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# Mineral processing characteristics of natural zeolites from the Aritayn Formation of northeast Jordan

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**Abstract.** The inferior grade of natural zeolite ores in comparison to their synthetic counterparts has been identified as a possible factor responsible for the relatively small market share of the former. This paper describes the results of laboratory-scale mineral processing trials carried out on relatively low-grade natural zeolite ores from the Aritayn Formation of northeast Jordan to improve their purity through removal of unwanted gangue constituents. Appropriate sample preparation and mineral processing methods were selected which utilised contrasts in texture, particle-size, hardness, specific gravity and magnetic susceptibility between gangue and target constituents to achieve beneficiation. Sample preparation by autogenous comminution was able to selectively liberate zeolite minerals from the surface of pyroclasts and therefore was an effective method of pre-concentration. Subsequently, using widely-available magnetic and gravity separation equipment, a high-grade concentrate containing 89% zeolite was produced at a recovery of 37% from a lapilli tuff of 47% head grade.

## Mineral processing of natural zeolites

Eyde (1993) noted that the grade of most commercial natural zeolite ores (zeolite content about 75%) is lower than that of many other industrial mineral commodities, such as kaolin, limestone, glass sand, etc. Eyde identified this deficiency as being partly responsible for the low sales of natural zeolites and the large market share of their synthetic counterparts. However, he suggested that the purity of natural zeolites could be improved using currently available mineral processing technology. Eyde concluded that more financial resources within the natural zeolite industry need to be allocated to the production of processed high-purity products which are competitive with their synthetic counterparts in terms of price and performance.

To date, only a minor amount of research on the mineral processing of natural zeolites has been carried out. In the U.S.A., a preliminary study (Mondale et al. 1978) and a later more comprehensive investigation (Mondale et al. 1988) upgraded 10 sedimentary (ash tuff) zeolite deposits, including chabazite, clinoptilolite, erionite and mordenite ores, by standard wet beneficiation methods such as classification (hydrocycloning), gravity separation (wet tabling) and froth flotation. In the majority of these deposits, the zeolite minerals present were less than 0.04 mm in size. Samples were prepared by jaw-crushing to $-1/4$ inch ($-6.35$ mm) and roller crushing to $-20$ mesh ($-0.85$ mm). Crushing to this size typically produced 25–50% material passing $-100$ mesh ($-0.15$ mm).

The present study describes an attempt to improve the purity of relatively low-grade natural zeolites (lapilli tuffs) from northeast Jordan using standard mineral processing methods. In particular, the use of petrographic, mineralogical and physical property data to help plan processing trials was tested. Appropriate sample preparation and mineral processing methods were selected on the basis of contrasts in texture, particle-size, hardness, specific gravity and magnetic susceptibility between target and gangue constituents.

## Mineral processing: facts and definition

A brief description of mineral processing terminology and notation used is given next. The main aim of mineral processing is to remove unwanted constituents of the ore (the *gangue*) and concentrate the mineral of value (the *target*) in a product at high grade and high recovery. The *grade* is defined as the weight percent of target mineral present in the product, and the *recovery* is the amount of the target mineral in the concentrate expressed as a proportion of the target mineral in the original or *head* sample (see Wills 1992). Usually, a balance has to be struck between grade and recovery such that a product of the desired grade is obtained from the mineral deposit at an economically acceptable recovery. Another important factor is the *yield* which is the proportion of the total weight of the head sample contained in the concentrate. Prior to crushing and grinding, the texture of the ore (in terms of the distribution and particle-size of target and gangue constituents) is usually examined to help determine the amount of size-reduction necessary to produce discrete particles, i.e. the *liberation* size.

The following notation is used in the text to express particle-size: the plus symbol + is used as a prefix to denote "greater than" the size specified and, conversely, the minus prefix − denotes "less than" the size specified. For example, a size fraction which contains particles of between 0.5 min and 0.25 mm in size is written in shorthand form as −0.5 +0.25 mm.

## Natural zeolites of the Aritayn Formation

A continental plateau lava of Neogene-Quaternary age, the Harrat Ash-Shaam basaltic super-group, is exposed in the northeastern part of Jordan. Recently, the Aritayn Formation of the Harrat Ash-Shaam basaltic super-group, which consists of inter-bedded, poorly-cemented air-fall tuffs and agglomerates, was found to contain natural zeolite deposits of possible economic significance (Ibrahim 1996). The petrology, mineralogy, chemistry and origin of these natural zeolites are described in a companion study in this volume (Ibrahim and Hall 1996).

Four 40 kg-size pyroclastic rock samples were collected from the Aritayn Formation for mineral processing experiments. Locality details are given elsewhere in this volume (Ibrahim and Hall 1996). The mineralogy of the four samples is shown in Table 1. The samples are only of moderate grade (47–60% zeolite content) and two types of zeolite assemblage are present. Jabal Aritayn (site B1) and Jabal Hannoun (site B5) contain faujasite and phillipsite, whereas Jabal Aritayn (site B2) and Tell Rimah (site B3) contain phillipsite and chabazite.

The samples collected at Jabal Aritayn (site B2), Tell Rimah (site B3) and Jabal Hannoun (site B5) are altered, friable, vesicular, vitric lapilli tuffs. The pyroclasts in these three samples are cemented by a matrix of zeolite minerals and calcite. In contrast, the sample collected at Jabal Aritayn (site B1) is a welded, vesicular, vitric agglomerate and does not contain a matrix.

In all four pyroclastic rocks collected, vitric clasts predominate with only subordinate proportions of crystal fragments and lithic clasts. Vitric clasts consist of altered sideromelane (volcanic glass). Olivine and clinopyroxene phenocrysts are present in an altered glassy groundmass containing plagioclase microlites. Crystal fragments mainly consist of olivine and orthopyroxene, with lesser clinopyroxene and minor spinel. Lithic clasts include: (1) fractured olivine-rich basalt partially altered to iddingsite; (2) ultramafic, spinel-bearing peridotite and pyroxenite xenoliths; and (3) sandstone and limestone epiclasts derived from the sedimentary cover. In the Jabal Aritayn (site B2), Tell Rimah (site B3) and Jabal Hannoun (site B5) samples, pyroclasts are typically < 5 mm in size. In the Jabal Aritayn sample (site B1), pyroclasts are usually between 1 mm and 6 mm in size.

Zeolite minerals generally occur within the outer part of inter granular cavities, as thin coatings or crusts on the surface of pyroclasts, and as amygdaloidal growth in vesicles. However, in the vitric agglomerate sample, Jabal Aritayn (site B1), zeolite minerals are present in amygdaloidal form only. Calcite forms a blocky cement in the centre of inter granular cavities. Faujasite occurs in Jabal Aritayn (site B1) and Jabal Hannoun (site B5) samples as isolated and aggregated, equant (octahedral) crystals. Isolated crystals of faujasite are from 60 μm up to 300 μm in diameter. Also, druzy faujasite rims on pyroclast surfaces are between 30 μm and 240 μm in thickness. Phillipsite is present in all samples in the form of radial spherulitic crystal aggregates and isolated euhedral prismatic crystals. Phillipsite crystals are commonly <0.1 mm long and infrequently up to 0.5 mm in length. Chabazite is present in Jabal Aritayn (site B2) and Tell Rimah (site B3) samples as isolated or aggregated crystals which are commonly <0.8 mm long.

## Methods

### *Mineralogy*

X-ray diffraction (XRD) analysis was carried out using a Philips PW 1700 automatic X-ray diffractometer. Prior to X-ray diffraction analysis, samples were ground for 10 min using a McCrone micronizing mill. Using the powdered samples obtained, randomly oriented mounts were prepared by back-loading into standard aluminium sample holders. Instrumental conditions were as follows: CoK$\alpha$ tube at 45 kV voltage and 40 mA current, 3–50 °2$\theta$ angular range and 0.9 °2$\theta$/minute scan speed.

Qualitative mineralogy was determined by conventional Hanawalt search procedures and also by reference to a Joint Committee on Powder Diffraction Standards (JCPDS) database of standard mineral patterns.

Using the sizing and specific gravity methods of DeGennaro and Franco (1979) and Mondale et al. (1988), faujasite, phillipsite and chabazite were separated from samples for use as XRD standards. Individual dilution mixtures for faujasite, phillipsite and chabazite were prepared from known proportions of these three zeolite minerals using the +4 mm size fraction from the Jabal Hannoun sample (site B5) as a matrix. The resulting standards were prepared

**Table 1.** Quantitative mineralogy of the four pyroclastic rock samples: total zeolite (Z), phillipsite (P), faujasite (F), chabazite (Ch) and calcite (Ca) content

| Sample | Z (%) | P (%) | F (%) | Ch (%) | Ca (%) | "Pyroclasts" (%)[a] |
|---|---|---|---|---|---|---|
| Jabal Aritayn (site B1) | 47.9 | 35.2 | 12.7 | | 3.9 | 48.2 |
| Jabal Aritayn (site B2) | 59.5 | 32.6 | – | 26.9 | 6.4 | 34.1 |
| Tell Rimah (site B3) | 59.5 | 26.8 | | 32.7 | 9.5 | 31.0 |
| Jabal Hannoun (site B5) | 46.8 | 17.7 | 29.1 | – | 11.1 | 42.1 |

[a] Pyroclast content calculated by subtraction

by grinding in a McCrone micronizing mill for 10 min, to ensure thorough mixing, and analysed by XRD under identical instrumental conditions to those listed above. From the XRD data obtained, calibration curves of zeolite content (weight %) vs XRD intensity (cps) were constructed for phillipsite (7.16 Å line), faujasite (3.77 Å line) and chabazite (2.93 Å line). Correlation coefficients of 0.955, 0.995 and 0.993 were obtained for the calibration graphs for phillipsite, faujasite and chabazite, respectively. The precision of each calibration was tested by carrying out six repeat XRD analyses using an identical sample. For all three calibration curves, repeatability for zeolite quantification was within ±1.7%.

Calcite was quantified by constructing an XRD calibration curve of calcite content (wt.%) versus 3.03 Å intensity (cps) using 12 products from the mineral processing trials. For this calibration curve, calcite content was determined from the decomposition weight loss of this mineral (Bish and Duffy 1990) as measured by thermogravimetric analysis (TGA).

### *Sample preparation*

In this study, two different methods of sample preparation (comminution routes) were investigated (Fig. 1): (1) autogenous milling, a self-grinding process achieved by the action of ore particles on each other, and (2) compression milling which involves particle breakdown through fracture induced by an applied stress. In both sample preparation methods, preliminary crushing was carried out using a Dodge bottom-pivoted jaw-crusher set at a discharge aperture of 8 mm.

Compression milling was carried out on +0.5 mm size feed from the jaw-crusher in order to minimise the amount of fine particles resulting. A pilot-scale Sturtevant roll crusher was used in which particles are ground by compression between two horizontally-mounted, counter-rotating, smooth-surfaced steel rolls.

The second type of sample preparation, autogenous milling, was also carried out on the +0.5 mm size feed from the jaw-crusher. A customised laboratory-scale batch tumble mill was used. This consisted of a 20 l volume polypropylene container fitted with four baffles rotated using the drive of a Pascall 9FS ball mill. Samples were tumbled for three 30 min cycles. After each cycle, the −0.5 mm size fraction was removed by dry screening to prevent over-grinding. As the tumble mill rotates the feed cascades and particle-to-particle impact causes particle-size reduction by abrasion and chipping.

After sample preparation, the feed obtained was dry-screened through a stack of 4, 2, 0.5, 0.25, 0.125 and 0.063 mm aperture, 300 mm diameter, stainless steel sieves using an automatic Fritsch Analysette sieve shaker.

### *Mineral processing*

For magnetic separation, the −0.5 + 0.25 mm and −0.25 + 0.125 mm size fractions obtained from sample preparation were processed using a Carpco (Model No. MIH. 13.111-5) high-intensity, induced-roll, laboratory-scale magnetic separator. Instrumental conditions were as follows: 250 g/h/cm feed rate, 109 rpm cylinder speed and 2 mm air gap. Under these conditions, tailings (< 1 Amp), middlings (3–1 Amps) and concentrates (> 3 Amps) were produced from two passes at a field strength of 1 Amp/11 000 Gauss and 3 Amps/15 500 Gauss, respectively.

For gravity separation, the −0.5 + 0.25 mm and −0.25 + 0.125 mm size fractions obtained from sample preparation were processed using a Mozley (MK II) laboratory shaking table. The 'V' profile tray was used, as recommended for feed sizes of between 2 mm and 0.125 mm. Tray slope, oscillation speed and amplitude were set at 15°, 60 rpm and 6.33 cm, respectively.

## Predicting mineral processing behaviour

To some extent, it is possible to predict sample preparation and mineral processing behaviour from mineralogical and petrographic characteristics, as follows:

*Particle-size.* A large proportion of the gangue is present as coarse pyroclasts (− 5 + 2 mm), whereas the target zeolite minerals are present as a matrix (− 1 mm). Therefore, size-classification methods such as sieving may be able to separate and enrich zeolite minerals within a fine-fraction. Sample preparation should ideally aim to concentrate the zeolite minerals as discrete particles of between 0.5 mm and 0.125 mm in size for two reasons. Firstly, the petrographic information indicates that, in particles above 0.5 mm in size, zeolite is likely to be locked within 'middling' grains, i.e. composite particles which contain both target and gangue minerals. These respond poorly to mineral processing due to their hybrid character. Secondly, the efficiency of gravity separation (wet tabling) and

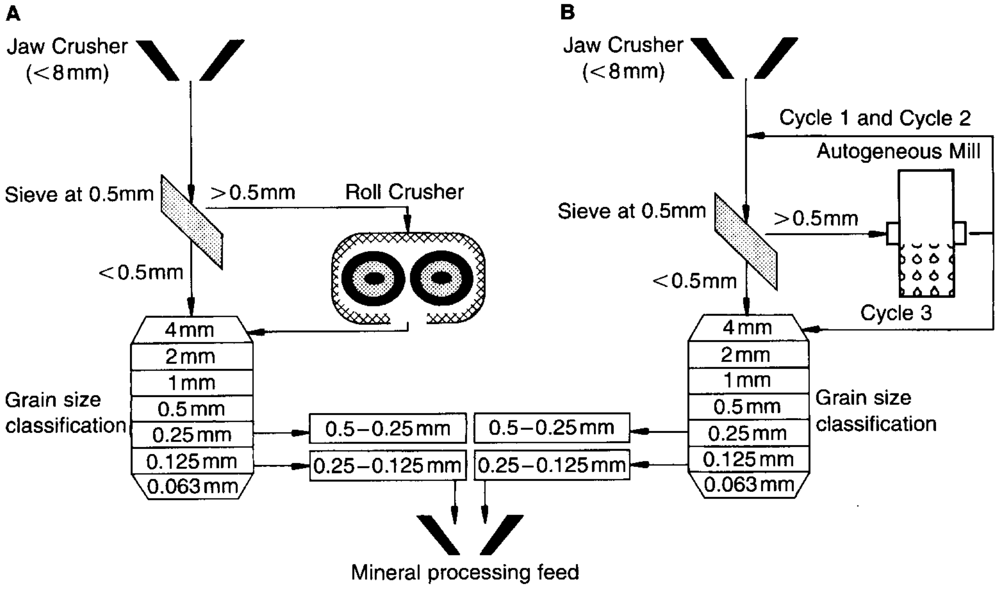

**Fig. 1.** Flow sheets for the two different types of sample preparation used: **A** compression milling, **B** autogenous milling

high-intensity magnetic separation are both maximised for a feed size of approximately −0.5 + 0.125 mm (see Fig. 1.8, in Wills 1992). Therefore, between 0.5 mm and 0.125 mm in size, zeolite minerals are likely to be both well-liberated and of the optimum size for mineral processing.

*Texture.* The zeolite minerals are present as an encrusting cement on the surface of pyroclasts. Therefore, an autogenous milling process, based on particle-to-particle impact and abrasion, may be able to selectively release target minerals from the surfaces of gangue pyroclasts. In contrast, compression milling is unlikely to be effective, as this process is most suited to the liberation of target minerals when these are distributed evenly within a matrix of gangue minerals.

*Mineral hardness.* Calcite is softer (Moh's hardness 3) than faujasite, phillipsite and chabazite (Moh's hardness between 4 and 5) (Gottardi and Galli 1985). Calcite also encloses the earlier zeolite minerals. Therefore, due to their relative hardness and textural association, it is probable that the liberation of zeolite minerals will also 'unlock' calcite from the rock. The pyroclasts in the Aritayn Formation samples consist of hydrous, altered volcanic glass and are probably considerably weaker than fresh sideromelane. Differences in hardness between target and gangue constituents are therefore likely to be small.

*Magnetic properties.* The altered pyroclasts present are enriched in residual iron and may exhibit sufficient magnetic susceptibility to enable their removal by magnetic separation.

*Specific gravity (SG).* The likely effectiveness of gravity separation methods can be predicted using the concentration criterion (*CC*) (Wills 1992), as follows:

$$CC = (SG \text{ of target mineral} - 1)/(SG \text{ of gangue mineral} - 1)$$

Concentration criteria (*CC*) values were calculated for faujasite, phillipsite and chabazite (Table 2). If *CC* values are between 2.5 and 1.75 then commercial separation is usually possible only for a feed size of + 0.15/0.25 mm. When *CC* values fall between 1.75 and 1.25, commercial separation is typically only feasible for + 1 mm size feed. In Table 2, the *CC* values indicate that gravity separation of zeolite from primary volcanic minerals and lithic clasts is likely to be possible for feed sizes of + 0.15/0.25 mm. Predicting the processing behaviour of vitric clasts is more problematic as their *SG* values depend on original chemical composition and subsequent degree of alteration. The *CC* values calculated here, based on published *SG* data for fresh sideromelane and palagonite, indicate that gravity separation of vitric clasts from zeolite minerals is likely to be either not possible or possible only for + 1 mm size feed, depending on the degree of alteration (Table 2).

## Processing trials

Firstly, a simple mineral processing route was tested on all four natural zeolite samples. This consisted of sample preparation by autogenous milling followed by high-intensity dry magnetic separation.

Then, following on from this, the mineral processing characteristics of one individual sample, the vitric lapilli tuff from Jabal Hannoun (site B5), were investigated in more detail. This sample was chosen for particular attention because of its high faujasite content, this being a mineral with a potentially higher value than the others present. Initially, by comparing autogenous and compression

**Table 2.** Concentration criteria (*CC*) values for gravity separation of zeolite minerals from the other constituents of pyroclastic rocks (after Wills 1992)

| Constituent | *SG* | Concentration criterion faujasite | Concentration criterion phillipsite | Concentration criterion chabazite |
|---|---|---|---|---|
| *Target minerals* | | | | |
| Faujasite[a] | 1.92 | | | |
| Phillipsite[a] | 2.20 | | | |
| Chabazite[a] | 2.10 | | | |
| *Gangue minerals* | | | | |
| Calcite[a] | 2.71 | 1.86 | 1.43 | 1.55 |
| Forsterite[a] | 3.27–3.37 | 2.47–2.58 | 1.89–1.98 | 2.06–2.35 |
| Diopside[a] | 3.28 | 2.48 | 1.90 | 2.07 |
| Augite[a] | 3.34 | 2.54 | 1.95 | 2.13 |
| Magnetite[a] | 5.18 | 4.54 | 3.48 | 3.80 |
| Spinel[a] | 3.55 | 2.77 | 2.13 | 2.32 |
| Hematite[a] | 5.26 | 4.63 | 3.54 | 3.87 |
| Goethite[a] | 3.30–4.30 | 2.50–3.59 | 1.92–2.75 | 2.09–3.00 |
| Ilmenite[a] | 4.72 | 4.04 | 3.10 | 3.38 |
| *Volcanic glass* | | | | |
| Sideromelane[c] | 2.77 | 1.92 | 1.48 | 1.61 |
| Sideromelane[b] | 2.20–2.70 | 1.30–1.85 | 1.00–1.42 | 1.09–1.55 |
| Sideromelane[d] | 2.98 | 2.15 | 1.65 | 1.80 |
| Palagonite[d] | 2.44–2.11 | 1.21–1.54 | 0.93–1.18 | 1.10–1.29 |
| *Lithic clasts* | | | | |
| Basalt[c] | 2.98 | 2.15 | 1.65 | 1.80 |
| Pyroxenite[c] | 3.23 | 2.42 | 1.86 | 2.03 |
| Peridotite[c] | 3.23 | 2.42 | 1.86 | 2.03 |

*SG* data from:
[a] Mursky and Thompson (1958)
[b] Mondale et al. (1978)
[c] Daly et al. (1966)
[d] Furness (1978)

methods, optimum sample preparation conditions were established, by examination of the liberation characteristics and the performance of subsequent high-intensity magnetic separation. After optimum sample preparation conditions were established, multi-stage mineral processing routes were tested which involved combined gravity separation and high-intensity magnetic separation.

## Mineral processing results: all samples

### *Autogenous comminution*

Total zeolite grade, recovery and yield values for size fractions obtained from autogenous comminution are shown in Table 3. For the vitric lapilli tuffs, Jabal Aritayn (site B2), Tell Rimah (site B3) and Jabal Hannoun (site B5), a significant increase in zeolite grade was obtained for the size range −0.5 + 0.125 mm, at an appreciable recovery, as was desired. As stated previously, zeolite minerals in this size range are likely to be well-liberated and therefore amenable to mineral processing. In contrast, any zeolite remaining in the + 0.5 mm fractions of these samples is likely to be present as 'middling' grains, and would require further comminution prior to mineral processing. Autogenous comminution was particularly effective for the Tell Rimah (site B3) sample as a zeolite grade averaging 80.9% was obtained at a recovery of 52.9% for the − 0.5 + 0.125 mm size fractions. Therefore, significant pre-concentration of zeolite minerals between − 0.5 + 0.125 mm can be achieved by autogenous comminution of these lapilli tuffs. In addition, low recovery in the − 0.125 mm size range (10–18%) indicates that only a minor proportion of zeolite was lost to the fine-fraction.

**Table 3.** Response of all four samples to sample preparation by autogenous comminution: total zeolite grade (G), recovery (R) and yield (Y) data. Please note that in the text, for reasons of brevity and clarity, results for mineral processing feed (− 0.5 + 0.25 mm and − 0.25 + 0.125 mm fractions) have been combined and are discussed in terms of a single − 0.5 + 0.125 mm fraction

| Size fraction (mm) | (A) Crusher | | | (A) Crusher + (B) Autogenous mill | | |
|---|---|---|---|---|---|---|
| | G | R | Y | G | R | Y |
| *Jabal Aritayn (site B1)* | Head grade 47.9% | | | | | |
| +4 | 44.2 | 9.3 | 10.2 | 37.7 | 2.1 | 2.8 |
| −4 + 2 | 55.6 | 28.6 | 25.0 | 56.6 | 20.6 | 17.7 |
| −2 + 1 | 56.3 | 17.5 | 15.1 | 59.4 | 14.5 | 11.8 |
| −1 + 0.5 | 57.5 | 18.1 | 15.2 | 63.3 | 13.7 | 10.5 |
| −0.5 + 0.25 | 43.9 | 13.7 | 15.1 | 49.9 | 25.4 | 24.7 |
| −0.25 + 0.125 | 34.1 | 7.7 | 10.9 | 37.3 | 13.7 | 17.9 |
| −0.125 + 0.063 | 27.4 | 2.8 | 4.9 | 30.9 | 4.0 | 6.3 |
| −0.063 | 32.4 | 2.4 | 3.6 | 34.7 | 6.0 | 8.5 |
| *Jabal Aritayn (site B2)* | Head grade 59.5% | | | | | |
| +4 | 57.7 | 9.2 | 10.1 | 53.9 | 3.8 | 4.2 |
| −4 + 2 | 67.3 | 21.8 | 20.5 | 60.8 | 15.7 | 15.4 |
| −2 + 1 | 65.5 | 18.6 | 12.4 | 60.0 | 10.3 | 10.2 |
| −1 + 0.5 | 76.7 | 16.0 | 12.4 | 79.8 | 13.7 | 10.3 |
| −0.5 + 0.25 | 79.0 | 17.0 | 12.8 | 76.3 | 25.2 | 19.6 |
| −0.25 + 0.125 | 53.3 | 12.1 | 13.5 | 69.5 | 17.8 | 15.3 |
| −0.125 + 0.063 | 33.9 | 6.6 | 11.6 | 33.6 | 7.9 | 14.0 |
| −0.063 | 28.2 | 3.3 | 6.9 | 30.2 | 5.6 | 11.1 |
| *Tel Rimah (site B3)* | Head grade 59.5% | | | | | |
| +4 | 48.1 | 7.0 | 8.7 | 44.7 | 3.4 | 4.6 |
| −4 + 2 | 53.2 | 19.8 | 22.1 | 51.4 | 12.1 | 14.1 |
| −2 + 1 | 55.9 | 10.8 | 12.6 | 53.0 | 7.3 | 8.2 |
| −1 + 0.5 | 63.8 | 10.8 | 11.0 | 54.3 | 6.3 | 6.7 |
| −0.5 + 0.25 | 80.4 | 16.4 | 12.2 | 82.6 | 26.4 | 19.0 |
| −0.25 + 0.125 | 75.7 | 19.2 | 15.1 | 79.2 | 26.5 | 19.9 |
| −0.125 + 0.063 | 49.7 | 10.2 | 12.0 | 46.8 | 10.6 | 13.5 |
| −0.063 | 36.7 | 3.9 | 6.4 | 31.2 | 7.2 | 13.8 |
| *Jabal Hannoun (site B5)* | Head grade 46.8% | | | | | |
| +4 | 32.4 | 6.3 | 19.0 | 19.2 | 1.7 | 4.3 |
| −4 + 2 | 39.2 | 18.5 | 22.1 | 21.6 | 6.3 | 13.9 |
| −2 + 1 | 52.5 | 13.6 | 12.7 | 35.2 | 13.3 | 7.7 |
| −1 + 0.5 | 65.2 | 16.5 | 11.8 | 55.2 | 8.5 | 7.2 |
| −0.5 + 0.25 | 66.6 | 19.4 | 13.7 | 67.6 | 31.9 | 22.1 |
| −0.25 + 0.125 | 45.8 | 20.6 | 21.0 | 47.7 | 28.2 | 27.2 |
| −0.125 + 0.063 | 24.4 | 2.7 | 5.1 | 30.2 | 6.5 | 10.1 |
| −0.063 | 26.0 | 2.5 | 4.5 | 25.2 | 3.5 | 6.5 |

The coarser-grained vitric agglomerate, Jabal Aritayn (site B1), behaved anomalously as autogenous comminution only concentrated zeolite within the + 0.5 mm size fractions. The agglomerate-size pyroclasts probably broke down to a lesser extent than the lapilli-size pyroclasts present in the other samples. Also, the zeolite minerals in Jabal Aritayn (site B1) are inherently more difficult to liberate because of their amygdaloidal form. For this sample, further cycles in the tumble mill would be necessary to unlock zeolite from coarse + 0.5 mm fractions and improve liberation between 0.5 mm and 0.125 mm.

### *Magnetic separation*

After sample preparation by autogenous comminution, as described already, magnetic separation was carried out on − 0.5 + 0.25 mm and − 0.25 + 0.125 mm fractions of all four samples (Table 4). The quantitative mineralogy of the concentrates obtained are listed in Table 5.

**Table 4.** Single-stage magnetic separation of all four samples: total zeolite grade (G), recovery (R) and yield (Y) of concentrates

| Processing route | − 0.5 + 0.25 mm | | | −0.25 + 0.125 mm | | |
|---|---|---|---|---|---|---|
| | G | R | Y | G | R | Y |
| *Jabal Aritayn (site B1)* | | | | | | |
| (A) Crusher | 43.9 | 13.7 | 15.1 | 34.1 | 7.7 | 10.9 |
| (B) Autogenous mill | 49.9 | 25.4 | 24.7 | 37.3 | 13.7 | 17.9 |
| (C) Magnetic separation | 91.3 | 19.4 | 10.2 | 90.8 | 24.8 | 13.1 |
| *Jabal Aritayn (site B2)* | | | | | | |
| (A) Crusher | 79.0 | 17.0 | 12.8 | 53.3 | 12.1 | 13.5 |
| (B) Autogenous mill | 76.3 | 25.2 | 19.6 | 69.5 | 17.8 | 15.3 |
| (C) Magnetic separation | 87.2 | 17.4 | 11.9 | 90.1 | 18.0 | 11.9 |
| *Tell Rimah (site B3)* | | | | | | |
| (A) Crusher | 80.4 | 16.4 | 12.2 | 75.7 | 19.2 | 15.1 |
| (B) Autogenous mill | 82.6 | 26.4 | 19.0 | 79.2 | 26.5 | 19.9 |
| (C) Magnetic separation | 91.3 | 23.8 | 15.5 | 96.0 | 22.3 | 13.8 |
| *Jabal Hannoun (site B5)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Autogenous mill | 67.6 | 31.9 | 22.1 | 47.7 | 28.2 | 27.7 |
| (C) Magnetic separation | 82.8 | 25.4 | 14.2 | 90.7 | 7.6 | 3.9 |

**Table 5.** Quantitative mineralogy of the concentrates from the magnetic separation of all four samples: total zeolite (Z), phillipsite (P), faujasite (F), Chabazite (Ch) and calcite (Ca) content

| Processing | − 0.5 + 0.25 mm | | | | | − 0.25 + 0.125 mm | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Z (%) | P (%) | F (%) | Ch (%) | Ca (%) | Z (%) | P (%) | F (%) | Ch (%) | Ca (%) |
| Jabal Aritayn B1 | 91.3 | 76.0 | 15.3 | | 4.7 | 90.8 | 69.9 | 20.9 | | 7.3 |
| Jabal Aritayn (B2) | 87.2 | 57.3 | – | 29.9 | 9.4 | 90.1 | 57.8 | – | 32.3 | 9.1 |
| Tell Rimah (B3) | 91.3 | 41.6 | – | 49.8 | 8.5 | 96.0 | 42.7 | – | 53.4 | 3.5 |
| Jabal Hannoun (B5) | 82.8 | 31.6 | 51.1 | – | 13.0 | 92.7 | 35.2 | 57.4 | – | 6.4 |

**Table 6.** Jabal Hannoun sample (site B5): sample preparation characteristics in response to compression and autogenous methods. Total zeolite grade (G), recovery (R) and yield (Y) data. Please note that in the text, for reasons of brevity and clarity, results for mineral processing feed ( − 0.5 + 0.25 mm and − 0.25 + 0.125 mm fractions) have been combined and are discussed in terms of a single −0.5 + 0.125 mm fraction

| Size fraction (mm) | (A) Crusher + (B) Compression mill | | | (A) Crusher + (B) Autogenous mill | | |
|---|---|---|---|---|---|---|
| | G | R | Y | G | R | Y |
| + 4 | – | – | | 19.2 | 1.7 | 4.3 |
| − 4 + 2 | – | – | | 21.6 | 6.3 | 13.9 |
| − 2 + 1 | 33.7 | 1.4 | | 35.2 | 13.3 | 7.7 |
| − 1 + 0.5 | 54.3 | 17.4 | | 55.2 | 8.5 | 7.2 |
| − 0.5 + 0.25 | 55.6 | 36.9 | | 67.6 | 31.9 | 22.1 |
| − 0.25 + 0.125 | 44.4 | 34.1 | | 47.7 | 28.2 | 27.2 |
| − 0.125 + 0.063 | 29.9 | 5.2 | | 30.2 | 6.5 | 10.1 |
| − 0.063 | 29.8 | 5.1 | | 25.2 | 3.5 | 6.5 |

**Table 7.** Jabal Hannoun sample (site B5): total zeolite grade (G), recovery (R) and yield (Y) of concentrates from magnetic separation. Please note that in the text, for reasons of brevity and clarity, results for mineral processing feed ( − 0.5 + 0.25 mm and − 0.25 + 0.125 mm fractions) have been combined and are discussed in terms of a single − 0.5 + 0.125 mm fraction

| Processing route | − 0.5 + 0.25 mm | | | −0.25 + 0.125 mm | | |
|---|---|---|---|---|---|---|
| | G | R | Y | G | R | Y |
| *Route (1)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Magnetic separation | 80.3 | 14.3 | 8.3 | 76.5 | 6.8 | 4.2 |
| *Route (2)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Compression mill | 55.6 | 36.9 | | 44.4 | 34.1 | |
| (C) Magnetic separation | 77.4 | 20.6 | | 77.7 | 11.7 | |
| *Route (3)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Autogenous mill | 67.6 | 31.9 | 22.1 | 47.7 | 28.2 | 27.7 |
| (C) Magnetic separation | 82.8 | 25.0 | 14.2 | 90.7 | 7.6 | |

## Mineral processing: Jabal Hannoun sample

### *Sample preparation*

The sample preparation characteristics of the Jabal Hannoun sample (site B5), in response to both compression and autogenous comminution, are summarised in Table 6. In terms of the − 0.5 + 0.125 mm fractions, the compression mill did not appreciably enhance zeolite grade (50.0%) but a good recovery was achieved (71.0%). Conversely, the autogenous mill significantly enhanced zeolite grade of the − 0.5 + 0.125 mm fractions (57.7%) but at a lower recovery (60.1%). At first glance, these contrasting results for the two comminution methods appear to reflect the trade-off between grade and recovery that is usual for any mineral processing operation. However, their true significance only becomes clear when compared to the zeolite grade (56.2%) and recovery (40.0%) for the − 0.5 + 0.125 mm size range of the jaw-crushed feed (see Table 3). From this it can be seen that the grade and recovery values for jaw-crushed feed were *both* increased by subsequent autogenous comminution. This confirms that autogenous comminution *selectively* liberated zeolite minerals, i.e. during sample preparation, target mineral particles were released while gangue constituents remained locked within the rock.

The influence of compression and autogenous comminution methods on subsequent high-intensity dry magnetic separation is outlined in Table 7. It can be seen that use of autogenous sample preparation increased the separation efficiency of subsequent magnetic separation. For magnetic separation of the − 0.5 + 0.125 mm fractions prepared by autogenous mill (Route 3 in Table 8), a zeolite grade averaging 86.8% was achieved at 32.6% recovery. In comparison, the performance of magnetic separation for the − 0.5 + 0.125 mm fractions prepared by compression mill (Route 2 in Table 8) was inferior, as the zeolite grade achieved was much lower (77.6%) for a similar recovery (32.3%). This suggests that the degree of liberation achieved by the compression method is less than that obtained using the autogenous preparation method. A possible explanation for this is that, in compression milling, particles may have fractured across (and not along) mineral boundaries producing a higher proportion of middling grains which then responded poorly to mineral processing.

### *Magnetic and gravity separation*

Results of combined magnetic and gravity separation for the Jabal Hannoun sample (site B5) are listed in Table 8. Quantitative mineralogical data for the concentrates obtained are presented in Table 9. As a summary, results for processing Route 6 (Table 8) are shown schematically in Fig. 2. It can be seen that, using the mineral processing

**Table 8.** Jabal Hannoun sample (site B5): total zeolite grade (G), recovery (R) and yield (Y) of concentrates from combined magnetic and gravity separation. Please note that in the text, for reasons of brevity and clarity, results for mineral processing feed (−0.5 +0.25 mm and −0.25 + 0.125 mm fractions) have been combined and are discussed in terms of a single −0.5 + 0.125 mm fraction

| Processing route | −0.5 + 0.25 mm | | | −0.25 + 0.125 mm | | |
|---|---|---|---|---|---|---|
| | G | R | Y | G | R | Y |
| *Route (4)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Magnetic separation | 80.3 | 14.3 | 8.3 | 76.5 | 6.8 | 4.2 |
| (C) Gravity separation | 88.6 | 13.0 | | 86.4 | 6.3 | |
| *Route (5)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Autogenous mill | 67.6 | 31.9 | 22.1 | 47.7 | 28.2 | 27.7 |
| (C) Magnetic separation | 82.8 | 25.0 | 14.2 | 90.7 | 7.6 | |
| (D) Gravity separation | 91.3 | 22.9 | | | | |
| *Route (6)* | | | | | | |
| (A) Crusher | 66.6 | 19.4 | 13.7 | 45.8 | 20.6 | 21.0 |
| (B) Autogenous mill | 67.6 | 31.9 | 22.1 | 47.7 | 28.2 | 27.7 |
| (C) Gravity separation | 80.7 | 13.8 | 10.9 | 81.5 | 24.7 | 14.1 |
| (D) Magnetic separation | 88.8 | 15.8 | | 89.7 | 20.8 | |

**Table 9.** Jabal Hannoun sample (site B5): total zeolite (Z), faujasite (F), phillipsite (P) and calcite (Ca) contents of mineral processing concentrates. The six processing routes are defined in Tables 7 and 8

| Processing | −0.5 + 0.25 mm | | | | −0.25 + 0.125 mm | | | |
|---|---|---|---|---|---|---|---|---|
| | Z (%) | F (%) | P (%) | Ca (%) | Z (%) | F (%) | P (%) | Ca (%) |
| Route 1 | 80.3 | 51.7 | 28.6 | NA | 76.5 | 52.7 | 23.8 | NA |
| Route 2 | 77.4 | 43.3 | 35.1 | NA | 72.7 | NA | NA | NA |
| Route 3 | 82.8 | 51.1 | 31.6 | NA | 90.7 | NA | NA | NA |
| Route 4 | 88.6 | 58.3 | 30.3 | NA | 86.4 | 60.3 | 26.1 | NA |
| Route 5 | 91.3 | NA | NA | NA | 90.7 | NA | NA | NA |
| Route 6 | 88.8 | NA | NA | NA | 89.7 | NA | NA | NA |

NA denotes data not available

Route 6, an average total zeolite grade of 89.3% was achieved at a recovery of 36.6% for the combined −0.5 + 0.125 mm fractions. The results in Table 8 indicate that separation efficiency for the −0.5 + 0.25 mm fraction is optimised using Route 5, whereas Route 6 is more efficient for the −0.25 + 0.125 mm fraction. This suggests that, in order to maximise the overall efficiency of the operation, fine- and coarse-size fractions may require different processing configurations.

## Conclusions

On the basis of the contrasts in the physical properties of target and gangue constituents, such as texture, hardness, particle-size, specific gravity and magnetic susceptibility, it was predicted that autogenous comminution, magnetic separation and gravity separation were likely to be effective processing methods. This was largely confirmed by experimental findings.

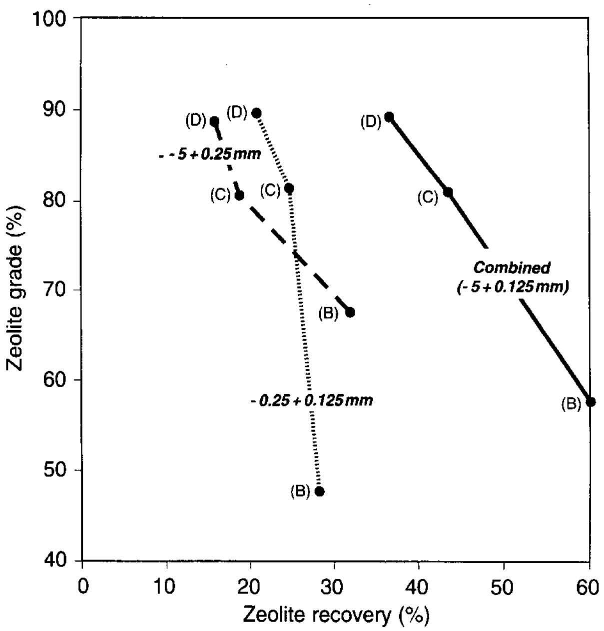

**Fig. 2.** Zeolite grade versus recovery for −0.5 + 0.25 mm and −0.25 + 0.125 mm fractions of Jabal Hannoun sample for the following mineral processing route: Autogenous mill (*B*) → gravity separation (*C*) → magnetic separation (*D*). This corresponds to Route 6 in Table 8

It was demonstrated, for the Jabal Hannoun lapilli tuff, that sample preparation by autogenous comminution was an effective pre-concentration method able to release target zeolite minerals selectively to the optimum size fractions for mineral processing (−0.5 + 0.125 mm). In contrast, compression comminution was not selective and released gangue constituents as well as target minerals to the −0.5 + 0.125 mm size range. Use of −0.5 + 0.125 mm feed from the autogenous mill also improved the efficiency of subsequent magnetic separation. In comparison, feed obtained from the compression mill was poorly-liberated and responded less-well to magnetic separation.

The results of this study indicate that conventional mineral processing technology, using widely-available magnetic and gravity separation equipment, is capable of producing high-grade concentrates from relatively low-grade natural zeolites at reasonable recoveries. For the Jabal Hannoun sample (47% head grade), a product containing 89% zeolite was obtained at a recovery of 37%. However, the mineral processing methods described in this study are likely to be mainly applicable to coarse-textured and poorly-consolidated natural zeolite ores.

We conclude that in future it may be possible to produce viable commercial products from natural zeolite ores currently considered too impure to be of economic significance. An overriding obstacle to the use of mineral processing technology within the natural zeolite industry is likely to be the costs involved. However, it is common practise for producers of natural zeolites to use crushing and grinding to prepare products for different end-uses. Our results demonstrate that significant improvements in purity can accompany this type of sample preparation and could off-set some of the costs involved by adding-value to the products obtained.

## References

Bish, D.L., Duffy, C. (1990) Thermogravimetric analysis of minerals. In: Stucki, J.W., Bish, D.L., Mumpton, F.A. (eds.) Thermal analysis in clay science, CMS Workshop Lectures, vol. 3

Daly, R.A., Manger, G.E., Clark Jr. S.P. (1966) Density of rocks. In: Clark Jr., S.P. (ed.) Handbook of physical constants, Rev. Edn. Geol. Soc. Am. Memoir 97:20–26

De Gennaro, M., Franco, E. (1979) Arricchimento e separazione delle zeoliti di rocce piroclastiche. L'Indust. Miner. 30:329–339

Eyde, T.H. (1993) One size doesn't fit all. Extended abstract. Zeolite '93, Program and Abstracts of the 4th International Conference on the Occurrence, Properties and Utilization of Natural Zeolites, Boise, Idaho, June 20–28, 1993

Furness, H. (1978) Element mobility during palagonitisation of a subglacial hyaloclastite in Iceland. Chem. Geol. 22:249–264

Gottadi, G., Galli, E. (1985) Natural zeolites. Minerals and rocks 18. Springer, Berlin New York Heidelberg

Ibrahim, K. (1996) Geology, mineralogy, chemistry, origin and uses of the zeolites associated with Quaternary tuffs of Northeast Jordan. Ph.D. Thesis, University of London, 249 pp

Ibrahim, K., Hall, A. (1995) New occurrences of diagenetic faujasite in the Quaternary tuffs of north-east Jordan. Eur. J. Mineral 7:1129–1135

Ibrahim, K. and Hall, A. (1996) The authigenic zeolites of the Aritayn Volcaniclastic Formation, north-east Jordan. Min. Dep. this volume

Mondale, K.D., Mumpton, F.A., Aplan, F.F. (1978) Beneficiation of natural zeolites from Bowie, Arizona: a preliminary report. In: Sand, L.B., Mumpton, F.A. (eds.) Natural zeolites, occurrences, properties, use. Pergamon Press, Oxford

Mondale, K.D., Mumpton, F.A., Aplan, F.F. (1988) Properties and beneficiation of natural sedimentary zeolites. In: Carson, D.J.T., Vassilion, A.H. (eds.) Process mineralogy VIII. Minerals, Metals, and Materials Society

Mursky, G.A., Thompson, R.M. (1958) A specific gravity index for minerals. Can. Mineral. 6:273–287

Willis, B.A. (1992) Mineral processing technology, 5th Edn. Pergamon Press, Oxford, 855 pp

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