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EuroPeg_PetroDB: A petrophysical database of European pegmatite ores and wall rocks

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EuroPeg_PetroDB: A petrophysical database of European pegmatite ores and wall rocks

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Geology for society

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Summary

In the frame of the GREENPEG project NGU and terratec Geophysical Services have compiled a petrophysical database of European pegmatite ores and wall rocks from so far four different sites with different types of pegmatites in different settings.
With the aim to develop toolsets for hidden pegmatite exploration, the GREENPEG project wants to overcome the lack of exploration technologies for pegmatite ore deposits. Here, a comprehensive petrophysical database contributes with knowledge on petrophysical contrast between pegmatites and wall rocks facilitating a right choice of geophysical methodologies and a more efficient exploration.
Petrophysical measurements were therefore performed on hand specimens, drill cores and in selected boreholes at two of the three project demonstration sites Tysfjord (Norway), Wolfsberg (Austria) and Leinster (Ireland). In addition, hand specimens from a pegmatite test site in Portugal/Spain were included as well.

The measurements on specimens were carried out at the NGU petrophysical laboratory, acquiring density, susceptibility, remanence, thermal conductivity and radiometric isotopes content for U, Th and K.
Specimens represent samples from both pegmatites and wall rock to map potential contrasts in the petrophysical parameters between these two lithologies as a basis for geophysical exploration.

Within the GREENPEG project two wireline downhole geophysical logging campaigns were performed and measurements done in several boreholes at the demonstration sites Leinster and Wolfsberg. The borehole probes measured with a sample interval of 1 to 10 cm over the entire depth of the borehole and therefore provide a high-resolution in-situ data set of the rock formation.

The database is uploaded and available on the open data repository Zenodo (www.zenodo.com) under a Creative Commons Attribution 4.0 International (CC BY 4.0) license. This repository is used by the GREENPEG project to give access to data collected and acquired by the project.

Keywords

Petrophysics	Density	Susceptibility
Pegmatite	Database	Resistivity
Remanence	Wall rock	

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1. INTRODUCTION

In the frame of the GREENPEG project NGU together with TERRATEC Geophysical services has measured and compiled a petrophysical database of European pegmatite ores and wall rocks. The GREENPEG project is funded by the European Commission Horizon 2020, with the major objective to develop multi-method exploration toolsets for the identification of European, buried, small-scale (0.01-5 million m^3) pegmatite ore deposits of the Nb-Y-F (NYF) and Li-Cs-Ta (LCT) chemical types.

The targeted raw materials are Li, high-purity quartz for silica and metallic Si, ceramic feldspar, REE, Ta, Be and Cs, which are naturally concentrated in pegmatite rocks. 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. The GREENPEG project aims to 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. Validation of the new approach will be ensured from industry-led trials at locations in Austria, Ireland and Norway, while application studies will also be done in Finland, Portugal and Spain.

As an important part of these toolsets, a comprehensive understanding of petrophysical properties of different pegmatite types and adjacent wall rocks is crucial for the right choice of geophysical exploration tools, for maximizing success rate, and for economic efficiency.

The project is coordinated by the Natural History Museum of the University of Oslo and involves three exploration services/mining operators, one geological survey, three consulting companies and five academic institutions from eight European countries (Figure 1).

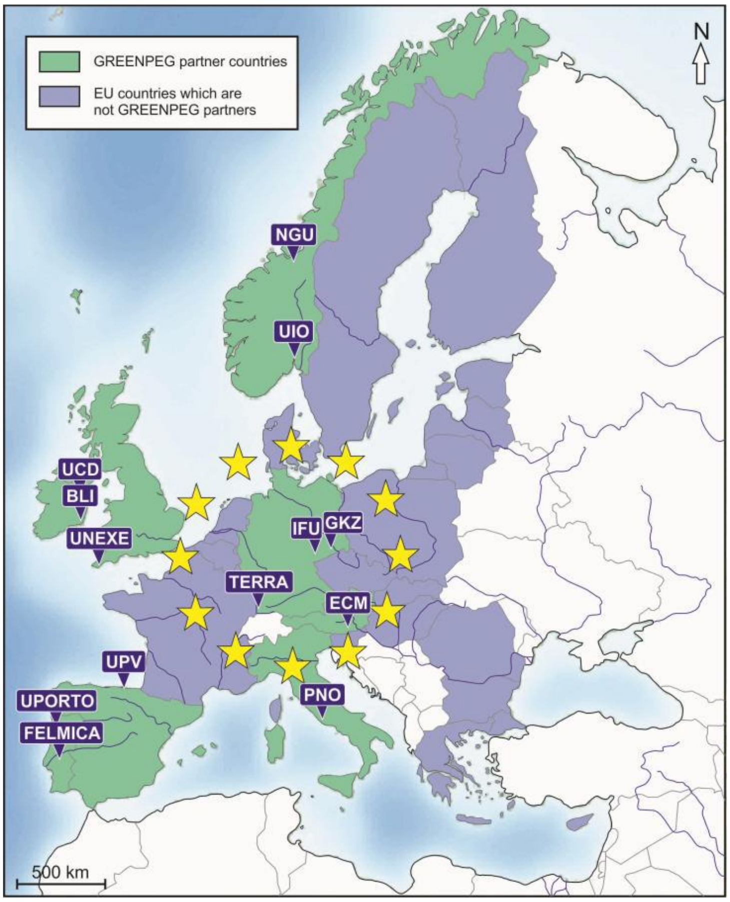

Figure 1. Map of Europe with headquarters of GREENPEG partners. Countries of GREENPEG partners are shown in green.

The GREENPEG test sites host different types of pegmatites, i.e., different in terms of mineralogy and formation, in different types of wall rock. Samples from the project's three test sites of known pegmatite locations in Norway (Tysfjord), Ireland (South Leinster), and Austria (Wolfsberg) as well as from demonstration sites in Spain and Portugal (Figure 2) were acquired and analysed at NGU. Data from LCT- and NYF- type pegmatites in different geological and tectonic settings results in a diverse database, representative and applicable to a wide range of pegmatite occurrences in Europe. Petrophysical properties of hand specimens and drill cores were measured at the NGU laboratory and compiled in the here presented database.

The database is uploaded and accessible on the open data repository Zenodo (www.zenodo.com) under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (Haase et al., 2022). This repository is used by the GREENPEG project to give access to data collected and acquired by the project. Besides assigning a digital object identifier (DOI) to uploaded datasets, the repository allows dataset updates with versioning. The database is meant to be updated with new data on a regular basis. We recommend at maximum one annual update, and only when relevant new data has become available.

Figure 2. Overview map with GREENPEG test sites and the demonstration site.

2. SAMPLE COLLECTION

Samples of hand specimen were collected during the project's field campaigns between 2020 and 2022. Core samples were taken from drill cores of recent drilling campaigns in Leinster and Wolfsberg (see also Chapter 4.3) and collected for the Tysfjord site from NGU's drill core repository. The sampling was carefully carried out, securing that for all sites representative samples from both pegmatite and wall rock were collected. All samples were sent to NGU for petrophysical analysis at the in-house laboratory.

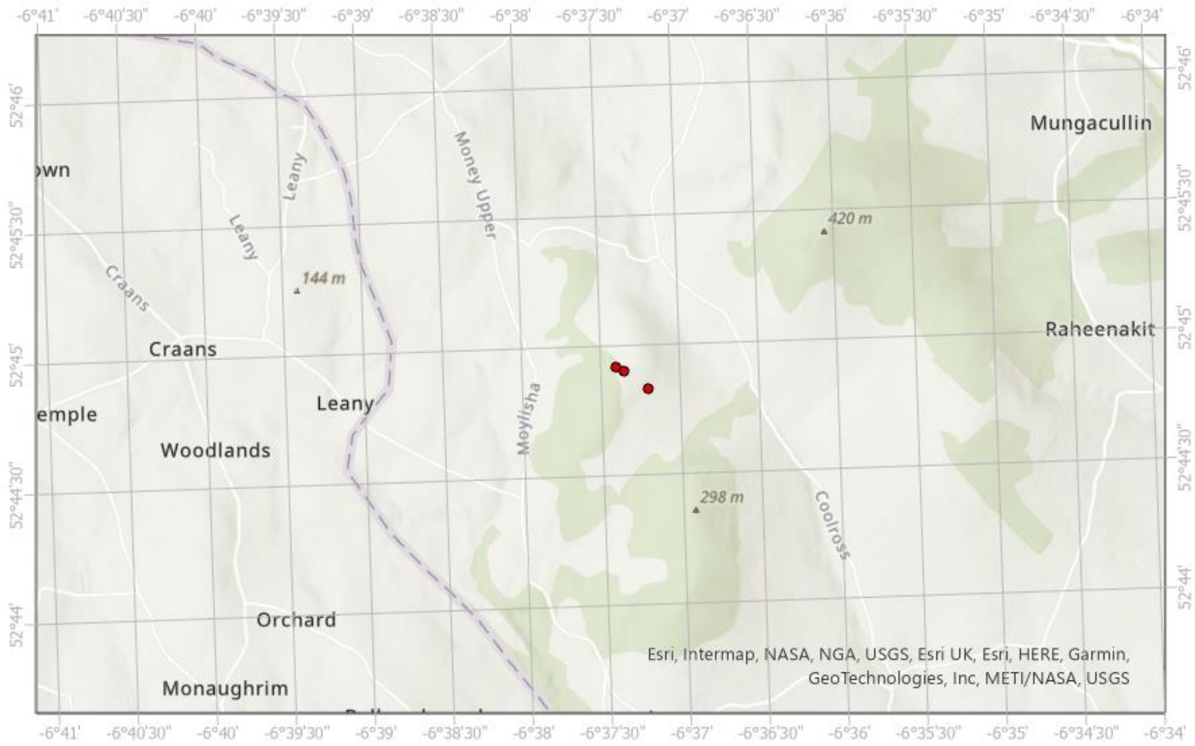

Figure 3. Location of the three boreholes in Leinster (Ireland) from which drill core samples were taken for the petrophysical database.

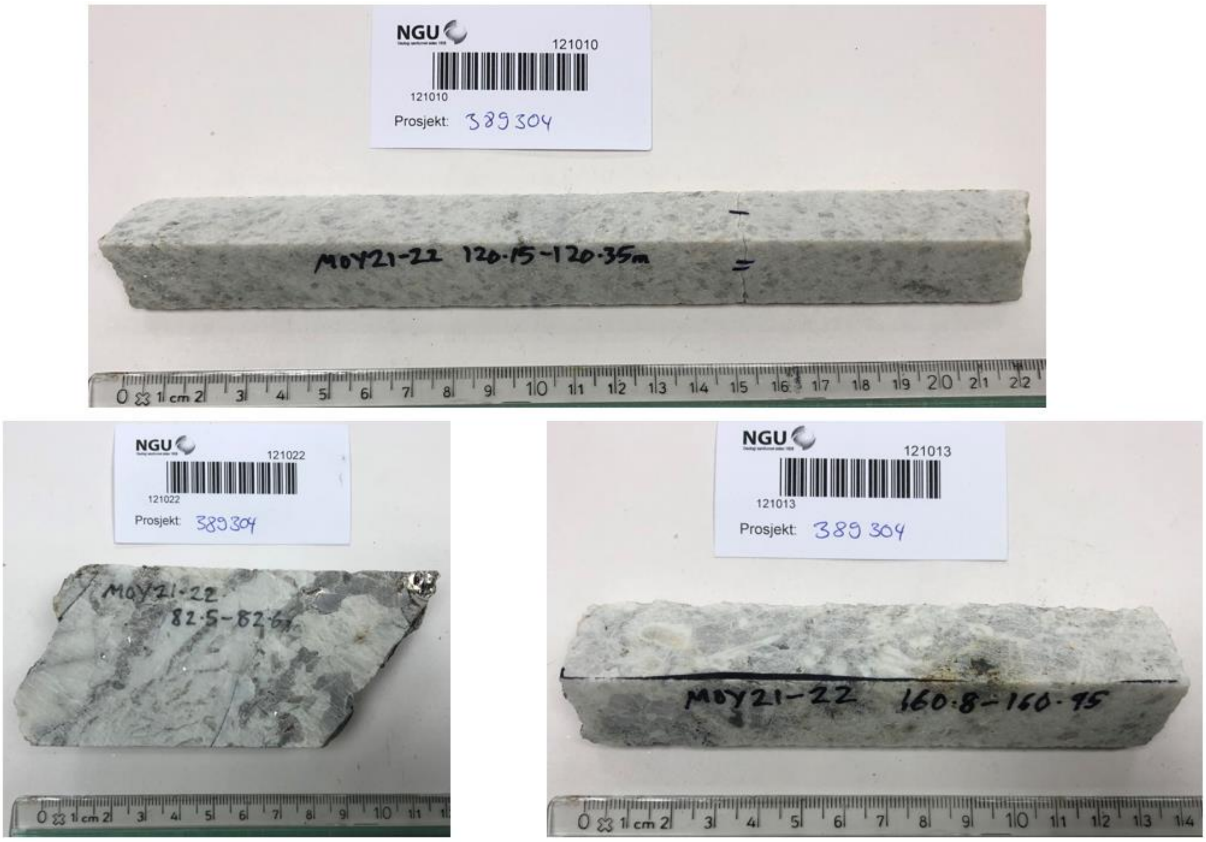

Figure 4. Photographs of three drill core samples from Leinster (Ireland). Top: Albitised pegmatite (LCT-type). Bottom left: Simple pegmatite with granophyric textures. Bottom right: Spodumene pegmatite (LCT-type).

At the Leinster site in Ireland, project partner Blackstairs Lithium Limited (BLI) carried out a drilling campaign at the Moylisha prospect from April to June 2021. All boreholes were drilled within porphyritic granite hosting a number of pegmatites. The dip of the inclined drilled holes ranges from ~20° to 46° near the surface. The depth of the drill holes ranges from 183 m to 345 m. Six boreholes were logged by project partner terratec Geophysical Services in 2021, and three of these drill cores (Figure 3) were sampled for petrophysical investigations: MOY18-13, MOY21-22, and MOY21-23. Examples of collected specimens comprising LCT-type pegmatites from Leinster drill holes are shown in Figure 4.

At the Norwegian demonstration site, drilling campaigns were carried out from the 1970s to the 1990s, covering some of the known pegmatite occurrences. These drillholes have a small diameter (5 cm) and were not designed for geophysical logging. In 2005, a 780 m long borehole was drilled near the Drag village (Figure 5). Drillhole logging was carried out in 2006 and 2009, with the objective to perform heat flow and temperature measurements (Elvebakk & Rønning, 2012). The borehole was mainly drilling through the Tysfjord granite gneiss with some intercalations of pegmatites. After 2005, no new drillings were carried out in the Tysfjord area.

All Tysfjord drill cores are stored and accessible at the National Drill Core and Sample Centre at Løkken in central Norway (https://www.ngu.no/en/topic/national-drill-core-and-sample-centre). Here, samples were collected for the petrophysical measurements. Localities of the Tysfjord site samples taken for petrophysical measurements are illustrated in Figure 5. Two examples of pegmatite specimens from the Tysfjord drill cores are shown in Figure 6.

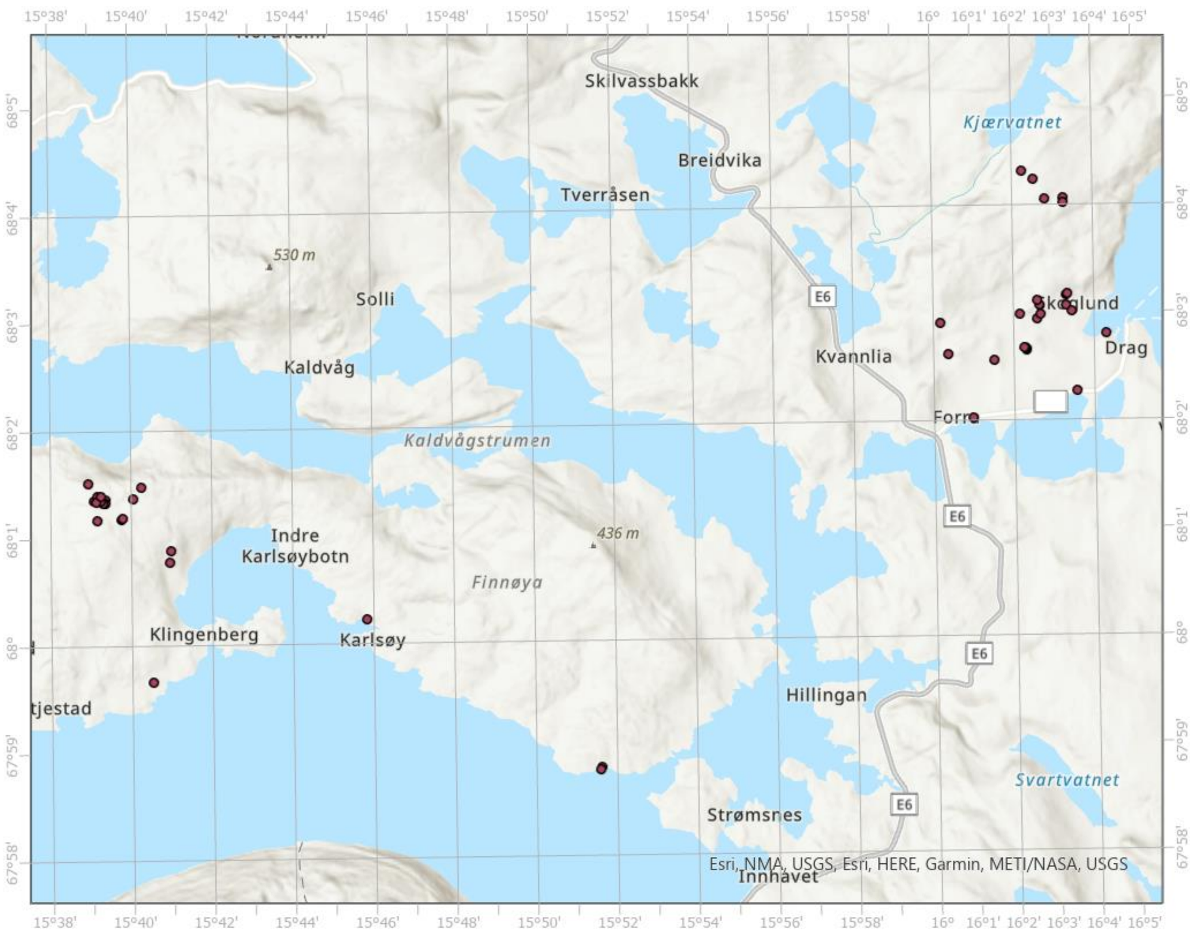

Figure 5. The Tysfjord area in Norway and the location of the samples for the petrophysical database indicated by red dots. The dot cluster in the west is at the Håkonhals mine. The cluster in the east is at the Jennyhaugen mine and surroundings.

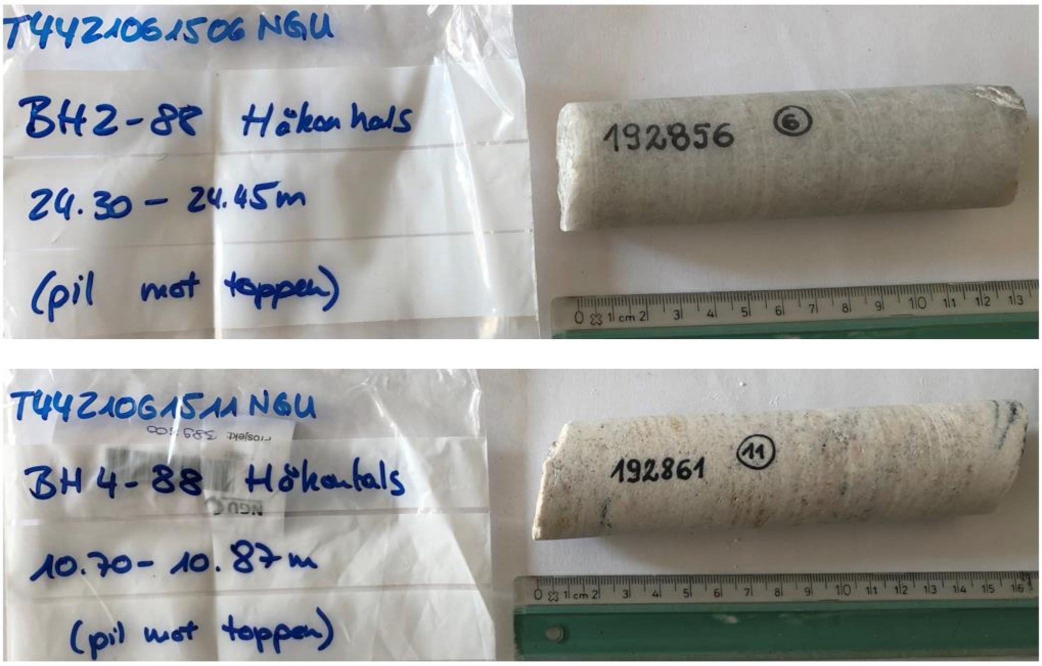

Figure 6. Photographs of two drill core samples from the Håkonhals mine at Tysfjord. Top: Quartz core of the pegmatite (NYF-type). Bottom: Wall zone of the pegmatite (NYF-type).

At the Wolfsberg site in Austria an underground mine, exposing spodumene pegmatites, has been made accessible to the GREENPEG project partners. It gives a unique insight in the setting and contact relationship of pegmatites and their wall rocks. The dyke-like pegmatites are hosted in two different wall rocks: mica schists and amphibolite (Figure 8). Ca. 150 boreholes were drilled at the site over the last decades. For the database, 36 drill core samples from nine boreholes were taken (P15-3, P15-22, P15-25, P18-03, P18-06, P18-12, P18-13, P18-14, P18-25) and two boreholes were logged (P18-13, P15-22). Four additional samples were collected in the underground mine (Figure 7).

Additional mapping and fieldwork is planned at all demonstration and test sites and it is expected that more samples for the petrophysical database will be collected during the second half of the project. More samples from the test sites in Spain and Portugal will be included. It is suggested to maintained and extended the database after the end of the project, that it serves as a comprehensive tool for European pegmatite research and exploration.

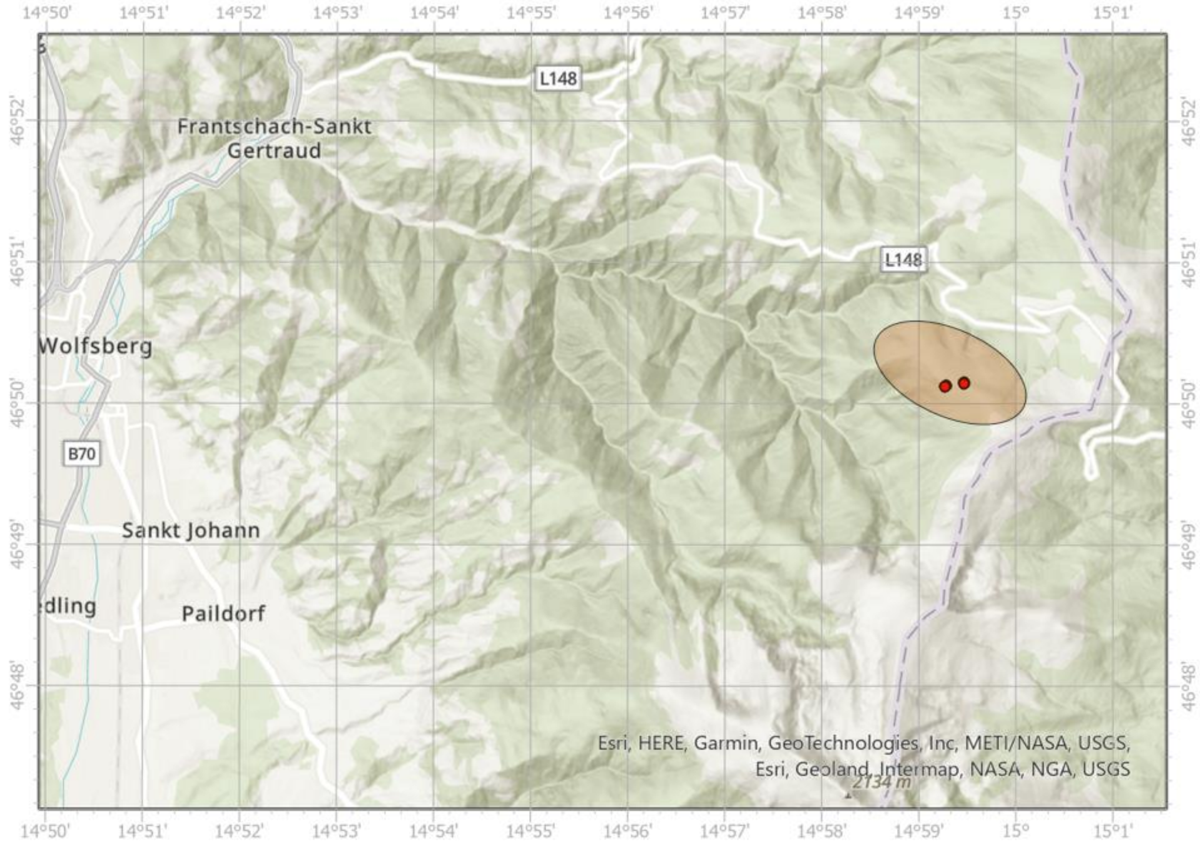

Figure 7. Sample locations from the Austrian demonstration site in Wolfsberg. The ellipse indicates the area where the drill core samples were taken. The red dots show surface projections of locations of hand specimen collected in the underground mine.

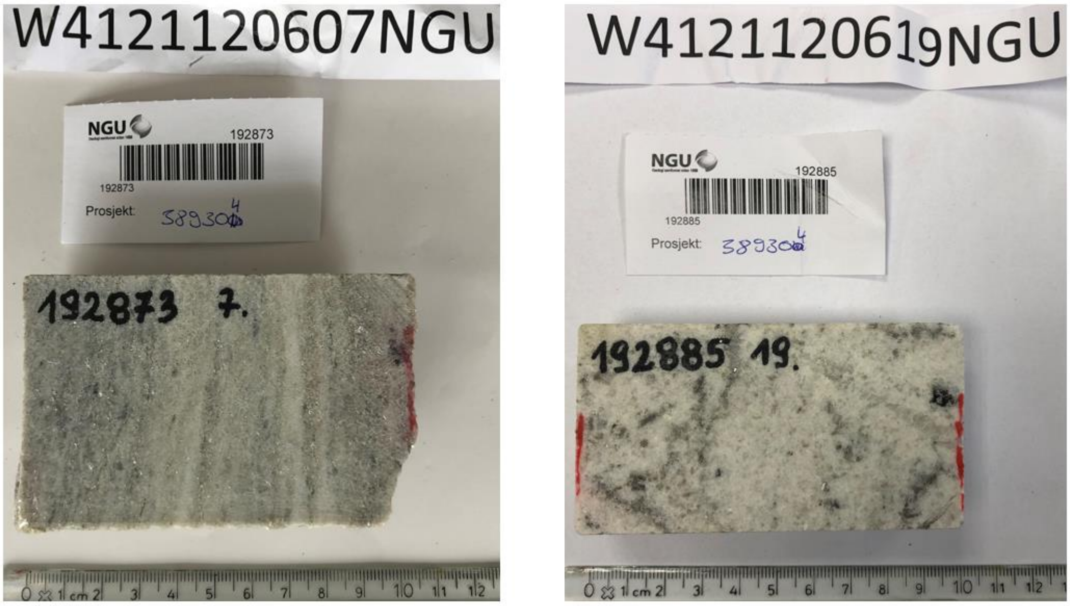

Figure 8. Photographs of two drill core samples from the Wolfsberg site. Left: Strongly foliated, mica schist-hosted spodumene pegmatite (LCT-type). Right: Non-foliated, amphibolite-hosted spodumene pegmatite (LCT-type).

3. DATABASE CONTENT AND FORMAT

Table 1 lists the content of the database together with a brief description of the individual items. This table is also included in the metadata file that accompanies the database. The database currently consists of an Excel file in a zip-compressed folder, together with the image data. At the end of the project, it is planned to provide this database in an ArcGIS Pro and QGIS geodatabase format.

In the Excel file, as well as in Table 1, a colour coding is applied to better distinguish between the different analysis types: yellow for laboratory analysis, blue for handheld measurements, and green for geophysical borehole logging. The first 11 columns in the Excel file contain general information about the sample (see also Table 1):

Lab nr. is a distinct number that a sample gets assigned when entering a laboratory. For now, the database contains only samples analysed at the NGU laboratory.

Sample ID is the ID given to a sample according to project, field campaign, or personal nomenclature.

UTM zone, **UTM X** and **UTM Y** define the original field location of the sample. Locations were mostly measured with handheld GPS and an accuracy of ±3 m. In the current stage of the project, the database does not contain location information for all samples due to confidentiality reasons.

Elevation is only used for hand specimens and gives the elevation above sea level in meters. The elevation is taken from local DEMs based on the measured GPS locations.

Drillhole onset elevation is used for samples taken from a drill core. Also here, values are taken from local DEMs, and the accuracy is limited by the handheld GPS location.

Drillhole from and **Drillhole to** defines the depth interval in the drillhole from which a sample was taken. These values have often higher accuracy than the drillhole onset elevation measurement because once extracted, the drill core is usually examined in great detail with a resolution independent of its absolute position.

Rock type gives lithological information about the sample. Samples were collected and classified by different people and the amount of information given here varies. When descriptions start with a "?", the precise lithology is not exactly known, and the sample is yet to undergo thin section analysis.

Pegmatite family, relation gives further information about the sample. For example, the pegmatites are distinguished between NYF- and LCT-type, the wall rock is also categorised depending on the pegmatite type. Some, but not all, pegmatites form a halo, which is an additional useful information as some of the petrophysical properties are altered in the litho-geochemical halo of the pegmatite. However, halos do not form sharp boundaries. Chemical enrichments of incompatible elements (Li, Cs, Rb, Sn, W, U, Th) defining the halo decline with distance from the pegmatite, some elements decline more rapidly than others. There is a continuum between wall rock and halo and the given relation in the database might not be absolute.

After this general information, the petrophysical properties determined in the NGU laboratory and during geophysical drillhole logging in the field are listed in the database. The detailed description of these, including information about the analytical methods and accuracy/uncertainty are provided in the following chapter.

The last columns of the database contain again more general information:

Location, **Area,** and **Country** are the names related to the original location of the sample at different scales. Area can, e.g., be geographical regions or municipalities. Location can be city or settlement names.

Sample type distinguishes between core samples and hand specimen collected in the field. In the case of core samples, the drillhole ID is provided here in addition.

Photo contains a link to an image file with the photograph of the sample. All samples were photographed with a scale and either the Lab nr., Sample ID or both.

Table 1. List over the content (columns) of the petrophysical database and a short description.

Field	Description
Lab nr.	Distinct sample ID from laboratory (here: NGU)
Sample ID	Sample ID (e.g., from the project or field campaign)
UTM zone	UTM zone
UTM X	x-coordinate in UTM (Easting)
UTM Y	y-coordinate in UTM (Northing)
Elevation	Elevation above sea level (for hand specimen)
Drillhole onset elevation	Elevation above sea level of the start of the drillhole
Drillhole from	Depth location of the sample in the drillhole (top of sample)
Drillhole to	Depth location of the sample in the drillhole (bottom of sample)
Rock type	Information about the sample (lithology, mineralogy)
Pegmatite family, relation	Pegmatite type (LCT or NYF), wall rock, halo
Volume	Sample volume in cm^3
Density	Sample density in g/cm^3
Pore volume	Pore volume in cm^3
Open porosity	Open porosity in %
Susceptibility	Magnetic susceptibility in 10^{-6} SI
Remanence	Magnetic remanence in mA/m
Thermal conductivity, k	in W/mK
Specific heat capacity, c_p	in J/kgK
Dose rate	Radiation dose rate in nS/h
Potassium	Potassium concentration in %
Uranium	Uranium concentration in ppm
Thorium	Thorium concentration in ppm
Nat. Gamma Ray	Total natural Gamma Ray in API
Conductivity LS	Long space conductivity of the borehole formation in mmho
Resistivity	Formation resistivity in Ohm*m
Chargeability	Chargeability in %
Magnetic Susceptibility	Magnetic susceptibility in 10^{-5} cgs
K2O	K_2O content in % calculated with Gamman Software from full spectrum
U3O8	U_3O_8 content in ppm calculated with Gamman Software from full spectrum
ThO2	ThO_2 content in ppm calculated with Gamman Software from full spectrum
Vp	P-wave velocity in m/s
Vs	S-wave velocity in m/s
Vp/Vs-Ratio	Without unit
Poisson's Ratio	Without unit
Location	Origin location of the sample (local scale location) (with drillhole ID)
Area	Origin area of the sample (regional scale location)
Country	Origin country of the sample
Sample type	Core sample or hand specimen
Photo	Link to photo of the sample incl. scale and ID

4. DATA ANALYSIS

4.1 Laboratory analysis

All collected drill core and hand-specimen samples were analysed in the petrophysical laboratory at NGU. This secures that the results are optimally comparable. Analyses carried out at the NGU laboratory are quality-secured and follow the ISO/IEC 17025 standard.

Volume, density, pore volume and open porosity are measured according to the European standard EN 1936:2006 (E) with a Sartorius AX 4202 precision scales. The measurement uncertainty is 0.01 g. Open porosity is expressed by the ratio of the volume of open pores to the apparent volume of the sample. Magnetic susceptibility was measured with a method developed in-house at NGU in 2015 (Koziel, 2022). Measurements are given in 10^{-6} SI. Depending on the measuring range, different uncertainties are to be expected (Table 2). Magnetic remanence was estimated using the FGM3D sensors and the FGM3D DT data acquisition system from Sensys. The measurement uncertainty depends on the measuring range (Table 2). When measuring samples with a remanence >140 A/m the uncertainty may be higher than indicated in the table and is not documented as of date. Thermal conductivity was measured with a TCi Thermal Conductivity Analyzer (with MTPS sensor). Specific heat capacity was calculated by means of directly measured effusivity, density and thermal conductivity. The calibration method Ceramics-HR was applied, allowing for a measurement range of 1.1–29 W/mK with a 2.5% relative uncertainty (when a Pyroceram 40 TCi control sample was used). Water is used as a contact between sample and sensor.

Table 2. Measurement uncertainties for different measuring ranges of magnetic susceptibility and remanence.

Measuring range	**Relative uncertainty**
Magnetic susceptibility (10^{-6} SI)	
<100	60%
100 – 1000	6%
1000 – 100000	0.6%
>100000	0.1%
Magnetic remanence (mA/m)	
<140000	7.5%

4.2 Handheld measurements

A Super-Spec RS 125 gamma ray spectrometer from Radiation Solutions Inc. was used for handheld gamma ray measurements of the samples. Data was recorded over an interval of 3 min and then averaged. Limitations of the handheld measurements are that the samples are smaller than the 103 cm^3 NaI crystal, and that measurements were not conducted in a closed and shielded environment. Both can lead to recording of background radiation, influencing the measurement accuracy.

4.3 Geophysical drillhole logging

Within the GREENPEG project, two wireline downhole geophysical logging and measurement campaigns were performed in several boreholes at the Leinster and Wolfsberg sites between October 2020 and October 2021. The borehole probes applied measure with a sample interval of 1 to 10 cm over the entire depth of the borehole and therefore provide a high-resolution in-situ data set of the rock formation (Table 3). The penetration depth ranges from a few centimetres to several meters depending on the measuring method and parameter. The extraction and evaluation of the logging data used in petrophysical database was carried out by the GREENPEG project partner terratec Geophysical Services.

Table 3. Overview of the borehole probes applied, and the parameters used for the petrophysical database for each tool.

	Probe	**Manufacturer**	**Parameter used for database**	**Distance between measure-ments**
1	Dual Induction (DIL38)	LIM LOGGING SA, Luxembourg	Formation conductivity, long spacing	1 cm
2	Uranium Exploration (UEP42)	LIM LOGGING SA, Luxembourg	Formation resistivity, Chargeability	1 cm
3	Magsus (QL40-MGS)	ALT – Advanced Logic Technology, Luxembourg	Magnetic susceptibility	1 cm
4	Spectral Gamma (GRS42)	LIM LOGGING SA, Luxembourg	Spectral Gamma Ray -> K_2O, U_3O_8, ThO_2-content	10 cm
5	Full Wave Form Sonic (QL40-FWS)	ALT – Advanced Logic Technology, Luxembourg	Full Wave Form Sonic -> Vp, Vs, Vp/Vs Ratio, Poisson's Ratio, total count natural Gamma Ray	5 cm

The data was processed with the WellCAD Software from ALT (Advanced Logic Technology SA). The Spectral Gamma Ray data was additionally pre-processed using the Gamman Software, released by Medusa Sensing BV, Netherlands. The software contains an implementation of the Full Spectrum Analysis (FSA) method which comprises the mathematically most efficient method to derive nuclide concentrations from gamma ray spectra.

From the resulting multiparameter composite logs, data of 12 parameters (Table 1) was extracted from those depth intervals of the borehole where core samples were taken for laboratory analysis. However, the core samples analysed in the laboratory cannot be directly correlated with the borehole logging results without careful evaluation and a thorough depth check. The depth of the core provided at the drill core storage boxes strongly depends on drilling depth accuracy, a common geographical reference and possible core losses during the drilling. The borehole measurements with the continuous readings over the entire depth can normally be used to increase the quality control of the core depth. In the frame of the GREENPEG project, the logging data were adjusted manually to the core sections used for the petrophysical database if necessary. This was done using the image data from the optical and acoustical scanner, which provide a 360° image of the borehole wall. However, small uncertainties in depth remain, so that the depth section in the logs does not cover the exact 100% of the depth interval of the laboratory samples, but a little less. Considering that borehole measurements determine rock properties of a certain rock volume around the measurement point within the borehole, the laboratory measurement can never reproduce the borehole measurement environments. Nevertheless, the borehole data complement the drillcore sample database by providing *in situ* parameters from the drillhole. An average of the respective parameters collected over the depth intervals of the laboratory samples were imported into the database.

For the Leinster site, data were extracted from the boreholes MOY21-22 and MOY21-23 for which laboratory samples were taken. For the Wolfsberg site, data from boreholes P18-13 and P15-25 were taken. In the case of drillhole P18-13, measurements were performed through the PVC casing and no depth adjustments could be made due to the lack of borehole imaging. The uncertainty of the depth section is therefore greater than in the other drillholes.

ACKNOWLEDGEMENTS

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