Emplacement of granites in a transitional regime from volcanic arcs to post-collisional: an evidence from the Gabal El-Zeit block, Gulf of Suez region, Egypt

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Abstract

Gabal El-Zeit block at the western coast of the Gulf of Suez region in Egypt consists of two varieties of Precambrian granites, namely monzogranite and a peripheral zone of alkali granite. Both granitic varieties display moderate (60.1-68.5 wt%) and high silica (73.36-76.16 wt%) contents with high Na₂O+K₂O (7.21-8.61 wt%), respectively. The investigated monzogranite is calc-alkaline metaluminous whereas the alkali granite is peralkaline. The primordial mantle normalized plots of the Gabal El-Zeit granites indicate that they are characterized by Ba, Sr, P and Ti negative anomalies and a moderate to weak negative Nb anomaly. These geochemical features are similar to those expected for magmas extracted during post-collisional high-K granites from the late Neoproterozoic Arabian Nubian Shield. Tectonic discrimination diagrams show that the monzogranite is formed in a volcanic-arc setting, whereas the alkali granites is a characteristic of post-collisional tectonics. The geochemical characteristics of the monzogranite are consistent with magmatism derived by partial melting of a slightly LILE-enriched amphibole-bearing (i.e. hydrated) mafic source. However, the studied alkali granite perhaps was originated by fractional crystallization process from the monzogranite due to the relative depletion in the contents of Al_2O_3 , MgO, CaO, Ba, and Sr with increasing silica which is also strengthened by other geochemical relationships. The collective field investigations and available geochemical data are consistent with a late- to post-collisional stage magmatism formed at the transition from volcanic-arc to withinplate tectonics. The monzogranite is ilmenite- and magnetite-bearing, either homogenous or as exsolution, whereas alkali granites contains homogeneous magnetite only. Therefore, the Fe-Ti content is a very useful tool to distinguish the two granitic varieties.

Keywords: Gabal El-Zeit, Monzogranite; Alkali Granite; Transition; Volcanic-Arc; Within-Plate.

1- Introduction

Granitic rocks are formed in a widespread range of tectonic settings that can be found in both orogenic and non-orogenic belts (Bonin, 1990; 1997). This is applied to the Precambrian Arabian-Nubian Shield (ANS) in northeastern Africa and the western Arabian Peninsula. There, early stages (pre-collision) are characterized by calc-alkaline granitoids or the older granitoids I that were formed ~870-650 1994) followed Ma (Stern, by slightly metamorphosed deformed granodiorite (older granitoids II) at the waning stage of the Pan-African orogeny that ended ~620-615 Ma (Stern and Hedge, 1985; Greiling et al., 1994). Postorogenic activities that lasted until ~550 Ma produced younger granites (including high-level A-type granites). The Gabal El-Zeit granites (GZG) represent an isolated fault-controlled block in the northern portion of the ANS in the Eastern Desert of Egypt, particularly in the Gulf of Suez region. The ANS is one of the largest tracts of juvenile continental crust (Pattchett and chase, 2002) that was formed in the late Proterozoic (Neoproterozoic) time as indicated by U-Pb zircon ages, Sr-Nd-Pb and lead isotopic data (Stern, 2002; Stoeser and Frost, 2006; Stern *et al.*, 2010; Ali *et al.*, 2009 and 2010). The ANS juvenile crust was formed as a result of a pre-collisional (island-arc) stage (~820-700 Ma), a syn-collisional stage (670-630 Ma) and a post-collisional stage (630-580 Ma) as indicated by Stern and Hedge (1985); Stern (1994); Abdel-Rahman (1995); Moghazi *et al.* (1998); Jarrar (2003); Farahat *et al.* (2007 and 2011); Mohamed and El-Sayed (2008); Mousa *et al.* (2008). The collisional stage terminated at ~ 615-600 Ma and subsequence structural collapse occurred only within the 595-575 Ma time span and was followed by transpressional tectonism along major shear zones (Greiling *et al.*, 1994; Beyth *et al.*, 1994).



Figure 1) Geological map of the Gabal El-Zeit area. Modified after Salman et al. (1988) and Younes et al (1998).

It is generally assumed that the alkaline granites are formed in a non-orogenic within-plate tectonic environment. However, several alkaline associations, are not confined to non-orogenic, post-date orogenic episodes by short interval of time, such as the Pan African ANS (Harris, 1985 and Sylvester, 1989). Some of these associations have been considered as orogenic, for example the Tertiary alkaline granite/rhyolite suite of Trans Pecos in Texas, USA (Barker, 1987).

Much debate exists on the syn- vs. late-orogenic geotectonic setting of the calc-alkaline

granitoids on one hand, and post-orogenic vs. anorogenic (i.e. continental rift) tectonic setting for the younger alkali granites in the other hand. Therefore, the present work focuses on the petrographical and geochemical features of the GZG to elucidate their petrogenetic evolution from late- to post-orogenic setting. This can help a lot to understand such a type of geotectonic transition in similar regimes all over the world. The present work also uses the tool of opaque mineralogy to distinguish between granaitic varieties from different tectonic settings that can be applied in the future for similar rocks elsewhere.

2- Geological setting

The Gabal El-Zeit area in the Gulf of Suez region lies between latitudes 27° 50'-28° 02' N and longitudes $33^{\circ} 25'-33^{\circ} 35'$ E, covering an area of about 25 km² (Fig. 1). The area is essentially represented by an igneous fault block that is exposed as a separate segment from the Eastern Desert basement rocks by the Oligocene-Miocene tectonics that led to the opening of the Red Sea, and subsequently the Gulf of Suez. Figure 1 shows that the area is occupied by a granitic core surrounded by Phanerozoic sedimentary strata that dip mostly due SW. The granitic core stands as a series of irregular crenulated peaks separated by a saddle of evaporite deposits which divides the GZG into the main Gabal El-Zeit range to the north and the Little Zeit range to the south outside Figure 1. From the east, the high granitic ranges end abruptly on a relatively flat, narrow shore that is composed of coral reefs of Miocene age. Particularly to the west, the granitic rocks disappear under a series of thick pile of much younger sedimentary rocks that crop out as parallel ridges of decreasing heights.

Structurally, the Gabal El-Zeit area records primary and secondary structures. The secondary structures are mainly affect the granitic rocks and are represented by joints that trend in the NW-SE, NE-SW and N-S directions, while faults are of normal and strickslip types trending ENE-WSW, E-W and N-S. Late- to post-orogenic trachytic and doleritic dykes intrude the GZG and follow the faults directions in the area. Previous geological and geochemical studies of the GZG were given by Schürmann (1926); El-Ramly (1972); Ghanem et al., 1973; Hashad (1980); Nafie (1981); El-Shatoury et al. (1984); Ragab (1995) and Nabil (1996) and most of these studies shed more light on petrochemical characteristics rather than on tectonic evolution and magma type. The very early work of Schürmann (1926) divided the Gabal El-Zeit granites into alkali granites and lime-alkali granites which are traversed by mafic and felsic dykes. Hashad (1980) gave an isotopic age of 592 Ma for the GZG block. El-Shatoury et al. (1984) mentioned that the riebeckite-bearing granite (alkali granite) is not fully discriminated from the younger or postorogenic granites because this riebeckite-granite occurs in the form of small bosses or dyke-like bodies, mostly controlled by deep-seated fractures (Younes et al., 1998). According to some field relationships, Nabil (1996) divided the GZG block from oldest to youngest into biotite-hornblende-quartz monzonite, hornblende-biotite monzonite and syenogranite.

3- Petrography

Based on the petrographic examination of the thin-sections, the rocks in the study area can be classified into monzogranite and alkali granites. The following, each rock variety is described systematically in order to characterize their mineralogy and textures that would help in petrogenesis alongside with the available geochemical data.

3.1- Monzogranite

The monozogranite is mainly composed of plagioclase, quartz, biotite, hornblende and Kfeldspar. Accessory minerals (apatite, zircon and titanite together with Fe-Ti oxides) are also encountered. Two generations of plagioclase crystals are identified, namely fine stout prisms

(Pl I) that are enclosed in larger euhedral to subhedral crystals (Pl II) (Fig. 2a).



Figure 2) Microphotographs of monzogranite. PPL: plane-polarized light; C.N.: crossed-nicols; R.L: reflected light (plane-polarized). a) Early plagioclase (PL I) inside younger zoned plagioclase (II) with core alteration, C.N. b) Common microcline perthite crystal, C.N. c) Replacement of biotite (Bt) by chlorite (Chl) reducing secondary magnetite needles (Mgt II). Notice the presence of primary coarse magnetite (Mgt I), P.P.L. d) Hemoilmenite intergrowth (Hem-Ilm) with continuous titanite reaction rim (Tnt) and another alteration to a mixture of rutile and hematite (Rt-Hem), R.L. e) Homogeneous ilmenite (Ilm) with narrow discontinuous titanite reaction rim (Tnt) and fresh pyrite inclusion (Py), R.L. f) Homogeneous

titanomagneitite (Mgt) with alteration to titanite (Tnt) along the cubic cleavage, R.L. g)Homogeneous titanomagnetite (Mgt) showing broad titanite reaction rim (Tnt), R.L. h) Recrystallization of homogeneous magnetite (Mgt) and development of triple junctions due to annealing, R.L.

In most cases, Pl II shows distinct zoning and lamellar twining and some crystals are highly altered to kaolinite and sericite especially at the core. Some few perthitized K-feldspars are encountered as flame-perthite crystals (Fig. 2b). Fresh subhedral flakes of biotite are highly pleochroic and show common alteration to dense masses of chlorite along cleavage and peripheries (Fig. 2c). This figure witnesses that chloritization of biotite results in fine magnetite streaks which are different from much coarser magmatic nearly equant magnetite. Also, biotite contains inclusions of zircon, apatite and surrounded by magnetite, titanite and epidote crystals when altered to chlorite. Hornblende is represented by euhedral to subhedral crystals illustrating simple and lamellar twining. Quartz crystals fill the interstices between other

minerals. Fe-Ti oxides are represented by either homogeneous ilmenite and relatively lesser amount of magnetite (with ratio of ~3:1), or hemoilmenite intergrowth that results from exsolution (Fig. 2d). Homogeneous ilmenite shows titanite reaction rim with variable intensity and occasionally has fresh pyrite inclusions (Fig. 2e). Homogenous magnetite alters to thin titanite along the cubic cleavage indicating a Ti-bearing variety (Fig. 2f). Titanite forms at the expense of Ti-bearing magnetite occurs as a broad continuous reaction rim (Fig. 2g). There are strong indication of Fe-Ti recrystallization as indicated by the thermal annealing texture and formation of triplejunction contacts, for example in magnetite (Fig. 2h).



Fig. 3: Microphotographs of alkali granite. PPL: plane-polarized light; C.N.: crossed-nicols; R.L: reflected light (plane-polarized. a) Corrosion of plagioclase (Pl) by growing microcline (Mc) and quartz (Qtz), C.N. b) Plagiocalse core of graphic intergrowth, C.N. c) Graphic intergrowth rimmed by myrmekitic intergrowth, C.N. d) Same caption of Fig. 2c.

3.2- Alkali granite

The alkali granite is mainly composed of Kfeldspar, plagioclase, quartz, biotite and hornblende. Kaolinite, sericite, chlorite and/or epidote are the main alteration products. Zircon, apatite, allanite and Fe-Ti oxides are the main accessories. Plagioclase is the least feldspar as an earlier phase that is highly corroded by growing K-feldspars and quartz (Fig. 3a). In some instances, plagioclase represents а substratum to develop the myrmekitic texture 3b). The K-feldspar phenocrysts (Fig. themselves exhibit perthitic texture (flame and vein type) in most, but common myermkitic and graphic textures are formed as well (Fig. 3c). Fresh plagioclase crystals exhibit zoning and lamellar twining whereas the altered crystals are kaolinized, intensively sericitized and epidotized. Quartz is represented by interstitial crystals and is encountered in the phases that form the myermkitic texture. Biotite flakes are partially or completely altered to chlorite and contain minute zircon crystals. Hornblende and allanite crystals are also encountered. Fe-Ti oxides are magnetite crystals only with complete absence of ilmenite. The amount of magnetite (Mgt I) in the alkali granite is remarkably low (less than 2 %) where total Fe-Ti oxides in monzogranite reach up to 5 % of

the rock volume. Similar to monzogranite, the biotite of alkali granite is chloritized and produced secondary magnetite (Mgt II) (Fig. 3d).

4- Methodology

The samples were chosen systematically to represent the different varieties of granitic rocks. The collected samples were investigated microscopically both in transmitted and reflected light in order to characterize their mineralogy and textures. The chemical analyses were carried out at the Polish Geological Institute of Geology, Warsaw. Both major and trace elements were analyzed using Sequential Spectrometer PW 2400 XRF. Concentrations of major elements were obtained on fused lithium tetraborate discs whereas the loss on ignition (L.O.I) was determined by heating powdered samples for more than 50 minutes at 1000 °C. Samples were prepared for trace-element analysis by making pressed powder pellets. The accuracy and precision of the analytical results are 1-3 % for major elements and 5-10 ppm for trace elements. The concentrations of 12 rareearth elements (La, Ce, Nd, Sm, Eu, Gd, Tb, Dy, Er, Yb and Lu) and Th were determined using a Jobin-Yvon 70 spectrometer.



Figure 4) Harker's diagrams showing variations of some major and trace elements versus SiO_2 . Symbols are Monzogranite: \circ alkali granites: \blacktriangle .

5- Geochemistry

5.1- Major and trace element characteristics

Following the normative classification of Streckeisen (1976), the studied GZG samples are monzogranite and alkali granite. Based on the chemical analyses (Table 1), the samples contain moderate and high silica contents (60.1-68.5 wt% and 73.36-76.16 wt%) with high Na_2O+K_2O (7.21-8.61wt%, respectively). On the Harker's diagrams, the contents of Al₂O₃, Fe₂O₃, TiO₂, MgO and CaO decrease with increasing silica (Fig. 4) and hence the separation of olivine, pyroxene, iron-titanium oxide and plagioclase are the major fractionating phases. Both varieties of granites are characterized by depletion in their Ni and Cr contents from 104 and 19 ppm to 232 and 40 ppm, respectively (Table 1) as a function of olivine separation during the evolution of the alkali granites. Also, the K₂O/Na₂O ratio increases with increasing silica (Table 1).

Hassan and Hashad (1990) provided the Na_2O-K_2O-CaO ternary diagram that has been accepted to discriminate the Egyptian granitic rocks. The investigated monzogranites are comparable to the Egyptian older granitoids, and follows the calc-alkaline trend (Fig. 5a). On

the other hand, the alkali granite samples fall in the field of the Egyptian younger granites (Fig. 5a). According to the Shand's index and the classification diagram of Maniar and Piccoli (1989), the studied mozogranite is mostly metaluminous to slightly peralkaline whereas the alkali granite is peralkaline and peraluminous (Fig. 5b). On the MALI (modified alkali-lime index) vs. SiO₂ diagram of Frost and Frost (2008), the investigated monzogranite falls in the alkali-calcic and calc-alkalic fields (Fig. 5c) whereas the alkali granite samples fall in the calc-alkalic field (Fig. 5c). The GZG samples plot in the high-K field in the diagram of Pecerillo and Taylor (1976) (Fig. 5d). The alkalinity of the GZG is well illustrated by the agpatic index or the [AI = (Na+K)/AI] vs. SiO₂ diagram (Fig. 5e). The monzogranite samples straddle the calc-alkaline metaluminous domain whereas the alkali granite samples mainly fall in the peralkaline domain. Variations of trace element enrichment/depletion of the GZG are demonstrated on the primordial mantle normalized diagram (Figs. 6a and b). The monzogranite is characterized by Ba, Sr, P and Ti negative anomalies and a moderate negative Nb anomaly. These geochemical signatures are for the identical post-collisional high-K granitoids from late-Neoproterozoic of the ANS, the East African Orogeny and late Pan-African granitoids in general (e.g. Beyth *et al.*, 1994; Hassanen, 1997; Liegeois *et al.*, 1998; Küster and Harms, 1999). The alkali granite shows closely similar trace element patterns with well developed Ba, Sr, P and Ti negative anomalies as feldspar and Fe-Ti oxides are major fractionating phases. The studied granitic rocks display weak and variable Nb anomaly in some samples.

5.2- REEs abundances

The GZG have moderate REE abundances $(\sum REE = 140 - 60 \text{ ppm}; \text{ Table 1, Fig. 6c, d})$, and characreized by chondritic normalized patterns with moderate slopes from La to Yb [(La/Yb)_N = 18-11.33 and 4.16-4.0] for the monzogranite and the alkali granite, respectively. The more or less flat HREE patterns rule out the involvement of garnet in the petrogenesis of these granitoids. Owing to the plagioclase fractionation (Eu/Eu^{*} = 0.418-0.409), there is a distinct Eu anomaly in

the case of alkali granite (Fig. 6d). Nardi (1987) suggested that the post-orogenic granites have generally lower HREE contents than typical anorogenic granites but the shapes of the REE patterns of the post-orogenic alkaline granites do not differ significantly from those of anorogenic alkaline granites such as those from Nigeria (Bowden and Kinnaird, 1984).

Sylvester (1989) used major elements to discriminate between calc-alkaline and peraluminous granites, alkali granites and highly fractionated calc-alkaline granites. The monzogranite samples fall in the calc-alkaline and peraluminous field while the alkali granite is confined to the alkaline field (Fig. 7a). In a series of diagrams designed by Whalen et al. (1987) to discriminate the A-type granites (Figs. 7b,c,d and e), the investigated monzogranite samples plot in the field of I-, S- and M-types granitoids whereas the alkali granite samples plot in the A-type field in addition to the I-, S-, and M-types fields.



Figure 5) Geochemical classification and magma type diagrams for the Gabal El-Zeit granites. a) Na_2O - K_2O -CaO ternary diagram to discriminate the Egyptian granitic rocks. b) Shand's index classification diagram after Maniar and Piccoli (1989). c) Modified alkali-lime index vs. SiO2 diagram after Frost and Frost (2008). d) K_2O -SiO₂ diagram after Peccerillo and Taylor (1976). e) Agpatic index vs. SiO₂ diagram.

The Rb, Nb and Y among some other trace elements have been used to discriminate between different tectonic settings of granitic rocks (Pearce *et al.*, 1984). The investigated monzogranite samples plot at the boundary between volcanic-arc and the syn-collision fields (Fig. 7f) whereas the alkali granite samples mostly fall in the post-collision field (Fig. 7f). Using the $SiO_2-Al_2O_3$ diagram of Maniar and Piccoli (1989), the monzogranite samples fall in the IAG field while the alkali granite samples fall in the post-collision field (Fig. 7g).



Figure 6) Trace and rare earth elements diagrams for the Gabal El-Zeit granites. Symbols as in Fig. 4. a and b) Primordial-mantle normalized diagrams for the investigated monzogranite and alkali granite. c and d) Chondrite normalized patterns.

The alkali granite samples mostly fall in the overlapping fields between within-plate and volcanic-arc fields on the SiO₂-Nb diagram of Pearce and Gale (1977) (Fig. 7h). Collectively, the forgoing diagrams characterize the tectonic setting of the GZG represents as transition between volcanic-arc and within-plate tectonic environment. Nevertheless, some samples of the alkali granite of this suite fall within the field assigned to the A-type granites of Whalen *et al.*

(1987) (Figs. 7b,c,d,e) and post-collisional granites field of Pearce (1996) (Fig. 7f and g). The investigated post-collisional samples from the GZG are similar to the alkali granites from other parts of NE Africa, and they are similar to felsic members of the contemporaneous Dokhan volcanics that are believed to form in a post-collisional setting (Mohamed *et al.*, 2000; Moghazi, 2003).



Figure 7) Tectonic discrimination diagrams for the Gabal El-Zeit granites. Symbols as in Fig. 4. a) Discrimination between calc-alkaline, peraluminous, alkali, and highly fractionated calc-alkaline granites after Sylvester (1989). b, c, d and e) Discrimination diagrams of A-type granites after Whalen et al. (1987). f) Rb-Y-Nb diagram to discriminate Gabal el Zeit granitoids after Pearce et al. (1984). g) Al2O3 vs. SiO2 diagram to discriminate Gabal el Zeit granitoids after Maniar and Piccoli (1989). h) Nb vs. SiO2 diagram of Pearce and Gale (1977) to illustrates the volcanic-arc and within-plate settings.

6- Discussion

6.1- Generalities and similarities with other Egyptian granites

It is widely accepted that during the closing stage of the Pan-African Orogeny, the calcalkaline magmatism was replaced by a postorogenic alkaline magmatism (Bentor, 1985; Beyth et al., 1994). Two post-orogenic associations are distinguished in many alkaline provenances in Africa (Bowden, 1985). The early association is related to the terminal phases of major orogenies (i.e. not strictly anorogenic), while the later association is related to progressive uplift, long-term doming and rifting (i.e. anorogenic). Major and trace element compositions of the GZG indicate that they are late-to post-orogenic as their bulk geochemistry is in harmony with the aspects of Loiselle and Wones (1979) and Beyth et al. (1994). Based on the field relationships and geochemical data, the studied monzogranites perhaps is related to an arc-stage, whereas the alkali granite is related to the early association of the post-collisional stage.

The dyke swarms and Dokhan volcanics are part of extension-related tectonomagmatic event, which had affected the Eastern Desert of Egypt during the final stages of the Neoproterozoic crustal evolution (Stern et al., 1984; Stern and Voegeli, 1987). The rocks of the Dokhan volcanics (basalts to rhyolites) suggested to be evolved by fractional crystallization (Stern and Gottfried, 1986; Abdel-Rahman, 1996). There is much geochemical evidence in accord with the formation of A-type granites by fractional crystallization of the parental magma of the Dokhan volcanics. Such evidence can be follows: summarized as 1) the isotopic composition and the age of the Dokhan volcanics, in addition to the A-type granites are indistinguishable (Stern and Hedge, 1985), 2) the chemical compositions of the highly fractionated members of the Dokhan volcanics share all the compositional characteristics of major and trace elements with the A-type granites, and 3) similarity the in tectonic setting of the two rock types (Stern *et al.*, 1984). The petrogenesis of granitic rocks in general and the post-orogenic and anorogenic (or A-type) alkaline granites in particular is a matter of debate for decades. The following sections present possible petrogenetic schemes of the GZG in correlation with similar rocks in the ANS in Egypt and adjacent areas.

6.2- Petrogenesis of the monzogranite

Plutonic rocks in orogenic belts are controlled by magmatic processes related to subduction (Brown et al., 1984) and are generated from a variety of protoliths by several processes. I-type granites are derived either by fractional crystallization of mantle-derived mafic magmas or by partial melting of lower crustal and/or upper mantle rocks (Guffanti et al., 1996; Johanson et al., 1997). Other processes such as magma mixing and crustal contamination could be also involved in their generation. The investigated monzogranite of the GZG block display high Ba, Sr, Rb, K and Th which is similar to the granitoids that form during the collisional stage of the ANS (Table 1). During this stage in the ANS, the arc-arc collision was still active where continuous addition of mantlederived materials and the collision between E and W Gondwanaland (Stern, 1994) that led to crustal thickening. The composition of the crust at this stage is predominantly calc-alkaline volcanic and plutonic rocks with an average amphibolitic composition. There are some evidence the against that investigated monzogranite was produced by extensive fractional crystallization of mantle-derive mafic magma (e.g. island-arc metagabbros). These evidences are: 1) the granitic melts derived from the extreme fractional crystallization of a gabbroic magma are characterized by strong enrichment in many HFSE (Turner et al., 1992), which is not the case for the investigated monzogranite (Fig. 6), 2) if the gabbro-diorite complex in the northern ANS and the K/Rb

investigated monzogranites are related to each other being formed by fractional crystallization processes, a collinear trend should be exist which is not the case (Fig. 4), 3) in the Eastern Desert of Egypt, large volumes of granite occur with only minor metagabbro-diorite rocks. The linear variation trends displayed by most major and trace elements of the investigated monzogranite samples (Fig. 4) can be ascribed to a variety of processes such as magma mixing and fractional crystallization. The presence of mafic enclaves in the monzogranite favours an evolution through mixing processes in terms of magma mingling. The relation between K/Rb and Sr with Rb (Fig. 8a, b) suggests no fractional crystallization processes between the investigated monozogranite and the metagabbro-diorite.



Figure 8) a and b) Rb versus K/Rb and Sr. The compositional range of the metagabbro-diorite complexes from the Egyptian basement is defined by El-Sheshtawi et al. (1995), Abu El Ela (1997) and El Sayed (2003). c) Discrimination diagrams for partial melts from various sources (Altherr et al. (2000). Symbols as in Fig. 4.

Accordingly, the negative correlation of CaO, MgO, Sr, Ba, P, Fe_2O_3 and TiO_2 with the silica content (Fig. 4) for the monzogranite samples are consistent with fractionation of plagioclase, K-feldspar, apatite, Fe-Ti oxides and/or titanite. As a consequence, although the generation of

the monzogranite from extensive fractional crystallization of a mantle-derived mafic magma is excluded, its evolution through fractional crystallization should not be totally discarded. In case that the investigated monzogranite is not related to the gabbro-diorite suite that form by

extensive fractional crystallization, the generation by partial melting of lower crustal the most plausible rocks seems to be mechanism. Many workers agree that the great volume of subduction-related granitoids are likely to be a fusion product of basaltic gabbroic magmas that pond and crystallize at the base of the crust (Beard and Lofgren, 1991; Tepper et al., 1993).Compositional differences of granitic melts produced by partial melting of various source rocks under variable melting conditions can be distinguished in the term of molar $CaO/(MgO=FeO^{t})$

vs.Al₂O₃/(MgO+FeO^t)(Altherr *et al.*, 2000). The major element ratios of the investigated monzogranite indicate that they are derived by partial melting of metabasic to tonalitic sources (Fig. 8c). Furthermore, the negative Nb and Ti anomalies can be explained by the presence of hornblende in the source. It is thus plausible that the monzogranite is derived by partial melting of a slightly LILE-enriched amphibole-bearing (i.e. hydrated) mafic source.

6.3- Petrogenesis of the alkali granites

Geochemical parameters indicate that the investigated alkali granites, like other postorogenic alkaline granites, are transitional between anorogenic alkaline granites and orogenic calc-alkaline granites of a mature magmatic-arc (Loiselle and Wones, 1979; Bonin, 2007). There are many models which can explain the genesis of A-type granites including: 1) differentiation (i.e. partial melting or fractional crystallization) of basaltic magmas (Loiselle and Wones 1979; Frost and Frost, 1997; Bonin 2007), 2) melting of deep crustal sources previously depleted in H₂O (Loiselle and Wones, 1979; Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987); 3) partial melting of charnockitic lower crust (Landenberg and Collins, 1996); 4) low degree of partial melting of I-type granites (King et al., 1997); and 5) dehydration melting of calc-alkaline or amphibole-bearing tonalite (Creaser et al., 1991; Skjerlie and Johnson, 1992). Also, mantle-

derived magmas may also assimilate crustal materials during their ascent or residence time in the crust to produce "mixed" source characteristics (Poitrasson *et al.*, 1995).

There is no evidence of extensive wall-rock assimilation and magma mixing for the investigated alkali granite for the following reasons. There are very few country rock as enclaves, the lack of any significance interaction between the monzogranite and the alkali granite rocks, the quite homogeneous petrographic and geochemical nature of each rock variety and the gradual transition between them, all together do not favour the hypothesis of wall-rock assimilation and magma mixing for their evolution. Generally, the ANS alkaline igneous rocks are considered as the products of either extensive fractional crystallization of mantlederived mafic magmas (e.g. Stern and Gottfried, 1986; Bonin, 2007) or partial melting of various crustal sources (e.g. Clemens et al., 1986; Creaser et al., 1991; King et al., 1997; Abdel-Rahman, 2001; Farahat et al., 2007; Ali et al., 2009). The calc-alkaline intrusions in Egypt were formed in compressional setting due to decompressional melting of mafic lower crust whereas melting and anatexis of crustal rocks resulted in alkaline intrusions (Ghoneim et al., 2015). Generally, calc-alkaline older granitoids in the northern Eastern Desert of Egypt were formed in the arc environment and resulted from partial melting (20-40%) of a hydrated LREEenriched source that was garnet-free but amphibole-bearing (e.g. El-Mahallawi and Ahmed, 2012).

Granitic rocks with A-type geochemical signatures have been interpreted as products of high-temperature partial melting of a granulitic residue from which a granitic melt was previously extracted (e.g. Collins *et al.*, 1982; Clemens *et al.*, 1986). However, the high contents of LILE, especially Th (23-66 ppm; Table 1) of the investigated alkali granite preclude their derivation from a Th-depleted granulitic residue in the lower continental crust.

It was suggested that A-type granites may be better modeled by partial melting of undepleted I-type tonalitic to granodioritic source (Sylvester, 1989; Creaser *et al.*, 1991; Skjerlie and Johnson, 1992). Although the derivation of the investigated alkali granite by partial melting of tonalitic to granodioritic source is geochemically possible, several lines of evidence are consistence with their evolution by extensive fractional crystallization from less differentiated magma (Stern and Gottfried, 1986; turner *et al.*, 1992).



Figure 9) Geochemical variation diagrams indicate that the investigated alkali granites were evolved by extensive fractional crystallization from the less differentiated monzogranite magma. Symbols as in Fig. 4. a) Rb/Sr vs. SiO2 diagram. b) Ba vs. Sr diagram. c and d) CaO/Al2O3 and K/Rb vs. differentiation index and Rb diagrams, respectively. e and f: Rb/Sr vs. Mg and TiO2 diagrams, respectively.

								Z-				
Sample	Z-1	Z-1`	Z-7	Z-6	Z-2	Z-3	Z-2`	3 🗆 🗆	Z-3`	Z-4	Z-5	Z-2''
SiO ₂	60.1	60.83	62.41	62.63	62.9	68.5	73.36	73.5	73.85	69.93	74.86	70.16
TiO ₂	0.81	0.78	0.66	0.66	0.68	0.38	0.11	0.14	0.13	0.13	0.12	0.07
Al ₂ O ₃	15.99	15.23	14.92	14.77	14.6	14.23	12.53	12.94	12.13	11.47	10.79	11.7
Fe ₂ O ₃	6.04	5.75	4.66	4.72	4.88	2.58	0.53	0.92	1.02	0.71	2.6	0.61
MnO	0.124	0.123	0.07	0.073	0.077	0.045	0.012	0.068	0.07	0.01	0.04	0.01
MgO	2.84	2.91	2.93	3.05	3.01	1.25	0.04	0.025	0.26	0.19	0.02	0.17
CaO	2.98	2.68	3.92	3.91	3.77	2.1	0.53	0.35	0.52	0.17	0.17	0.56
Na ₂ O	3.99	3.88	4.01	3.87	3.82	4.29	3.64	3.58	3.99	4.13	4.31	3.56
K ₂ O	3.48	3.72	3.15	3.25	3.22	3.62	4.89	5.13	4.59	4.32	4.31	5.19
P_2O_5	0.242	0.213	0.185	0.177	0.193	0.11	0.018	0.017	0.01	0.017	0.006	0.011
L.O.I	1.91	1.89	0.77	0.71	0.047	0.79	0.45	1.1	0.88	0.91	0.32	0.32
Sum	98.4	98.06	97.81	97.92	97.78	98.01	96.21	98.33	97.65	91.14	97.73	92.03
K ₂ O/Na ₂ O	0.87	0.96	0.79	0.84	0.84	0.84	1.34	1.43	1.15	1.05	1.00	1.46
Na ₂ O+K ₂ O	7.47	7.6	7.16	7.12	7.04	7.91	8.53	8.71	8.58	8.45	8.62	8.75
Ba	778	678	678	675	6.54	781	179	372	231	149	41	76
Со	19	14	13	14	13	< 3	< 3	< 3	< 3	<3	< 3	3
Cr	232	238	154	172		200	143	163	183	117	40	101
Ga	20	18	18	18	20	20	22	18	16	17	32	21
Hf	5	4	0	< 3	7	< 3	5	3	5	4	11	5
Nb	2.8	2.7	2.7	2.9	2.8	2.7	11	5	7	14	44	22
Ni	104	103	74	74	94	80	58	61	76	30	19	27
Rb	104	114	98	99	110	107	228	167	144	171	207	235
Sr	525	590	542	529	507	468	68	69	39	60	9	34
Ta	8	< 3	< 3	< 3	5	< 3	5	5	< 3	<3	6	<3
Th	46	43	37	41	43	48	63	38	53	23	66 -	49
U	6	8	5	11	6	8	14	< 3	9	6	5	24
V	118	132	100	103	112	43	8	< 3	6	<5	< 3	7
Y 7	14	12	15	13	11	12	10	110	14	18	23	22
Zr	194	238	130	150	129	91	19	118	158	130	517	81 12
	23 51				22 41	21		50		12		15
Ce Dm	51 7				41 6	20 5		28 9		23		20
rr Na	7				0	5 17		0 27		2.0		4 11
Nu Sm	27 1				21	1/		27 1		9		11 2
SIII En	4				00	07		4		$ \frac{2}{0.27} $		ے 1 28
Eu Cd	1.1				0.9	0.7		0.5		$\frac{0.27}{2}$		0.28
Gu Th	+ ~ 1				J	2 2		+ ~ 1		2 2		ے ا
Dv	3				$\frac{1}{2}$	1		3		$\frac{1}{2}$		$\frac{1}{2}$
Бу Но	1				0.8	07		1		2 1		2- 1
Fr	2				1	1		2		2		3
Vh	15				11	07		$\frac{2}{2}$ 1		$\frac{2}{28}$		42
Lu	< 0.5				< 0.5	< 0.5		< 0.5		0.5		0.8
Σ REE	127				102	90		140		60		71
					102	/ 0		1.0		00		· •

Table 1) Chemical analyses of G. El-Zeit granitoids

The studied alkali granite originates from the monzogranites (as a parental magma) by fractional crystallization process, and the evidence include: 1) the wide variation and decreasing contents of Al₂O₃, MgO, CaO, Ba, and Sr with increasing silica (Fig. 4) that are best explained by fractionation of plagioclase, K-feldspar, and Mg-rich minerals; 2) the depletion in Zr (Fig. 4), which indicates fractionation of zircon; 3) the wide variation in Rb/Sr ratios and its rapid increase with

increasing SiO₂ (Fig. 9a) and this requires a prolonged history of fractional crystallization (Halliday, et al., 1991). The role of feldspar fractionation is further indicated by the covariation in Ba and Sr which increase with progressive fractionation (Fig. 9b). Furthermore, the fractionation process between the investigated monzogranite and the alkali granite is confirmed by the decrease of CaO/Al₂O₃ and K₂O/Rb with ratios decreasing the differentiation index (Q+Or+Ab) and Rb

contents for the GZG, respectively (Figs. 9c and d). Systematic decrease in Fe₂O₃ and MgO with increasing (Fig. suggests silica 4) that fractionation of the primary ferromagnesian silicate minerals played a role in developing the compositional variation in the two varieties of the GZG and this results in the confinement of alkali feldspar granite as a relatively younger peripheral zone of the Gabal El-Zeit block (Fig. 1). MgO vs. Rb/Sr and TiO₂ vs. Rb/Sr variation diagrams (Fig. 9e and f) suggest that amphibole, pyroxene and Fe-Ti oxides fractionation were also important during the evolution of the alkali granites from the monzogranite parental magma. Recently, Ghoneim et al. (2015) suggested that transition from the calc-alkaline magma to the alkaline one occurred as a result of the tectonic transition from compression regime to tectonic relaxation (extension setting) during the last stage of the Pan-African Orogeny.

The opaque mineralogical study suggests that the monzogranite precursor is ilmenite and titanomagnetite-bearing which favours a considerable oxygen fugacity with enough Ti in the melt to be formed. On the other hand, the peripheral alkali granite contains magnetite only and formed at a relatively lower oxygen fugacity (Anderson and Smith, 1995) and retention of remaining Ti was only confined to crystallization of magnetite contemporaneous or just before the crystallization of biotite (Haggerty 1976; Morse, 2006). The equilibrium of hemoilmenite and titanomagnetite exsolution is controlled by trace elements (Polfavefs, 1983), interdiffusion and Fe³⁺ to Fe²⁺ reduction (Charilaou et al., 2011). With the increase of Ti in the magnetite structure, apatite appears (Wilson et al., 1996). In both varieties of the GZG, secondary magnetite as fine needles results from chloritization of biotite. This late deuteric-hydrothermal alteration took place at the latest stage of magmatic crystallization and possibly continued during and after the emplacement of the Gabal El-Zeit block. The

retention of Ti in biotite can be elucidated from the appearance of fine titanite during crystallization, and owing to the rarity of most chlorite structure to incorporate both Fe and Ti they form secondary magnetite and titanite instead.

7- Conclusions

- 1. The decrease of Al₂O₃, Fe₂O₃, TiO₂, MgO and CaO with increasing silica, reflects the separation of olivine, pyroxene, Fe-Ti oxides and plagioclase during the evolution of the alkali granites.
- 2. Geochemical features classify the GZG as high-K series. The investigated monzogranite straddles the calc-alkaline metaluminous domain while the alkali granite pertains a peralkaline nature.
- 3. The GZG are characterized by Ba, Sr, P and Ti negative anomalies and a moderate to anomaly. weak negative Nb These geochemical signatures are similar to those displayed by post-collisional high-K granitoids from the late Neoproterozoic ANS. These anomalies indicate that feldspar, apatite and Fe-Ti oxides are the major fractionating phases.
- Tectonic discrimination indicates that the 4. monzogranite is volcanic-arc or highly fractionated calc-alkaline granites whereas the alkali granites are calc-alkaline peraluminous or post-collisional granites. Accordingly, the tectonic setting of the GZG is transitional between volcanic-arc and within-plate tectonic setting environments.
- 5. The investigated monzogranite perhaps is derived by partial melting of a slightly LILE-enriched amphibole-bearing mafic source.
- 6. The data materialized in the present work give evidence that the peripheral alkali granite is the most highly evolved and it originates from the monzogranite parental magma by a fractional crystallization

process. The resultant alkali granite is hence rich in graphic and myrmekitic intergrowths that are completely lacking in the monzogranite precursor.

7. Opaque minerals in the late alkali granite are only titanomagnetite and developed at relatively lower oxygen fugacity than the case of earlier monzogranite that bears ilmenite (either homogeneous or in the form of exsolution) in addition to titanomagnetite.

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