Petrogenesis and Tectonic Evolution of I- and A-Type Granites of Mount Abu Kibash and Tulayah, Egypt: Evidence for Transition from Subduction to Post-Collision Magmatism

Amr El-Awady 1,*, Mabrouk Sami 2,*, Rainer Abart 3, Douaa Fathy 4, Esam S. Farahat 4, Mohamed S. Ahmed 5, Hassan Osman 4 and Azza Ragab 6

1 Geology Department, Faculty of Science, Zagazig University, Zagazig 44519, Egypt
2 Geosciences Department, College of Science, United Arab Emirates University, Al Ain 15551, United Arab Emirates
3 Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria; rainer.abart@univie.ac.at
4 Geology Department, Faculty of Science, Minia University, El-Minia 61519, Egypt; douaaafathy@mu.edu.eg (D.F.); esamfarahat1@mu.edu.eg (E.S.F.); hassanosman@mu.edu.eg (H.O.)
5 Geology and Geophysics Department, College of Science, King Saud University, PO. Box 2455, Riyadh 11451, Saudi Arabia; mohahmed@ksu.edu.sa
6 Department of Geology, Faculty of Science, Mansoura University, El-Mansoura 35516, Egypt; azzaragab@mans.edu.eg

* Correspondence: amelawady@zu.edu.eg or mora_72003@yahoo.com (A.E.-A.); mabrouksami@uaeu.ac.ae (M.S.)

Abstract: The Neooproterozoic granitic rocks of Mount Abu Kibash and Tulayah in the central Eastern Desert of Egypt are of geodynamic interest and provide us with important information about the evolution and growth of the northern part of the Arabian–Nubian Shield (ANS) continental crust. They are primarily composed of granodiorites and syenogranites based on new field, mineralogical, and geochemical analyses. The granodiorites are marked by an enrichment of LILEs such as Sr, K, Rb, Ba compared to HFSEs like Nb, Ta, Ti and show a higher concentration of LREEs relative to HREEs. This composition suggests a subduction-related setting and aligns with the characteristics of subducted I-type granites in the ANS. Chemistry of the analyzed primary amphiboles in the investigated granodiorites support a calc-alkaline nature, mixed source and subduction-related setting. The granodiorites represent an early magmatic phase in this setting, likely formed from a mix of mantle-derived mafic magmas and lower crust material, with subsequent fractional crystallization. On the other hand, syenogranites exhibit high SiO2 (72.02–74.02 wt%), total alkali (7.82–8.01 wt%), and Al2O3 (13.79–14.25 wt%) levels, suggesting their derivation from peraluminous (A/CNK > 1) parental magmas. Their REE-normalized patterns are flat with a pronounced negative Eu anomaly, typical of post-collisional A2-type granites worldwide. These rocks originated from the partial melting of a juvenile lower crustal source (tonalite) in a post-collisional setting, driven by lithospheric delamination that facilitated mantle upwelling and underplating to the lower crust. Interaction between the upwelled mantle and lower crust led to fertilization (enrichment with HFSE and alkalis) of the lithosphere before partial melting. Fractional crystallization coupled with less considerable crustal assimilation are the main magmatic processes during the evolution of these rocks. The transition from subduction to post-collisional setting was accompanied by crustal uplifting, thickening and extensional collapse of ANS continental crust that caused emplacement of large masses of A-type granites in the northern ANS.

Keywords: neooproterozoic; I- and A-type granites; subduction; peraluminous; post-collisional; Egypt
1. Introduction

The Neoproterozoic Arabian Nubian Shield (ANS) covers large areas in NE Africa and Arabia and was generated during the Pan-African Orogeny (900–550 Ma; [1]), which represents one of the most extensive episodes of continental crust formation in the Earth's history. The Late Neoproterozoic Pan-African Orogeny (PAO) encompasses subduction, accretion, and extension (rifting) processes together with an intervening collisional event [2]. This event produced widely distributed granitoids as an outstanding trait of the late development of the PAO, especially in the northern part of Egypt. The ANS consists mainly of juvenile Neoproterozoic crust that was formed by the protracted accretion of the island arcs [3] (Supplementary Figure S1). This juvenile crust was trapped between the continental regions of East and West Gondwana. The continental collision happened 640–650 Ma, following the accretion stage, which is believed to have ended ~700 Ma [4]. The post-collision stage took place between 630 and 580 Ma and was characterized by the emplacement of alkaline, calc-alkaline, and tholeiitic magmatism during the late Neoproterozoic time [5]. The generation of syn-orogenic calc-alkaline magmatism was related to subduction and collision events, while high-K calc-alkaline, alkaline, and peralkaline rocks were formed later as post-collisional magmatism during the final stages of the Pan-African orogeny (650–550 Ma) [6]. Granitic rocks occupy vast areas of about 60% of the exposed basement rocks of the ANS, specifically in the Eastern Desert of Egypt, Saudi Arabia, and Sudan [7]. Understanding the origin of granitic rocks helps us to constrain the geodynamic evolution beneath the northern ANS [8].

Granitic rocks are notably prevalent in the central part of the Egyptian Eastern Desert, which forms a significant section of the western ANS. In the Eastern Desert, granitic rocks are traditionally classified into two primary groups based on their age, petrography, and geochemistry: the older and younger suites. The older suite (850–610 Ma) characterized as grey, calc-alkaline, and syn-tectonic varies from diorites to granodiorites and occasionally to granites. Conversely, the younger suite (610–550 Ma) comprises pink to red granitic rocks that are calc-alkaline to alkaline and developed during late stage to post-tectonic phases, encompassing both I-type and A-type granites [9]. The relationship between these suites, indicative of late to post-collisional geological events, is still under scrutiny and remains unresolved. Mount Abu Kibash and Tulayah lie in the central Eastern Desert of Egypt (Figure 1) and comprise two different granite phases: granodiorites and syenogranites. These Neoproterozoic granitic rocks have different types, ages, and tectonic settings.

![Figure 1](image_url)

Figure 1. (a) Geological map of the central Eastern Desert of Egypt exhibiting the distribution of granitoids and other rock units of the basement rocks adjacent to the studied area (modified after [10]). (b) Geological map of Mount Abu Kibash and Tulayah in the central Eastern Desert of Egypt.

This paper presents the first comprehensive mineralogical and geochemical analyses of two distinct types of granitic rocks from Mount Abu Kibash and Tulayah: subduction-
related I-type granites and post-collisional A-type granites. The objective of this study is to explore the petrogenesis and geodynamic evolution of these granitic rocks as they transition from arc (subduction-related) to within-plate (post-collisional) settings within the ANS. Understanding the genesis of the investigated granitic rocks has important implications for continental crust growth in general and particularly for the ANS. This study also discusses the magmatic sources for the investigated granitic rocks and their crystallization conditions as well as the role of crustal contamination and fractional crystallization during their evolution.

2. Geologic Features and Petrography

Mount Abu Kibash and Tulayah, which are located roughly 45 km northwest of Mersa Alam city (Figure 1a), showcase a diverse geological makeup, including serpentinites with island-arc characteristics and various intrusive granitic rocks (Figure 1b). Serpentinites, among the oldest geological units in the area, are typically small outcrops in the eastern part of the mapped area, showing significant deformation and lineation. The granitic rocks in this region mainly consist of granodiorites, which are later intruded by syenogranites. The granodiorites form a massive outcrop with low to moderate relief to the east of the mapped area. These granodiorites, presenting a dark gray color and a medium to coarse grain, contain mafic xenoliths (Figure 2a), sometimes displaying a gneissic texture due to shearing and cut by dykes of different chemical composition. In general, the I-type granitoids of the central Eastern Desert have an absolute age of 710–630 Ma [11].

![Figure 2. Field photographs of Mount Abu Kibash and Tulayah granitic rocks in the central Eastern Desert of Egypt. (a) Rounded mafic xenolith hosted in granodiorite. (b) High relief syenogranite at Mount Abu Kibash.](image)

Syenogranites, covering an area of about 5 km², are situated on the western side of the study area, representing the most recent igneous activity. They represent the southward extension of Homrit Waggat syenogranites that have an absolute age of 628.3 ± 3.9 Ma by using zircon U–Pb zircon geochronology [12]. This rock type forms a moderately high hill (Figure 2b) that rises about 850 m above sea level and is elongated in a NW-SE direction (Figure 1b). The syenogranites are massive, coarse-grained, and predominantly pink to pinkish-grey, occasionally containing rare granodiorite xenoliths. In some places, especially the peripheries, local pegmatite and fluorite veins are present. Quaternary stream sediments extensively blanket the areas between various hills, with Wadi El Faliq serving as the primary stream traversing the study area.

Granodiorites are medium- to coarse-grained and exhibit hypidiomorphic granular texture (Figure 3a,b). They consist essentially of plagioclase (45–50 vol. %), quartz (20–30 vol. %), and K-feldspars (15–20 vol. %) as well as mafic minerals (2–3 vol. %) (Figure 3a,b). Accessory minerals are represented by zircon, apatite, titanite and Fe–Ti oxides (Figure 3b). Plagioclase (An16-17) is the common constituent and forms subhedral to anhedral prismatic twinned crystals. They are corroded along their peripheries by quartz
and myrmekitic texture at the contact with K-feldspars. They sometimes show zonation with sericitized altered cores and fresh rims, suggesting normal zoning. K-feldspars are represented by orthoclase and microcline perthite and mostly form anhedral crystals that fill the interstices between other phases. They are slightly sericitized and kaolinitized and sometimes corroded by host quartz, plagioclase and biotite crystals. Quartz forms anhedral grains that mostly fill interstices between other constituents (Figure 3a,b). Mafic minerals are represented by biotite and amphiboles (Figure 3a,b). Biotite is commonly fresh and mostly forms strongly pleochroic flakes and aggregates (Figure 3a). They are sometimes partly replaced by chlorite and iron oxides along their cleavage planes. Amphiboles mostly coexist with biotite as clusters (Figure 3a,b), as they represent a late crystallization stage of granodiorite melt. They mostly form subhedral, cracked, prismatic crystals that sometimes host apatite, sphene, magnetite and ilmenite inclusions (Figure 3b). Zircon occurs as prismatic euhedral crystals with pyramidal ends and high relief and sometimes show zonation. It is enclosed in quartz and biotite and forms pleochroic radioactive halos when hosted in the later mineral. Apatite occurs as needle-like and six-sided crystals enclosed in quartz and biotite. Titanite forms anhedral to subhedral small inclusions and wedge-shaped crystals hosted in biotite.

Figure 3. Photomicrographs and back-scattered electron (BSE) images showing the main petrographic features of Mount Abu Kibash and Tulayah granites: (a) aggregations of biotite (Bt), amphibole (Amph), plagioclase (Plg), K-feldspar (Kfs), and quartz (Qtz) reflecting a typical hypidiomorphic
texture of the studied granodiorite; (b) a close up BSE image within granodiorite showing the main mineral phases with the occurrence of ilmenite (Ilm) as an inclusion in amphiboles, (c) the occurrence of coarse- to medium-grained Bt, Plg, Kfs, and Qz minerals with hypidiomorphic texture in syenogranites; (d) BSE image showing the occurrence of magmatic biotite and the mutual relation between the mineral phases in syenogranites, (e) the occurrence of muscovite (Mus) in some syenogranite samples and forming with other minerals a hypidiomorphic texture (f) BSE image of a large ilmenite crystal sharing boundaries with muscovite and quartz in syenogranites.

Syenogranites are coarse-grained rocks with hypidiomorphic equigranular texture (Figure 3c–f). They consist chiefly of K-feldspar (35–40 vol. %), quartz (25–30% vol. %), and plagioclase (15–20% vol. %) as well as subordinate amounts of biotite and amphibole (~10 vol. %) (Figure 3c–f). Zircon, Fe–Ti oxides, apatite, and titanite are accessories while sericite, kaolinite, and chlorite represent secondary phases (Figure 3e,f). K-feldspar forms subhedral to anhedral tabular crystals of perthite and orthoclase perthite with minor microcline. Perthite grains sometimes have albite stringers and coarse patches. They are slightly altered to sericite and kaolinite and mostly corroded by quartz (Figure 3e). Quartz forms anhedral, interstitial grains (Figure 3c,e) and is sometimes intergrown with K-feldspars to form graphic texture. It sometimes hosts small plagioclase laths and biotite flakes. Plagioclase (An15–26) mostly occurs as subhedral prismatic crystals and sometimes as fine laths (Figure 3c,e). They are sometimes partly replaced by sericite and/or clay minerals, and few crystals show normal zoning (Figure 3c,e). Biotite flakes mostly fill the interstices between quartz and feldspars and are sometimes hosted in K-feldspars (Figure 3c,d). Primary muscovite mostly forms subhedral flakes that are interstitial to feldspars and quartz (Figure 3e,f). Zircon forms fine isolated euhedral crystals hosted mostly in biotite. Fe–Ti oxides (ilmenite and magnetite) occur as individual, subhedral subhedral crystals that are associated with and hosted in mafic minerals (Figure 3f). Apatite occurs as long rod-shaped crystals hosted in quartz and biotite. Titanite mostly forms wedge-shaped crystals and sometimes occurs as subhedral or granular crystals.

3. Materials and Methods

A complete description of the analytical methods is provided in the Supplementary Document S1. Here, we briefly explain the methods used in this study. Thirty-six refined polished thin sections were prepared for mineralogical and petrographic studies using an optical polarizing microscope in the Geology Department, Minia University (Egypt). A subset of these sections was selected and coated with carbon for analysis of major minerals using a CAMECA SX5 electron microprobe (CAMECA, Gennevilliers Cedex, France) at the Department of Lithospheric Research, University of Vienna (Austria). Calibration against both natural and synthetic standards was conducted with accuracy about 2%. Repeated measurements of these standards confirmed the stability of our calibration throughout the study. A total of 20 representative samples were selected for whole-rock major and trace analyses using a sequential Philips PW 2400 X-ray spectrometer (Malvern Panalytical, Malvern, UK) at the University of Vienna (Austria). The accuracy was routinely verified against geo-standard GSR-3 and other international standards, with a procedural error better than 2%. REEs compositions were measured using ICP-MS (Perkin Elmer Elan 9000) with an analytical accuracy greater than 5%, except for La, Er, and Pr. Precision for duplicate measurements was better than 2% for most elements.

4. Results

4.1. Mineral Chemistry

Feldspars, including plagioclase and alkali feldspars, were analyzed from granodiorites and syenogranites and listed in Supplementary Table S1. Plagioclase in both types of granites is of oligoclase composition (Figure 4a) with a small variation in anorthite content (An16–17) in granodiorites and a slightly wider range in syenogranites (An15–26). The ana-
lyzed alkali feldspars are homogenous orthoclase in composition with lower orthoclase content (Or\textsubscript{94}, on average) and higher Al\textsubscript{2}O\textsubscript{3} (18.76 wt%, on average) content being observed in syenogranites relative to granodiorites (Or\textsubscript{96}; Al\textsubscript{2}O\textsubscript{3}, 17.53 wt%). The alkali feldspars show sanidine composition (Figure 4a) according to the feldspar classification diagram.

Figure 4. Mineral chemistry of silicate minerals in the studied granites. (a) Ab-An-Or ternary classification diagram indicating feldspar composition. (b) Classification diagram of biotite [13]. (c) (FeOt + MnO) – 10 * TiO\textsubscript{2} – MgO ternary diagram discriminating between primary, re-equilibrated, and secondary biotite [14]. (d) Mg–Ti–Na ternary diagrams discriminating between primary and secondary muscovite [15]. (e) Si vs. Mg/Mg + Fe + 2 binary diagram for amphiboles nomenclature [16]. (f) Ti vs. (Na + K) discrimination diagram of the studied amphiboles [17].

Micas are represented by trioctahedral mica (biotite) and dioctahedral white mica (muscovite) and are listed in Supplementary Table S1. Biotite is observed in granodiorites and syenogranites, while muscovite is recorded only in syenogranites. Biotite in syenogranites has higher Al\textsubscript{2}O\textsubscript{3} (15.93–17.05 wt%), MgO (8.58–9.18 wt%) and lower
FeO (19.21–21.25 wt%) relative to that in granodiorites (Al₂O₃, 13.36–13.69 wt%; MgO, 6.22–6.74 wt%; FeO, 25.35–25.62 wt%). Biotite is classified as Fe-biotite (Figure 4b) when plotted on the Tischendorf, et al. [13] diagram. The chemical compositions of the analyzed biotite are consistent with primary biotite based on the FeO + MnO – TiO₂ × 10 – MgO discrimination diagram (Figure 4c; [14]).

Muscovite is observed only in syenogranites and has an average composition of SiO₂ (46.17 wt%), Al₂O₃ (29.41 wt%), FeO (6.44 wt%), MgO (1.29 wt%), and K₂O (10.12 wt%). Muscovite has textural and chemical compositions comparable with muscovite of primary origin. It forms subhedral to euhedral crystals of medium-size and occur as clot crystals that mostly have TiO₂ content greater than 0.6 wt%, consistent with magmatic muscovite (e.g., [15]). Additionally, the analyzed muscovites have compositions comparable with primary muscovite when plotted in the Mg–Ti–Na discrimination diagram (Figure 4d; [15]).

Amphiboles are observed only in granodiorites (Supplementary Table S1; Figure 4e). Petrographic investigations and chemistry of amphiboles suggest primary (magmatic) origin (Figure 4e,f). According to the Ti versus Na + K diagram [17], the analyzed amphiboles are plotted in a magmatic amphibole field (Figure 4f). They have low and limited range of Mg# (0.33–0.35) and are classified as ferro-edenite based on the classification diagram of Leak et al. [16] (Figure 4e).

4.2. Whole-Rock Geochemistry

The representative whole rock geochemical data of 20 samples are presented in Supplementary Table S2. Based on the SiO₂ content of the investigated granitic rocks, it is obvious that a small compositional gap is observed between granodiorites (66.04–69.31 wt%) and syenogranites (72.02–74.02 wt%). Syenogranites have higher K₂O (4.24–4.4 wt%) and lower Al₂O₃ (13.79–14.25 wt%), Fe₂O₃ (1.96–2.36 wt%), MgO (0.21–0.44 wt%), and Na₂O (3.57–3.62 wt%) relative to granodiorites (K₂O = 2.45–2.7 wt%; Al₂O₃ = 14.78–16.03 wt%; Fe₂O₃ = 3.09–4.65 wt%; MgO = 1.27–1.94 wt%; Na₂O = 4.05–4.24 wt%). According to the TAS classification diagram, syenogranites are plotted in the granite field, while granodiorites fall as expected in the granodiorite field (Figure 5a). This is generally consistent with petrographic investigations. The Na₂O–K₂O–CaO ternary diagram suggested by Hassan and Hashad [18] provides good separation of the Egyptian granitic rocks (Figure 5b). It shows that the investigated syenogranites are in harmony with Egyptian younger granites while granodiorites are comparable with Egyptian calc-alkaline older granitic rocks (Figure 5b). The total alkalis (Na₂O + K₂O = 6.5–8.01 wt.% ) and differentiation index (D.I. = 71.9–90.15) (Supplementary Table S2) are comparable with ANS granites.

Figure 5. Whole-rock chemistry of Mount Abu Kibash and Tulayah granites. (a) TAS classification diagram [19]. (b) Na₂O–K₂O–CaO ternary diagram of Egyptian granitic rocks [18]. Trondhjemites and calc-alkaline fields are after Barker and Arth [20].
Harker variation diagrams were plotted to indicate the relation between SiO$_2$ content and selected major and trace elements in the investigated granitic rocks. They show higher concentrations of TiO$_2$, Al$_2$O$_3$, MgO, P$_2$O$_5$, FeO$_t$, Ba, Sr, Zr, and Cr and lower abundances of K$_2$O, Rb, and Y in granodiorites relative to syenogranites (Figure 6). Most elements of the investigated granitic rocks (TiO$_2$, Al$_2$O$_3$, MgO, P$_2$O$_5$, FeO$_t$, Ba, Sr, Zr, Sc, V, Cr and Ni) show a linear decrease with increasing SiO$_2$, except K$_2$O, Rb and Y, which are positively correlated (Figure 6).

Figure 6. Harker variation diagrams of selected major oxides (TiO$_2$, (a); Al$_2$O$_3$, (b); MgO, (c); K$_2$O, (d); P$_2$O$_5$, (e); Fe$_2$O$_3$, (f) and trace elements (Rb, (g); Ba, (h); Sr, (i); Zr, (j); Y, (k); Sc, (l); V, (m); Cr, (n); Ni, (o) vs. SiO$_2$. Fields in K$_2$O vs. SiO$_2$ (d) after Rickwood [21]. Upper crust values are after Rudnick and Gao [22].
The trace and REEs contents of the whole-rock samples are given in Supplementary Table S2. The REEs are normalized to chondrite (Figure 7a,c), while trace elements are primitive mantle-normalized [23]. The studied syenogranites have higher average contents of REEs (ΣREEs = 50 ppm) than granodiorites (ΣREEs = 41 ppm). The REEs chondrite-normalized patterns of syenogranites (Figure 7a) display slight enrichment of light rare earth elements (LREE) relative to heavy rare earth elements (HREE) (LaN/LuN = 1.76–1.89) with strong negative Eu anomaly (Eu/Eu* = 0.26–0.29) and are in harmony with REE patterns of Homrit Waggat and Gabal El-Ineigi post-tectonic (A-type) granites of the Eastern Desert [24] and Qianlishan A2-type granites of South China [25]. On the other hand, the REEs-normalized patterns of granodiorites (Figure 7c) are strongly enriched in LREE relative to HREE (LaN/LuN = 9.21–9.59) with small negative Eu anomalies (Eu/Eu* = 0.77–0.8) and show similarities with Homrit Waggat syn-tectonic granites [24].

Figure 7. Bulk-rock chemistry of Mount Abu Kibash and Tulayah granites. (a,c) Chondrite-normalized REE patterns of the investigated granodiorites and syenogranites. (b,d) Multi-element-normalized diagram of the studied granodiorites and syenogranites. Chondrite and primitive mantle normalization values and chondrite values are from Sun and McDonough [23]. Fields of Homrit Waggat A- and I-type granites [24], Gabal El-Ineigi A-type granites [26], and Qianlishan A2-type granites [25] are used for comparison.

Trace element-normalized patterns of syenogranites and granodiorites analyses (Figure 7b,d) show clearly different patterns. Syenogranites display negative anomalies of Sr, Ba, P, and Ti and enrichment in K, Rb, Th, Ta, and Nb (Figure 7b) similar to Homrit Waggat post-tectonic (A-type) granites [24]. On the other hand, granodiorites are enriched in large ion lithophile elements (LILE = Sr, K, Rb, Ba) relative to high-field-strength elements (HFSE = Ta, Nb, Zr, Ti) (Figure 7d) similar to Homrit Waggat syn-tectonic granites [24].

5. Discussion

5.1. Granitic Rocks Crystallization Conditions (T, P and fO2)

Estimation of temperatures, pressures, and depths of the investigated granitic rocks either from bulk-rock chemistry or mineral chemistry are important for understanding the
evolution of these granitic rocks. Zircon saturation temperatures ($T_{Zr}$) were estimated by applying the equation of Boehnke et al. [27] based on zircon content obtained from the whole-rock chemistry of the studied granites. The calculated zircon temperature ranges from 787 °C to 827 °C for granodiorites and from 772 °C to 803 °C for syenogranites (Supplementary Table S2). The estimated temperatures are consistent with calculated $T_{Zr}$ of A-type granites in the ANS (750–830 °C) [8,26]. The elevated $T_{Zr}$ in the investigated granitic rocks suggest that the magma from which the granodiorites and syenogranites crystallized was significantly hot, promoting zircon saturation.

The chemical data of plagioclase in the investigated granites was used to obtain their crystallization temperature [28]. By plotting the analyzed plagioclase on Ab–An–Or diagram, we found that plagioclase from granodiorites crystallized at ~840 °C, while the crystallization temperatures of plagioclase from syenogranites ranged from 850 °C to 900 °C (Figure 8a). The Ti content of amphiboles is controlled by temperature under certain conditions ($fO_2 < 2$ log units, subalkaline systems, and coexistence with Ti-phases such as rutile, ilmenite, or titanite) [29]. Applying the thermometric equation of Liao et al. [29] ($T°C = 2400/(1.52 − \log Ti_{Amp}) − 273$) to amphiboles in granodiorites gave temperatures ranging from 756 °C to 771 °C (Supplementary Table S2). The equation yielded lower temperatures for Biotite (~700–730 °C for granodiorites; ~710–740 °C for syenogranites) when Ti is plotted against Mg/(Mg + Fe) [30] (Figure 8b). This indicates late crystallization of biotite at lower temperatures relative to amphiboles and early crystallization of plagioclase, consistent with our petrographic investigations.

**Figure 8.** Crystallization conditions (P–T–$fO_2$) of the studied granites. (a) Ab–An–Or thermometry diagram [28]. (b) Ti vs. Mg/(Mg + Fe) for the analyzed biotite showing temperature isotherms [30]. (c) Ab–Qz–Or ternary diagram for the studied granitic rocks [31]. (d) Fe/(Fe + Mg) vs. AlIV + AlVI for the analyzed biotite. Ilmenite and magnetite series after Anderson et al. [32].
Based on normative values of Qz, Ab, and Or obtained from whole-rock chemistry (Supplementary Table S2), numerical equations of Yang [33] were used to estimate the crystallization pressure of granitic intrusions: (1) \( P = -0.2426 \times (\text{Qtz})^3 + 26.392 \times (\text{Qtz})^2 - 980.74 \times (\text{Qtz}) + 12,563 \) and (2) \( P = 0.2426 \times (\text{Ab} + \text{Or})^3 - 64.397 \times (\text{Ab} + \text{Or})^2 + 2981.3 \times (\text{Ab} + \text{Or}) - 464 \). where \( P \) is pressure in MPa, and the sum of normative Qtz, Ab, and Or is 100%. The calculated pressure of the investigated granodiorites ranges from 2.3 to 3.4 kbar (2.9 kbar on average) and point to depth of ~8 km, while the syenogranites show lower pressures (1.3–1.5 kbar; 1.4 kbar on average), suggesting crystallization of the latter at shallower depths (3.6 km) (Supplementary Table S2). This is in agreement with plotting normative Ab, Qtz, and Or on the ternary diagram of Tuttle and Bowen [31], which gives similar results (~3 kbar for granodiorites and ~2.5 kbar for syenogranites) that are consistent with pressure estimates for granites of the ANS (Figure 8c). The estimated depths for both types of granites suggest their crystallization in the upper crust. Crystallization pressure can also be calculated by using the Al content in hornblende [34]. Applying the geobarometer equation of Anderon and Smith [34] \( (P \text{ (kbar)} = 4.76 \times \text{Al–}3.01) \) on hornblende from the investigated granodiorites gives pressures ranging from 2 to 2.6 kbar, which is slightly lower than results obtained from bulk rock chemistry (~3 kbar).

Oxygen fugacity \( (f_{O_2}) \) can be calculated on the basis of zircon composition. We used the equilibrium expression of Wones [35] \( \log f_{O_2} = -30,930/T + 14.98 + 0.142 \times (P–1)/T \) to estimate the oxygen fugacity of the studied granites, where \( T \) is temperature (in kelvin) and \( P \) is pressure (in bars). Using the calculated pressure and temperature \( (T_{Zr}) \), the estimated oxygen fugacity ranges between ~12.7 and ~13.9 for granodiorites and between ~13.6 and ~14.4 for syenogranites (Supplementary Table S2). These results indicate that the studied granites were generated from relatively oxidized magmas. The \( \text{Fe}/(\text{Fe} + \text{Mg}) \) ratios of the analyzed biotite in granodiorites and syenogranites vary between 0.56 and 0.7, supporting their crystallization under relatively oxidizing conditions ranging from ~QFM +0.5 to QFM + 1.5 [32] (Figure 8d). Moreover, the simultaneous occurrence of magnetite, titanite, and quartz with amphibole in the investigated granodiorites suggests relatively high oxygen fugacity of the melt [36]. Absence of clear negative Eu anomaly in the REE-normalized pattern of granodiorites (Figure 7c) supports their crystallization under high \( f_{O_2} \), where oxidizing conditions can transform the valence of Eu into the trivalent state, rendering it unable to enter the structure of plagioclase.

5.2. Role of Crustal Contamination and Fractional Crystallization

The studied granitic rocks parent melts may have been affected by many processes (e.g., crustal contamination and fractional crystallization) that modified their chemical composition during their evolution. The investigated granodiorites host mafic xenoliths, and their plagioclase crystals sometimes show complex zonation, suggesting magma mixing. Granodiorites also have relatively low SiO\(_2\) content and show magnesian character (Supplementary Table S2, Figure 6), which supports their contamination by basaltic melt. We also used several characteristic ratios of major oxides and trace elements to infer magmatic processes like bulk assimilation (BA), assimilation-fractional crystallization (AFC), and fractional crystallization (FC) [37]. The K/Rb ratio (166.73–410.24) and Rb content (51–219.26 ppm) of the investigated granitic rocks (granodiorites and syenogranites) (Supplementary Table S2) follow AFC trends, indicating the role of these processes (Figure 9a). Based on the Th/Nb ratio vs. Zr diagram (Figure 9b), granitic rocks show obvious AFC trends. Moreover, CaO/Na\(_2\)O ratio decreases with increasing SiO\(_2\) content (Figure 9c) from granodiorites to syenogranites and follows an AFC trend. Wide ranges of K/Rb, Ba/Nb and Zr/Nb ratios (Supplementary Table S2) are clearly observed in both types of granitic rocks (granodiorites and syenogranites) and also indicate the role of continental crustal contamination, as constant values of these ratios indicate simple fractional crystallization [38].
Figure 9. Bulk-rock chemistry of the studied granites showing the role of contamination and fractional crystallization in their evolution. (a) Rb vs. K/Rb diagram [37]. (b) Zr vs. Th/Nb variation diagrams showing fractional crystallization (FC), assimilation fractional crystallization (AFC), and bulk assimilation (BA) trends [39]. (c) SiO$_2$ vs. CaO/Na$_2$O diagram with AFC trend. (d) Zr vs. TiO$_2$ diagram for the studied granites.

The linear variations of most major oxides with silica (Figure 6a–f) can be the result of either fractional crystallization or the mixing of two different melts. The clear systematic decrease of Al$_2$O$_3$, Ba, and Sr with increasing SiO$_2$ concentration (Figure 6b,h,i) in addition to the clear negative Ba and Sr anomalies in trace element-normalized pattern of syenogranites (Figure 7b) probably reflect fractionation of plagioclase. Although plagioclase is a major constituent of the investigated granodiorites and a minor phase in syenogranites, the steep slope of Ba and Sr (Figure 6h,i) against SiO$_2$ suggests fractionation of plagioclase from the granodiorite melts during their evolution. This can be confirmed by using the Zr versus TiO$_2$ (Figure 9d) diagram which indicates that plagioclase was the main fractionating phase during the evolution of the investigated granitic rocks. Moreover, the strong negative Eu anomaly in syenogranites may suggest intensive plagioclase fractionation from their parent melt, while the small negative Eu anomaly in granodiorites indicates a weak effect of plagioclase fractionation (Figure 7a,c). The linear decrease of Fe$_2$O$_3$ and MgO with increasing silica (Figure 6c,f) in both syenogranites and granodiorites may reflect extraction of primary ferromagnesian silicate minerals. Furthermore, the negative linear relations of TiO$_2$, P$_2$O$_5$, FeO, and V against SiO$_2$ (Figure 6a,e,f,m) in addition to the negative anomalies of P and Ti in trace element-normalized pattern (Figure 7b,d) may be due to the fractionation of apatite and Fe-Ti oxide minerals. Decreasing Zr with increasing SiO$_2$ (Figure 6j) in both granite...
suites indicates zircon fractionation. On the other hand, the positive correlations between K\textsubscript{2}O, Rb and SiO\textsubscript{2} are the result of K-feldspar accumulation in syenogranites (Figure 6d,g). In syenogranites, the depletion of CaO, MgO, Fe\textsubscript{2}O\textsubscript{3}, and TiO\textsubscript{2} (Figure 6a,c,f) may indicate amphibole fractionation during evolution of syenogranite magmas. High FeO/MgO ratios for the investigated granodiorites and syenogranites (2.25–2.58 and 5.39–9.58, respectively; Table S2) suggest that their parental melts have been influenced by extensive magmatic differentiation (e.g., [38]). Enrichment of LREEs relative to HREEs in the investigated granodiorites (LaN/LuN = 9.21–9.59) and syenogranites (LaN/LuN = 1.76–1.89) (Figure 7a,c) also indicates the role of fractional crystallization during evolution. The concave-upwards middle-to-heavy REE-normalized patterns of granodiorites (Figure 7c) also suggest hornblende fractionation. In addition, HREE depletion in granodiorites (Figure 7c) may be the result of retention of garnet in the residue or fractionated garnet during their petrogenesis.

5.3. Magmatic Sources

Based on field relations, petrographic investigations, mineral chemistry and bulk-rock chemistry, we did not observe an obvious petrogenetic relationship between the granodiorites and the syenogranites. Based on Nb and K\textsubscript{2}O/MgO versus 10\textsuperscript{4} × Ga/Al diagrams (Figure 10a,b; [40]), granodiorites fall in I type, while syenogranites lie in A-type granite fields. The two types of granites were mostly derived from two different sources and are not linked by fractional crystallization as indicated by the obvious discontinuous trends of most major oxides and trace elements (Figure 6). Moreover, by plotting our data on \((\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3 + \text{MgO}) - 3 \times (\text{CaO}) - 5 \times (\text{K}_2\text{O}/\text{Na}_2\text{O})\) discrimination diagrams [41], granodiorites were mostly derived from a high-K mafic source, while syenogranites were extracted from a tonalitic, felsic source (Figure 10c). Our suggestion about the two different magma sources is also confirmed by the different content (Supplementary Table S2) and patterns of REE-normalized and trace-element-normalized diagrams of granodiorites and syenogranites (Figure 7). Differences in Nb-Ta anomalies (Figure 7b,d) in the investigated granodiorites and syenogranites may also suggest source differences (e.g., change in tectonic setting with increasing continental crust thickness). Both types of granitic rocks are characterized by high content of SiO\textsubscript{2} (66.04–74.02 wt%), precluding their generation directly by partial melting of mantle peridotites since low-degree partial melting of mantle peridotites cannot generate dacitic magma [42]. Moreover, the investigated granitic rocks (I- and A-types) show enrichment of HFSE (e.g., Nb, Ta, Zr, Hf; Figure 7b,d) and low Mg\# (0.17–0.47) (Supplementary Table S2), precluding their generation by partial melting of an enriched lithospheric mantle source, as felsic rocks extracted from enriched lithospheric mantle are characterized by depletion of HFSEs and high Mg\# values [43].
Figure 10. Bulk-rock chemistry showing different types and sources of the studied granites. (a,b) $10^4 \times \text{Ga/Al}$ against Nb and K$_2$O/MgO for distinguishing between I, S, M and A-type granites [40]. (c) Al$_2$O$_3$/(FeO$^\text{I} +$ MgO) – 3*CaO – 5*(K$_2$O/Na$_2$O) ternary diagram [41]. (d) Rb vs. K$_2$O diagram [44].

The I-type geochemical character of the studied granodiorites is concluded from the abundance of amphiboles and biotite as mafic silicates (Figure 3a,b) and the common occurrence of titanite and Fe-Ti oxides as accessory phases. The investigated granodiorites have major oxide, trace and rare earth element compositions that are comparable with upper continental crust composition [45]. The granodiorites have average SiO$_2$ (67.59 wt%), TiO$_2$ (0.53 wt%), Al$_2$O$_3$ (15.31 wt%), FeO$_\text{I}$ (3.75 wt%), MgO (1.55 wt%), MnO (0.08 wt%), CaO (3.28 wt%), Na$_2$O (4.15 wt%), K$_2$O (2.59 wt%), and P$_2$O$_5$ (0.11 wt%) contents (Supplementary Table S2) similar to the average composition of continental crust (SiO$_2$ = 66.6 wt%; TiO$_2$ = 0.64 wt%; Al$_2$O$_3$ = 15.4 wt%; FeO$_\text{I}$ = 5.04 wt%; MgO = 2.48 wt%; MnO = 0.1 wt%; CaO = 3.59 wt%; Na$_2$O = 3.27 wt%; K$_2$O = 2.8 wt%; P$_2$O$_5$ = 0.15 wt%; Figure 6). Moreover, the REE-normalized patterns of granodiorites are consistent with upper continental crust, suggesting their generation by partial melting of the crust (Figure 7c). Moreover, granodiorites have low Ce/Pb (2.6 on average) and Nb/U (9.31) ratios similar to those of continental crust (Ce/Pb ~ 4 and Nb/U ~ 10) [46]. In contrast, Nb/Ta (25.05–41.43) and Zr/Hf (45.23–70.86) ratios of granodiorites (Supplementary Table S2) are higher than those of continental crust (Nb/Ta = 11.43; Zr/Hf = 35.68; [22]) and the chondritic value (Nb/Ta = 17.6, Zr/Hf = 34.2; [47]). The Zr/Hf ratio of the investigated granodiorites (Supplementary Table S2) is consistent with the range of mantle-derived continental and oceanic intraplate basaltic rocks (38–87; [48]). The very low P$_2$O$_5$ and TiO$_2$ contents and low Mg# of granodiorites (<46) (Supplementary Table S2) as well as the lack of coexisting mafic rocks argue against their direct derivation by fractional crystallization of mantle-derived magma [49]. From the previously mentioned features of the investigated granodiorites, there are mixed geochemical characteristics of both crust and mantle sources, so we suggest mixed crustal-mantle source. This is supported by the granodiorite K/Rb ratios (281.7–410.23), which
fall in between that of a typical crustal source (K/Rb = 250) and a mantle-derived magma (K/Rb = 1000) (Figure 10d). In addition, on the Rb versus K/Rb diagram (Figure 9a), the granodiorite samples follow simultaneous assimilation and fractional crystallization trends. The occurrence of xenoliths and mafic microgranular enclaves within granodiorites (Figure 2a) also suggests the role of magma mixing in generating granodiorites. The high-K mafic source of the investigated granodiorites (Figure 10c) suggests their generation by dehydration and partial melting of intermediate and mafic crustal sources above a subduction zone, likely due to an increasing geothermal gradient resulting from basalt underplating [24]. The generated crustal melts can mingle with buoyant fractionation products of the underplated mantle-derived magmas [50] and then be contaminated by upper-level crustal materials during ascent [51]. The mixing of mantle-derived mafic magmas and more felsic crustal melts was proposed by Griffin et al. [52] for generating both I- and A-type granites.

On the other hand, A-type granites (like the studied syenogranites) have been generated either by extensive fractionation of mantle-derived parental mafic melts, with or without contribution of crustal rocks [53,54], or by partial melting of crustal rocks [55]. Moreover, recent studies on A-type granites based on trace element and Nd-Sr isotopic data suggested mixed mantle-derived magmas and crustal materials, followed by fractional crystallization [5,56]. Syenogranites have characteristic features of A-type granites, as they have higher alkaline content (A/CNK = Al₂O₃/CaO + Na₂O + K₂O > 1), Ga/Al and FeO/MgO (Figure 10a,b) ratios, and enrichment of high field strength elements (HFSE = Nb, Ta, Zr, ~2–100 times MORB) (Figure 7b) relative to granodiorites (I-type) [57]. The absence of contemporaneous large volumes of mafic rocks in Mount Abu Kibash and Tulayah, precludes the first hypothesis regarding extensive fractionation of the mantle source. The chemistry of syenogranites suggests their derivation from a tonalitic, felsic source (Figure 10c), consistent with the model advocated by Creaser et al. [58] for the generation of A-type granites through partial melting of an undepleted I-type tonalitic to granodioritic source. Moreover, King et al. [59] suggested that aluminous A-type granites (like the studied syenogranites) were formed by partial melting of felsic crustal source rocks, while peralkaline A-type granites resulted from fractionation of mafic melts. The peraluminous nature of the studied syenogranites (A/CNK > 1; Supplementary Table S2) supports the hypothesis that their primary melts were derived by partial melting of a juvenile crustal source, succeeded by extensive fractional crystallization and assimilation (Figure 10d). The K/Rb ratio of the investigated syenogranites are plotted on and beside the crustal line (K/Rb = 250; [44]), suggesting their derivation by partial melting of crustal source rocks (Figure 10d). In addition, the average Nb/Ta ratio (12.85) of the investigated syenogranites are close to that of continental crust (Nb/Ta = 11.43; [22]), supporting their crustal source. The Y/Nb ratio (1.25–3.18) (Supplementary Table S2) of the investigated granitic rocks (granodiorites and syenogranites) also suggests a crustal source (Y/Nb > 1.2 for crustal source magmas [60].

5.4. Petrogenesis and Geodynamic Evolution

The selected granitic rocks (syenogranites and granodiorites) for bulk-rock analyses were mostly fresh and did not show any signs of alterations, except slight sericitization of feldspars in some samples. The fresh nature of the studied granitic rocks is also indicated by their low loss of ignition (LOI = 0.4–0.97 wt%); this makes our analyses useful as a petrogenetic indicator.

By plotting the analyzed granites on SiO₂ versus Na₂O + K₂O-CaO (Figure 11a), granodiorites show calc-alkaline nature and show similarities with Eastern Desert (ED) I-type granites, while syenogranites mostly plot on the line between calc-alkaline and alkali-calcic fields, consistent with ED A2-type granites. In the binary discrimination diagram of Sylvester [61], for rocks having SiO₂ > 68 wt%, granodiorites are plotted in the calc-alkaline field and are consistent with ED I-type granites; whereas syenogranites fall in the calc-alkaline and highly fractionated calc-alkaline fields and show similarities to ED A2-type granites (Figure 11b). Syenogranites are similar in their SiO₂ content and
FeO^t/FeO + MgO ratio to ferroan A-type granites, ED A2-type granites, and Qianlishan A2-type granite, while granodiorites are consistent with magnesian granites and ED I-type granites (Figure 11c) [62]. Syenogranites are characterized by an obvious peraluminous character (A/CNK > 1) similar to ED A2-type granites while granodiorites show a metaluminous to mildly peraluminous nature consistent with ED I-type granites, based on their alumina saturation indices (A/CNK = 0.95–1.03) (Figure 11d). The peraluminous nature of the studied syenogranites is confirmed by the detection of normative corundum (Al₂O₃ =1.04–1.46 wt.%) and the occurrence of muscovite in all samples (Figure 3e,f; Supplementary Table S1). Moreover, syenogranites have high silica content (SiO₂ = 72.02–74.02 wt%) (Supplementary Table S2) similar to that of the peraluminous granites in the Eastern Desert of Egypt (SiO₂ = 71–78 wt.%) [24,26]. The agpaitic index (AI = molar (Na + K/Al)) for granodiorites is < 0.7 (Supplementary Table S2), indicating a calc-alkaline metaluminous signature and I-type granites [63,64].

The calc-alkaline nature (Figure 11a,b) of the investigated granodiorites as well as the enrichment of LILE (e.g., Sr, K, Rb, Ba) relative to HFSE (e.g., Nb, Ta, Ti) (Figure 7d) suggest partial melting of a mantle wedge that was formerly metasomatized by slab-derived fluids [65]. On the Y + Nb vs. Nb tectonic discrimination diagram (Figure 11e) of Pearce et al. [66], granodiorites show volcanic arc features similar to ED I-type granites, while syenogranites have within-plate setting and post-collisional characteristics (A-type granites) that are in harmony with the Hf-Rb/30−3*Ta ternary diagram (Figure 11f, [67]). Likewise, on the SiO₂ versus FeO^t/(FeO^t + MgO) discrimination diagram, granodiorites lie in island-arc granites (IAG) and ED I-type granites fields, while syenogranites are plotted in post-orogenic granites (POG) and ED A2-type granites fields (Figure 11g).

A-type granites were subdivided into two types of different tectonic settings (Figure 11h): (1) A1 granites that form in an intraplate tectonic environment and have mantle signatures; and (2) A2 granites that are generated in a post-collisional setting and have a crustal affinity [60]. The investigated syenogranites have an A2-type affinity (Figure 11h) when plotted on the Y-Nb-Ce discrimination diagram [60]. Moreover, the high Y/Nb ratios (>1.2) of the investigated syenogranites also suggest A2-type granite [60]. This is consistent with several studies on A-type granites of the Eastern Desert of Egypt, which were classified as A2 granites and interpreted to have been generated in a post-collisional setting and matching with other occurrences in the ANS [9,24]. The syenogranites show nearly flat REE-normalized patterns with strong negative Eu anomaly, similar to Egyptian A-type granites like those of Homrit Waggat and Gabal El-Ineigi [24,26] (Figure 7a). By plotting the studied granitic rocks on a K₂O-Na₂O-CaO ternary diagram (Figure 11i), granodiorites show similarities with phase II calc-alkaline rocks that include diorites, tonalite/granodiorite with minor gabbros and monzogranites (subduction-related Egyptian granitic rocks; ~635–620 Ma), while syenogranites fall in late phase III, which comprise undeformed granites with minor granodiorite (late to post-collisional Egyptian younger granites; ~610–600 Ma) [5].
Figure 11. Bulk-rock chemistry of the studied granites. (a) SiO$_2$ vs. (Na$_2$O + K$_2$O) – CaO discrimination diagram [62]. (b) 100*(MgO + FeO$^+$ + TiO$_2$)/SiO$_2$ vs. molar (Al$_2$O$_3$ + CaO)/(FeO + Na$_2$O + K$_2$O) discrimination diagram for distinguishing between different types of granitic magma [61]. (c) FeO$^+$/[FeO$^+$ + MgO] vs. SiO$_2$ [62]. (d) Molar Al$_2$O$_3$/(Na$_2$O + K$_2$O) vs. Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O) for the studied granites [68]. (e) Y + Nb vs. Rb tectonic discrimination diagram of Pearce et al. [66]; the post-collisional granite field is from Pearce [65]. The A-type granite field in previous diagrams is after Whalen et al. [40]; Eastern Desert (ED) A2-type and I-type granites are after Azer et al. [24] and Farahat et al. [9]; Qianlishan A2-type granite field is after Chen et al. [25]. (f) Hf-Rb/30 – 3*Ta tectonic discrimination diagram after Harris et al. [67]. (g) SiO$_2$ vs. FeO$^+$/[FeO$^+$ + MgO] discrimination diagram [68]. (h) Y-Nb–3Ga ternary plot [69]; A1 = A-type granitoids with an ocean island basalt-type source; A2 = A-type granitoids with crust-derived magma. (i) Na$_2$O-K$_2$O-CaO ternary discrimination diagram showing different types of Egyptian granitoids [26], where I = old calc-alkaline phase, II = early subphase of young calc-alkaline phase, and III = late subphase of young calc-alkaline phase.

The chemistries of primary amphiboles and biotite have become valuable tools for determining their magma source, magma type, and tectonic setting [70,71]. The analyzed primary amphiboles from the investigated granodiorites have Al$_2$O$_3$ (5.61–6.39 wt%) and TiO$_2$ (1.32–1.41 wt%) contents (Figure 12a) similar to those generated from a crustal-mantle mixed source [72]. They have low K (apfu; 0.1–0.14), consistent with amphiboles generated from calc-alkaline magmas (Figure 12b; [71]). Furthermore, they have SiO$_2$
(44.78–45.74 wt%) and Na$_2$O (1.16–1.46 wt%) contents that are consistent with suprasubduction zone amphiboles (Figure 12c), indicating generation of granodiorites in a subduction zone environment [73]. Plotting the analyzed biotites on the FeO-MgO-Al$_2$O$_3$ ternary plot of Abdel-Rahman [70], granodiorites fall in the calc-alkaline orogenic suite, suggesting their generation in a subduction setting; while syenogranites mostly plot in the peraluminous suite, suggesting their formation in an extensional setting (Figure 12d).

![Figure 12](image.png)

**Figure 12.** Mineral chemistry of amphiboles and biotite from the studied granites. (a) TiO$_2$ vs Al$_2$O$_3$ for the studied primary amphiboles [72]. (b) Cations of Al$^{iv}$ vs. K binary diagram discriminating between alkaline and calc-alkaline magma [71]. (c) SiO$_2$ vs. Na$_2$O binary diagram of amphiboles [73] (I-Amph = within-plate amphiboles; S-Amph = Supra-subduction amphiboles). (d) FeO-MgO-Al$_2$O$_3$ ternary discrimination diagram of biotite [70].

According to the above discussion, we can conclude that Mount Abu Kibash and Tulayyah granites (granodiorites and syenogranites) were formed during two different stages during the transition from collisional stage (volcanic arc) to post-collisional stage (extensional environment). The intrusion of granitic rocks in the studied area commenced with the emplacement of calc-alkaline I-type granodiorites in a volcanic arc setting during the accretion of a volcanic arc system onto the East Gondwana margin during the evolution of the juvenile ANS crust (Figure 13). Granodiorites parent melts were generated by hydrous partial melting of the mantle wedge as a result of slab dehydration (Figure 13a). This yielded a primary basic magma that moved upward and came into contact with the lower crust (Figure 13a), with the high temperature of the generated basic melt increasing the continental geotherm and thereby resulting in melting of the lower crust to form intermediate magma. This is in agreement with many previous studies which state that subduction-related granitic rocks are mostly the product of melting of basaltic/gabbroic magmas that pond and crystallize at the base of the crust [24,26,74]. The resultant melts fractionated during their ascent in the upper crust to form the investigated I-type granodiorites. This interpretation is supported by the Rb vs. K/Rb diagram (Figure 9a) that...
shows that the studied granodiorites follow assimilation and fractional crystallization trends. The transition from a subduction stage to an extensional setting took place in the ANS at 600 ± 10 Ma [75] and was accompanied by the intrusion of late to post-collisional Egyptian younger granites like the studied syenogranites (Figure 13b). The emplacement of syenogranites (A-type) happened after crustal thickening and the lithospheric delamination that took place after a slab break-off event [76] (Figure 13b). The last event was accompanied by high thermal anomaly resulting from upwelling of hot asthenosphere during lithospheric delamination [77]. Upwelling of asthenospheric melts and their underplating caused fertilization (enrichment in HFSEs and alkalis; Figures 7b and 13b) of the lithosphere before partial melting. This is in agreement with Martin [78] who stated that the upwelling of the asthenospheric mantle below areas subjected to extension causes mantle degassing and subsequent melting, whereby the released fluids are alkali and silica bearing and can transport a variety of elements like HFSEs and metasomatize the upper mantle and the lower to middle crust. The high temperature asthenospheric melts promoted partial melting of preexisting tonalites in the lower crust (Figure 10c) to generate the post-collisional, peraluminous magmas that eventually crystallize the investigated syenogranites (A-type granites). Fractionation of these crustal melts took place during their ascent and before their crystallization in the upper crust to form evolved granites like the studied syenogranites (Figures 9 and 11b). Therefore, the syenogranites intruded into and post-date the granodiorites (Figure 13b). The suggested post-orogenic regime for syenogranites (A-type) is also in agreement with many workers (e.g., [8,24]) who agree that the A-type granites were emplaced in an extensional setting related to the post-collisional collapse of the Pan-African Orogeny. The transition from a compressional to an extensional setting is dominated in the ANS at 600 ± 10 Ma [75] and was accompanied by crustal uplifting, thickening, and extensional collapse of the ANS continental crust (Figure 13b), leading to emplacement of large masses of A-type granites at the end of Pan-African orogenic event [12]. So, this transition represents an episode of strong magmatic activity (A-type granites) during the evolution of the ANS.

Figure 13. Sketch showing emplacement of Mount Abu Kibash and Tulayah granitic intrusions within the central Eastern Desert of Egypt in different tectonic stages during the evolution of the ANS. (a) Generation of granodiorites (I-type granite) during the collisional stage in a subduction-related setting (active continental margin) and (b) emplacement of syenogranites (A-type granites) during the post-collisional stage.

6. Concluding Remarks
1. The Mount Abu Kibash and Tulayah area in the central Eastern Desert of Egypt have two different granite phases: I-type (granodiorites) and A2-type (syenogranites). The
I-type granites represent the earlier phase that are slightly altered, deformed, and intrude the A2-type granites (later phase) that are fresh and undeformed.

2. Granodiorites (I-type) have a crustal-mantle mixed source while syenogranites (A2-type) were generated by partial melting of lower juvenile crustal source (tonalite). Evolution of both types was controlled by simultaneous assimilation and fractional crystallization.

3. Both I- and A-type granites were crystallized at low pressure (<3.5 kbar) in the upper continental crust but at average temperatures of 807 °C and 792 °C, respectively. The I-type granites were generated from calc-alkaline, metaluminous magma during a collisional stage (volcanic arc), while the A2-type granites are peraluminous and formed in a post-collisional stage (extensional environment). The syenogranites were formed after crustal thickening and lithospheric delamination that caused upwelling of hot asthenosphere. Underplating of upwelled mafic melts beneath lower crust caused fertilization of the lithosphere by HFSEs and alkalis before partial melting.

4. The transition from subduction to post-collisional setting was accompanied by strong magmatic activity and emplacement of large masses of A2-type granites as a result of crustal uplifting, thickening, and extensional collapse of the ANS continental crust that occurred at the end of Pan-African orogenic event.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/min14080806/s1: Document S1: Analytical methods; Table S1: EMPA analyses of feldspars, muscovite, biotite and amphiboles; Table S2: Whole-rock major, trace, and REEs geochemical composition of the studied granites. Figure S1: Geological map of the Arabian-Nubian Shield, where the Eastern Desert occupy the northwest portion of the shield.

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