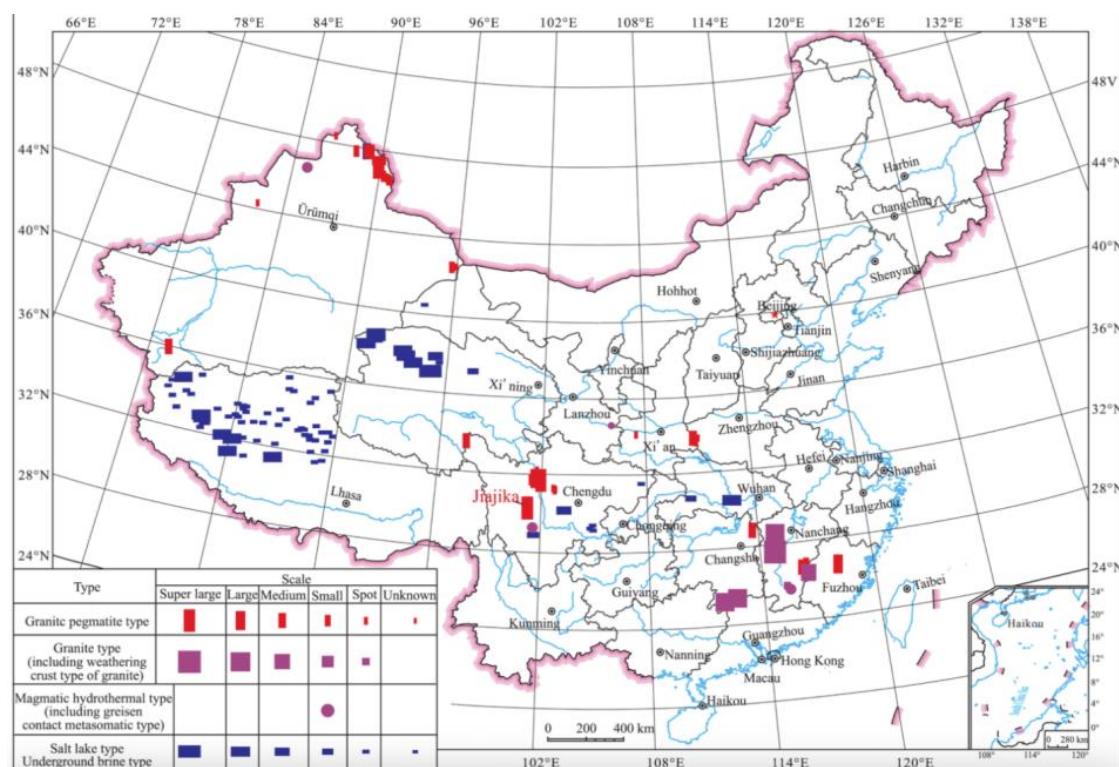


Figure 3: Map of Locations and Relative Sizes of Major Lithium Deposits in China. Figure Courtesy [3]

Article presents China's lithium resources as very limited because China's lithium resources are still highly dependent on foreign imports due to not being able fully develop its native exploitation potential and inferior quality of its mineral resources. China's lithium resources are geographically scattered and often distant. Lithium is mainly hosted in brines, lithium spodumene hard rock, and lepidolite. Brines are mainly distributed in salt lakes in Qinghai and Tibet regions representing over two-thirds of China's lithium resources. Because of relatively low lithium concentration and elevated levels of impurities and magnesium it has been challenging to extract lithium from such brines. Lithium hard rock spodumene and lepidolite, which constitute about 25 % of China's known lithium resources, are mainly located in Sichuan and Jiangxi. Spodumene deposits are typically located in distant high-altitude areas with difficult environmental surroundings with limited access to water and very fragile vegetation and nature. In summary, the exploitation of lithium resources in China is severely restricted by environmental considerations, mining technology, and transport distances and thus relatively high cost-structure of mines compared to global competitors [13].

Lithium Production and Reserves in Africa

According to British Geological Survey [7] African lithium mineral resources are globally significant and provide opportunities for African countries to expand their mining operations and seek economic growth, employment and prosperity. Such African countries (Zimbabwe, Namibia, Ghana, Democratic Republic of Congo and Mali) have substantial lithium resources with high lithium grades and the potential for lithium mining. However, there is general lack of infrastructure to support mining. For example, Africa has poor transport connections, insufficient electric power networks, lack of lithium ore beneficiation and refining into exportable lithium chemicals, and manufacturing of battery components. This leads to a low value-added scheme where only lithium ore concentrate is exported and thus value is added outside Africa; and paradoxically products using lithium-ion batteries are then imported. There is big potential for Africa's lithium resources to contribute an important growing share of global economic battery business. This requires development of the whole African battery supply chain and requires development of regional cooperation in mining, refining, shipping and transportation and energy infrastructure [7].

British Geological Survey presents African lithium mineral resources to be significantly smaller than newer calculations presented by USGS. Figure 4 presents lithium resource locations in Africa along the supply chain routes. Lithium resources appear to be located along the coast and where road or rail infrastructure is available. To improve Southern Africa transport infrastructure ongoing Lobito Corridor development project aims to improve rail connections is for Angola, Zambia, and the Democratic Republic of Congo. Development of renewable energy sources (solar, wind) and battery energy storage systems (BESS) may help solve energy infrastructure deficiency in Africa. There appear to be vast areas on Africa which either have not been explored or do not appear to host discovered lithium resources [4,7,14].

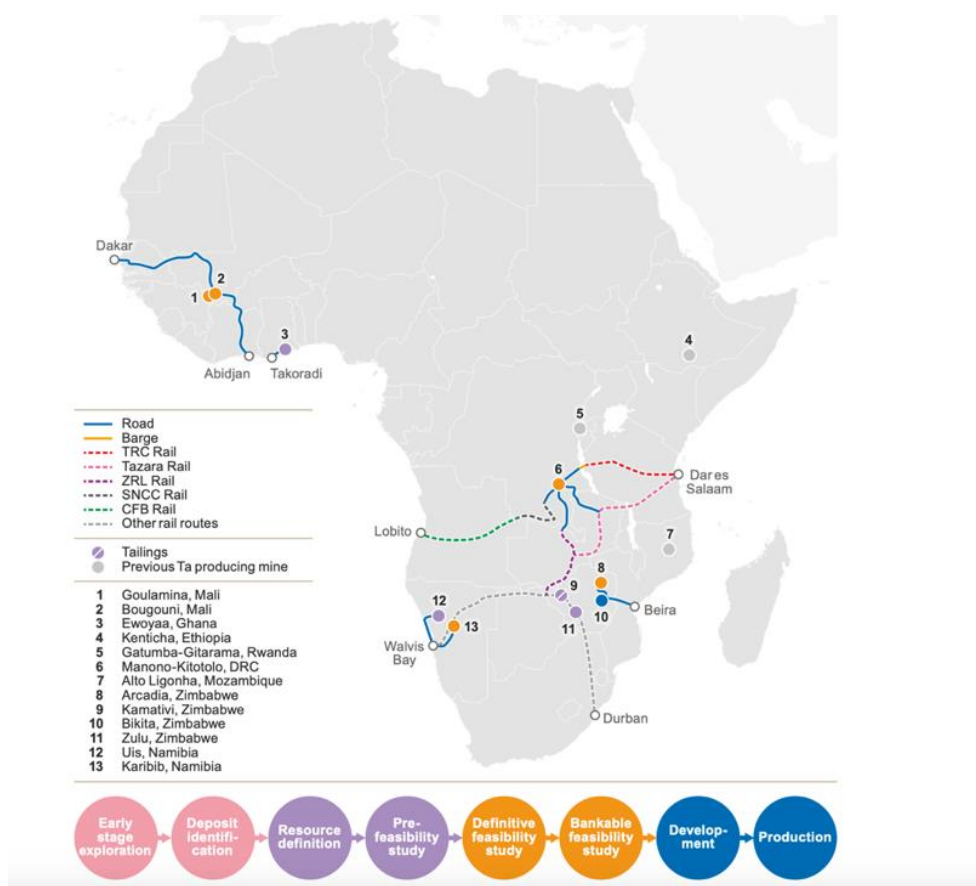


Figure 4: Africa Map Presenting the Known Lithium Resources with Connections to Road, Rail, and Port Infrastructure Available for Lithium Supply Chains. Figure Courtesy [7]

Research Problem: Potential Lithium Supply Disruptions

Recently Gardiner et al. discussed potential black-swan type of scenarios, i.e. sequences of events, to lithium supply chain caused by global geopolitics subject to unexpected and substantial changes that can disrupt and force restructuring of the current supply chains [15].

Let's consider an imaginary geopolitical scenario, where because of deteriorating trade relations between U.S. and China, they somehow get into military conflict over Taiwan islands, resulting Pacific Ocean ship transport routes to be partly blocked from regular ship transport as illustrated in Figure 1. The blockage is two-sided as both US enforces it with its allies and China enforces it with its allies to prevent opposing coalition from benefitting from the embargo. This would mean that shipping of lithium ore would be immediately halted to China and South Korea. Japan would become the only ore refining capability remaining. After a month or so, as ore storages ran out, lithium production would drop dramatically both in China and South Korea. China would be able to keep some 25-30% capacity due to its domestic resources. South-Korea goes to less than 10%. Japan would be able to produce 100% level, but its production capacity would be shipped to mostly to U.S., probably leading to situation that Europe would get very little refined lithium, because U.S. would need the Japan refining capacity for military priority needs. So, looking it is from European point of view, this is very worrisome scenario within next 2-5 years.

Based on the above scenario, it would be advisable for Europeans to mitigate these kinds of supply chain risks by building up scalable supply chain front-end for lithium, i.e. mining reserves, mining infrastructure and refining capacity. Scalable means that under business-as-usual conditions lithium supply chain front-end is hibernating with small costs, but under black-swan type abnormal conditions, the front-end can be activated rather quickly. Scaling is similar in principle to the concept of renewable sun/wind energy grid backed by coal-powered power-stations, but in much longer time frame.

Potential enabling technology for scalability is smart mining technology that utilizes artificial intelligence to control autonomous drilling, hoisting and transporting of ore; long-distance ultra high-speed photonics; and on-site underground wireless communications technology to control the operations of various autonomous mining equipment [16-18].

As Europe aims to strengthen its military capabilities on the long run, military re-armament projects can provide a vehicle to provide a floor for demand upon which to build sustainable and reliable supply chain for lithium [19].

There has been recently some positive developments to mitigate risks in Europe. There have been recently opening of a new lithium pegmatite-type mine and refinery in Kaustinen/Kokkola in Finland by South-African Sibanye-Stillwater; and a large-scale brine-type mining and refinery operations in Argentina by French Eramet. Their significance lies in development of know-how and intellectual property (IP) for refining process and equipment for both pegmatite and brine type of lithium deposits. From that knowledge and IP, it is possible to build refineries within Europe and also outside Europe in "green field" developing countries, such as Pakistan, where there is geologically high potential for pegmatite and/or brine type of lithium rich deposits. "Green field" refers to geographic areas which, in the light of available geological studies, show promising geology for valuable minerals and seem tentatively economically, environmentally and socially feasible for commercial mining, but have not yet been sufficiently explored, documented and verified for identifying commercially feasible deposits [20-22].

Geological Survey of Finland has conducted assessment of probable lithium resources in Finland and provides a map (Figure 5) showing the known lithium permissive tracts, i.e. areas within which the geology permits the existence of lithium mineral deposits. The biggest known lithium discoveries are in the western side of Central Finland Granitoid Complex where also Sibanye-Stillwater's Kaustinen lithium mine is located. However, the planned life of this mine is presently limited to just 18 years. Therefore, further exploration of commercially viable lithium ore elsewhere in Finland to keep feeding the refinery built in Kokkola is highly motivated. There are potential permissive tracts in Northern Finland around the Central Lapland Granitoid Complex which has been selected by the author for focused study in this article [11].

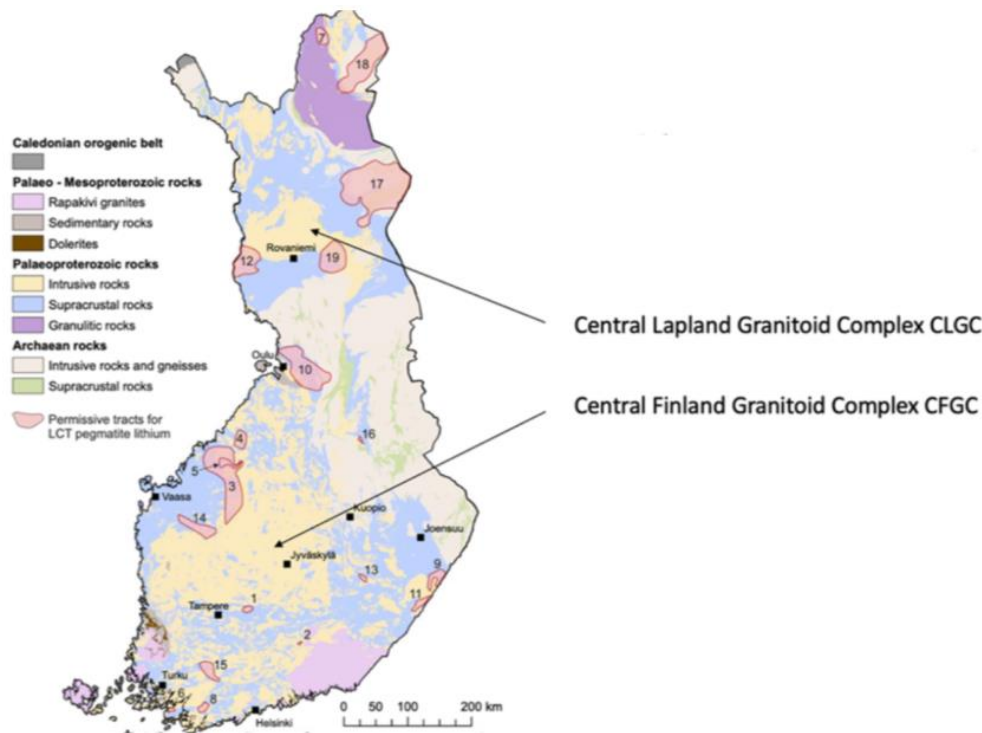


Figure 5: Location of the pegmatite lithium Permissive Tracts in Finland. Figure Courtesy [11]

Research Method

Mineral Systems Modelling

Mineral systems approach is a systematic, holistic, computerized and geological stored data assisted approach for prospecting of valuable target minerals [23]. This approach has been under rigorous scientific development for over 30 years. There is considerable geological knowledge captured and accumulated in these models. The model typically defines mapping criteria for the following geological processes:

- Sources processes extract the fundamental mineral deposit components (energy, melts, fluids, metals and ligands) from their mantle or crustal origins;
- Transport processes drive the movements of the essential ingredients from source regions to trap regions via melts and fluids;
- Trap processes direct and focus melt and fluid flows into physical (such as pressure, temperature change) or chemical (potential of hydrogen (pH), mixing fluids, surrounding rock composition) deposit locations;
- Deposition processes direct selective collection of metals from melt and fluid flows passing through the traps;
- Preservation processes selectively maintain and protect the collected metals against geological dispersion processes over time.

According to Turnbull et al [24] the minerals system approach aims on gaining understanding and describing explicitly what is known of the processes that control the behavior of a chosen target mineral within wider geological tectonic system. This approach is applicable in geological green field areas with incomplete or partial datasets. In the following paragraphs we first address the leading scientific contributions in pioneering countries for mineral systems modeling for lithium, and then look at the tools, empirical work, and results of mineral system modeling for lithium in Northern Finland.

New Zealand Lithium Mineral Systems Model

The geological conditions from which the lithium mineral systems model by Turnbull et al is specific to New Zealand. It describes comprehensive mineral systems model based on fuzzy logic for lithium mineral potential. Turnbull et al work is limited to pluton magma fragmentation model for pegmatites but is somewhat intermixed with another model for hydrothermal clay lithium that is significant in New Zealand [24]. According to Turnbull et al, the data types are extracted combinations of potential host geological map units and faults, mapped rock features, rock types, specific stratigraphic units, mineral types, whole-rock geochemical analyses of the ore element (lithium), pathfinder elements cesium, boron, chlorine, phosphorus, niobium, rubidium, tin, tantalum and other key elements calcium, sodium, aluminum, potassium, and rubidium [24]. According to Turnbull et al the main data sources are: New Zealand Quarter Million Mapping Project (QMAP) database geological map units, faults and other mappable features; New Zealand rock, mineral and geoanalytical database (PETLAB) geological, geochemical and mineralogical samples; New Zealand industry-acquired geochemical data (REGCHEM) geochemical rock chip, soil, stream sediment and pan concentrate samples; New Zealand Petroleum and Minerals Online Exploration Database and Mineral Reports; legacy geochemical data from mineral reports; Peer-reviewed literature; and samples from the National Petrology Reference Collection at Institute of Geological and Nuclear Sciences Limited (GNS Science) [24].

Australian Lithium Mineral Systems Model

The geological conditions from which the lithium mineral systems model by Duuring et al is specific to Australia but Australia as a continent is sufficiently wide to hold different kinds of geological settings and conditions. The model is mainly inspired by the classic pluton magma fractioning pegmatite genesis hypothesis but it has elements of the anatectic partial melting pegmatite genesis hypothesis incorporated as well. The Australian model is less comprehensive and detailed compared to the New Zealand model. According to During [25], the data types are extracted combinations of potential host geological map units, geochronology, metamorphic facies, structures, mapped rock layers, rock types, fertility indicators and ratios, zircon and apatite chemistry, pathfinder elements (lithium, cesium, tantalum, beryllium, boron, fluorine, phosphorus, manganese, gallium, rubidium, niobium, tin, hafnium) and other key elements (fluorine, molybdenum, tungsten, indium, uranium, scandium, strontium). The main data sources used are: Geological proxy layer available in the Atlas (Web service providing layered view of Western Australian mineral deposits); WAROX (Geological Survey of Western Australia geoscientific data) database; and MINEDEX (mines and mineral deposits of Western Australia) database [25].

Prospectivity Modeling Tools

In this research, it was selected to use Open Access fuzzy logic –based prospective modelling tools MPM (Mineral Prospectivity Modeler) and public geological databases of the Geological Survey of Finland (GTK). MPM is an online web-based tool for assessing regional scale mineral prospectivity with open-access server-based geospatial datasets covering area of northern Finland. MPM can be operated with any web browser, and it does not require installation of software applications into the user's computer. However, MPM suffers from closed architecture; it is not possible to import data from outside sources, and storing of models is restricted to printing of computed charts. MPM tool supports interactive and visual computation on multiple input data sources through concepts of fuzzy logic mathematical framework addressing imprecision and uncertainty. The choice of each fuzzy function or operator is relative to the computation logic depending on the structure of the particular mineral systems model [26,27].

Description of Available Proxy Data

According to MPM provides the following spatial computation input data for mineral systems modeling: (1) Geophysical data: low-altitude aero-geophysical data; Recalculated magnetic (total magnetic field), Recalculated apparent resistivity, Recalculated electro-magnetic (EM) quadrature (EM-imaginary), Recalculated EM in-phase (EM-real); (2) Geochemical data: regional till and weathered bedrock geochemistry for 25 elements: gold, barium, calcium, cobalt, chromium, copper, iron, potassium, lanthanum, manganese, nickel, phosphorus, tellurium, thorium, vanadium; (3) Structural geology data derived from GTK's digital bedrock map of Finland (lithological/stratigraphic geological units in which faults, diverse overprinting lines and dykes are represented), and regional Bouguer data: Density of structures, Distance to domain boundaries, Distance to structures, Distance to black shales, Density of lithological contacts, Distance to gravity worms. Additionally MPM has (4) Pre-calculated prospectivity models library: Iron oxide-copper-gold (IOCG) deposits and occurrences, Magmatic platinum group element (PGE) deposits and occurrences (Magmatic PGE, Magmatic nickel-copper (Ni-Cu) deposits and occurrences (Magmatic Ni-Cu), Orogenic gold (Au) deposits and occurrences (Orogenic Au); (5) Finally, MPM has visualisation data: Linkage to GTK Mineral Deposits and Exploration web services for visualization-only, data cannot be used as input for computation [26]. (<http://gtkdata.gtk.fi/mdae/index.html>).

The mapping from New Zealandia lithium model to MPM data sources is weak. Out of 20 proxy data elements there is mapping available for 17 elements (85%), out of which 10 (50%) are for visualization and only 7 (35%) are computational. Of the 7 computational proxy data the required data elements are available for only 4 proxies (20%). Important geochemical indicators, such as ASI (aluminum saturation index) and K/Rb (potassium/rubidium ratio), cannot be computed due to MPM till data missing important elements and MPM not supporting arithmetic computations. Pathfinder elements cannot be used due lack of elements in MPM.

The mapping from Australian lithium model to MPM data sources is also weak. Out of 47 proxy data elements there is mapping available for 22 elements (47%), out of which 13 (28%) are for visualization and only 9 (19%) are computational. Of the 9 computational proxy data, the required data elements are available for only 2 proxies (4%). Important geochemical fertility indicators cannot be computed due to MPM till data missing important elements. Pathfinder elements cannot be used due lack of elements in MPM.

Empirical Work in Northern Finland

In existing geological literature, there are only a few research published on mineral system models for lithium-rich pegmatites. The purpose of empirical evaluation was to assess the two pioneering mineral systems models found in the scientific geological literature, the New Zealand lithium mineral systems model by Turnbull et al and the Australian lithium mineral systems model by Duuring against the geological conditions and proxy data sources available in Northern Finland, as well as evaluate the MPM tools for geological conditions, its available proxy data sources, computational logic and visualization capabilities [24,25].

Based on the study of the New Zealandia and Australian lithium mineral systems models and comparing to available data sources in MPM it was detected that the following MPM till data elements are both relevant and computationally available: barium, calcium, potassium, lanthanum, manganese, phosphorus, thorium. Following till data elements were selected as

proxies for sedimentary (S-type) granites: potassium and barium because they represent compatible elements, which tend to stay in the parent granite. Following till data elements we selected as proxies for fractioning incompatibles: phosphorus, lanthanum, thorium, manganese, which tend to behave similarly as lithium entering pegmatites. Following structural data sources were selected as proxy for structures: distance to structures and distance to worms since they represent areas close to faults, shear zones and fractures. This comes from the mapping from both New Zealandia and Australian mineral systems model data sources to MPM computational data sources.

Figure 6 presents Fuzzy logic computational model developed during experimentation with the MPM tool. On the left side are the blue oval data sources from top to bottom: till data potassium (K) and barium (Ba); till data phosphorus (P), lanthanum (La), thorium (Th), and manganese (Mn); and distance to structures, distance to worms. Green boxes represent fuzzy overlays and memberships whose functions and parameters are described in white overlapping comment boxes. Fuzzy membership functions Large and Small are used to scale data to fuzzy computation scale. Fuzzy overlay function Gamma is used to combine fuzzy data sources. In the middle field blue ovals represent intermediate computation results. Oval 51 contains the proxy for S-type granites. Data source for thorium was found unreliable in some areas in Northern Finland, so it is not used for computation for S-type granites proxy. Oval 57 contains the proxy for fractional incompatibles. Oval 64 contains the proxy for structures. Oval 70 contains the main outcome i.e. the lithium prospectivity model.

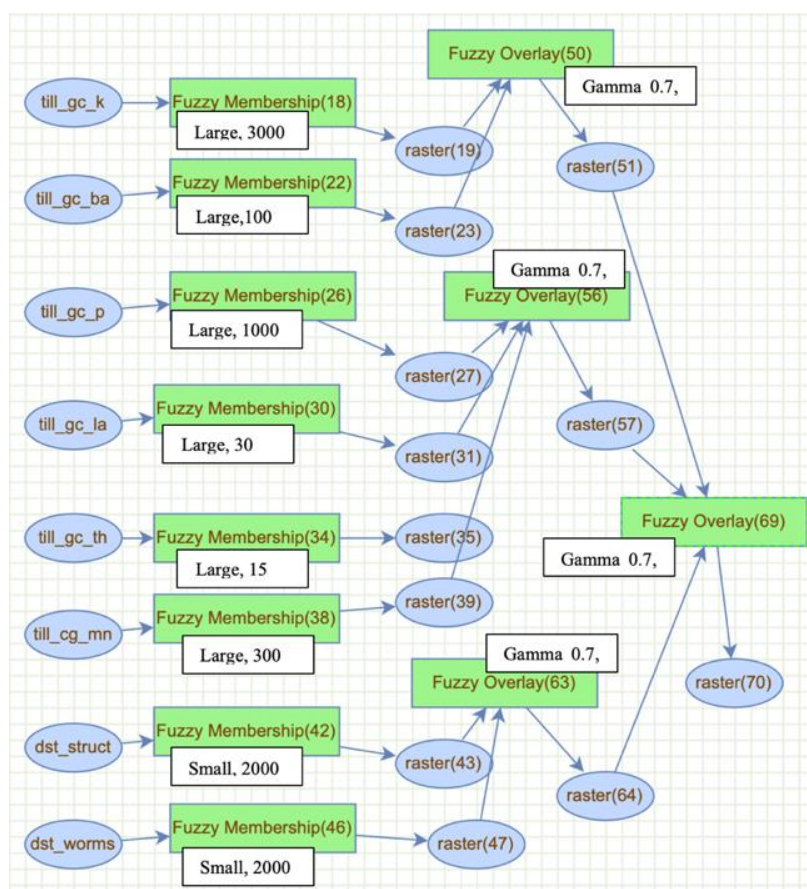


Figure 6: MPM Tool Fuzzy Logic Computational Model for Prospectivity Charts

Results and Discussion

Proxy and Prospectivity Charts

Figure 7 presents S-type granite proxy chart computed as fuzzy gamma (K, Ba). Highest values of S-type granites appear to be north-west from Muonio-Kolari-Kittilä area, south-west from Ylitornio-Tornio-Tervola area, Salla to east, and from Sodankylä-Pelkosenniemi-Savukoski to further north-east.

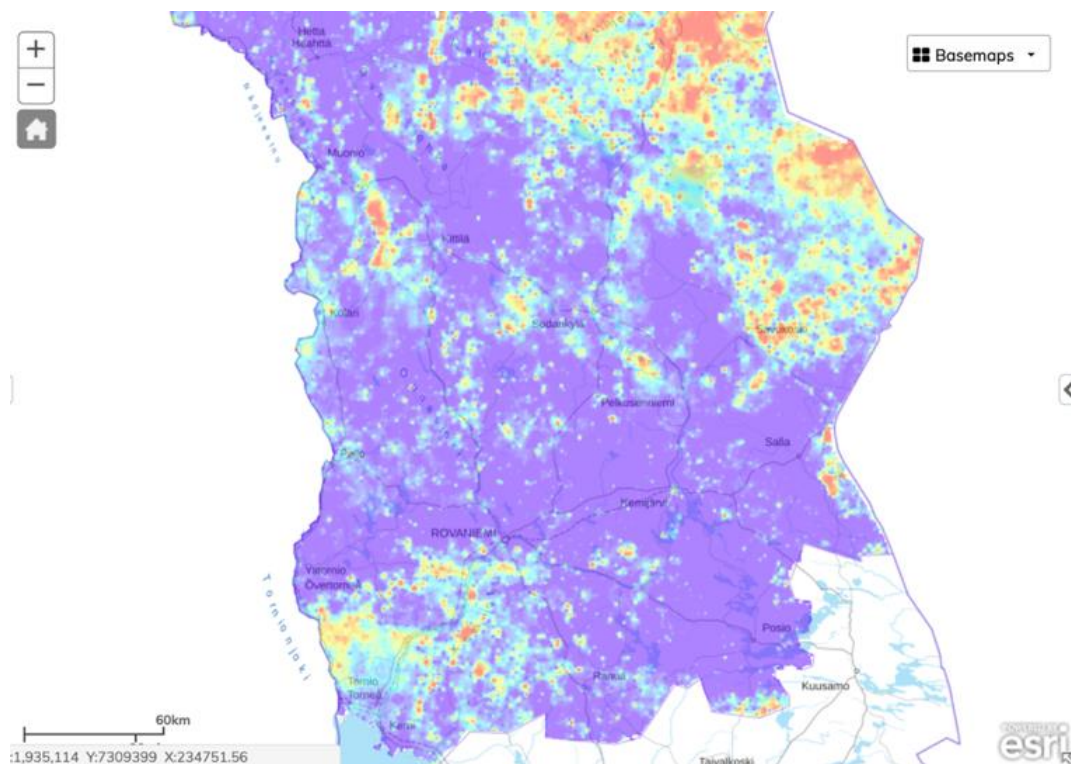


Figure 7: S-Type Granites -Proxy Chart for Northern Finland

Figure 8 presents fractioning incompatibles proxy chart computed as fuzzy gamma (P, La, Mn). High values of fractioning incompatibles appear to be on the Western border, all the way from Hetta-Muonio-Kolari-Kittilä-Pello down to Ylitornio-Tornio-Tervola. There are high values also in west from Sodankylä, north-east from Savukoski, and Vuotso-Saariselkä-Kuttura-Pokka area.

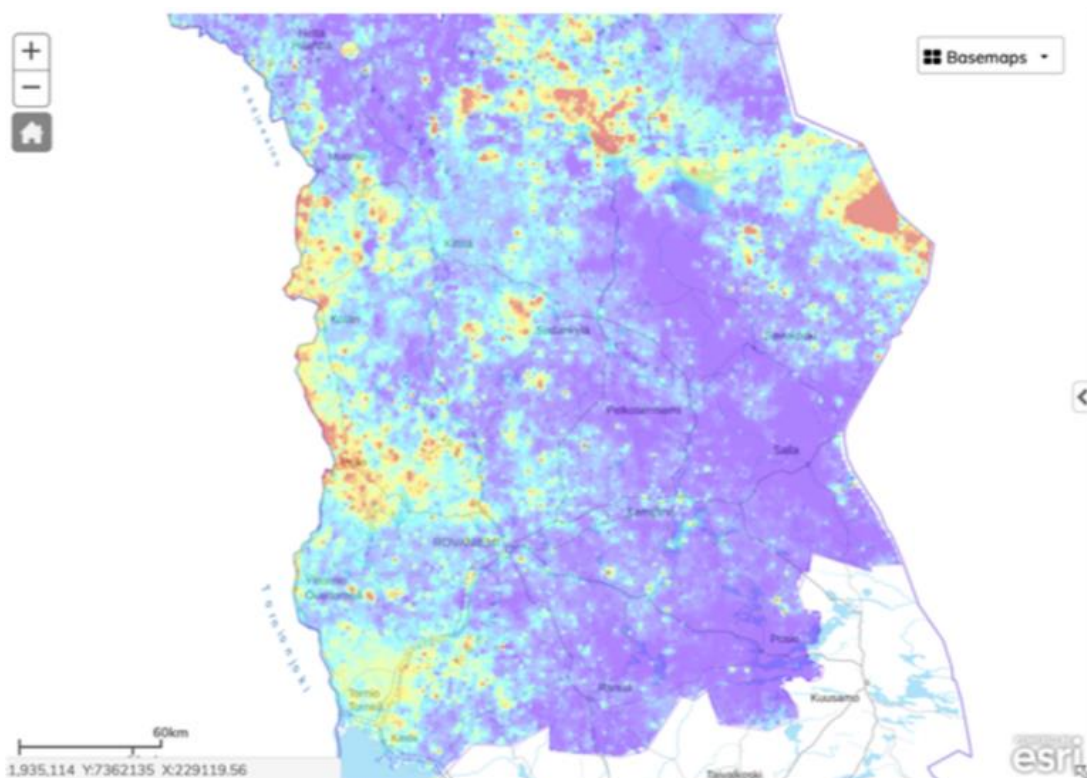


Figure 8: Fractioning Incompatibles -Proxy Chart for Northern Finland

Figure 9 presents structural proxy chart computed as fuzzy gamma (distance to structures, distance to worms). High values indicate areas which are likely for pegmatites because of the structural faults, fractures or shear zones. In is interesting that all shapes appear to be curved, which can be interpreted that they are not young.



Figure 9: Structural -Proxy Chart for Northern Finland

Figure 10 presents the resulting lithium pegmatite prospectivity chart. High values of lithium appear to be on the Western border, all the way from Muonio-Kolari-Kittilä-Pello down to Ylitornio-Tornio-Tervola. There are high values also in west from Sodankylä, north-east from Savukoski, and Vuotso-Saariselkä-Kuttura-Pokka area.

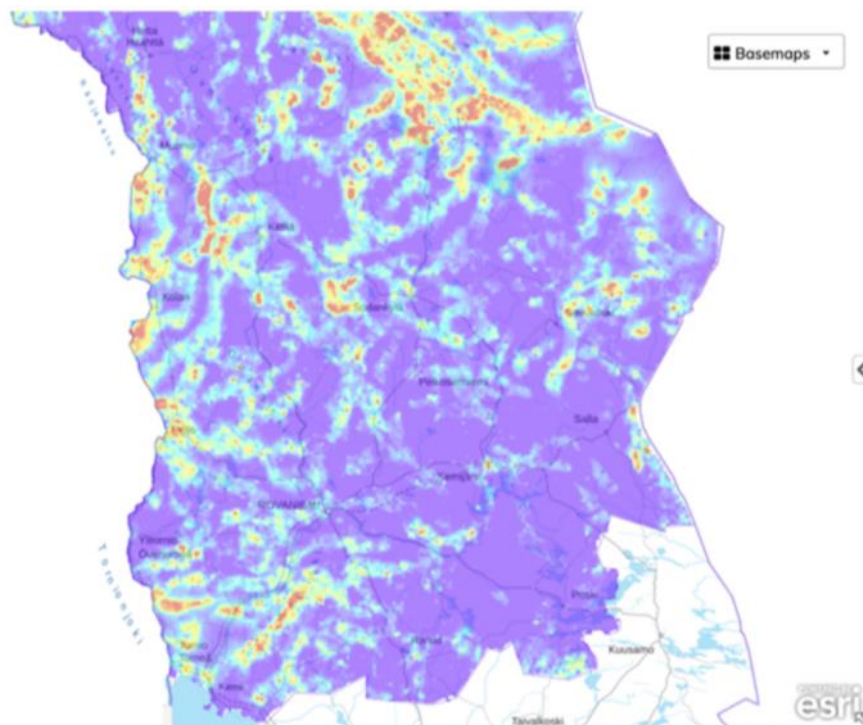


Figure 10: Lithium Pegmatite -Prospectivity Chart for Northern Finland

Validation of Prospectivity Chart

To analyse lithium prospectivity chart (Figure 10) for ease of visual comparison it is placed side by side with visualisation of actual lithium till data produced from GTK Hakku (Geological Survey of Finland search and download service) service using QGIS (Quantum Geographic Information System) tools, is shown in Figure 11. Visual comparison to actual lithium till data generated with QGIS tool heatmap of GTK-Hakku-Li_ppm_511P data validates the prospectivity model: prospectivity model elevated values match high lithium till data values as well. Reverse relation appears not to hold, i.e. high lithium till data values do not necessarily imply high values in prospectivity model. Further validation is required with more accurate data sources and more powerful tools, such as QGIS [28,29].

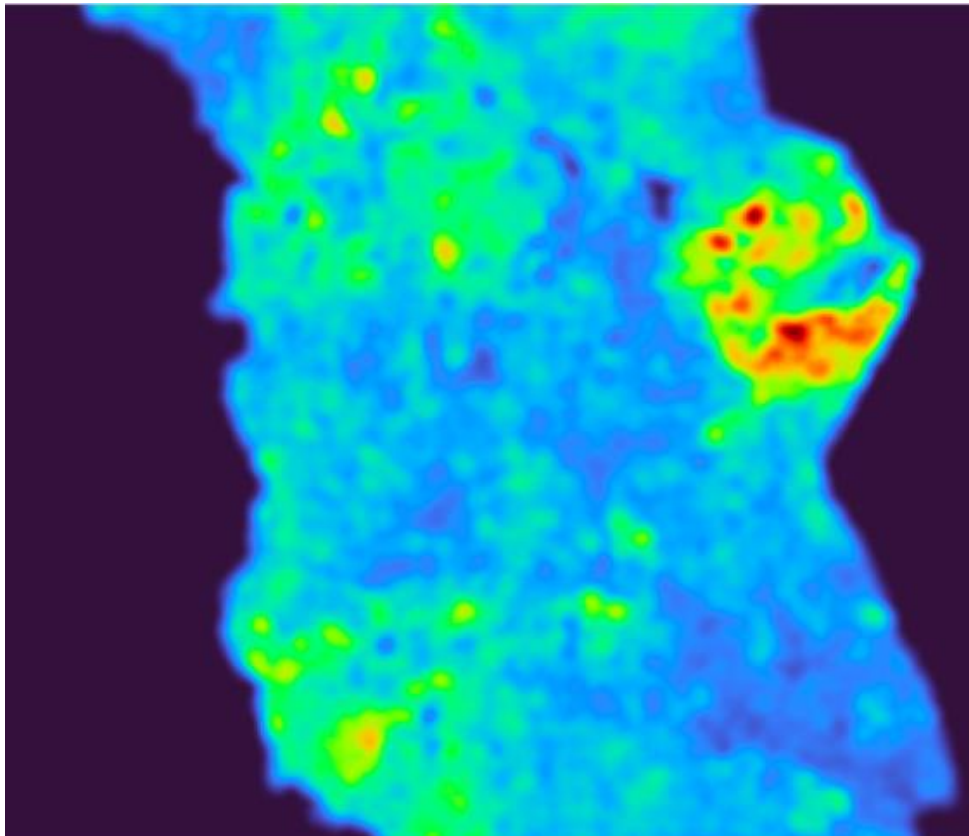


Figure 11: Heatmap Visualisation of Lithium Till Data for Northern Finland

Conclusions

Lithium supply security has become crucial for electric grid transition towards renewable energy sources and for automotive, electronics and military technology companies in Europe. Global supply chains of lithium for batteries are currently dominated by sources in Australia, South America, and China, with processing and manufacturing of the battery compounds, components and assemblies established in China, South Korea, and Japan. Limited geographical spatial distribution in the supply chain presents potential geopolitical and logistics embargo risks for security of supply. Many countries and regions are starting to consider development of local or trusted partnership-based supply chains to ensure at least minimum level of self-sufficiency. A scenario is presented involving Pacific Ocean shipping embargo whose fallout would be catastrophic for European refined lithium supply chain geopolitical sustainability.

The foreseen growth in demand for battery raw materials has been identified to offer an opportunity and a challenge for natural resource-rich countries. In this paper we identified the swing producers who possess the capability to grow production lithium production based on existing, already identified lithium resources.

There is a possibility for developed nations to increase their self-sufficiency for engaging in, and building long-term geopolitical sustainability to, the lithium supply chains through ensuring minimum-level long-term access to their own latent potential lithium resources through mineral systems modelling based prospectivity analysis and discovery for lithium resources. It would be advisable for Europeans to build up scalable supply chain front-end for lithium, i.e. mining reserves, mining infrastructure, ore transport logistics, and refining capacity. Scalable means that under business-as-usual conditions lithium supply chain front-end is hibernating with small costs, but under black-swan type abnormal conditions, the front-end could be activated rather quickly. Potential enabling technologies for scalability are smart mining, photonics, and underground wireless communications.

We present a case study within Europe conducted in Northern Finland for identifying and mapping potential lithium-bearing pegmatites in prospectivity chart for lithium resources. This chart is an example of support information that can be used in public awareness campaigns, in negotiations with supply chain current and new actors, and in national strategy decisions on policies for decarbonisation of energy and transport, and in planning cross-border cooperation between nations.

Finally, increasing European cooperation with developing countries in geological exploration, transport infrastructure, mining and refining is recommended. Such cooperation has long-term potential to build resilient supply chains in developing countries for sourcing critical minerals and overcoming local lack of environmental protection, funding, infrastructure and knowhow. Combined, these measures provide long-term opportunities to reduce vulnerability to geopolitical supply chain risks in Europe.

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Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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