MINERALPRODUKSJON

Research paper

Mineral characterization with focus on iron in processed granitic pegmatite, Southern Norway

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ABSTRACT

Occurrence of Fe-containing minerals in processed granitic pegmatite (Glamsland pegmatite field, Norway) has been quantified and compared to the occurrence of Fe minerals in the original raw material. Process mineralogical investigations including semi-quantitative X-ray Fluorescence (XRF), and quantitative methods like point counting (optical microscope), image analysis (IA) of Back Scatter Electron (BSE) images and mineral chemistry by Electron Probe Micro Analysis (EPMA) have been used. From this quantification, historical claims concerning quality differences in the raw materials are confirmed, and the reason why some raw materials are easier to process than others can be explained. The existing beneficiation process easily removes mineral particles rich in iron if the particles are present as free mineral grains, but if the iron-rich minerals are present as interlocked grains they will not be removed to the same extent. Altered minerals may create trouble through flotation. This may be explained due to splitting along grain boundaries and micro fractures creating slime, something that lowers the efficiency of the process.
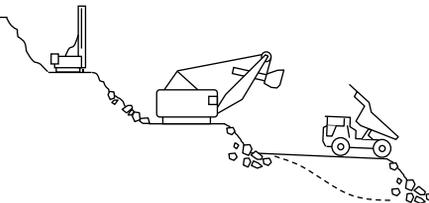
I. INTRODUCTION

In previous work (Hestnes and Sørensen, 2012; Hestnes et al., 2013) the nature of granitic pegmatite as a raw material for production of feldspar and quartz used in products like porcelain, ceramics, glass and glass fibre have been investigated. In these investigations the occurrence of iron, as the main quality parameter, has been of particular focus due to its colouring effect in further processes. Because of the general heterogeneous nature of pegmatites, regarding grain size, texture and chemistry, the Fe content in a mineral concentrate need not be directly dependent on the Fe content in the raw material source. Thus, the evaluation of the potential of a pegmatite deposit as a raw material for industrial purposes is not straightforward, and generally must be related to a specific beneficiation process.

In this paper processed material which has been treated according to a laboratory procedure replicating parts of the full scale process of Sibelco Nordic, Lillesand, has been compared with the raw material presented in Hestnes et al. (2013). The raw material is granitic pegmatite from three different deposits in the Glamsland pegmatite field, Southern Norway, formerly mined by Sibelco Nordic, Lillesand. As in earlier works on this raw material, the focus in the investigation will be on the feldspar minerals since Fe in quartz from the Glamsland deposits is known to be stable and low in Fe2O3 (Sibelco Nordic, 2010).

The work presented is process mineralogical investigations, with an aim of comparing the occurrence of iron in the key raw materials with their corresponding processed materials. The paper will try to explain the different behaviour of the raw materials in the mineral beneficiation process, and why they give different product qualities. Due to the process mineralogical approach of the investigation no attempts on making changes to the full scale process are made. This process mineralogical knowledge will be of value for exploration in the Glamsland pegmatite field in particular, and for industrial granite pegmatites in general.

2. EXPERIMENTAL

2.1 Materials

In the period 1968-2011 the granitic pegmatites from the Glamsland pegmatite field was mined, with three deposits of importance in the last decade. These three were Lørdagsheia (LH), the C-deposit (C) and the Heståsknipen (HK). The materials investigated in this study were granitic pegmatites (raw material) from these three deposits, which were pre-treated in the laboratory procedure described in chapter 2.2. Mineralogical characterizations of the raw materials were described in Hestnes et al. (2013), and some of the data from this investigation will be used in the study presented here. The mineralogy of the raw materials consists of the main minerals quartz (qtz), albite (ab), and microcline (mc), minor minerals are muscovite (mu) and biotite (bt), and trace minerals are garnet and sulphides like pyrite and pyrrhotite (Hestnes, 2012a, b). Chlorite has also been found by image analysis (IA) performed on back scatter electron (BSE) images (Hestnes et al., 2013).

Experience from the Sibelco Nordic, Lillesand, dressing plant has shown that different raw materials behave differently in the beneficiation process, and give products of different quality. This experience was used to label different areas of the deposits as suitable for different product qualities, thereby defining the key raw material types of the Glamsland pegmatite field (Hestnes et al., 2013). Three key

raw materials have been investigated; one (LRT1) known to give the best quality product, and two (LRT3 and LRT4) of lower quality. LRT3 is known to create problems in the beneficiation process, while both LRT3 and LRT4 are known to give lower quality products that had to be blended before shipment to customers.

2.2 Sample preparation

The sample preparation was performed according to a laboratory procedure (Hestnes, 2012c) that replicated parts of the beneficiation process at Sibelco Nordic, Lillesand (Pers. Comm. Johannessen, 2008) (Figure 1). The laboratory procedure consisted of two parts; the first part included sieving, crushing, grinding and desliming; while the second part included removal of Fe-containing minerals through flotation and magnetic separation. The raw materials (fraction size ~1-150 mm) were subjected to jaw crushing to ensure that all the material would pass a 1.68 mm sieve. The crushing was conducted in four consecutive stages. The 1.68 mm fraction was retrieved prior to each stage in order to avoid over-crushing of the material. After crushing, the material was ground in batches in a polyurethane-coated laboratory mill (inner diameter of 250 mm, length of 150 mm) using a 4.0 kg predefined charge of steel grinding balls. Each batch comprised 1.0 kg solid feed and 1.0 L water. The ball mill was run at constant speed of 72 revolutions per minute (RPM) (85 % of critical speed) for 20 minutes. After grinding the pulp was deslimed and split into raw material samples and processed material samples. The raw material samples were dried and sieved before further analysis, while the processed material samples were scrubbed, deslimed again before conditioning and flotation. The flotation was a reverse flotation process removing mica and iron-bearing minerals. After flotation the product from the processed material samples was dried before it was subjected to high intensity magnetic separation using a Carpo magnetic separator. A magnetic field of 5A and 35 revolutions per second (RPS) was used to remove iron containing minerals.

Both the raw materials samples and the final products from the processed samples were then sieved to produce the following size fractions; >600 μm, 500-600 μm, 425-500 μm, 300-425 μm, 212-300 μm, 150-212 μm, 75-150 μm and <75 μm. For this study three of the fraction sizes were investigated further; 75-150 μm, 212-300 μm, and 425-500 μm. In this paper these fraction sizes are defined as +75 (75-150 μm), +212 (212-300 μm), and +425 (425-500 μm). The fraction samples were either used as bulk samples or as polished thin sections in the investigations performed. For LPT1 fraction +425 no thin section was made due to an insufficient amount of available material.
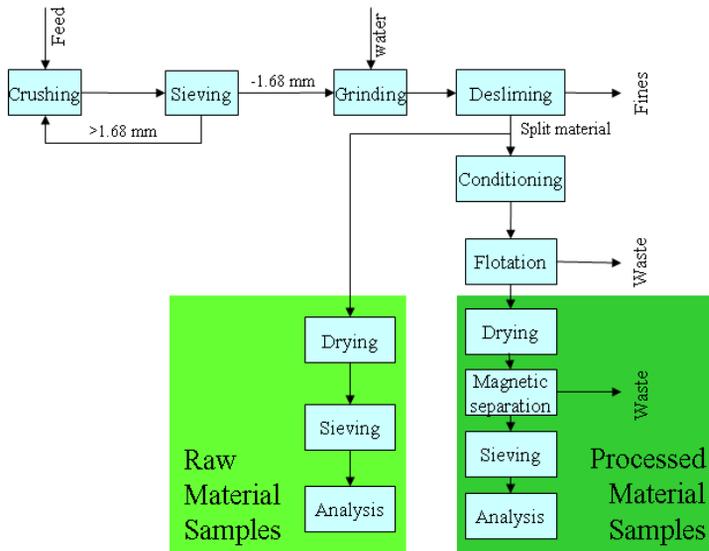
Figure 1. Flow sheet describing the first part of the laboratory procedure, the preparation of the sample material.

1. The fraction samples for bulk analysis were ground further in laboratory mills of agate with agate grinding element, and then pressed to powder tablets.

2. The polished thin sections were made by cementation of the fractionated material with epoxy resin (EPOTEK-301, 2012).

From observation of the flotation process preformed in the laboratory, the green pegmatite (T3) created more slime than the other two key materials. This knowledge have also been reported from the full scale process (Pers. Comm. Johannessen), claiming that raw materials that are of a more altered type will split along the wet process creating slime, lower the efficiency of the flotation process and consume more chemicals than raw materials that are less altered.

2.3 Methods

Bulk chemistry was analysed by XRF on powder tablets at the Sibelco Nordic, Lillesand laboratory. The instrument was an ARL Advant'XP instrument with Thermo software. Instrument conditions; electric current 70 mA, voltage 40 kV, analyse time 160 seconds. The samples were analysed using a program specified for the material analysed based on international standards, and the results were given as content of SiO2, Al2O3, total-Fe2O3, K2O, Na2O, MgO, CaO, and TiO2.

Point counting (Glagolev, 1934, Chayes, 1956, Hetzner, 1998) was performed on polished thin sections to quantify the defined particle classes (Table 1) of the fractionated material using an optical microscope of type Nikon Optiphot. The settings of the microscope were Oculars CFW 10x, objective lens of M Plan 5 DIC 0.1 NA and M Plan 10 DIC 0.25 NA. The point counting instrument used was a PELCON Point counter (Pelcon Point Counter software Version 1.8) and a key-pad of 9 digits (Sandberg Auto gear). The particle classes were defined based on textural aspects such as intergrowths and alteration in the minerals. Epoxy is extracted from the results by recalculating the content of the other particle classes.

Table 1. Point counting classes.

Point counting class	Mineral
Qtz	Quartz
Mc pure	Microcline
Mc perthites	Microcline with perthites
Mc altered	Altered microcline
Ab altered (1)	Albite with some alteration
Ab altered (3)	Albite which is strongly altered
Bt	Biotite
Mu	Muscovite
Epoxy	Epoxy

To quantify inclusions and intergrowths in the feldspar mineral quantitative Image Analysis (IA) was performed on Back Scatter Electron (BSE) images based on grey level intensities (Goldstein et al., 2003, Reed, 2005). For the IA a Hitachi SU 6600 Scanning Electron Microscope with Bruker Quantax 800 Espirit 1.9.3.3047 software were used. Instrument settings during analysis were; probe current 18 mA, voltage 20 kV / 31μA, working distance 15 mm. Energy dispersive spectrometry (EDS) helped to connect grey level in the BSE images to mineralogy. The output of the IA was an area % (image resolution 4096x3072 pixels), which was recalculated into weight % using the feature area measured and defined mineral densities from Deer et al. (1992). As previously stated quartz has not been focused on in this investigation, and therefore only albite and microcline particles were analysed. To prevent mistakes regarding content of quartz being mistakenly recognized as albite a number of analysis was checked by Energy Dispersive Spectroscopy (EDS) for chemical content. The number of particles quantified for each processed material is approximately 25 albite particles and 25 microcline particles. The precision was 1 decimal in the reported results.

Because bulk chemistry analysed at Sibelco Nordic, Lillesand, reports the values of Fe as Fe_2O_3 this is also the notation of Fe-oxides that will be reported in this paper. This is done to make it easier to compare results from different analysis methods, and for methods that reports the Fe values as FeO these values have been recalculated to Fe_2O_3.

3. RESULTS

3.1 Bulk Chemistry

The bulk chemistry of both raw material (Hestnes et al., 2013) and processed material is presented in Table 2. From these results it can be seen that the content of Fe2O3 is reduced after treatment in the beneficiation process. This is illustrated in Figure 2. Also the content of TiO2 and MgO is reduced. For content of MgO the values for the processed materials are below the detection limit of 0.002 Wt.%.

Table 2. XRF results of raw material (LR) and processed material (LP). For content of MgO some values are below the detection limit, and are termed bdl = below detection limit. Normalized values.

| Deposit area	Rock type	Key material	Fraction	Chemistry (Wt. %)							
				SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	TiO_2	MgO
Lørdagsheia	Pink pegmatite	LRT1	+ 425	78.19	12.31	0.81	3.73	3.97	0.84	0.046	0.110
			+ 212	76.29	13.54	0.65	4.19	4.34	0.90	0.032	0.064
			+ 75	74.90	14.44	0.45	4.69	4.56	0.92	0.019	0.021
		LPT1	+ 425	79.05	12.20	0.04	3.71	4.13	0.84	0.002	Bdl
			+ 212	76.97	13.42	0.04	4.18	4.47	0.91	0.001	Bdl
			+ 75	74.53	14.88	0.04	4.79	4.80	0.96	0.002	Bdl
Heståsknipen	Green pegmatite	LRT3	+ 425	78.72	11.88	0.87	3.75	3.75	0.89	0.044	0.089
			+ 212	76.45	13.36	0.74	4.05	4.27	1.03	0.032	0.058
			+ 75	74.75	14.57	0.51	4.39	4.66	1.08	0.018	0.019
		LPT3	+ 425	80.48	11.63	0.08	1.83	4.74	1.21	0.001	Bdl
			+ 212	78.03	13.16	0.08	2.02	5.32	1.38	0.001	Bdl
			+ 75	76.27	14.25	0.08	2.28	5.62	1.48	0.001	Bdl
C-deposit	Red pegmatite	LRT4	+ 425	80.68	11.34	0.38	1.86	4.50	1.19	0.016	0.026
			+ 212	78.40	12.77	0.42	1.98	5.06	1.36	0.011	0.013
			+ 75	76.33	14.09	0.36	2.24	5.52	1.46	0.007	0.001
		LPT4	+ 425	80.48	11.27	0.10	3.74	3.59	0.80	0.001	Bdl
			+ 212	78.08	12.77	0.09	3.90	4.19	0.95	0.001	Bdl
			+ 75	76.03	14.03	0.09	4.27	4.54	1.03	0.001	Bdl
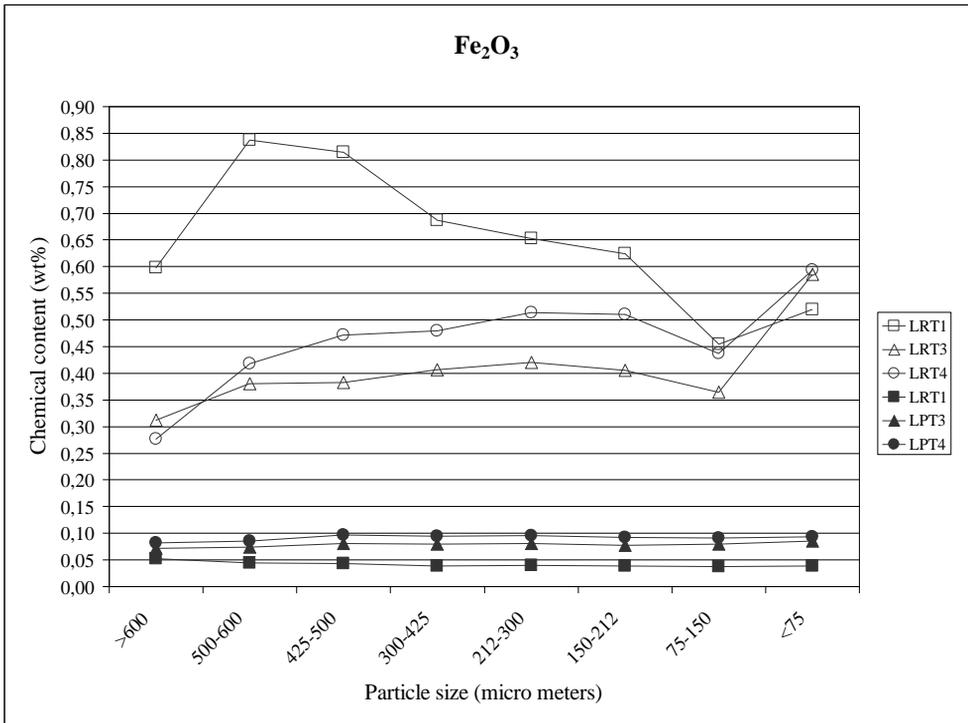
Figure 2. Content of Fe2O3 in the key raw materials and their corresponding processed equivalents.

3.2 Mineralogy

Point counting on polished thin sections was applied to quantify the mineralogical content in the chosen fraction sizes of the processed materials. Table 3 includes point counting of the raw material from Hestnes et al. (2013) compared with the results from point counting of the processed material. These results were further used in the calculation of the distribution of Fe in the different mineral particles.

IA was performed on BSE images of polished thin sections of the fractionated processed materials to quantify inclusions and intergrowths in the feldspar minerals. In Figure 3 examples of albite and microcline particles are presented. In these BSE images the darkest grey colour represents muscovite, dark grey colour represents albite, grey represents microcline, and light grey represents biotite, while Fe-minerals are represented by bright white due to higher average atomic number in the minerals. It can be seen that the albite particles contain several mineral inclusions. LPT3 contains more interlocked mineral grains than the other two, and is dominated by interlocked grains of biotite. The microcline particles all contain albite and Fe-minerals, but in contrast to the albite particles where all

minerals are present as interlocked grains only the Fe-minerals in the microcline particles are present as interlocked grains. Albite in the microcline particles is present as perthite lamellaes.

Table 3. Mineralogical content (Wt. %) in each fraction size calculated from point counting of the processed material (LPT), compared to corresponding raw materials (LRT) from Hestnes et al. (2013). The values are normalized.

Key material	Fraction	Number of points	Minerals (Wt. %)							
			Qtz	Mc pure	Mc perthite	Mc altered	Ab altered (1)	Ab altered (3)	Bt	Mu
LRT1	+ 75	751	47.2	5.4	29.9	0.0	10.1	4.1	1.6	1.7
	+ 212	790	37.3	12.8	12.1	0.0	19.2	14.0	3.8	0.8
	+ 425	635	36.3	5.4	16.9	0.3	17.9	19.4	1.9	2.0
LPT1	+ 75	776	38.6	10.4	25.9	4.9	8.0	12.1	0.0	0.0
	+ 212	636	35.3	19.8	18.6	4.2	15.8	6.2	0.0	0.0
LRT3	+ 75	705	41.2	4.8	7.5	9.3	6.0	29.9	0.2	1.1
	+ 212	791	47.3	6.2	6.0	0.0	19.8	19.2	0.7	0.8
	+ 425	557	49.5	3.8	8.0	0.0	14.4	24.1	0.3	0.0
LPT3	+ 75	864	46.3	8.6	11.7	0.9	6.6	23.0	0.9	2.1
	+ 212	782	39.0	8.3	12.3	2.3	10.3	27.6	0.0	0.2
	+ 425	379	47.2	1.7	17.8	6.3	8.9	18.0	0.0	0.0
LRT4	+ 75	706	31.9	7.5	29.7	5.0	8.8	15.6	0.8	0.7
	+ 212	722	42.3	4.9	22.0	0.0	12.6	16.1	1.4	0.7
	+ 425	796	45.1	11.1	15.8	0.0	11.2	14.5	1.5	0.8
LPT4	+ 75	916	29.5	12.0	20.7	5.4	16.0	13.5	1.2	1.6
	+ 212	628	41.0	10.4	24.3	0.8	14.4	8.7	0.4	0.0
	+ 425	391	44.3	4.2	28.1	1.2	9.4	11.9	0.0	0.8

Table 4 gives the results of the IA of the processed material compared to the results of the corresponding raw materials from Hestnes et al. (2013). Comparison of the results of albite particles for pink pegmatite (LRT1 and LPT1) reveals that the content of biotite and Fe-minerals have been reduced, while for green pegmatite (LRT3 and LPT3) the content of sericite, muscovite, and biotite have been reduced. Considering the red pegmatite (LRT4 and LPT4) the albite particles show a reduction in biotite. For microcline particles no significant difference can be seen between processed and raw materials.
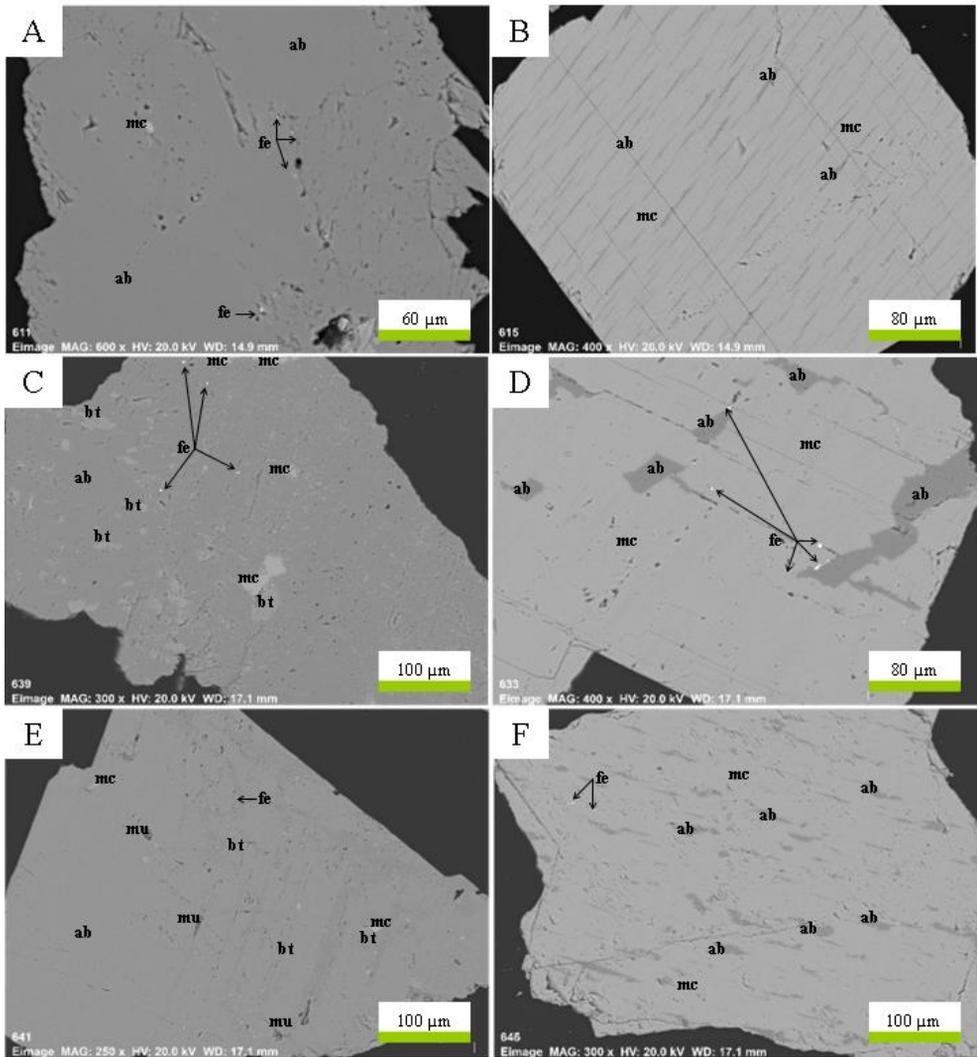
Figure 3. BSE images of A) LPT1 albite (+212), B) LPT1 microcline (+212), C) LPT3 albite (+425), D) LPT3 microcline (+425), E) LPT4 albite (+425) and F) LPT4 microcline (+425). Minerals present in the BSE images; muscovite (Mc), albite (Ab), biotite (Bt), microcline (mc) and Fe-minerals (Fe). In the BSE images of albite the other minerals (Mu, Bt, Mc and Fe) are present as mineral inclusions. In the BSE images of microcline particles Ab is present as perthite lamellae while Fe is present as mineral inclusions.

Table 4. Image analysis on BSE images of fractionated raw materials (LRT) and their corresponding processed materials (LPT). The values are average and standard deviation of all analysed mineral particles of albite and microcline in polished thin sections.

Key material	Fraction		Albite (Wt. %)							Microcline (Wt. %)		
			Sericite	Muscovite	Albite	Biotite	Microcline	Chlorite	Fe-minerals	Albite	Microcline	Fe-minerals
LRT1	+ 75	Average	0.0	2.4	93.5	1.2	2.5	0.0	0.4	12.2	87.7	0.0
		Stdev.	0.0	2.6	4.8	2.2	4.4	0.0	0.5	11.3	11.2	0.0
	+ 212	Average	0.0	0.0	95.2	3.2	0.5	0.0	1.1	12.1	87.8	0.0
		Stdev.	0.0	0.0	3.9	3.8	1.1	0.0	2.5	10.1	10.0	0.1
	+ 425	Average	0.0	1.1	96.4	0.8	1.0	0.1	0.6	12.6	87.3	0.1
		Stdev.	0.0	4.4	5.9	1.8	1.8	0.4	1.2	6.8	7.0	0.2
LPT1	+ 75	Average	0.0	1.0	98.7	0.0	0.1	0.0	0.1	6.1	93.9	0.0
		Stdev.	0.0	2.2	2.1	0.0	0.2	0.1	0.1	1.7	1.7	0.0
	+ 212	Average	0.0	0.4	96.7	2.5	0.3	0.0	0.1	9.8	90.1	0.1
		Stdev.	0.0	1.1	2.1	2.3	0.5	0.0	0.1	5.8	5.9	0.1
LRT3	+ 75	Average	1.9	1.7	93.8	1.2	1.0	0.1	0.2	10.7	89.1	0.1
		Stdev.	6.2	3.6	7.3	2.6	2.2	0.2	0.3	6.7	6.8	0.1
	+ 212	Average	2.3	1.5	91.8	2.9	1.3	0.0	0.2	12.9	86.9	0.2
		Stdev.	4.8	2.8	7.2	4.2	1.7	0.0	0.3	6.5	6.6	0.2
	+ 425	Average	4.9	0.0	90.4	2.5	2.0	0.0	0.2	16.3	83.6	0.1
		Stdev.	7.3	0.0	9.4	3.0	3.5	0.0	0.2	11.9	11.9	0.1
LPT3	+ 75	Average	0.0	0.9	97.8	0.7	0.4	0.0	0.2	17.6	82.0	0.4
		Stdev.	0.0	2.3	2.2	1.1	0.6	0.0	0.2	12.3	13.0	0.8
	+ 212	Average	4.2	0.8	90.0	3.1	1.6	0.0	0.3	10.5	89.2	0.2
		Stdev.	4.0	1.7	4.1	4.3	2.8	0.0	0.3	4.9	5.0	0.2
	+ 425	Average	2.8	0.6	92.4	1.7	2.2	0.0	0.3	12.9	86.9	0.2
		Stdev.	5.2	1.4	6.9	3.0	2.8	0.0	0.5	7.9	7.9	0.3
LRT4	+ 75	Average	0.0	0.0	97.1	1.7	0.6	0.0	0.6	10.1	89.8	0.1
		Stdev.	0.0	0.0	4.2	2.7	1.7	0.0	0.8	8.5	8.5	0.4
	+ 212	Average	0.0	0.0	94.8	2.2	2.7	0.0	0.3	11.2	88.8	0.1
		Stdev.	0.0	0.0	6.6	3.6	6.3	0.1	0.4	6.2	6.2	0.1
	+ 425	Average	0.0	0.0	96.8	1.6	1.0	0.0	0.6	13.2	86.7	0.1
		Stdev.	0.0	0.0	2.6	2.2	1.3	0.1	0.9	6.2	6.2	0.1
LPT4	+ 75	Average	0.0	5.0	93.4	0.9	0.3	0.0	0.4	8.2	91.7	0.1
		Stdev.	0.0	1.7	3.0	1.4	0.4	0.0	0.6	2.1	2.2	0.1
	+ 212	Average	3.8	0.8	91.4	1.2	2.4	0.0	0.5	13.3	86.5	0.2
		Stdev.	5.6	2.6	7.2	1.8	3.3	0.0	0.4	5.6	5.6	0.1
	+ 425	Average	1.4	1.8	92.3	1.6	2.5	0.0	0.4	13.5	86.4	0.1
		Stdev.	3.9	5.1	7.2	1.6	5.3	0.0	0.5	3.7	3.6	0.1

3.3 Mineral chemistry

To quantify the occurrence of iron in the processed key raw materials the mineral chemistry of the corresponding raw materials from Hestnes et al. (2013) is used (Table 5).

Table 5. Mineral chemistry of LRT1, LRT3 and LRT4 from EPMA (Hestnes et al. 2013). The values are normalized to 100 Wt. % for albite, microcline, muscovite, Fe oxides and Fe sulphides, while for biotite, chlorite and sericite the values are normalized to 95 Wt. % due to content of H2O (Deer et al., 1992). The number of points analysed are listed inside parentheses after the minerals.

Key raw material	Mineral	Statistics	Oxides (Wt,%)										
			Al_2O_3	Na_2O	K_2O	Fe_2O_3	SiO_2	MgO	CaO	MnO	TiO_2	SO_3	ZrO_2
LRT1	Albite (39)	Average	19.77	10.13	0.14	0.01	67.72	0.00	2.20	0.01	0.01	0.00	0.00
		Stdev	0.64	0.65	0.06	0.01	0.95	0.01	0.77	0.01	0.01	0.00	0.00
	Microcline (27)	Average	17.06	0.79	15.38	0.01	66.72	0.00	0.01	0.01	0.00	0.00	0.00
		Stdev	0.18	0.18	0.48	0.01	0.52	0.01	0.01	0.01	0.01	0.00	0.00
	Chlorite (16)	Average	19.75	0.04	0.52	39.97	26.95	6.63	0.02	0.63	0.46	0.01	0.02
		Stdev	1.36	0.04	0.50	2.04	1.38	0.45	0.03	0.11	0.42	0.02	0.04
	Biotite (5)	Average	18.11	0.04	6.80	30.74	32.07	5.04	0.00	0.47	1.65	0.03	0.05
		Stdev	0.39	0.03	2.06	3.17	1.65	0.65	0.00	0.12	0.51	0.03	0.04
LRT3	Albite (38)	Average	19.83	10.40	0.17	0.01	67.26	0.00	2.31	0.02	0.00	0.00	0.00
		Stdev	0.74	0.59	0.09	0.02	1.13	0.01	0.90	0.00	0.01	0.01	0.00
	Microcline (27)	Average	17.07	0.76	15.85	0.01	66.28	0.00	0.01	0.02	0.01	0.00	0.00
		Stdev	0.13	0.17	0.30	0.01	0.16	0.01	0.01	0.00	0.01	0.00	0.00
	Chlorite (3)	Average	19.60	0.04	0.07	36.31	30.53	1.70	0.47	6.17	0.06	0.02	0.03
		Stdev	1.36	0.02	0.13	7.97	5.31	1.06	0.47	4.91	0.10	0.01	0.05
	Muscovite (7)	Average	18.13	0.95	15.14	0.03	65.70	0.00	0.01	0.01	0.00	0.01	0.01
		Stdev	0.10	0.36	0.57	0.02	0.17	0.00	0.01	0.01	0.01	0.01	0.02
	Sericite (3)	Average	36.50	0.39	11.00	0.20	46.91	0.00	0.03	0.00	0.00	0.00	0.00
		Stdev	0.37	0.05	0.13	0.23	0.12	0.00	0.02	0.00	0.01	0.00	0.00
	Fe-sulph. (6)	Average	0.27	0.11	0.02	33.69	0.69	0.02	0.01	0.01	0.00	65.18	0.01
		Stdev	0.08	0.03	0.03	1.50	0.25	0.01	0.02	0.01	0.00	1.38	0.01
	Fe oxides (3)	Average	2.98	0.30	0.86	81.40	11.27	0.11	0.40	2.40	0.00	0.25	0.03
		Stdev	1.98	0.34	0.89	5.79	5.20	0.11	0.07	4.14	0.00	0.33	0.04
LRT4	Albite (24)	Average	19.94	10.13	0.16	0.01	67.35	0.00	2.38	0.02	0.01	0.00	0.00
		Stdev	0.74	0.47	0.09	0.01	1.24	0.01	0.88	0.00	0.02	0.00	0.00
	Microcline (29)	Average	17.07	0.75	15.72	0.01	66.40	0.00	0.01	0.02	0.01	0.00	0.00
		Stdev	0.09	0.13	0.27	0.01	0.23	0.01	0.02	0.00	0.01	0.00	0.00
	Biotite (28)	Average	17.88	0.06	8.32	29.37	33.29	3.88	0.01	0.48	1.65	0.03	0.02
		Stdev	0.27	0.02	1.47	2.22	1.11	0.40	0.02	0.05	0.24	0.02	0.03
	Fe oxides (28)	Average	4.16	0.74	0.21	84.73	9.59	0.13	0.33	0.06	0.01	0.01	0.02
		Stdev	2.10	0.98	0.18	8.43	5.23	0.09	0.23	0.04	0.03	0.02	0.03

3.4. Distribution of Fe in the processed materials

Table 6 presents total Fe2O3 of the feldspar particles and the distribution of Fe2O3 in these particles. Table 7 gives the overall Fe2O3 distribution by mineral

component present in the processed key raw materials. In both Table 6 and 7 the processed materials are compared to the corresponding key raw material values from Hestnes et al. (2013).

Table 6. Distribution of Fe2O3 in albite and microcline containing particles of processed key raw materials, calculated from the results of Image Analysis and chemistry from EPMA. Corresponding key raw material values and mineral chemistry EPMA data are taken from Hestnes et al. (2013).

| Key material | Fraction | Distribution of Fe$_2$O$_3$ in Albite particles (Wt. %) | | | | | | | | Distribution of Fe$_2$O$_3$ in Microcline particles (Wt. %) | | | |
		Sericite	Muscovite	Albite	Biotite	Microcline	Chlorite	Fe-minerals	Total Fe$_2$O$_3$	Albite	Microcline	Fe-minerals	Total Fe$_2$O$_3$
LRT1	+75	0.000	0.001	0.009	0.366	0.000	0.000	0.370	0.745	0.001	0.009	0.018	0.028
	+212	0.000	0.000	0.009	0.988	0.000	0.000	0.902	1.899	0.001	0.009	0.025	0.035
	+425	0.000	0.000	0.009	0.255	0.000	0.043	0.492	0.799	0.001	0.009	0.104	0.115
LPT1	+ 75	0.000	0.000	0.009	0.000	0.000	0.020	0.098	0.127	0.001	0.010	0.030	0.040
	+ 212	0.000	0.000	0.009	0.769	0.000	0.000	0.071	0.849	0.001	0.010	0.054	0.064
LRT3	+75	0.004	0.001	0.014	0.369	0.000	0.019	0.106	0.513	0.002	0.011	0.057	0.070
	+212	0.004	0.000	0.014	0.866	0.000	0.000	0.087	0.973	0.002	0.010	0.088	0.100
	+425	0.010	0.000	0.014	0.747	0.000	0.000	0.091	0.861	0.002	0.010	0.049	0.061
LPT3	+75	0.000	0.000	0.015	0.195	0.000	0.000	0.113	0.324	0.003	0.010	0.191	0.204
	+212	0.008	0.000	0.013	0.918	0.000	0.000	0.171	1.112	0.002	0.011	0.106	0.118
	+425	0.005	0.000	0.014	0.524	0.000	0.000	0.146	0.690	0.002	0.010	0.097	0.109
LRT4	+75	0.000	0.000	0.012	0.486	0.000	0.000	0.544	1.042	0.001	0.013	0.101	0.115
	+212	0.000	0.000	0.012	0.638	0.000	0.008	0.271	0.929	0.001	0.013	0.055	0.069
	+425	0.000	0.000	0.012	0.477	0.000	0.008	0.478	0.976	0.002	0.012	0.122	0.137
LPT4	+75	0.000	0.002	0.012	0.266	0.000	0.000	0.360	0.640	0.001	0.013	0.051	0.065
	+212	0.007	0.000	0.012	0.339	0.000	0.000	0.454	0.813	0.002	0.012	0.148	0.162
	+425	0.003	0.001	0.012	0.463	0.000	0.000	0.346	0.824	0.002	0.012	0.094	0.108

The Fe2O3 distribution of the albite and microcline particles is based on the mineralogy in weight % of the feldspar particles analysed by IA (Table 4) and the content of Fe2O3 in the minerals found by EPMA (Table 5). For some minerals (muscovite in LPT1 and LPT4, and sericite in LPT4) no corresponding mineral phase was found by EPMA. In this case the mineral chemistry for these minerals was taken from other key raw materials where this mineral phase was found. Because these minerals have been identified by one or several methods, the following assumptions were made to be able to calculate the distribution of Fe2O3 in the mineral phases. Biotite was found by IA in LPT3, but not by EPMA, and therefore an average value of the mineral chemistry for biotite in LRT1 and LRT4 was used. LPT1 was considered to be the most similar in mineralogy to LPT4, and therefore the use of mineral chemistry from Fe oxides of LRT4 was used in the

calculation for LPT1 in both albite and microcline particles in Table 6. For Fe-minerals in LPT3 the relation of the number of mineral particles found in the sample (Fe oxides 6: Fe sulphides 3) giving a ratio of 2:1 was used in the calculation of Fe2O3 for both albite and microcline in LPT3.

Regarding albite particles in all processed materials (Table 6) the Fe2O3 distribution is related to the content of biotite and Fe-minerals. For the microcline particles in the processed materials, the distribution of Fe2O3 can be connected to content of Fe-minerals.

Table 7 presents the overall Fe2O3 distribution by mineral component present in the fractionated key raw materials. The results were based on the mineralogy found by point counting (Table 3) and on mineral chemistry (Table 5). For 'Mc perthite + altered' and 'Ab altered (1) + (3)' the content of Fe2O3 was taken from the total Fe2O3 content of the albite and microcline particles from Table 6. Quartz was not included due to its low Fe content (Sibelco Nordic. 2010).

Table 7. Overall content of Fe2O3 from the mineral components in the processed key raw materials based on point counting and EPMA. The values are compared to corresponding raw material values from Hestnes et al. (2013).

Key material	Fraction	Content of Fe$_2$O$_3$ from mineral components (Wt. %)				
		Mc pure	Mc perthite + altered	Ab altered (1) + (3)	Bt	Mu
LRT1	+75	0.001	0.008	0.106	0.498	0.001
	+212	0.001	0.004	0.631	1.154	0.000
	+425	0.001	0.020	0.298	0.577	0.001
LPT1	+ 75	0.001	0.012	0.026	0.000	0.000
	+ 212	0.002	0.015	0.187	0.000	0.000
LRT3	+75	0.001	0.012	0.184	0.062	0.000
	+212	0.001	0.006	0.380	0.205	0.000
	+425	0.000	0.005	0.331	0.101	0.000
LPT3	+ 75	0.001	0.026	0.096	0.265	0.001
	+ 212	0.001	0.017	0.421	0.000	0.000
	+ 425	0.000	0.026	0.186	0.000	0.000
LRT4	+75	0.001	0.040	0.255	0.236	0.000
	+212	0.001	0.015	0.266	0.425	0.000
	+425	0.002	0.022	0.250	0.431	0.000
LPT4	+ 75	0.002	0.017	0.189	0.364	0.000
	+ 212	0.001	0.041	0.188	0.114	0.000
	+ 425	0.001	0.032	0.176	0.000	0.000

From Table 7 it can be seen that after the beneficiation process in the laboratory the key raw materials had obtained a reduction in the content of Fe2O3 from biotite and altered albite. The reduction in content of Fe2O3 from biotite was particularly high for the pink pegmatite (LRT1 and LPT1). The green pegmatite

(LRT3 and LPT3) showed the least reduction in content of biotite or altered albite related Fe2O3 of the key raw materials.

4. DISCUSSION

The investigations presented in Hestnes et al. (2013) gave process mineralogical knowledge about the distribution of Fe2O3 in the minerals in the key raw materials of the Glamsland pegmatite field. From this work it is known that the minerals containing the most Fe2O3 are Fe-oxides, chlorite, Fe-sulphides, biotite and sericite. Altered albite particles also contains an increased content of Fe2O3.

From Table 7 a reduction of Fe2O3 can be seen in the processed equivalents compared to the key raw materials investigated. The reduction is due to the removal of the mineral components biotite and altered albite, a removal which also leads to products less rich in Fe2O3. This reduction in Fe2O3 is largest for LPT1 compared to LPT3 and LPT4. Figure 2 presents the content of Fe2O3 in the key raw materials and their processed equivalents graphically based on the results of bulk chemistry (XRF) presented in Table 2. From this figure it can be seen a distinct reduction in Fe2O3 content in the pink pegmatite (LPT1). The results from bulk chemistry also confirm the results seen in Table 7.

In Table 6 the total Fe2O3 of the feldspar particles and the distribution of Fe2O3 split on the minerals of these particles (IA) are presented. It is seen that in the albite particles of the processed materials the distribution of Fe2O3 is related to the content of biotite and Fe-minerals, while for the microcline particles the distribution of Fe2O3 is related to only Fe-minerals. These results confirm those presented for the raw material in Hestnes et al. (2013). From Table 4, the IA of albite particles indicate a reduction, after processing, of biotite and Fe-minerals for the pink pegmatite (LRT1 and LPT1). For the green pegmatite (LRT3 and LPT3) the content of sericite, muscovite and biotite is reduced in the albite particles, while for the red pegmatite (LRT4 and LPT4) a reduction in biotite can be seen. In the albite particles of the red pegmatite, sericite and muscovite are present in larger amounts in the processed material than in the raw material. For microcline particles no significant difference can be seen between processed and raw materials.

When the distribution of Fe2O3 of the mineral particles present in the key raw materials are compared with the processed materials (Table 6 and 7), it can be seen that the Fe2O3-containing minerals which have been removed are chlorite, biotite, sericite and altered albite. The Fe-minerals have not been reduced to the same extent as the other Fe-containing minerals. The key material which has undergone

the largest reduction in content of Fe2O3 is the pink pegmatite which is the key raw material with the highest amount of biotite. The combined flotation and magnetic separation included in the laboratory process reduces the content of Fe2O3 by the reduction of the mineral components biotite, sericite, and altered albite. The minerals that appear as free mineral particles are extracted from the raw material by the laboratory procedure if they contain Fe. Altered minerals and minerals that split along grain boundaries easily and thereby creates slime through the wet process, is mostly removed through desliming. Interlocked particles (seen in BSE images) that contain Fe2O3 will not be removed to the same extent as the free mineral particles in the existing beneficiation process. These particles will therefore contaminate the processed material and the following products.

Historically the pink pegmatite was the raw material that gave the best product. This has been confirmed by this investigation. LRT1 contains Fe-rich minerals like biotite and chlorite as individual mineral particles, and Fe-oxides as interlocked mineral grains in albite and microcline particles. Biotite is mostly removed by the combined flotation and magnetic separation, while the Fe-oxides will not be removed. Since the pink pegmatite contains less interlocked Fe-minerals than the green and red pegmatite it is possible to create a processed product with minor amounts of Fe2O3.

The raw material of the green pegmatite (LRT3) has historically created trouble during the beneficiation process and given a product high in Fe2O3. This can be explained in this study. The green pegmatite has more alteration of the primary igneous minerals, including sericitisation, and more altered albite than the pink and red pegmatite. Therefore they may split more easily along grain boundaries and micro fractures creating slime through the beneficiation process and also make the consumption of flotation chemicals increase. This raw material (LRT3) contains more interlocked grains of Fe-minerals in the albite and microcline particles than LRT1, and because of these interlocked grains of Fe-minerals it is not possible to make a processed material (LPT3) with low enough Fe2O3 content to avoid blending with other less Fe-rich product material to pass the quality control.

The raw materials of the red pegmatite (LRT4) contained a high content of Fe2O3 (Hestnes et al., 2013). From the processed key material (LPT4) it can be seen that free mineral grains of biotite are removed by the beneficiation process, but interlocked grains of Fe-minerals in albite and microcline particles were not possible to remove. The red pegmatite (T4) contains both biotite and interlocked grains of Fe-minerals, and therefore it is hard to remove enough Fe2O3 to get a processed product which does not have to be blended to satisfy quality demand.

The analyses performed in this investigation have been done on a total of 8 polished thin sections of fractionated processed material. Also included in this paper are the results presented in Hestnes et al. (2013), which included 9 polished thin sections of fractionated raw material. The number of samples is not large, but it represents the materials common for the different deposit areas and pegmatite types. Where the number of samples gives the most uncertainty is in the content of muscovite and biotite, especially considering point counting. Also the danger of calculation mistakes needs to be kept in mind considering the IA. The IA performed on BSE images gives an output in area %. This area % is supposed to represent a volume %, but to be able to compare the results of the IA with other analysis methods the area % is recalculated into weight %. This recalculation can be a source of error, and ought to be kept in mind.

5. CONCLUSIONS

The main objective of the investigation presented in this paper has been to compare the occurrence of iron in the key raw materials with their corresponding processed materials. It has also been a focus on the behaviour of the key raw materials in the laboratory process to try to explain why the different raw materials give different product qualities. The scope of this work has not been to optimize the process.

The key raw materials from the Glamsland pegmatite field have been treated in a laboratory process replicating parts of the full scale beneficiation process at Sibelco Nordic, Lillesand. The most important conclusions of this investigation are:

- Fe-containing mineral particles that are present in the pulp as free particles are removed either by flotation or through high intensity magnet separation after drying.

- Altered raw material will easily split along grain boundaries and micro fractures, and will create slime through the beneficiation process.

- Interlocked mineral particles that contain Fe_2O_3 are more difficult to remove in the existing beneficiation process today.

- Because of these findings the historical claim saying that the pink pegmatite (LRT1) gives the best product (LPT1) is explained. The reason why a raw material with relative high Fe_2O_3 content comes out as a good product low in Fe_2O_3 is due to the occurrence of the Fe-containing minerals. Fe-rich mineral components like biotite and altered albite are

present as free mineral particles and can therefore be removed through flotation and magnetic separation.

- The green pegmatite (LRT3) is claimed to create troubles through the beneficiation process and give a product with high content of Fe2O3. This investigation confirms this claim, and explains it by the grade of alteration of especially the albite in the key raw material. In the beneficiation process the green pegmatite produces slime and the mineral particles constantly split increasing the surface area. Also the green pegmatite contains interlocked mineral particles high in Fe2O3, which will not be removed resulting in a product (LPT3) rich in Fe2O3.

- The red pegmatite (LRT4) contains minerals which are high in Fe2O3, and these minerals are present mainly as interlocked grains inside both albite and microcline particles. Therefore the beneficiation process run today is not able to remove these Fe-minerals, and the product (LPT4) remains high in Fe2O3.

- This study highlights a central concept of process mineralogy. The economic potential of a raw material may be difficult to assess without relating it to a relevant beneficiation process. In this study the raw material with the highest Fe2O3 content, the pink pegmatite, gave the best product (lowest Fe2O3 content). More important than the initial Fe2O3 content in the raw material is the occurrence of the Fe-minerals, and how they interact with the beneficiation process.

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