Glass- and ceramic-grade feldspar from waste

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Abstract

In a typical feldspar operation, extraction and size reduction may account for 20 to 25% of operating costs. Production of feldspar from feldspathic quarry fines and / or mine tailings would reduce these costs as the material has already been extracted and crushed. Other benefits would include a reduction in waste treatment and disposal costs, an increase in the revenue realised per tonne of material extracted and, ultimately, an environmental benefit from a reduction in feldspar mined.

Feldspathic waste materials, in the form of granite fines from an aggregate quarry in Europe and tailings from a former tin mine in Namibia, have been processed on a laboratory-scale to investigate the feasibility of producing glass- and ceramic-grade feldspar products. A combination of magnetic separation and a two-stage froth flotation was used to remove iron-bearing minerals and mica, and to separate quartz from feldspar. An HF-free froth flotation process was used for the latter. High-purity feldspar was produced with Fe_2O_3 and alkali contents similar to those of commercial feldspar. High-purity quartz was also produced as a by-product. On the basis of these laboratory results, the potential for scaling-up the processing of feldspathic waste to a commercial scale would appear to be a viable prospect.

INTRODUCTION

Feldspar is a common rock-forming mineral that occurs as sodium, potassium and calcium varieties. Na- and K-feldspars (also known as the alkali feldspars) are exploited as a source of alkalis, alumina and silica for the manufacture of glass and ceramics. Alkali feldspars are major constituents (50-70%) of granite-related rocks. Feldspar of commercial significance generally occurs as relatively large crystals (>3 cm) free of iron-bearing impurities and easily separated from other minerals. These can be found in coarsely-crystalline igneous rocks such as granitic pegmatite and alaskite. Other sources of feldspar currently exploited include : feldspathic sediments (such as sands and gravels), aplite, anorthosite and feldspathic tailings.

Processing of feldspar

Feldspar workings are usually open-cast, often employing bench mining and occasionally dredging (for unconsolidated feldspathic sands and gravels). Many worked pegmatites are zoned, and occasionally pure feldspar, quartz and mica can be extracted by selective mining. The ore is either crushed (jaw or gyratory crushers, often in closed circuit) and screened, or washed and classified. Wet processing, such as hydrocycloning, may be used to remove, and concentrate, clay present in some deposits. In Germany kaolin is produced as a by-product from a weathered feldspathic sand (Burger, 1990). Coarse feldspar may be hand-, or photometrically sorted. In Norway a pure K-feldspar is hand-sorted for use in the production of artificial teeth (Olerud, 1995). Pure feldspar may simply be crushed and graded and sold in size ranges from 150 mm to 1 mm. In Italy aplite is simply crushed to -6 mm for use in ceramic tiles (Loughbrough, 1992).

The ore may then be further crushed and milled (rod milling is often preferred to avoid overgrinding, often in closed circuit with a classifier to maximise grinding capacity) then screened in preparation for fine processing. A three-stage froth flotation process is commonly carried out to separate mica, iron-bearing minerals and quartz impurities. An operation exploiting a granitic pegmatite in Norway is separating sodium from potassium feldspar. The processing is complex and requires the use of 10 different flotation reagents (Olerud, 1995). Commonly the particle size of ore processed by flotation ranges from a top size of 850 to 600 microns down to a lower size of 100 to 38 μm. A top size of 850 μm may be fine enough to liberate most feldspar but 600 μm is often preferred as it enables optimisation of the subsequent flotation. Fines are removed as they tend to preferentially absorb collector reagent and coat other non-feldspar grains (which will then behave as feldspar and float, thus reducing separation efficiency and concentrate grade). A ceramic-grade feldspar product could be produced at this point by classification to remove -75 μm fines.

Froth flotation of feldspar is carried out under acidic conditions, using amine-based collectors. HF is generally used as an activator in this process, although the mechanism(s) by which it enhances flotation are poorly understood. Two mechanisms have been suggested: (i) formation of alumino-fluoride, or sodium or potassium fluorosilicate ions ,which are absorbed onto the surface of the feldspar creating negatively charged sites upon which the amine cation is preferentially absorbed; (ii) depression of silica by fluoride replacing surface hydroxyl groups, thus reducing the number of negatively charged sites and inhibiting the absorption of amine (Rao & Forssberg, 1993).

HF-activation of the process is highly efficient, producing almost perfect separation of quartz and feldspar from the rougher flotation stage onward. Fluoride salts, such as sodium fluoride, may be used as an alternative to HF (although their use in the highly acidified pulps will generate HF). Use of HF can, however, lead to problems. It is hazardous, damaging to the environment, expensive, and corrosive to the flotation cells. Therefore it requires careful handling and management of the flotation process. The increasing awareness of the environmental pollution caused by HF restricts its use and has encouraged the search for alternatives. Non-HF flotation reagents have been developed over the last twenty years that have gone some way to solving these problems. These include the following collector combinations: diamine (N-alkyltrimethylene diamine) - petroleum sulphonate; and tallow diamine-sodium oleate. Sulphuric acid is used with both to regulate pH (Yachuan *et al*., 1993).

Following flotation the products may be upgraded by high-intensity magnetic separation, gravity separation, air classification and electrostatic separation. The feldspar concentrates produced by fine processing have a particle-size distribution suitable for glass-manufacture. Ceramic manufacturers require a feldspar product with a much finer particle-size, generally -75 µm. This is produced by grinding the feldspar concentrate to the desired particle-size using, for example, ceramic-lined ball mills in closed circuit with air classifiers. Fine grinding is expensive and may account for up to 20% of production costs. This explains why ceramic-grade feldspar can cost up to five times as much as glass-grade feldspar.

Benefits of processing waste

In many countries the known reserves of industrial-grade feldspar are becoming depleted, or are expensive to process because of the necessity to exploit deposits that are fine-grained or have complex mineralogical associations. This has encouraged the search for alternative sources of feldspar.

In Portugal, K-feldspar is commonly produced from granitic pegmatites for the ceramics industry. However shortages in the supply of K-feldspar are being experienced as reserves are becoming depleted. In the attempt to solve this problem an unusual alternative source of feldspar has been identified. Unizel Minerais Lda is exploiting a tailings dump from a former tin mine, which ceased production in the 1960s. This dump contains approximately 1 million tonnes of sand-grade feldspathic tailings. The tailings contain approximately 60% feldspar (Na- and K-feldspar) and 30% quartz, plus minor amounts of mica and iron-bearing minerals. The 'deposit' is homogeneous and relatively straightforward to process. The tailings are dried, fine-roller crushed and screened. Air classification is used to remove the mica, and high-intensity magnetic separation to remove the iron-bearing minerals. The feldspar product is a mixed Na- and K-feldspar with an iron content between 0.2 and 0.3% (Loughbrough, 1993).

Benefits from processing of feldspathic mine tailings or quarry fines include the following (see also Fig 1) :

- Lower operational costs. The extraction and crushing has already been carried out. These account for up to 20 to 25% of production costs.

- Lower disposal costs. Processing the tailings of an active operation would would reduce the amount disposed of as tailings. Tailings may represent up to 30% of the head feed and consume up to 6% of production costs.

- Increased revenue. The sale of feldspar produced would increase the revenue realised per tonne of material extracted.

- Reduced environmental impact. A reduction in the amount of waste material produced would reduce the amount of land required for its disposal.

- Reduced mining. Competition from feldspar produced from waste may ultimately reduce market share of feldspar produced by mining. This may lead to a reduction in the amount of mining carried out.

Laboratory processing methodology

The froth flotation methodology currently used for processing of feldspar in the British Geological Survey (BGS) laboratories has been modified from the standard practice recommended for use with the reagents supplied by AKZO Nobel (Figure 2).

Initial sample characterisation is carried out to determine factors likely to affect processing performance and/or product quality. This includes: X-ray diffraction, to determine mineralogy; particle-size analysis, to aid determination of liberation size; and optical microscopy, to identify any inclusions, coatings and/or surface staining present. Bulk chemical composition is determined by X-ray fluorescence (XRF). When necessary, composition of individual feldspar phases is determined by a CAMECA SX50 electron microprobe equipped with wavelength dispersive analytical methods.

Typically a sample is prepared by either screening or crushing (jaw crushing, roller milling and/or cone grinding) a sub-sample (~ 1kg) to the liberation size (this will be influenced by the upper particle size limit that can practically be floated, between 850 and 600 μm). The crushed sample is wet screened to remove fines (-100 μm)

The first processing step is magnetic separation, using a Carpco high-intensity induced roll magnetic separator, which removes iron-bearing and other magnetically susceptible minerals. The non-magnetic product forms the feed for froth flotation.

Froth flotation is carried out in two stages, the first to remove mica and the second to separate quartz and feldspar (Figure 3). Flotation is performed using a standard Denver D12 laboratory flotation machine with Pyrex cell. Suspensions are made with de-ionised water, pH is regulated with sulphuric acid and caustic soda, and any excessive frothing is moderated with heavy distillate. Mica removal is carried out using alkylamine acetate (Armoflote 64) as collector and methyl isobutyl carbinol (MIBC) as frother. Conditioning is for 4 minutes at a pH of 2.5 to 2.7 and a pulp density of 50 to 60 wt % solids. Flotation is carried out at a pH of 3 to 3.3 and a pulp density of 20 to 30 wt % solids. Quartz-feldspar separation is effected using a fatty acid derivative as collector (Armoflote 543) and MIBC as frother. Prior conditioning is for 4 minutes at a pH of 1.8 to 2.0 and a pulp density of 50 to 60 wt % solids. Flotation is carried out at the same pH and a pulp density of 20 to 30 wt % solids. Flotation can be repeated as necessary to increase feldspar recovery.

All products are scrubbed with caustic soda to remove reagent residues. A final magnetic separation, using a Frantz isodynamic magnetic separator, is carried out to remove any remaining iron-bearing minerals prior to assay by XRF.

Case study 1 : Granite fines

Several mineral processing trials have been carried out at BGS over the last few years to determine the potential for the production of glass-grade feldspar from granitic fines produced by a European aggregate quarry. No locality details or company names can be revealed due to commercial sensitivity (a contact name can be supplied on request).

The granitic fines consist mainly of K-feldspar, Na-feldspar (plagioclase) and quartz, with minor amounts of biotite mica and pyroxene, and a trace of magnetite and apatite. The K-feldspar occurs mainly as laths up to 3 mm, the larger grains with inclusions of quartz, apatite and plagioclase. The plagioclase feldspar occurs as small laths, up to 1 mm in diameter, which are commonly sericitised. The particle-size distribution of the fines is : 30% gravel (+2 mm), 60% sand (2mm to 63 µm) and 10% silt / clay (-63 µm) grade material. The feldspar is well liberated in those size fractions finer than 1 mm.

The mineral processing trials have taken two forms;

i) Magnetic separation, using the Frantz isodynamic magnetic separator, to produce combined quartz-feldspar concentrates, and
ii) Combined magnetic separation and froth flotation, as outlined in the previous section, to produce feldspar concentrates.

Both magnetic separation and froth flotation trials were successful in producing concentrates of quartz and feldspar, and feldspar respectively. Table 1 gives a summary of the average assays produced during these trials. The compositions of typical commercial glass- and ceramic-grade feldspar are given for comparison. The quartz-feldspar concentrates contain on average 74.6% SiO_2, 0.26% Fe_2O_3, 4.6% Na_2O and 3.5% K_2O. The feldspar concentrates contain on average 68.6% SiO_2, 0.22% Fe_2O_3, 6.3% Na_2O and 4.0% K_2O.

The combined quartz-feldspar products compare favourably with ceramic-grade feldspar, such as that produced by Unizel Minerais Lda (Portugal). The pure feldspar products have a similar composition to glass-grade feldspar, such as that produced by the Feldspar Corporation (USA). However the iron content of the products was generally between 0.2% and 0.3% Fe_2O_3. This is significantly higher than the maximum iron content (0.08% Fe_2O_3) generally demanded by the glass industry.

The high iron content of the feldspar, produced from the granitic fines, is due to the presence of inclusions (or middling grains) of biotite and magnetite. Processing material finer than 180 µm did not result in products with an iron content lower than 0.2%. It seems likely that these inclusions would be liberated below 100 µm. However at this size an effective separation would not be achieved by flotation.

In summary the quartz-feldspar concentrates produced from the granitic fines by magnetic separation alone have a similar composition to commercial ceramic-grade feldspar products. However the feldspar concentrates contain significantly more iron than commercial glass-grade feldspar products.

Case study 2 : Uis mine tailings, Namibia

An investigation is currently being carried out on feldspathic-tailings, from a former tin mine at Uis in Namibia in an attempt to produce ceramic-grade feldspar. This forms part of an industrial minerals resources survey being carried out by a BGS team (funded by the SYSMIN programme of the European Development Fund) based at the Geological Survey of Namibia in Windhoek.

Tin has been produced from the Uis pegmatite swarm since the 1920s. The major producer closed its mine in 1990, due to a collapse in the price of tin, and left behind an estimated 75 million tonnes of sand-grade feldspathic tailings. Two samples (size fractions between 500 and 125 μm) were processed at the BGS using the standard laboratory methodology for feldspar processing.

The tailings from Uis consist mainly of alkali feldspar (K- and Na-feldspar) and quartz, with a minor amount of muscovite and trace amounts of magnetite and chlorite. The alkali feldspar occurs as laths, with the coarser grains often having a surface iron staining. The feldspar present in both samples is well liberated.

The processing was successful in producing concentrates of feldspar. Table 2 gives the chemical composition of the concentrates and several industrial-grade products for comparison. The feldspar concentrates contain on average 69.2% SiO_2, 0.06% Fe_2O_3, 5.4% Na_2O and 5.1% K_2O. The feldspar products have a similar composition to commercial mixed alkali ceramic-grade and glass-grade feldspar products. However the main market for ceramic-grade feldspar, which is in South Africa, demands a potassium feldspar. The feldspar produced from the tailings was a mixed sodium / potassium feldspar and therefore does not meet the market requirements.

Further work being considered for future investigations includes :
(i) Dry processing using air classification to remove muscovite. This would minimise the amount of process water required and may also produce a pure mica product.
(ii) Froth flotation to separate sodium and potassium feldspar. This would satisfy the demand for a pure potassium feldspar.

In summary the feldspar concentrates produced from the Uis tailings are similar in composition to commercial ceramic- and glass-grade feldspar products.

Conclusion

Industrial grade feldspar is typically produced from coarse-grained feldspathic rocks such as granitic pegmatites and alaskite. The ore is extracted by bench mining (or dredging) and is commonly processed by a combination of magnetic separation and froth flotation to remove iron-bearing impurities, mica and quartz. The feldspar produced has a particle-size distribution suitable for glass manufacture. Fine grinding is required to produce feldspar suitable for the manufacture of ceramics. In many countries the reserves of industrial grade feldspar are becoming depleted. This has lead to the search for alternative sources of feldspar. In Portugal feldspathic mine tailings are currently being exploited to produce industrial-grade feldspar. The benefits of such processing include savings in the costs of extraction, crushing and tailings disposal, increased revenues and reduced environmental impact.

The BGS methodology for the laboratory processing of feldspar involves a combination of magnetic separation and two-stage froth flotation (as modified from AKZO Nobel standard practice). This has been applied to samples of granitic fines from a European aggregate quarry and tailings from a former tin mine at Uis in Namibia. The quartz-feldspar concentrates produced from the granite fines are similar in composition to commercial ceramic-grade feldspar products. The feldspar concentrates produced from the granite fines contain significantly more iron than commercial glass-grade feldspar products. The feldspar concentrates produced from the Uis tailings are similar in composition to commercial ceramic- and glass-grade feldspar products.

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Table 1. Feldspar (and quartz) produced from granitic fines, European aggregate quarry

Product	SiO2 (wt %)	TiO2 (wt %)	Al2O3 (wt %)	Fe2O3 (wt %)	MnO (wt %)	MgO (wt %)	CaO (wt %)	Na2O (wt %)	K2O (wt %)	P2O5 (wt %)	LOI (wt %)	Total (wt %)
Granitic fines												
Head sample	69.99	0.32	14.76	1.80	0.03	0.71	1.95	4.44	3.77	0.10	1.33	99.20
Magnetic separation												
-1 mm to 125 µm (av. 3)	74.70	0.03	14.10	0.21	0.01	0.07	1.45	4.58	3.57	0.02	0.56	99.30
-850 to 125 µm (av. 18)	74.46	0.04	13.93	0.31	0.01	0.09	1.53	4.55	3.42	0.02	0.84	99.20
Froth flotation												
-600 to 106 µm	67.83	0.02	19.08	0.19	0.00	0.03	1.59	6.16	4.59	0.01	0.52	100.02
-500 to 106 µm (av. 9)	69.50	0.03	17.64	0.22	0.00	0.01	1.40	5.76	4.23	0.01	0.63	99.43
-300 to 106 µm	68.45	0.04	19.15	0.26	0.00	0.06	1.72	6.89	3.19	0.01	0.48	100.25
Quartz concentrate												
-300 +106 µm	99.35	0.01	0.14	0.02	0.00	0.00	0.03	0.05	0.08	0.00	0.07	99.75
Commercial ceramic-grade feldspar *												
-1 mm	75.00	na	15.00	0.30	na	na	na	4.50	3.30	na	na	na
Commercial glass-grade feldspar **												
C-20 (-1 mm to 75 µm)	68.90	na	18.75	0.07	na	trace	1.85	7.15	3.85	na	0.13	na

Key : na = not available; * = Unizel Minerais Lda, Portugal (Loughbrough, 1993); ** = Feldspar Corporation, USA (Harben, 1995)

Table 2. Feldspar (and quartz) produced from tin mine tailings, Uis, Namibia

Sample	SiO2 (wt %)	TiO2 (wt %)	Al2O3 (wt %)	Fe2O3t (wt %)	MnO (wt %)	MgO (wt %)	CaO (wt %)	Na2O (wt %)	K2O (wt %)	P2O5 (wt %)	LOI (wt %)	TOTAL (wt %)
-500 +250 µm												
Head	71.52	0.04	15.41	0.48	0.05	0.17	1.39	3.41	2.76	1.39	2.42	99.04
Feldspar concentrate	68.68	0.00	16.86	0.07	0.01	0.00	0.32	5.59	4.81	1.55	1.14	99.03
Middling	75.57	0.00	13.28	0.33	0.00	0.00	0.31	5.24	2.68	0.94	0.80	99.15
Tailing	80.96	0.01	11.41	0.11	0.01	0.06	0.13	2.70	1.05	0.39	2.25	99.08
-250 +125 µm												
Head	71.10	0.06	15.68	0.62	0.05	0.25	1.44	3.58	2.71	1.34	2.36	99.19
Feldspar concentrate	69.67	0.01	16.16	0.05	0.00	0.00	0.42	5.28	5.44	1.31	0.68	99.02
Commercial ceramic-grade feldspar *												
-1 mm	75.00	na	15.00	0.30	na	na	na	4.50	3.30	na	na	na
Commercial glass-grade feldspar **												
C-20 (-1 mm to 75 µm)	68.90	na	18.75	0.07	na	trace	1.85	7.15	3.85	na	0.13	na

Key : na = not available; * = Unizel Minerais Lda, Portugal (Loughbrough, 1993); ** = Feldspar Corporation, USA (Harben, 1995)

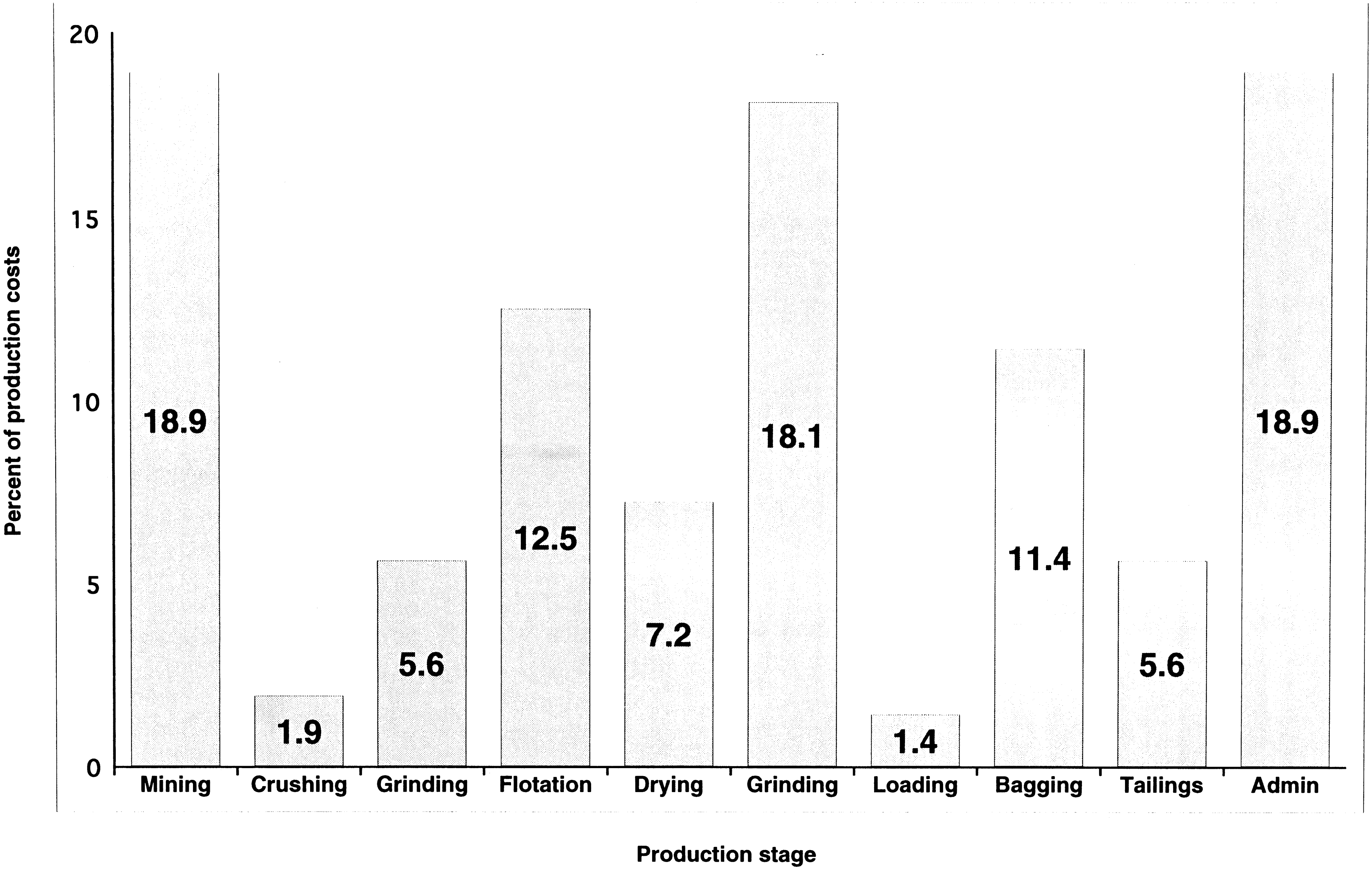

Figure 1. Distribution of feldspar production costs (Kauffman & Van Dyk, 1994)

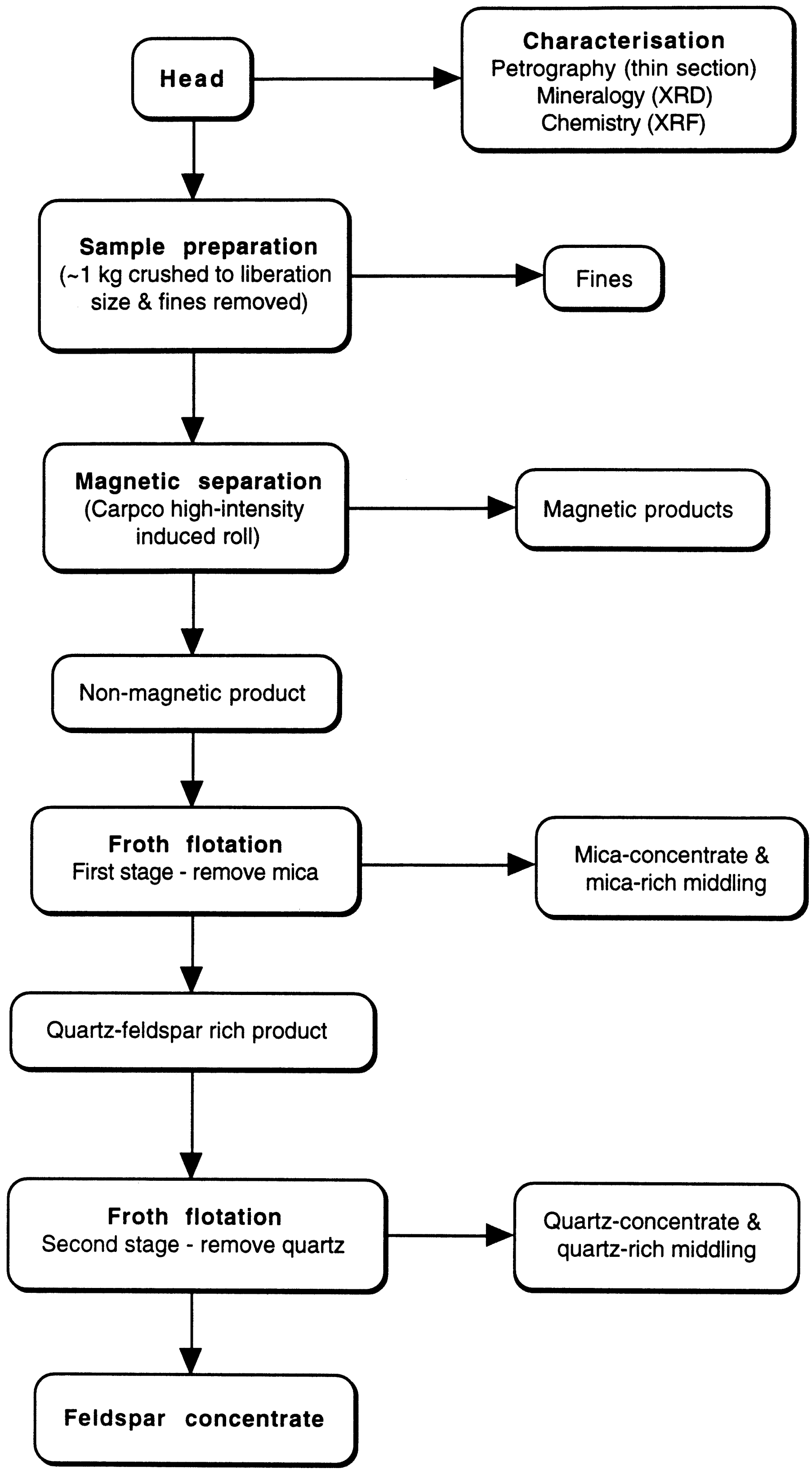

Figure 2. BGS methodology for laboratory feldspar processing

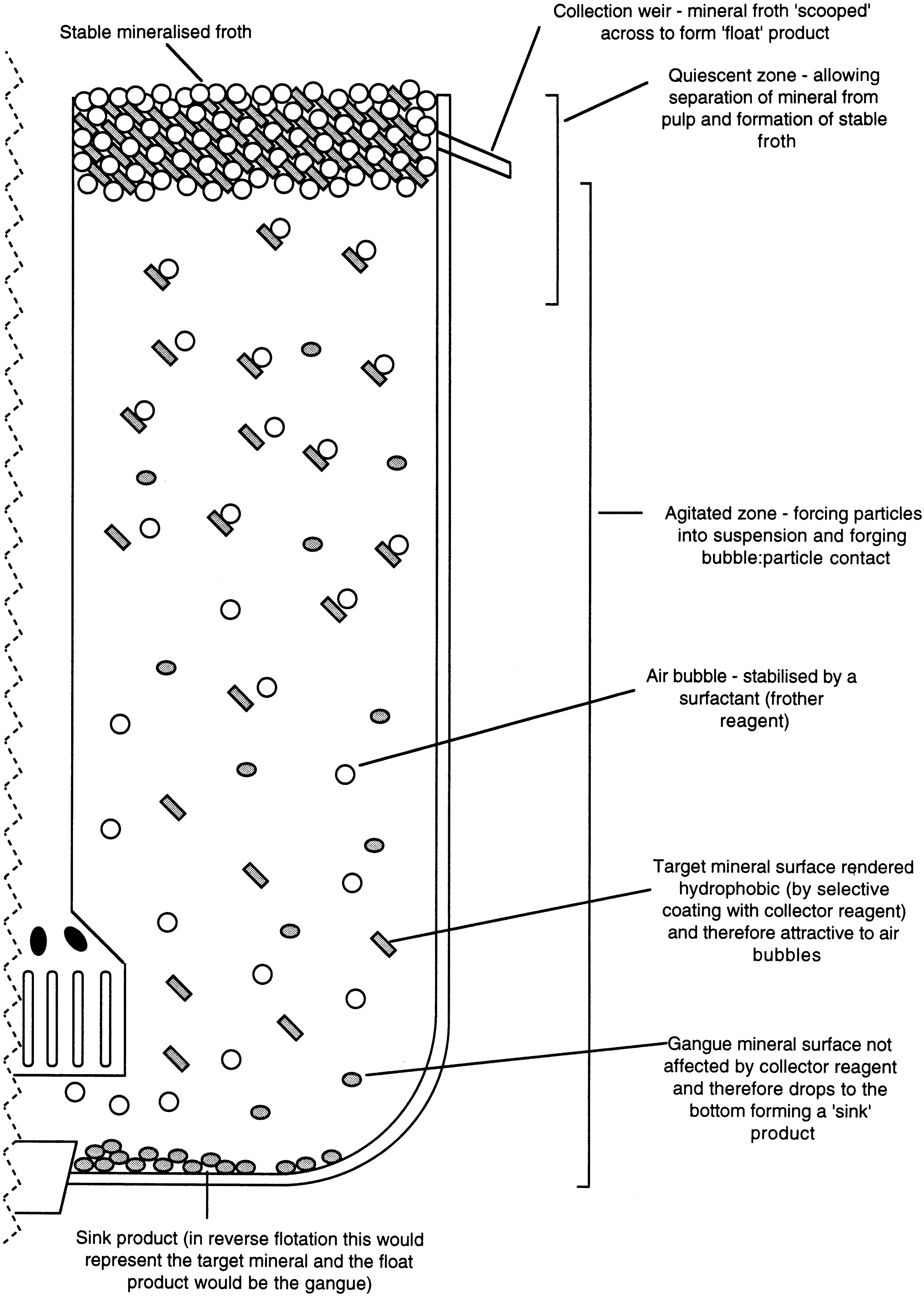

Figure 3. Cut-away diagram illustrating the theory of froth flotation