Evaluation of granitic rocks as feldspar source: Al Madinah, Western Part of Saudi Arabia

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1. Introduction

Feldspar, as the most common rock-forming mineral, has many applications in different industrial applications. It lowers the melting point of quartz, controlling the viscosity of glass. It also lowers glass melting point, lowering production costs as well. Feldspars are used in ceramics to mix with the clay and make the final piece stronger and better. They are also used as fillers in paint, rubber and plastics and find their place in many other household items such as tableware, flooring and giftware. Other industrial uses include latex foam, glaze, mild abrasives, welding electrodes and road aggregates. For glass, feldspar serves principally as a source of alumina, which acts as a stabilizer, improves durability, increases viscosity during glass formation and acts as a matrix former. The mineralogical composition of most feldspar minerals can be expressed in terms of the ternary system: orthoclase (KAlSi3O8), albite (NaAlSi3O8) and anorthite (CaAl2Si2O8). Chemically, the feldspars are silicates of aluminium, containing sodium, potassium, iron, calcium, or barium or combinations of these elements [1]. In general, around 1.5–2% Al2O3 is required for container and flat glass, and up to 15% for certain glass fibers. The alkalis in feldspar act as a flux by chemically attacking the other glass batch minerals such as quartz [2]. In ceramics, sodic feldspar is particularly useful in ceramic body and glaze. Potassic feldspar is more expensive, but is preferred in porcelain enamels and in high-voltage electrical porcelain. Feldspar for use in glass and ceramics must have low iron. Traditionally, feldspar was extracted from pegmatites by hand sorting. Nowadays, processing techniques such as flotation make it possible to extract feldspar from several types of granitoid and alkaline intrusive rocks, including syenites, leucocratic granites, albites, alaskite and aplites [2] and from metavolcanic rocks [3]. Previously, all feldspar of Saudi Arabia was extracted from pegmatite deposits. The high demand of feldspar for industrial activities (especially ceramics and glass manufactures) leads to consider alternative resources during recent years. This area, which is located at Al Madinah area in the western part of KSA, is composed of alkali granitic rocks suitable for feldspar exploration. There are scarce studies on the Precambrian basement granitic rocks at Al Madinah area as feldspar source.

This paper is the first attempt in delineating the different rock types in the basement granitic rocks of the study area and describing their petrographic, mineralogical and geo-chemical characteristics as well as the economic potential of feldspar.

2. Geological setting

Many researchers have carried out studies on the geology of the Kingdom of Saudi Arabia. Among the earlier ones were Brown and Jackson [4]. Several other contributors include USGS-ARAMCO [5–8].
Geologically, Saudi Arabia is divided into four extensive terrains. These are: (1) Precambrian to Proterozoic Arabian shield, (2) Phanerozoic Arabian Platform, having clastic, calcareous and evaporitic successions, (3) Tertiary “harrats” (extensive basalt plateaus) and (4) Narrow Red Sea coastal plain [9]. The western half of Saudi Arabia belongs to the shield, where diverse igneous and metamorphic rocks are exposed and at places are overlain by lava flows (Figure 1).

The Madinah area is part of the basement complex of Saudi Arabia and is geologically part of the Arabian Shield (AS), which underwent several Precambrian tectonic events during the 900–540 Ma period [10–21]. Three major stratigraphic-plutonic cycles are recognized [22–27]:

1. greywacke, pelite, chert and basalt of the Farri group, and included mafic-ultramafic complexes of possible ophiolitic character (Farriyan cycle of [26]).
2. tholeiitic and calc-alkalic volcanic-volcanoclastic successions of the Birak and A1 Ays groups, and coeval calc-alkalic gabbro-diorite-tonalite or granodiorite plutons (Aysian cycle of [26]).
3. volcanic-volcanoclastic and clastic sedimentary successions of the Hadiyah and Furayh groups and coeval granitic, monzonitic, syenitic and gabbroic intrusions (Hadiyan cycle of [26]).

Generally, the late-Precambrian granitoids of Al Madinah are grouped into two principal subdivisions (Figure 2). These are older (820–715 Ma) and younger (686–517 Ma) assemblages. The former constituted by granodioritic or trondhjemitic petrographic association [28], the latter is composed of dominant alkali granite, alkali feldspar granite and monzogranite association.

Recent geochronologic studies [29,30] indicate that the Farri and A1 Ays groups are, at least partly, stratigraphic equivalents, while the Biorak group is older than the A1 Ays group. On terms of age and lithologic character the Farri, Al Ays and Birak groups and the Hadiyah and Furayh groups are, respectively, equivalent to sequences B and A of the central Shield [31].

Two different evolutionary models have been proposed for this region [26]. Consider that the area evolved through three episodes of intracratonic rifting with related bimodal volcanism and sedimentation and local emplacement of ophiolitelike ultramafic bodies, followed by compression and syntectonic plutonism. In contrast, Camp and Roobol [32] argue that the three cycles of volcanicity, sedimentation and plutonism developed in an evolving oceanic island arc and sequentially represent accretionary prism deposits, island arc and fore-arc deposits, and intramassif basin deposits.

3. Location of the studied granitic rocks

Granitic rocks of Late-Precambrian age (feldspar deposits) are widely distributed in Al Madinah area. The most important feldspar deposits are exposed in five main locations: Bayda, Jammah, Industrial city, Abar Al

Figure 1. Map showing the location of the study area and the main geological units of King Saudi Arabia (KSA).
Mashi and Yanbu road (Figure 3). The granitic lithologies in the studied areas consist predominantly of alkali granite, alkali feldspar granites, monzogranite with subordinate granodiorite, quartz syenite and syenite. These fine to coarse-grained granites belong to the younger, post-tectonic granitoids.

3.1. Bayda’a Mountain

The granitoid rocks outcrops extensively in Al Bayda area (Plate 1(a)). The plutonics are cross-cut by numerous dykes of varying composition. The granitic lithologies in this area consist predominantly of alkali granite, alkali feldspar granites, monzogranite with subordinate granodiorite and quartz syenite. These rocks display medium to coarse-grained of pink to greyish-buff colour.

3.2. Jammah Mountain

The plutonic rocks comprise the following units: alkali granite, alkali feldspar granite, monzogranite, quartz syenite and syenite. Two main varieties of granite were distinguished: (i) a medium-grained, commonly reddish granite-syenite, (ii) a coarse-grained white to grey granite. These rocks are cross-cut by numerous dykes of varying composition and mainly composed of medium to coarse grained (Plate 1(b,c)).

3.3. Industrial city

Locally, the field characteristics of the granitoid formation have a relatively homogeneous composition (Plate 1(d)). It is mainly composed of medium to coarse-grained alkali granite to alkali feldspar granite.

3.4. Abar Al Mashi

The plutonic rocks range in composition from alkali granite to alkali feldspar granite; these rocks display medium to coarse grained (Plate 1(e)).
3.5. Yanbu road

It is mainly composed of fine-grained alkali feldspar microgranites. There are numerous basic and acidic dyks intruded into the basement rocks (Plate 1(f)).

4. Materials and methods of investigation

4.1. Materials

For this study, 15 representative samples of granitic rocks were collected from the area around Medina, KSA. Sample locations are shown on map (Figure 3). Each sample weighed about 10 kg. In the laboratory, the samples were subjected to disintegration by crushing and grinding. Each sample was mixed well several times to form a composite and homogeneous sample. After that, each of these composite samples was divided using the coining and quartering method into sub samples for mineralogical and chemical investigations.

The methods of investigation of this work consist of the following:

(i) Geological method
(ii) Laboratory method

4.2. Geological method

In the geological method, rock and mineral samples were collected from the granitic rock outcrops and the coordinates of the location where the samples were collected were recorded on a field notebook using a Global Positioning Systems (GPS). Samples were collected mainly from the rocks that show the presence of the targeted mineral (feldspar). In the field, the general direction of trending of the host rocks was recorded and strike and dip values were
taken from granite (using Geological Compass Clinometer) were noted and recorded. The sampling was done randomly and each sample was labelled and assigned a location number. The mineralogical and geochemical samples collected were sent to the laboratory for whole-rock geochemical analysis while some were kept as back-up samples for further reference.

4.3. Laboratory method

The laboratory method consists of thin section preparation and whole-rock mineralogical and geochemical analyses of the mineral and rock samples collected in the field. In the present work, two analytical techniques were considered to determine the mineralogical composition of the studied samples of granites: (i) petrography (optical analysis of thin section) and (ii) X-ray diffraction (XRD). (i) The thin sections were prepared in the workshop of Department of Geology, Taibah University, Al Madinah. Observation and description of the thin section was done in the laboratory of the same organization. (ii) X-ray diffraction (XRD) was used to determine the mineralogical composition of the studied samples. Firstly, about 200 g of dried bulk samples was broken by a small hammer and hand crusher primarily to reduce the rock aggregate to smaller particles and finally to get the powder samples. The samples were then analysed using X-ray Diffractometer (SHIMADZU Labx XRD-6000), with Ni-filtered Cu-Kα radiation, operating at 40 kV/30 mA, at the Department of Physics, Taibah University, Madinah, KSA. The goniometer velocity was 0.02° (2θ) per 1s in the interval between 5 and 80° (2θ). The powder data

Plate 1. Photograph of a granitic rock for different sites in Al Madinah area.
were analysed with the Stoe WinXPOW software package.

Fifteen representative samples representing the main plutonic lithologies were selected for chemical analysis. The content of major oxides (SiO₂, TiO₂, Al₂O₃, total iron as Fe₂O₃, MnO, MgO, CaO, Na₂O, K₂O, SO₃, P₂O₅) was determined for all samples by inductively coupled plasma spectrometry (I.C.P.) at The Saudi Geological Survey in Jeddah. Loss on ignition (LOI) was determined using a muffle furnace at 1000°C for 90 min.

5. Results and discussion

5.1. Petrographic descriptions

By observing and interpreting of the petrographic characteristics with the polarizing microscope, certain clear differences between the main petrographic variations of the granitic rocks are identified: (1) alkali feldspar granite; (2) syenogranite; (3) monzogranites (4) quartz syenite and (5) syenite.

5.1.1. Alkali feldspar granite association

Alkali feldspar granites are coarse grained of pink to greyish-buff colour. Petrographically, this rock consists essentially of potash feldspars (orthoclase-perthite, microcline, microcline-perthite), quartz, plagioclase (oligoclase) and muscovite with a subordinate amount of biotite. Zircon, sphene, apatite and iron oxides are the main accessory minerals, while epidote, sericite, chlorite and kaolinite are the main secondary minerals. It is characterized by hypidiomorphic, perthitic and porphyroclastic textures with stumpy euhedral rectangular bush feldspar crystals surrounded by finer cataclastic constituents, which are white and greyish red in colour (Figures 3(b) and 4(a)). Potash feldspars are the most dominant minerals represented by orthoclase-perthite, microcline and microcline-perthite. Orthoclase-perthite occurs as subhedral to anhedral tabular and prismatic crystals ranging in size from 2.3 to 4.3 mm in length and from 1.9 to 3.5 mm in width. They are of flame-string, patchy-type and show simple twinning. They usually enclose plagioclase, quartz and micas. Microcline and microcline-perthite occur as subhedral crystals ranging in size from 3.9 to 6.1 mm in length and from 2.5 to 4.3 mm in width showing cross-hatch twinning. Some crystals enclose fine streaks of albite giving perthitic texture; others are surrounded by finer plagioclase crystals. Cracks in perthite facilitate the movements of late iron-rich solutions, which cause iron staining and give the rock its red colouration. Quartz is less dominant than perthite. It occurs as subhedral to anhedral crystals ranging from 4.1 to 6.3 mm in length and from 2.1 to 3.7 mm in width, which usually contains inclusions of apatite, zircon and sericite. Several quartz crystals show myrmekitic and graphic textures (Figures 4(a) and 4(b)). Quartz crystals show cracking and wavy, undulose extinction and corrode by plagioclase, mica and perthite. The cracked quartz crystals are usually filled with iron oxides. Plagioclase (oligoclase An⁴⁰–⁴⁹) occurs as subhedral to euhedral cracked tabular crystals ranging in size from 3.2 to 5.4 mm in length and from 2.5 to 4.2 mm in width. Plagioclase occurs mostly as a component of the perthite and shows zoning and albite-lamellar twinning. Muscovite occurs as irregular flakes, corroded by quartz, plagioclase and perthite. In some cases, muscovite flakes appear to be squeezed and deformed due to tectonic stresses. Biotite occurs rarely as small irregular flakes which are corroded by quartz; feldspars have zoned zircon surrounded by pleochroichal haloes inclusion at the contact with quartz. Biotite show pleochroism in x = yellow and in y = z = brownish green and highly altered to chlorite, shredded iron oxides along cleavage planes and peripheries. Zircon occurs as small euhedral prismatic crystals ranging from 0.14 to 0.3 mm in length and from 0.1 to 0.21 mm in width. Zircon when enclosed in biotite gives rise to pleochroic haloes. It is observed as inclusions in feldspar, quartz and biotite and characterized by a very high relief and strong zoning. Sphene occurs as euhedral to subhedral rhombic crystals and as irregular grains of light brown colour, reaching up to 0.7 × 1.4 mm and exhibiting very high relief associated with zircon and iron oxides. Apatite occurs as minute euhedral prismatic and needle-like crystals associated with K-feldspar, plagioclase and biotite. Epidote occurs as green to pale yellow crystals fill the cracks on altered feldspar minerals with iron oxides and sericite. Iron oxides (haematite and magnetite) are subordinatines and occur as subhedral to anhedral grains up to 0.4 mm across.

5.1.2. Syenogranite association

Syenogranite rock is medium to coarse grained, ranging from pink to pinkish white in colour characterized by equigranular, perthitic and hypidiomorphic textures (Figure 4(c,d)). The rock consists principally of potash-feldspar (orthoclase-perthite, orthoclase and microcline-perthite) and quartz with subordinate plagioclase, muscovite and biotite. Apatite, zircon, sphene and iron oxides represent the accessory minerals while sericite and chlorite occur as secondary minerals.

Potash-feldspar is the most dominant mineral represented by and orthoclase-perthite orthoclase and microcline-perthite but the former is more dominant. It occurs as subhedral tabular crystals ranging from 4.1 to 7.5 mm in length and from 1.3 to 3.7 mm in width and usually shows simple Carlsbad twinning. Muscovite and iron oxides are found as inclusions in potash-feldspars. Orthoclase-perthites are corroded by
Figure 4. Photomicrographs show the main petrographic variations of the granitic rocks from Al Madinah area. CN 40× (Cross Nikon 40× magnification). Kfs: alkali feldspar. Or: orthoclase, Mic: microcline, Qz: quartz, Pl: plagioclase, Ab: albite, O: oligoclase, Bt: biotite, Mus: muscovite.
quartz and plagioclase. Orthoclase occurs as subhedral tabular crystal up to $4 \times 2.8$ mm and shows simple carlsbad twinning. Microcline-microperthite occurs as euhedral rectangular crystals (2 × 2 mm) showing cross-hatch twinning; some crystals enclose fine streaks of albite giving perthitic texture and altered to kaolinite. Quartz occurs as subhedral to anhedral crystals of various shapes ranging in size from 0.5 to 4.9 mm in length and from 0.3 to 2.9 mm in width and shows undulose extinction. Quartz usually contains inclusions of zircon and apatite. Plagioclase is albite to oligoclase composition (An$_{12-22}$) occurring as subhedral to euhedral tabular crystals ranging from 2.5 to 5.6 mm in length and from 1.9 to 3.4 mm in width. It is sometimes stained with iron oxides and altered to epidote along their twin planes, with fresh crystals showing the albitic lamellar twinning and oscillatory zoning. Zircon, apatite and iron oxides are found as inclusions in plagioclase. Biotite occurs as pale-brown to reddish-brown fine flakes up to 1.2 mm or as irregular patches up to 2.5 mm across. It is strongly pleochroic with $x$ = straw yellow and $y = z$ = deep brown. Most biotite minerals are corroded by quartz, oligoclase and contain inclusions from sphene, zircon and apatite. Muscovite occurs as small to medium irregular colourless flakes ranging from 0.16 to 1.9 mm in length and from 0.2 to 1.2 mm in width of high interference colour and encloses zircon, apatite and iron oxides. Chlorite forms green irregular patches and flakes interlarded with biotite; it is pleochroic from pale yellow to pale green and show blue interference colours. Zircon occurs as small euhedral prismatic crystals ranging from 0.16 to 0.35 mm in length and from 0.11 to 0.21 mm in width forming minute inclusions in quartz, plagioclase and biotite. Some zircon crystals are occasionally surrounded by strong pleochroic haloes due to their radiogenic effects. Sphene occurs as elongated to irregular rhombohedral crystals of pale-brown colour, which is usually associated with chloritized biotite and kaolinitized feldspars. It is corroded by quartz, biotite and feldspars. Apatite is found as minute euhedral prismatic and needle-like crystals, included in plagioclase, quartz and biotite as minute inclusions. Sericite are found along cracks and twin planes of microcline and plagioclase; it is characterized by yellowish interference colour. Iron oxides occur as fine grains along the margins of biotite. Orthoclase-perthite occurs as subhedral crystals ranging in length from 2.5 to 6.3 mm and in width from 1.3 to 4.3 mm, which is mainly of string and flame-like types. Orthoclase-perthite is rarely showing clear simple twinning and is corroded by quartz and biotite. Perthite encloses apatite, zircon, plagioclase and quartz especially along their peripheries. The cracks are filled with iron oxides and sericite. Some perthite are deformed and are slightly kaolinized as well as sericitized. Quartz occurs as interstitial, subhedral to anhedral crystals ranging from 2.3 to 5.7 mm in length and from 1.5 to 4.3 mm in width exhibit undulose extinction and are highly cracked which filled with iron oxides (Figure 4(e)). Quartz corrodes plagioclase and perthite and contains apatite, zircon and iron oxides as inclusions. Quartz frequently dusted with iron oxides and clay minerals especially along their peripheries. Plagioclase (oligoclase and andesine An$_{25-35}$) occurs as subhedral to euhedral tabular crystals ranging from 4.1 to 6.7 mm in length and from 2.6 to 3.9 mm in width. Plagioclase crystals show lamellar twinning and corroded by quartz, perthite and altered to epidote, while the cracks are usually filled with iron oxides. Apatite, zircon and iron oxides are found as inclusions in plagioclase. Biotite is found as small irregular and elongated flakes showing preferred orientation. It has often yellowish-brown ($x$) pleochroic to deep brown ($y = z$) and characterized by pleochroic haloes (Figure 4(f)). It varies in length from 2.7 to 3.9 mm and from 0.9 to 2.3 mm in width. Biotite flakes are usually charged with opaques, zircon and apatite as inclusions especially along cleavage planes. Biotite flakes are corroded by quartz and feldspars and altered to chlorite. Muscovite occurs as small elongated or irregular flakes or as interstitial between plagioclase, quartz and potash-feldspar. Zircon occurs as small euhedral prismatic and pyramid crystals ranging from 0.2 to 0.35 mm in length and from 0.15 to 0.23 mm in width, included in quartz, biotite and feldspars. It is sometimes rimmed with iron oxides. Sphene is occurring as elongated irregular rhombic crystals corroded by quartz, biotite and feldspars. Apatite is found as tiny euhedral prismatic crystals included in quartz, biotite and feldspars. Iron oxides occur interstitially fill the cracks of feldspars and quartz, as well as, the cleavage planes of micas and found as inclusions in all mineral constituents. Clay minerals are the secondary minerals after feldspars’ alteration.

5.1.3. Monzogranite association

Monzogranite is coarse grained of pale pink colour, unfoliated exhibit hypidiomorphic texture (Figure 4(e)). The rock is essentially composed of potash-feldspar (orthoclase-perthite and perthite), quartz and plagioclase. Mica is mainly muscovite, which is sometimes interlarded with biotite. Zircon, sphene, iron oxides and apatite are accessory minerals, while epidote, sericite and chlorite are secondary minerals.

5.1.4. Syenite association

Syenite is an intrusive igneous rock of variable colour but typically light coloured, characterized by phaneritic texture of medium to coarse grained belonging to the alkali series of intermediate plutonic rocks. Alkali feldspar (e.g. orthoclase) is the major mineral component of syenite, total feldspar content is $>$65% and quartz is typically lacking with minor mica, augite, hornblende.
and magnetite. Plagioclase can also be present. Titanite is a common accessory mineral.

Alkali feldspar forming the majority of most syenitic rocks is usually intergrown with sodium-rich plagioclase feldspar (usually oligoclase). Such feldspar intergrowth is named *perthite* (Figure 4(g)) and this is the reason why syenite is more common rock type than alkali feldspar syenite which contains almost no plagioclase. Plagioclase may appear in syenitic rocks in addition to perthitic alkali feldspar also as a separate phase. Dark mica biotite and amphibole hornblende are usual mafic constituents. Common accessory minerals are zircon, apatite, sphene, magnetite and ilmenite.

5.1.5. Quartz Syenite association

Quartz syenite is an igneous rock that solidified slowly in the crust in a similar manner to granite. A true syenite also compositionally resembles granite. The most notable difference is the absence or very low quantity of quartz while it is an essential component of granite. The dominant mineral is alkali feldspar, usually orthoclase. This rock type is found in a wide variety of colours.

This rock is made up of orthoclase, plagioclase, quartz and mica. Euhedral plagioclase is striking, where it forms bladed crystals. Most grains contain a core of plagioclase with either simple twinning, multiple twinning or combined albite and pericline twinning that is surrounded by a pronounced outer zone (Figure 4(h)). The outer zone is more strongly kaolinized than the core. The outer zone has only rare, narrow twin lamellae, and is probably albite or sodic oligoclase. An extinction angle of plagioclase in the core reveals a fairly constant composition (An29). Quartz is interstitial, confined to the outer plagioclase zone.

a. Photomicrograph of Alkali feldspar granites consists mainly of potash feldspars, quartz and plagioclase with hypidiomorphic, perthitic and porphyroclastic textures. Quartz show graphic and myrmekitic textures. (CN 40× (Cross Nikon 40× magnification)).

b. Photomicrograph of Alkali feldspar granites consists mainly of orthoclase-perthite, orthoclase, microcline, microcline-perthite, quartz and plagioclase with hypidiomorphic, perthitic and porphyroclastic textures. Quartz shows graphic and myrmekitic textures, and also wavy and undulose extinction. (CN 40×).

c. Photomicrograph of Syenogranite consists mainly of potash-feldspar, quartz, plagioclase (shows zoning and albite-lamellar twinning), muscovite and biotite with equigranular and hypidiomorphic textures (CN 40×).

d. Photomicrograph of Syenogranite consists mainly of orthoclase-perthite, orthoclase and microcline-perthite), quartz and plagioclase with equigranular and hypidiomorphic textures. (CN 40×).

e. Photomicrograph of Monzogranite consists mainly of potash-feldspar, quartz (shows wavy and undulose extinction), plagioclase, muscovite and biotite with hypidiomorphic texture. Biotite shows pleochroism, altered to chlorite and iron oxides along cleavage planes and peripheries (CN 40×).

f. Photomicrograph of Monzogranite consists mainly of perthite, orthoclase, quartz, plagioclase and biotite with hypidiomorphic texture. Biotite show pleochroism and altered to chlorite along cleavage planes and peripheries (CN 40×).

g. Photomicrograph of Syenite consists mainly of alkali feldspars (showing cross-hatch twinning and enclose fine streaks of albite giving perthitic texture (CN 40×).

h. Photomicrograph of Quartz Syenite shows alkali feldspar together with quartz and mica.

5.2. X-ray diffraction

Representative samples represent the different varieties of Al Madinah granitoids were chosen and examined by X-ray diffraction. The results of the traces for random X-ray diffraction (XRD) of the studied samples (granite material) show that quartz, K-feldspar (microcline + orthoclase) and plagioclase (mainly oligoclase, albite) are the main minerals in these samples, while mica (biotite + muscovite) as accessories, iron oxides as traces and calcite as secondary minerals (Figure 5(a–e)). The whole-rock samples of alkali granites showed that they are mostly composed of quartz, orthoclase and small amounts of muscovite and haematite (Figure 5(a)). The samples of alkali feldspar granites mainly consist of K-feldspar (orthoclase + microcline) albite, quartz and accessory minerals as biotite and muscovite (Figure 5(b)). The samples belonging to syenite deposit are essentially composed of K-feldspar (orthoclase-microcline), Na-feldspar (albite-oligoclase) and quartz in minor amounts (Figure 5(c)), while the samples of quartz syenite are essentially composed of quartz, K-feldspar (orthoclase-microcline), Na-feldspar (albite-oligoclase) (Figure 5(d)). The monzogranite composed of quartz and K-feldspar (orthoclase), orthoclase-perthite together with variable amounts of plagioclase (albite-andesine) (Figure 5(e)). The obtained results show a complete agreement with the petrographical description.

5.3. Geochemistry

5.3.1. Major element geochemistry

The geochemistry of the major oxides of the granitic rocks from Al Madinah area will be discussed here, in order to determine what type of specialized granites they represent. The whole-rock major elements’
geochemistry of the studied samples is presented in Table 1, together with CIPW norms.

These data in Table 1 reveal that the Al Madinah granitoids show a variable range in chemical composition with moderate to high silica SiO$_2$ contents ranging from 64.8 to 77.6 wt. % and low content of CaO (0.51–1.90 wt.%), MgO (0.08–0.60 wt.%), Fe$_2$O$_3$ (0.095–2.82 wt.%), TiO$_2$ (0.08–0.52 wt.%), MnO (<0.05–0.07 wt.%) and P$_2$O$_5$ (0.05–0.13 wt.%). Total alkali content ranges from 8.71 to 11.21 wt.%, while Al$_2$O$_3$ ranges from 10.98 to 16.21 wt.%. K$_2$O varies between 4.27 and 5.25 wt.% and is approximately equal to Na$_2$O, which ranges from 4.07 to 5.96 wt.%. K$_2$O/Na$_2$O ratio ranges from 0.88 to 1.24 indicate that there is a considerably similar amount of potash and sodic feldspar character of A Madinah granitoids. CIPW normative compositions have been calculated on an anhydrous basis for the analysed Al Madinah granitoid samples (Table 2).

The TiO$_2$ and Na$_2$O+K$_2$O vs. SiO$_2$ plots (Figure 6). Figure 6 clearly discriminates the studied samples contain variation correlation of oxide elements. As noted that, the Al Madinah granitic samples show little variation in SiO$_2$ and while FeOt (0.96), TiO$_2$ (0.94), MgO (0.86) and CaO (0.84) exhibit negative correlation, Na$_2$O (0.88) and K$_2$O (0.77) show positive correlation with increasing in SiO$_2$. A lack of iron-enrichment in the basement rocks with fractionation suggests their calc-alkaline nature [33,34].

5.3.2. Geochemical classification of Al Madinah granitic rocks

The R1–R2 multi-cationic diagram (Figure 7(a)) uses some major oxides to provide more precise names for the studied rocks. The diagram is based on the cation proportions of the plutonic rocks, to include all of the major cations, normative mineralogy, the degree of silica saturation and the combined changes in Fe/(Fe + Mg) and (Ab + Or)/An ratios. The R1 and R2 parameters were calculated from the chemical analyses (oxide percentages converted to multication). The granites of the Al Madinah have been classified using the R1–R2 diagram of De La Roche et al. [35]. For the Al Madinah granites, most of the investigated samples plot in the field of alkali granite and granite, while other samples plot in the monzonite, quartz monzonite, quartz syenite and syenite fields.

The granites of the Al Madinah have been classified using the total alkali (Na$_2$O+K$_2$O) versus silica (SiO$_2$) TAS diagram of Middlemost [36]. For the Al Madinah granites, most of the samples plot in the field of alkali granite and granite, while other samples plot in the alkali quartz syenite field (Figure 7(b)).

The geochemical characteristics of Al Madinah granites are carried out using TAS (total alkali vs. silica diagram by Middlemost [36]). The granite samples are plotted in granite and quartz monzonite fields except one sample in the syenite field (Figure 7(c)).

5.3.3. Magma types of granitic rocks

On the AFM plot [33] to discriminate between tholeiitic and calc-alkaline suites, all samples of Al Madinah granites occupy the calc-alkaline affinity, indicating their (Na$_2$O + K$_2$O) rich nature (Figure 8(a)). A similar observation has also been confirmed in SiO$_2$-FeO*/MgO

![Figure 5. X-ray diffraction pattern of the selected representative samples from Al Madinah granitoids (feldspar ores). (a) alkali granite, (b) granite, (c) syenite, (d) quartz syenite, (e) quartz monzogranite.](image-url)
Table 1. Geochemical data and CIPW norms of representative samples from Al Madinah granites.

| Oxides (wt. %) | Sample location | F1 | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F13 | F14 | F15 |
|---------------|-----------------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|
|               | Bayda Mountain  | 64.83 | 66.70 | 67.83 | 72.41 | 73.84 | 73.09 | 69.75 | 72.53 | 73.12 | 71.99 | 73.12 |
| SiO₂          | Abar Al Mashi   | 74.52 | 77.66 | 72.83 | 74.54 | 75.91 | 74.52 | 72.41 | 73.84 | 73.09 | 69.01 | 71.99 |
| TiO₂          | Industrial city | 16.36 | 15.21 | 15.35 | 15.41 | 15.69 | 15.21 | 14.60 | 13.60 | 13.67 | 14.77 | 13.48 |
| Al₂O₃         | Jammah Mountain| 2.84  | 2.63  | 2.41  | 2.30  | 2.14  | 2.30  | 2.14  | 2.30  | 2.14  | 2.30  | 2.14  | 2.30  | 2.14  | 2.30  | 2.14  |
| Fe₂O₃(T)      | Yanbu Road      | 0.52  | 0.47  | 0.44  | 0.43  | 0.41  | 0.43  | 0.41  | 0.43  | 0.41  | 0.43  | 0.41  | 0.43  | 0.41  | 0.43  | 0.41  |
| MnO           |                | 6.00  | 0.50  | 0.48  | 0.49  | 0.13  | 0.18  | 0.08  | 0.12  | 0.11  | 0.12  | 0.11  | 0.12  | 0.11  | 0.12  | 0.11  |
| MgO           |                | 5.96  | 5.61  | 5.61  | 5.48  | 5.14  | 4.80  | 4.49  | 4.27  | 4.07  | 4.27  | 4.07  | 4.27  | 4.07  | 4.27  | 4.07  |
| Na₂O          |                | 5.25  | 5.20  | 5.08  | 4.46  | 4.72  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  | 4.50  |
| K₂O           |                | 0.13  | 0.12  | 0.12  | 0.11  | 0.11  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  | 0.05  |
| SO₃           |                | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 | <0.25 |
| LOI           |                | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  | 0.84  |
| Total         |                | 99.63 | 99.66 | 99.68 | 99.67 | 99.91 | 99.90 | 99.66 | 99.91 | 99.90 | 99.72 | 99.78 | 99.82 | 99.70 | 99.75 | 99.83 |
| K₂O + Na₂O    |                | 11.21 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 | 10.81 |
| K₂O/Na₂O      |                | 0.88  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  | 0.93  |
| Al₂O₃/K₂O     |                | 3.12  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  | 3.02  |
| A.S.I         |                | 0.88  | 0.90  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  | 0.89  |
| P.I           |                | 0.95  | 0.95  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  | 0.96  |
| MALI          |                | 9.31  | 9.22  | 9.21  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  | 9.32  |
| CIPW norm (Mineralogy (mol %)) | | Qz | 7 | 11 | 13 | 13 | 34 | 30 | 37 | 31 | 30 | 20 | 29 | 31 | 18 | 24 | 29 |
|               | Kfs (Or + Mic) | 31 | 30 | 30 | 30 | 26 | 28 | 37 | 31 | 28 | 28 | 27 | 25 | 30 | 28 | 27 |
|               | Pl (O + Ab)   | 53 | 50 | 49 | 49 | 34 | 37 | 31 | 31 | 37 | 46 | 37 | 37 | 45 | 42 | 38 |

Notes: LOI: Loss on ignition; Qz: quartz; Kfs: alkali feldspar; Pl: plagioclase; Or: orthoclase; Mic: microcline; O: oligoclase; Ab: albite; An: andesine. A.S.I: Alumina saturation index (Al₂O₃/(CaO + Na₂O + K₂O)), molar ratio; P.I: Peralkalinity index (Na₂O + K₂O)/Al₂O₃, molar ratio; MALI: Na₂O + K₂O – CaO%. 
plot [34]; most of the samples occupy the calc-alkaline series field (Figure 8(a)).

On SiO₂, K₂O plot [37], all samples from Al Madinah granites plot occupying the high-K calc-alkaline series with exception of some sample lies close to shoshonite series (Figure 8(b)).

Based on the 100 (MgO + FeO⁺ + TiO₂)/SiO₂ vs. (Al₂O₃ + CaO)/(FeO⁺ + Na₂O + K₂O) diagram (Figure 8(c)) of Sylvester [38], the samples of Al Madinah granites are distributed between the alkaline and the highly fractionated, calcic-alkaline fields.

Debon and Le Fort [39] classification being divided granites into the following types: I – peraluminous with two-mica (muscovite > biotite), II – peraluminous with biotite > muscovite, III – peraluminous with biotite (usually alone, at times with a few amphiboles); IV – metaluminous with biotite ± amphibole ± orthopyroxene ± clinopyroxene; V – exceptional rocks as carbonatites, etc., and VI – leucogranites. The metaluminous nature of Al Madinah granites is evident from major cation parameters of Debon and Le Fort [39], which essentially consist of biotite + amphibole ± pyroxene assemblage (Figure 8(d)).

Figure 8(e) shows A–B diagram [39] with fields of various types of peralkaline rocks as outlined by Villaseca et al. [40]. Boundary line of I- and S-type granitoids is drawn based on data from the Lachlan Fold Belt [41,42]. Figure 8(e) shows discrimination diagram for the Al Madinah granitoids. In the B–A plot, first used by Debon and Le Fort [39], and later modified by Villaseca et al. [40], indicating aluminium saturation where A = Al–(K + Na + 2Ca) and B = Fe + Mg + Ti.

### Table 2. Comparison of average chemical composition of Al Madinah granites with world granitic rocks.

| Oxide (wt. %) | Madinah, KSA | Jordan | Egypt | Germany | Czech | Sweden | Norway | Japan |
|---------------|--------------|--------|-------|---------|-------|--------|--------|-------|
| SiO₂          | 70.15        | 71.50  | 75.04 | 71.82   | 73.38 | 75.50  | 75.91  | 72.51 |
| TiO₂          | 0.36         | 0.70   | 0.22  | 0.10    | 0.16  | 0.00   | 0.14   | 0.00  |
| Al₂O₃         | 14.25        | 13.62  | 13.03 | 16.30   | 13.97 | 15.17  | 11.66  | 14.11 |
| Fe₂O₃ (T)     | 2.04         | 1.06   | 1.07  | 0.95    | 1.90  | 1.86   | 1.43   | 2.79  |
| MnO           | 0.06         | 0.03   | 0.06  | 0.92    | 0.05  | <0.05  | <0.05  | 0.24  |
| MgO           | 0.39         | 0.36   | 0.26  | 0.25    | 0.47  | 0.30   | 0.13   | 0.37  |
| CaO           | 1.30         | 1.23   | 0.75  | 0.50    | 0.75  | 0.00   | 0.67   | 2.20  |
| Na₂O          | 5.03         | 5.47   | 3.87  | 4.38    | 3.20  | 4.25   | 4.75   | 3.20  |
| K₂O           | 4.84         | 4.95   | 4.43  | 4.62    | 4.69  | 4.58   | 4.46   | 4.38  |
| K₂O + Na₂O    | 9.87         | 10.42  | 8.30  | 9.00    | 7.89  | 8.83   | 9.20   | 7.58  |
| Al₂O₃/K₂O     | 2.95         | 2.75   | 2.94  | 3.53    | 2.98  | 3.31   | 2.57   | 3.22  |
| K₂O/Na₂O      | 0.96         | 0.90   | 1.14  | 1.05    | 1.47  | 1.08   | 0.94   | 1.37  |
a geochemical grouping can be made among the samples included in this study (Figure 8(e)). The B–A plot shows that Al Madinah granites plot within the metaluminous field and one sample plot in the boundary between f-P, i-P of felsic and weak peraluminous field. (h-P = Highly Peraluminousgranitoid, m-P = Moderately-Peraluminousgranitoid, I-P = Low-Peraluminousgranitoid, f-P = Felsic-Peraluminousgranitoid).

5.3.4. Tectonic Setting of granitic rocks

Tectonic discrimination diagrams use the concentrations of various chemical components to suggest environments for granite formation. These have been used on the studied plutons and are presented in Figure 8. Based on the tectonic discrimination diagrams devised by Pitcher [43], the R1–R2 multication factors [35] classify the Al Madinah granitic samples as granite, corresponding to granitic rocks formed in Late-Orogenic and syn-collision tectonic setting (Figure 9).

6. Evaluation and investment opportunities of feldspar ore deposits in Al Madinah area

On the basis of the mineralogical and chemical results, it has been noted that the granitic rocks in Al Madinah area are sources for feldspar (K-spar and Na-spar), which find extensive use in the glass, ceramics and filler industries.

The average chemical composition of granitic rocks (feldspar ores) from Al Madinah area (Table 2) is compared with the average chemical composition of the two types of specialized granites recognized in the Arabian shield by El-Gaby [44] and [45] as well as the average chemical composition of the specialized granites (feldspar ores) of the world [46–50].

The results of the chemical composition of Al Madinah granites (Table 2) revealed that they are characterized by higher total alkali content ((Na2O + K2O) with an average of 9.87%. In addition, the results show higher total alkali content of Al Madinah granites, compared to the younger granite of Egypt (8.30%), and the world’s specialized granites [Germany (9.0%), Sweden (8.83%), Norway (9.20%), Czech (7.89%) and Japan the total alkalis are 7.58%, but they have relatively lower total alkalis content compared to the Jordan granites (with an average 10.4%).

Compared with the specialized world granites (feldspar ore deposits), the feldspar ore in Al Madinah area is more favourable for exploitation of the feldspar ores in Al Madinah area for the following reasons:

- Less in Ferro-magnesium minerals
- Higher alkali content
- Easier exploitation
More accessible
- Easy for mining

So, the selective open pit mining method was found to be the cheapest and safest and gave the highest recovery; besides, it would permit almost a 100% recovery.

7. Conclusions

Potential sources of feldspar in Al Madinah area include Granites and Syenites. Granites present potentially very large sources of potash and soda feldspar, whereas the syenites, which are potential sources of potash-feldspar, are of small to modest size. The glass and ceramics industries provide a major market for soda and potash-feldspar.

Results of this study show that the materials from Al Madinah area yield a more suitable composition of feldspar when compared with that of the world’s specialized granites. The results indicate that the total alkali content (Na₂O + K₂O) ranges from 8.6 to 11.2 wt.% (with an average of 9.86 wt.%). The iron oxides occurred in a

Figure 8. (a) AFM diagram [33] or AFM diagram [34] shows all of Al Madinah granites are calc-alkaline field. (b) SiO₂–K₂O diagram [37] shows all the samples of Al Madinah granites occupying the high-K calc-alkaline series with exception of some sample lies close to shoshonite series. A: Abar Al Mashi, B: Bayda’s Mountain, I: Industrial city, J: Jammah Mountain, Y: Yanbu Road. This representation of the different symbols for each locality applies for all other Figures from 6 to 9. (c) 100 (MgO + FeO* + TiO₂)/SiO₂ vs. (Al₂O₃ + CaO)/FeO* + Na₂O + K₂O) of (Sylvestre) [38]. (d) A–B diagram [39] shows the plotted samples of Al Madinah granitoid rocks. Each of its six sectors, numbered from I to VI, corresponds to a specific mineral assemblage. I, II and III are peraluminous sectors, while IV, V and VI are metaluminous sectors. (e) B–A plot after Villaseca et al. [40]. Al Madinah granites plot as metaluminous, whereas one sample plots in boundary between weakly and felsic peraluminous grading towards metaluminous.
low quantity in the analysed samples. The percentages range from 0.95 to 2.83 wt.% (with an average of 1.89 wt. %), which are thought to be produced from the alteration of the mafic (Ferro-magnesium) minerals that are present in the rock.

On the basis of petrography, mineralogy and geochemistry, the granitic samples of the study area scatter across the fields of alkali granite, granite, quartz monzonite and quartz syenite, and one sample classifying as a syenite. The geochemical data also point out that the samples are of high calc-alkaline nature and of metaluminus type with the exception of some sample lies close to shoshonite, suggesting an I-type granites.

Al Madinah granites were emplaced in a very similar tectonic environment that spans the Pan-African orogeny and implies late stage of island-arc accretion to post-collision events, followed by the waning (relaxation) of the orogeny. This suggestion is supported by the chemical characteristics of the studied granitoids and by comparison with other chemically similar granitoids in the Arabian Shield.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Perkins D. Mineralogy. Upper Saddle, NJ: Prentice-Hall Inc; 2015.

[2] Harben P, KuZˇr var M. Industrial minerals: A global geology. 3rd ed. London: Industrial Minerals Ltd. Metal Bulletin PLC; 1997, pp. 490.

[3] Palomba M, Padalino G, Baldracci A. An unusual occurrence of an exploitable K-feldspar deposit hosted in the Ordovician porphyroids (Southern Sardinia) geology, mineralogy, geochemical features and economic potential. Ore Geol Rev. 2010;37:202–221.

[4] Brown GFR, Jackson O. The Arabian shield. Int’l Geological Congress 2, 21 session 9; 1960. p. 69–77.

[5] USGS-ARAMCO. Geological map of Arabian Peninsula, U. S. geological survey misc. Geol Invest Map. 1963: 1-270-A.

[6] Schmidt DL, Hadley WR, Greenwood L, et al. Stratigraphy and tectonism in southern part of the pre-cambrian shield of Saudi Arabia. Saudi Arab Dir Gen Bull Miner Res. 1973;8:13.

[7] Johnson PR. Explanatory Notes on the Map of Proterozoic Geology of western Saudi Arabia. Saudi Arabian Geological Survey Technical Report SGS-TR-2006–4, 2005. p. 62.

[8] Johnson PR, Kattan FH. Lithostratigraphic revision in the Arabia shield: The impacts of geochronology and tectonic analysis. Arab J Sci Eng. 2008;33(1):3–16.

[9] Greenwood WR, Hadley DG, Anderson RE, et al. Late proterozoic cratonization in southwestern Saudi Arabia. Phil Trans R Soc London Ser A. 1976;280:517–527.

[10] Stoeser DB, Camp VE. Pan-African microplate accretion of the Arabian shield. Geol Soc Am Bull. 1985;96:817–826.

[11] Stoeser DB, Stacey JS, Evolution, U-Pb geochronology, and isolate geology of the Pan-African Nabihtah orogenic belt of the Saudi Arabian shield. In: El-Gabt S, Greiling RO, editor. The Pan-African belt of Northeast Africa and adjacent areas, Friedrich, vieweg and sohn. 2002;7(1):103–124.

[12] Nehlig P, Asfirane F, Genna A, et al. Thieblemont. aeronomagnetic map constrains cratonization of the Arabian shield. Terra Nova. 2001;13:347–353.

[13] Johnson PR, Kattan FH. Oblique sinistraltanspression in the Arabian shield: the timing and kinematics of a neoproterozoic suture zone. Precamb Res. 2001;107:117–138.

[14] Johnson PR, Kattan FH. Lithostratigraphic revision in the Arabian shield: the impacts of geochronology and tectonic analysis. Arab J Sci Eng. 2008;33(1):3–16.

[15] Gehrig P, Asfirane F, Genna A, et al. Thieblemont. aeronomagnetic map constrains cratonization of the Arabian shield. Terra Nova. 2001;13:347–353.

[16] Nehlig P, Genna A, Asfirane F. A review of the Pan-african evolution of the Arabian shield. GeoArabia. 2002;7(1):103–124.

[17] Genna A, Nehlig P, Le-Goff E, et al. Proterozoic tectonism of the Arabian shield. Precambrian Res. 2002;117:21–40.

[18] Volesky JC, Stern RJ, Johnson PR. Geological control of massive sulfide mineralization in the NeoproterozicWadiBidah belt shear zone, southwestern Saudi Arabia: inferences from orbital remote sensing and field studies. Precambrian Res. 2003;123:235–247.

[19] Meert JG, Lieberman BS. The neoproterozoic assembly of Gondwana and its relationship to the Ediacaran-Cambrian radiation. Gondwana Res. 2008;14:5–21.

[20] Stern R, Johnson P. Continental lithosphere of the Arabian plate: a geologic, petrologic and geophysical synthesis. Earth Sci Rev. 2010;101:29–67.

[21] Bamousa A, Matar S, Daoudi M, et al. Structural and geomorphic features accommodating groundwater of Al-

Figure 9. Classification and nomenclature of granitoid rocks using the parameters R1 and R2 of De La Roche et al. [35], calculated from multication proportions. The diagram show plots of the studied Al Madinah granites on a major granitic classification diagram (fields after Pitcher [43]).
