



GREENPEG – exploration for pegmatite minerals to feed the energy transition: first steps towards the Green Stone Age

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Abstract: The GREENPEG project, which is funded by the European Commission Horizon 2020 ‘Climate action, environment, resource efficiency and raw materials’ programme, aims to develop multimethod exploration toolsets for the identification of European, buried, small-scale (0.01–5 million m³) pegmatite ore deposits of the Nb–Y–F (NYF) and Li–Cs–Ta (LCT) chemical types. The project is being coordinated by the Natural History Museum of the University of Oslo and involves four exploration services/mining operators, one geological survey, one non-profit helix association of administration, industry and academia, two consulting companies and five academic institutions from eight European countries. The target raw materials are Li, high-purity quartz for silica and metallic Si, ceramic feldspar, rare earth elements, Ta, Be and Cs, which are naturally concentrated in granitic pegmatites. Silicon and Li are two of the most sought-after green technology metals as they are essential for photovoltaics and Li-ion batteries for electric cars, respectively. GREENPEG will change the focus of exploration strategies from large-volume towards small-volume, high-quality ores and overcome the lack of exploration technologies for pegmatite ore deposits by developing toolsets tailored to these ore types. This contribution focuses on the methods applied in the GREENPEG project and as such provides a potential pathway towards the ‘Green Stone Age’ from the perspective of pegmatite-sourced minerals.

Critical raw materials, and other non-critical metals for the production and storage of renewable (green) and industrial minerals, are increasingly required energy, including high-purity silica (i.e. quartz), Si,

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Li, rare earth elements (REEs), Be, Ta, ceramic feldspar and Cs. One of the most sought-after green technology metals is Li, which is needed to meet growing demand for lithium-ion batteries, e.g. for electric vehicles and battery storage farms. Most Li is extracted from pegmatites or evaporitic brines (Kesler *et al.* 2012; Mohr *et al.* 2012).

China dominates the global production of REEs (95%) and silicon metal (61%), Australia that of Li (60%), USA that of Be (90%) and African countries that of Ta (75%), meaning that these key raw materials have to be imported and their security of supply is, therefore, a risk factor for the European economy (Fig. 1, Table 1; European Commission 2019). Of most concern is that China is steadily increasing its control of the mining and production of critical raw materials and has acquired, and is still expanding, a dominant position in the critical raw material supply chain. In addition, EU mining-related activities have dramatically declined in the last century (e.g. Federal Ministry of Industry Agriculture and Regions Ministry of Austria 2021) and, over recent decades, Europe has lost expertise in exploration and mining, leading, for example, to insufficient understanding of hard-rock mineral resources. Today, Canada and Australia are the world leaders in exploration technologies and therefore European enterprises have to buy in their services to explore for new deposits. For the raw materials high-purity quartz, Li, REEs

and Be, in particular, there is now an urgent need to take measures to stimulate mining by regaining European expertise and increasing the efficiency of exploration to minimize environmental impacts and costs. Achieving this will ensure a stable and responsibly mined supply of critical raw materials and other important metals and industrial minerals for manufacturing, most importantly for renewable energy devices, and to ensure high added value in Europe. Another reason for European mining decline is the negative public environmental perception of mining (e.g. Kivinen *et al.* 2020), which makes it difficult for small and medium-sized enterprises in particular to build a business case and to acquire relevant consents. Stimulating technological innovation in mineral exploration and mining towards more sustainable environmental efficacy will, together with an ‘open-from-the-start’ dissemination strategy, improve the image of this industry and change the prevalent ‘not in my backyard’ attitude in Europe.

Granitic pegmatites can be economically enriched in a variety of critical and other rare metals (Linnen *et al.* 2012; London 2016; Bradley *et al.* 2017), industrial minerals (Glover *et al.* 2012) and gemstones (Simmons *et al.* 2012; listed in Table 2) and are thus strategically important exploration targets. In terms of chemistry and rare metal abundance, Černý (1991a) distinguished Li–Cs–Ta (LCT) and Nb–Y–F (NYF) pegmatites, a classification still

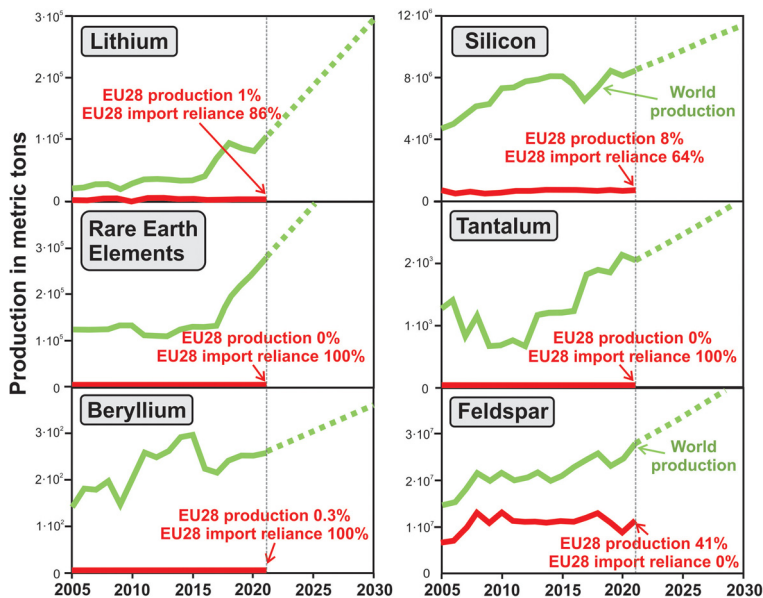


Fig. 1. Comparison of world (green lines) and EU28 country (red lines) production of silicon, feldspar, Li, rare earth elements (REEs), Ta and Be from 2005, with a prediction of world production up to 2030. Except for feldspar, 90–100% of these raw materials are imported by the EU27 countries. Data for Cs are not available. Source: USGS (2021).

Table 1. GREENPEG exploration target commodities (hosted in pegmatite-type deposits) with indicated world/EU mine production, EU import reliance, net EU imports, end of recycling input rate, major uses and predicted EU demand in 2025. Uses in bold indicate applications important for the shift to green technologies.

GREENPEG target commodity	World/EU mine production (tonnes)	EU import reliance (%)	Net EU import* (tonnes)	End of recycling input rate (%)	Major end uses in EU	Expected EU demand in 2025 (tonnes)
Lithium	84 700/800	86	5000	0	Glass and ceramics (57%), batteries (25%) , cement (6%), lubricating greases (6%)	20 000
Silicon metal (produced from high-purity silica)	2 288 000/195 000	64	344 000	0	Chemical applications (54%), aluminium alloys (38%), solar cells and electronics (8%)	500 000
Feldspar	26 792 265/ 10 395 772	0	−3 600 000	10	Ceramics (36%), flat glass (30%), container glass (30%)	10 000 000
Rare earth elements	135 650/0	100	8350	1	Catalysts (23%), super magnets in wind turbines (22%) , alloys (16%)	20 000
Tantalum	1800/0	100	80	1	Capacitors (33%), super alloys (22%), sputtering targets (17%)	200
Beryllium	300/0	100	50	0	Electronic and telecommunications equipment (42%), transport and defence (44%), energy applications (8%) , industrial components (6%)	100
Caesium	10/0	100	2	85	Drilling fluids for oil and gas production (95%), photoelectric cells (3%) , fluoroscopy equipment (1%), atomic clocks (1%)	3

Source: [European Commission \(2019\)](#).

*Net EU import = Import minus export.

Table 2. Estimated ore mineral content in lithium–caesium–tantalum (LCT) and niobium–yttrium–fluorine (NYF) pegmatites

Raw material (mineral)	LCT pegmatites		NYF pegmatites	
	Ore mineral content in pegmatite (%)	Element of interest in ore mineral (%)	Ore mineral content in pegmatite (%)	Element of interest in ore mineral (%)
Quartz	5–25	SiO ₂ (100); Si metal (47)	20–35	SiO ₂ (100); Si metal (47)
Ceramic feldspar	50–75	(K,Na,Ca)Al _{1–2} Si _{2–3} O ₈	50–65	(K,Na,Ca)Al _{1–2} Si _{2–3} O ₈
Industrial mica*	1–10	(K,Fe) _{2–3} (Al, Si) ₄ O ₁₀ (OH) ₂ (100)	1–10	(K,Fe) _{2–3} (Al, Si) ₄ O ₁₀ (OH) ₂ (100)
Lithium mica [†]	1–5	Li (c. 1–3.5)	Up to 1 [‡]	Li (c. 1–3.5)
Spodumene	Up to 35	Li (3.7)	–	–
Petalite	Up to 35	Li (2.1)	–	–
Amblygonite	Up to 1	Li (3.4)	–	–
Pollucite	Up to 1	Cs (28)	–	–
Columbite–tantalite	Up to 1	Ta (c. 5–70), Nb (c. 2–55)	Up to 0.1	Ta (c. 5–70), Nb (c. 2–55)
Beryl	Up to 1	Be (5)	Up to 1	Be (5)
Allanite	–	–	Up to 0.5	REEs (c. 15–32)
Monazite	–	–	Up to 0.1	REEs (c. 44–56)

According to Glover *et al.* (2012), Linnen *et al.* (2012), Kesler *et al.* (2012) and this study. REEs, Rare earth elements.

*Industrial mica mined from pegmatites include various types of muscovite (ferroan muscovite, lithian ferroan muscovite, muscovite, lithian muscovite, ferroan polyolithionite, polyolithionite), biotite (magnesian siderophyllite, siderophyllitem, lithian siderophyllite) and phlogopite (ferroan phlogopite).

[†]Micas mined from pegmatites for lithium include lithian muscovite, lithian ferroan muscovite, ferroan polyolithionite, polyolithionite ('lepidolite') and trilithionite.

[‡]Chemically evolved NYF pegmatites may contain in very rare cases considerable amounts of lithium mica such as the Upper Høyaldalen pegmatite in Tørdal, Norway (Rosing-Schow *et al.* 2018).

widely applied. Pegmatite deposits are common in Europe but are an underexplored resource type (e.g. Gourcerol *et al.* 2019). There are a few mines in Europe for Li, Be, Ta from LCT pegmatites and ceramic feldspar (Portugal, Finland, France), and for quartz (Norway) from NYF pegmatites, but there is huge potential to find more deposits. As most exposed and near-surface deposits have already been discovered, exploration will need to be for concealed deposits. This, however, presents a challenge as pegmatites are generally considered to be geophysical non-responders in that they are non-magnetic, contain insufficient minerals that have conductive or magnetic properties and may not have a sufficiently high density to create a measurable contrast with their host rocks (Beus *et al.* 1968; Trueman and Černý 1982; Galeschuk and Vanstone 2005, 2007; Selway *et al.* 2005; Bradley *et al.* 2017). So far, the only known mineralized pegmatites are those exposed at the surface, discovered through Sn–Ta placer deposits (Blockley 1980) and geochemical halos by combining rock lithochemistry and selective leach soil geochemistry (Galeschuk and Vanstone 2005), or detected accidentally by drilling campaigns for other mineralization types (Černý *et al.* 1996). Recent developments in geophysical methods towards higher

sensitivities may allow detection of hidden pegmatites but they have yet to be tested. Another exploration approach is through high-resolution remote sensing methods, although they allow only surface interpretation. Significant improvement in the coverage and accuracy of satellite data used for remote sensing-based image processing and interpretation is becoming increasingly important to define areas of potential interest for the exploration of pegmatite ore bodies (Cardoso-Fernandes *et al.* 2020a). The PROSPEG project has pioneered adjustment of remote sensing methods to pegmatite exploration (Sinergeo 2015).

In order to overcome the challenges of pegmatite exploration, a multi- and interdisciplinary consortium of five academic and research institutions, six consulting and mining companies, one geological survey and one non-for-profit association established the 54-month GREENPEG project aiming to develop multimethod exploration toolsets for the identification of pegmatite deposits. The GREENPEG project is financed by the European Commission as part of the Horizon 2020 climate action, environment, resource efficiency and raw materials programme (called SC5-10-2019-2020). The following challenges were the motivation for the technology-oriented GREENPEG pegmatite

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exploration project: (1) the sudden increase in demand for critical raw materials required for the shift to green technologies; (2) the lack of exploration tools and workflows tailored to pegmatite-type deposits; and (3) a need to minimize the environmental and social impacts of exploration activities. GREENPEG consequently aims to develop and deliver innovative, competitive and environmentally friendly exploration toolsets at Technical Readiness Level 7 to explore for buried LCT and NYF pegmatites for use by small and medium-sized enterprises. The development of the integrated toolsets is based on a new genetic model for most European pegmatite-type ore deposits and a new multilevel (province, district and prospect scale) approach combining several technological innovations and integrated solutions. This contribution focuses on the scientific and methodological approach applied in GREENPEG for the development of efficient and environmentally and socially responsible exploration tools for hidden pegmatite-type deposits.

The scientific approach of GREENPEG

New models for pegmatite formation

The NYF pegmatites are affiliated with anorogenic suites that form in extensional settings involving A-type magmas, whereas Proterozoic and Phanerozoic LCT pegmatites are generally considered to be members of calc-alkaline S-type suites that form in an orogenic subduction-related setting (Černý 1991a; Martin and De Vito 2005; London 2008;

Černý *et al.* 2012; Bradley *et al.* 2017). The sources of Archean LCT pegmatites are differentiated I-type suites, where the tectonic setting is debatable (e.g. Sweetapple and Collins 2002).

The overall aim of GREENPEG is to develop two new multimethod exploration toolsets for the identification of European, buried, small-scale (0.01–5 million m³, corresponding to an estimated resource target size of 0.025–12.5 million tonnes) and clustered pegmatite ore deposits of the NYF and LCT chemical types. The GREENPEG toolsets are based on new genetic models for the majority of European pegmatite-type ore deposits (Müller *et al.* 2015, 2017; Barros and Menuge 2016; Konzett *et al.* 2018). The new models imply that the distribution of most European rare metal pegmatites is controlled by the chemistry and degree of partial melting of wall rocks and the presence of major tectonic structures such as regional shear zones. This represents a radical shift from the majority of previous models, which suggest that pegmatites crystallize from the residual, most fractionated melts released during the final crystallization of large-volume granitic intrusions (Černý 1991a, b; Černý and Ercit 2005; London 2008; Černý *et al.* 2012; Fig. 2a). This is based on the observation that swarms of pegmatites commonly occur in and around granitic intrusions of a similar age.

Recent findings challenge the residual melt hypothesis by showing that some pegmatites can form by direct partial melting of metamorphic rocks, exemplified by occurrences in the eastern USA, Austria, Namibia and southern Norway

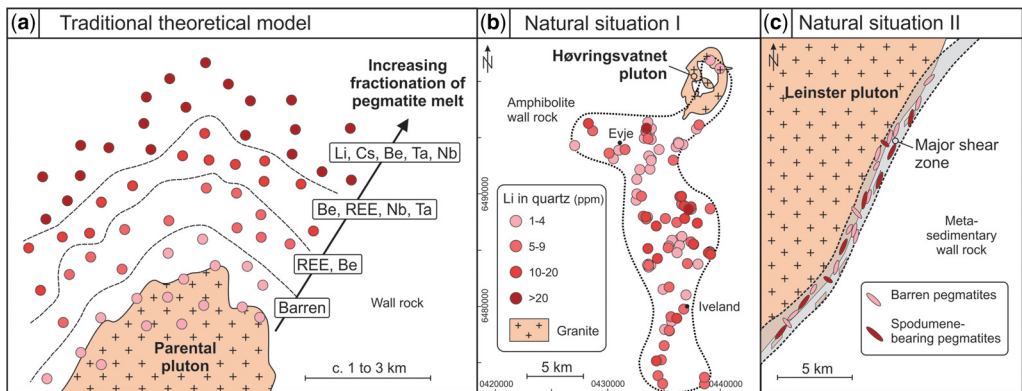


Fig. 2. (a) Traditional chemical zoning of a pegmatite field (coloured dots: ‘barren’ to rare-metal-enriched pegmatites) in spatial relation to a supposed parental pluton (Černý 1991a). (b) Lithium in quartz in pegmatites from the Evje-Iveland pegmatite field in Norway, showing no distinct zoning (Müller *et al.* 2015); the area is comparable with the Tysfjord demonstration site; high Li in quartz is indicative of high levels of rare metals (REEs, Be and Ta) in the deposit. One coloured dot represents one pegmatite body. Field chemical zoning has no genetic relation to the adjacent pluton in the north (Høvringsvatnet). (c) Spodumene-bearing and barren pegmatites aligned in a shear zone along the margin of a granite pluton (Leinster demonstration site) with no regional zonation of different types of pegmatite in the pegmatite field.

(Simmons *et al.* 1996, 2016; Müller *et al.* 2015, 2017; Schuster *et al.* 2017; Fuchsloch *et al.* 2018; Konzett *et al.* 2018; Webber *et al.* 2019). These studies revealed that either pegmatites and spatially related granites have differences in the crystallization age of more than 40 myr, or that there are simply no granite plutons associated with the pegmatites evident from mapping and Bouguer anomaly patterns. In south Leinster, Ireland, where the ages of pegmatites and the adjacent granite overlap, geochemical modelling is inconsistent with fractionation of granitic magmas as a source of LCT pegmatites, but consistent with a direct anatectic origin (Barros and Menuge 2016). In these cases, the composition of the pegmatite melt depends on the type of melted source rock (predominantly amphibolites to form NYF-type melts and metasediments to form LCT-type melts) and not on differentiation via pluton-sized intrusions. For anatectic LCT pegmatites, micas, garnet and staurolite, which are widespread in metasedimentary rocks, are seen as a source for lithophile elements such as Li (London

2005, 2018; Vignola *et al.* 2008; Konzett *et al.* 2018). Inclusions of staurolite in pegmatitic beryl provide particularly compelling evidence for direct melting of metasedimentary rocks (Konzett *et al.* 2018). One question yet to be resolved is that production of spodumene pegmatites, many of which are saturated in spodumene at the time of intrusion (Barros *et al.* 2020), nevertheless probably requires the mobility of unusually low-degree partial melts, or as yet undocumented extreme enrichments of Li and other rare metals in metasedimentary source rocks. Scenarios of both pluton-related and pluton-unrelated formation of ‘barren’ and mineralized pegmatites are illustrated in Figure 3.

In a new pegmatite classification scheme, Wise *et al.* (2022) distinguish mineralogically between three pegmatite groups. These straightforward identifiable mineralogical groups are further subdivided genetically, related either to granite plutons (residual melts of granite magmatism – RMG pegmatites), or to the formation by anatexis of metaigneous and/or metasedimentary protoliths (direct products of

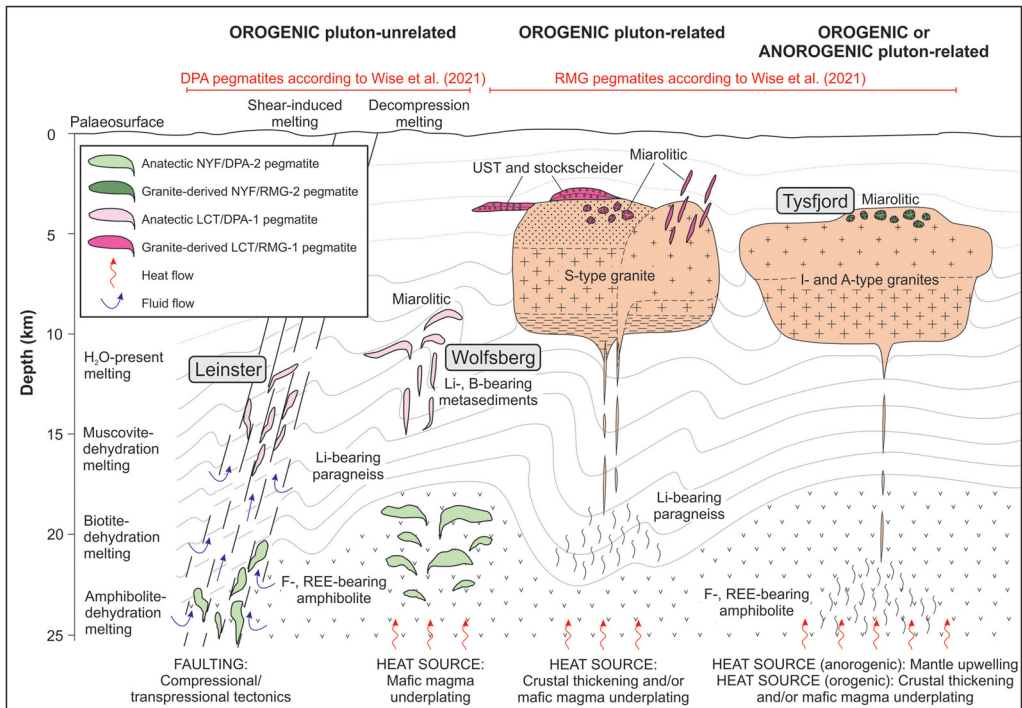


Fig. 3. Schematic crustal profile illustrating the contrasting controls on the formation of pegmatites in a pluton-related, compared with a pluton-unrelated, scenario. In the case of pluton-unrelated settings, the degree of partial melting and source rock composition control the formation of barren or mineralized pegmatites. The indicated dehydration melting depths correspond to geothermal gradients of 35–40°C km⁻¹. Modified from Müller *et al.* (2017). ‘Miariolitic’ does not necessarily imply that all pegmatites have developed open cavities. In the case of Tysfjord, for example, the Proterozoic pegmatites were metamorphosed during the Caledonian orogeny and possibly pre-existing cavities were destroyed by shearing (Müller *et al.* 2022).

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anatexis – DPA pegmatites; Fig. 3; Table 3). The subdivision allows genetic information to be obtained from mineral assemblages. Depending on the chemical signature of the partial melts, having S-, A- or I-type affinity, Wise *et al.* (2022) subdivides them into DPA-1 (enriched in Be, Nb, Ta, P and Li), DPA-2 (enriched in REEs, U and Be), DPA-3 (enriched in Al, Be and B), RMG-1 (enriched in Be, Nb, Ta, P, Sn, Li and Cs), RMG-2 (enriched in REEs, Be, Nb and F) and RMG-1 + 2 groups (enriched in B, Be, REEs, Nb, Ti, Li and Ca). This new pegmatite classification approach is important for pegmatite exploration because anatectic pegmatites produce heterogeneously zoned pegmatite fields (e.g. Leinster and Evje–Iveland shown in Fig. 2). The geochemical zoning of pegmatite fields shown in Figure 2a does not apply to most of the European pegmatite provinces as they are formed by partial melting of metamorphic rocks. According to this classical model, the most fractionated, and thus Li-, Cs-, Be- and Ta-mineralized, pegmatites occur furthest from their parental granite pluton. This scenario does, however, appear to be applicable to the

Variscan Iberian Pegmatite Province, where pegmatites are magmatically related to granite intrusions (e.g. Roda-Robles *et al.* 2018). For most other provinces, such as the South Scandinavian pegmatite province, the Koralpe province in Austria and the Leinster Province in Ireland, pegmatite chemistry and mineralogy are controlled by the degree of partial melting and type of wall rocks and in some cases, melt emplacement is localized by the presence of major tectonic structures (Fig. 2b, c). These settings produce heterogeneously regionally zoned pegmatite fields.

For exploration, this means that a rethinking of conventional methodological approaches is required to establish efficiently the regional zoning of pegmatite fields. Where pegmatites are exposed at the surface, the GREENPEG project seeks to develop a district scale (<25 km²) trace-element-in-quartz assessment tool which aims to establish the regional-scale chemical zoning of pegmatite fields from the Al, Li, Ge and Ti concentrations of pegmatite quartz (Fig. 2b; Müller *et al.* 2015, 2021; see also the following section).

Table 3. General characteristics of residual melts of granite magmatism (RMG) and direct products of anatexis (DPA) type pegmatites

<i>RMG</i>			
Petrogenetic type – mineralogical group	RMG – group 1	RMG – group 2	RMG – groups 1 + 2
Typical source rock Granite chemistry	S-type granites Peraluminous	A-type granites Peralkaline and metaluminous to mildly peraluminous	I-type granites Peraluminous to metaluminous
Relation of pegmatites to source	Interior to marginal	Interior to marginal	Interior to marginal
Typical geochemical signatures	Be, Nb, Ta, P, Sn, Li, Cs	REE, Be, Nb, F	B, Be, REE, Nb, Ti, Li, Ca
<i>DPA</i>			
Petrogenetic type – mineralogical group	DPA – group 1	DPA – group 2	DPA – group 3
Typical source rock	Granulite to amphibolite facies metasediments and metaigneous rocks of granitic S-type signature	Granulite to amphibolite facies F-rich amphibolites and metaigneous rocks of granitic A-type signature	Granulite to amphibolite facies metagreywackes and metaigneous Al-rich rocks
Relation of pegmatites to source	Segregations of anatectic melts	Segregations of anatectic melts	Segregations of anatectic melts
Typical geochemical signatures	Be, Nb, Ta, P, Li	REE, U, Be	Al, Be, B

According to Wise *et al.* (2022).

Pegmatite crystallization and the formation and utilization of geochemical halos around pegmatites

The development of chemical halos around pegmatites in adjacent country rocks is a well-known phenomenon but has received little attention, with few published studies of halo geochemistry in particular (e.g. Trueman and Černý 1982; Shearer *et al.* 1986; Breaks 1989; Breaks and Tindle 1997; Selway *et al.* 2005). Mobile, fluxing and incompatible elements such as Li, Cs, U, Th, Ta, Sn, B and F may form halos many times larger than the pegmatite bodies themselves (Breaks and Tindle 1997). The most extensive Li anomaly associated with rare-element pegmatites identified so far has a width of 100–750 m (Pryslak 1981). Halos might in principle form at any time between magma emplacement and the final crystallization of pegmatites, or even during subsequent metamorphism. In some LCT pegmatites, crystallization evolves from a coarsely pegmatitic to a much finer-grained albitic stage. This transition is associated both with the autometamorphic destruction of spodumene, amongst other phases, and with the redistribution of Li, Ta, Nb and Sn (e.g. Kaeter *et al.* 2018, 2021), as fluids of increasing water content unmix. Whilst the Ta tenor in pegmatite minerals may be increased in this process (e.g. Kaeter *et al.* 2018, 2021), Li is either incorporated into micas and/or lost from the pegmatite. Lithium, Ta, Nb and Sn are enriched in LCT pegmatite halos (Barros *et al.* 2020) and halo formation through the release of hydrothermal fluid into wall rocks may be the trigger for the transition to finer-grained, albitic crystallization within pegmatites.

With advances in technology, such halos, and those which are considerably smaller (<2 m width), can often be identified using geochemical, mineralogical and geophysical methods, including remote sensing techniques. At prospect scale, bulk whole-rock analysis of metasomatically altered host rocks surrounding pegmatites is one possible exploration tool for finding hidden or blind pegmatites (Černý 1989). Portable X-ray fluorescence analysis may also play a role, although this method is limited by relatively high detection limits and the inability to detect lithium. Portable laser-induced breakdown spectroscopy is a more promising technique for the study of LCT pegmatites because it can detect lithium on both ground rock and individual centimetre-scale crystals, albeit with significant data-normalization challenges (e.g. Guezencoc *et al.* 2019), and portable gamma ray detectors show promise for the detection of Th-rich halos around NYF pegmatites. There may also be a place for portable X-ray diffraction to determine mineralogy where fines are produced during mining or

exploration drilling (Uvarova *et al.* 2016). Figure 4 illustrates possible scenarios of halo development with respect to pegmatite type (LCT and NYF) and the shape of pegmatite bodies. Factors controlling the extent of geochemical halos are the amount and type of fluxes emanating from the crystallizing pegmatite and the porosity and permeability of the host rock. Where rocks potentially hosting pegmatites are exposed, GREENPEG will establish district-scale (<25 km²) geochemical sampling procedures and drone-borne hyperspectral methods to identify metasomatic halos of hidden pegmatite bodies.

The technological approach of GREENPEG

Exploration for buried pegmatites, both concealed by overburden and occurring at depth, presents a major exploration challenge and there has been an extremely low discovery rate for pegmatite ores. The general failure of conventional exploration methods is due to the nature of pegmatite ore bodies, which are relatively small, their indistinct geophysical responses, and our relatively poor understanding of petrophysical and chemical–mineralogical properties, including the complex textural, mineralogical and chemical variability of pegmatites and their country rock halos. Wall rock lithogeochemical (Trueman and Černý 1982; Černý 1989; Galeschuk and Vanstone 2007) and soil and stream-sediment geochemical exploration have only led to a few surface discoveries (Selway *et al.* 2005; Galeschuk and Vanstone 2007) and globally have had relatively low success, perhaps because they have not been combined with geophysical surveys. Although it is commonly recognized that only an integrated approach can provide exploration success, cost-efficient toolsets specifically tailored for pegmatite ore exploration currently do not exist.

In addition, there have been few European initiatives to develop exploration tools optimized for pegmatite deposits. This is mainly because pegmatite exploration, over the last few decades, has not been attractive for commercial investment owing to an allegedly poor cost–benefit ratio. This is surprising since pegmatite-type deposits are common and may be highly prospective in Europe, in particular in Norway, Austria, Ireland, France, Sweden, Finland, Portugal and Spain, and there is huge potential to find more, particularly concealed deposits. Owing to the sudden increase in demand for Li for battery production, there is a significant drive for European small and medium-scale enterprises to explore for more domestic Li resources. Addressing this, however, will require optimized exploration tools, new and enhanced skills and dedicated methods and devices. In addition, European databases for pegmatite-type deposits are long out of date. GREENPEG will

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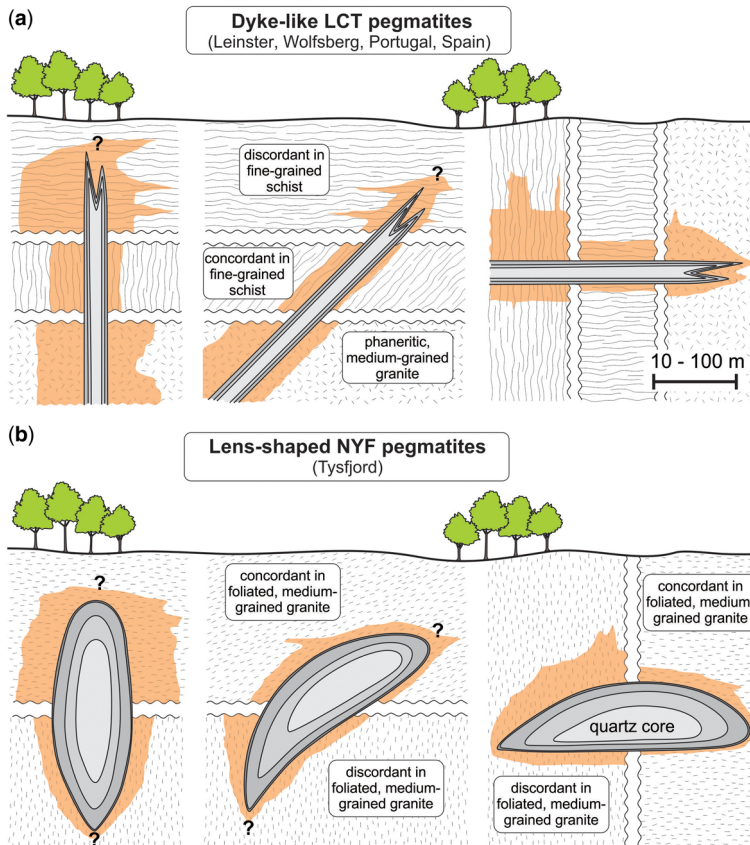


Fig. 4. Different types of chemical halos surrounding dyke-like (a) and lens-shaped (b) pegmatites depending on the nature of the host rocks (granite and/or schist). The foliation strike relative to the strike of the pegmatite body might have also an effect on the extension of the halo as illustrated.

remedy the lack of tools for pegmatite exploration by developing cost- and time-effective toolsets which combine frontier acquisition technologies like high-resolution data from satellites, helicopters and drones, automatic big data analysis using artificial intelligence and machine learning algorithms, and conventional geophysical and geochemical techniques.

To enhance the use of remote sensing in pegmatite exploration, new combinations of image processing techniques will be applied to different satellite image types (Landsat, ASTER and Sentinel-2) to automatically identify areas with potential for economic pegmatite bodies (Cardoso-Fernandes *et al.* 2019). These new methods will be tailored to LCT and NYF pegmatites and their ores and to the different settings (i.e. wall rocks, vegetation, topography) of European pegmatites, to increase exploration success. The traditional classification methods applied to satellite images are red–green–blue combinations, band ratios and principal component analysis (e.g.

Cardoso-Fernandes *et al.* 2019). The major limitations of this approach are dense vegetation and snow coverage in Arctic regions. Therefore, additional image processing steps, such as machine learning image classification algorithms (random forests and support vector machines; Noi and Kappas 2017) will be applied to Landsat-8 and Sentinel-2 satellite images to overcome these limitations. First tests have revealed that when comparing traditional band ratios of the bands 4/12 method and the new support vector machine algorithm, both applied to Sentinel-2 images, the support vector machine learning much more successfully identifies pegmatite bodies (Teodoro *et al.* 2021; Fig. 5).

The geophysical–geochemical method combinations (toolsets) include three new instrumental demonstrations (piezoelectric spectrometer, helicopter-complementary nose stinger magnetometer and drone-borne hyperspectral–magnetometric–radiometric system) and two new datasets (petrophysical

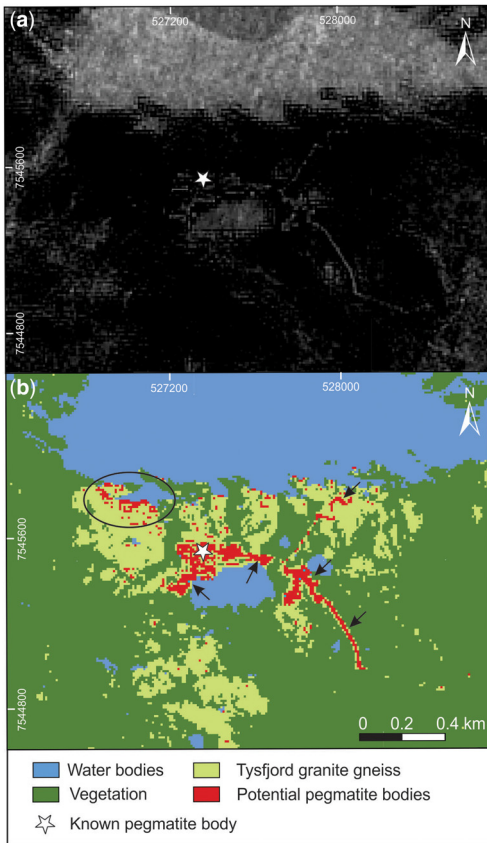


Fig. 5. Comparison between the conventional band ratio 4/12 method (a) and the support vector machine learning (SVM) algorithm (b) applied to Sentinel 2 images established for the Håkonhals area on the Finnøy island in Tysfjord, northern Norway. In (b) a new potential pegmatite (black circle) has been identified, as well as pegmatite mine dumps and roads paved with pegmatite gravel (black arrows). The applied projection is UTM/33N WGS84.

and hyperspectral properties of pegmatite ores). The piezoelectric spectrometer design developed by GREENPEG is an integrated part of its toolsets for rapid and efficient detection of buried pegmatite ore bodies. The instrument demonstration is based on a concept developed and successfully deployed in the former Soviet Union and Canada to explore for gold-bearing quartz veins and pegmatites (Sobolev *et al.* 1984; Maxwell *et al.* 1992; Neishtadt *et al.* 2006; Neishtadt and Eppelbaum 2012). It utilizes the strongly piezoelectric nature of pegmatites (specifically quartz) in exploration. This method has, however, for various reasons, never been commonly used in exploration, although this low-cost piezoelectric spectrometry is the only method that directly

accesses a specific petrophysical characteristic of most pegmatites. The integration of a drone-borne hyperspectral–magnetometric–radiometric system will allow efficient detection of hidden decametre-scale pegmatite ore bodies, which will close the gap between airborne and ground measurements. The demonstration deployment of the first European nose stinger magnetometer will allow lower altitude airborne surveys (down to about 50 m above ground), with low flight line distance, to acquire high-resolution data in areas of strong topography and vegetation, such as in certain areas of the Alps and Scandinavia (Wolfsberg and Tysfjord demonstration sites, respectively). This new system will increase safety as it replaces the existing magnetic bird system hanging 30 m below the helicopter (Geotech 1997), which is difficult to fly in mountainous areas, and it also brings the instruments closer to the ground to produce higher resolution datasets.

These tools help to identify buried (up to 100 m depth), small (0.01–5 million m³/0.025–12.5 million tonnes) and clustered pegmatite ore bodies more effectively and are designed to be easily deployable by small and medium-sized enterprises to explore for buried LCT and NYF pegmatites. The development of the integrated toolsets is based on the new genetic model developed by GREENPEG partners, which is valid for the majority of European pegmatite-type ore deposits introduced above. The second foundation of toolset development is the new multilevel approach: province scale (500–10 000 km²), district scale (25–500 km²) and prospect scale (<25 km²) (Fig. 6). Each scale approach combines several technological innovations to produce integrated solutions. The starting method combinations of each scale are given in Table 4. Methods or method combinations that do not lead to efficient pegmatite detection during testing will be removed from the list. The methods listed in Table 4 are not efficient individually for discovering pegmatite deposits, but are likely to be successful if combined appropriately. Each combination requires adjustments, optimization and extensive testing to Technical Readiness Level 7 in the three European demonstration sites, for integration into the toolsets and commercialization.

GREENPEG will develop and validate the new exploration toolsets during six test campaigns in three active and representative European demonstration sites, leased by GREENPEG partners for LCT and NYF pegmatite exploration: Wolfsberg, Austria; South Leinster, Ireland; and Tysfjord, Norway (Table 5). These sites present a wide spectrum of challenges in exploration for European pegmatite deposits, such as variable wall rocks (Leinster), dense vegetation and long winter snow cover (Norway), extreme (alpine) topography (Wolfsberg), thick soil cover (Leinster), tills and glacial sediments

GREENPEG – exploration to feed the energy transition

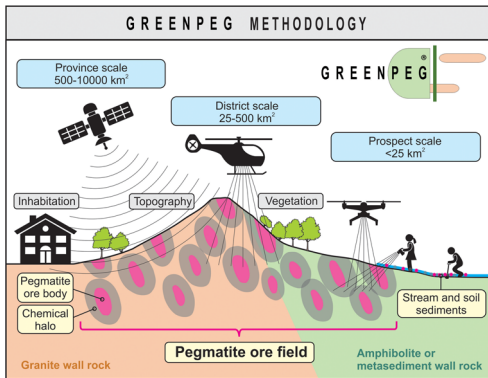


Fig. 6. Schematic sketch of exploration methodologies for buried, small-scale pegmatite ore bodies at province, district and prospect scale. The choice of exploration methods depends on the type of wall rocks, vegetation and topography.

hampering conventional soil geochemistry-based exploration (Norway) – features that will ensure that the delivered toolsets are robust and flexible enough to be applicable in manifold environments. The Tysfjord and Wolfsberg sites are connected to operating processing plants (European Lithium 2018; The Quartz Corp 2018) that require a sustainable supply of European ore. Without this, they will incur a larger CO₂ footprint related to the import of large masses of non-European ores over long distances (e.g. the high-purity silica plant in Tysfjord is currently short of domestic resources and therefore uses pegmatite ores from North Carolina, USA). There are more European countries hosting LCT pegmatites with economic potential (Spain, Portugal and Finland), which are very similar to the Irish and Austrian fields. To keep within a practicable project budget and duration, they have not been chosen as demonstration sites, but will be considered as prospective areas for the testing of some aspects of the toolsets at different stages of the project.

The wealth of geophysical and geochemical data obtained (Table 4) will be translated by the GREENPEG partners into practicable geological information, including pegmatite fertility maps and 3D ore body models. The GREENPEG choice of geophysical and geochemical methods is based on a well-designed strategy depending on the specific characteristics of the pegmatite ores:

- (1) low contrast of petrophysical properties compared with their wall rocks;
- (2) high mineralogical variability within and between different pegmatite types;
- (3) specific magnetic properties (Table 6) and radioactivity of pegmatite-forming minerals;

- (4) relatively small ore body volumes (0.01–5 million m³/0.025–12.5 million tonnes) and lateral extent;
- (5) the occurrence of pegmatites in clusters (fields); and
- (6) the existence of lithochemical halos of Li, Cs and Th, U (B, F, Rb, Ta and Sn) at a scale of 1–50+ m around pegmatite bodies.

Province scale (500–10 000 km²) methodologies

The province-scale (500–10 000 km²) methodologies comprise the processing of accessible Landsat-8, Sentinel-2 and ASTER satellite images by applying new red–green–blue combinations, band ratios and subsets for principal component analysis, satellite radar images (Sentinel-1) and airborne LiDAR (light detection and ranging) data for topographic mapping of province-scale tectonic structures (faults), which potentially controlled pegmatite emplacement at the three demonstration sites (Table 4). For comparison, prospective areas will also be evaluated in northern Portugal (based on previous experiences and results of the PROSPEG remote sensing project; Sinergeo 2015), west Spain and central Finland. Data evaluation also includes reassessment of existing province-scale radiometry, magnetometry and electromagnetic remote sensing data.

The image processing involves the differentiation of spectral signatures of pegmatites and their chemical halos from those of host rocks, using machine learning algorithms (random forest and support vector machine) and a spatial resolution (for anomaly identification) of 10–15 m (Cardoso-Fernandes *et al.* 2019, 2020b). The lineament extraction from radar images will be performed manually after applying directional filtering to the images and automatically using geomatic techniques (Adiri *et al.* 2017; Boutrame *et al.* 2019; Javhar *et al.* 2019). To calibrate and validate the results obtained with satellite data, a spectral library for pegmatite minerals from the three demonstration sites will be established. The satellite image-based pegmatite mapping aims to define target areas for further district- and prospect-scale exploration.

District scale (25–500 km²) methodologies

Most European countries, including the three countries hosting the demonstration sites, have only regional airborne geophysical coverage (typically 250–1000 m flight line spacing), which is insufficient for pegmatite exploration. The GREENPEG district-scale (25–500 km²) methodology includes airborne high-resolution gamma-ray radiometry, magnetometry and electromagnetics

Table 4. Exploration techniques to be tested by GREENPEG for identification of LCT and NYF pegmatites in the three demonstration sites

Scale of methodology	Exploration method	Method principle	Utilized pegmatite/wall rock properties	Specified conditions for pegmatite exploration	Advantages and disadvantages for pegmatite exploration	Main aim	References
Province scale (500–10 000 km ²)	Discrimination of spectral signatures from satellite images	Processing of Landsat-8, Sentinel-2 and ASTER satellite images through red–green–blue combinations, band ratios, principal component analysis and machine learning algorithms	Contrasts in spectral reflection of minerals, rocks and soils	Discrimination of spectral signatures of pegmatites and their chemical halos from those of host rocks to automatically identify pegmatite bodies >10 m	Disadvantages: small size of pegmatites, dense vegetation in central and northern Europe and snow coverage in Arctic regions	Province-scale localization of pegmatites and/or their geochemical halos	Cardoso-Fernandes <i>et al.</i> (2019, 2020a, b, 2021a, b), Noi and Kappas (2017)
	Radar image processing	Combination of different illumination directions using Sentinel-1 radar image sets to detect physiographic expressions of different dimensions	Topography of structures related to pegmatite formation	Identification of large-scale faults and shear zones where pegmatite emplacement was controlled by faults (Wolfsberg, Leinster). The lineament extraction is to be performed either manually after applying directional filtering to the images or automatically using geomatic techniques	Disadvantage: fault systems related to pegmatite melt emplacement have to be discriminated from other structures. Manual correction of automatically extracted lineaments	Province-scale identification of the fault systems which are related to pegmatite melt emplacement	Adiri <i>et al.</i> (2017), Boutrame <i>et al.</i> (2019), Javhar <i>et al.</i> (2019)
	Airborne LiDAR (light detection and ranging)	Time-resolved surface laser scanning utilizing time differences of the reflected light to map structures in 3D on the Earth's surface	Topography of structures related to pegmatite formation	Identification of large- to small-scale faults and shear zones where pegmatite emplacement was controlled by faults (Wolfsberg, Leinster) or morphological pegmatite ridges formed by glacial abrasion (Tysfjord)	Disadvantage: LiDAR data are only available for Norway and northern Portugal	Province-scale identification of the fault systems and morphological features which are related to pegmatite formation	Grebby <i>et al.</i> (2010), Johnson <i>et al.</i> (2015), Scheiber <i>et al.</i> (2015), Putkinen <i>et al.</i> (2017)
District scale (25–500 km ²)	Helicopter-borne high-resolution radiometry	Use of contrasts in gamma-ray emissions (U, Th, K) among different rock units and structures	Concentration of U, Th and K	Efficient to identify U-, Th- and K-enriched pegmatites less than 0.5 m below ground surface. The principal advantage of radiometrics is its ability to map different types of silica-rich rocks, allowing pegmatites to be distinguished from granites and silica-rich metasediments	Advantage: NYF pegmatites are commonly enriched in U-, Th- and K-bearing minerals compared with wall rocks Disadvantage: Low penetration depth of the method (<0.5 m, Fig. 7)	District-scale localization of pegmatites and/or their geochemical halos	Nasuti <i>et al.</i> (2015), Thomas <i>et al.</i> (2016)
	Helicopter-borne high-resolution magnetometry	Use of contrasts in the strength of magnetism among different rocks to outline the extension of geological units and structures	Magnetism (Table 5)	Pegmatites of the NYF type may contain magnetic minerals such as magnetite, biotite and allanite–(Ce), which allow the detection of buried pegmatites embedded in low-magnetic host rocks. As aerial magnetometer surveys are relatively low cost, they are particularly attractive in the early stages of exploration, when large areas need to be assessed rapidly	Advantage: method penetration depth of several tens of metres allowing identification of hidden ore bodies and structures independent of soil and vegetation cover. Disadvantage: pegmatites are commonly poor in magnetic minerals or magnetic minerals are heterogeneously distributed within pegmatite bodies	District-scale localization of pegmatites, lithological and structural mapping	Nasuti <i>et al.</i> (2015), Thomas <i>et al.</i> (2016)

	Helicopter-borne high-resolution electromagnetics	Response of the ground to the propagation of electromagnetic fields composed of an alternating electric intensity and magnetizing force	Electric conductivity	High-resolution electromagnetic surveys, in a favourable setting, can aid in producing 3D maps of buried pegmatite bodies down to a depth of several hundred metres and can be used to map tectonic structures with deep, clay-mineral-rich weathering	Advantage: penetration depth of several tens of metres allowing identification of buried ore bodies (Fig. 7)	District-scale localization of pegmatites and/or their geochemical halos and three-dimensional maps of buried pegmatite bodies	Thomas <i>et al.</i> (2016)
Prospect scale (<25 km ²)	Drone-borne hyperspectral imaging	Identification of rocks and minerals using spectral reflectance of minerals to determine their composition and to map their surface spatial distribution	Spectral reflection	Geochemical halos caused by Li, Cs, Th, U (B, F, Rb, Ta, Sn) around pegmatite bodies may provide subsurface information for buried bodies up to a depth of 25 m. GREENPEG, therefore, focuses on the spectral properties of soils and vegetation covering pegmatite bodies	Disadvantage: drone flying in forests with high trees (>10 m) might not be feasible	Prospect-scale localization of pegmatites and/or their geochemical halos	Jakob <i>et al.</i> (2017), Heincke <i>et al.</i> (2019), Jackisch <i>et al.</i> (2019)
	Drone-borne and ground-based magnetometry	Use of contrasts in the strength of magnetism among different rocks to outline the extension of geological units	Magnetism	Drone-borne and ground-based magnetometer allow modelling of magnetized buried ore bodies with higher precision than helicopter-borne magnetometry	Advantage: penetration depth of several tens of metres allowing identification of hidden ore bodies and structures. Disadvantage: pegmatites are commonly poor in magnetic minerals	Prospect-scale localization and 3D modelling of buried pegmatites	Malehmir <i>et al.</i> (2017), Heincke <i>et al.</i> (2019), Jackisch <i>et al.</i> (2019)
	Drone-borne and ground-based radiometry	Use of differences in gamma-ray emissions among different rock units	Concentration of U, Th, Cs and K	Airborne radiometric measurements are believed to be one of the most effective geophysical methods to detect near-surface pegmatites (<0.5 m depth) owing to their specific mineral content, some pegmatites, in particular those of the NYF type, and their halos are more radioactive than their host rocks. Differences between pegmatites, halos and host rocks are expected to be less distinct for LCT pegmatites, but may be nevertheless be detectable	Advantage: NYF pegmatites are commonly enriched in radioactive isotopes compared with wall rocks Disadvantage: low penetration depth (<0.5 m). However, where pegmatites form radioactive halos at decameter scale, pegmatites at 10–20 m depth may be detectable	Prospect-scale localization of pegmatites and/or their geochemical halos	Hoover <i>et al.</i> (1992)
	Ground-based piezoelectric spectrometry	Measurement of the piezoelectric effect triggered by mechanical impacts (hits)	Electric polarization of piezoelectric minerals such as quartz	High-resolution piezoelectric method utilizes the electric polarization of quartz. This method has excellent potential for detecting hidden quartz-rich pegmatites but has not yet been applied in pegmatite ore exploration	Advantage: penetration depth of several ten of metres allowing identification of hidden ore bodies (Fig. 7)	Prospect-scale localization and 3D modelling of buried pegmatites	Neisstadt <i>et al.</i> (2006)

(Continued)

Table 4. *Continued.*

Scale of methodology	Exploration method	Method principle	Utilized pegmatite/wall rock properties	Specified conditions for pegmatite exploration	Advantages and disadvantages for pegmatite exploration	Main aim	References
	Ground-based ground-penetrating radar	Uses conductivity contrasts among rock units to identify and model hidden low-conductivity bodies	Conductivity	Pegmatites have high silica contents and low conductivities and are thus ideal for ground-penetrating radar pulse depth penetration	Advantage: buried pegmatites with low conductivities may be detectable up to 100 m depth (Fig. 7). Disadvantage: small, relatively conductive layers can seriously impair the depth of penetration	Prospect-scale localization and 3D modelling of buried pegmatites	Francke and Utsi (2009)
	Ground-based high-resolution gravimetry	Uses the density contrast among rock units to identify and model hidden ore bodies	Density	The method allows the modelling of the 3D outline of pegmatite bodies. The challenge is the generally low-density contrast between pegmatites (c. 2.65 g cm ⁻³) and their host rock, commonly amphibolite (c. 2.8–3.1 g cm ⁻³), schist (2.7–3.2 g cm ⁻³) or granite (c. 2.6–2.8 g cm ⁻³)	Advantage: penetration depth of several hundreds of metres, allowing identification of hidden ore bodies (Fig. 7). Low operation costs. Disadvantage: depth of penetration and resolution depends on the density contrast	Prospect-scale localization and 3D modelling of buried pegmatites	Yarosh (1964)
	Ground-based two-dimensional resistivity and induced polarization	Uses contrasts in the resistivity and the chargeability of different rock types	Resistivity and chargeability	Pegmatites display the high-resistivity values. Once processed, the data provide 2D sections visualizing contacts between buried pegmatites and host rocks and associated structures	Advantage: penetration depth of several tens of metres, allowing the identification of hidden ore bodies	Prospect-scale localization and 3D modelling of buried pegmatites	
	Ground-based soil Ah and C-horizon mapping	Use of chemistry of Ah and C-horizon soil samples collected in transects across pegmatites and their potential geochemical halos (25–100 m sample spacing)	Chemistry of soils covering pegmatites	Soil samples are analysed by four-acid ICP–OES and ICP–MS. A subset of samples is analysed following metaborate fusion, to test the extent to which this releases more Ta, Nb, Zr and other high field strength elements from minerals resistant to four-acid digestion. A subset of samples is also subject to mobile metal ion analysis, to examine whether more soluble elements (Li, Cs) are taken up into the soil profile in groundwater solutions rising from weathered bedrock. Soil analysis will examine the extent to which bedrock signals are present in till-derived soils in glaciated terrains as well as in non-glacial soils	Disadvantage: approximate location of soil-covered pegmatites has to be known. Till-derived soils may bear inherited signals from the parental ice area (Tysfjord)	Prospect-scale localization of soil-covered pegmatites	Dimmell and Morgan (2005), Galeschuk and Vanstone (2007), Steiner (2019)

Ground-based stream sediment mapping	Use of the chemistry of pathfinder minerals in stream sediments to classify the ore potential and locate parental pegmatites	Chemistry of pegmatite pathfinder minerals	Pathfinder minerals (columbite group minerals, tourmaline, garnet, micas) are characterized texturally and chemically by SEM mineral liberation analysis, QEMSCAN [®] analysis, EPMA and LA-ICP-MS to relate grains to fertile or barren pegmatite sources. The stream sediment datasets will be utilized for catchment basin analysis to locate buried pegmatite bodies and to better target economically attractive parts of pegmatite fields	Disadvantage: catchment areas of sampled streams have to be available within pegmatite fields, which is not the case for the Tysfjord demonstration site	Prospect-scale localization of pegmatites	Carranza (2008), Kaeter <i>et al.</i> (2018, 2021)
Ground-based (outcrop and drill core) lithochemical Li, Cs, Th and U (B, F, Rb, Ta and Sn), gamma ray scintillometer and portable laser-induced breakdown spectroscopy wall rock halo mapping	Use of whole rock and portable analytical methods to determine the lateral extension of lithochemical halos surrounding pegmatites	Geochemistry	Lithochemical Li, Cs, Th, U (B, F, Rb, Ta, Sn) wall rock halo mapping utilizes the special behaviour of pegmatite melt that fluxing and other elements may escape during pegmatite crystallization and be trapped in adjacent wall rocks by the process of metasomatism, forming geochemical halos. Wall rock sample profiling is performed using a handheld portable X-ray fluorescence spectrometer, scintillometer and portable laser-induced breakdown spectroscopy for field and borehole measurements and with higher precision and lower detection limits, laboratory ICP-ES, ICP-MS and ion chromatography bulk rock analysis. Mapping of the dispersion of these fluxing elements in the metasomatic halos around pegmatites has been used as an exploration tool to define anomalies of hidden pegmatites	Advantage: geochemical halos may extend up 50 m into the wall rock (Fig. 7), which may allow identification of pegmatite bodies by remote sensing or helicopter-borne geophysics. Disadvantage: for sampling, pegmatites have to be exposed at the surface or intersected by drill holes	Establishment of halo distance algorithms for Li, Cs, Th and U (B, F, Rb, Ta and Sn) in relation to pegmatite size (Fig. 7) for the prospect-scale localization of buried pegmatites	Galeschuk and Vanstone (2007), Barros <i>et al.</i> (2016).
Ground-based (outcrop and drill core) Al-, Ti-, Ge- and Li-in-quartz mapping	Use of the Al, Ti, Ge and Li content of pegmatite-forming quartz to establish chemical zoning of pegmatite fields and vector into areas of highest ore potential	Geochemistry of quartz	The prospect-scale distribution of Al, Ti, Ge and Li content of pegmatite-forming quartz, determined by LA-ICP-MS, establishes the regional (<25 km ²) chemical zoning of pegmatite fields and utilizes quartz as pathfinder to locate pegmatites of economic potential. The abundance of Al, Ti, Ge and Li in quartz indicates the silica quality and the fractionation degree of pegmatites and, thus, the potential for Li and high-purity silica mineralization	Advantages: up to 100 quartz LA-ICP-MS analyses can be performed in one day after the procedure is set up. Disadvantage: for sampling pegmatites have to be exposed at the surface or hit by drill holes	Establishment of 2D Al-, Ti-, Ge- and Li-in-quartz distribution for the prospect-scale localization of mineralized pegmatites	Flem and Müller (2012), Müller <i>et al.</i> (2015, 2021)
Borehole: magnetic susceptibility	Use of contrasts in magnetic susceptibility among different rock units	Magnetic susceptibility	Determination of the contrasts in magnetic susceptibility between pegmatite and host rocks (including the lithochemical halo) <i>in situ</i> for refinement of airborne-obtained magnetometry data	Advantage: large datasets are collected within short time and at low costs. Disadvantage: drill holes have to be available	Refinement of geophysical methodology by gaining physical properties	

(Continued)

Table 4. *Continued.*

Scale of methodology	Exploration method	Method principle	Utilized pegmatite/wall rock properties	Specified conditions for pegmatite exploration	Advantages and disadvantages for pegmatite exploration	Main aim	References
	Borehole: spectral gamma-ray including total count gamma	Use of contrasts in gamma-ray emissions (U, Th, K) among different rock units	Concentrations of U, Th and K	<i>In situ</i> determination of the contrasts in gamma radiation between pegmatite and host rocks (including the lithochemical halo) for refinement of airborne-obtained radiometry data	Advantage: large datasets are collected within short time periods and at low cost. Disadvantage: drill holes have to be available	Refinement of geophysical methodology by gaining physical properties	
	Borehole: resistivity	Uses contrasts in the resistivity and the chargeability of different rock types	Resistivity	<i>In situ</i> determination of the contrasts in resistivity and the chargeability between pegmatite and host rocks (including the lithochemical halo for refinement of airborne-obtained data	Advantage: large datasets are collected within short time and at low costs. Disadvantage: drill holes have to be available	Refinement of geophysical methodology	
	Borehole full wave form sonic	Uses contrasts in the wave velocity to map inhomogeneities in the rocks	P, S wave velocity	<i>In situ</i> determination of the wave velocity of pegmatites and host rocks including the lithochemical halo	Advantage: large datasets are collected within short time and at low costs. Disadvantage: drill holes have to be available	Refinement of geophysical methodology by gaining physical properties	
	Borehole optic and acoustic scanners	Optic and / or acoustic hardness contrast	Oriented image of the borehole wall	<i>In situ</i> determination of the optic and acoustic properties of pegmatites and host rocks including the lithochemical halo	Advantage: large datasets are collected within short time and at low costs. Disadvantage: drill holes have to be available	Detailed structural analysis, measurement of the true thickness of pegmatites	
Establishment of databases	Database of petrophysical properties of pegmatites and wall rocks	Laboratory-measured petrophysical properties of rocks and minerals for refinement of geophysical data obtained in the field	Petrophysical properties	Petrophysical properties (density, magnetic susceptibility, remanent magnetization, pore volume) are obtained from hand specimens and existing drill core samples to establish a petrophysical database of pegmatite ores and their wall rocks. These data link geological, geochemical and geophysical field data to the development of ore body models	–	Refinement of geophysical methodology in respect to petrophysical properties of pegmatites and their host rocks	Bär <i>et al.</i> (2020)
	Reflectance spectra library of minerals, rocks and soils	Laboratory-measured	Spectral reflectance of geological material	Establishment of a reflectance spectra library of minerals, rocks and soils with an ASD FieldSpec 4 spectroradiometer. The library is used for calibration of satellite image processing and drone-borne hyperspectrometry results. Obtained spectra are compared with spectra of existing spectral libraries of the United States Geological Survey and ECOSystem Spaceborne Thermal Radiometer Experiment on the Space Station	–	Adjustment of satellite image and hyperspectral data interpretation to locate pegmatites	Kokaly <i>et al.</i> (2017), Meerdink <i>et al.</i> (2019), Cardoso-Fernandes <i>et al.</i> (2021b)

After testing, the best method combinations will be brought together to create toolsets applicable by small and medium-sized enterprises for the exploration of European pegmatite deposits. 2D, Two-dimensional; 3D, three-dimensional; LA–ICP–MS, laser ablation inductively coupled plasma mass spectrometer; SEM, scanning electron microscope; ICP–OES, inductively coupled plasma atomic emission spectroscopy.

Table 5. Characteristics of GREENPEG demonstration sites in Europe

Pegmatite field	Pegmatite type	Wall rock	Size of field (km ²)	Number of known pegmatite bodies	Potential economic commodities	Mining history	GREENPEG partner in charge	Resources (Mt)	Vegetation/topography
Wolfsberg, Austria	LCT	Amphibolite mica schist	25	14	Li, Fs and HPS (Ta and Cs)	Exploration brownfield: test mining for Li in 2018	ECM (exploration owner)	Indicated: 6.3 at 1.17% Li ₂ O	Alpine forest/mountainous
South Leinster, Ireland	LCT	Meta-sediment/granite	70	18	Li, Fs and HPS (Ta and Cs)	Exploration greenfield	BLI (site explorer)	Inferred: 0.6 at 1.5% Li ₂ O	Grassland and forest/hilly
Tysfjord, Norway	NYF	Granite	20	22	HPS and Fs (Be and REE)	Exploration brownfield: HPS: From 1996; Fs: 1906–1960	NGU (site explorer)	Indicated: 0.4 at 100% HPS, 0.2 at 100% Fs	Open forest and fields/mountainous

Cs, Caesium; Fs, feldspar; HPS, high-purity silica; Li, lithium; Ta, tantalum.

Table 6. List of magnetic minerals found in pegmatites

Strongly magnetic minerals (ferromagnetic)	Moderate magnetic minerals (paramagnetic)	Weakly magnetic minerals (paramagnetic)
Magnetite	Biotite	Allanite-(Ce)
Pyrrhotite (monoclinic)	Aeschnite-(Y)	Gadolinite-(Y)
Titanomagnetite	Columbite group minerals	Spessartine
	Fergusonite-(Y)	Monazite-(Ce)
	Almandine	Pyrrhotite (hexagonal)
	Samarskite-(Y)	Xenotime-(Y)
	Ilmenite	Pyrochlore group minerals
	Black tourmaline	Titanite
		Coloured tourmaline

After Petrovskaya (2016).

with a flight-line separation of 30–50 m and an elevation of 30–50 m above ground, adapted to the small size of pegmatite ore bodies and clusters. The surveys cover 20–70 km² of each demonstration site, depending on the size of the targeted pegmatite cluster. In addition, existing geophysical data, including (1) national resource databases held by geological surveys and (2) archives of airborne geophysics (U–Th–K gamma-ray spectrometry, magnetics), will be gathered and reassessed.

Prospect-scale (<25 km²) methodologies

For prospect-scale exploration (<25 km²), combinations of an instrumental heavy-duty drone, a magnetometer, gamma-ray and hyperspectral spectrometers and a ground-based piezoelectric spectrometer are being developed and tested (Table 4). Stream and soil sediment sampling and analysis, whole-rock lithochemical Li, Cs, Th and U (B, F, Rb, Ta and Sn), portable X-ray fluorescence, portable laser-induced breakdown spectroscopy and scintillometer wall rock halo mapping, and trace-elements (Li, Al, Ti, Ge) in-quartz mapping will allow vectoring to areas with the highest ore potential and quality. Together with surveys of ground-based ground-penetrating radar, high-resolution gravimetry and two-dimensional resistivity/induced polarization integrated modelling, this will deliver high-resolution three-dimensional maps of pegmatite ore bodies at a depth of up to 100 m.

GREENPEG will deliver improved algorithms based on an extended dataset for the penetration depth of different geophysical and geochemical methods in relation to ore body size and physical contrast. Figure 7 illustrates the current knowledge on the predicted depth of penetration of a variety of GREENPEG applied methods for hidden pegmatite ore bodies (Yarosh 1964; Trueman and Černý 1982; Selway *et al.* 2005; Neishtadt *et al.* 2006; Galeschuk and Vanstone 2007). The dataset is,

however, very limited. This illustration will be refined in the course of the project and adjusted to different types of pegmatites (LCT and NYF).

Borehole geophysics using existing boreholes is being applied to obtain physical rock properties such as magnetic susceptibility, electric resistivity and chargeability, natural gamma-ray, spectral gamma-ray and P and S wave velocities to refine results of airborne geophysics. Petrophysical data, including measurements of rock density, magnetic susceptibility, remanent magnetization and pore volume, will be obtained from hand specimens and drill core samples from the three demonstration sites. From the petrophysical results and borehole geophysics, a European petrophysical database of pegmatite ores and their wall rocks will be established. These data will provide a link between geological, geochemical and geophysical data in the integrated interpretation and development of ore body models.

In addition, GREENPEG will gather and reassess existing geochemical (soil and stream sediment chemistry), geophysical and geological (surface distribution of European pegmatites) data, for example, information from the Geological Survey of Norway (NGU 2017), Tellus (2017), Laboratório Nacional de Energia e Geologia (Pires 1995), Instituto Geológico y Minero de España (IGME 2017), Sociedad de Investigación y Explotación Minera de Castilla y León (SIEMCALSA 2017), Sistema de Información Geológico Minero de Extremadura (SIGEO 2017) and Dirección General de Energía y Minas from Xunta de Galicia (DGEM 2017). Existing and new data will be gathered and compiled in GIS format files and shared publicly through the open-access data repository Zenodo developed under the European OpenAIRE programme (Zenodo 2021).

Contribution to responsible exploration

Responsible exploration, like responsible mining (Goodland 2012; Bice 2016; Mudd 2020),

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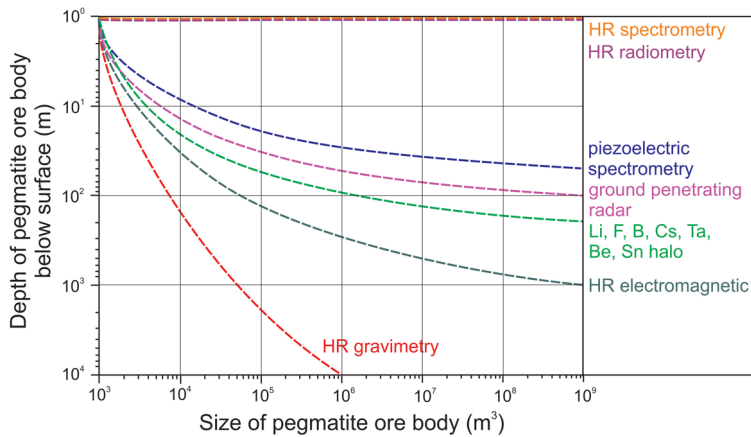


Fig. 7. Predicted penetration depth of various geophysical and geochemical methods in relation to the size of buried pegmatite ore bodies, based on a very limited dataset (Yarosh 1964; Trueman and Černý 1982; Selway *et al.* 2005; Neishtadt *et al.* 2006; Galeschuk and Vanstone 2007). The penetration depth, however, applies only if the geophysical and geochemical contrast between pegmatites and wall rock is given. HR, High-resolution.

minimizes negative environmental and social impacts and seeks to maximize the positive impacts. Historically, the extractive mining industries have often had a poor reputation in this regard. Exploration, as the pathfinder for mining, has often therefore a similar reputation despite the fact that exploration activities inherently have much lower impacts.

There are already various schemes for ‘responsible exploration’. Of these, early discussions with GREENPEG partners identified the Prospectors and Developers Association of Canada scheme, e3 Plus, as a practical scheme to apply, with a number of useful toolkits (PDAC 2014). In addition, the MIREU project has developed guidelines and a toolkit to help develop and maintain social licence to operate during exploration and mining (MIREU 2021). It is clear that having good communication between exploration companies and the public is essential. Examples from GREENPEG partners and others will be assessed and reported to promulgate best practice.

Environmental screening prior to invasive exploration techniques, such as drilling, is a common regulatory requirement, and sometimes more extensive environmental impact assessments are carried out ahead of exploration, particularly for larger project areas or when recommended following initial screening – likewise, remediation of exploration sites. For example, a number of mining countries require exploration operations’ rehabilitation reports (e.g. Northern Territory Government 2016; Government of Western Australia 2022), documenting at least the rehabilitation actions being carried out (e.g. Osborne and Brearley 1999). GREENPEG will develop an additional environmental impact technique of applying life cycle assessment (LCA)

to make a quantitative assessment of environmental impacts of the exploration toolkits. Besides the direct environmental impacts on landscape and biodiversity, mineral exploration campaigns vary considerably in their use of energy and materials, and consequently in their global warming potential, pollution and other environmental and social impacts.

Typically, these impacts are lower in the early stages of exploration and rise progressively if and when the chances of exploration success increase. We expect that the use of remotely sensed data, advanced image processing techniques and ground-based sampling and measurements will have lower negative impacts than some of the processes that use fossil fuels and are common to many exploration campaigns, such as airborne geophysical surveys, drilling to acquire rock samples (e.g. diamond drilling to recover drillcore) and for down-hole surveys, and the movement of people and materials to and from an exploration area. The latter techniques could lead to significant global warming potential emissions in an exploration campaign that might be reduced by the increased use of lower impact techniques, or by modifying the way that they are used. There is potential for the GREENPEG toolsets to be favoured because of their lower environmental impacts. In addition, many of the lessons learned and ‘hotspots’ of environmental impact will be applicable to exploration for mineral resources other than those related to pegmatites.

Life cycle assessment has already proved promising when used at the exploration stage to predict the impacts of future mining (Pell *et al.* 2021), but we are not aware of any previous detailed study of the effects of the actual exploration techniques. Data are being gathered on the field activities of the

GREENPEG team as they carry out testing of exploration methods. Whilst this is not an exact analogy for commercial exploration, it is expected to reveal the main environmental impacts. The objectives are to devise ways to minimize environmental impacts in pegmatite exploration overall. By identifying the most impactful exploration activities and new techniques developed within GREENPEG, the toolkits can be optimized towards the lowest impact before the release of the exploration toolsets.

Using LCA in the exploration and development stages of mining ('forecast LCA') can help to significantly reduce the environmental impacts of the mining phase by identifying which processes can or should be modified (Shields *et al.* 2011; Villares *et al.* 2017; Farjana *et al.* 2019; Pell *et al.* 2019; Wall and Pell 2020). These processes could be the type and machinery of extraction, ore and waste transport, mineral processing, mining waste handling, etc. This approach will be extended to see if it can be used to help balance the time and effort spent on exploration v. uncertainties at the mining stage. It may be that more work (and thus impacts) at the exploration stage could help mitigate the (larger) environmental impacts at the mining stage.

As far as the public and communities are concerned, there are often local concerns that are more important to them than the quantified impacts of an LCA, and consideration will be given to this too, with interviews and social research in the GREENPEG field study areas. Exploration for Li, for example, and its possible future mining has been being highly controversial in Portugal, as in other parts of Europe. A questionnaire was conducted amongst inhabitants from two communities of Barroso-Alvão, Portugal, to document their perceptions concerning the transparency of communication by the specialists, media and mining enterprises (Ribeiro *et al.* 2021). The results revealed insufficient understanding and transparency, leading to the population's potential disapproval of exploration activities. Geoethical dilemmas were raised such as the need for reliable communication and geoscientists' role in informed consent. One of the main conclusions was that in the education on and communication of geosciences, citizens' engagement in the activities is required for developing the knowledge and acceptance of the need of natural resources (Ribeiro *et al.* 2021).

Anticipated advances in the GREENPEG project

GREENPEG will develop the first toolsets for pegmatite exploration in Europe which are based on the specific properties of the ores, e.g. low density and conductivity, in some cases elevated gamma-ray

emissions and magnetic signature, small ore body size and distinctive mineral geochemistry and diversity, depending on the nature of the pegmatite. The delivered toolsets will lower exploration costs by improving ore body targeting and reducing exploration time, and will be, as much as is currently possible, responsible and socially acceptable.

In improving certain geophysical devices, the ground-based piezoelectric spectrometry method will be re-designed and refined for pegmatite ore exploration. The low-cost, easy-to-use piezoelectric spectrometer will be an integral part of the toolsets for rapid and efficient detection of buried pegmatite ore bodies. The certified demonstration of the first European nose stinger with magnetometer constructed by GREENPEG will make it possible for small and medium-sized enterprises in Europe and abroad to fly airborne surveys, using light European helicopters to explore for small pegmatite bodies and other critical raw materials. Another advance will be the integration of a drone-borne hyperspectral-magnetometric-radiometric system, which will close the spatial resolution gap between airborne and ground data. Drones will also replace more costly airborne geophysics where possible. Drone-borne systems have the advantage of being cost-effective, easily deployable and with a short turn-around time for high-resolution data. Never before, however, have drone-borne systems been applied in geophysical exploration for pegmatite deposits. Modern drone-borne systems are now able to carry hyperspectral cameras, magnetometers and gamma-ray spectrometers (Medusa Institute 2018; Jackisch *et al.* 2019), which are ideal for the realization of GREENPEG objectives. To unlock the innovation potential of the three GREENPEG instrumental developments, the piezoelectric spectrometer, the helicopter nose stinger magnetometer and the drone-borne hyperspectral-radiometric system, an agreement among GREENPEG users will be set up to obtain a 'freedom to operate', which will allow each partner to use some of their respective patented technology.

Technological advances in laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) instrumentation are lowering operational costs and running times, and increasing the accuracy and precision of measured trace element data (e.g. Sader and Ryan 2020). New applications using this technique, developed by GREENPEG, will allow the regional mapping of trace elements in quartz and identification of geochemical pegmatite source discriminators to establish the chemical zoning of pegmatite fields and to vector in on the areas of highest ore potential. These advances and optimizations will be integrated and upscaled by GREENPEG into toolsets applicable by small as well as larger enterprises to target European pegmatite ores successfully.

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Geophysical data from the project will be integrated into two freely accessible databases and analysed to derive parameters for the detection of hidden pegmatite ores. The first will be a petrophysical database containing information about the density, magnetic susceptibility, remanent magnetization and micropore volume of pegmatite ores and their wall rocks. This will inform new geophysical exploration methods and, more specifically, provide algorithms for predicting penetration depths in relation to pegmatite size, which will result in the production of high-precision three-dimensional fertility maps for European pegmatite ores. The second will be a data library of reflectance spectra for Li-bearing and other pegmatite-related minerals that can be easily used by small and medium-sized enterprises to process satellite images for pegmatite exploration.

Conclusions and outlook

GREENPEG will unlock high-value pegmatite-bound mineral resources of rare metals and industrial minerals through the release of environmentally and socially responsible and cost-optimized exploration toolsets deployable primarily by small and medium-sized enterprises. In addition, increasing exploration success, whilst reducing worker and instrument time and costs, will make European explorers more competitive and strengthen European brands and entrepreneurship. The new toolsets developed will reduce risk in the supply of critical and green technology raw materials for manufacturing in Europe. This will safeguard the long-term competitiveness of Europe in the production of green energy and energy storage devices, reduce levels of imports and therefore transport distances, and equip European exploration companies with state-of-the-art exploration knowhow and tools to ensure that these resources are supplied to manufacturers from European deposits, and following EU regulations on environmental and societal impacts.

The valorization of relatively small European pegmatite-type deposits in time and space, by applying the GREENPEG approach of integrated exploration technologies, will – in contrast to many other, usually more complex and/or larger deposit types – minimize exploration time, costs, environmental and social impacts and speed up deposit development at reduced investment cost. This will contribute to a technically and economically realistic, and more rapid, timeline to production, exactly when the supply is needed. GREENPEG has a clear demonstration strategy based on testing the methods developed at two brownfield sites, one in Austria and the other in Norway, and a greenfield site in Ireland, which are representative of pegmatite-prospective zones in Europe.

In the wider context, by developing more environmentally and socially sensitive toolsets, GREENPEG will foster a positive perception of the European exploration industry by stakeholders, policy makers and citizens.

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Data availability All data generated or analysed during this study are included in this published article.

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