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Exploring Syenites from Ring Complexes in the Eastern Desert (Egypt) as Ceramic Raw Materials

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ABSTRACT

The aim of this study is to assess the potential as ceramic flux of some feldspar sources in the Egyptian Eastern Desert, particularly syenites from Abu Khruq, which is the most promising ring complex, taking into account various issues, including the occurrence of nepheline syenites. This late Cretaceous ring complex shows zones of alkaline rocks arranged concentrically with quartz-syenite at the border and an inner zone of nepheline syenite. Both rock types are made up essentially of alkali feldspar with minor amounts of alkali pyroxene, amphibole and biotite, but the former contains interstitial quartz and the latter nepheline. The coexistence of silica-saturated and silica-undersaturated rocks is likely the result of crustal contamination. Geochemical data indicate that alumina (12-18%) and alkali (8-13%) contents are lower than nepheline syenites used in the ceramic manufacture and the Fe_2O_3 content is high (4.1-6.4%). Thus, the investigated syenites must be beneficiated to be usable in the ceramic industry. Lab-scale mineralurgical treatments (comminution and magnetic separation) were carried out and the beneficiated samples were characterized from the chemical and technological viewpoints. Abu Khruq syenites resulted to be suitable for the production of ceramic tiles.

Keywords: beneficiation; ceramic flux; feldspar; nepheline syenite; ring complex.

INTRODUCTION

The progressive depletion of the main feldspathic flux deposits in the World (albitites, pegmatites and aplites), under the increasing global demand, is forcing the ceramic industry to search for suitable substitutes. Among the potential alternatives, alkaline intermediate igneous rocks, comprising nepheline syenites and further syenite types, are the best deputy, in force of their high feldspar amount (generally over 70%), the low or null content in quartz and possible occurrence of feldspathoids, particularly nepheline (Allen and Charsley, 1968; Garth Platt, 1996). However, syenitic rocks usually exhibit a mafic index close to 30, which makes crucial the beneficiation treatments in order to achieve the market requirements for ceramic fluxes (McLemore, 2006; Potter, 2006). In addition, the common syenite paragenesis, where amphiboles and pyroxenes accompany biotite, turns less effective the usual mineralurgical steps based on magnetic separation, because of the relatively low magnetic susceptibility of inosilicates (Drzymala, 2007). In these conditions, the comminution and sieving steps become fundamental to ensure a proper liberation of mafic minerals. That is necessary to have a sufficiently high yield in the subsequent separation stage and thus an economically sustainable processing. For these reasons, the exploitation of syenitic rocks as valuable fluxes is still a challenging task for the ceramic industry.

Besides that nepheline syenite is still utilized in the ceramic manufacturing since 1937 (Spence, 1938), its mining is limited to few world-class deposits in Canada (Payne, 1968), Norway (Geis, 1979) and Russia (Nedosekova et al., 2009). In further countries, the nepheline syenite production has been limited and discontinuous: Brazil (Enrich et al., 2005), India (Joshi et al., 1993), Iran (Mazhari et al. 2012) and Turkey (Burat et al., 2006). Alkali syenite was tested in Poland by Partyka (2011) and Partyka et al. (2012) as a potential raw material for ceramics, and the investigations confirmed its suitability for some ceramic applications. Nevertheless, it was used in Spain as a ceramic flux only for a short time (Garcia-Ten and Regueiro, 2008).

One of the most promising areas for syenite prospecting is Egypt, where several intrusive alkaline complexes, Cambrian to late Cretaceous in age, outcrop in the Eastern Desert (El Ramly and Hussein, 1985; Mogahed, 2016). They lie along the major tectonic lineaments (Figure 1) and represent the northward extension of ring complexes associated with the East African rift system (Bowden, 1985; Vail, 1989).

There are six major periods of alkaline magmatism within the basement of the Eastern Desert of Egypt. These alkaline magmas were thought to be originated in the asthenosphere mantle synchronous with changes in plate motion and emplaced preferentially along the weakness zones (De Gruyter and Vogel, 1981). In 1982, El Ramly and Hussein suggested that the alkaline magma of the ring complexes was formed from the partial fusion of the upper mantle, which produced heat and volatiles and caused the melting of the lower crust. Both magmas could give a variety of rock types resulting in the formation of

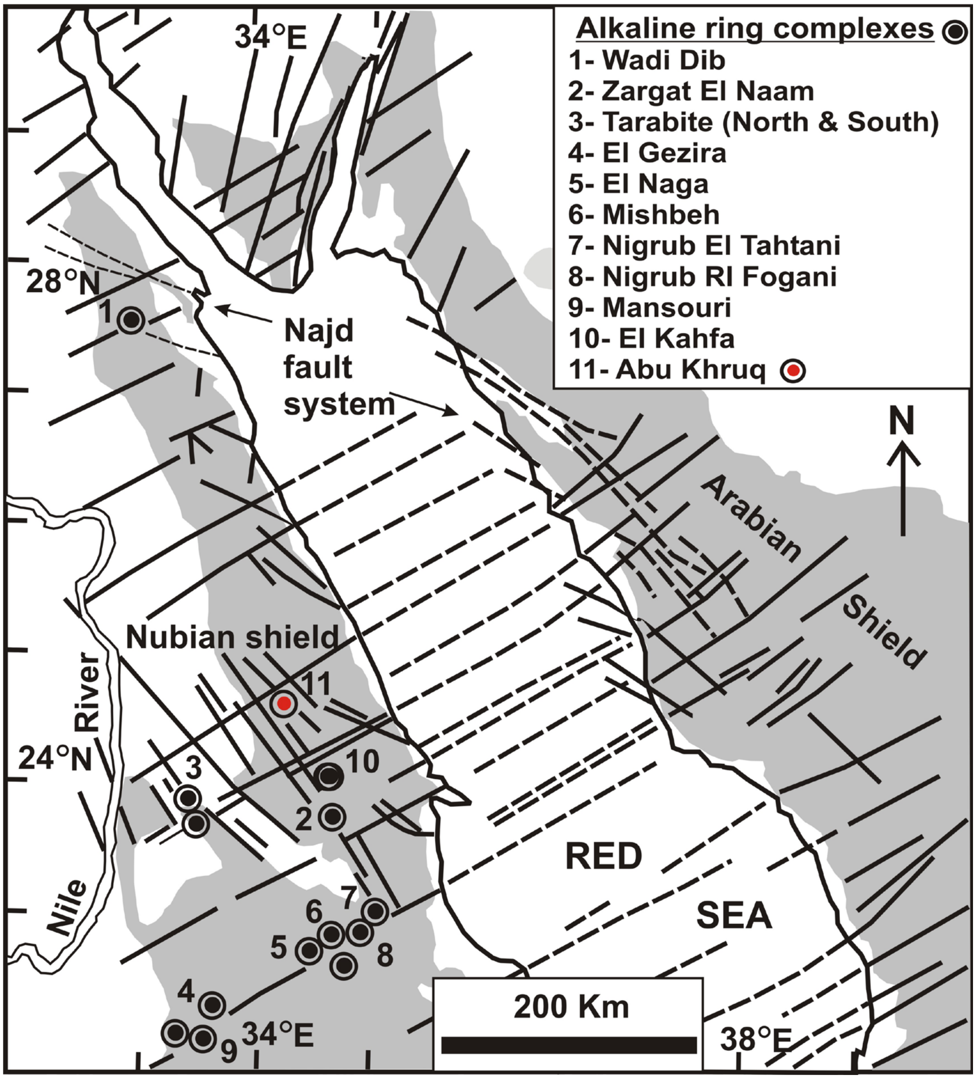

Figure 1. Distribution of the alkaline ring complexes in the Egyptian Eastern Desert (Mogahed, 2016).

the ring complexes. It is widely shown that the alkalinity and silica saturation of the ring complexes is related to the age; the early phases of the complexes are poorer in alkalis and richer in silica as compared to the younger ones.

Several Authors studied the ring complexes in the southern Eastern Desert (El Ramly et al., 1971; El Ramly and Hussein, 1985; Fitton and Dunlop, 1985; El-Nisr and Saleh, 2001; Ghazaly and Sinah, 2002; Saleh, 2006; Ragab et al., 2007). The syenite sources available in the ring complexes are summarized in Figure 2, in order of decreasing prospects in terms of outcrop surface, occurrence of nepheline syenite, and logistic issues.

The aim of this study is to assess the potential of feldspar sources constituted by syenoids in the Egyptian Eastern Desert (El Ramly and Hussein, 1985) by focusing the attention on the most promising ring complex. Taking into account geological, petrographic and logistic issues, including the occurrence of nepheline syenites, the Abu Khruq complex (Obeid and Lalonde, 2013) resulted to be the best prospect, also because it contains the largest reserves of feldspars (Negm et al., 2001).

GEOLOGICAL OUTLINE

The Abu Khruq ring complex crops out between the Nile River and the Red Sea and is situated in longitude 34º18’08”N and latitude 24º38’55”E, north of Wadi Shait. It is about 7 km in diameter and lies along the main structural lineament, which is a deep-seated block fault, having N30ºW trend parallel to the Red Sea (Garson and Krs, 1976).

The complex emplaced into the late Proterozoic Pan African country rocks and belongs to Mesozoic alkaline episodes (Serencsits et al., 1981), perhaps synchronous with the major rifting of the south Atlantic region (Mogahed, 2016). It consists of alkali gabbro, nepheline syenite and quartz syenite and is associated with volcanic masses, including phonolite, trachyte and rhyolite (Figure 3).

These rocks occur as incomplete ring dykes, sheets and high cones (about 600-900 m above the sea level). The gabbros were first emplaced as irregular bodies, and then followed by syenites. Early formed syenites forming the outer rings were oversaturated to saturated in silica, while the latest were undersaturated, occurring in the core of the complex. The nepheline syenites are separated from quartz syenites by a long ring-shaped wadi representing perhaps the main fracture originated during the rock emplacement. The syenites are generally gray in colour, but close to the shear zones they became reddish, being due to circulating of Fe-rich hydrothermal solutions.

The gabbroic rocks yielded Rb-Sr age of 89 Ma, concordant with those given by syenite of ~100 Ma (Lutz et al., 1988), being consistent with K-Ar dating given by Serencsits et al. (1981) and reflecting cogenetic origin; syenites are most probably fractionated from alkaline mafic magma.

EXPERIMENTAL

Seven syenite samples were collected: four (Sy1 to Sy4) were characterized by chemical analysis (major oxides and minor elements by XRF-WDS) and petrographic study (thin sections under polarized optical microscope and calculation of CIPW norm). Further three samples (AS, NS, QS) were tested by performing (Figure 4): crushing, drying, laboratory-scale grinding at 0.8 mm, de-dusting of the grinded product (<0.1 mm fraction removal), and laboratory-scale magnetic separation of the 0.8-0.1 mm fraction.

Magnetic separation was performed in a roll magnetic separator equipped with a permanent magnet with a nominal power of 11,000 gauss. During the test, three outputs were collected: non-magnetic, intermediate and magnetic fractions. Non-magnetic and intermediate products were analyzed in order to give a wider idea about the possible final products.

RESULTS AND DISCUSSION

Petrographic description of syenites

The samples of different rock types have been studied petrographically in thin sections, and accordingly the syenitic rocks of the Abu Khruq ring complex can be classified into quartz syenites and nepheline syenites; the former are located in the outer ring of the complex and enclosed irregular masses of syenogranite, while the core is occupied by nepheline syenites.

Quartz syenites are medium- to coarse-grained rocks showing hypidomorphic texture. They are made up of alkali feldspar (75-85 % modal), mafic minerals (5-15%), quartz (5-7%) and plagioclase (2-4%). Zircon, apatite, sphene and opaque minerals are the main accessories. Perthitic orthoclase is the dominant alkali feldspar reaching up 5 mm in length, in which orthoclase plays host to sodic feldspar (Albite) (Figure 5a). Beside regular perthitic intergrowths, albite is intergrown as laths and crystals as well. Albite is also present as fine-grained crystals outside of perthitic intrgrowths. Sometimes, alkali feldspar crystals are poikilitically enclosing pyroxene. The mafic minerals are represented mainly by alkali pyroxene (aegirine-augite, aegirine), but amphibole is also identified. Large pyroxene crystals are subhedral to anhedral, but smaller ones forms fine prisms. Pale aegirine-augite is sometimes zoned with dark green aegirine (Figure 5b). Amphibole occurs as small crystals or forms reaction around aegirine (Figure 5c). Quartz is found as interstitial material or forms micrographic

Ring Complex	Extension (km²)	Syenoids outcrops (km²)	km off road	km to the Nile	Nepheline syenite
Abu Khruq	32.4	12.1	0	250	+++
Umm Risha	38.2	23.3	40	140	
Khaifa	13.4	1.6	5	290	+
Mishbeh	36.0	30.2	100	500	
Zargat Na'am	20.4	12.7	20	340	
Hadayib	12.6	8.8	60	140	
Mansouri	15.7	12.4	150	180	
Maladob	4.6	4.6	90	500	
Tarbtie	9.3	5.7	20	80	
Wadi Dib	4.1	3.0	65	280	
El Naga	2.1	1.4	160	500	
El Gezira	5.4	2.7	100	180	
Nigrub Tahtani	3.6	3.4	90	500	
Nigrub Fogani	12.1	-	90	500	

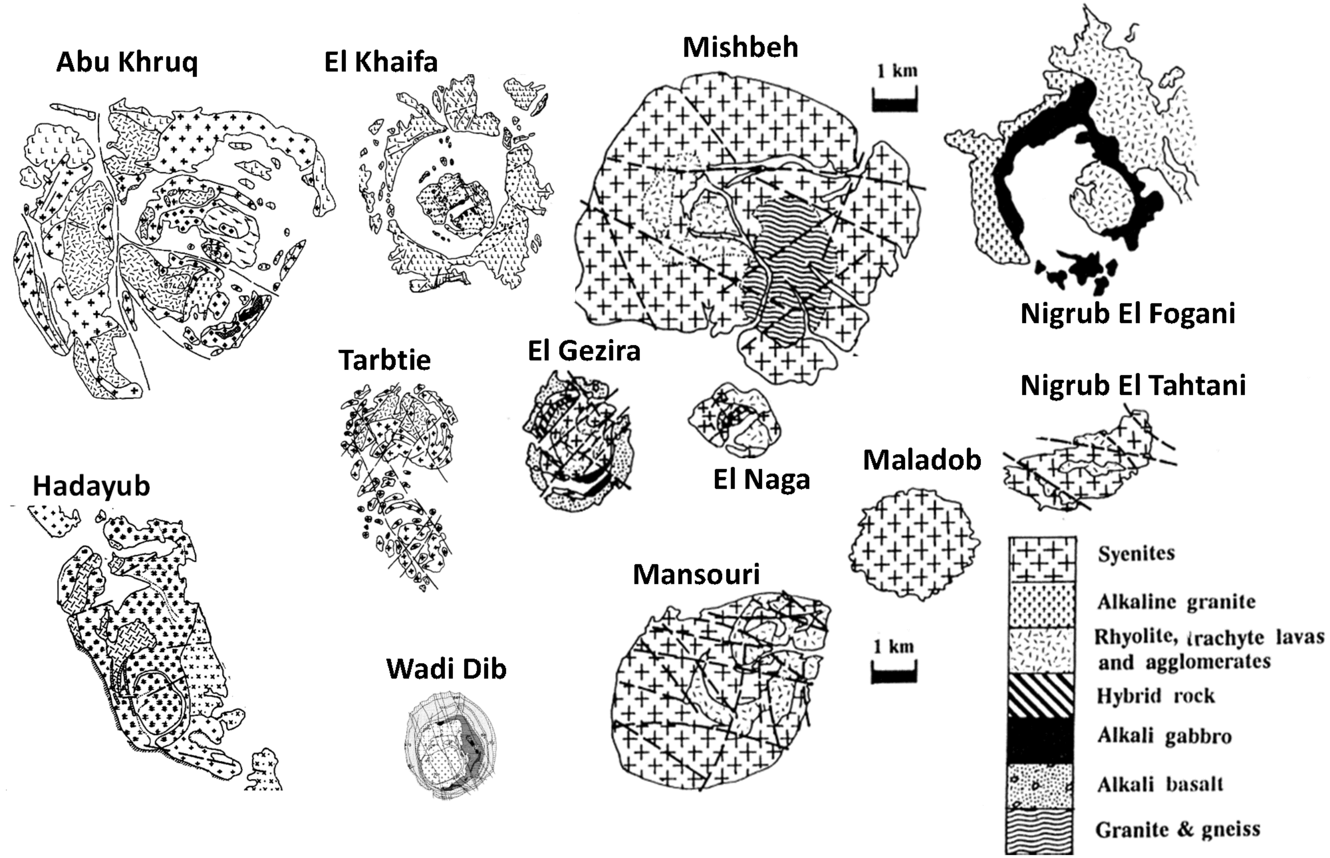

Figure 2. Geological sketch of the main ring complexes in the Eastern Desert, Egypt (El Ramly et al., 1971; El Ramly and Hussein, 1985; Mohamed, 2006).

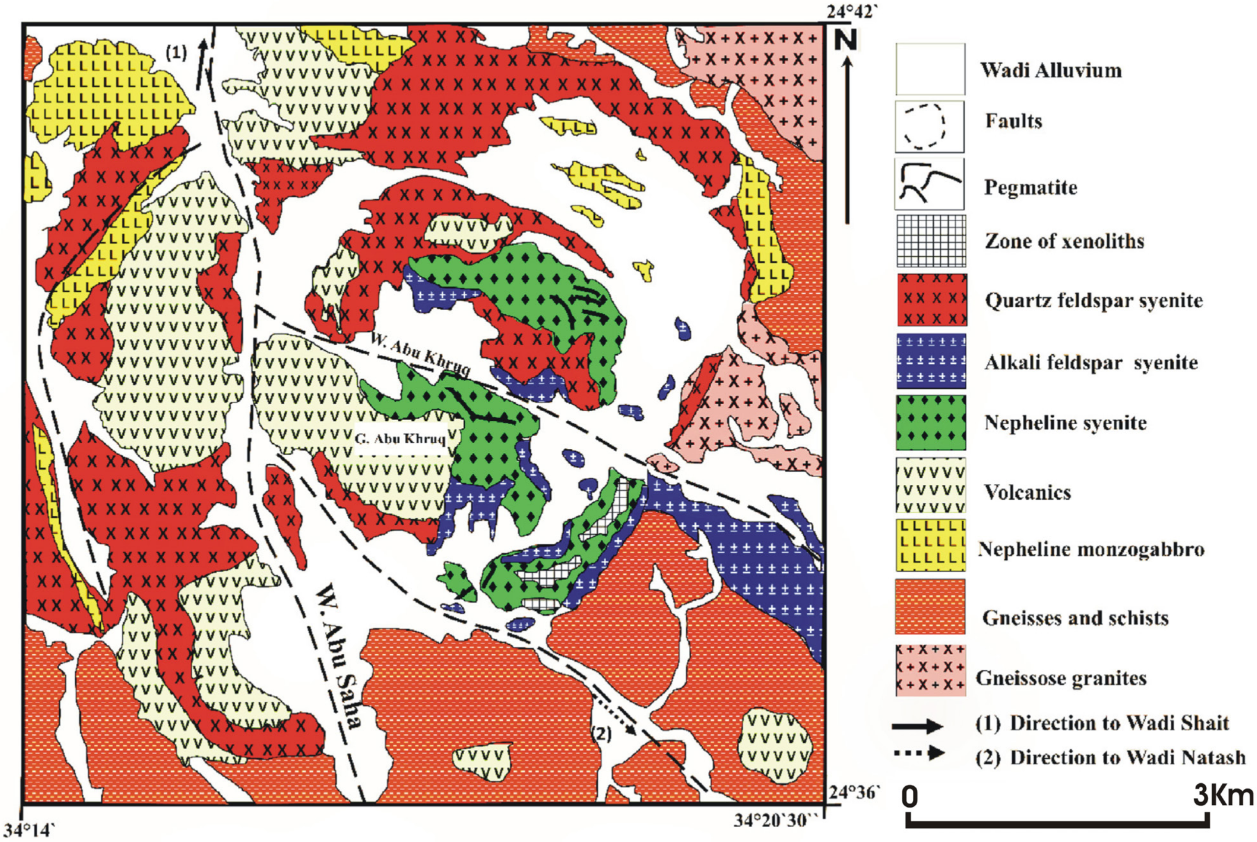

Figure 3. Geological map of the Abu Khruq area showing various lithologies (modified after Mogahed, 2016)

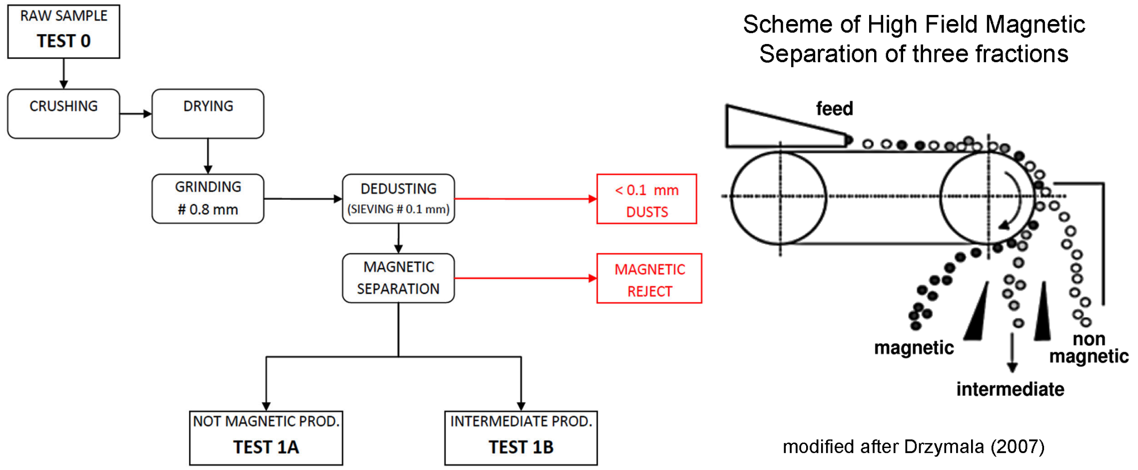

Figure 4. Mineralurgical treatment of Abu Khruq syenites.

intergrowths with alkali feldspar producing granophyric texture (Figure 5d).

Nepheline syenites are medium-grained rocks consisting of alkali feldspar (80% modal), mafic minerals (13%) and nepheline (7%) with zircon and opaque minerals as accessory minerals. Perthitic intergrowths are common (Figure 6a), but alkali feldspars occur also as euhedral to subhedral, tabular crystals containing inclusions of albite laths, aegirine and/or biotite. Pyroxene is sodic and is present as euhedral to subhedral prismatic crystals varying

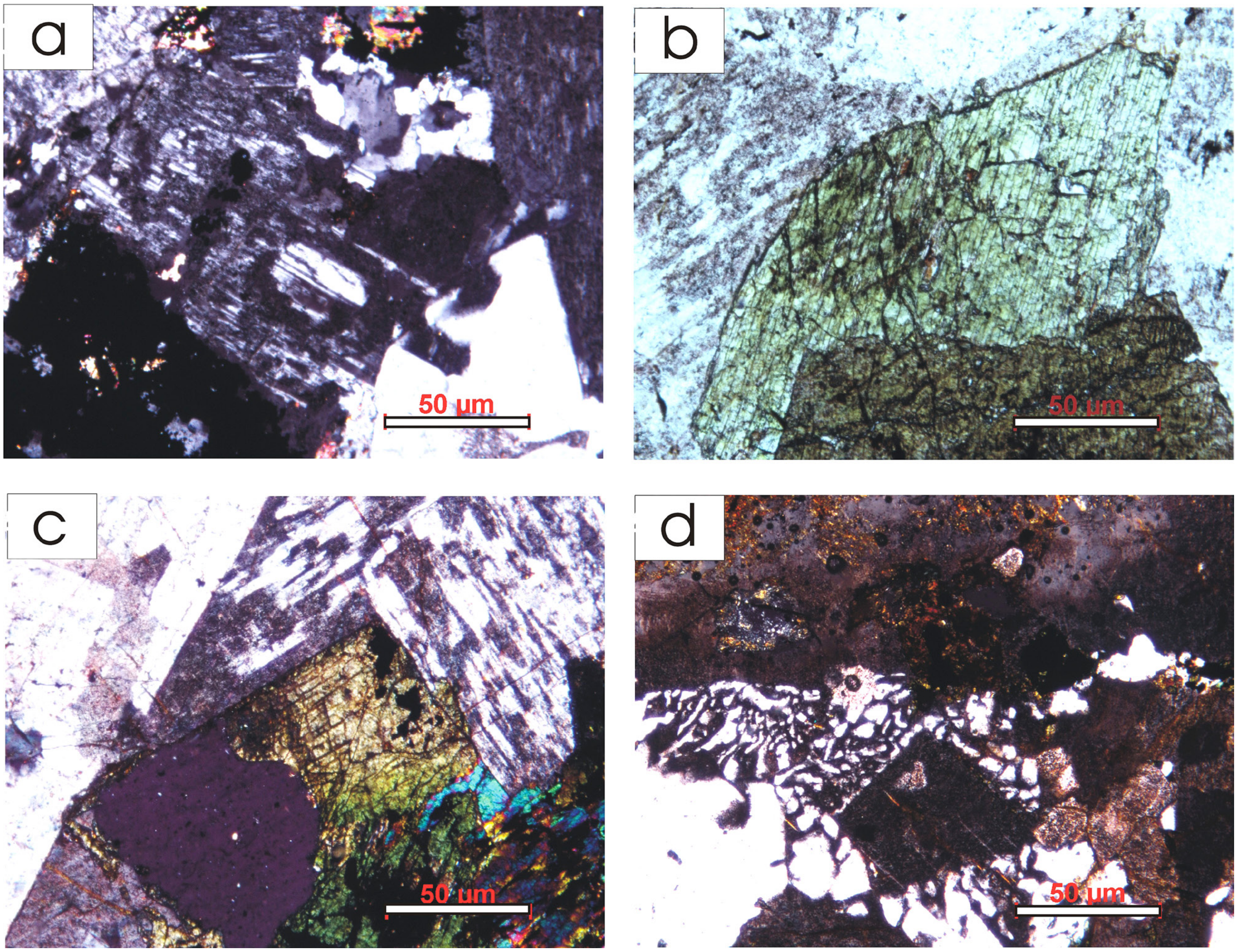

Figure 5. Micrographs of thin sections of the Abu Khruq quartz syenites. See text for explanation.

in size from 1 to 4.5 mm. Zonal structure is common in pyroxene with colourless to pale green aegirine-augite cores mantled by deeper green aegirine margins indicating an increase in Na content and aegirine component towards the rims. Biotite forms tablets and is iron-rich, showing reddish brown to nearly black pleochroism (Figure 6b). Sometimes, biotite resorbs and rims aegirine grains (Figure 6c). Nepheline is the most abundant feldspathoid occurring as euhedral to subhedral crystals corroding or filling the interstices between feldspar. The large crystals reach up to 4 mm in length and are uncommonly altered to sericite and analcite (Figure 6d).

Syenogranites are identified within quartz syenites. They are coarse-grained rocks consisting of tabular feldspar (74% modal), quartz (18%), plagioclase (7%) and little biotite. The accessories include zircon and opaque minerals. Alkali feldspar is mainly represented by coarse orthoclase microperthite and forms also small laths. Plagioclase occurs either as corroded prismatic crystals or as laths within alkali feldspar. Quartz is anhedral, rounded and interstitial to the feldspar (Figure 7a). Biotite appears as fine crystals and commonly associated with opaque minerals (Figure 7b).

Composition of syenites

The chemical composition (major oxides and trace elements) of samples is shown in Table 1 together with their normative composition.

Most of the Abu Khruq rock compositions range from nepheline syenites, quartz syenites to syenogranites (Figure 8), the latter are irregularly mixed and occur within the quartz syenites towards the north. All rock types plot in the alkaline field above the dividing line of Miyashiro (1978). The quartz syenites show a wide range of quartz-normative (7.31-11.95%), which reaches 29.81% in syenogranite, whereas nepheline syenite is nepheline-normative, being consistent with its alkaline character.

The Abu Khruq rocks - including various syenite types and syenogranite - show silica contents varying from 59 to 71 wt% (Table 1), with the differentiation index (i.e., the

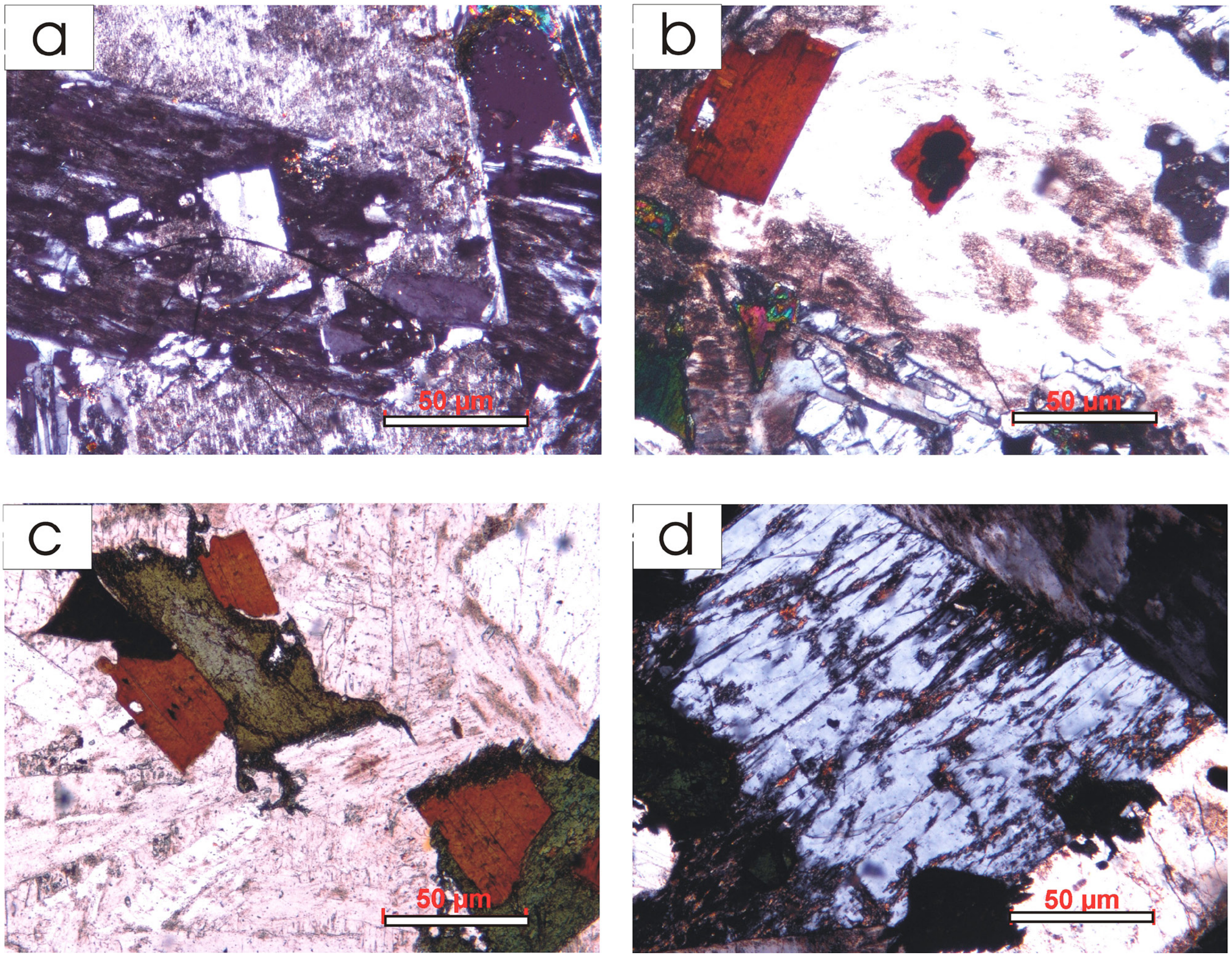

Figure 6. Micrographs of thin sections of the Abu Khruq nepheline syenites. See text for explanation.

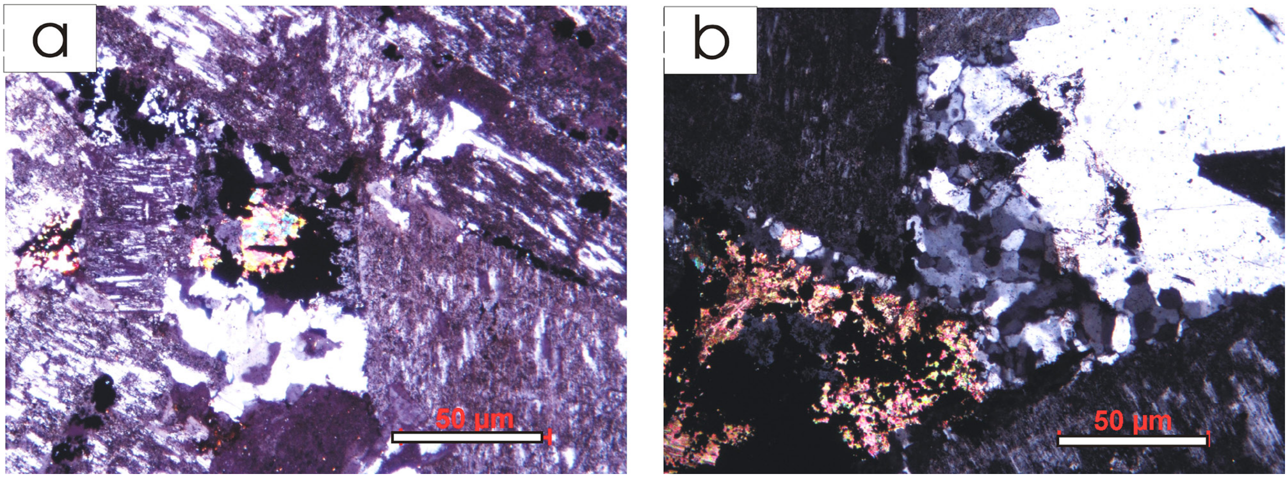

Figure 7. Micrographs of thin sections of the Abu Khruq syenogranites. See text for explanation.

Table 1. Chemical composition of various rock types of the Abu Khruq Complex.

%wt	Quartz-syenite	Syenogranite	Quartz-syenite	Nepheline syenite
Major oxides	Sy1	Sy2	Sy3	Sy4
SiO_2	63.49	70.58	64.15	58.99
TiO_2	1.02	0.41	0.54	0.28
Al_2O_3	15.28	11.99	15.76	17.98
Fe_2O_3	5.98	4.06	5.91	6.44
MnO	0.29	0.16	0.15	0.18
MgO	0.09	0.10	0.12	0.09
CaO	1.06	1.87	1.90	1.02
Na_2O	6.54	4.02	5.64	6.58
K_2O	4.68	4.35	4.48	6.04
P_2O_5	0.07	0.02	0.10	0.06
L.o.I.	0.98	1.72	0.60	1.74
Total	99.48	99.28	99.35	99.40
CIPW norm				
Quartz	7.31	29.81	11.95	0.00
Plagioclase	52.26	34.03	50.65	51.06
Orthoclase	27.95	25.92	27.35	35.69
Nepheline	0.00	0.00	0.00	2.63
Hematite	5.37	4.06	5.91	6.44
Diopside	0.48	0.54	0.64	0.48
Wollastonite	0.75	1.68	0.61	0.19
Acmite	1.75	0.00	0.00	0.00
Ilmenite	0.62	0.34	0.32	0.39
Apatite	0.16	0.05	0.23	0.14
Zircon	0.10	0.27	0.10	0.22
Periclase	0.00	0.00	0.00	0.13
Sphene	1.70	0.56	0.91	0.00
Halite	0.11	0.30	0.19	0.30
Thenardite	0.05	0.34	0.23	0.20
Trace elements (ppm)				
Ba	382.3	291.5	1045.9	186.0
Co	33.9	42.2	16.7	23.9
Cr	<2.0	<2.0	<2.0	2.4
Ga	36.7	37.7	33.7	34.6
Nb	89.3	146.5	64.4	113.5
Ni	<2.0	3.2	<2.0	<2.0
Rb	80.4	125.0	73.3	143.7
Sr	48.8	33.5	208.7	34.1
Ta	2.1	2.1	<2.0	2.0
Zn	200.6	230.1	113.4	141.1
Pb	14.0	12.7	8.0	10.8
Cu	8.2	<2.0	<2.0	<2.0
Zr	531.0	1363.1	540.7	1084.2
Y	61.9	130.5	57.2	69.3
V	37.7	13.8	14.2	9.6
La	2.1	2.1	<2.0	2.0

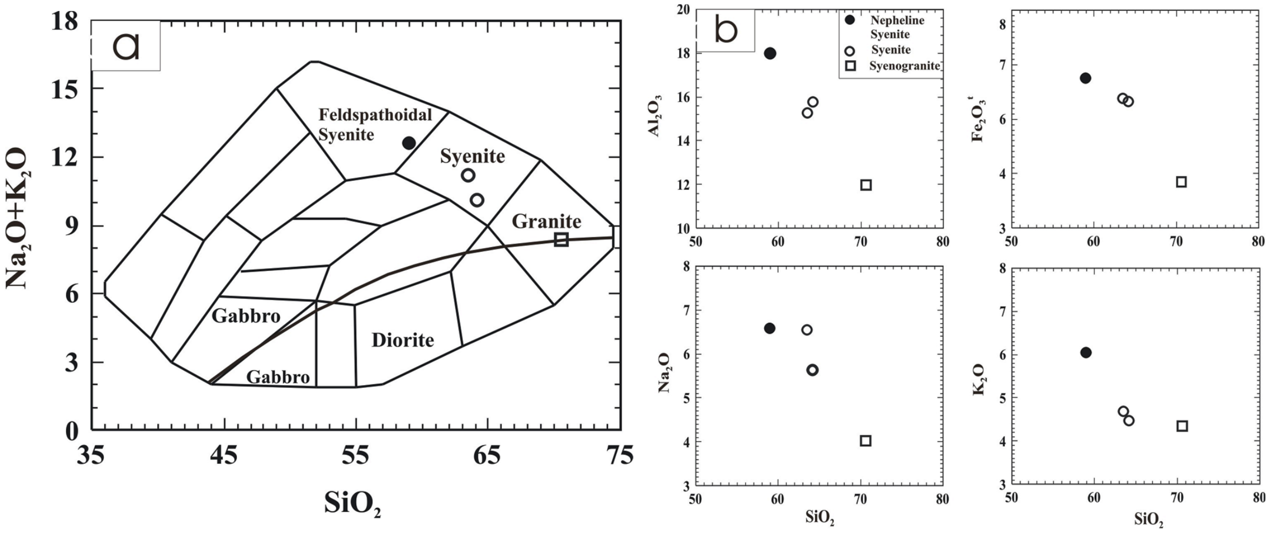

Figure 8. Geochemical classification of Abu Khruq Ring Complex.

sum of quartz, feldspars and feldspathoids the normative constituents) ranging from 84 to 88 and the color index (i.e., the percent, by volume, of mafic minerals) from 10 to 11. They show a wide range of Al_2O_3 (12-18 wt%) and $Fe_2O_3^t$ (4.1-6.4 wt%), while MgO (0.09-0.12 wt%), and CaO (1.0-1.9 wt%) are in a narrow interval. They are characterized by high total alkali content (8.4-12.6 wt%). As shown in the silica variation plots (Figure 8), the silica contents are negatively related to Al_2O_3, $Fe_2O_3^t$, Na_2O and K_2O. The nepheline syenites have the highest Al_2O_3, Na_2O, and K_2O concentrations, due to the predominance of alkali feldspar and feldspathoids.

The quartz syenites contain low and highly variable Sr concentrations, as it is difficult to state any relation having only four results. The Sr commonly cumulates in plagioclase and its low contents in most samples indicate the presence of plagioclase in small proportions.

Mineralurgical treatments

The raw syenites underwent the beneficiation test with different results in terms of grinding behavior and magnetic separation yield (Table 2). The loss of product due to dust (<0.1 mm) formation during grinding is significant, being from 17% to 20%, even though it is within the usual range for feldspathic fluxes. The feed is the complementary fraction, thus ranging from 80% to 83% by weight, which was normalized to 100% for sake of comparison. Although the non-magnetic fraction is similar in all the samples (spanning from 51.5% to 55.4%) the total yield of magnetic treatment is different, resulting best for AS (83%) and decreasing to 76% (QS) and 69% (NS). Such a clearly distinct behavior depends on mineralogical composition and textural issues that affect the mineral liberation and magnetic separation efficiency, particularly the degree by which pyroxene, amphibole and biotite may be included into feldspar crystals. From

Table 2. Yield of beneficiation treatments of syenites.

Beneficiation steps		AS	QS	NS
De-dusting (removal of fraction <0.1 mm) after grinding (wt.%)		20.5	20.4	17.0
Magnetic separation yield (% wt)	Starting amount after de-dusting	100.0	100.0	100.0
	Non-magnetic fraction (Test 1A)	52.9	55.4	51.5
	Intermediate fraction (Test 1B)	30.2	21.1	17.5
	Non-magnetic + Intermediate fractions (Test 1A+1B)	83.1	76.5	69.0
	Magnetic Reject	16.9	23.5	31.0
	Total beneficiation yield (considering de-dusting loss)	66.1	60.9	57.3

the petrographic study, the incorporation of fine-grained aegirine and biotite is more common in nepheline syenite than in alkalisyenite or quartz-syenite, which can explain the results of magnetic separation. Once the de-dusting loss is considered, the total beneficiation yield turns to 66% (AS) down to 57% (NS).

The chemical composition of raw and beneficiated syenites is summarized in Table 3. In particular, it is possible to lower the iron oxide content from 3.7% to 0.46% (QS), from 4.8% to 0.52% (NS) and from 5.1% to 0.6% (AS) by a single magnetic separation treatment.

These results are in line with previous studies on Abu Khruq syenoids (Ibrahim et al., 2002; Abouzeid and Negm, 2014) and on the syenites of another Egyptian ring complex, El-Kahfa (Negm et al., 2000). Plotting all these data together, a non-linear relationship between yield and selectivity of magnetic separation stands out: the lower the iron amount, the lower the yield (Figure 9). This fact is probably linked to similar textural features and mineral liberation of syenoids, where a part of mafic minerals occur as small inclusions into the feldspars. Our data substantially fit those obtained in previous trials, even though with a lower yield when compared to the laboratory tests of Ibrahim et al. (2002) for an amount of chromophore oxides in the 0.4-0.6% range. Our simulation of the industrial magnetic treatment suggests

Table 3. Chemical composition (%wt) of beneficiated syenites.

	process	TEST 0	TEST 1A	TEST 1B	TEST 1A+B
	particle size	raw	0.8-0.1 mm	0.8-0.1 mm	0.8-0.1 mm
	sample	input sample	non-magnetic fraction	intermediate fraction	intermediate+ non-magnetic
ALKALI SYENITE	Al_2O_3	17.70	19.40	20.50	19.80
	TiO_2	0.42	0.04	0.08	0.05
	Fe_2O_3	5.10	0.60	1.42	0.90
	MgO	0.23	0.10	0.15	0.12
	CaO	1.28	0.33	0.75	0.48
	Na_2O	6.75	7.19	6.95	7.10
	K_2O	5.40	6.28	5.61	6.04
	L.o.I.	2.60	1.30	1.80	1.50
	Total yield	100.00	42.10	24.00	66.10
QUARTZ SYENITE	Al_2O_3	20.10	20.90	23.90	21.70
	TiO_2	0.19	0.01	0.02	0.01
	Fe_2O_3	3.70	0.46	0.77	0.55
	MgO	0.16	0.11	0.10	0.11
	CaO	0.79	0.21	0.28	0.23
	Na_2O	9.45	8.73	11.40	9.47
	K_2O	5.29	6.45	4.67	5.96
	L.o.I.	2.90	1.40	1.60	1.50
	Total yield	100.00	44.10	16.80	60.90
NEPHELINE SYENITE	Al_2O_3	17.50	19.60	20.50	19.80
	TiO_2	0.46	0.04	0.07	0.05
	Fe_2O_3	4.80	0.52	1.04	0.65
	MgO	0.21	0.10	0.13	0.11
	CaO	1.27	0.30	0.57	0.37
	Na_2O	7.22	7.72	8.19	7.84
	K_2O	5.34	6.05	5.63	5.94
	L.o.I.	2.30	1.30	1.60	1.40
	Total yield	100.00	42.70	14.60	57.30

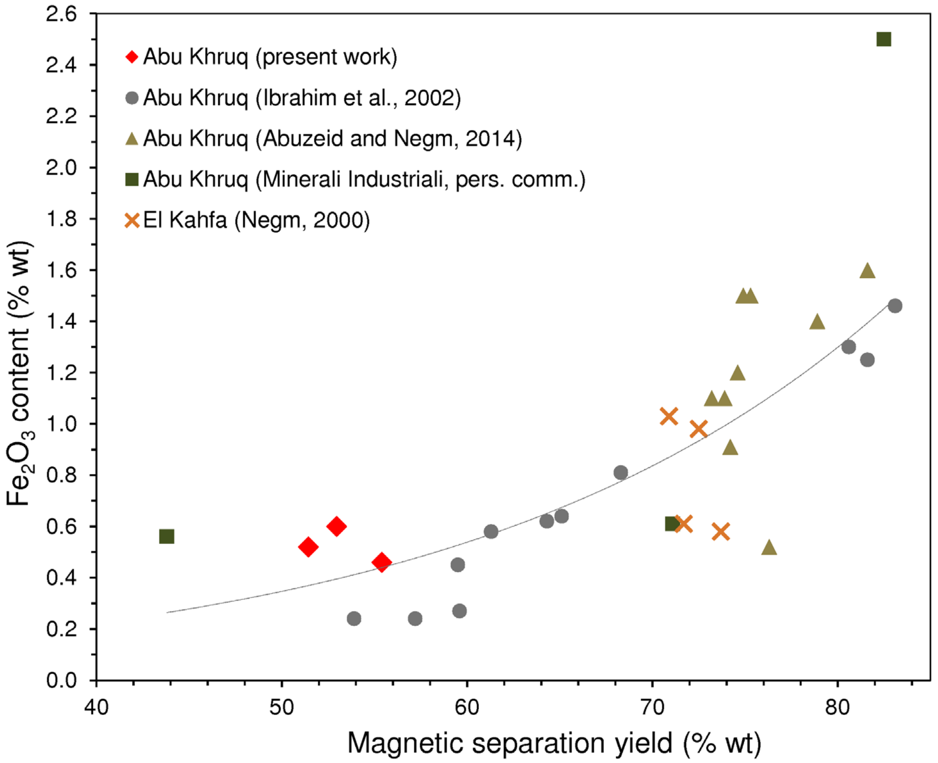

Figure 9. Magnetic separation yield, i.e. percent of non-magnetic fractions, versus concentration of iron oxide for Abu Khruq and El-Kahfa syenites.

that, in order to get iron oxide below 0.3%, the yield will be lower than 50%. This is the indication of lab-scale magnetic treatments and the development of an optimized grinding and sieving scheme (possibly integrated by further beneficiation techniques) is needed to obtain a lower chromophore oxide content.

The behavior during beneficiation of Abu Khruq syenites can be compared to that of nepheline syenites in the literature. The amount of chromophore oxides is contrasted with the equivalent content of feldspars, as defined in Figure 10. Values can overpass 100% because of the occurrence of feldspathoids, which have higher alkali contents with respect to feldspars. The link between the raw mineral to the final product indicates the beneficiation strategy, which can be mainly aimed at removing the mafic minerals and minimizing the loss of alkalis (vertical paths) or addressed to a simultaneous reduction of Fe_2O_3+TiO_2 and enrichment of feldspars and feldspathoids (tracks inclined to right). The lowest content of chromophore oxides (joined to an alkali enrichment) are obtained in deposits under exploitation, like the well-known Ontario and North Cape nepheline syenites. Significantly, the best results are achieved for the lower amounts of Fe_2O_3+TiO_2 in the raw syenites (Figure 10).

The Abu Khruq syenites exhibit distinct beneficiation paths for AS and QS on one side and for NS on the other side (Figure 10). The former show the expected trend with a simultaneous lowering of chromophore oxides and a gain in alkalis. However, the Fd_{eq} values are lower than in other deposits, because of the absence of nepheline in the alkalisyenites and quartz-syenites from Abu Khruq. In contrast, the NS sample suffers some alkali loss together with the removal of mafic minerals, so resulting in a path inclined to the left. Such a behavior is likely due to fine-grained pyroxene and biotite, intimately mixed with feldspars and nepheline, whose separation can occur only together with some felsic minerals attached. However, the Abu Khruq nepheline syenite beneficiated by Ibrahim et al. (2002) behaved in a much better way, achieving a significantly increased Fd_{eq} value, even though with a Fe_2O_3+TiO_2 sum comparable to our results. This circumstance suggests that the textural and mineralogical features of Abu Khruq syenites leave room to improve the yield of beneficiation treatments. At the same time, it implies that getting below 0.3% of chromophore oxides is likely not possible by using a simple mineralurgical processing (grinding, sieving, magnetic separation) on the dry basis that is the only reasonably implementable in the desert.

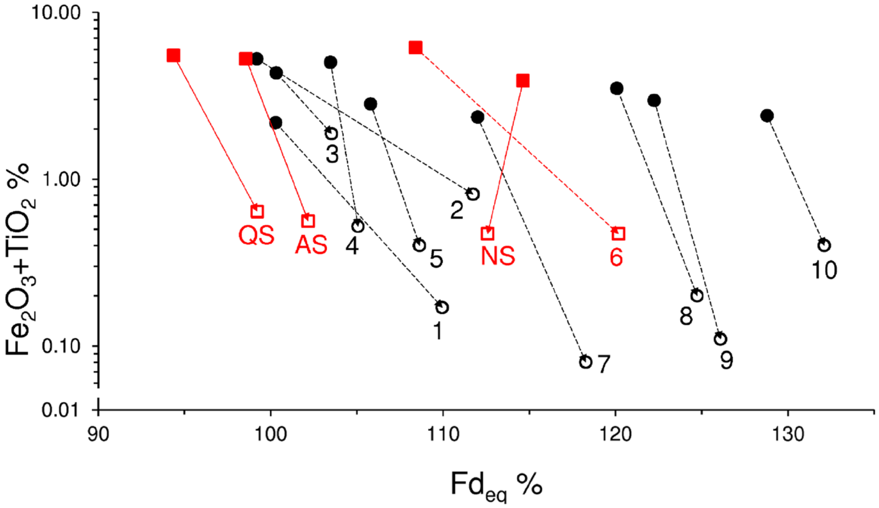

Figure 10. Beneficiation paths of nepheline syenites: equivalent feldspar content (Fd_{eq}) versus chromophore oxides amount (Fe_2O_3+TiO_2). Each path connects the raw mineral (full symbol) to the final product (empty symbol). Samples under investigation (AS, NS, QS) are compared with literature data about the following deposits: 1) Razgah, Iran (Jorjani and Amirhosseini, 2007). 2) Wind Mountain, New Mexico, USA (McLemore, 2006). 3) Lavrinha, São Paulo, Brazil (company data). 4) Bayindir, Kirşehir, Turkey (Otlu et al., 1998). 5) Zandrivierspoort, South Africa (Pantshi and Theart, 2008). 6) Abu Khruq, Eastern Desert, Egypt (Abdallah, 2006; Ibrahim et al., 2002). 7) Blue Mountain, Ontario, Canada (Payne, 1968; Minnes, 1983). 8) Canaan, Rio de Janeiro, Brazil (McLemore, 2006). 9) Stjernøy, North Cape, Norway (Geis, 1979; Minnes, 1983). 10) Cantagalo, Rio de Janeiro, Brazil (Riella et al., 2002; Coelho, 2009). Fd_{eq} is the percentage of feldspars corresponding to the Na, K and Ca oxides, $Fd_{eq}=(Or_{eq}+Ab_{eq}+An_{eq})$, calculated as: $Or_{eq}=\%K_2O/0.1692$; $Abeq=\%Na_2O/0.1182$; $An_{eq}=\%CaO/0.2016$, being 16.92%, 11.82% and 20.16% the weight percentages of K_2O, Na_2O and CaO, respectively, in the nominal orthoclase, albite and anorthite.

Technological behavior

Fusibility of ceramic fluxes is affected by the amount and type of feldspars and feldspathoids, along with the occurrence of mafic minerals and other components, like quartz, muscovite, etc. It must be considered that feldspars do not behave during heating at ambient pressure as expected by their melting mechanism. In fact, both plagioclase and K-feldspar melt congruently at temperatures similar for sodic and potassic terms (Raith et al., 2016). For these reasons, it is common practice to test fusibility by hot-stage microscopy (Dondi et al., 2001) and plot results in a fusibility chart (Figure 11). From this standpoint, the differences in melting behavior of ceramic fluxes depend to a good extent on the amount of refractory or fusible phases associated to feldspars. The former (essentially quartz) worsen the fusibility: granite fluxes and feldspathic sands, respectively rich and very rich in quartz, exhibit usually a low to very low fusibility. On the other hand, the most effective among the fusible phases are the mafic minerals, which lower the temperatures of melting and particularly of softening. That is the reason why raw syenites are more fusible than beneficiated ones, being classified with a high to extremely high fusibility (Figure 11). Beneficiated samples, anyway, exhibit a high fusibility, which is similar to the most important fluxes on the market, i.e. sodic feldspars.

CONCLUSIONS

Large resources of feldspathic fluxes are available as different kinds of syenitic rocks in the ring complexes of the Egyptian Eastern Desert. The most promising appears to be the Abu Khruq ring complex from various points of views. Petrographic, mineralogical and geochemical examinations of the syenitic rocks from this locality show that alkaline rocks occur, ranging in composition from quartz syenite, to alkali syenite to nepheline syenite. All these rock types contain alkali feldspar as a main constituent together with minor amounts of various ferromagnesian minerals (alkali pyroxene, amphibole and biotite). Besides, quartz occurs as interstitial material or micrographic intergrowths with alkali feldspar in quartz syenite, while large nepheline crystals are present in the nepheline syenite. The association of both silica-undersaturated and silica-oversaturated rock compositions has been described in the continental settings (Fitton and Dunlop, 1985). This could be ascribed to the contamination of silica-undersaturated magma by the pre-existing silica-rich crustal rocks. This explanation is more convincing

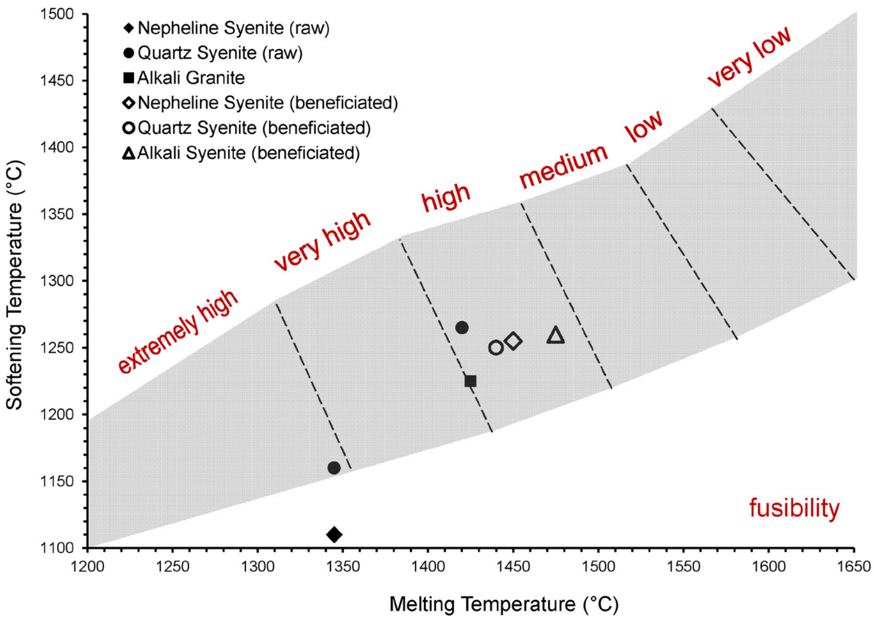

Figure 11. Fusibility chart (Dondi et al., 2001) of the Abu Khruq rocks.

for the Abu Khruq ring complex, as it is found in contact with silica enriched granitic rocks.

The Abu Khruq syenites (excluding granites) show silica contents ranging from 59 to 64 wt%, a rather wide range of Al_2O_3 (15-20 wt%) and $Fe_2O_3^t$ (3.7-6.4 wt%), while MgO and CaO fluctuate in narrow intervals (0.09-0.23 and 0.8-1.9 wt%, respectively). The total alkali content is rather high (10.1-14.7 wt%) aiming at ceramic applications. The nepheline syenite has the highest Al_2O_3, Na_2O, and K_2O concentrations as well as a distinct abundance of alkali feldspar and feldspathoid.

Beneficiation trials demonstrate it is feasible to get fluxes with suitable technological behavior for the ceramic tile production. Additional mineralurgical treatment must be planned in order to obtain high quality fluxes with low amount of chromophore oxides. Beneficiated syenites will be tested in the manufacturing of ceramic tiles in an incoming paper.

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