# Sedimentary Zeolite Deposits in Jordan

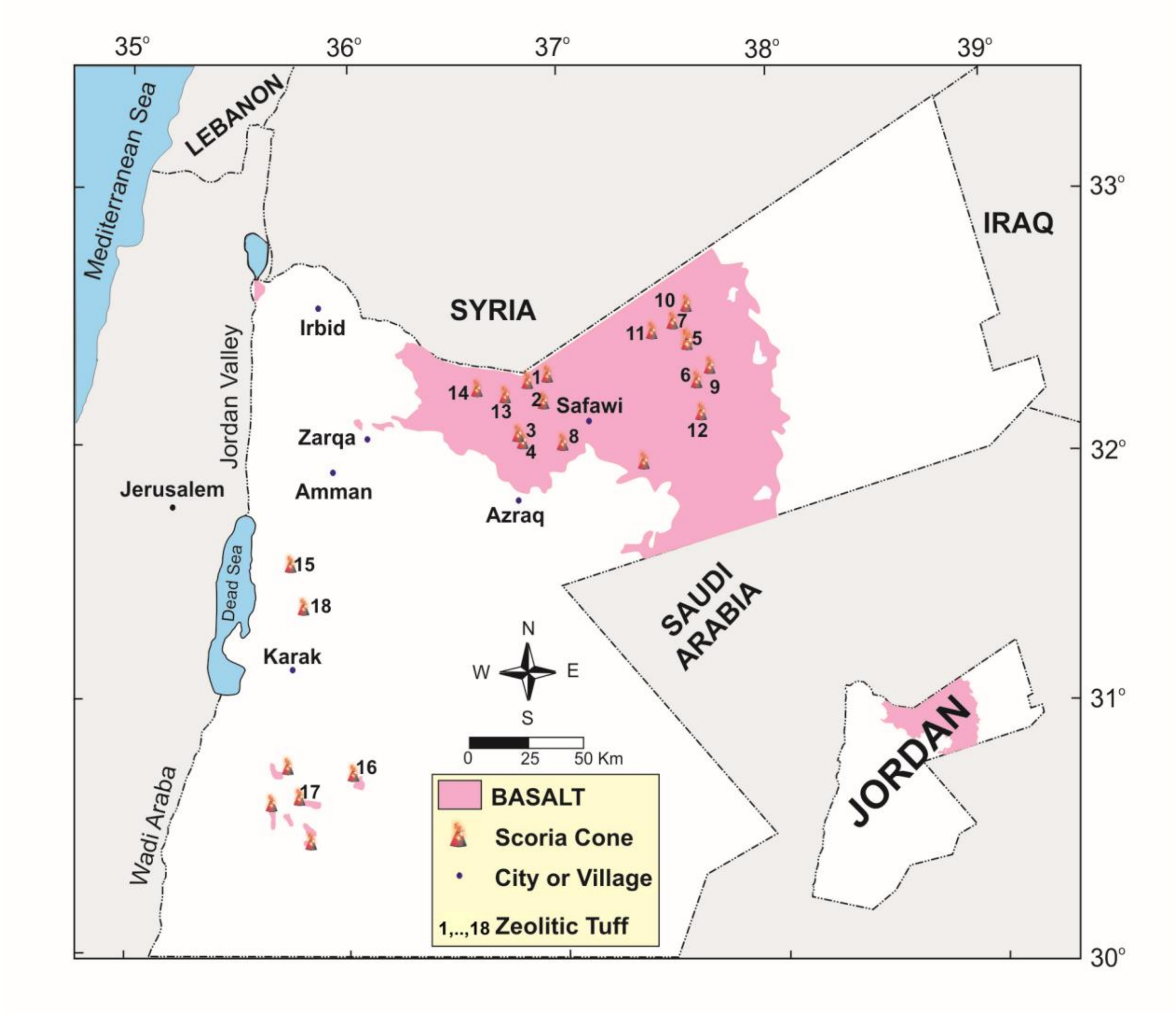

Table 1: Location of the zeolitic tuff localities in Jordan (see map)

| Locality Name | | Longitude (N) | Latitude (E) |
|---|---|---|---|
| 1 | Tell Rimah North | 32° 19' 11 | 36° 52' 49" |
| 2 | Tell Rimah South | 32° 18' 55 | 36° 52' 54 |
| 3 | Jabal Aritayn North | 32° 04' 44 | 36° 51' 23 |
| 4 | Jabal Aritayn South | 32° 04' 36 | 36° 51' 37 |
| 5 | Jabal Hannoun | 32° 23' 15 | 37° 37' 44 |
| 6 | Ashgof Wira | 32° 17' 10” | 37° 39' 34” |
| 7 | Jabal Tarboush | 32° 23' 29 | 37° 37' 06 |
| 8 | Tell Hassan | 32° 01' 05 | 36° 37' 25 |
| 9 | Ashgof North | 32° 18' 18” | 36° 37' 21” |
| 10 | Tall Humilan | 33° 25' 20” | 37° 33' 29” |
| 11 | Tall Al Boughaili | 32° 26' 10” | 37° 32' 40” |
| 12 | Lithyam | 32° 12' 33” | 37° 40' 60” |
| 13 | Jabal Ufyhim | 32° 04' 44” | 36° 51' 23” |
| 14 | Jabal Jalad | 32° 09' 04” | 36° 52' 36” |
| 15 | Wadi Zarqa Ma’in | 31° 36' 09” | 53° 35'49’ |
| 16 | Tall Juhira | 30° 38' 47” | 35° 49' 37” |
| 17 | Tall Amir | 30° 37' 23” | 35 ° 49' 43” |
| 18 | Al Alia | 30° 33' 05” | 35° 47' 58” |

## Introduction:

The Neogene-Quaternary plateau lavas of Jordan are part of the major "North Arabian Volcanic Province" which extends from Syria across Jordan into Saudi Arabia, covering in Jordan some 11,000 km$^2$ (Ibrahim, 1993, Tarawneh *et al.*, 2000). These lavas are predominantly alkali olivine basalts and are classified as the Harrat Ash-Shaam super-group (HASB), with a thickness from 100 m to 1500 m (Ibrahim, 1993). The HASB has an age range from 26 Ma to <0.5 Ma (Tarawneh *et al.*, 2000). Fissure dykes trending NW-SE which are parallel to the Red Sea (Ibrahim *et al.*, 2003) are the main source of volcanic activity along with local point-sourced volcanism. The number of vents in Jordan and adjacent areas exceeds 1000 vents. The HASB contains the Rimah Pyroclastic Group consisting of volcaniclastic and scoriaceous deposits erupted from volcanic centres. It includes a volcanic tuff formation (the Aritayn Formation). Economic zeolite deposits were first discovered and recorded in the Aritayn Formation in northeast Jordan by Dwairi (1987) followed by Ibrahim and Hall (1995, 1996) and Ibrahim (1996; 2004). Further discoveries were reported in central Jordan by Ghrir (1998), Al-Dwairi (2007), Dwairi *et al*. (2009) and Khoury *et al*. (2015). Table 1 gives the location of the important zeolitic tuff localities in Jordan (data from Ibrahim, 1996, and Khoury *et al.*, 2014).

## Geology of the Aritayn formation:

The formation was developed from stratified scoria cones and is made up of bedded, sorted air-fall lapilli-tephra and tuff. Lithologically, the formation is composed of stratified showers of ash and lapilli (sub-rounded to angular) volcanic clasts with minor basaltic bombs and basaltic blocks. About 40 wt% of the formation is composed of ash-size particles. Lapilli clasts are juvenile and cognate with subordinate clasts of accidental origin. The cementing material of the volcanic tuff is zeolites and carbonates. The zeolites occur as a cement material of the volcanic clasts or as a filling material inside the vesicles as shown in Figure 1.

According to Ibrahim and Hall (1995, 1996) and Ibrahim (1996), the Aritayn Formation was subdivided into three longitudinal diagenetic zones, with respect to the degree of alteration of the basaltic glass. The upper zone is made up of fresh tephra that comprises a grayish black, friable, vitric lapilli and ash fragments. The middle zone comprises palagonitized tuff that is characterized by variable colours of violet, dark brown to reddish brown. The diversity of colours is related to the palagonization process of the volcanic glass (sideromelane) (Figure 2). The lower zeolitized tuff zone is composed of highly altered lapilli granules and ash particles, where tuff granules become soft and friable.

Figure 1: Volcanic rock clasts in a cement of zeolite and calcite (white), Aritayn Formation

Figure 2: Quarrying of the Aritayn Formation

## Chemistry of volcanic tuff and volcanic glass:

Chemical analyses of tuffs from the different diagenetic zones are given in Table 2 which reveals a marked decrease in the amount of $SiO_2$ and $Na_2O$ from fresh tuff to phillpsite-chabazite tuff, accompanied by an increase in LOI (loss on ignition). The rest of the elements show a relatively smaller variation between the original and the altered tuff. An important feature is the strong depletion of $Na_2O$ in the phillipsite-chabazite sub-zone, and its relative enrichment in the lower faujasite-phillipsite sub-zone.

Table 2: Selected chemical analyses of different types of volcanic tuff and volcanic glass from Jordan

| Oxides | Tuff | | | | | Volcanic glass | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Fresh | Palagonite | PHI - CHA | FAU - PHI | | Fresh | | Palagonite | |
| | J58 | J38 | J9 | J33 | | J58 | J77 | J50 | J59 |
| $SiO_2$ | 42.20 | 37.09 | 39.40 | 35.60 | | 45.27 | 46.36 | 38.87 | 23.96 |
| $TiO_2$ | 2.34 | 2.06 | 2.56 | 2.19 | | 3.44 | 4.32 | 5.65 | 10.48 |
| $Al_2O_3$ | 12.64 | 9.65 | 12.73 | 11.13 | | 16.20 | 15.83 | 9.78 | 5.63 |
| $Fe_2O_3$ | 13.37 | 13.03 | 11.45 | 10.59 | | 11.80 | 9.07 | 25.35 | 39.32 |
| MnO | 0.18 | 0.18 | 0.16 | 0.13 | | 0.25 | 0.49 | 0.20 | 1.11 |
| MgO | 9.40 | 14.69 | 7.44 | 9.73 | | 4.08 | 4.41 | 1.33 | 2.28 |
| CaO | 9.35 | 7.68 | 6.52 | 6.44 | | 10.78 | 11.10 | 5.82 | 3.79 |
| $Na_2O$ | 3.13 | 1.38 | 0.26 | 2.43 | | 3.29 | 3.60 | 0.58 | 0.64 |
| $K_2O$ | 1.49 | 1.29 | 1.84 | 1.60 | | 2.16 | 2.30 | 0.16 | 0.42 |
| $P_2O_5$ | 0.62 | 0.76 | 0.42 | 0.32 | | 0.51 | 0.18 | n.d. | 0.04 |
| | | | | | | | | | |
| LOI | 3.39 | 10.75 | 16.00 | 18.22 | | | | | |
| Total | 98.11 | 98.56 | 98.78 | 98.38 | | 97.78 | 97.66 | 87.74 | 87.67 |

Data from Ibrahim and Hall, 1996.

Chemical analyses of the fresh volcanic glass show their similar composition. When projected in the TAS diagram of Le Bas *et al.* (1986), they lie in the field of basanite. As shown in Table 2, the palagonite is depleted in Si, Al, Na, K and Ca, and enriched in Fe and Ti compared with the fresh volcanic glass. Also, in contrast to the fresh sideromelane, the chemical composition of palagonite is rather variable, depending on the degree of palagonitization. The Fe and Ti contents of the palagonite are proportional to the degree of the palagonitization.

### Mineralogy

X-Ray diffraction results indicate the presence of phillipsite in all the studied localities. Chabazite is present in most localities. Faujasite is found in five localities: Jabal Hannoun, Tell Rimah, Jabal Aritayn, Tall Humilan and Wadi Zarqa Ma'in (Ibrahim and Hall, 1995, 1996; Khoury *et al.*, 2015). Analcime is found in five localities: Tilal al Hisnawat, Tall Al Boughali, Lithyam, Jabal Jalad, and Tall Amir (Ibrahim, 2004; Khoury *et al.*, 2015). Natrolite occurs as a major constituent in Tilal al Hisnawat (Ibrahim 2004). The non-zeolite constituents include olivine, clinopyroxene and feldspars. Hematite, calcite and smectite are among the secondary minerals.

### Petrography

*Volcanic tuff:*

The studied volcanic tuffs show different textures that range between massive, poorly cemented lapilli vitric tuff to coarse-grained vitric ash tuff. Clasts are mostly sub-rounded to sub-angular. The vitric clasts are altered to sideromelane (palagonite). Palagonite clasts occur in several forms and colors depending on the degree of palagonitization. The alteration processes involve the formation of zeolites (phillipsite, chabazite, faujasite), smectite and calcite. Zeolites may reach up to 30% by volume of the whole rock (Figure 3 and Figure 4).

*Zeolites*:

Phillipsite is the most abundant zeolite and occurs in all localities. It occurs as colourless thin rims to the pyroclastic grains or inside vesicles. It occurs as isolated euhedral prismatic crystals and radiated fan shape aggregates. In many of the studied localities, phillipsite rims grows directly on palagonite granules; otherwise it follows the growth of faujasite. This sequence of paragenesis was first reported by Ibrahim (1996) and Ibrahim and Hall (1996).

Chabazite occurs in transparent rhombohedral crystals showing simple penetration twinning. Chabazite follows the crystallization of phillipsite. Faujasite and chabazite were rarely reported together in the same sample.

Faujasite is reported as a minor constituent. It occurs in colourless, equant, isotropic, isolated or aggregated crystals that are 50 to 100 µm in size (Ibrahim and Hall, 1995). Faujasite grows directly on the walls of the vesicles and around palagonite clasts and always precedes phillipsite growth. Faujasite also crystallizes following the formation of smectite.

Analcime is colourless, equant, up to 70 µm in diameter with polygonal crystal habit. Natrolite is restricted to the intergranular spaces between palagonite granules in the form of cement. Petrographic study indicates that natrolite occurs in fibrous crystals and forms fan-like aggregates.

Figure 3: Phillipsite-Chabazite tuff

Figure 4: Faujasite tuff

## Scanning electron microscope (SEM):

SEM results indicate that phillipsite occurs as prismatic crystals that are commonly less than 150 µm long and 20 µm wide. Larger crystals 0.5 mm long 120 µm wide are uncommon (Figure 5A). Rosettes of radiating and spherulitic crystal form are typical and abundant (Figure 5A). In some samples phillipsite occurs in two generations, phillipsite crystals of the first generation are larger in size and are terminated by a two-sided dome (Figure 5A).

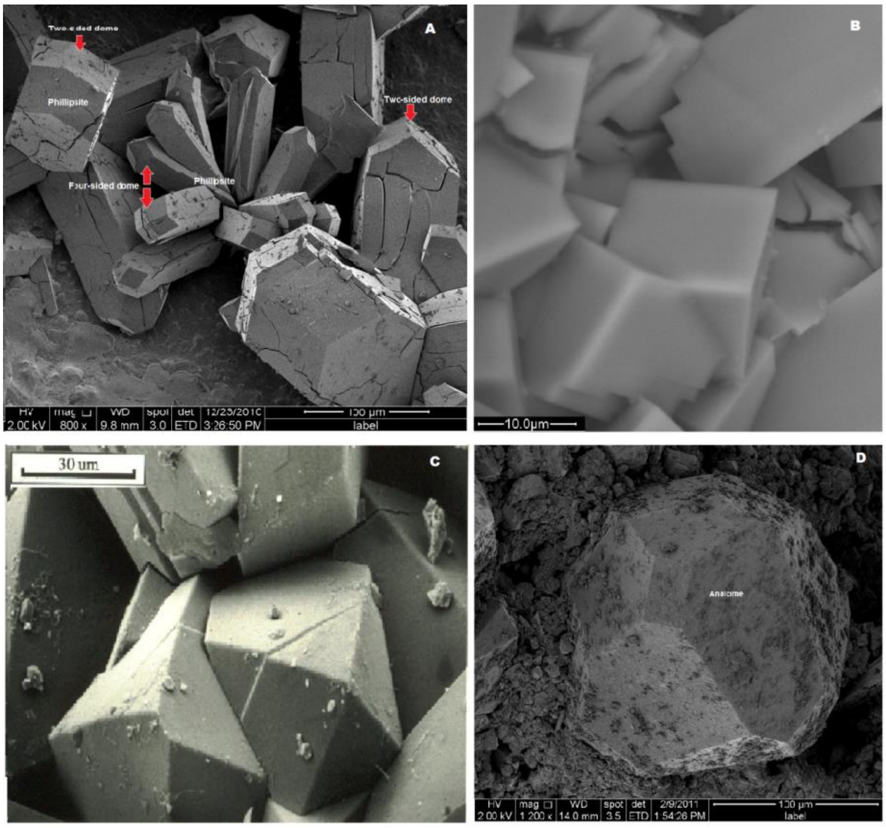

Figure 5: SEM images of zeolite minerals from Jordan. (A) Phillipsite crystals. (B) Chabazite crystals. (C) Faujastite crystals. (D) Analcime crystal.

Chabazite forms aggregates of sugar-like habit. Euhedral, equant well-crystalline, rhombic crystals with penetration twining are typical for chabazite. The rhombohedral crystal size varies between 10 µm and 40 µm. Very large crystal aggregates reaching up 300 µm are also present (Figure 5B).

Faujasite crystals grow as individual equant octahedral crystals. The crystal size varies between 50 µm and 120 µm. SEM shows that the mineral occurs in the form of octahedral crystals, sometimes with spinel twinning (Figure 5C) (Ibrahim and Hall, 1995).

Analcime is very rare in the studied localities and is identified by X-ray diffraction in four localities. Analcime is present as euhedral well-formed crystals, typically with trapezohedral form (Figure 5D). The size could reach up to 150 µm (Ibrahim, 2004; Khoury *et al.*, 2015).

SEM images show that natrolite occurs in the form of perforated prismatic, often acicular, radiating crystals, which are up to 225 µm long and 30 µm wide, sometimes with two-sided domes terminating the crystals as shown in Figure 6 (Ibrahim, 2004).

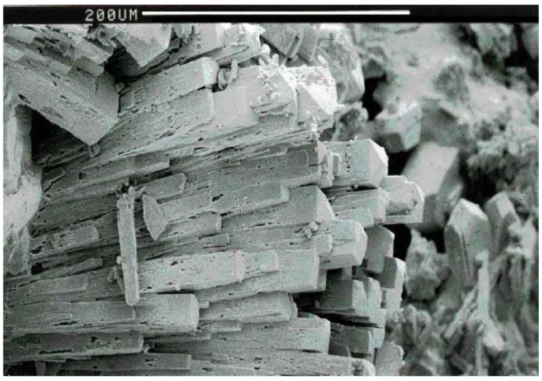

Figure 6: SEM image of Jordanian natrolite showing perforated fibrous crystals capped with four-sided pyramids (Ibrahim, 2004)

**Chemistry**

The average compositions of faujasite, phillipsite, chabazite and natrolite in a selection of specimens are given in Table 3, Table 4 and Table 5. The detailed chemistry of the zeolite minerals is discussed in Ibrahim and Hall (1995, 1996), Ibrahim (1996) and Ibrahim (2004).

**Paragenesis**

According to Ibrahim and Hall (1995, 1996), the paragenetic sequence of the authigenic minerals in the Aritayn Volcaniclastic Formation is as follows: fresh sideromelane → palagonite → smectites (saponite → montmorillonite) → faujasite → phillipsite → chabazite → natrolite → calcite.

Table 3: Selected chemical analyses of faujasite and chabazite from Jordan (from Ibrahim and Hall, 1996)

| **Oxides** | **Faujasite** | | | | | **Chabazite** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **F1** | **F2** | **F3** | **F4** | **F5** | **C1** | **C2** | **C3** | **C4** | **C5** |
| $SiO_2$ | 48.30 | 48.10 | 46.58 | 49.12 | 47.60 | 52.31 | 53.36 | 54.90 | 46.90 | 55.27 |
| $TiO_2$ | 0.04 | 0.05 | n.d. | 0.05 | n.d. | n.d. | n.d. | 0.04 | n.d. | n.d. |
| $Al_2O_3$ | 16.51 | 16.11 | 17.27 | 16.23 | 17.62 | 17.56 | 17.06 | 16.88 | 20.61 | 16.02 |
| $Fe_2O_3$ | 0.18 | 0.12 | 0.10 | 0.16 | n.d. | n.d. | 0.20 | 0.08 | 0.15 | n.d. |
| CaO | 6.29 | 4.54 | 3.48 | 5.47 | 4.03 | 5.06 | 4.80 | 4.71 | 6.34 | 2.35 |
| MgO | 0.39 | 0.36 | 0.39 | 0.58 | 1.45 | 1.25 | 1.49 | 1.91 | 0.05 | 2.17 |
| $Na_2O$ | 2.59 | 2.63 | 3.96 | 2.78 | 3.33 | 0.71 | 0.50 | 0.28 | 3.36 | 1.28 |
| $K_2O$ | 0.54 | 2.93 | 2.72 | 0.78 | 0.45 | 4.32 | 3.40 | 3.12 | 3.46 | 3.46 |
| SrO | n.d. | n.d. | 0.52 | n.d. | 0.31 | n.d. | n.d. | n.d. | 0.04 | n.d. |
| Total | 74.84 | 74.83 | 75.05 | 75.17 | 74.79 | 81.21 | 80.81 | 81.07 | 80.91 | 80.54 |
| **Atomic proportions** | | | | | | | | | | |
| Si | 136.15 | 137.11 | 135.50 | 137.57 | 133.89 | 8.58 | 8.70 | 8.79 | 7.88 | 8.96 |
| Al | 54.85 | 54.21 | 58.33 | 53.57 | 58.41 | 3.40 | 3.28 | 3.18 | 4.09 | 3.06 |
| Ca | 19.00 | 13.87 | 10.69 | 16.41 | 12.15 | 0.89 | 0.84 | 0.81 | 1.14 | 0.41 |
| Mg | 1.64 | 1.53 | 1.67 | 2.42 | 6.08 | 0.30 | 0.36 | 0.45 | 0.01 | 0.52 |
| Na | 14.16 | 14.54 | 22.00 | 15.10 | 18.16 | 0.23 | 0.16 | 0.09 | 1.09 | 0.40 |
| K | 1.94 | 10.66 | 9.94 | 2.79 | 1.62 | 0.91 | 0.71 | 0.64 | 0.75 | 0.72 |
| Fe | 0.38 | 0.26 | 0.22 | 0.34 | 0.00 | 0.00 | 0.03 | 0.01 | 0.02 | 0.00 |
| Ti | 0.09 | 0.11 | 0.00 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sr | 0.00 | 0.00 | 0.86 | 0.00 | 0.51 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O | 384 | 384 | 384 | 384 | 384 | 24 | 24 | 24 | 24 | 24 |
| E% | -4.09 | -3.03 | 0.44 | -3.56 | 2.26 | -4.28 | 0.37 | -2.04 | -1.69 | 2.72 |
| Si/Al | 2.48 | 2.53 | 2.29 | 2.57 | 2.29 | 2.52 | 2.65 | 2.76 | 1.93 | 2.93 |
| Na/K | 7.29 | 1.36 | 2.21 | 5.42 | 11.24 | 0.25 | 0.23 | 0.14 | 1.45 | 0.56 |
| Na/Ca | 0.75 | 1.05 | 2.06 | 0.92 | 1.50 | 0.26 | 0.19 | 0.11 | 0.96 | 0.98 |
| K/Ca | 0.10 | 0.77 | 0.93 | 0.17 | 0.13 | 1.02 | 0.85 | 0.79 | 0.66 | 1.76 |
| CEC* | 3.39 | 3.27 | 3.39 | 3.30 | 3.39 | 3.57 | 3.33 | 3.38 | 4.11 | 3.06 |

nd: not detected; E%: charge balance; CEC*: theoretical CEC

Table 4: Selected chemical analyses of phillipsite from Jordan (from Ibrahim and Hall, 1996)

| **Oxides** | **Phillipsite** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **P1** | **P2** | **P3** | **P4** | **P5** | **P6** | **P7** |
| $SiO_2$ | 53.66 | 48.01 | 54.28 | 54.68 | 49.38 | 52.28 | 47.15 |
| $TiO_2$ | 0.00 | 0.05 | 0.01 | 0.13 | n.d. | n.d. | n.d. |
| $Al_2O_3$ | 19.55 | 22.45 | 18.50 | 17.23 | 22.79 | 20.78 | 22.74 |
| $Fe_2O_3$ | 0.12 | 0.13 | 0.04 | 0.12 | 0.23 | n.d. | n.d. |
| CaO | 6.02 | 9.04 | 1.22 | 1.32 | 7.70 | 1.30 | 6.11 |
| MgO | 0.09 | 0.08 | n.d. | 0.03 | 0.12 | n.d. | n.d. |
| $Na_2O$ | 1.54 | 0.34 | 5.49 | 4.62 | 1.01 | 6.91 | 2.14 |
| $K_2O$ | 4.52 | 5.62 | 6.15 | 6.32 | 6.53 | 5.83 | 7.08 |
| SrO | n.d. | n.d. | n.d. | n.d. | 0.28 | 0.50 | n.d. |
| Total | 85.50 | 85.72 | 85.69 | 84.45 | 88.04 | 87.60 | 85.22 |
| **Atomic proportions** | | | | | | | |
| Si | 11.22 | 10.27 | 11.44 | 11.65 | 10.33 | 10.90 | 10.22 |
| Al | 4.82 | 5.66 | 4.59 | 4.33 | 5.55 | 5.12 | 5.81 |
| Ca | 1.35 | 2.07 | 0.28 | 0.30 | 1.73 | 0.29 | 1.42 |
| Mg | 0.03 | 0.03 | 0.00 | 0.01 | 0.04 | 0.00 | 0.00 |
| Na | 0.63 | 0.14 | 2.24 | 1.91 | 0.41 | 2.80 | 0.90 |
| K | 1.21 | 1.54 | 1.66 | 1.72 | 1.74 | 1.55 | 1.96 |
| Fe | 0.02 | 0.02 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 |
| Ti | 0.00 | 0.01 | 0.00 | 0.02 | 0.04 | 0.00 | 0.00 |
| Sr | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 |
| O | 32 | 32 | 32 | 32 | 32 | 32 | 32 |
| E% | 5.59 | -3.22 | 3.43 | 1.85 | -2.22 | 1.20 | 2.06 |
| Si/Al | 2.33 | 1.81 | 2.49 | 2.69 | 1.86 | 2.13 | 1.76 |
| Na/K | 0.52 | 0.09 | 1.35 | 1.11 | 0.24 | 1.81 | 0.46 |
| Na/Ca | 0.46 | 0.07 | 8.00 | 6.37 | 0.24 | 9.66 | 0.63 |
| K/Ca | 0.90 | 0.74 | 5.93 | 5.73 | 1.01 | 5.34 | 1.38 |
| CEC* | 2.61 | 4.57 | 3.51 | 3.32 | 4.57 | 4.03 | 4.37 |

CEC*: theoretical CEC

**Origin**

*Open hydrological system:* The zeolitization process is attributed to the transformation of basaltic glass (sideromelane) into palagonite by reaction with percolating meteoric water, indicating an open hydrological system (Hay and Iijima, 1968a, b). This process was adopted to explain the zeolitization process in the Aritayn Formation by Ibrahim and Hall (1995, 1996), Ibrahim (1996) and Khoury et al. (2015).

*Closed hydrological system:* According to Ibrahim (2004), a stratified, hard, fine-ash natrolite tuff unit is exposed in a closed palaeo-basin in the Tilal al Hisnawat area in northeast Jordan. The formation of the zeolites is a direct result of the transformation of volcanic glass into palagonite by reaction with percolating water in a closed hydrological system.

**Physical and engineering properties:** The most important physical and engineering properties of zeolitic tuff from Jordan are listed in Table 6. One of the physical parameters for the cement industry is hydraulicity, namely the capacity which hydraulic cements or their ingredients have for hardening under water. The Jordan Cement Company (1985) reported that the presence of zeolite in the volcanic tuff, significantly enhances this parameter.

**Reserves and production** According to the Natural Resources Authority, the estimated zeolitic tuff reserves in various areas in Jordan are shown in Table 7.

Table 5: Selected chemical analysis natrolite from Jordan (from Ibrahim 2004)

| **Oxides** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 48.07 | 47.68 | 47.90 | 48.15 | 47.43 | 47.19 | 48.28 | 48.18 | 47.12 | 48.14 |
| $Al_2O_3$ | 26.18 | 25.96 | 25.87 | 26.45 | 26.29 | 26.66 | 26.20 | 26.06 | 26.71 | 26.04 |
| $Fe_2O_3$ | 0.41 | 0.60 | 0.63 | 0.68 | 0.84 | 0.32 | 0.77 | 0.40 | 0.66 | 0.68 |
| CaO | 0.44 | 0.45 | 0.58 | 0.61 | 0.95 | 0.01 | 0.54 | 0.55 | 0.52 | 0.86 |
| MgO | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Na_2O$ | 15.72 | 14.90 | 15.29 | 15.19 | 14.78 | 15.70 | 14.69 | 15.66 | 16.07 | 14.76 |
| $K_2O$ | 0.14 | 0.09 | 0.03 | 0.10 | 0.00 | 0.14 | 0.17 | 0.10 | 0.02 | 0.08 |
| BaO | 0.00 | 0.00 | 0.06 | 0.00 | 0.23 | 0.00 | 0.09 | 0.00 | 0.03 | 0.21 |
| Total | 90.95 | 89.68 | 90.36 | 91.18 | 90.52 | 90.02 | 90.74 | 90.95 | 91.13 | 90.77 |
| Atomic proportions | | | | | | | | | | |
| Si | 24.23 | 24.31 | 24.29 | 24.18 | 24.05 | 24.01 | 24.33 | 24.28 | 23.80 | 21.31 |
| Al | 15.56 | 15.60 | 15.47 | 15.66 | 15.72 | 15.99 | 15.57 | 15.48 | 15.91 | 15.50 |
| Fe | 0.15 | 0.23 | 0.24 | 0.26 | 0.32 | 0.12 | 0.29 | 0.15 | 0.25 | 0.26 |
| Ca | 0.24 | 0.24 | 0.31 | 0.33 | 0.52 | 0.01 | 0.29 | 0.30 | 0.28 | 0.47 |
| Na | 15.36 | 14.73 | 15.03 | 14.79 | 14.53 | 15.49 | 14.36 | 15.30 | 15.74 | 14.45 |
| K | 0.09 | 0.06 | 0.02 | 0.06 | 0.00 | 0.09 | 0.11 | 0.06 | 0.01 | 0.05 |
| Ba | 0.00 | 0.00 | 0.01 | 0.00 | 0.05 | 0.00 | 0.02 | 0.00 | 0.01 | 0.04 |
| O | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 | 32 |
| E% | -2.30 | 2.12 | -1.46 | 0.95 | 0.41 | 2.56 | 3.19 | -3.00 | -2.59 | -0.13 |
| Si/Al | 1.56 | 1.56 | 1.57 | 1.54 | 1.53 | 1.50 | 1.56 | 1.57 | 1.50 | 1.57 |

Table 6: Physical and engineering properties of the zeolitic tuff

| **Parameters** | **Range** |
|---|---|
| Colour | Yellowish to dark brown |
| Water absorption (%) | 8.53-10.8 |
| Abrasive value (%) | 35-52 |
| Unit weight (kg/m$^3$) | 980-1010 |
| Specific gravity (g/cm$^3$) | 1.56-1.80 |
| Void ratio | 17.54-30 |
| Porosity (%) | 15-35 |
| Strength (N/cm$^2$) | 280-1212 |
| Loss on Ignition (%) | 3-16 |
| CEC (meq/g) | 0.94-2.16 |
| Attrition resistance (wt. loss %) | 4.5-8.9 |
| Packed bed density (g/cm$^3$) | 0.94-1.15 |
| Pulse velocity (m/sec) | 3333-3564 |
| Surface abrasion (mm) | 27-28 |
| Soundness (%) | 8-9 |
| T.D.S. (ppm) | 1250-1500 |
| Elongation (%) | 11.1 (mean value) |
| Flakiness (%) | 22.6 (mean value) |
| Thermal stability (°C) | 300-600 |

Data from Jordan Cement Company 1985; Malabeh, 1993; Ibrahim, 1997; El-Hamed and Abdlehadi, 2001.

Table 7: Geological reserves of zeolitic tuff deposits (modified from Nawasreh et al., 2006)

| Area | Geological reserves (million tonnes) |
|---|---|
| Tell Rimah (North and South) | 46.0 |
| Jabal Aritayn (North and South) | 170.0 |
| Jabal Hannoun | 9.2 |
| Ashgof Wira | 1.7 |
| Other NE areas | 472.0 |
| Other areas in Jordan | 1340.0 |

**Main applications**

*Cement industry:*

Zeolitic tuff production in Jordan started in 1998, and therefore it is a relatively new sector. Currently around 1,000,000 tonnes/year of zeolitic tuff is consumed by cement factories to produce pozzolanic cement.

*Lightweight concrete*

Volcanic tuff and scoria are the main source for lightweight aggregates. These materials are suitable for producing lightweight concrete, which could be used in many building structures (El Hamed and Abdlehadi, 2001). Due to the huge reserves of tuffaceous materials, Jordan is considered as an excellent source for such aggregates.

Table 8: Specifications of slow release fertilizers from Jordan

| Parameter | Range |
|---|---|
| Grain size | Distribution from 0 to 3 mm |
|  | Classification (average wt.%): Sand = 60, Silt = 30, Clay = 10 |
| Colour | Brown, light brown to yellowish brown |
| Water retention (holding capacity) | >80% higher than ordinary soils |
| CEC | 70-150 meq/100 gram |
| EC ($mS.cm^{-1}$) | 0.01-0.2 |
| pH | 7.5-8.5 |
| Adsorbed and structural water | 6-18 wt.% |

| Chemistry | Average % |
|---|---|
| $SiO_2$ | 33.8 |
| $Al_2O_3$ | 12.3 |
| $Fe_2O_3$ | 12.1 |
| $TiO_2$ | 2.0 |
| CaO | 10.7 |
| MgO | 7.4 |
| $K_2O$ | 2.2 |
| $P_2O_5$ | 1.8 |
| Minor components ($Na_2O$, $MnO_2$) | <1% |
| Trace elements (micronutrients) | Co, Cu, Cr, Zn, Mo, Se, etc. |
| LOI and organic matter | Balance to 100 |

| MIneralogy | Average % |
|---|---|
| Phillipsite | 10-50 |
| Chabazite | 10-50 |
| Total zeolites | 30-70 |
| Non zeolites | Volcanic glass (palagonite), olivine, plagioclase, pyroxene, iron oxides, smectite clays, calcite, organic matter and cellulose |

*Agriculture applications*

The total output during 2004 was 1600 tonnes, produced by three companies and consumed in agricultural applications. Given the size of the agricultural sector in the region, it is estimated that the market potential for these applications is large. In terms of Jordan's cultivated land, each two percent increase in land treated with zeolitic tuff would result in an increase in zeolitic tuff demand of 100,000 tonnes/y and 50,000 tonnes/y in animal feed and odour control. The total expected demand potential is 360,000 tonnes/y depending on previous assumptions.

The zeolitic tuff is used mainly as slow-release fertilizer and in animal feed. ZeoGreen and ZeoLux are environmentally friendly products in the market produced by two different companies (Table 8). They are 100% natural potassium slow-release mineral fertilizers, enriched with micronutrients and with very high water holding capacity. They are sold in Jordan, Iraq, Qatar, Dubai, Kuwait and in Saudi Arabia.

*Wastewater treatment*

Zeolitic tuff from Jordan has already been successfully tested in removing selected heavy metals from industrial wastewater. It has also been used in treatment of wastewater of municipal origin and in the treatment of grey water (Ibrahim, 1996; Ibrahim et al., 2002, 2016; Ibrahim and Jbara, 2009; Rawajfih et al., 2010; Hussein et al., 2014; Al Dwairi et al., 2014)

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