



GEOCHEMISTRY AND PETROGENESIS OF THE CALC-ALKALINE GRANITOIDS FROM THE NORTHERN ARABIAN–NUBIAN SHIELD. A CASE STUDY FROM WADI EL-AKHDER GRANITOIDS, SOUTHERN SINAI, EGYPT

Moustafa Mohamed Mogahed

Geology Department, Benha University-Egypt, P.O. Box 13518, Benha, Egypt;
E-mail: mustafa.ahmed01@fsc.bu.edu.eg

ABSTRACT

I-type granitoids emplaced during pre-collision stages of the Neoproterozoic Pan-African Orogeny, are widely distributed in the southern Sinai Peninsula and constituting 30% of the basement outcrops. Petrological, geochemical, and mineral chemistry data are presented for the I-type, Wadi El-Akhder granitic suite (AGR), in order to determine their origin and geotectonic implications. The tonalite–granodiorites of Wadi El-Akhder have geochemical characteristics of medium-K calc-alkaline, metaluminous to mildly peraluminous granitoids formed in an island-arc environment, which are conformable with well-known Egyptian older granitoids rocks (G_1). They have low Al_2O_3 , FeO^* , MgO , MnO , CaO , TiO_2 , Sr , Ba , and V contents, but possess high contents of Na_2O , K_2O , Nb , Zr , Th , and Rb . The studied AGR are generally characterized by enrichment of LILE and LREE and depletion of HFSE relative to N-MORB values, and follow assimilation and fractional crystallization (AFC) trends indicative of extensive crustal contamination of magma derived from a mantle source. The studied granitic rocks show high CaO/Na_2O ratios (0.82-1.54) being decrease from tonalite to granodiorites, whereas they have also high Al_2O_3/TiO_2 ratios (16.69-27.61) increasing toward the granodiorites. These features indicate that emplacement of the granitoid were strongly affected by magma mixing of felsic and mafic melts. The chemical characteristics of the AGR are remarkably similar to those of subduction-related granitoids from the Arabian-Nubian Shield (ANS).

Keywords: Southern Sinai; Arabian–Nubian Shield; I-type granite; magma mixing.

INTRODUCTION

Basement outcrops in Sinai Peninsula, comprise the northernmost part of the ANS (Fig. 1). ANS was evolved through four main stages. The oceanic, island arcs and plutonic rocks were formed during the subduction stage (~950-850 Ma, Bentor 1985; Genna et al. 2002; Johnson and Woldehaimanot 2003; Kroner et al. 1990; Stern and Manton 1987). The continental collision (~850-650 Ma, Avigad and Gvirtzman 2009; Be'eri-Shlevin et al. 2009) resulting from continuing convergence between East and West Gondwana to form the East African Orogen (Stern 1994). The post-collision stage (~650–580 Ma) marks stabilization of the shield and is characterized by widespread calc-alkaline magmatism, mainly of intermediate to felsic composition and the occurrence of a vast peneplain (Avigad and Gvirtzman 2009; Avigad et al. 2005). The last stage (Gass 1981; Roobol et al. 1983) representing late to post-orogenic, intracratonic and within-plate magmatism is characterized by the severe igneous activity where alkaline to peralkaline granites were emplaced.

The Precambrian rocks occurring at the southern part of the Sinai Peninsula can be divided into metamorphic complexes (old continental gneisses), intermediate to acidic subduction-related volcanics and metasediments (island arcs), subduction-related granites (older granites), post-orogenic granites (younger granites), rift-related volcanics and finally alkaline anorogenic granites (El-Tokhi et al. 2009).

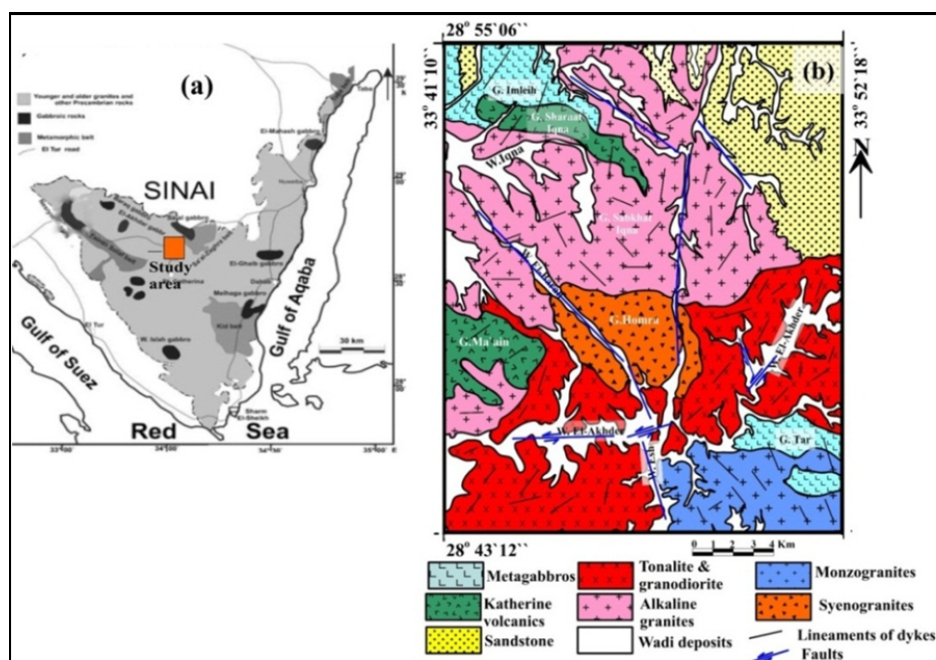
Understanding the origin of the granitoid rocks has important implications for the continental crust growth in general and for the ANS in particular. The Egyptian granitoids are broadly subdivided into three main cycles: the first cycle of synorogenic granitoids (Gray and Shaitian types) with ages ranging between 626 ± 2 and 780 ± 7 Ma (Dixon 1981; Stern and Manton 1987; Struchio et al. 1982). The second cycle of

younger granitoids (late orogenic granites) which were dated in Sinai and Egypt at 560–600 Ma (Bielski et al. 1979). Moreover, the epizonal granites and mesozonal granodiorites were recorded as the major varieties of plutonic rocks in the North Eastern Desert of Egypt (Stern et al. 1984). The mesozonal granodiorites represent the older variety and exhibiting calc-alkaline affinity. The epizonal granites are younger, representing anorogenic magmatic pulse unrelated to subduction-zone magmatism, related to the major episode of NW-SE to NS directed rifting in northernmost Afro-Arabia (Stern 1985) and generally known as pink, or Pan-African granites (Stern et al. 1984).

Generally, the granitoid rocks in Sinai Peninsula exhibiting evolution trend from calc-alkaline through alkaline to per-alkaline granitoids. Calc-alkaline granitoids are older and comprise diorite-tonalite-granodiorite suites (Granite I) and Alkaline to per-alkaline granitoids are younger and comprise calc-alkaline younger biotite granite, younger post-tectonic granite or late-tectonic monzogranite (e.g., Abdel-Rahman and El-Kibbi 2001; Ahmed et al. 1993; El-Mettwaly et al. 1992; El-Sheshtawi et al. 1993; Furnes et al. 1996; Moghazi 1999; Moghazi 2002; Mohamed et al. 1994). This trend is similar to that recognized among granitic rocks in the Eastern Desert of Egypt.

Although the granitoid rocks from the ANS have been subjected to numerous investigations concerning their petrogenesis and geotectonic evolution, but much controversy still persists on their source regions and the role of fractional crystallization against crustal anatexis (e.g., Beyth et al. 1994; Stern and Gottfried 1986). Wadi El-Akhder area, southwestern Sinai, Egypt (Fig. 1), represents a good example for resolving these issues, as it constitutes the biggest batholith of the older granitic rock in southeastern Sinai (Bentor 1985).

Fig. 1: (a) Map of southern Sinai, Egypt (Gahlan et al., 2017) exhibiting the location of the studied area. b) Geological map of Wadi El-Akhder granitic rocks.



Heikal et al. (1985) mentioned the granitoid rocks around Wadi El-Sheikh that comprising the study area as two groups older and younger granitoids. Stern and Hedge (1985) gave the age of 632 Ma (U-Pb method) and 780 Ma (Rb-Sr method) for the older granitoids of Heikal et al. (1985) that intruded into the gneisses of Feiran-Solaf metamorphic belt. The calc-alkaline granitoids in the study area are related to compressional environment. Moreover, El-Mettwaly and Mashaal (1989) and Mashaal et al. (1999) showed that the granitoids rocks of Wadi Ager, which occur beyond the western border of the mapped area, are calc-alkaline, I-type orogenic granodiorite that emplaced under compressional environment.

The present study introduces new data on the petrology, geochemistry and mineral chemistry of the older granitic rocks in Wadi El-Akhder area, southwestern Sinai, Egypt in order to elucidate their tectonic environments and to shed some light on their origin.

GEOLOGIC SETTINGS

Wadi El-Akhder area is located at the southwestern part of the Sinai Peninsula and is bounded by the Feiran-Solaf metamorphic belt from the west and Katherina Ring Complex from the east (Fig. 1). The area is bounded by latitudes 28°43'12" and 28° 55' 06" N, and longitudes 33° 41' 10" to 33°52' 18" E, covering about 550 km² (Fig. 1). It is dissected by a high density of faults due to its proximity to both the NW-trending faults of the Gulf of Suez system and the NNE-trending faults of the Gulf of Aqaba system. The main map-scale units in the area include metagabbros, subduction-related syn-tectonic granitoids (AGR), monzogranites, Katherine volcanics, alkaline granites, syenogranites, and Phanerozoic sedimentary cover (Fig. 1). The metagabbroic rocks crop out in the northwestern and southeastern corners of the studied area (Fig. 1), are intruded by tonalites, monzogranites (Fig. 2a) and Katherine volcanics. On the other hand, the Katherine volcanics crop out at G. Sharaat Iqna and G. Maa'in (Fig. 1), are generally classified into trachytes, rhyodacites and rhyolites and intruded by alkaline granites (Fig. 2b).

The chronological sequence of the different rock units in the mapped area starts with metagabbros followed by the emplacement of AGR during the late phase of the Pan-African Orogeny. This was followed by the intrusion of monzogranite. Afterwards, extrusive Katherine volcanics were erupted and syenogranite and alkali granites were intruded.

The investigated syn-tectonic granitoids (equivalent to G1 Egyptian granites of Hussein et al., 1982) are represented in Wadi El-Akhder area by tonalites and granodiorites. The exposures of these granitoids are limited compared to the other granitic types. They cover the area around the northern and southern flanks of Wadi El-Akhder (Fig. 1) occupying an area of about 130km² (about 40 %) of the whole surface of the study area. The tonalites crop out along the central parts of Wadi El-Akhder and representing the core of AGR, whereas the granodiorites crop out at the entrance of Wadi El-Akhder and extended to the east beyond the limits of the mapped area intruding the well-known Feiran-Solaf gneisses.

Wadi El-Akhder granitoids are coarse- to medium-grained, with low to moderate relief and normally dark gray color. They are highly jointed and show bouldery weathering. Sometimes they exhibit weak gneissosity, which is commonly observed along the contact with gneissic rocks. Generally, these rocks have xenoliths of the pre-existing gneisses and amphibolites which mainly striking N50-60°E (Fig. 2c). The granitic rocks are intruded by monzogranites alkali granites with sharp contact (Fig. 2d). In some places, AGR occur as xenoliths (Fig. 2e) or roof pendant within the monzogranites and alkali granites (Fig. 2f). Moreover, the area is dissected by numerous felsic and mafic dykes. These dykes striking N-S, NNE-SSW, NE-SW and E-W. The felsic dykes are represented by microgranite porphyry, granophyre, porphyritic rhyolite and aplite with N-S and NNE-SSW predominant trends. The mafic dykes are mostly basaltic in composition acquiring commonly NE-SW and E-W directions.

PETROGRAPHY OF THE STUDIED GRANITIC ROCKS

These granitoids exhibit a wide range of mineralogical composition and textural variations. They are mainly of granodioritic in composition but with locally tonalitic and are characterized by containing mafic minerals ranging from 15% to 25% of the whole rock volume and exhibiting different varieties of textures ranging from hypidiomorphic, local gneissose, granoblastic, perthitic to porphyritic.

Microscopically, the granodioritic rocks could be subdivided into biotite granodiorite, gneissose granodiorite and rare adamellite. The biotite granodiorite is composed mainly of plagioclase (40-50% by volume), potash feldspars (10%), quartz (30%) and biotite with rare hornblende (Fig. 3a). Plagioclases are subhedral to euhedral crystals, ranging in composition from andesine to oligoclase with more sodic rims and occur as megacrysts embedded in crushed quartz and feldspar groundmass or occur as inclusions in the perthite. Potash feldspars are mainly represented by perthitic orthoclase and microcline. Quartz occurs both as small discrete grains and intergrown with interstitial microcline. The mafic minerals range from 10-15% of the whole rock and constitute brown biotite which may be partially chloritized and rarely subhedral to euhedral green hornblende and augite (Fig. 3b). The accessory minerals are iron-oxides, sphene, apatite and zircon (Fig. 3b). The gneissose granodiorite has the same composition of the biotite granodiorite but possess slightly gneissose texture. The adamellite is essentially composed of potash

feldspars (up to 40% by volume) exhibiting subsolvous texture, plagioclases (30%) which are frequently zoned, less quartz (20%) and equal amounts of biotite and hornblende (Fig. 3c).

The tonalitic varieties of the studied syn-tectonic granitoids are mainly composed of plagioclases, potash feldspars, biotite, hornblende and quartz (Fig. 3d). Plagioclases are more calcic (An_{64-70}) whereas potash feldspars occur as subhedral to anhedral orthoclase-perthite and containing biotite inclusions. Brown biotites are generally chloritized and sometimes replacing hornblende crystals. Quartz generally occurs as anhedral grains that is usually form quartz ocelli where the quartz is rimmed by hornblende and/or biotite (Fig. 3d).

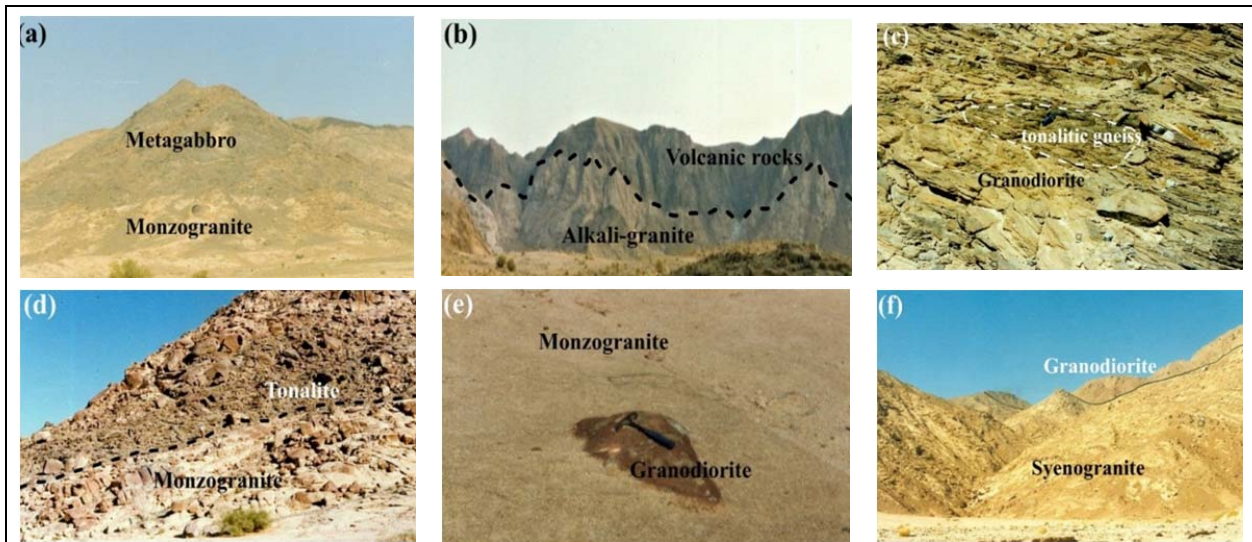


Fig. 2: Representative field photographs from the studying area showing, (a) Roof pendant of metagabbros carried by monzogranite. (b) Low-angle contact between the acidic volcanic rocks of Gabal sharat Iqna and alkali granites. (c) Granodiorite from southwestern part of the mapped area exhibiting weak foliation and enclosing old relics of tonalitic gneiss. (d) Low-angle contact between AGR (tonalite) and monzogranite along Wadi Esh. (e) Xenolith of granodiorite in monzogranite, along Wadi El-Akhder. (f) Syenogranite carry roof pendant of pre-existing granodiorite (upper side).

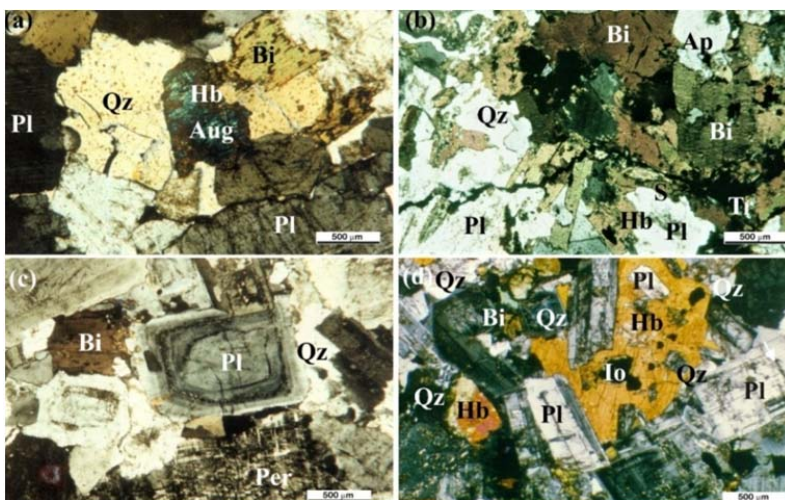


Fig. 3: (a) Biotite-granodiorite showing biotite flakes, hornblende, kaolinized plagioclase and quartz. (b) Cumulate of brown-biotite, iron oxide, apatite, sphene with altered plagioclase and quartz. (c) Adamellite showing zoned plagioclase, microperthite, biotite, hornblende and quartz. (d) Tonalite exhibiting plagioclase and quartz which is rimmed by hornblende and biotite form quartz ocelli. All images are in crossed-polarized light. Abbreviations: Qz- quartz; Pl- plagioclase; Per- perthite; Bi- biotite; Hb- hornblende and S- sphene.

ANALYTICAL TECHNIQUES

Mineral analyses were performed by electron microprobe analysis (EMPA) at the Far Eastern Geologic Institute, Vladivostok of the Russian Academy of Sciences, using a JEOL JXA8100 instrument with three wave spectrometers, completed with an INCA x-sight energy dispersive spectrometer. Corrections for dead-time, atomic number, absorption and fluorescence effects were made, using the computer programs

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based on the methods of (Sweatman and Long 1969). Representative EMPA data of minerals (amphiboles, biotites and feldspars) are given in Tables (1, 2, 3 and 4).

After petrographic screening ten samples representing the studied granitic rocks (4 tonalites and 6 granodiorites) exhibiting least alteration has been selected for chemical analysis. Loss on ignition (LOI) and whole-rock chemical analyses were carried out for major oxides, trace elements and rare earth elements (REEs) at the Far Eastern Geologic Institute, Vladivostok of the Russian Academy of Sciences.

Trace-elements and the REEs analyses were carried out by LA-ICP-MS (laser ablation-inductively coupled plasma-mass spectrometry) using an Agilent 7500 s quadrupole ICP-MS system attached to a New Wave/Merchantek UP213 laser ablation system. The analytical conditions of such element were a beam diameter of 40µm and a 5 Hz repetition rate. The typical precision and accuracy of these NIST- 610 analyses are 2–5% for REEs, Ta, Hf, Th, U, Y, Sr and Nb at the ppm concentration level and from 7 to 10% for elements such as P, Mn, Fe and Ga (Norman et al. 1998; Norman et al. 1996). Whole-rock major and trace element data are reported in Table 5.

MINERAL CHEMISTRY

The microprobe analyses for major elements together with the recalculated cations of the amphiboles, biotites and feldspars in the studied granitic rocks are listed in Tables (1-4).

Table 1: Electron microprobe analyses of amphiboles from the studied granitic rocks of Wadi El-Akhder area southwestern Sinai, Egypt.

Rock type	Syn-tectonic granitoids Wadi El-Akhder granitic rocks (AGR)								
	Tonalites			Granodiorites					
Petro. Name	T17/1			G19/1					
Sample No.	T17/1			G19/1					
Amph. Name	Actinolite								
Amph. class.	Calcic								
SiO ₂	47.97	47.14	47.28	48.78	48.83	50.13	51.91	51.11	
TiO ₂	1.33	0.91	1.12	0.96	0.86	0.87	0.77	0.93	
Al ₂ O ₃	8.33	9.91	10.37	8.89	9.03	8.87	5.27	6.84	
FeO*	9.24	10.48	9.23	10.16	9.87	9.65	10.47	9.72	
MnO	0.49	0.69	0.71	0.37	0.87	0.34	0.30	0.39	
MgO	17.11	17.41	17.41	15.97	16.41	16.71	17.61	17.51	
CaO	11.38	10.34	11.21	9.13	8.65	8.89	9.55	9.12	
Na ₂ O	0.81	0.61	0.71	1.88	2.03	1.79	1.34	1.57	
K ₂ O	0.41	0.33	0.41	0.62	0.51	0.23	0.19	0.41	
Total	97.07	97.82	98.45	96.76	97.06	97.28	97.01	97.06	
Formula based on 23 oxygen atoms and assuming a total of 13 cations exclusive of Ca, Na and K									
Si	6.83	6.64	6.61	6.86	6.85	6.96	7.24	7.12	
Al ^(iv)	1.17	1.36	1.39	1.14	1.15	1.04	0.76	0.88	
Sum T site	8	8	8	8	8	8	8	8	
Ti	0.14	0.1	0.12	0.1	0.1	0.11	0.1	0.12	
Al ^(vi)	0.22	0.29	0.32	0.33	0.34	0.38	0.1	0.24	
Fe ³⁺	0.59	0.82	0.76	1.19	1.14	1.11	1.19	1.11	
Fe ²⁺	0.42	0.14	0.17	0.03	-	-	-	-	
Mg	3.63	3.66	3.63	3.35	3.43	3.41	3.61	3.53	
Sum C site	5.00	5.01	5.00	5.00	5.01	5.01	5.00	5.00	
Mn ²⁺	0.06	0.08	0.08	0.04	0.10	0.04	0.04	0.05	
Fe ²⁺	0.10	0.27	0.14	0.09	0.10	0.17	0.17	0.17	
Ca	1.74	1.56	1.68	1.38	1.30	1.32	1.43	1.36	
Na	0.11	0.08	0.10	0.51	0.55	0.48	0.36	0.42	
Sum B site	2.00	2.00	2.00	2.02	2.05	2.01	1.99	2.00	
Na	0.11	0.08	0.10	0.03	0.05	0.02	0.00	0.01	
K	0.07	0.06	0.07	0.11	0.09	0.04	0.03	0.07	
Sum A site	0.19	0.14	0.17	0.14	0.14	0.06	0.04	0.08	
Pkbar (Hollister et al., 1987)	3.12	4.52	4.87	3.55	3.65	3.43	1.12	1.57	
Pkbar (Schmidt, 1992)	3.64	4.82	5.12	4.00	4.09	3.90	1.21	2.34	

Table 2: Electron microprobe analyses of the biotite from the granitic rock of Wadi El-Akhder area, southwestern Sinai Peninsula, Egypt.

Rock type	Syn-tectonic granitoids Wadi El-Akhder granitic rocks (AGR)							
	Tonalites			Granodiorites				
Petro. Name	T17/1			G19/1				
Sample No.	T17/1			G19/1				
SiO ₂	41.58	40.78	40.44	38.81	38.55	37.91	38.82	38.55
TiO ₂	3.54	3.91	4.73	2.03	1.91	1.45	2.06	1.97
Al ₂ O ₃	13.91	14.49	15.22	16.71	16.48	16.34	16.76	16.57
FeO*	20.11	21.37	20.51	24.57	24.41	25.98	24.91	23.49
MnO	0.19	0.19	0.18	0.68	0.21	0.17	0.18	0.36
MgO	10.73	9.48	8.65	7.45	8.06	7.51	8.14	8.41
Na ₂ O	0.12	0.17	0.16	0.31	0.11	0.16	0.12	0.19
K ₂ O	8.54	8.47	8.81	8.33	8.73	7.06	7.63	8.44
Total	98.72	98.86	98.70	98.89	98.46	96.58	98.62	97.98
Formula based on 22 oxygen atoms								
Si	6.17	6.08	6.03	5.90	5.89	5.90	5.89	5.89
Al ^(iv)	1.83	1.92	1.97	2.10	2.11	2.10	2.11	2.11
Al ^(vi)	0.60	0.63	0.71	0.89	0.85	0.90	0.88	0.87
Ti	0.40	0.44	0.53	0.23	0.22	0.17	0.23	0.23
Fe ²⁺	2.00	2.17	2.06	2.61	2.61	2.86	2.65	2.49
Mn	0.02	0.02	0.02	0.09	0.03	0.02	0.02	0.05
Mg	2.37	2.11	1.92	1.69	1.84	1.74	1.84	1.91
Na	0.03	0.05	0.05	0.09	0.03	0.05	0.04	0.06
K	1.62	1.61	1.68	1.62	1.70	1.40	1.48	1.64
FeO/MgO	1.69	2.03	2.13	2.97	2.73	3.11	2.75	2.51

Amphibole

Amphiboles constitute the main mafic minerals in the studied tonalite and granodiorite. Results of the analyzed amphiboles together with atoms per formula unit calculated on the basis of 23 oxygens are given in Table 1. The Fe³⁺ and Fe²⁺ were calculated using the 13-CNK method (Leake et al. 1997; Leake et al. 2003). The analyzed amphiboles are mostly possess Ti (apfu) >0.1 (Table 1), a characteristic of primary igneous amphiboles (Girardeau and Mevel 1982). In addition, the analyzed amphiboles show decreasing of Si, Ti, Al, Fe⁺³ and Mg from the tonalites to granodiorites, whereas the Na, K and Ca increase.

According to the classification of (Leake et al. 2003), the analyzed amphiboles from the studied granitic rocks are mainly calcic in composition (Fig. 4a). The analyzed amphiboles are essentially actinolite in tonalites and granodiorite (Fig. 4b) and exhibiting a general increasing of their Na and K contents with the increasing of their Al contents (Table 1).

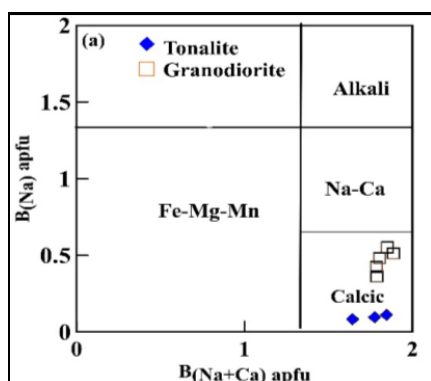
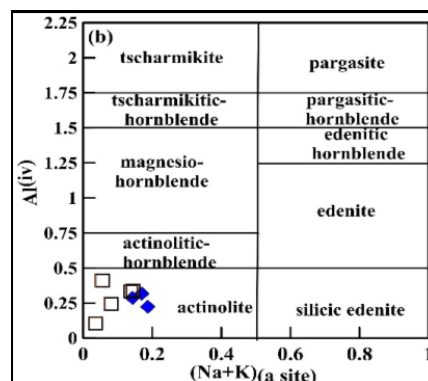


Fig. 4. (a) B_{Na} vs. $B_{(Ca+Na)}$ classification diagram of amphibole (Leake et al. 1997). Symbol in Figs. 4-10: ◆-tonalites and □-granodiorites.



(b) Plot of $Al^{(iv)}$ vs. $(Na+K)$ in A-site for the analyzed amphiboles from the studied granitic rocks. Nomenclature from (Hawthorne et al. 2012).

Generally, the amphibole compositions could be used as pressure indicator as their Al (apfu) is general increase with pressure based on the equation $[P(\text{kbar}) = 5.64 (\text{Al}^{\text{iv}} + \text{Al}^{\text{vi}} - 4.76)]$ suggested by Hollister et al. (1987). The studied AGR have an average of Al (apfu) (~1.39). Accordingly, the average of calculated crystallization pressure estimates of the AGR of about 3.23 Kbar (Table. 1). In addition, the hornblende barometry of (Schmidt 1992) was applied for the studied granitic rocks and yield average pressure of about (3.64 ± 0.6) Kbar (Table 1).

Biotite

Biotite occurs in all the studied granitic samples. Results of EMPA are shown in Table (2) together with the number of atoms per formula unit based on 22 oxygens in the anhydrous total. Based on the chemical composition of the analyzed biotite they are belonging to primary magmatic biotites (Fig. 5a). Moreover, the biotite changes from calc-alkaline to slightly peraluminous in the AGR (Figs. 5b and c). The analyzed biotite has Al_2O_3 contents with an average of 16.02 and has high contents of FeO, MgO and Na_2O and low contents of K_2O (Table 2). On the $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$ vs. Al (apfu) diagram of (Rieder et al. 1999), the studied mica from AGR lies within the chemical composition of biotite (Fig. 5d).

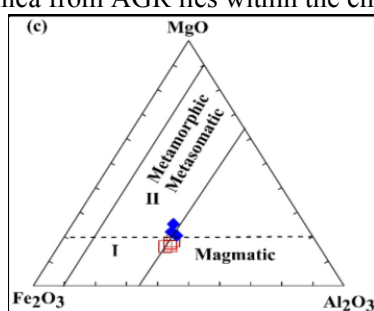
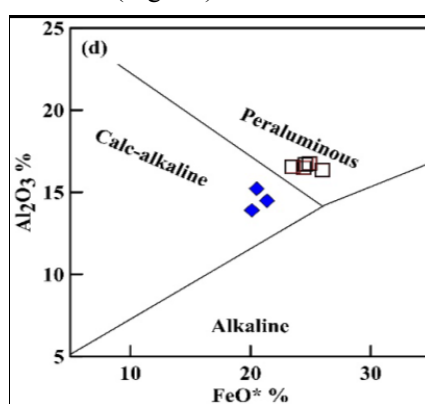
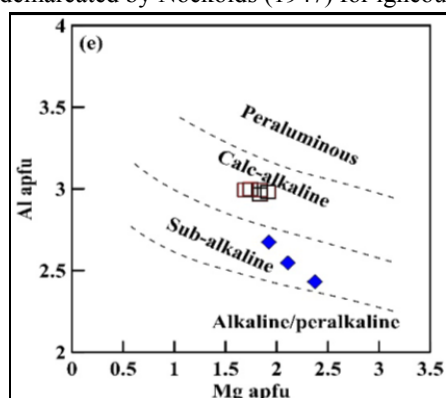


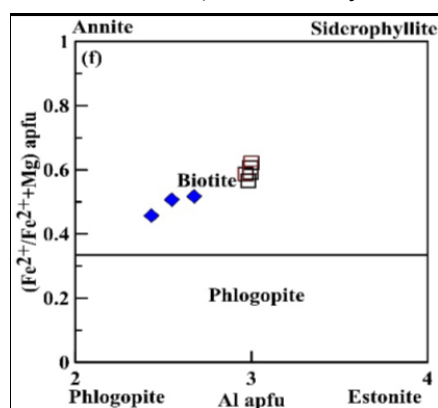
Fig. 5: a) Fe_2O_3 -MgO- Al_2O_3 ternary diagram of biotites in the studied granitic rocks. Dashed line separates biotites of magmatic environment from those of metamorphic-metasomatic environment (Gokhale 1968), whereas the area between the solid lines indicates the zone demarcated by Nockolds (1947) for igneous rocks.



(b) FeO^* vs. Al_2O_3 biotite discriminant diagram (Abdel-Rahman 1994) for the analyzed biotites.



(c) $\text{Mg}_{(\text{apfu})}$ - $\text{Al}_{(\text{apfu})}$ diagram (Nachit et al. 1985) applied for the analyzed biotites.



(d) Nomenclature scheme of the studied biotite based on the Al vs. $\text{Fe}^{2+}/(\text{Mg} + \text{Fe}^{2+})$ diagram of Deer et al. (1992).

Feldspars

The plagioclase and alkali feldspars were analyzed from all the studied granitic types and their analyzed data are given in Tables 3 and 4.

Generally, the analyzed plagioclase from AGR are homogeneous in composition and possess high contents of Al_2O_3 (19.21-27.11 wt.%), Na_2O (7.41-12.07 wt.%) and with low contents of CaO (3.23-8.61 wt.%; Table 3). They are sodic enriched and have wide variation of anorthite contents ($\text{An}_{12.35-37.98}$) and ranging in composition from oligoclase to calcic-andesine (Fig. 6). In addition, the alkali feldspars from AGR (Fig. 4g) have composition ranging from $(\text{An}_{0.66} \text{Ab}_{15.48} \text{Or}_{83.86})$ to $(\text{An}_{0.78} \text{Ab}_{2.20} \text{Or}_{97.02})$.

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Table 3: Electron microprobe analyses of the plagioclase feldspars from Wadi El-Akhder area, SW Sinai Peninsula.

Rock type	Syn-tectonic granitoids Wadi El-Akhder granitic rocks (AGR)									
Petro. Name	Tonalites					Granodiorites				
Sample No.	T17/1					G19/1				
SiO ₂	60.98	61.12	59.34	60.37		63.41	62.55	57.14	58.19	56.59
Al ₂ O ₃	24.41	24.03	25.51	24.17		20.11	19.21	25.63	24.26	27.11
FeO*	0.15	0.27	0	0.18		0.14	0.11	0.08	0.12	0
CaO	5.61	5.61	7.06	6.04		4.52	3.23	6.07	8.61	7.55
Na ₂ O	8.03	8.15	7.41	8.13		10.11	12.07	8.48	7.64	8.05
K ₂ O	0.35	0.64	0.22	0.25		0.78	0.91	0.91	0.24	0.11
Total	99.53	99.82	99.54	99.14		99.07	98.08	98.31	99.06	99.41
CaO/(Na ₂ O+K ₂ O)	0.67	0.64	0.93	0.72		0.42	0.25	0.65	1.09	0.93
Cations calculated on basis of 32 oxygens										
Si	2.72	2.72	2.66	2.71		2.81	2.76	2.56	2.62	2.52
Ti	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Al	1.29	1.26	1.35	1.28		1.05	1.00	1.35	1.29	1.42
Fe ³⁺	0.00	0.01	0.00	0.01		0.01	0.00	0.00	0.00	0.00
Fe ²⁺	0.01	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Ca	0.27	0.27	0.34	0.29		0.21	0.15	0.29	0.41	0.36
Ba	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
Na	0.70	0.70	0.64	0.71		0.87	1.03	0.74	0.67	0.69
K	0.02	0.04	0.01	0.01		0.04	0.05	0.05	0.01	0.01
tot. cat.	5.00	5.00	5.00	5.00		5.00	5.00	5.00	5.00	5.00
An	27.29	26.56	34.05	28.69		19.04	12.35	26.98	37.89	33.93
Ab	70.68	69.83	64.68	69.89		77.05	83.51	68.21	60.85	65.48
Or	2.03	3.61	1.26	1.41		3.91	4.14	4.82	1.26	0.59

Table 4: Electron microprobe analyses of the alkali-feldspars from Wadi El-Akhder area, SW Sinai.

Rock type	Syn-tectonic granitoids Wadi El-Akhder granitic rocks (AGR)						
Petro. Name	Tonalites			Granodiorites			
Sample No.	T17/1			G19/1			
SiO ₂	63.14	63.37	63.01		63.18	63.71	63.55
Al ₂ O ₃	18.71	18.34	18.31		18.55	18.63	18.34
FeO*	0.39	0.13	0.11		0.31	0.00	0.31
CaO	0.26	0.15	0.12		0.23	0.11	0.16
Na ₂ O	0.56	0.56	0.59		0.31	0.51	0.25
K ₂ O	16.31	16.21	16.67		16.51	16.31	16.73
Total	99.37	98.76	98.81		99.09	99.27	99.34
Cations calculated on basis of 32 oxygens							
Si	2.93	2.96	2.94		2.95	2.96	2.96
Ti	0.00	0.00	0.00		0.00	0.00	0.00
Al	1.02	1.01	1.01		1.02	1.02	1.01
Fe3	0.02	0.01	0.00		0.01	0.00	0.01
Fe2	0.00	0.00	0.00		0.00	0.00	0.00
Mn	0.00	0.00	0.00		0.00	0.00	0.00
Mg	0.00	0.00	0.00		0.00	0.00	0.00
Ca	0.01	0.01	0.01		0.01	0.01	0.01
Ba	0.00	0.00	0.00		0.00	0.00	0.00
Na	0.05	0.05	0.05		0.03	0.05	0.02
K	0.97	0.97	0.99		0.98	0.97	0.99
Tot. cat.	5.00	5.00	5.00		5.00	5.00	5.00
End members							
An	1.26	0.73	0.57		1.12	0.54	0.78
Ab	4.90	4.95	5.08		2.74	4.51	2.20
Or	93.85	94.32	94.35		96.13	94.95	97.02

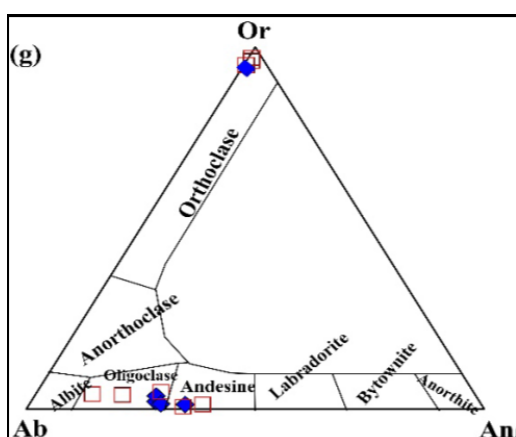


Fig. 6: Classification diagram for feldspars from the studied granitic rocks, compositional fields are after (Deer et al., 1992).

MODAL ANALYSIS

The modal abundances of the quartz and feldspars for the studied granitic rocks are given in Table 5. The modal proportions of alkali feldspar, plagioclase and quartz are shown in figure 7. Based on the IUGS nomenclature (Streckeisen 1976), the studied AGR samples plot in the field of tonalite and granodiorites.

Table 5: Modal analyses for the granitic rocks from Wadi El-Akhder area, SW Sinai Peninsula.

Rock type	Syn-tectonic granitoids										
	Wadi El-Akhder granitic rocks (AGR)										
Petro. Name	Tonalites					Granodiorites					
Modal components											
Quartz	27.31	27.16	28.50	24.78		21.94	24.30	24.38	25.09	23.26	28.76
Orthoclase	8.92	7.92	6.62	14.24		15.25	11.41	12.29	10.76	16.78	16.13
Albite	28.01	27.84	28.52	29.95		35.03	36.64	35.71	37.91	37.91	27.59
Anorthite	20.95	21.74	21.13	15.10		12.92	13.43	12.47	11.73	7.14	16.32
Plagioclase	48.95	49.58	49.65	45.06		47.95	50.07	48.18	49.64	45.05	43.90

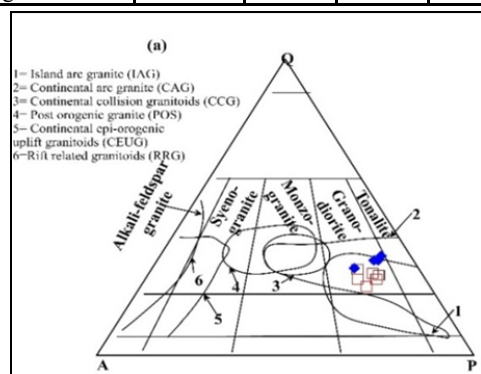


Fig. 7: Classification of granitic rocks in the QAP diagram, according to their actual (modal) mineral constituents (after Streckeisen 1976). Tectonic setting fields (after Maniar and Piccoli 1989).

WHOLE-ROCK CHEMISTRY

The chemical analyses of the studied granitic rocks and some of their calculated normative mineral compositions are listed in Table 6. Generally, the SiO₂ contents are broadly high for granitic rocks. The studied granitic rocks exhibiting a range of SiO₂ from approximately 64.98 to 66.08 wt.% for tonalites and 66.28 to 67.54 wt.% for granodiorite (Table 6). Molar norm composition shown in a Q' vs. ANOR diagram indicate that the granitoids form a continuous suite from granodiorite to tonalite (Fig. 8).

Based on the classification diagram of the Egyptian granitoids (Hassan and Hashad 1990), the investigated tonalite and granodiorite are akin to the calc-alkaline Egyptian older granitoids (Fig. 9a). The TAS diagram of Le Maitre et al. (1989) was chosen among recent schemes as it provides a classification with alkaline and calc-alkaline fields (Fig. 9b). The dividing line between alkaline and non-alkaline series from Irvine and Baragar (1971) and Miyashiro (1978) have also been plotted for comparison. Almost all of the tonalites and granodiorites samples from the studied AGR plot in the calc-alkaline field (Fig. 9b).

The studied granitic rocks have relatively higher contents of K₂O ranging from 1.12 to 2.84 wt.%. Based on the nomenclature of Rickwood (1989), the AGR are classified as medium-K calc-alkaline rocks (Fig. 10a). Based on the aluminum saturation index [A/CNK; molecular Al₂O₃/(CaO+Na₂O+K₂O)] (Fig. 10b), the studied granitic rocks plot mainly in the metaluminous field. There is no significant gap between the compositionally different studied AGR types suggesting that the rocks of each series are cogenetic.

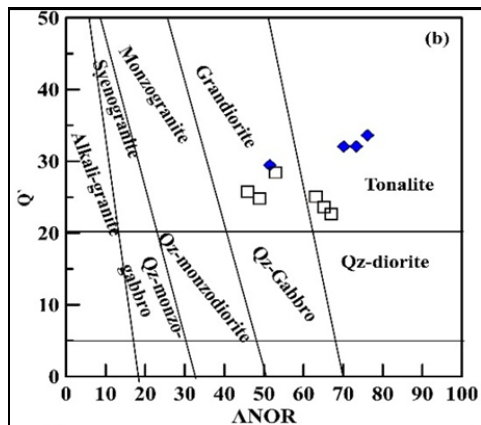


Fig. 8: Q' [100*Q/(Q+Or+Ab+An)] vs. ANOR [100*An/(Or+An)] diagram for normative classification of the studied granitic rocks (Streckeisen and Le Maitre 1979).

Table 6: Whole-rock analyses for the granitic rocks from Wadi El-Akhder area, SW Sinai Peninsula.

Rock type	Syn-tectonic granitoids Wadi El-Akhder granitic rocks (AGR)									
	Tonalites				Granodiorites					
Petro. Name										
Sample	T17/1	T26/1	T28/2	T29/1	G19/1	G21/1	G24/1	G39/2	G/41/1	G64/1
Lat. 28°N	46°52''	46°22''	46°6''	48°7''	48°48''	45°4''	43°30''	43°57''	46°22''	47°7''
Long. 33°E	45°2''	47°3''	48°11''	50°17''	42°42''	42°15''	44°3''	46°42''	50°39''	52°3''
SiO ₂	64.98	65.17	65.53	66.08	66.28	66.99	66.26	66.90	67.36	67.54
TiO ₂	0.91	0.86	0.82	0.77	0.67	0.66	0.61	0.59	0.56	0.52
Al ₂ O ₃	15.12	14.83	14.50	13.97	14.34	14.13	13.76	13.64	13.06	14.30
FeO*	3.92	3.45	3.77	4.26	4.70	3.92	3.21	3.68	3.69	2.87
MnO	0.18	0.13	0.13	0.11	0.10	0.12	0.11	0.15	0.05	0.12
MgO	2.41	2.86	2.21	2.17	1.81	1.74	1.51	1.48	1.27	1.16
CaO	4.63	4.91	5.18	4.96	4.63	4.49	4.26	3.96	3.67	4.05
Na ₂ O	3.31	3.29	3.37	3.54	4.14	4.33	4.22	4.48	4.48	3.26
K ₂ O	1.51	1.34	1.12	2.41	2.58	1.93	2.08	1.82	2.84	2.73
P ₂ O ₅	0.31	0.34	0.19	0.23	0.05	0.13	0.10	0.13	0.13	0.16
LOI	0.73	0.98	1.42	1.03	0.63	1.24	2.63	2.66	2.97	2.54
Total	99.14	99.63	98.92	99.21	99.32	99.53	98.97	98.54	98.93	98.71
Trace and REE elements contents (ppm)										
V	48	82	72	61	97	83	69	116	78	78
Cr	51	57	48	43	40	38	40	36	40	41
Co	16	18	14	18	13	14	21	8	6	10
Ni	40	22	32	28	18	14	14	14	12	19
Cu	9	7	6	8	8	9	761	3	9	7
Zn	11	42	13	27	30	24	53	12	25	40
Cs	5	5	4	4	3	5	2	2	2	3
Ga	12	12	12	18	17	16	15	16	15	20
Rb	93	86	77	92	112	88	102	117	102	117
Sr	805	770	865	835	519	593	454	398	326	326
Y	6	7	8	9	7	7	7	6	6	5
Zr	149	104	151	140	138	93	157	147	141	137
Nb	12	11	15	15	11	10	17	16	13	13
Ba	1221	1296	1430	1675	1199	1284	1056	1140	1268	996
Hf	4	3	3	2	3	3	4	4	4	5
Ta	1	2	2	2	1	2	2	1	2	2
Pb	21	29	19	18	17	27	23	21	25	25

Table 6. (continued)

Geochemistry and petrogenesis of the calc-alkaline Granitoids

Rock type	Syn-tectonic granitoids Wadi El-Akhdar granitic rocks (AGR)										
	Tonalites				Granodiorites						
Petro. Name	T17/1	T26/1	T28/2	T29/1	G19/1	G21/1	G24/1	G39/2	G/41/1	G64/1	
Sample	T17/1	T26/1	T28/2	T29/1	G19/1	G21/1	G24/1	G39/2	G/41/1	G64/1	
Th	14.48	16.48	15.48	16.09	16.02	16.56	22.08	24.26	27.04	25.87	
U	8.50	4.70	5.04	4.40	7.50	5.30	5.70	6.03	6.60	5.80	
La	25.90	32.17	38.19	42.56	30.75	35.74	41.47	46.21	51.42	58.52	
Ce	47.48	55.18	62.80	69.99	56.45	62.80	69.88	76.13	102.84	84.84	
Pr	4.98	5.67	6.45	7.34	6.06	6.60	8.01	8.91	11.29	12.56	
Nd	15.95	18.15	21.10	24.52	17.46	22.11	25.66	29.82	36.98	25.66	
Sm	3.82	4.44	4.84	5.75	5.07	5.07	6.57	7.47	8.86	9.88	
Eu	1.20	1.45	1.28	1.69	1.18	2.11	1.70	1.73	2.02	1.77	
Gd	2.63	3.20	2.87	3.64	3.09	5.63	4.08	4.84	5.75	6.68	
Tb	0.40	0.46	0.52	0.59	0.49	0.61	0.67	0.86	1.04	0.79	
Dy	2.20	2.68	3.05	3.47	2.14	3.74	3.36	4.07	4.84	6.25	
Ho	0.39	0.47	0.35	0.59	0.46	0.66	0.71	0.81	0.96	0.74	
Er	0.95	1.32	1.13	1.56	1.28	1.58	1.92	2.23	2.48	2.71	
Tm	0.13	0.18	0.19	0.22	0.19	0.26	0.26	0.30	0.36	0.29	
Yb	0.82	1.04	1.48	1.22	1.31	1.56	2.06	2.29	2.55	2.06	
Lu	0.13	0.16	0.24	0.20	0.22	0.27	0.30	0.35	0.37	0.41	
ΣREE	107	127	144	163	126	149	167	186	232	213	
Petrochemical parameters											
Q`	32.06	32.08	33.62	29.47	25.78	28.43	23.63	25.08	22.67	24.84	
ANQR	70.13	73.30	76.15	51.47	45.86	52.90	65.16	63.08	67.02	48.91	
CaO/Na ₂ O	1.40	1.49	1.54	1.40	1.12	1.04	1.01	0.88	0.82	1.24	
Al ₂ O ₃ /TiO ₂	16.69	17.33	17.60	18.05	21.44	21.43	22.59	23.08	23.37	27.61	
Fe ₂ O ₃ /MgO	2.10	1.72	2.01	1.82	2.26	2.17	2.26	1.85	2.01	2.00	
A/CNK	0.98	0.94	0.90	0.80	0.80	0.99	0.94	0.96	0.96	0.99	
AI	0.47	0.46	0.47	0.60	0.67	0.60	0.54	0.54	0.54	0.63	
(Ga/Al)*10 ⁴	1.89	1.98	1.82	1.95	2.01	2.12	2.20	2.14	2.12	2.28	
Rb/Sr	0.12	0.11	0.09	0.11	0.22	0.15	0.23	0.29	0.31	0.36	
Ba/Sr	1.52	1.68	1.65	2.01	2.31	2.16	2.32	2.87	3.89	3.06	
Ba/Rb	13.07	15.01	18.62	18.17	10.69	14.67	10.31	9.77	12.38	8.54	
Th/La	0.40	0.43	0.36	0.36	0.52	0.46	0.53	0.52	0.53	0.44	
Th/Ta	10.13	10.84	8.46	9.52	10.75	10.48	10.99	17.71	16.69	16.07	
La/Nb	2.97	3.60	2.92	2.91	2.89	3.51	2.47	2.87	4.08	4.57	
Ba/Nb	100.87	122.22	96.55	109.25	112.69	126.19	62.99	70.90	100.63	77.72	
Eu/Eu*	1.09	1.12	0.96	1.05	0.84	1.20	0.93	0.82	0.81	0.63	
(La/Lu) _N	20.01	20.94	16.48	21.84	14.30	13.68	14.27	13.68	14.27	14.91	

Lat., latitude (all locations start with 28°N); Long., longitude (all locations start with 33°E); FeO* refers total Fe is expressed as FeO; (AI = (Na+K)/Al (atom %) is the calculated alipaitic index.

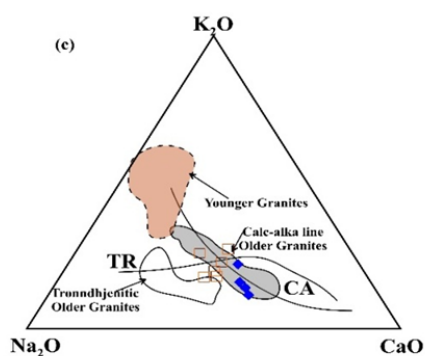


Fig. 9a: Classification diagram of the Egyptian granitic rocks after (Hassan and Hashad 1990). The trondhjemitic (TR) and calc-alkaline (CA) trends are from Barker and Arth (1976).

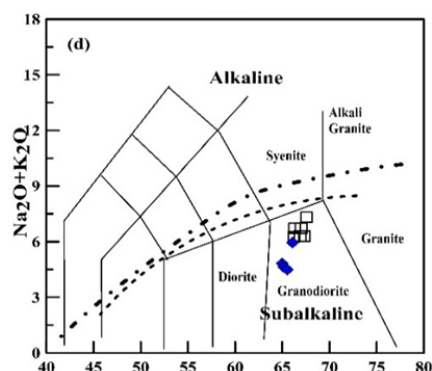


Fig. 9 b: Total alkalis (Na₂O + K₂O) vs. silica (SiO₂) diagram (Le Maitre et al. 1989). Dashed lines of Irvine and Baragar (1971) and Miyashiro (1978) are lines discriminate between alkaline and subalkaline rocks.

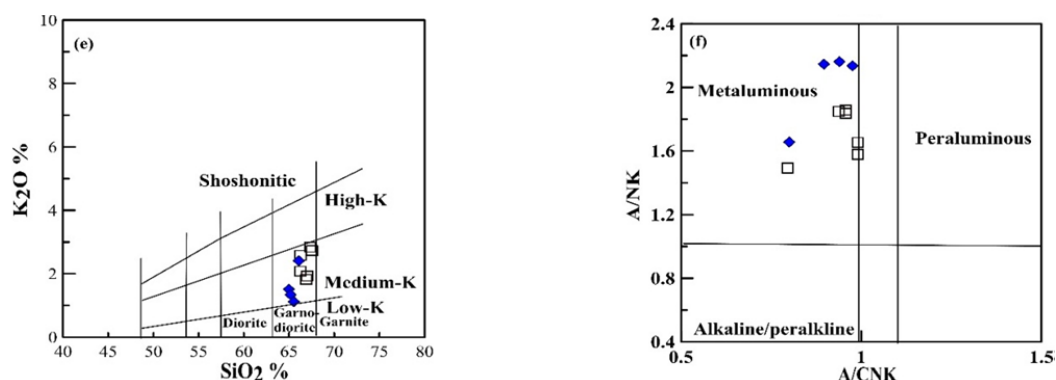
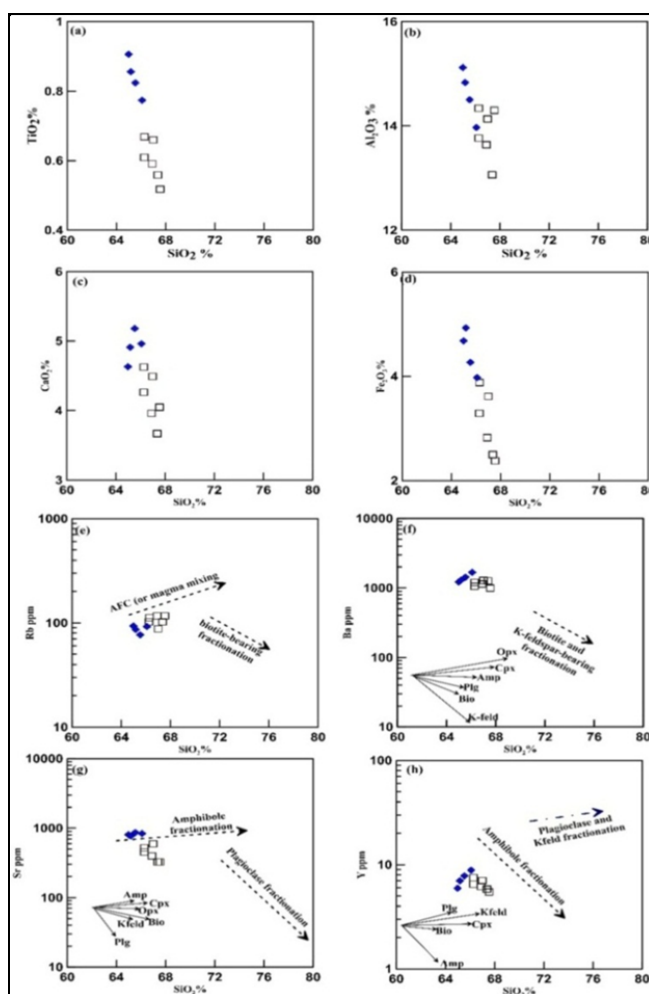


Fig. 10a: K₂O vs. SiO₂ variation diagram for the studied granitic rocks. Fields are after (Rickwood 1989). b: Al/(Na+ K) vs. Al/(Ca+Na+K) (mol.%): fields are after (Maniar and Piccoli 1989).

Harker variation diagrams were used to evaluate major oxides and trace elements variations in the studied granitic rocks. The studied AGR have high contents of Al₂O₃, TiO₂, CaO and Fe₂O₃ (Fig. 11). Most elements of the studied AGR show linear decreases with increasing SiO₂; except K₂O, Na₂O, Rb, Nb, Zr and Ba (Table 6; Fig. 11), which probably indicate fractionation of plagioclase (CaO and Sr decrease), and amphibole (CaO, Fe₂O₃, MgO, TiO₂ and Y decrease). The contents of both K₂O and Ba show an initial increase until 66 wt.% SiO₂ followed by a decrease in the higher SiO₂ range, suggesting the initiation of K-feldspar fractionation (Fig. 11).

Fig. 11: Harker variation diagrams for the studied granites. Arrows indicate theoretical Rayleigh fractionation vectors modeled for crystallization of individual mineral phases. Partition coefficients used for the modeling are from the compilation of Rollinson (1993). Abbreviations: amp = amphibole; plg = plagioclase; K-feld = K-feldspar; bio = biotite; cpx = clinopyroxene; opx = orthopyroxene.



Geochemistry and petrogenesis of the calc-alkaline Granitoids

The near-linear variations of major oxides with silica can be explained either by magmatic differentiation from a common parent melt, or by mixing of melts from two (or more) discrete compositional sources (e.g. mantle- and crust-derived melts), or both. Moreover, the studied granitic rocks have very high FeO/MgO ratios (>1.72 , Table 6), indicating that their parental magmas have experienced extensive magmatic differentiation (e.g., Whalen et al. 1987). The studied granitic rocks have a wide range of CaO/Na₂O ratios being decrease from tonalites to granodiorites (Table 6) and their Al₂O₃/TiO₂ ratios have a negative correlation with CaO/Na₂O ratios (Fig. 12).

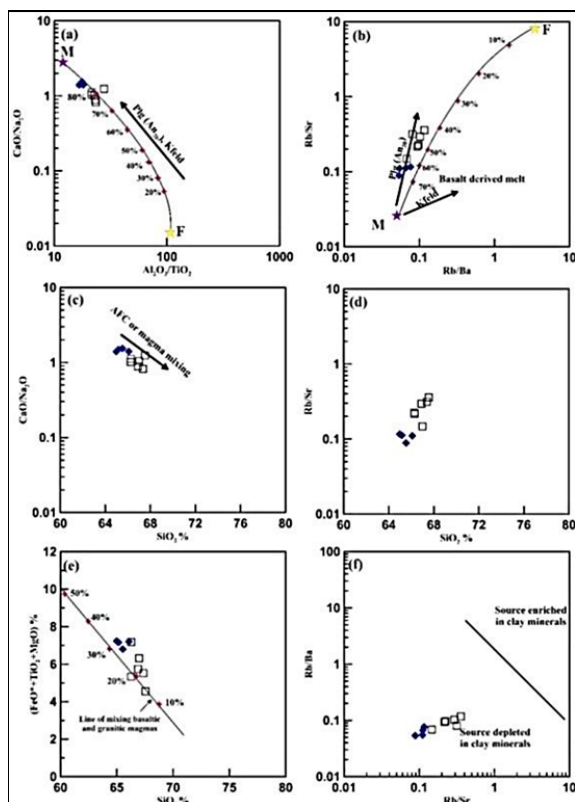


Fig. 12: Variation diagrams for the studied granites. a) CaO/Na₂O versus Al₂O₃/TiO₂ (Sylvester 1998). The line of the mixing of basaltic and granitic melts was calculated between Phanerozoic basalt (Condie 1993) (point M “mafic”) and melt produced from crustal melt is taken as the 850°C, 10 kbar crust-derived (experimental) melt (Point F “Felsic”) after Patiño Douce and Johnston (1991). b) Rb/Ba vs. Rb/Sr diagram. End-member compositions for mafic and felsic melt are the same as in Fig. 12a. c) and (d) Variations of CaO/Na₂O and Rb/Sr, respectively with silica contents of the studied granitic rocks. e) (FeO*+TiO₂+MgO) versus SiO₂ diagram. The line of the mixing of basaltic and granitic melts is the same as in Figure 12a. f) Rb/Ba–Rb/Sr. Dashed line separates the fields of the sources enriched and depleted in clay components (Sylvester 1998).

The concentrations of some incompatible trace elements (e.g., Ba, Sr, and Y) markedly decrease with increasing silica (from tonalites to granodiorites). The geochemical data of the studied granitic rocks shows varying ratios of incompatible elements with low values of Rb/Sr ratio (0.09 to 0.36), low values of Ba/Sr ratio ranges from 0.92 to 1.73 and high values of Ba/Rb ratio (8.54 to 18.62; Table 6). Such variation in these geochemical ratios (e.g., Ba/Rb, Ba/Sr, Rb/Sr and Rb/Ba), indicates high fractionation nature of the studied granitic rocks, which can be attained by magmatic differentiation (Obiora and Ukaegbu 2010; Rajesh 2007; Taylor 1965). The limited variation in the ratios of the incompatible elements of Rb/Sr, Ba/Sr and Ba/Rb for each group of the studied granitic rocks (Table 6) indicates that granitic rock suite was affected by variable degree of partial melting (e.g., Guffanti et al. 1996; Roberts and Clemens 1993).

The values of High Field Strength Elements (HFSE) (U, Zr, Nb, Hf, Ta) and Large Ion Lithophile Elements (LILE) (Cs, Ba, Pb, Sr, and REE) of the studied granitic rocks (Table 6) compared well with the values of average granite and crust of Taylor and McLennan (1985). The enrichment of some of the HFSE like Nb, Hf and Ta in the studied granitic rocks suggests volatile concentrations during the evolution of granites. The contents Rb and Th of the studied AGR (Table 6) show abnormally high values compared to average granite and crust of Taylor and McLennan (1995).

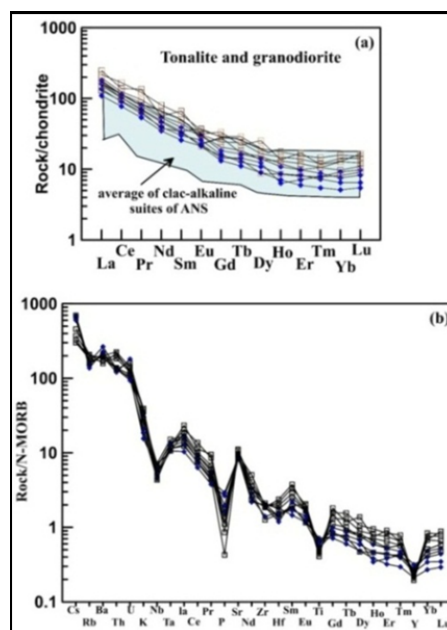
Rare-Earth Elements (REE) concentrations together with statistical parameters are listed in Table 6. The values of High Field Strength Elements (HFSE) (U, Zr, Nb, Hf, Ta) and Large Ion Lithophile

Elements (LILE) (Cs, Ba, Pb, Sr, and REE) of the studied granitic rocks compared well with the values of average granite and crust of Taylor and McLennan (1985). The enrichment of some of the HFSE like Nb, Hf and Ta in the studied granitic rocks suggests volatile concentrations during the evolution of granites. The contents Rb and Th of the studied AGR (Table 6) show abnormally high values compared to average granite and crust of Taylor and McLennan (1995).

The chondrite-normalized REE patterns are presented in Figure (13). All analyzed samples are characterized by fractionation between Light Rare-Earth Elements (LREE) and Heavy Rare-Earth Elements (HREE) (Figs. 13a and b). The high level of enrichment in the LREE relative to the HREE in all the studied granitic rocks suggests a high degree of fractionation. In addition, most of the analyzed samples of AGR are characterized by concave-upward REE profiles resulting from depletion of the middle REE (Gd to Er) relative to the other HREE (Fig. 13a). Moreover, the studied tonalite samples from AGR exhibit highly fractionated REE patterns $[(La/Lu)_N = 16.48-21.84]$, whereas the studied granodiorite samples are less fractionated $[(La/Lu)_N = 13.68-14.91]$. Generally, the studied AGR are characterized by moderately fractionated HREE segments, and have slight or no negative Eu anomalies ($Eu/Eu^* = 0.63-1.20$; Fig. 13a). Moreover, the REE concentrations of the studied AGR are conformable with those of calc-alkaline granitoids granites from the ANS (Fig. 13).

MORB-normalized element patterns for the studied granitic rocks (Fig. 13b) exhibiting enrichment in the most incompatible elements (e.g., Rb, Ba, and Th) with respect to the LREE, and show decreasing of the enrichment factor with increasing compatibility of the elements (Fig. 13b). Moreover, the studied granitic rocks show an overall enrichment in large ion lithophile elements (LILE; Rb, Ba, Th, U, K) compared to normalization values and prominent negative anomalies for high-field-strength elements (HFSE; Ti, Hf, Zr, Nb and Ta). The depletion of the HFSE are characteristic of subduction-related magmas and may be attributed to crustal contamination and are thought to be resulted from the relative enrichment of mantle source by the influx of LILE from the dehydrating slab (e.g., McCulloch and Gamble 1991). Furthermore, the studied granitic rocks show prominent negative P anomalies (Fig. 13b) suggesting the influence of apatite and/or hornblende in the fractionating assemblages of granitic magmas.

Fig. 13: (a) Chondrite-normalized REE patterns for the studied granitic rocks. Normalizing values are from Sun and McDonough (1989). Fields of the calc-alkaline suite in the ANS are adapted from Azer (2013). (b) N-MORB normalized multi-element patterns of trace elements in the studied granitic rocks. N-MORB concentrations from Sun and McDonough (1989).



DISCUSSION

Magma types and constraints on potential sources

Based on the aluminum saturation index and the mineral composition of the analyzed biotite, the studied granitic rocks exhibit an increase in alkaline character from tonalites to granodiorites. The relatively low agpaitic index (<1) for the studied AGR evidences their calc-alkaline nature and they are

related to I-type granite (Figs.14a and b). Furthermore, the studied AGR are magnesian and have low $10^4 \times \text{Ga}/\text{Al}$ ranging from 1.82 to 2.28 with an average 2.05, which is comparable with the average of I-type granite.

The nature of the parent melts forming the granitic magmas can be obtained from the least-differentiated samples of the granitic suites (e.g., Kessel et al. 1998; Mushkin et al. 2003). For the studied AGR, tonalites represent the least-evolved granitic rocks (e.g., the less siliceous granitic samples). They have high Ba and Sr concentrations, and their REE patterns are characterized by concave-upward patterns without significant Eu anomalies (Fig. 13a). These features seem to indicate a plagioclase (and garnet)-poor, but amphibole rich sources (e.g., Bacon and Druitt 1988; Grove and Donnelly-Nolan 1986; Hildreth and Moorbath 1988; Koprubasi and Aldanmaz 2004). Wyllie (1984), introduces experimental evidence, for the generation of granitic magmas from the dehydration melting of metabasaltic sources by AFC processes toward more felsic compositions. Moreover, Douce and McCarthy (1998), introduced similar experiments suggesting that the dehydration melting of K-rich metabasaltic sources yield strongly peraluminous melts, which is in contrast with the predominantly metaluminous nature of the studied AGR. Furthermore, they are medium-K type (Fig. 10a), therefore, partial melting of the solely metabasaltic rock is not a suitable source for the studied AGR, because metabasaltic rocks have low K_2O contents (e.g., Rapp and Watson 1995; Roberts and Clemens 1993).

The medium-K contents and high Fe/Mg ratios of the studied AGR (Fig. 10a, Table 6), indicated that their primary liquid source should be most likely a metaluminous protolith. Moreover, they are characterized by high abundances incompatible trace elements (LILE, HFSE) with slightly negative Nb and Ta anomalies, which could not be explained by direct derivation from crustal protoliths. The combined negative Nb-Ta and Zr-Hf anomalies (Fig. 13b) and the relatively high values of Th/Ta, La/Nb, and Ba/Th (Table 6) indicate derivation of these granitoids from subduction-modified mantle source (e.g., Beyth et al. 1994; Jarrar et al. 2008; Kessel et al. 1998; Mushkin et al. 2003; Stern and Voegeli 1987).

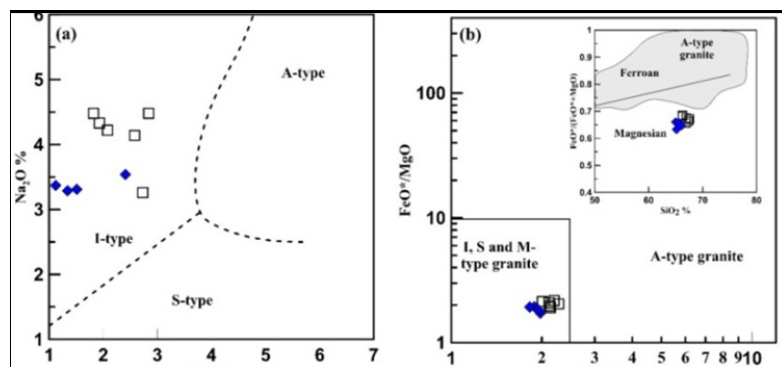


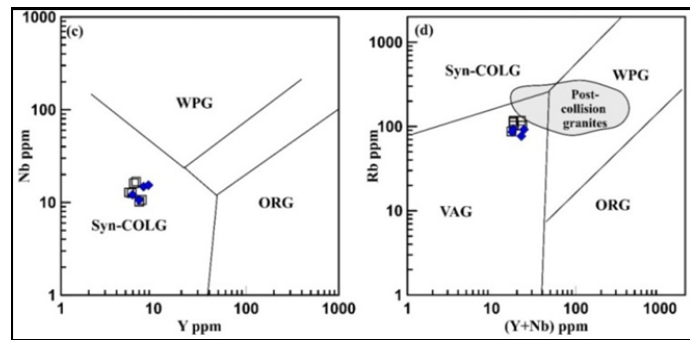
Fig. 14: Discrimination diagrams for the studied granitic rocks (a) K_2O versus Na_2O (Collins et al. 1982) (b) $10^4 \times \text{Ga}/\text{Al}$ versus FeO^*/MgO (Whalen et al. 1987). The inset diagram shows the variation of SiO_2 versus $\text{FeO}^*/(\text{FeO}^* + \text{MgO})$ (Frost et al. 2001).

Tectonic setting

I-type (subduction-related) and S-type granites (collision-related) were identified by Chappel and White (1974). Later, the A-type (Collins et al. 1982) and M-type granites (Whalen et al. 1987) were recognized to accommodate within-plate granites and granites generated in oceanic arc tectonic environments, respectively. Pearce et al. (1984) suggested several diagrams for discriminating a variety of tectonic settings of granites. The studied AGR plot in the fields of syn-collision (Syn-COLG) and volcanic arc granites (VAG) (Figs. 15 a and b, respectively). In addition, based on the tectonic settings of the granitic rocks proposed by Maniar and Piccoli (1989; Fig. 7), the studied AGR samples plotted in the overlapped fields of calc-alkaline granite (CAG) and island arc granite (IAG).

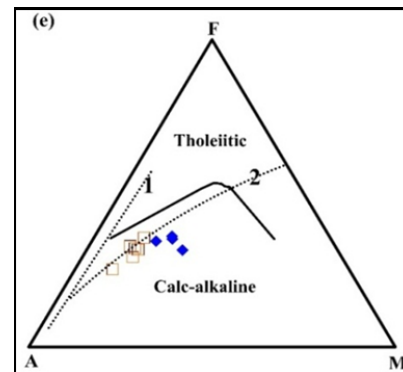
The plots of the studied granitic rocks on the AFM diagram could be used to differentiate between compressional and tensional suites (Fig. 16). The investigated AGR samples are arranged on trend that tends to be nearly perpendicular to the F-M sideline for the entire trend pointing to compressional environment suggested by Petro et al. (1979).

Fig. 15: (a) Nb versus Y (Pearce et al. 1984). (b) Rb versus Y+Nb (Pearce, 1996). The shaded area points to the compositions of post-collision granitoids from Küster and Harms (1998).



The chemistry of the analyzed plagioclase indicates that the AGR have relatively high values of $\text{CaO}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ ranging from 0.25 to 1.09 (Table 3), which indicate calc-alkaline nature (Macdonald et al. 1987). In addition, Nachit et al. (1985) used the composition of biotite as an indicator for the nature of original parent magmas. They concluded that the chemical composition of biotite could discriminate among peraluminous (P), calc-alkaline (C), subalkaline (SA) and alkaline-peralkaline (A-PA) granites. The analyzed biotites plot in the calc-alkaline and subalkaline fields. Moreover, Abdel-Rahman (1994), suggested that the nature of the parental magmas from which the granitic rocks were originated could be assigned according to the composition of their igneous biotite. Moreover, Abdel-Rahman (1994) distinguished that, the biotite in alkaline (mostly anorogenic extension-related) suites including A-type granites are mostly iron-rich siliceous annite (av. FeO^*/MgO ratio of 7.04), whereas those in peraluminous suites are siderophyllitic in composition (av. FeO^*/MgO ratio of 3.48), whereas those in calc-alkaline, subduction-related orogenic suites are moderately enriched in MgO, with an average FeO^*/MgO ratio of 1.76. The FeO^*/MgO ratio of the analyzed biotite from AGR ranges from 1.5 to 4.59 with an average of 2.96, which is similar to the composition of biotite from calc-alkaline, subduction-related orogenic suite (Fig. 4d). Moreover, the $\text{Fe}/(\text{Fe}+\text{Mg})$ ratios of biotites from the studied AGR (0.46-0.62; Table 2). Anderson et al (1980) suggested that the $\text{Fe}/(\text{Fe}+\text{Mg})$ ratios of biotite depend on the oxygen fugacity. In a high $f\text{O}_2$, biotite can be oxidized and becomes rich in Mg. Therefore, the Mg-rich biotite of the investigated AGR reflects low oxygen fugacity during their formation. In addition, the high MgO contents of biotite from the studied AGR suggest a high temperature of crystallization (Klob 1970).

Fig. 16: AFM diagram after Irvine and Baragar (1971) and dashed lines 1 & 2 represent extensional and compressional suites after Petro et al. (1979)



The investigated I-type AGR are mainly granodiorite with subordinate tonalite, displaying metaluminous, calc-alkaline geochemical characteristics, and characterized by the scarcity of alkali feldspar, higher An contents, and higher mafic and iron-oxides contents. Wadi El-Akhder granitic rocks are depleted in SiO_2 , K_2O , Rb, Pb, Cr and have high proportions of MgO, FeO^* , TiO_2 , CaO, P_2O_5 and Sr contents. This suggests a mantle origin for the AGR as supported by the low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios (0.7029 ± 0.0008) in Sinai (Brelski 1982). Based on these characteristics, it is believed that these rocks are subduction-related granites resultant from partial melting of mafic source, leaving garnet- or amphibole-rich residues (Arth and Hanson 1975). A correlation was found between the depth of origin and the Sr/Rb ratio (Condie 1973). This feature is explained as a consequence of Sr fractionation between solid and liquid phases. Higher Sr/Rb ratios are an outstanding feature for greater depth (Condie 1973). The studied AGR have high Sr/Rb ratio (av. 8.76) indicating that magma formation started at intermediary or even

greater depths (>40 km; El-Tokhi et al. 2009). Furthermore, the multi-element spider plots could be used as an effective indicator for the discriminating the tectonic setting of the Egyptian granitoids rocks, especially the calc-alkaline (I-type) ones (Moghazi 2002). It is believed that the Egyptian calc-alkaline trondhjemite–tonalite–granodiorite suites were formed during the pre-collision (arc) stage between 715 and 685 Ma and prevailed during the collision stage between 665 and 614 Ma (Greiling et al. 1994; Stern and Hedge 1985). The multi-element spider plots normalized to N-MORB for the studied AGR (Fig. 13b), are generally more akin to those of the pre-collision (arc) stage (I-type) granites. However, they exhibit slightly higher Sr, K, Rb and Ba contents, approaching those of the collision stage granites from the Eastern Desert of Egypt and possibly reflecting a more advanced stage of the arc formation. Accordingly, the studied granites are typical examples for I-type granites of the ANS (Fig 10a).

Petrogenetic considerations

Fractional crystallization

The studied granitic rock exhibiting well-defined negative correlation trend of silica with some major oxides and trace elements contents (Fig. 6). This trend could be resulted from fractional crystallization of major and minor phases during the evolution of both granitic suites. The observed systematic variations of trace elements (Rb, Ba, Sr and Y) from tonalite to granodiorite in the studied AGR (Fig. 11) are ascribed by increasing fractionation of plagioclase and K-feldspar, accompanied by amphibole, biotite, and accessory phases, such as titanite, apatite, zircon, and allanite (Fig. 11; Table 5). Such a fractionation trend is also suggested by the variation in modal compositions that define magmatic differentiation from tonalite to granodiorite in the AGR (Figs. 5a and b). In addition, the REE chondrite-normalized pattern (Figs. 13a and b) for each of the studied granitic types are similar and exhibiting LREE enrichment with HREE depletion patterns indicating the influence of the fractional crystallization in the studied granitic types. Moreover, the absence of pronounced Eu anomalies in the AGR samples coupled with the concave-upward REE profiles (Fig.8a), which resulting from depletion of the middle REE (Gd to Er) relative to the other HREE could be attributed to the fractionation of hornblende, which is the major constituent for the MREE. In addition, the analyzed samples from AGR exhibiting a negative correlation between Y and SiO₂ (Fig. 6h), and show marked negative anomalies of Y in the multi-element spider diagrams normalized to N-MORB (Fig. 8b), indicating fractionation of hornblende (Pearce and Norry 1979). On the other hand, the absence or small negative anomalies of Eu, Ba and Sr (Fig. 13) coupled with a weak negative correlation of Ba and Sr with increasing SiO₂ (Fig. 11) in the studied AGR suggest that the fractionation of plagioclase has no important role in the evolution of the AGR.

The studied granitic rocks show a negative correlation of TiO₂ and P₂O₅ with increasing SiO₂ (Fig 6a; Table 6), which could be explained by the fractionation of titanomagnetite and apatite, respectively. Moreover, the depletion of Zr in the studied granitic rocks (Fig. 13b) may be due to the fractionation of accessory phases such as zircon and allanite. In addition, the studied granodiorites have higher SiO₂ contents than those of tonalites, but the former have the lowest values of Ba (Fig. 11f) which may account for biotite fractionation at the final stage of the magmatic process for AGR.

Evidence for magma mixing

The petrographic investigations of the studied AGR revealed that not only the fractional crystallization played a role in the modification of their parental melts but also magma mixing is contributed. Wadi El-Akhder granitic rocks include both mafic and felsic enclaves of varying sizes, shapes and compositions as well as common textural evidence that is account for interaction of mafic and silicic magmas such as quartz ocelli and complex zoning in plagioclase (e.g., Ahmad 2011; Baxter and Feely 2002; Choe and Jwa 2004; Palivcova et al. 1995).

The geochemical data of the studied AGR shows that these rocks lack of pronounced Eu anomalies (Fig.13a) and their contents of Sr, Ba, and Rb have weak correlation with SiO₂ (Fig. 11). These features indicate that fractional crystallization was not the most important compositional modification process and that chemical variations may have been largely blurred by accumulation and mixing of melts (Koprubasi and Aldanmaz 2004). The most important process in generating much of the geochemical variation of the studied AGR appears to be resulted from the variable degree of partial melting and degree of relative

mixing between mafic and felsic melts. In addition, tonalites and granodiorites of the studied AGR exhibiting a continuous trend of major-element variations, also support mixing of magmas formed by partial melting of mafic sources (e.g., Baxter and Feely 2002; Frost and Mahood 1987; Guffanti et al. 1996; Hibbard 1991; Reid et al. 1983).

The exchange of elements between the mafic melts and crustal contaminants during melting represents an important factor that may affect the element distribution of granitic melts (Miller and Mittlefehldt 1982; Mittlefehldt and Miller 1983). According to Sylvester (1989) and Jung and Pfänder (2007), the granitic melt generated from crustal sources of sedimentary origin tend to have lower CaO/Na₂O ratio (<0.2) than melts produced by melting of mafic compositions because the anorthite component of plagioclase in most crustal lithologies is quite low. However, derivation of granitic compositions from either crustal melts or more mafic mantle melts and subsequent fractionation of likely mineral assemblages will create similar trends that are characterized by an increase of the CaO/Na₂O ratio with an increasing silica content of the melt. The same conclusion will be reached when considering the variation in the Al₂O₃/TiO₂ ratio. The studied AGR show high CaO/Na₂O ratios (0.82-1.54) being a decrease from tonalite to granodiorites, they have also high Al₂O₃/TiO₂ ratios (16.69-27.61) increasing toward the higher silica granitic type (granodiorites). These features indicate that emplacement of these granitoids was strongly affected by magma mixing of felsic and mafic melts.

High-alumina granitoids can result either from the melting of a psammite (graywacke) source or from the mixing of basaltic melt with granitic melt produced from metapelites (Sylvester 1998). Considering the studied AGR, the mixing of mafic and felsic sources are supported by the high total contents of FeO*, MgO, and TiO₂ in the tonalite (6.81-7.224 wt.%), granodiorite (4.55-7.18 wt.%), which are relatively higher (Table 6) than those in granitoids melted out from a pure metapelitic source (Fig. 12e). Such effects can best be observed in the variations of major oxide ratios such as CaO/Na₂O and Al₂O₃/TiO₂ between mantle-derived mafic melts and crustal protoliths (Fig. 12a). The compositional points of AGR members (tonalites and granodiorites) are plotted close to the line of mixing of melts of different compositions in the CaO/Na₂O – Al₂O₃/TiO₂ and (FeO*+MgO+TiO₂) against SiO₂ diagrams (Fig. 12a and e). In addition, all the studied granitic rocks are characterized by low Rb/Ba (0.05–0.15) and Rb/Sr (0.09–0.18) ratios and the location of their composition points in the field of sources depleted in clay minerals (Fig. 12f). Moreover, the plots of Rb/Sr vs. Rb/Ba for the studied AGR exhibit a linear array of increasing Rb/Sr with Rb/Ba (Fig. 12b), supporting the effects of variation in crustal contamination of mantle-derived basaltic magma.

DePaolo (1981) stated that the ratio of Th/La in granitic rocks could be used as indicator for the effects of crustal contamination of the magma derived from a component that is more mafic than the contaminant. The studied granitic rocks exhibit increasing ratio of Th/La with increase in silica content (Fig. 17b), indicating the effects of crustal contamination of a magma derived from a component that is more mafic than the contaminant. The rocks from the AGR plot mostly along AFC trajectories drawn for $r = 0.3$ and 0.5 . The results obtained from the variation of Th/La ratios of the studied granitic rocks confirming the interpretation from both the major- and trace-element data (Fig. 12), which indicate the more pronounced effects of crustal contamination (or mixing) during the emplacement of the studied granitic rocks.

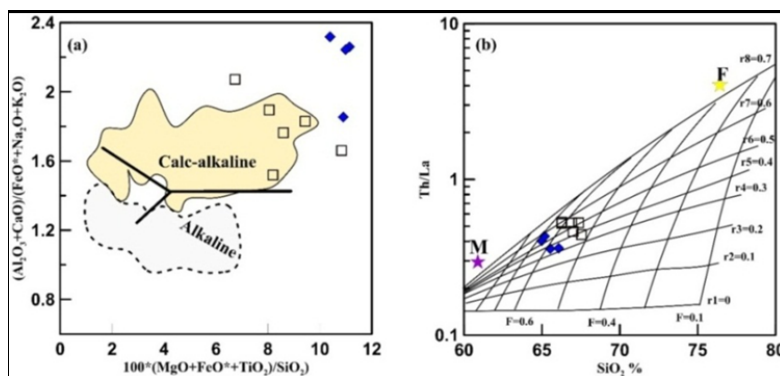


Fig. 17: (a) Discrimination diagram of Sylvester (1989); the calc-alkaline and alkaline fields of the ANS are adapted from Be'eri-Shlevin et al. (2009). (b) Modeling of the assimilation and fractional crystallization (AFC) process based on DePaolo (1981) and using the assimilation-sensitive ratio of Th/La. Selected source and contaminant end-member compositions represent the average enriched mantle-derived basaltic melts and average crustal composition, respectively (Aldanmaz et al. 2000). The F value denotes the ratio of magma mass to original magma mass.

CONCLUSIONS

The area of Wadi El-Akhder comprises syn-tectonic granitoids (AGR). Geochemically, the AGR are medium-K, calc-alkaline, metaluminous tonalite–granodiorite suite related to I-type granites that is formed during the pre-collision (arc) stage of the evolution of the ANS continental crust. The studied AGR are characterized by high abundances incompatible trace elements (LILE, HFSE) with slightly negative Nb and Ta anomalies, this could not be explained by direct derivation from crustal protoliths. The combined negative Nb-Ta and Zr-Hf anomalies and the relatively high values of Th/Ta, La/Nb, and Ba/Th of the AGR refers to derivation from subduction-modified mantle source. AGR show high CaO/Na₂O ratios (0.82-1.54) being a decrease from tonalite to granodiorites, whereas they have also high Al₂O₃/TiO₂ ratios (16.69-27.61) increasing toward the higher silica granitic type (granodiorites). These features indicate that emplacement of these granitoids were strongly affected by magma mixing of felsic and mafic melts.

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Mogahed, M. M.

جيوكيميائية وأصل نشأة صخور الجرانيتات الكلسي - قلووية في شمال الدرع العربي النوبي. حالة دراسية من جرانيتات وادي الأخضر، جنوب سيناء، مصر

مصطفى محمد مجاهد

كلية العلوم - جامعة بنها

الخلاصة

تعد صخور الجرانيتات ذات النشأة النارية والتي تكونت في مراحل قبل التصادم من حركة البان أفريقية البانية للجبال خلال حقبة النيوبروتيروزي من أكثر الصخور انتشاراً في جنوب سيناء حيث أنها تمثل حوالي ٣٠% من صخور القاعدة . وتقدم هذه المخطوطة دراسات بترولوجية وجيوكيميائية بالإضافة الي تحليل كيميائي للمعادن الأساسية لصخور الجرانيتات القديمة الموجودة في منطقة وادي الأخضر وذلك كمحاولة لفهم الوضع التكتوني وأصل نشأة هذه الصخور . إن صخور الجرانيتات القديمة بمنطقة وادي الأخضر بجنوب غرب سيناء تتكون أساساً من صخور الجرانوديورايت بالإضافة الي صخور التوناليت. وهذه الصخور تحتوي على نسبة بوتاسيوم وألمونيوم متوسطة وتنتمي للصخور الكلسي-قلوية والتي تكونت في منطقة أقواس الجزر البركانية. أظهرت التحاليل الكيميائية لصخور الجرانيتات المدروسة أنها تحتوي على نسب منخفضة من أكاسيد الحديد والماغنسيوم والمنجنيز والكالسيوم وكذلك الاسترانسيوم والباريوم والفانديوم في حين أنها تحتوي على نسب عالية من أكاسيد الصوديوم والبوتاسيوم وكذلك عناصر النيوبيوم والتاليوم والزيرون والثوريوم والريبيديوم . كما أن هذه الصخور تضم نسب مرتفعة من العناصر الأرضية النادرة الخفيفة والعناصر كبيرة الحجم منخفضة الشحنة ونسب منخفضة من العناصر كبيرة الحجم وعالية الشحنة مقارنةً بصخور أعراف وسط المحيط العادية. وتظهر الصخور المدروسة اتجاهات تدل على أنها نشأت من ماجما في منطقة الوشاح تأثرت بعملية التمايز الصهيري وأنها تعرضت لمراحل من التلوث الصهيري أثناء تطورها. وتؤكد هذه المخطوطة بأن الخصائص الكيميائية لصخور الجرانيتات المدروسة بمنطقة وادي الأخضر بجنوب سيناء تتشابه مع صخور جرانيتات الدرع العربي النوبي المتكونة بمناطق الانضواء.