

# Characterisation of Mining Tailings for the Beneficiation of Rare Earth Elements Minerals

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## Abstract

Presently, South Australia has significant amount of rare earth elements (REE) remaining in mining tailings generated from the extraction of primary commodities such as gold, copper, and uranium. As a result of the complex low-grade nature and varying characteristics of REE minerals in ores, it is important to expand the knowledge of the chemical and mineralogical characteristics, prior to developing beneficiation protocols for REE. This paper reports on the chemical and mineralogical characteristics of a typical South Australian mining tailings for REE beneficiation. Inductively coupled plasma mass spectrometry (ICP-MS) and Quantitative Evaluation of Minerals by Scanning Microscopy (QEMSCAN) were used to identify and characterise the REE and associated gangue minerals in the tailings. The results indicate that: (i) light REE (LREE) are more abundant than heavy REE (HREE); (ii) the REE-bearing minerals in the tailings are bastnäsite, monazite, stetindite, stillwellite, and florencite; and (iii) hematite/magnetite association, goethite/limonite association, and quartz are the major gangue minerals in the tailings. Correlation analysis conducted on the chemical data was useful in predicting the relationship between the REE and non-REE phases although some limitations were encountered. Liberation analysis indicates that the REE minerals are generally unliberated, forming complex middling associations with the gangue minerals. A combination of the chemical and mineralogical analyses provides comprehensive and accurate information on the deportment of REE, as well as their associations with gangue minerals. The data obtained is useful in identifying potential methods for recovering the REE from the mine tailings.

**Keywords:** Bastnäsite, Beneficiation, Florencite, Monazite, Rare earth elements (REE), Stetindite, Stillwellite

## 1 Introduction

Rare earth elements (REE) comprise of the lanthanide series of chemical elements: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). Scandium (Sc) and yttrium (Y) are mostly included in this group of elements because of the similarities in their chemical properties to the lanthanide series. This group of elements are becoming increasingly important due to their pivotal role in modern, high-technology and manufacturing industries (hybrid cars, wind turbines, fuel cells, electronics, medical and defense technologies and metallurgy/specialty alloys) (Geoscience-Australia, 2012; Gupta and

Krishnamurthy, 2004; Haque *et al.*, 2014; Jordens *et al.*, 2013; U.S.G.S, 2018; Zhang and Edwards, 2012; Zhanheng, 2011).

There are no easy substitutes for REE in most of their applications, which has contributed to their increased global demand. Over the past decade China has remained the largest supplier, responsible for over 80% of the global REE demand. Over the years, China's reduction in REE production and export restrictions have highlighted the need for the rest of the world to develop their REE resources (Abaka-Wood, 2019; Abaka-Wood *et al.*, 2016b; Binnemans *et al.*, 2015; Golev *et al.*, 2014).

However, the current efforts to meet the increasing global demand for REE, coupled with the fast depletion of high grade, rich ore reserves have

motivated attempts to examine the feasibility of recovering REE from low grade ores and other unconventional resources such as mining tailings, permanent magnets, electronic wastes, and fluorescent lamps (Binnemanns *et al.*, 2015; Birtel *et al.*, 2015; Dehaine *et al.*, 2017; Filippov *et al.*, 2010; Filippov *et al.*, 2016; Ippolito *et al.*, 2017; Machacek *et al.*, 2015; Pavón *et al.*, 2018).

Australia is among the world's most notable REE producers. A Mineral Resource estimation by the United State Geological Survey (USGS) in February 2018 indicated Australia holds about 3.4 Mt rare earth oxides (REO), representing approximately 2.8% of the economically demonstrated global reserves (U.S.G.S, 2018). However, South Australia is known to host about 83% of the total Australian REO resources, most of which are Submarginal and Inferred resources, mainly in mining tailings (Geoscience-Australia, 2012, 2014).

This study forms part of an ongoing investigation to ascertain the feasibility of recovering REE from South Australian mining tailings. Specifically, the aim of this study is to establish the chemical and mineralogical characteristics of a typical South Australian mining tailings using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Quantitative Evaluation of Minerals by Scanning Microscopy (QEMSCAN) analyses. These characteristics were used to predict possible beneficiation methods which may be exploited to recover the REE.

## 2 Material and Methods Used

## 2.1 Material

A tailings sample obtained from a South Australian mining operation was used in this investigation. ICP-MS and QEMSCAN were employed as quantitative tools to characterise the tailings sample. These characterisation techniques have been identified as effective and efficient in evaluating REE mineralisation in different ores (Abaka-Wood *et al.*, 2016a; Edahbi *et al.*, 2018; Smythe *et al.*, 2013). Particle size distribution of representative tailings samples was determined by laser diffraction using Mastersizer 2000 (Malvern Instruments Ltd., UK). Prior to the measurements, representative subsamples of the material were pulped to 30 wt.% using Milli-Q water at an agitation rate of 800 rpm for 60 min for enhanced particles dispersion.

## 2.2 Methods Used

### 2.2.1 Sample Preparation

In order to obtain representative samples for ICP-MS and QEMSCAN analyses, 10 kg of the tailings was air-dried for 48 h. The dried sample was then rolled out with a cylindrical metal bar to break up agglomerated particles. Effective mixing of the sample was achieved using a macro standard riffle splitter (Carpco, Holland). A micro standard riffle splitter (Laval Lab, Canada) was then used to obtain the required samples for the analyses.

### 2.2.2 ICP-MS analysis

ICP-MS analysis was conducted on representative samples to identify the distribution of elemental species to aid in mineral phase identification. An aliquot of each sample was accurately weighed and fused with lithium metaborate at high temperature in platinum (Pt) crucible. The fused glass was then digested in nitric acid to ensure complete ore dissolution before analysis. The information obtained from this test is crucial in determining the head chemical assay of the material.

With reference to the chemical composition of the sample, correlation analysis was used to study the relationship between the REE and non-REE. Pearson's correlation coefficient which measures the degree of statistical interrelation between two sampled data, was used for this purpose (Ahlgren *et al.*, 2003; Chi *et al.*, 2006; Lu *et al.*, 2002; Sedgwick, 2012). For two sets of measured data  $x = [x_1, x_2, \dots, x_n]$  and  $y = [y_1, y_2, \dots, y_n]$ , Pearson's correlation coefficient ( $r_{xy}$ ) is given by (Chi *et al.*, 2006; Lu *et al.*, 2002; Sedgwick, 2012);

$$r_{xy} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad \dots \dots \dots (1)$$

where;

where  $n$  is the number of measured values in each set of data. When  $|r_{xy}| \geq 0.5$ , a strong relationship between the two chemical species exists and vice versa.

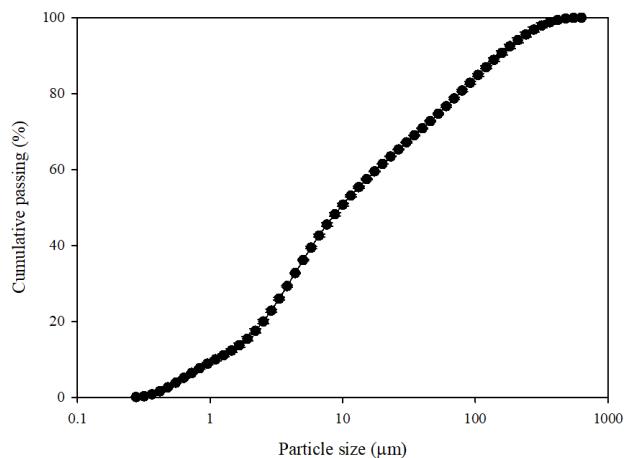
## 2.2.2 QEMSCAN analysis

A subsample of the tailings material was riffled successively to obtain the required mass for the analysis. The sample was then mounted in epoxy resin to produce blocks of cross-sectional diameter, 30 mm, polished and then carbon coated. Manual investigation (with 1 000 000 counts) allowed for developing Species Identification Protocol (SIP) to specify the elemental composition of unclassified phases which were present in the samples. Specific attention was given to the discrimination of REE minerals. The Particle Mineral Analysis (PMA) method of QEMSCAN measurement was used to quantify the percentage mineral mass abundance, liberation, and locking statistics data of the minerals present.

## 3 Results and Discussion

### 3.1 Particle size distribution

The assessment of particle size distribution of samples is crucial in mineral processing. This forms a critical aspect of selecting beneficiation methods. A graphical representation of the particle size distribution of the sample obtained via laser diffraction is presented in Figure 1. The results suggest that most of the particles are fine, with about 90% of the materials finer than 150 µm and 50% finer than 10 µm. With majority of the particles finer than 150 µm, the material may not require further particle size reduction which may prove to be economical, since about half of energy expended in mineral processing is consumed by comminution (Nadolski *et al.*, 2014; Radziszewski, 2013; Wills and Napier-Munn, 2006). However, the dominance of fine particles in the material also highlights the possibility of experiencing significant processing challenges.



**Figure 1 Particle Size Distribution of the Mining Tailings obtained using Laser Diffraction (Mastersizer, 2000)**

### 3.2 Chemical Composition

The results of ICP-MS analysis (Table 1) show that the tailings material is dominated, in terms of REE composition by the light REE (LREE = 97% of REE), in the order Ce>La>Nd>Pr>Sm. Cerium (Ce = 2230 ppm) is the most abundant REE in the material, whereas yttrium (Y = 88 ppm), is the most abundant heavy REE. In terms of the non-REE, the essential elements present include Fe (26.2%), Si (18.6%), and Al (3.9%).

**Table 1 Chemical Composition of the Mining Tailings obtained via ICP-MS Analysis**

REE	Concentration (ppm)	Non-REE	Concentration (%)
La	1530	Al	3.9
Ce	2230	Ca	1.71
Pr	196	Cu	0.057
Nd	534	Fe	26.2
Sm	44	Mg	0.15
Eu	15.5	P	0.15
Gd	30	S	0.31
Tb	3.5	Si	18.6
Dy	20	Th	0.0034
Ho	4	U	0.0165
Er	10		
Tm	2		
Yb	10		
Lu	1.5		
Y	88		

### 3.2.1 Relation between REE Species

Pearson's correlation coefficient analysis conducted on the REE in the samples have been presented in Table A1 of the Appendix. It can be seen from the correlation analysis, that the correlated coefficient values were all positive and generally  $> 0.5$  (except for Lu-Tm), indicating a strong correlation between all the REE. However, the correlation among the LREE (i.e. LREE-LREE) was stronger than those between the LREE-HREE and HREE-HREE. The relatively low coefficient values obtained for Lu and Tm compared to all other REE can be attributed to the significantly low abundance of the elements ( $< 2$  ppm), indicating that both elements are depleted in the material. Although the chemical data suggests that, the LREE are more abundant, the HREE are expected to be mineralised along with the LREE (in trace amount), having identical properties and interactions as the LREE. This agrees with the literature that REE have identical chemical properties as REE generally exists as third valence in compounds (Abaka-Wood *et al.*, 2016b; Chi *et al.*, 2006; Jordens *et al.*, 2013). The strong correlation among the REE is also related to the similarity in REE ionic radii which renders REE interchangeable in most minerals and are consequently very difficult to separate chemically (Krishnamurthy and Gupta, 2015).

### 3.2.2 Relation between REE and non-REE Species

The Pearson's correlation coefficient analysis on selected LREE (La, Ce, Pr, and Nd), Y, and non-REE species in the material is shown in Table A2 of the Appendix section. The relationship between the REE and gangue elements may be crucial in predicting or inferring the mineralogy of REE in relation to gangue minerals. The results indicate  $|r_{xy}| > 0.5$  between REE; and Fe, P, Si, Th, and U, which suggests that the REE could be mineralised as monazite [(Ce, La, Nd, Th, U)PO<sub>4</sub>] or (Ce, La, Th, Ca)(PO<sub>4</sub>, SiO<sub>4</sub>, SO<sub>4</sub>), xenotime (YPO<sub>4</sub>), brannerite [(U, Ca, Y, Ce, La)(Ti, Fe)<sub>2</sub>O<sub>6</sub>] or stetindite (CeSiO<sub>4</sub>) (Abaka-Wood *et al.*, 2017; Bowell *et al.*, 2011; Cheng *et al.*, 1993; Gilligan and Nikoloski, 2015; Salatic, 1967).

Furthermore, the correlated coefficient value of dependency between Fe and Si is 0.97, which suggests a strong association between the iron oxides and silicate minerals. The results also show

that, except for Al and Mg, all other non-REE have strong relation with the REE.

## 3.3 Mineralogical Composition

### 3.3.1 Bulk Ore Mineralogy

Although the correlation analysis provides information on the relationship of the chemical species and may be used to predict some mineral phases, it is not exhaustive, hence the results and projections made need to be confirmed via mineralogical analysis.

Detailed mineralogical examination of a bulk composite sample of the mining tailings conducted via QEMSCAN analysis (Table 2) indicated that, the essential minerals present are mainly silicate minerals including quartz, illite, muscovite, annite and feldspar; and iron oxides (hematite/magnetite and goethite/limonite). Quartz and magnetite-hematite are the major gangue minerals in the material, with mass abundances of 29.53% and 20.66%, respectively.

The content of valuable REE bearing minerals is 1.11%, that includes critical and strategic minerals such as bastnäsite, monazite, stetindite, brannerite, florencite and stillwellite, in sub-economic values as shown in Table 2. Bastnäsite makes up about 82% of the total REE minerals, followed by monazite, making up only approximately 6%; hence bastnäsite is the major REE mineral in the ore.

For most mineral phases identified during the QEMSCAN analysis, there was a good agreement with the chemical data obtained via ICP-MS and correlation analyses. For example, through the correlation analysis it was predicated that the REE were mineralised as monazite, brannerite and stetindite. On the other hand, the analysis could not identify bastnäsite as one of the REE minerals, which is an example of the limitation of the correlation analysis. Also, no Y/HREE bearing mineral was identified (e.g. xenotime), as predicted during the correlation analysis.

### 3.3.2 Liberation Characteristics of REE Minerals

The mass percentage of the REE minerals in each liberation class was determined and the results presented in Figure 2. The minerals were grouped in terms of percentage of mineral's surface exposure

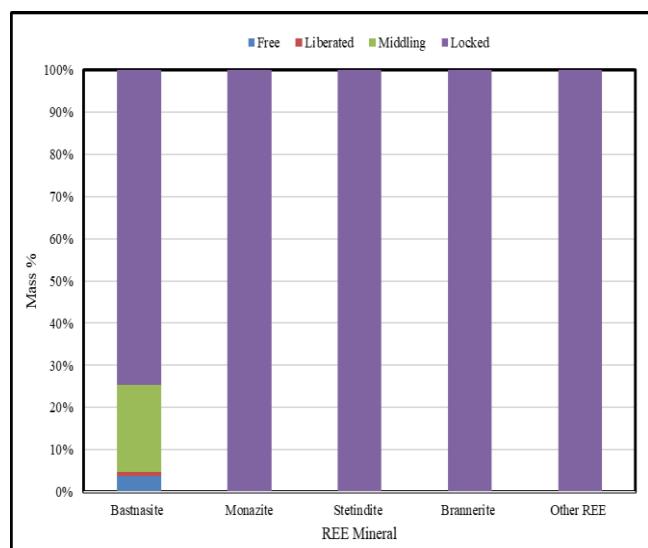
( $x$ ) as free (100%), liberated ( $80 < x < 100\%$ ), middling ( $50 < x \leq 80\%$ ) and locked ( $x \leq 50\%$ ).

From Figure 2, the REE minerals are generally locked in the various gangue minerals. For example, the results suggest that except for bastnäsite, the remaining REE minerals are completely locked in the gangue minerals. Approximately 4% of the bastnäsite particles are free, whereas 21% form complex middling with the gangue minerals and 75% are locked.

**Table 2 The Mass Abundance (%) of Minerals in Tailings Sample obtained via QEMSCAN Analysis**

Mineral	Description	Mineral Mass (%)
Bastnäsite	(Ce, La, Y)CO <sub>3</sub> F associations. Ce predominated	0.91
Monazite	(Ce,La)PO <sub>4</sub> associations. Ce predominated	0.07
Stetindite	CeSiO <sub>4</sub> associations, predominated by Ce	0.05
Other REE	Stillwellite and florencite associations	0.02
Quartz	SiO <sub>2</sub> associations	29.53
Muscovite	(KF) <sub>2</sub> (Al <sub>2</sub> O <sub>3</sub> ) <sub>3</sub> (SiO <sub>2</sub> ) <sub>6</sub> associations	8.82
Annite	KFe <sub>3</sub> <sup>2+</sup> AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub> associations	4.76
Illite	K <sub>1-x</sub> (Al,Mg,Fe) <sub>2</sub> (Si,Al) <sub>4</sub> O <sub>10</sub> associations	4.65
Feldspar	Orthoclase, plagioclase, albite, anorthite, associations	1.26
Kaolinite-Serpentine	Kaolinite, berthierine, serpentine associations	1.09
Nontronite	Na <sub>0.3</sub> Fe <sub>2</sub> ((Si,Al) <sub>4</sub> O <sub>10</sub> ) associations	0.25
Other Silicates	Minnesotaite, biotite, amphibole, pyrophyllite, chlorite associations	1.59
Magnetite/Hematite	Magnetite and hematite associations	20.66
Goethite/Limonite	Goethite and limonite associations	14.70
Wustite	FeO associations	4.62
Rutile-Ilmenite	Ti-oxide, FeTi-oxide associations	0.17
Uraninite	UO <sub>2</sub> and U <sub>3</sub> O <sub>8</sub> associations	0.92
Coffinite	USiO <sub>4</sub> associations	0.29
Brannerite	(U, Ca, Ce)(Ti, Fe) <sub>2</sub> O <sub>6</sub> associations	0.06
Fluorite	CaF <sub>2</sub> associations	2.36
Siderite	FeCO <sub>3</sub> associations	0.76

Other Carbonates	Calcite, ankerite associations	0.57
Baryte	BaSO <sub>4</sub> and Ba-S-O associations	0.73
Sulphides	Chalcocite, covellite, chalcopyrite, pyrite, associations	0.95
Others	Apatite, halite, anhydrite, and other unclassified phases	0.22



**Figure 2 REE Minerals Liberation Characteristics in the Tailings Material**

### 3.4 Possible Beneficiation Methods

The economic beneficiation of bastnäsite, and monazite has been well documented (Abaka-Wood *et al.*, 2018; Cao *et al.*, 2019; Ferron *et al.*, 1991; Özbayoğlu and Atalay, 2000). Typically, most REE are recovered via caustic leaching methods or sulphuric acid baking-water leaching process, after preconcentration using physical separation (including magnetic, gravity, desliming and electrostatic) and froth flotation (Abaka-Wood *et al.*, 2016b; Faris *et al.*, 2019; Jordens *et al.*, 2013).

It can be seen from the results that the grade of REE minerals in the tailings material is dramatically low compared to the other minerals. The need to reject the gangue minerals by exploiting the differences in the physical properties prior to extraction of REE is crucial in achieving high quality REE products, as well as reducing the usage and cost of chemical process.

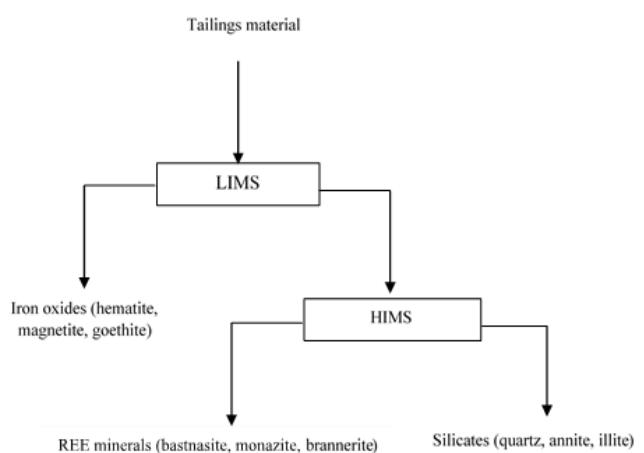
Physical characteristics that may be considered in the beneficiation process may include specific

gravity and magnetic properties of the minerals. Particle size distribution among other factors is paramount in selecting unit operations for REE minerals beneficiation. From the processing point of view, the particle size range of the tailings material may be ideal for both magnetic and gravity separation (Wills and Napier-Munn, 2006).

The magnetic properties of the key gangue and REE minerals in the material have been summarized in Table 3. Magnetic separation utilises the differences in the behaviour of the mineral of interest and gangue minerals in magnetic fields. Bastnäsite and monazite (which make up about 88% of the REE minerals) are weakly paramagnetic (Abaka-Wood *et al.*, 2016a; Jordens *et al.*, 2013). Theoretically, to achieve significant separation, the iron oxides (ferromagnetic/strongly paramagnetic) may be rejected at lower magnetic field intensities, whilst concentrating the weakly paramagnetic REE minerals at higher magnetic field intensities from the silicate minerals. This may be achieved by a combination of low intensity magnetic separator (LIMS) and high intensity magnetic separator (HIMS) as presented in Figure 3.

**Table 3 Magnetic Properties of Selected Minerals in the Tailings Material**

Mineral	Magnetic property
Bastnasite	Paramagnetic
Monazite	Paramagnetic
Stetindite	-
Brannerite	Paramagnetic
Stillwellite	-
Florencite	-
Quartz	Diamagnetic
Muscovite	Paramagnetic
Annite	Diamagnetic
Illite	Diamagnetic
Hematite	Weakly ferromagnetic/strongly paramagnetic
Magnetite	Ferromagnetic
Goethite	Weakly ferromagnetic/strongly paramagnetic
Limonite	Weakly ferromagnetic/strongly paramagnetic
Wustite	Ferromagnetic



**Figure 3 Theoretical Flowsheet for Upgrading REE Minerals via Magnetic Separation**

Gravity concentration involves the separation of minerals of different specific gravities by their relative movement in response to forces acting (gravitation/centrifugal, buoyant and drag forces) on particles in a viscous medium such as heavy media, water or, less commonly, air (Wills and Napier-Munn, 2006).

Concentration criterion, which is used to assess the feasibility of separating minerals is given by;

$$\text{Concentration criterion (CC)} = \frac{D_h - D_f}{D_l - D_f} \quad \dots\dots(4)$$

where  $D_f$  is the specific gravity of the fluid,  $D_l$  and  $D_h$  are the specific gravities of the light and heavy minerals, respectively. It has been suggested that the efficiency of separation decreases with decreasing value of CC, with  $CC \geq /2.5/$ , implying easy separation (Wills and Napier-Munn, 2006).

The CC for bastnäsite and monazite (REEM) separation from the main gangue minerals have been summarised in Table 4. The data indicate that separation of REEM from iron oxides may not be feasible, whereas REEM from silicates may be theoretically feasible.

**Table 4 Concentration Criterion for Separation of REE Minerals (REEM) from Selected Gangue Minerals in the Tailings Material**

Species separation	CC
REEM/Quartz	2.56
REEM /Muscovite	2.25
REEM /Annite	1.89
REEM /Illite	2.35
REEM /Hematite	0.95

REEM /Magnetite	0.99
REEM /Goethite	1.46
REEM /Limonite	1.64
REEM /Wustite	0.82

CC may be misleading, as particle characteristics (e.g. liberation, size) play key role in gravity separation. This has been extensively proved through detailed and systematic investigation by Abaka-Wood *et al.* (2019).

Froth flotation utilises the differences in the surface wettability of minerals to effect separation. This separation technique has been predominantly exploited in the beneficiation of REE minerals from ores of varying mineralogical compositions. Mineral particles may range from ones which have affinity for water, referred to as hydrophilic and those that tend to repel water known as hydrophobic (Abaka-Wood *et al.*, 2016b; Abaka-Wood *et al.*, 2017, 2018; Filippov *et al.*, 2010; Filippov *et al.*, 2016; Gupta and Krishnamurthy, 2004). Collectors such as oleic acid, linoleic acid, sodium oleate, alkyl hydroxamic acid, dodecylamine, naphthenic acid, sodium dodecyl sulphate, N-hydroxyl phthalicimide, and styrophosphonic acid may be used to enhance the hydrophobicity of REE minerals, whilst sodium silicate, starch, sodium sulphide, tartaric and citric acids may be introduced during flotation to render the gangue minerals hydrophilic (Abaka-Wood *et al.*, 2016b; Abaka-Wood *et al.*, 2017; Dehaine *et al.*, 2017; Gupta and Krishnamurthy, 2004; Jordens *et al.*, 2013).

## 4 Conclusions

The results from this study indicated that ICP-MS and QUEMSCAN analyses can be used to determine the chemical and mineralogical characteristics of complex low-grade REE bearing tailings material. ICP-MS analysis revealed that the tailings material was enriched with LREE with almost depleted HREE content. QUEMSCAN analysis conducted on the material provided detailed mineralogical data of the material. Bastnäsite, monazite, stetindite, brannerite, florencite, and stillwellite were identified as the REE-bearing minerals.

Furthermore, quartz and hematite/magnetite associations were found to be the main gangue minerals. The REE minerals are generally unliberated, forming complex middling associations with the gangue minerals.

The data obtained from ICP-MS and QUEMSCAN analyses are essential in ore characterisation with respect to selecting metallurgical parameters to aid in REE extraction. Magnetic and gravity separation were identified as potential physical separation unit operations alongside froth flotation, for REE minerals beneficiation.

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## References

- Abaka-Wood, G.B. (2019), "Beneficiation of Rare Earth Elements Minerals from Tailings as an Analogue of Complex Low Grade Ores", *PhD Thesis in Minerals, Materials, and Resources Engineering*, Future Industries Institute, University of South Australia, Adelaide, Australia, 268 pp.
- Abaka-Wood, G.B., Addai-Mensah, J., Skinner, W (2016a), "Magnetic separation of monazite from mixed minerals", in: Chemeca (Ed.), *Chemeca Conference 2016*. Engineers Australia, Adelaide, Australia, pp. 605-612.
- Abaka-Wood, G.B., Addai-Mensah, J., Skinner, W. (2016b), "Review of flotation and physical separation of rare earth element minerals", *4th UMaT Biennial International Mining and Minerals Conference*, Tarkwa, Ghana, pp. MR 55-62.
- Abaka-Wood, G.B., Addai-Mensah, J., Skinner, W. (2017), "Selective flotation of rare earth oxides from hematite and quartz mixtures using oleic acid as a collector", *International Journal of Mineral Processing*, Vol. 169, pp. 60-69.
- Abaka-Wood, G.B., Addai-Mensah, J., Skinner, W. (2018), "A study of selective flotation recovery of rare earth oxides from hematite and quartz using hydroxamic acid as a collector", *Advanced Powder Technology*, Vol. 29, pp. 1886-1899.
- Abaka-Wood, G.B., Quast, K., Zanin, M., Addai-Mensah, J., Skinner, W. (2019), "A study of the feasibility of upgrading rare earth elements minerals from iron-oxide-silicate rich tailings using Knelson concentrator and Wilfley shaking table", *Powder Technology*, Vol. 344, pp. 897-913.
- Ahlgren, P., Jarneving, B., Rousseau, R. (2003), "Requirements for a cocitation similarity measure, with special reference to Pearson's correlation coefficient", *Journal of the Association for Information Science and Technology*, Vol. 54, pp. 550-560.

- Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Pontikes, Y. (2015), "Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review", *Journal of Cleaner Production*, Vol. 99, pp.17-38.
- Birtel, S., Kern, M., Höfig, T.W., Krause, J., Gutzmer, J. (2015), "Geometallurgical Assessment: Beneficiation of Rare Earth Minerals as a Possible By-Product from the Vergenoeg Fluorite Mine, South Africa", in: André-Mayer AS, Cathelineau, M., Muchez, P., Pirard, E., Sindern, S. (Eds.), *13th SGA Biennial Meeting 2015*, Nancy, France, pp. 1383-1386.
- Bowell, R., Grogan, J., Hutton-Ashkenny, M., Brough, C., Penman, K., Sapsford, D.J. (2011), "Geometallurgy of uranium deposits", *Minerals Engineering*, Vol. 24, pp. 1305-1313.
- Cao, Z., Cao, Y., Qu, Q., Zhang, J., Mu, Y. (2019), "Separation of bastnäsite from fluorite using ethylenediamine tetraacetic acid as depressant", *Minerals Engineering*, Vol. 134, pp. 134-141.
- Cheng, T.-W., Holtham, P., Tran, T. (1993), "Froth flotation of monazite and xenotime", *Minerals Engineering*, Vol. 6, pp. 341-351.
- Chi, R.-A., Dai, Z.-X., Xu, Z.-G., Wu, Y.-X., Wang, C.-W. (2006), "Correlation analysis on partition of rare earth in ion-exchangeable phase from weathered crust ores", *Transactions of Nonferrous Metals Society of China*, Vol. 16, pp. 1421-1425.
- Dehaine, Q., Filippov, L.O., Jousset, R. (2017), "Rare earths (La, Ce, Nd) and rare metals (Sn, Nb, W) as by-products of kaolin production – Part 2: Gravity processing of micaceous residues", *Minerals Engineering*, Vol. 100, pp. 200-210.
- Edahbi, M., Benzaazoua, M., Plante, B., Doire, S., Kormos, L. (2018), "Mineralogical characterization using QEMSCAN® and leaching potential study of REE within silicate ores: A case study of the Matamec project, Québec, Canada", *Journal of Geochemical Exploration*, Vol. 185, pp. 64-73.
- Faris, N., Ram, R., Tardio, J., Bhargava, S., Pownceby, M.I. (2019), "Characterisation of a ferruginous rare earth bearing lateritic ore and implications for rare earth mineral processing", *Minerals Engineering*, Vol. 134, pp. 23-36.
- Ferron, C.J., Bulatovic, S.M., Salter, R.S. (1991), "Beneficiation of rare earth oxide minerals", *Materials Science Forum*, Trans Tech Publ, pp. 251-270.
- Filippov, L., Filippova, I., Severov, V. (2010), "The use of collectors mixture in the reverse cationic flotation of magnetite ore: The role of Fe-bearing silicates", *Minerals Engineering*, Vol. 23, pp. 91-98.
- Filippov, L.O., Dehaine, Q., Filippova, I.V. (2016), "Rare earths (La, Ce, Nd) and rare metals (Sn, Nb, W) as by-products of kaolin production – Part 3: Processing of fines using gravity and flotation", *Minerals Engineering*, Vol. 95, pp. 96-106.
- Geoscience-Australia, (2012), "Australia's Identified Mineral Resources 2011", *Geoscience Australia*, Canberra, pp. 72-78.
- Geoscience-Australia (2014), "Australia's Identified Mineral Resources 2013", *Geoscience Australia*, Canberra, pp. 107 - 115.
- Gilligan, R., Nikoloski, A.N. (2015), "The extraction of uranium from brannerite—A literature review", *Minerals Engineering*, Vol. 71, pp. 34-48.
- Golev, A., Scott, M., Erskine, P.D., Ali, S.H., Ballantyne, G.R. (2014), "Rare earths supply chains: Current status, constraints and opportunities", *Resources Policy*, Vol. 41, pp. 52-59.
- Gupta, C.K., Krishnamurthy, N. (2004), *Extractive metallurgy of rare earths*, CRC press, Florida.
- Haque, N., Hughes, A., Lim, S., Vernon, C. (2014), "Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact", *Resources*, Vol. 3, pp. 614-635.
- Ippolito, N.M., Innocenzi, V., De Michelis, I., Medici, F., Vegliò, F. (2017), "Rare earth elements recovery from fluorescent lamps: a new thermal pretreatment to improve the efficiency of the hydrometallurgical process", *Journal of Cleaner Production*, Vol. 153, pp. 287-298.
- Jordens, A., Cheng, Y.P., Waters, K.E. (2013), "A review of the beneficiation of rare earth element bearing minerals", *Minerals Engineering*, Vol. 41, pp. 97-114.
- Krishnamurthy, N., Gupta, C.K. (2015), *Extractive metallurgy of rare earths*, 2 ed. CRC press, 869 pp.
- Lu, W., Zhu, Y., Sha, J., Zhu, H. (2002), "SPSS for Windows statistical analysis", *Publishing House of Electronics Industry*, Beijing.
- Machacek, E., Richter, J.L., Habib, K., Klossek, P. (2015), "Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties", *Resources, Conservation and Recycling*, Vol. 104, pp. 76-93.
- Nadolski, S., Klein, B., Kumar, A., Davaanyam, Z. (2014), "An energy benchmarking model for mineral comminution", *Minerals Engineering*, Vol. 65, pp. 178-186.
- Özbayoğlu, G., Atalay, M.Ü. (2000), "Beneficiation of bastnaesite by a multi-gravity separator", *Journal of alloys and compounds*, Vol. 303, pp. 520-523.
- Pavón, S., Fortuny, A., Coll, M., Sastre, A. (2018), "Rare earths separation from fluorescent lamp

- wastes using ionic liquids as extractant agents", *Waste management*, Vol. 82, pp. 241-248.
- Radziszewski, P. (2013), "Energy recovery potential in comminution processes", *Minerals Engineering*, Vol. 46, pp. 83-88.
- Salatic, D., 1967. Floatability of monazite and zircon related to electrochemical changes on their surfaces. *Trans. IMM*, C231-237.
- Sedgwick, P. (2012), "Pearson's correlation coefficient", *BMJ: British Medical Journal (Online)* pp. 345.
- Smythe, D.M., Lombard, A., Coetzee, L.L. (2013), "Rare Earth Element deportment studies utilising QEMSCAN technology", *Minerals Engineering*, Vol. 52, pp. 52-61.
- U.S.G.S. (2018), "Mineral commodity summaries 2018, in: Survey", U.S.G. (Ed.). *U.S. Geological Survey*, Washington, 200 pp.
- Wills, B.A., Napier-Munn, T.J. (2006), *Wills' Mineral Processing technology: An introduction to the practical aspects of ore treatment and mineral recovery*, 7 ed. Elsevier Science & Technology Books, 444 pp.
- Zhang, J., Edwards, C. (2012), "A review of rare earth mineral processing technology", *44th Annual Meeting of the Canadian Mineral Processors*, CIM, Ottawa, Canada, pp. 79–102.
- Zhanheng, C. (2011), "Global rare earth resources and scenarios of future rare earth industry", *Journal of Rare Earths*, Vol. 29, pp. 1-6.

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## APPENDIX

**Table A1 Pearson's Correlation Coefficient Matrix among 15 REE in the Mining Tailings**

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
La	1.00	1.00	1.00	0.99	0.99	0.89	0.97	0.88	0.87	0.89	0.91	0.77	0.87	0.74	0.98
Ce		1.00	0.99	0.98	0.99	0.87	0.96	0.86	0.85	0.89	0.90	0.73	0.85	0.74	0.98
Pr			1.00	1.00	0.99	0.92	0.98	0.91	0.90	0.93	0.93	0.80	0.90	0.76	0.99
Nd				1.00	0.98	0.95	1.00	0.94	0.94	0.95	0.95	0.83	0.94	0.78	0.99
Sm					1.00	0.88	0.96	0.87	0.86	0.90	0.89	0.73	0.86	0.80	0.98
Eu						1.00	0.96	0.98	0.99	0.95	0.94	0.92	0.98	0.75	0.92
Gd							1.00	0.96	0.96	0.97	0.97	0.86	0.96	0.79	0.99
Tb								1.00	0.99	0.98	0.96	0.93	0.99	0.70	0.92
Dy									1.00	0.97	0.97	0.92	1.00	0.74	0.92
Ho										1.00	0.96	0.84	0.96	0.78	0.93
Er											1.00	0.85	0.97	0.74	0.96
Tm												1.00	0.92	0.50	0.81
Yb													1.00	0.76	0.93
Lu														1.00	0.79
Y															1.00

**Table A2 Pearson's Correlation Coefficient Matrix among Key REE and non-REE in the Mining Tailings**

	La	Ce	Pr	Nd	Y	Al	Ca	Cu	Fe	Mg	P	S	Si	Th	U
La	1.00	1.00	1.00	0.99	0.98	0.10	0.51	-0.51	0.69	0.18	0.94	0.91	-0.79	0.93	0.58
Ce		1.00	0.99	0.98	0.98	0.06	0.49	-0.51	0.71	0.13	0.93	0.89	-0.81	0.94	0.57
Pr			1.00	1.00	0.99	0.09	0.59	-0.45	0.69	0.23	0.93	0.89	-0.81	0.92	0.64
Nd				1.00	0.99	0.09	0.64	-0.41	0.70	0.27	0.92	0.88	-0.83	0.90	0.70
Y					1.00	0.03	0.59	-0.50	0.75	0.20	0.92	0.90	-0.87	0.89	0.79
Al						1.00	-0.05	0.34	-0.61	0.76	0.39	0.37	0.44	-0.09	-0.24
Ca							1.00	0.26	0.43	0.56	0.44	0.33	-0.60	0.42	0.94
Cu								1.00	-0.67	0.62	-0.41	-0.50	0.55	-0.55	0.06
Fe									1.00	-0.36	0.46	0.42	-0.97	0.71	0.65
Mg										1.00	0.38	0.31	0.12	-0.04	0.37
P											1.00	0.97	-0.61	0.79	0.44
S												1.00	-0.62	0.72	0.39
Si													1.00	-0.76	-0.78
Th														1.00	0.51
U															1.00