

# Geology, mineralogy, and metallurgical processing of the Norra Kärr heavy REE deposit, Sweden



Mark Saxon<sup>1, a</sup>, Magnus Leijd<sup>1</sup>, Kurt Forrester<sup>2</sup>, and Johan Berg<sup>1</sup>

<sup>1</sup> Tasman Metals Ltd., Vancouver, BC, Canada, V6E 3V7

<sup>2</sup> GBM Minerals Engineering Consultants Limited, Twickenham, United Kingdom, TW1 3QS

<sup>a</sup> corresponding author: msaxon@tasmanmetals.com

Recommended citation: Saxon, M., Leijd, M., Forrester, K., and Berg, J., 2015. Geology, mineralogy, and metallurgical processing of the Norra Kärr heavy REE deposit, Sweden. In: Simandl, G.J. and Neetz, M., (Eds.), Symposium on Strategic and Critical Materials Proceedings, November 13-14, 2015, Victoria, British Columbia. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015-3, pp. 97-107.

## 1. Introduction and project location

The Norra Kärr peralkaline complex is about 300 km southwest of Stockholm in southern Sweden (Fig. 1). As the only heavy REE deposit in the European Union, Norra Kärr is significant for the security of future REE, zirconium (Zr) and hafnium (Hf) supply (European Commission's European Rare Earths Competency Network; ERECON, 2015). The project is well serviced by power and other infrastructure that will allow year-round mining and processing. A four-lane highway links Scandinavia to mainland Europe and passes with 1 km of Norra Kärr. The skill-rich cities of Linköping and Jönköping, lie within daily commuting distances from Norra Kärr. A rail line that passes within 30 km of the site may be used to transport feed stocks and products. If Norra Kärr is developed, European REE users will no longer require substantial material stockpiles to deal with market uncertainties.

## 2. Project history

The Norra Kärr peralkaline complex was discovered in the early 20th century by Dr. K.E. Norman of the Geological Survey of Sweden during bedrock mapping (Thulin, 1996), and described in detail by Törnebohm (1906), who named the intrusion after a local farm, and Adamson (1944).

Limited exploration of Norra Kärr for Zr and nepheline was conducted by the Swedish mining company Boliden AB in the 1940s and again during the 1970s. At the time, little or no value was placed on REEs and few assays were completed.

Following the global rise in REE prices and the need for secure long-term non-Chinese REE supply, Tasman Metals Ltd. claimed the project in 2009. Surface rock chip sampling and mapping showed REE and Zr-enriched mineralization, and drilling began in December 2009. Norra Kärr is now the one of the largest heavy (REE) projects in the world, with a particular enrichment of the high-value elements, dysprosium (Dy), terbium (Tb), and yttrium (Y). More than 20,000 m of drilling has been completed, with consistent resource drilling to 200 m vertical depth. Tasman has been granted a 25 year renewable Mining Lease for Norra Kärr by the Swedish Mining Inspectorate.

Mining consultants RungePincockMinarco Limited prepared a Preliminary Economic Assessment (PEA) for the Norra Kärr deposit in 2013. In January 2015, a Pre-Feasibility Study (PFS), completed by GBM Minerals Engineering Consultants Limited updated a Mineral Resource.

## 3. Geology

The Norra Kärr peralkaline complex is a small, Proterozoic complex of agpaitic nepheline syenite rocks. The term 'agpaitic' is restricted to peralkaline nepheline syenites containing complex silicates of zirconium, titanium, REEs, and fluorine and other volatiles, and lack simple Zr minerals like zircon and baddeleyite. Zirconium (up to 2 wt.% ZrO<sub>2</sub>) is mainly hosted in rock-forming complex Na-Ca-Zr silicate minerals such as members of the catapleiite, eudialyte, rosenbuschite, and wöhlerite groups (Sørensen, 1997).

The Norra Kärr complex was emplaced along a north-south trending corridor of ductile shear zones in the westernmost part of the Paleoproterozoic Trans Scandinavian Igneous belt (TIB). The TIB comprises an elongate array of mainly felsic plutonic and volcanic rocks extending for about 1400 km along the Scandinavian Peninsula from southeastern Sweden to northwestern Norway. Norra Kärr intruded rocks of the TIB, specifically the Växjö Granite of the Småland-Värmland belt, with U-Pb zircon crystallization ages of 1.81 to 1.76 Ga (Andersson and Wikström, 2004). Recently, Sjöqvist et al. (2014) reported a U-Pb zircon age of 1781 ± 8 Ma from unaltered Växjö Granite country rock adjacent to the Norra Kärr intrusion. Zircon from fenitized Växjö Granite that formed during magmatism-related alkaline alteration yielded a U-Pb age of 1489 ± 8 Ma, which is considered to record when the Norra Kärr intrusion was emplaced (Sjöqvist et al., 2014). New Ar-Ar step heating gave plateau ages on sodic amphibole (1.1 Ga) from Norra Kärr and muscovite and biotite from the country rocks (0.94 Ga) which correspond to ages derived for Sveconorwegian shear zones in the area (Sjöqvist et al., 2014).

At surface, the intrusion is roughly elliptical, with a north-south long axis of about 1300 m and an east-west short axis of about 500 m (Fig. 1). Structural observations from drill

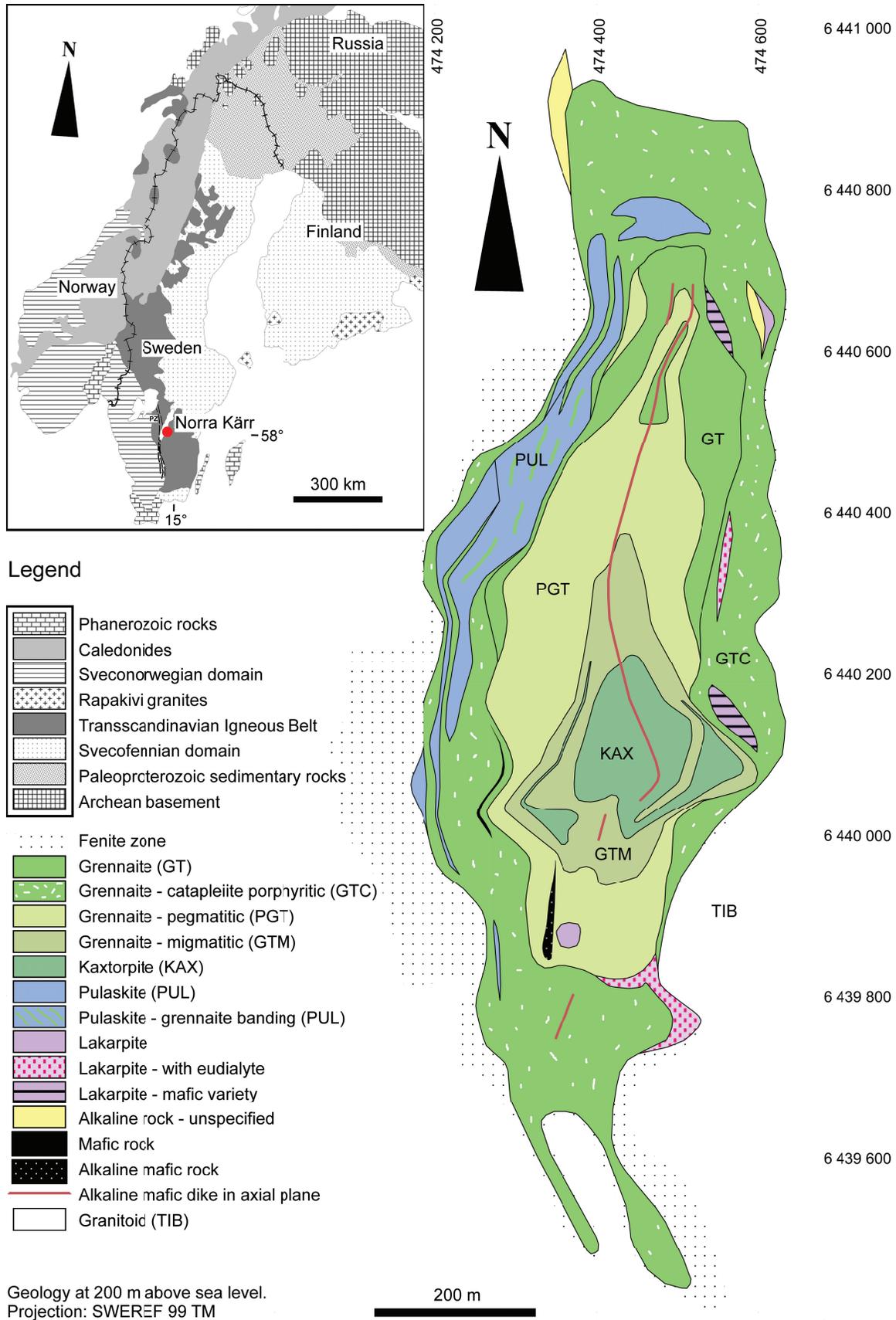


Fig. 1. Geology and location of the Norra Kärr peralkaline complex, Sweden.

core suggest that the intrusive defines a west-dipping (45-60°) doubly plunging synform (Fig. 2). Based on gross magmatic layering and orientation of early deformation fabrics, the body may have been emplaced as a sill (possibly lopolithic) into the Palaeoproterozoic granite-gneissic basement of the TIB.

At surface, the Norra Kärr intrusion exhibits a concentric layering, similar to Ilmaussaq (Sørensen et al., 2011) and Lovozero (Khomyakov, 1995). By analogy, it is probable that there was at least a degree of igneous differentiation, followed by deformation and metamorphic overprint. Layering at Norra Kärr from the synformal core out to the flanks consists of the sequence described in Table 1. Rock units are referred to by informal names derived from local features.

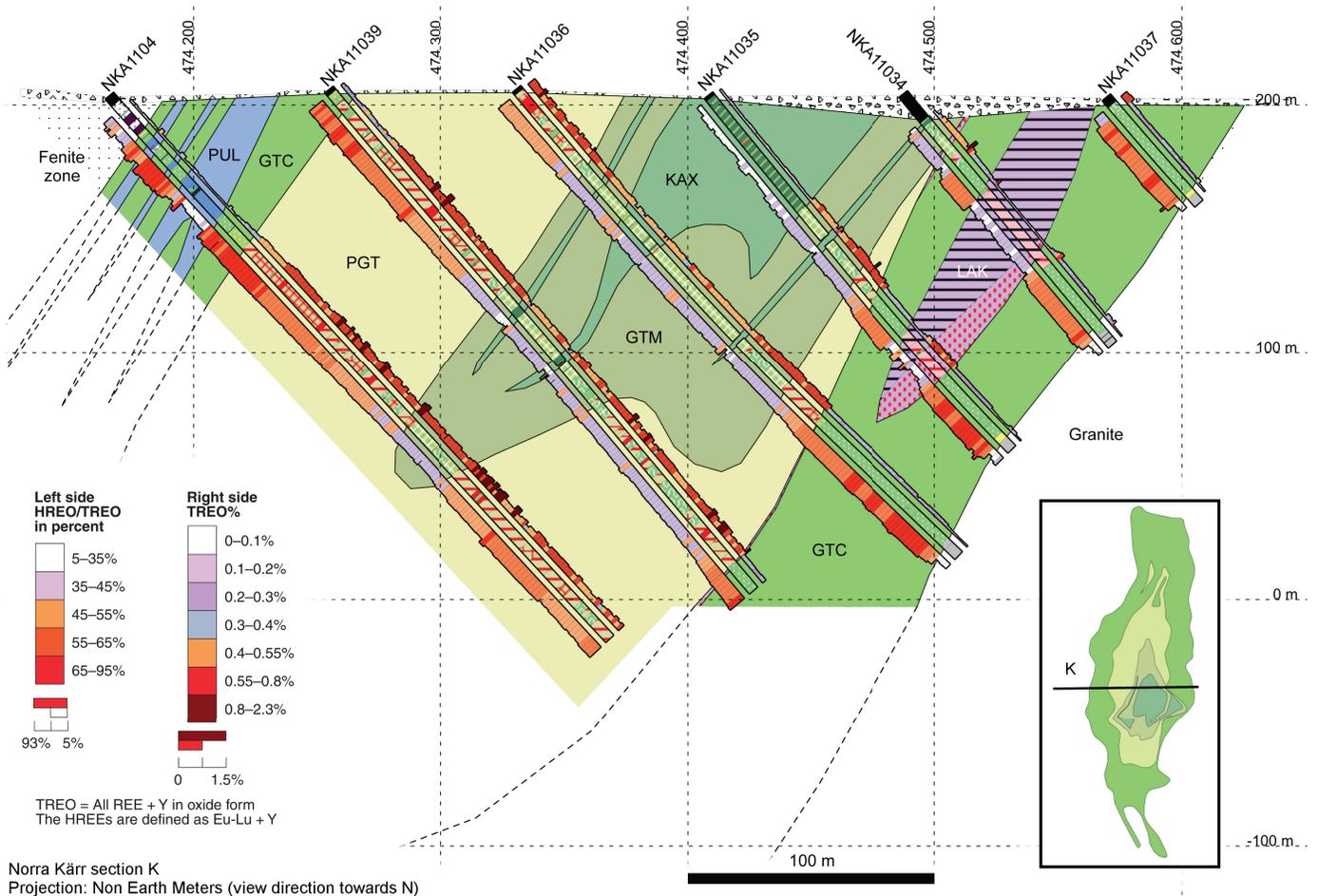
Approximately 80% of the intrusion consists of varieties of 'grennaite', an aegirine-rich nepheline syenite carrying the zirconosilicate minerals, eudialyte and catapleite. The modal mineralogy of the three main varieties is shown in Table 2. The grennaite rock type may be analogous to a deformed and partly recrystallized lujavrite (Le Maitre, 2002), displaying some similarity to the Ilmaussaq Alkaline complex in south Greenland (Sørensen et al., 2011).

The remaining 20% of the complex consists of poorly Zr-

REE mineralized sodic-amphibole bearing lithologic units informally named kaxtorpите and lakarpите (Table 1) and pulaskite. The average major element, REE-Zr and U-Th content of the principal rock types of Norra Kärr is shown in Table 3. Along with its high heavy REE fraction, Norra Kärr mineralized units are relatively low in thorium (Th) and uranium (U). Thorium in Norra Kärr is below the level of the regional-scale granites of the TIB.

The kaxtorpите is an REE-poor lithology, found in the centre of the synform. The rock consists mainly of eckermannite and sodic pyroxene, microcline, albite and altered nepheline (to zeolite). The kaxtorpите is folded, and infolded bands of grennaite are common towards the margins of the unit. Through the central part of the intrusion, the kaxtorpите thins out at depth, which supports the idea that a lopolithic intrusive has been deformed into a synform (Fig. 2).

The series of REE-mineralized grennaite units surrounds the kaxtorpите synform core. The grennaite is subdivided into three distinct units: fine grained grennaite (GTC); pegmatitic grennaite (PGT); and migmatitic grennaite (GTM), based mainly on textural features and spatial setting. The major element chemistry and bulk mineralogy do not vary significantly



**Fig. 2.** Geological cross section through the central part of the complex. The distribution of TREO and percentage of HREO are shown beside the drillholes.

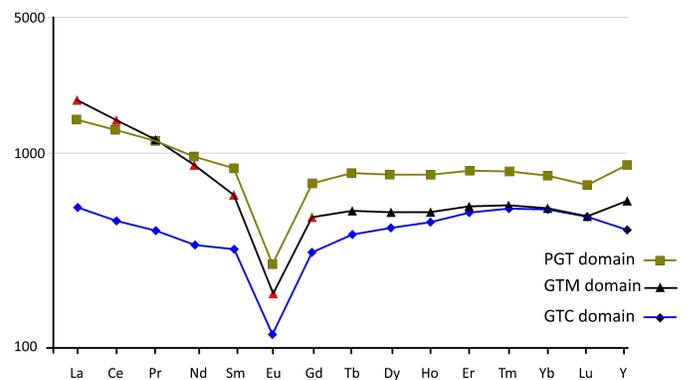
**Table 1.** Rock units comprising the Norra Kärr Peralkaline complex, Sweden.

Rock Type (Map Code)	Relative Position	Description
Kaxtorpite (KAX)	In the central part of the complex, probably as the core of a synform; offset cone-shaped body that does not persist to depth.	Relatively dark, medium grained, commonly folded rock. Alkali feldspar-eckermannite-aegirine with lesser nepheline-zeolite-pectolite. Towards margins commonly interfolded with bands of fine-grained grennaite.
GTM domain Grennaite (GTM)	Innermost grennaite unit, wrapping around the central kaxtorpite.	Medium REE-grade. Recrystallized to almost migmatitic grennaite. Commonly folded. Alkali feldspar-aegirine-nepheline-zeolite-eudialyte-catapleiite mineralogy.
PGT domain Grennaite (PGT)	More than 100 m wide zone between the GTM and GTC type grennaites. Principal mineral resource unit.	Variably recrystallized ground mass with highly varying coarser grained, leucocratic bands and zones. From just 5-10% leucocratic, thin schlieren to more than 10 m wide very coarse-grained pegmatitic zones.
GTC domain Grennaite (GTC)	Outermost grennaite zone that lies along the outer contacts of the intrusive.	Very fine-grained, foliated grennaite with 2-10%, elongated to locally band-like laths of catapleiite porphyroblasts. Eudialyte only very rarely visible by naked eye.
Lakarpite (LAK)	Elongated bodies along the eastern contact between the PGT and GTC varieties of grennaite.	Medium- to coarse-grained, albite-arfvedsonite-microcline-nepheline dominated rock. Locally carrying pink eudialyte close to its contacts with surrounding grennaite.
Pulaskite (PUL)	Elongated bodies close to the W and N contacts of the intrusive. Locally as large boudins within GTC type grennaite.	Medium- to coarse-grained alkali feldspar syenite with some amphibole-aegirine and minor nepheline. Characterized by coarse microcline augen.
Fenite Aureole (FEN)	Mainly exposed or drilled along the western contact as a 5-100 m wide zone of sodic metasomatic alteration of surrounding granite.	Characterized by albitization and by aegirine and alkali amphibole replacing biotite.

between these three varieties. The distribution of the REE varies between the grennaite units (Fig. 3), and the percentage of HREEs within TREO varies from about 40% in the more central GTM variety and gradually increases outwards to about 65% in the GTC zone (Fig. 4).

Grennaite of the GTM domain is found in the central part of the synform, immediately surrounding the barren core of kaxtorpite. GTM grennaite is recrystallized commonly bears a folded foliation. The extent of the recrystallization varies from a gneissic diffuse medium-grained texture close to the kaxtorpite to a slight coarsening of the texture farther away from the central kaxtorpite core. TREO and ZrO<sub>2</sub> grade of GTM is typically in the range of 0.53% and 1.49%, respectively.

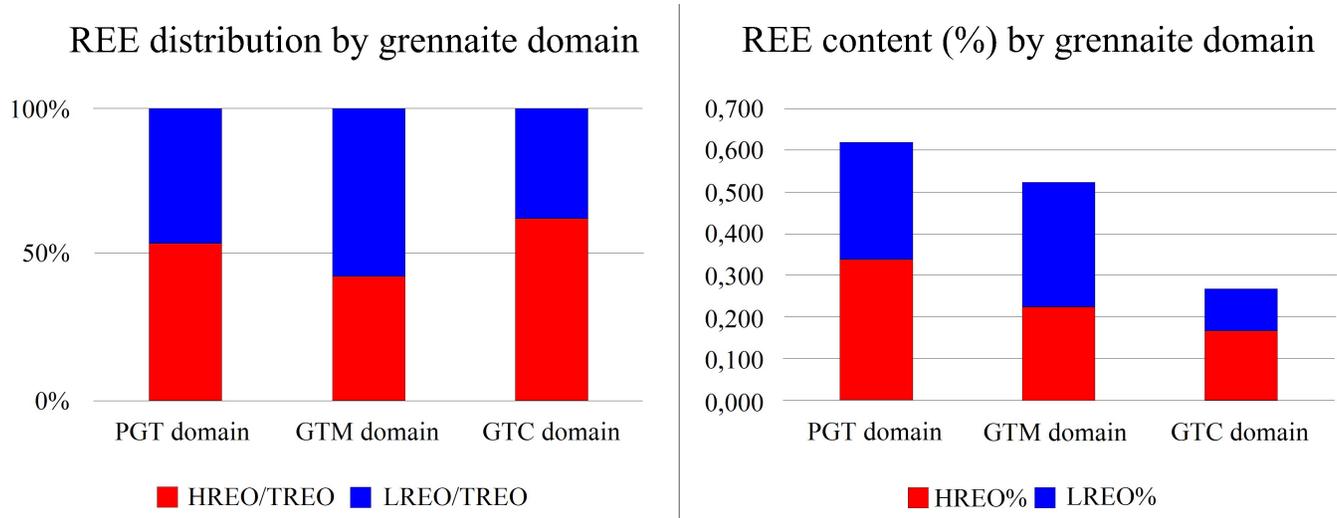
Surrounding this domain, lies a wide zone of well mineralized, leucosome-rich partly pegmatitoidal textured grennaite, defined as the PGT domain. This unit is inhomogeneous, ranging from zones with 5-10% of 1 cm wide, medium-grained, leucocratic schlieren in finer grained PGT grennaite, to several metre wide zones of very coarse-grained nepheline-syenite pegmatite. The pegmatitic zones and schlieren consist of the same minerals as the fine-grained PGT grennaite, though are generally poorer in



**Fig. 3.** Chondrite-normalized REE distribution for mineralized domains.

aegirine and richer in feldspar, nepheline and eudialyte.

The grain size of the minerals in the thinner schlieren is around 5 mm. Zones up to 10 m wide of very coarse-grained nepheline syenite are also common. The eudialyte content and thus the REE grade is generally more elevated with greater pegmatitic texture. Zones with less leucocratic schlieren in



**Fig. 4.** Relative and absolute contribution of heavy REE (HREO) and light REE (LREO) to total REE content in each grenaite unit. PGT forms the most significant mineralized rock type by both volume and grade.

**Table 2.** Modal mineralogy of the three varieties of mineralized grenaite (GTM, PGT, GTC).

Mineral	PGT domain	GTM domain	GTC domain
Aegirine	21.4	21.2	16.6
Albite	17.7	20.4	28.0
Anorthoclase	1.3	1.5	1.8
Microcline	16.0	18.1	14.5
Nepheline	11.2	8.0	20.7
Zeolite (Natrolite-Analcime)	16.3	16.0	9.6
Eudialyte	8.2	7.0	4.4
Catapleiite	4.0	2.5	3.1
Mica-alteration	2.9	4.1	0.8
Fluorite	0.2	0.4	0.2
Prehnite	0.3	0.3	0.2
Britholite-Ce	0.08	0.09	0.01
Mosandrite	0.08	0.09	0.02
Galena	0.14	0.04	0.00
Calcite-Mn	0.05	0.09	0.02
Zircon	0.05	0.07	0.00

general carry REE grades well above the cut off. Typical TREO and ZrO<sub>2</sub> concentrations of PGT are 0.62% (Fig 4) and 2.01% respectively.

Outside of the PGT domain and closer to the granite contact, the grenaite groundmass becomes gradually finer grained to an

aphanitic and schistose texture. Typically this domain, known as GTC grenaite, is porphyritic in appearance, with a few percent of 1-30 mm long, lath like, elongate to needle shaped porphyroblasts of the rare zirconosilicate mineral catapleiite. Typical TREO and ZrO<sub>2</sub> grades of GTC are 0.27% (Fig. 4) and

**Table 3.** Major element geochemistry of the principal rock types comprising the Norra Kärr complex. TREO refers to total rare earth oxides whereas %HREO corresponds to the proportion of heavy rare earth oxides within TREO in %wt.

	<b>Kaxtorpite (KAX)</b>	<b>PGT domain</b>	<b>GTM domain</b>	<b>GTC domain</b>	<b>Lakarpite (LAK)</b>	<b>Pulaskite (PUL)</b>
SiO <sub>2</sub> %	60.2	55.6	56.7	56.5	64.7	62.0
Al <sub>2</sub> O <sub>3</sub> %	13.7	16.5	17.3	18.5	15.8	15.7
Fe <sub>2</sub> O <sub>3</sub> %	4.3	6.4	5.3	4.6	2.9	4.2
CaO%	2.7	1.3	1.5	0.6	1.8	2.4
MgO%	1.6	0.2	0.2	0.1	0.9	1.2
Na <sub>2</sub> O%	8.8	10.8	10.2	11.5	7.4	6.9
K <sub>2</sub> O%	3.0	3.7	3.8	3.6	5.2	5.0
TiO <sub>2</sub> %	0.5	0.1	0.1	0.0	0.3	0.4
MnO%	0.6	0.2	0.4	0.1	0.1	0.2
TREO%	0.20	0.62	0.53	0.27	0.23	0.13
%HREO	30.10	55.40	43.10	63.50	42.10	40.80
ZrO <sub>2</sub> %	0.33	2.01	1.49	1.35	0.55	0.35
Th ppm	68	6	11	5	25	25
U ppm	24	12	21	5	10	8

1.35% respectively.

The lakarpite (LAK) unit is a rare and sporadic low REE grade alkaline unit, composed principally of sodic amphibole, albite, microcline with minor sodic pyroxene, nepheline and fluorite. Both mesocratic and melanocratic varieties occur. It forms an intermittent, elongated body in the eastern part of the intrusive. The lakarpite may contain abundant REE-poor, bright pink eudialyte especially close to contacts with grennaite.

Pulaskite (PUL) occurs mainly along the western and northern contacts of the intrusion. It is a medium-coarse grained rock low in REEs and typically carries large rounded microcline augen in a groundmass of albite, aegirine, amphibole, microcline and minor biotite and nepheline. Rosenbuschite, apatite, titanite and fluorite occur as accessories. Pulaskite may occur together with fine-grained grennaite as alternating zones.

The PGT type mineralization makes up about 75% of the mineral resource at Norra Kärr and the GTM type most of the remaining. The GTC and less common alkaline rocks are currently excluded due to lower grades or lower process certainty.

#### 4. REE mineralogy and distribution

Norra Kärr is unusual for a REE deposit in that nearly all of the REE are found in the one mineral, and not distributed through multiple phases. The complex zircon-silicate mineral eudialyte (Na<sub>4</sub>(Ca,Ce)<sub>2</sub>(Fe<sup>2+</sup>,Mn,Y)ZrSi<sub>8</sub>O<sub>22</sub>(OH,Cl)<sub>2</sub>) hosts greater than 95% of REE, with lesser amounts in a secondary Ca-LREE-F-silicate mineral tentatively identified as britholite,

with trace mosandrite and cerite. In comparison to most other similar deposits, the eudialyte at Norra Kärr is REE rich and also contains a very high proportion of HREO (Fig. 5). The low-REE sample from Norra Kärr reported by Schilling et al. (2011) was taken from an unrepresentative outcrop of the lakarpite unit that lies outside the mineral resource.

Various mineral studies (e.g., Sjöqvist et al., 2013), have shown that, within the resource, the TREO content of the eudialyte varies between 6% and 10%. The percentage of HREO in the mineral also varies from about 30% in the more central GTM zone to above 70% in the more distal GTC zone. Electron microprobe and Laser Ablation ICP-MS analyses of eudialyte from different parts of the Norra Kärr intrusion suggest that the REE distribution in the mineral is proportional to that in the corresponding whole rock. These data have further shown that the TREO content and percentage of HREO is highest in eudialyte found in the GTC unit. However, the relatively low (4.4%) total content of eudialyte compared to 8.2% in the PGT and 7.0% in the GTM rock types result in a low total REE grade, and GTC's current exclusion from the mineral resource.

Sjöqvist et al. (2013) defined three compositional varieties of eudialyte group minerals at Norra Kärr: 1) Fe-rich, REE-poor, classical pink eudialyte; 2) Fe-Mn-bisected, HREE-rich eudialyte from pegmatitic grennaite (PGT); and 3) Mn-rich, LREE-rich eudialyte from 'migmatitic' grennaite (GTM). The pink, REE-poor eudialyte occurs locally, within the lakarpite unit in contact with grennaite and only a very small part of

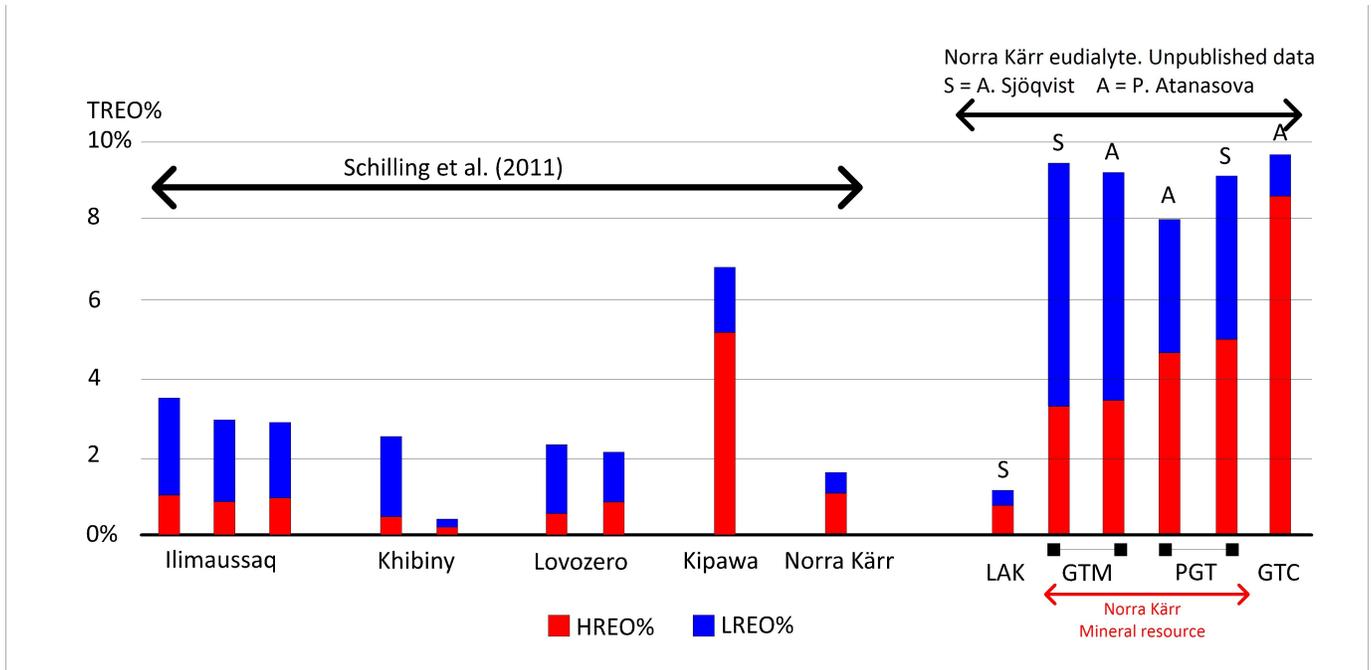


Fig. 5. Laser ablation ICP-MS analyses of eudialyte from various locations worldwide.

the mineral resource belongs to this variety. The HREE-rich eudialyte, which varies from mid to dark orange-brown to deep yellow or red, is the greatest contributor to the Norra Kärr resource.

In contrast to the REE, which are only found in significant amount in eudialyte, Zr and Hf are distributed through two minerals. Approximately 60% of the Zr is hosted by eudialyte, with the balance contained in the hydrated zirconosilicate catapleiteite ( $\text{Ca}/\text{Na}_2\text{ZrSi}_3\text{O}_9 \cdot 2\text{H}_2\text{O}$ ). Current metallurgical design does not envisage recovery of these elements.

## 5. Mineral resources

The indicated mineral resource in a planned pit at Norra Kärr stands at 31.1 million tonnes grading 0.61% TREO (Short et al., 2015), corresponding to a 20 year mine life. Additional mineralized rock, about four times the volume of the quoted resource, is known to lie beneath and along strike from the planned pit. The indicated mineral resource is based on TREO cut-off grade of 0.4% and has a high HREO/TREO proportion (Short et al., 2015; Table 4).

## 6. Proposed mining

Under the model assumed by Short et al., (2015), Norra Kärr could be exploited by open pit mining. The deposit crops out or lies under only a thin soil cover, and is typically greater than 100 m wide, such that risk of dilution or loss is extremely low. Mineral extraction methods have taken account of two constraints, blasting fragmentation and the nearby E4 highway. Fragmentation has been required to meet a maximum size of 600 mm and planned blasting has been designed with a safety envelope for a nearby highway. Mined waste totals 17.3 Mt for total rock movement of 40.8 Mt.

Underground mining was also considered. It presents the potential to reduce the land use footprint, a significant consideration in ensuring project sustainability.

## 7. Metallurgical testing

As established above, greater than 95% of REEs at Norra Kärr are hosted by the Na-Ca zirconosilicate mineral eudialyte. The name eudialyte is taken from the Greek to mean ‘easily dissolved’, due to the mineral’s high solubility in weak acid. However, despite this solubility and simplicity of the ‘cracking’ stage of processing, to date eudialyte has not been used commercially as a source for REE or Zr.

Historically, pregnant leach solutions (PLS) from eudialyte ores have resisted purification and REE separation due to the high silica content of the PLS. The past 5 years of research by various exploration companies, applying continuous solution monitoring and 21<sup>st</sup> century chemicals and equipment have contributed to providing silica management solutions, and preventing or limiting the formation of unfilterable silica gels.

### 7.1. Beneficiation

In 2012, German mineral processing consultants at DORFNER Analysenzentrum und Anlagenplanungsgesellschaft mbH (ANZAPLAN) were engaged by Tasman to determine the most suitable mineral beneficiation route for the Norra Kärr mineralized material. ANZAPLAN conducted mineralogical characterization and testing on domain specific composite samples. Samples from each domain were crushed and ground, then subjected to mineralogical characterization employing automated scanning electron microscope based mineral liberation analysis (MLA) technology. The mineral characterization determined that, despite hand specimen scale

**Table 4.** Indicated mineral resources and reserves from Norra Kärr REE project. From Short et al., (2015).

Tonnes (M)	TREO (%)	%HREO in TREO	Dy <sub>2</sub> O <sub>3</sub> (%)	Y <sub>2</sub> O <sub>3</sub> (%)	Eu <sub>2</sub> O <sub>3</sub> (%)	La <sub>2</sub> O <sub>3</sub> (%)	Nd <sub>2</sub> O <sub>3</sub> (%)	Ce <sub>2</sub> O <sub>3</sub> (%)	Gd <sub>2</sub> O <sub>3</sub> (%)	Tb <sub>2</sub> O <sub>3</sub> (%)	Pr <sub>2</sub> O <sub>3</sub> (%)	Sm <sub>2</sub> O <sub>3</sub> (%)	Lu <sub>2</sub> O <sub>3</sub> (%)
Indicated Mineral Resource Estimate, 0.4% cut-off													
31.1	0.61	52.6	0.027	0.218	0.002	0.057	0.067	0.128	0.020	0.004	0.017	0.018	0.003
Probable Mineral Reserve Estimate													
23.6	0.59	53.1	0.027	0.215	0.002	0.055	0.065	0.124	0.020	0.004	0.016	0.018	0.002

variations, the constituent mineralogy was indistinct between the domains and displayed only minor variability (Fig. 6). The minor variation in modal mineralogy translates into only minor differences in geochemistry. The high degree of similarity of potentially economic rock domains with regard to mineralogy and grade is viewed as promising, limiting the need for blending or selective mining.

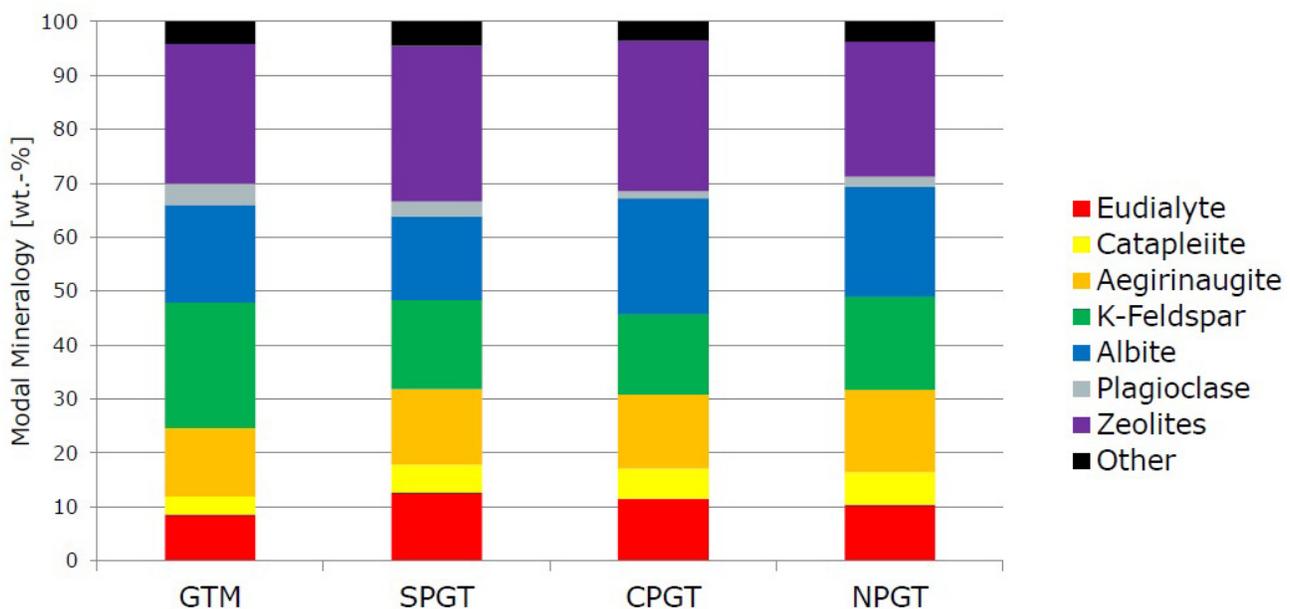
The degree of eudialyte liberation was satisfactory for particle sizes of 60 µm to 80 µm. Several beneficiation methods were investigated to upgrade the eudialyte. The principal finding is that due to paramagnetism of the eudialyte, magnetic separation alone was sufficient for eudialyte beneficiation, and adequately rejected much of the acid consuming gangue. A follow-up study identified the Metso HGMS technology as most appropriate to recover eudialyte using a single stage magnetic separation.

## 7.2. Leaching

Diagnostic leach tests were conducted by ANSTO to determine the minimum acid activity required to dissolve eudialyte. It was determined that a mild acidic environment, around pH 1, was required to dissolve the eudialyte while leaving intact most of the accompanying minerals. Additionally, tests were

conducted at various temperatures to determine the impact on leaching kinetics and pulp handling. The results indicated that a leach temperature of 30°C is sufficient to maintain satisfactory leach kinetics and pulp condition. Follow-up tests further examined the mineral solubility at constant acidities, around the determined range, at various pulp densities to determine the operating limits for silica in solution. When operating at higher pulp densities a threshold limit was exceeded whereby the silica would precipitate from solution causing the pulp to gel. REE extractions into solution were routinely in excess of 90%.

The PLS generated by the sulphuric acid dissolution of the eudialyte mineral concentrate has a characteristically high silica concentration that is in excess of that acceptable for metal recovery by traditional solvent extraction. To remove the silica, the pH is increased from the leach condition to a value in excess of pH 3 to destabilize the silica, causing it to precipitate. The neutralization residue, comprised largely of silica and minor contributions of Zr and aluminium (Al), is then separated from the PLS and washed to recover the entrained solution. The testing to date indicates that the neutralization process is capable of producing a clarified liquor suitable for solvent extraction (unpublished data).

**Fig. 6.** Mineral distribution of Norra Kärr mineralized rock types as determined by MLA.

### 7.3. Solvent extraction

The principal method tested to recover the REEs from the PLS was solvent extraction. ANSTO conducted the preliminary definition work using a PLS mixture generated as part of the leaching and neutralisation definition programmes. Phase disengagement studies determined that an elevated operating temperature was required to ensure satisfactory phase disengagement within the system. Kinetic loading studies determined that the rate at which equilibrium was attained was faster than the phase separation kinetics.

Equilibrium loading isotherms were generated using a primary amine solvent in order to determine its loading capacity and the likely number of equilibrium stages required to extract the REEs from the aqueous PLS into the organic solvent. The equilibrium loading work enabled the determination of the organic to aqueous ratio as well as the number of stages to effect an acceptable level of extraction.

The REEs were strongly complexed with the solvent and resulted in excessive acid requirements to achieve satisfactory stripping efficiency. An alternative reactive stripping process was assessed, whereby oxalic acid was contacted with the loaded organic causing the formation of a rare earth oxalate precipitate at the interface of the two phases. The precipitate was then separated from the two phases by centrifugation, producing a mixed oxalate concentrate. The resulting concentrate was

subjected to chemical analyses (Table 5), demonstrating high REE content with low degree of impurities. The balance of the assay mass is the oxalate anion and hydration water from the oxalate salts.

### 8. Process flowsheet

Metallurgical testwork has allowed the determination of a flowsheet to prepare a mixed REE oxide product with characteristics suitable for immediate sale or toll separation (Figs. 7, 8).

### 9. Conclusions and recommendation for future research

Norra Kärr is a peralkaline intrusion-hosted HREE deposit, where the main ore mineral is eudialyte. The project is in the advanced stage of development with established probable reserves sufficient to supply all of Europe's REE needs for several decades. More specifically, it has a potential to produce more than 250 tonnes per annum of Dy for the same period of time. Immediate targets for additional research include: the coarse removal of Ce and/or La on the mine site to reduce subsequent separation charges; the consideration of alternative acids to limit waste streams and improve reagent recyclability; and comparative test work to limit the use of the most expensive reagents and consumables.

**Table 5.** REE oxalate concentrate chemical analyses. Sample prepared and assayed by ANSTO. Relative % distribution indicated high proportion of HREE. LREE = Ce-Sm; HREE = Eu-Lu+Y.

Element	Overall Recovery [%]	Weight [%]	Relative % Distribution
La	77.84	4.935	10.9
Ce	78.02	10.750	23.6
Pr	78.82	1.458	3.2
Nd	79.01	6.763	14.9
Sm	79.42	1.650	3.6
Eu	79.44	0.269	0.6
Gd	79.32	1.657	3.6
Tb	79.13	0.351	0.8
Dy	78.78	2.191	4.8
Ho	78.00	0.491	1.1
Er	77.40	1.288	2.8
Tm	76.89	0.182	0.4
Yb	76.10	1.138	2.5
Lu	75.48	0.149	0.3
Y	72.92	12.210	26.8
Impurity		0.171	
TREE		45.48	100
LREE		23.91	56.2
HREE		21.58	43.8

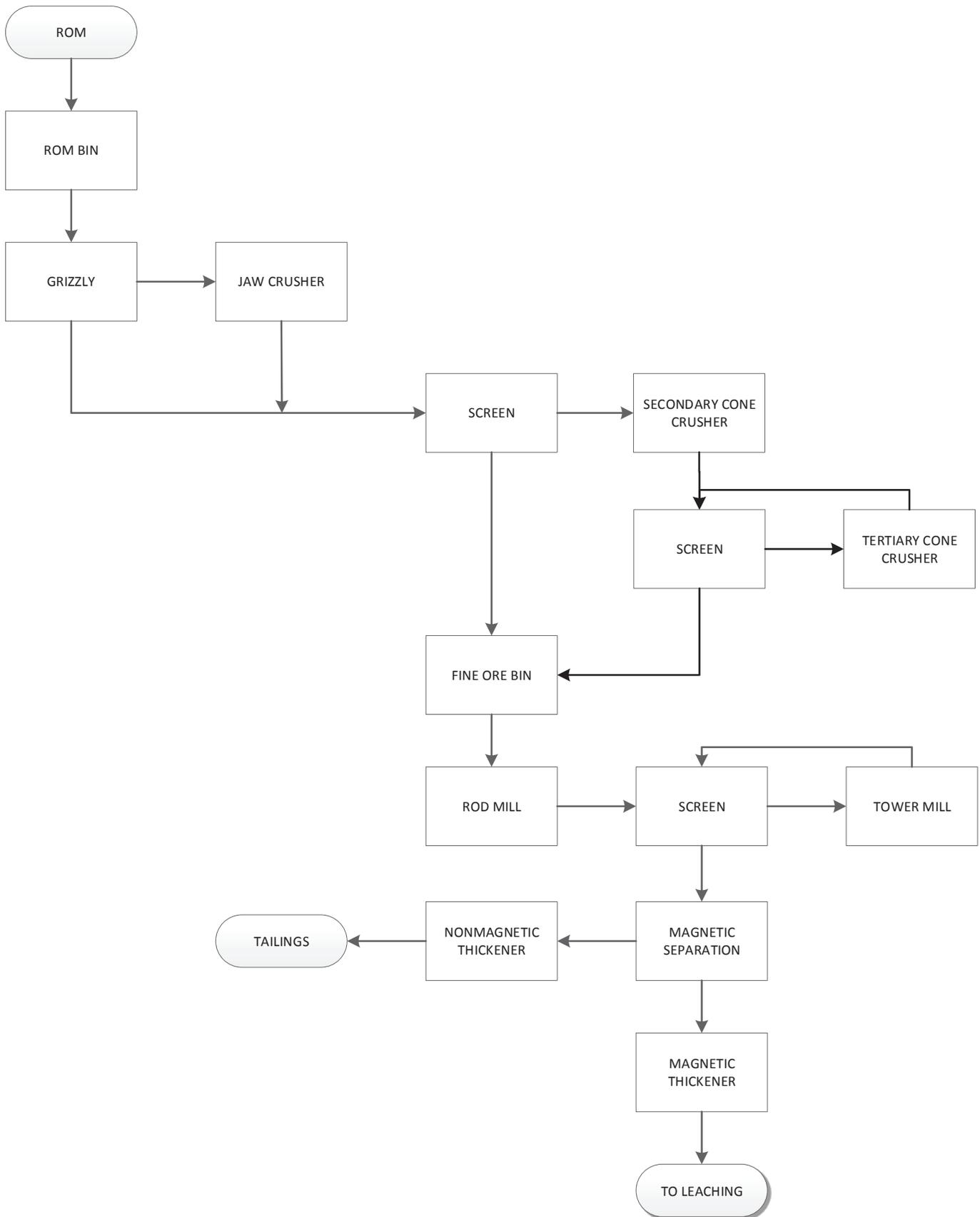


Fig. 7. Comminution and beneficiation block flow diagram.

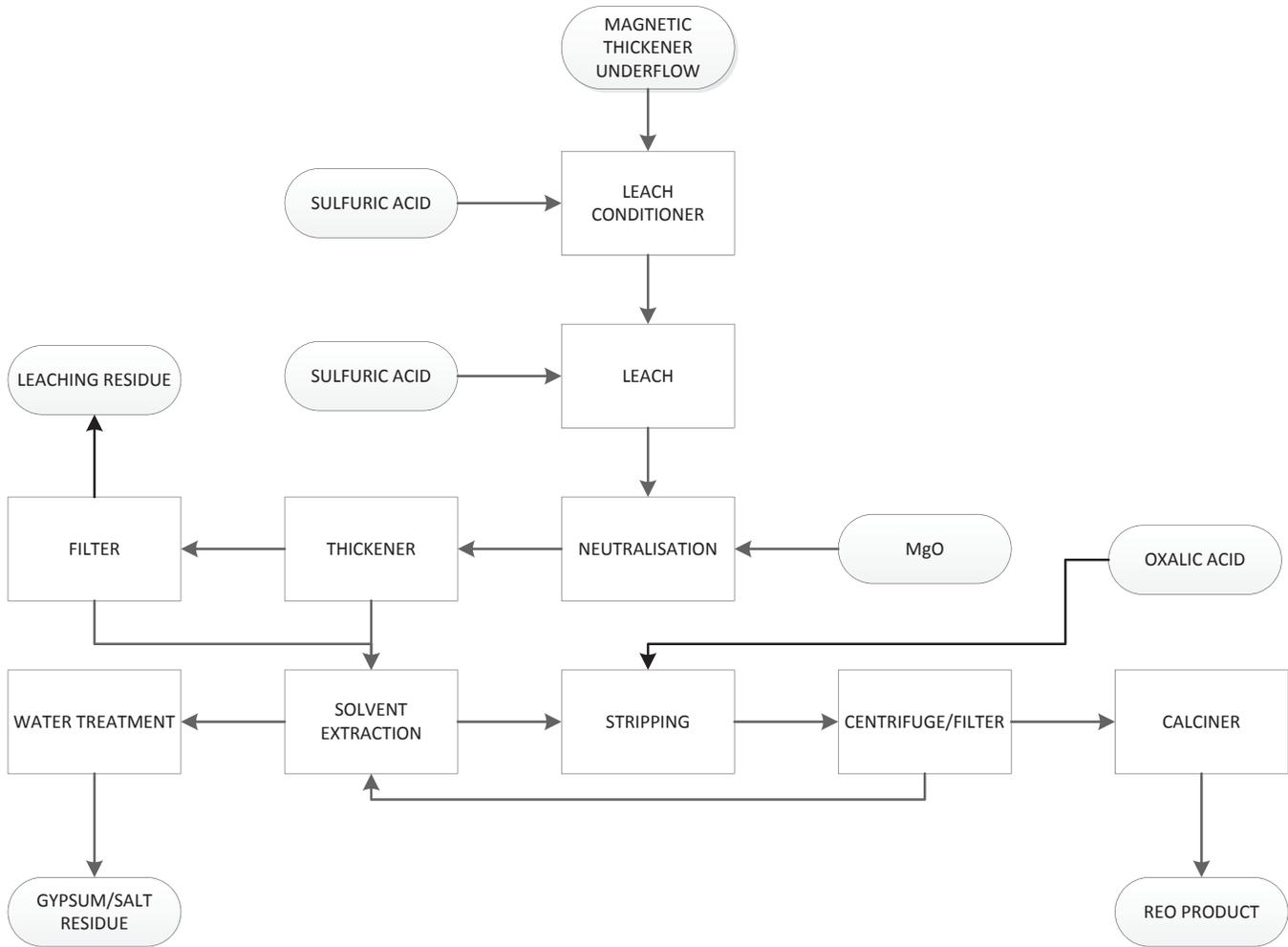


Fig. 8. Hydrometallurgical extraction and recovery block flow diagram.

### References cited

- Adamson, O.J., 1944. The petrology of the Norra Kärr district: An occurrence of alkaline rocks in southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar*, 66, 113–255.
- Andersson, U.B., and Wikström, A., 2004. The Småland-Värmland Belt: Overview. In: Högdal, K., Andersson, U.B., and Eklund, O., (Eds.), *The Transscandinavian Igneous Belt (TIB) in Sweden: a review of its character and evolution*. Geological Survey of Finland Special paper 37, 15–20.
- European Rare Earths Competency Network (ERECON), 2015. *Strengthening of the European Rare Earths Supply Chain – Challenges and policy options*. European Commission, DG GROWTH, 106p.
- Khomyakov, A.P., 1995. *Mineralogy of hyperagpaitic alkaline rocks*. Clarendon, Oxford, 223p.
- LeMaitre, R.W., (Ed.), 2002. *Igneous rocks: A classification and glossary of terms*, 2<sup>nd</sup> ed. Cambridge University Press, 236 pp.
- Schilling, J., Wu, F.-Y., McCammon, C., Wenzel, T., Marks, M.A.W., Pfaff, K., Jacob, D.E., and Markl, G., 2011. The compositional variability of eudialyte-group minerals. *Mineral Magazine*, 75, 87–115.
- Short, M., Moseley, G., Mounde, M., and La Touche, G.D., 2015. *Prefeasibility Study – NI 43-101 – Technical report for the Norra Kärr Rare Earth Element Deposit*. Tasman Metals Ltd., Vancouver, Canada, 384p.
- Sjöqvist, A.S.L., Cornell, D.H., Andersen, T., Erambert, M., Ek, M., and Leijd, M., 2013. Three compositional varieties of rare-earth element ore: Eudialyte-group minerals from the Norra Kärr alkaline complex, southern Sweden. *Minerals*, 3, 94–120.
- Sjöqvist, A.S.L., Cornell, D.H., Andersen, T., Andersson, U.B., Christensson, U.I., Ranjer, S.J.E., Holtstam, D., and Leijd, M., 2014. Geochronology of the Norra Kärr alkaline complex, southern Sweden. Abstract, 31<sup>st</sup> Nordic Geological Winter Meeting, Lund, Sweden, 95p.
- Sørensen, H., 1997. The agpaitic rocks—An overview. *Mineralogical Magazine*, 61, 485–498.
- Sørensen, H., Bailey, J.C., and Rose-Hansen, J., 2011. The emplacement and crystallization of the U–Th–REE-rich agpaitic and hyperagpaitic lujavrites at Kvanefjeld, Ilímaussaq alkaline complex, South Greenland. *Bulletin of the Geological Society of Denmark* 59, 69–92.
- Thulin, H., 1996. Norra Kärr - avsnitt 1 [in Swedish]. *Litofilen*, 1996/1, 17–51.
- Törnebohm, A.E., 1906. Katapleilit-syenit, en nyupptäckt varietet af nefelinsyenit i Sverige [in Swedish]. *SGU Ser. C*, 199, 1–54.

