

Article

Mineral Chemistry, Whole-Rock Characterization, and EnMap Hyperspectral Data Analysis of Granitic Rocks of the Nubian Shield: A Case Study from Suwayqat El-Arsha District, Central Eastern Desert, Egypt

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Abstract

Gabal (G.) Suwayqat El-Arsha contains two distinct phases of granitoids: I-type granodiorite and A-type monzogranite. Both of them experienced intense fractional crystallization that affected plagioclase, alkali feldspar, quartz, and, to a lesser degree, ferromagnesian minerals. EnMAP hyperspectral data were used to discriminate between the different granitoid types through spectral analysis, using various techniques, including the Sequential Maximum Angle Convex Cone (SMACC) method. Granodiorite has high SiO₂ (68.21–71.44 wt%), Al₂O₃ (14.29–14.92 wt%), Fe₂O₃ (1.99–3.32 wt%), and CaO (2.34–3.87 wt%), whereas monzogranite has even higher SiO₂ (73.58–75.87 wt%) and K₂O (4.28–4.88 wt%). Both granodiorite and monzogranite exhibit calc-alkaline, peraluminous to metaluminous, and medium- to high-K characteristics, with attendant enrichment of light REE and LILE and depletion of heavy REE and HFSE. A negative Eu anomaly may indicate early plagioclase fractionation, especially in the monzogranite. The I-type granodiorite is likely derived from a high-K, mafic protolith that partially melted during lithospheric delamination, leading to severe fractional crystallization in the upper crust in a post-collisional environment. In contrast, the monzogranite exhibits A-type characteristics and was likely emplaced in an anorogenic setting. Both granites were affected by several episodes of hydrothermal alteration, resulting in silicification, kaolinitization, sericitization, and chloritization. The intrusions studied here exhibit key similarities with those in the Wadi El-Hima area, including tectonic setting, petrogenetic type, Neoproterozoic age (Stage I collisional: ca. 650–620 Ma; Stage II post-collisional: ca. 630–590 Ma), and mineralogical assemblages (notably two-mica granites). These correlations suggest that both suites form part of a regionally extensive batholith composed of I- and A-type granites, stretching from north of the Marsa Alam Road (Umm Salatit–Homrit Waggat) southward to at least Wadi El-Hima.



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Keywords: mineral chemistry; granodiorite; monzogranite; electron microprobe; lithological mapping; Sentinel-2; EnMap; Central Eastern Desert; Egypt

1. Introduction

The geology of the Nubian Shield evolved because of tectonic events recorded by the Neoproterozoic units in the Eastern Desert and Sinai areas of Egypt and northeastern Africa [1–8]. The crystalline basement complex of Egypt, which is part of the larger Arabian-Nubian Shield, is dominated by Precambrian, especially Neoproterozoic, granitoids, metamorphic rocks, and volcanic formations, which were formed and assembled through a series of Neoproterozoic to Cambrian (ca. 750–540 Ma) tectonic and magmatic events, including rifting, subduction, and continental collision. The Egyptian granitoids comprise approximately 57 vol% of the Neoproterozoic basement and are classified into two broad categories: (1) older granites (ca. 750–610 Ma; 27 vol% of total), associated with a first phase of continental crust formation [9–16], and (2) younger granites (ca. 610–580 Ma; 30 vol% of total), associated with a second phase of continental crust formation via subduction and continental collision [17,18]. The aim of this contribution is to constrain the origin and evolution of the Suwayqat El-Arsha granitic suite. This is achieved by integrating new geochemical data on their petrogenesis and fractional crystallization with advanced remote sensing analysis using EnMap (a first for the Nubian Shield) and Sentinel-2 data for improved lithological characterization. Also, to use advanced analytical techniques to “open the black box” of these granite formations, providing a quantitative, process-oriented model that explains how, from what, and under exactly what conditions these crucial basement rocks formed. This transforms the granites from mere map units into detailed archives of Neoproterozoic tectonic evolution.

In this study, we characterize the whole rock, trace element, and mineral chemistry of one older and one younger granitoid to provide critical insight into the general conditions, especially magmatic processes and crustal evolution, under which these rocks formed. In addition to lithogeochemical characterization, we use remote sensing lithologic mapping to distinguish rock units based on their unique spectral signatures, which reflect their mineral composition. This approach has been widely applied using multispectral and hyperspectral datasets [19].

2. Geologic Setting

Gabal (G.) Suwayqat El-Arsha (“El-Arsha”) is located in the central Eastern Desert (Figure 1) between 25°08′05″ and 25°12′24″ N latitude and 33°47′10″ and 33°55′54″ E longitude, north of the Idfu-Mersa Alam Road about 75 km west of Mersa Alam [20–22]. As the study area is mainly covered by ophiolitic rocks and granitoids, as well as small outcrops of island arc metavolcaniclastics (Figure 2a,b). On the ground and in satellite imagery, ophiolites are readily distinguished by their dark color, whereas granitoids stand out in lighter (yellowish green in the imagery) colors (Figure 2a). Ophiolitic rocks are the oldest rocks in the study area and comprise serpentinites, veins of talc-carbonates, and metagabbro. Serpentinites occur either as large masses in the southern part of the mapped area or as small hills distributed throughout the area. Veins of carbonates form Slabs in outcrop, lying on the ground in a creamy-white color, with pronounced cavernous weathering. Ophiolitic metagabbro occurs throughout the study area as large masses and small hills with variable heights or as blocks of different sizes incorporated within the ophiolitic mélange.

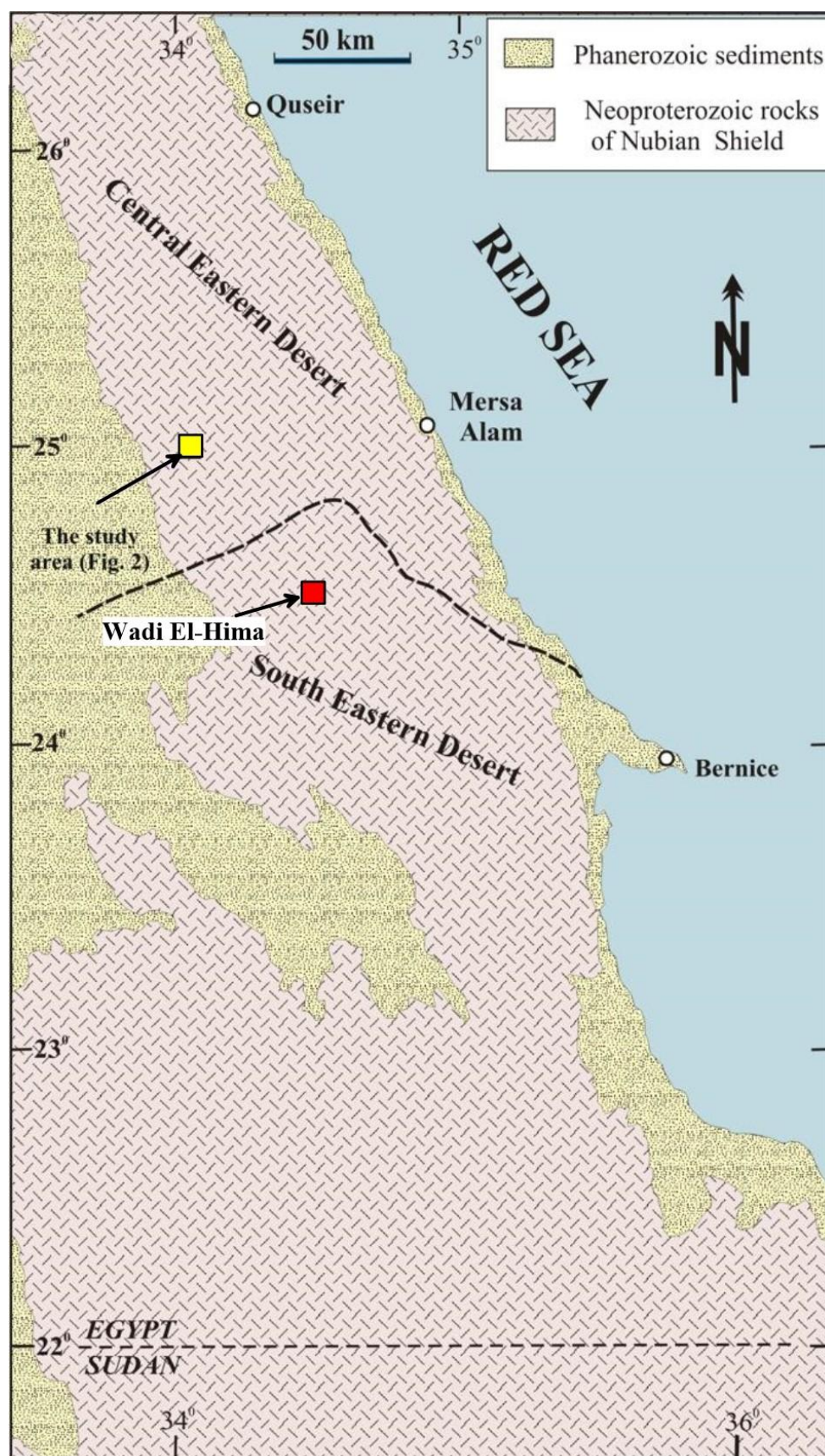


Figure 1. Geological map of central and southern Eastern Desert, including the studied area (after Shackleton [23]). Black dashed line indicates the approximate boundary between central to the north and southern to the south [23].

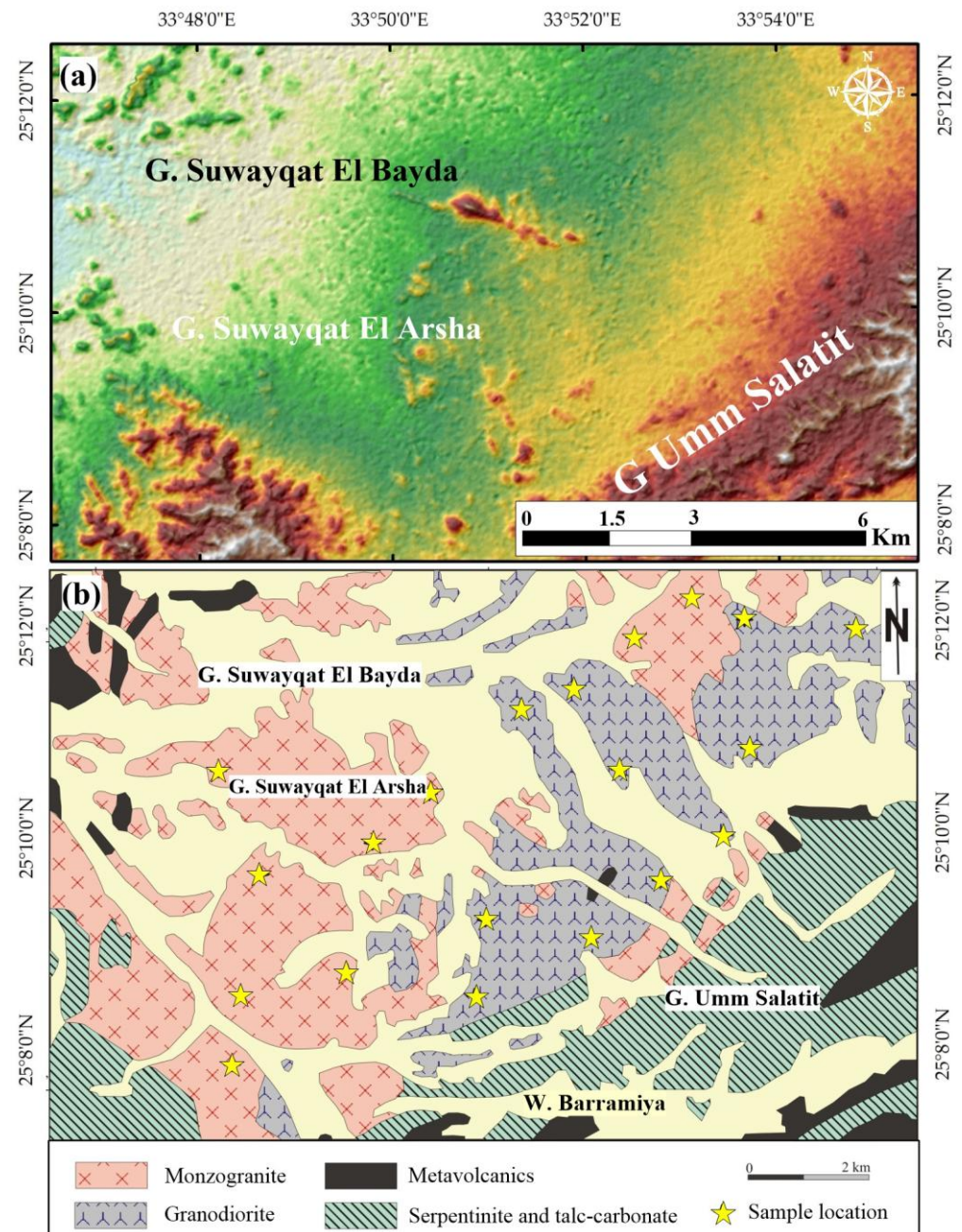


Figure 2. (a) Digital elevation model (DEM) map of the study area. (b) Geologic map of Suwayqat El-Arsha area (after [1,4,20,24]).

Felsic intrusive rocks in the study area are divided into two main phases: an early granodiorite cut by a later monzogranite. The granodiorite underlies the middle and eastern parts of the study area. It is a part of a much larger, intermediate batholith that extends from north of Marsa Alam Road (Umm Salatit-Homrit Wagat) to south Hafafit (Wadi El-Hima) [14,25–27]. It intrudes serpentinites and ophiolitic metagabbros with sharp intrusive contacts. In the southern part of the mapped area, the granodiorite is also observed to intrude small occurrences of island arc metavolcaniclastics. The granodiorite crops out as large, massive masses or forms low-relief rocks of grayish to white color with well-developed spheroidal weathering (Figure 3a). The granodiorite is cut by a few mafic and felsic dikes of variable thickness, as well as quartz veins. A few mafic xenoliths and enclaves are observed within the granodiorite. Earlier workers referred to granodiorite as gray granite [28].

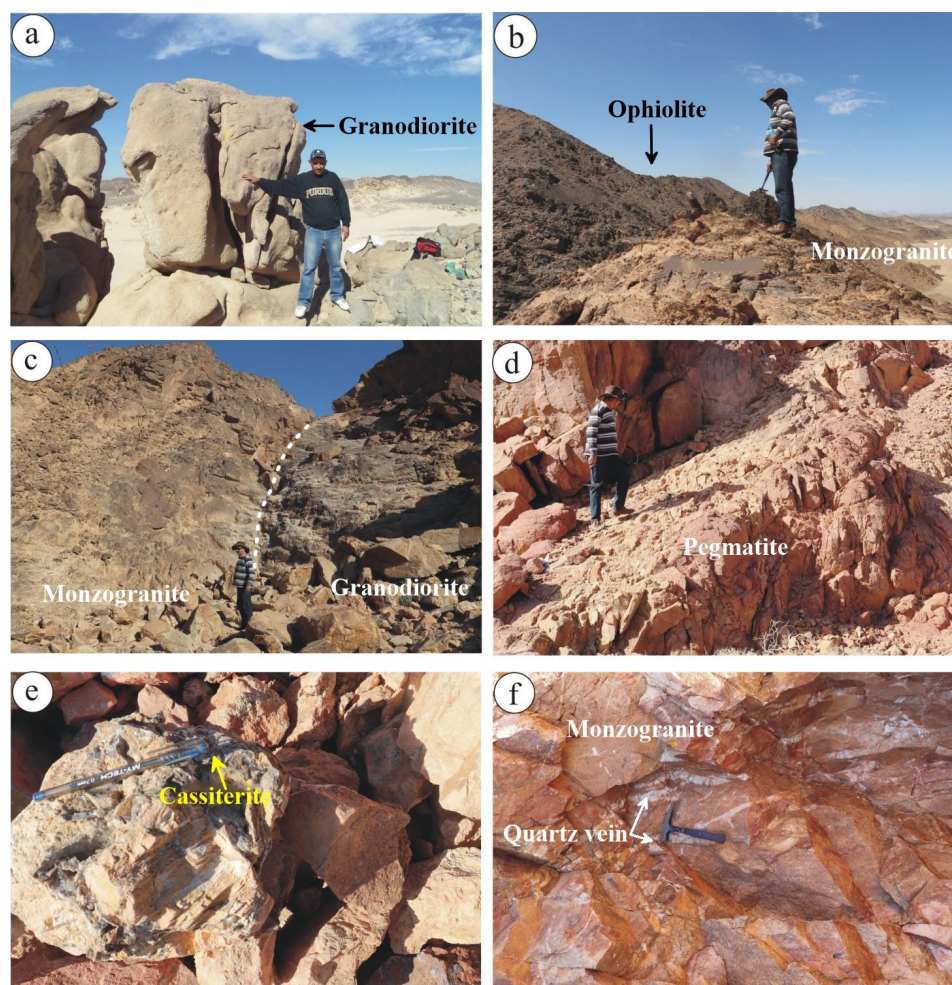


Figure 3. Field photographs showing the geological features at Suwayqat El-Arsha district. (a) Jointed blocks of granodiorite; (b) Sharp intrusive contact between ophiolite and monzogranite; (c) Intrusive contact between granodiorite and monzogranite; (d) Large cassiterite-bearing pegmatitic dike. (e) Cassiterite crystals within mineralized pegmatitic dikes. (f) Hydrothermally altered margin of monzogranite that shows silicification and hematitization cut by a variety of quartz veins.

Monzogranite represents the most common rock type in the study area and forms locally steep, highly resistant outcrops. It intruded the granodiorite and ophiolitic rocks with sharp intrusive contacts (Figure 3b,c). Most of the central part of the monzogranite is covered by alluvial deposits. It is homogenous, pink in color, medium- to coarse-grained, and locally, it has a porphyritic texture. In addition, a few fine- to medium-grained granitic dikes cut the monzogranite. The marginal zones of the monzogranite where it is in contact with the country rock show fine-grained, chilled margins tens of centimeters in width. Some offshoots and apophyses of monzogranite cut into the adjacent granodiorite and ophiolite. Coarse-grained pegmatitic dikes and pockets are observed at the margins of the monzogranite (Figure 3d). A few pegmatitic dikes are mineralized and contain large crystals of cassiterite (Figure 3e). The marginal part of the monzogranite experienced post-magmatic hydrothermal alteration, marked by hematite and quartz in some areas (Figure 3f).

3. Methods

3.1. Remote Sensing Datasets (Sentinel-2 and EnMap Hyperspectral Data)

In this study, a synergistic approach combining multispectral data from Sentinel-2 and hyperspectral data from EnMap was employed to delineate precisely the rock units within

the study area. Sentinel-2 data were specifically chosen for its superior spatial resolution (up to 10 m), offering a more detailed representation of distribution of lithologies compared to other commonly utilized datasets [29–31]. The Multi-Spectral Instrument (MSI) aboard the Sentinel-2 satellites facilitates terrestrial imaging from an altitude of approximately 786 km [32]. The Sentinel-2 imagery encompasses thirteen spectral bands spanning the visible to near-infrared (VNIR) and shortwave infrared (SWIR) regions. This study utilizes Sentinel-2 datasets provided by the European Space Agency (ESA). On 5 May 2020, a cloud-free Sentinel-2 MSI dataset was acquired and used for the current analysis.

To the best of knowledge, this is among the first applications of EnMap for comprehensive lithological mapping on the Nubian Shield. Reflected solar energy from the Earth's surface is recorded by the EnMAP satellite push-broom-style hyperspectral imager in 246 successive bands between 420 and 2450 nm. The mean bandwidth is 6.5 nm in the VNIR range and 10 nm in the SWIR range [33]. The sensor delivers a sweep width of 30 km and a spatial resolution of 30 m. EnMAP can capture strip lengths between 30 and 1000 km each day, with a daily capability of 5000 km [34].

The False Color Combinations (FCC) and Minimum Noise Fraction (MNF) image for Sentinel-2 data processing techniques are widely utilizing to achieve interpretable lithological differentiation. In particular, we used Sentinel-2 FCCs b12-b7-b3 and b12-b11-b4 in RGB [35], and MNF 3-1-2 components [36,37] used to identify and map rock units.

Sequential maximum angle convex cone (SMACC) is applied to EnMap data for better characterization of the distribution of the rock units [38]. For endmember extraction and unmixing, SMACC as quick, fully automated technique that works best with hyperspectral data. By choosing data vectors with the biggest angles with respect to the present cone, it repeatedly finds endmembers using a convex cone model [39]. The algorithm maintains non-negative abundances while updating abundance maps continually. When every data vector fits inside the convex cone within a given tolerance, the procedure is completed.

To thoroughly analyze the terrain structural features, employed as a gray-level spatial dependence matrix. The latter is a powerful tool for comprehensive textural analysis and has proven effective in delineating such features [40]. Fundamentally, this method quantifies textural attributes by assessing the spatial relationships and variability among neighboring pixel values. To achieve this, we implemented a moving 7×7 kernel (window) across imagery, examining the digital values of all pixels within the window. This second-order statistical analysis allowed us to calculate key textural attributes, including contrast and correlation, which are sensitive to the geological characteristics of the study area.

3.2. Field Work and Petrographic Studies

The field investigation involved sampling and describing the field relationships and structural setting of exposed rock units, particularly granitic rocks, which are the focus of the study. The petrographic study of 21 thin sections for the granitic rocks from the study area were carried out with a polarized light microscope at the National Research Center in Dokki, Egypt.

3.3. Analytical Investigations

Mineral chemical analyses were performed at the Department of Earth Sciences at the University of Western Ontario, Canada, using JEOL JXA-8530F field-emission electron microprobe analysis (EMPA). Operating conditions were 20 kV probe current, 40–60 nA accelerating voltage, 1–2 μm diameter beam, counting time of 5–10 s, natural and synthetic mineral standards, and a ZAF matrix correction routine. The standards were synthetic orthoclase for K, albite for Na and Al, anorthite for Ca, rutile for Ti, zircon for Zr and Si, fluorite for F, and fayalite for Fe.

Chemical analysis of the same 21 samples was performed at the Northwestern University, China. Powdered samples were heated at 1000 °C for 50 min to determine Loss on Ignition (L.O.I.). Samples were prepared for X-ray fluorescence (XRF, Rigaku RIX2100; Rigaku Corporation, Tokyo, Japan) by mixing 0.7 g of sample with 0.3 g of LiF, 0.4 g of NH_4NO_3 , 3.6 g of $\text{Li}_2\text{B}_4\text{O}_7$, and 2–3 drops of 1.5% (*w/w*) LiBr solution. This mixture was melted in a non-wetting precious metal crucible and poured into a glass disk prior to analysis. In parallel, 50 mg of sample powder were digested at 190 °C for 48 h in mixed HClO_4 , HNO_3 , and HF acids in steel bombs with polytetrafluoroethylene sleeves. After drying, residues were taken up in 80 mL of 2% HNO_3 with 10 ng/g of Rh as an internal standard. These solutions were analyzed on ICP-MS (Agilent 7500a) for trace and rare-earth elements. The analytical data were calibrated with international rock standards BCR-2, BHVO-1, and AGV-1. The analytical precision of this protocol, based on sample replicates, is better than 1% for major oxides and 5% for REE and trace elements.

4. Results

4.1. Remote Sensing Results

Sentinel-2 data combinations identified four main lithologies within the study area: serpentinite, granodiorite, monzogranite, and metagabbro. However, the detailed spectral and spatial characteristics of each unit were further refined and enhanced using SMACC “algorithm” analysis of EnMAP data. The Sentinel-2 FCCs bands (12-7-3 and 12-11-4 in RGB) effectively highlighted serpentinite rocks in black (Figure 2b or Figure 4a), predominantly exposed in the southeastern (G. Um Salatit) and southwestern (G. Barramiya) parts of the study area. North of these ophiolitic rocks, granodiorite appears as a faded brown hue, forming a circular belt that encloses monzogranite blocks (Figure 2b or Figure 4a,b). These lithologies are cut by prominent, long (10+ km), and continuous ENE-striking dikes that extend beyond the boundary of the study area toward the Gabal El Rukham district (Figure 4a,b). The long, prominent dikes are cut by a shorter set of NW-striking dikes, which is particularly evident within the monzogranite in the central portion of the study area (Figure 4a). In the northwestern part of the study area, metagabbro and metavolcanic rocks are exposed as discrete bodies and are represented in black on the FCC imagery, showcasing their scattered distribution.

The MNF analysis applied to Sentinel-2 data provides an improved visualization of the lithologies (Figure 4c). Serpentinite blocks are distinctly represented in cyan-green hues in the southern part of the study area. A prominent olive-green belt of granodiorite is well defined, separating the serpentinite from monzogranites, which appear in vivid pink tones. Monzogranite blocks are further highlighted in pink across the northeastern and northwestern parts of the terrain. Metagabbroic rocks are mapped as discrete blocks in the northwestern corner, while wadi deposits are clearly delineated in dark blue. Additionally, long dikes are depicted in bright hues, clearly intersecting one another with noticeable displacement within the monzogranite.

For a more comprehensive analysis, EnMap data were utilized for the first time over the Arabian-Nubian Shield (ANS) using the SMACC algorithm that enables precise delineation of rock units based on their spectral characteristics through endmember extraction. Endmember 3 effectively highlights serpentinite rocks, depicted in red (Figure 5a). This analysis not only delineates ophiolitic serpentinite but also captures their weathered and transported fragments distributed in adjacent wadis. Additionally, undetected pixels within the main serpentinite blocks are attributed to talc carbonates and marbles commonly associated with ophiolitic serpentinites [41]. The Figure 5b highlights felsic plutonic rocks, such as granodiorite and monzogranite, represented by yellow and dark-brown colors, respectively. Granodiorite forms a belt surrounding monzogranite, aligning with visual in-

terpretations derived from Sentinel-2 data (Figure 4). Figure 5c shows the small distribution of gabbro and metavolcanics.

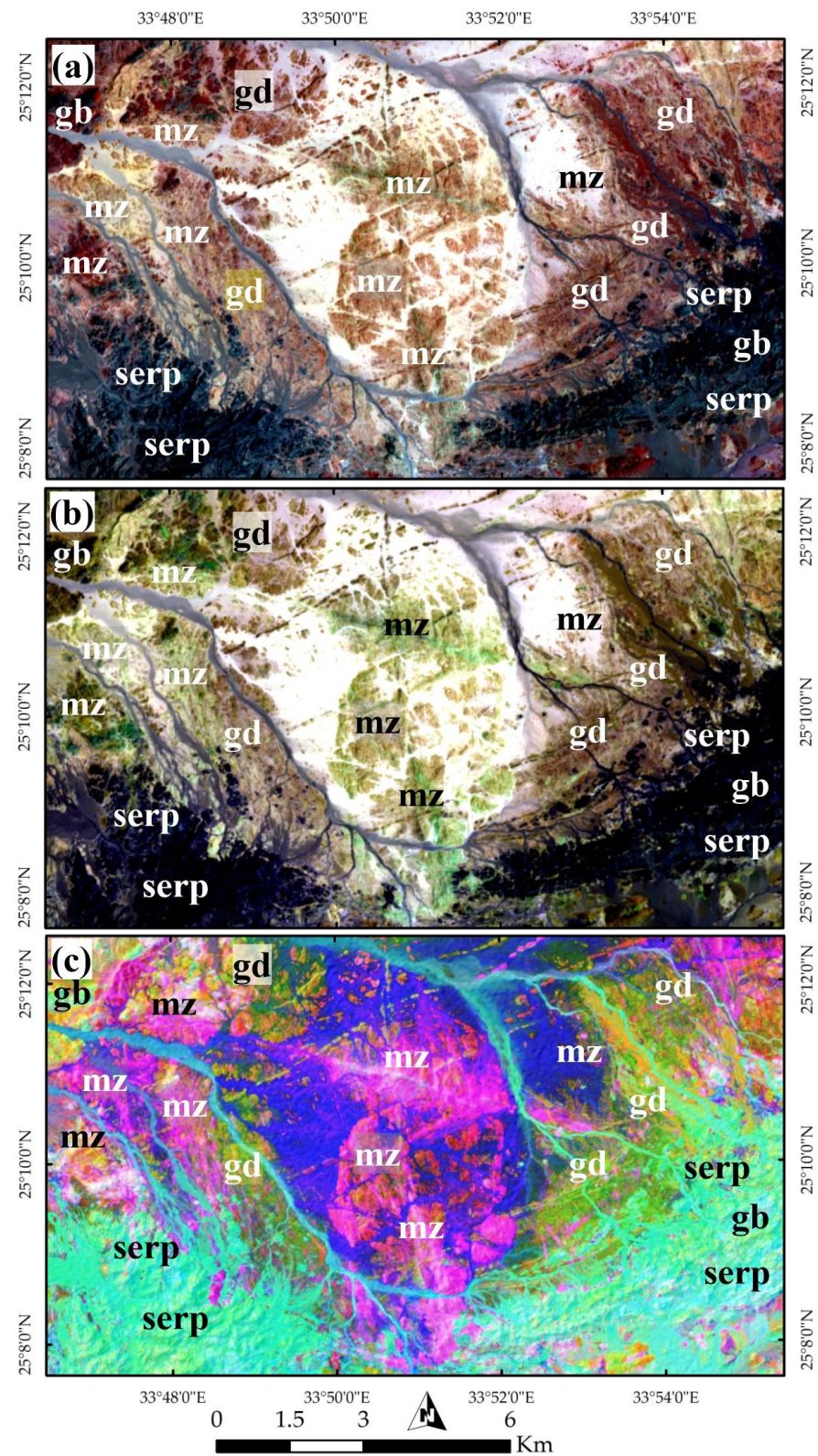


Figure 4. Sentinel-2 combinations of (a) FCC of 12-7-3 in RGB, (b) FCC of 12-11-4 in RGB, and (c) MNF3-MNF1-MNF2 in RGB, discriminating against main rock units in the study area. Abbreviations: (serp) Ophiolitic serpentinite, (gb) metagabbro–metavolcanic rocks, (mz) monzogranite, and (gd) granodiorite.

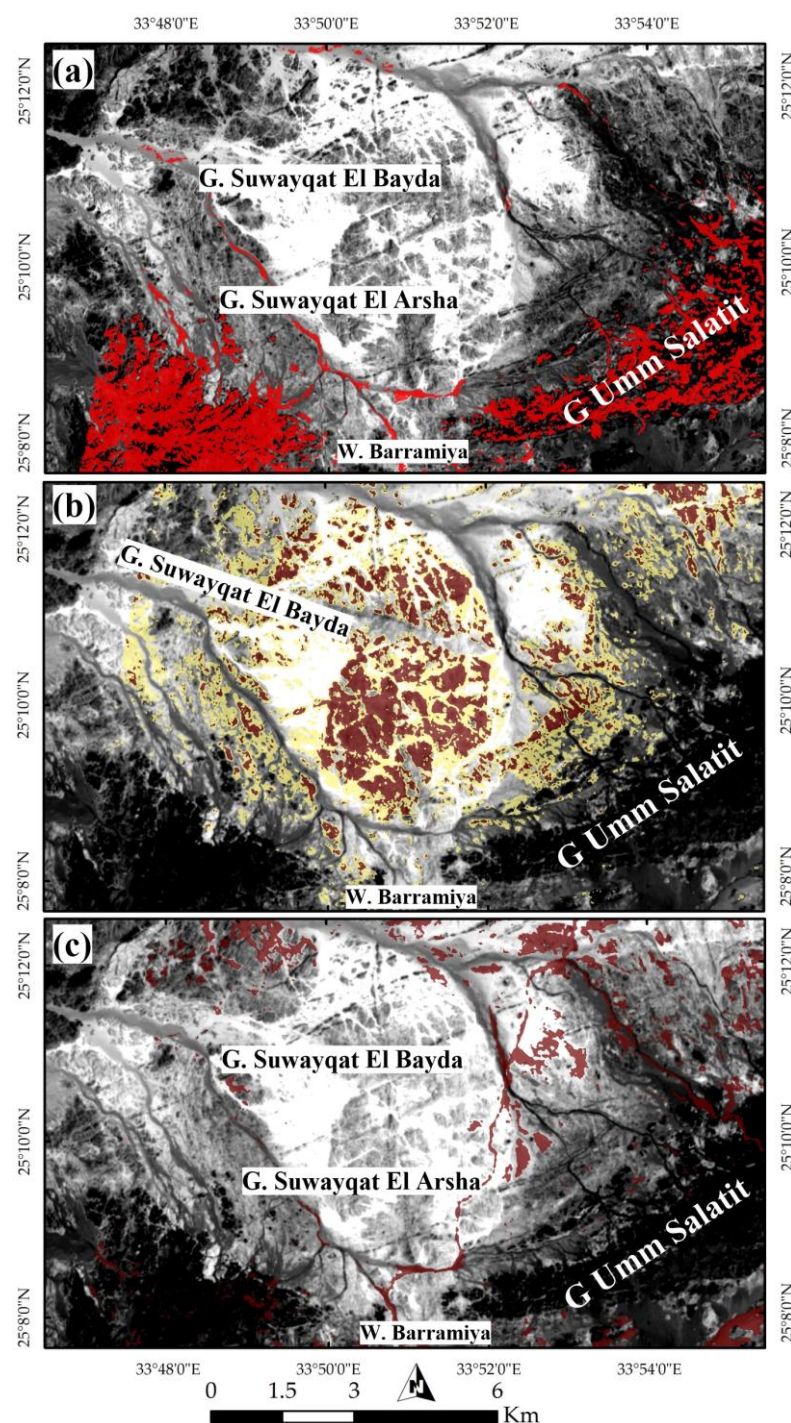


Figure 5. SMACC abundances. (a) Endmember 3 shows ophiolitic serpentinite (red), (b) Endmember 13 shows monzogranite (brown) and granodiorite (yellow), (c) Endmember 4 shows metagabbro and metavolcanics, undivided (brown).

The monzogranite and granodiorite are grouped under Endmember 13 due to their similar spectral signatures, reflecting shared mineral compositions. The spectral signatures of these granitic units are presented in Figure 6. In contrast, metagabbros and metavolcanics are represented by brown pixels in Endmember 4, predominantly exposed in the northern part of the study area. Certain pixels associated with ophiolitic serpentinite suggest either mineralogical resemblance to ophiolitic serpentinite, due to Fe-Mg-bearing minerals, or association with ophiolitic metagabbroic blocks. The spectral characteristics of the principal rock units identified within the study area are comprehensively presented in Figure 6.

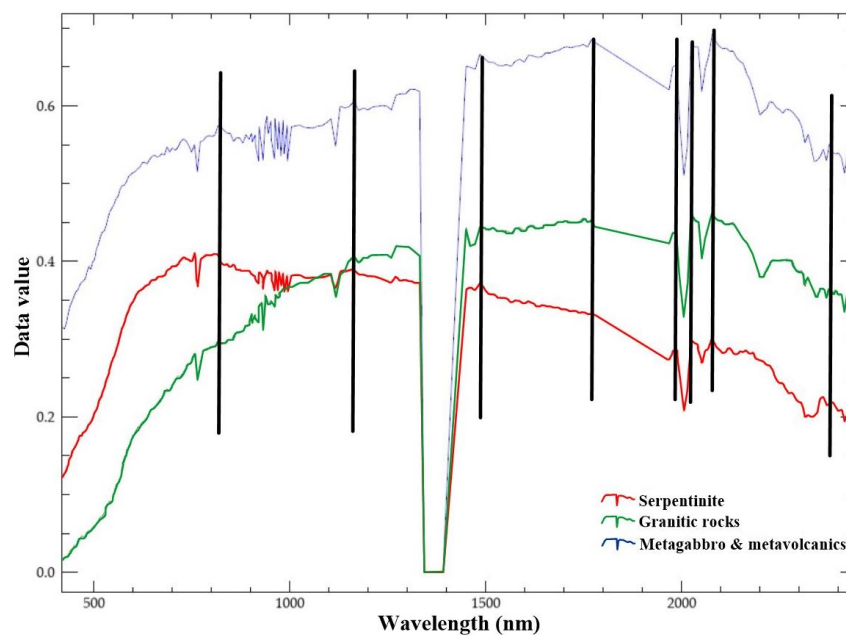


Figure 6. Variations in endmember spectral curves reflect the distinct lithologies through the SMACC analysis of EnMap data. The black line is referred to the highest pikes of spectral length.

To characterize the prominent and complex structural elements of the terrain, we applied textural analysis to Sentinel-2 data. A key technique, contrast analysis, was used to enhance the delineation of dike patterns by distinguishing them from host rocks and wadi deposits; the resulting pseudo-color image is presented in Figure 7. Furthermore, correlation values (Figure 8a) were calculated to map linear relationships between adjacent pixels, where high values typically correspond to structural features. The analysis reveals intricate structural details, with a close-up view (Figure 8b) clearly highlighting dominant NW–SE and subordinate NE–SW trends, indicated by elevated correlation values (brown shading).

To enhance interpretation, an additional close-up (Figure 8c) isolates and displays only the highest correlation values shown in red. This visualization effectively delineates the dominant tectonic trends—NE–SW, N–S, and NW–SE—which are well documented in the study area and are clearly evident through remote sensing analysis.

4.2. Petrography

4.2.1. Granodiorite

In hand specimen, granodiorite is whitish-gray, coarse-grained, and spotted with dark grains. Under the microscope, it is mainly composed of plagioclase, quartz, K-feldspar, mafic minerals, and opaques. Accessory minerals include apatite, titanite, and zircon. Plagioclase constitutes about 40–45% of the rock and occurs as euhedral to subhedral prismatic crystals reaching up to 2.2 mm in length and 1.8 mm. Normal zoning and albite twinning are pronounced in some crystals (Figure 9a), and other crystals are slightly to highly sericitized, especially in the cores. Quartz comprises about 20–25% of the rock about 2.4 mm in length and 2 mm in width and occurs as late anhedral grains filling the interstices between other minerals. K-feldspar (15–21 vol. %) occurs as anhedral interstitial crystals of orthoclase. Mafic minerals (4–7 vol. %) include biotite and amphibole. Biotite occurs as subhedral prismatic or platy crystals of yellowish-brown color (Figure 9b). Some biotite grains contain inclusions of apatite, and other crystals are chloritized. Amphibole occurs as subhedral grains and some of them show simple twinning (Figure 9c). Some amphibole crystals are slightly altered to chlorite and opaque minerals. Opaques (4–5 vol. %) include ilmenite and magnetite with minor pyrite. Ilmenite occurs as discrete prismatic crystals without exsolution and are locally replaced by

titanite. Magnetite occurs as prismatic and cubic crystals and is slightly altered to goethite. Very small, cubic pyrite crystals are found scattered in the rock. Titanite forms euhedral interstitial crystals associated with mafic minerals. Small inclusions of apatite are enclosed in plagioclase, biotite, and amphibole. A few euhedral crystals of zircon are commonly associated with amphibole or as inclusions in biotite.

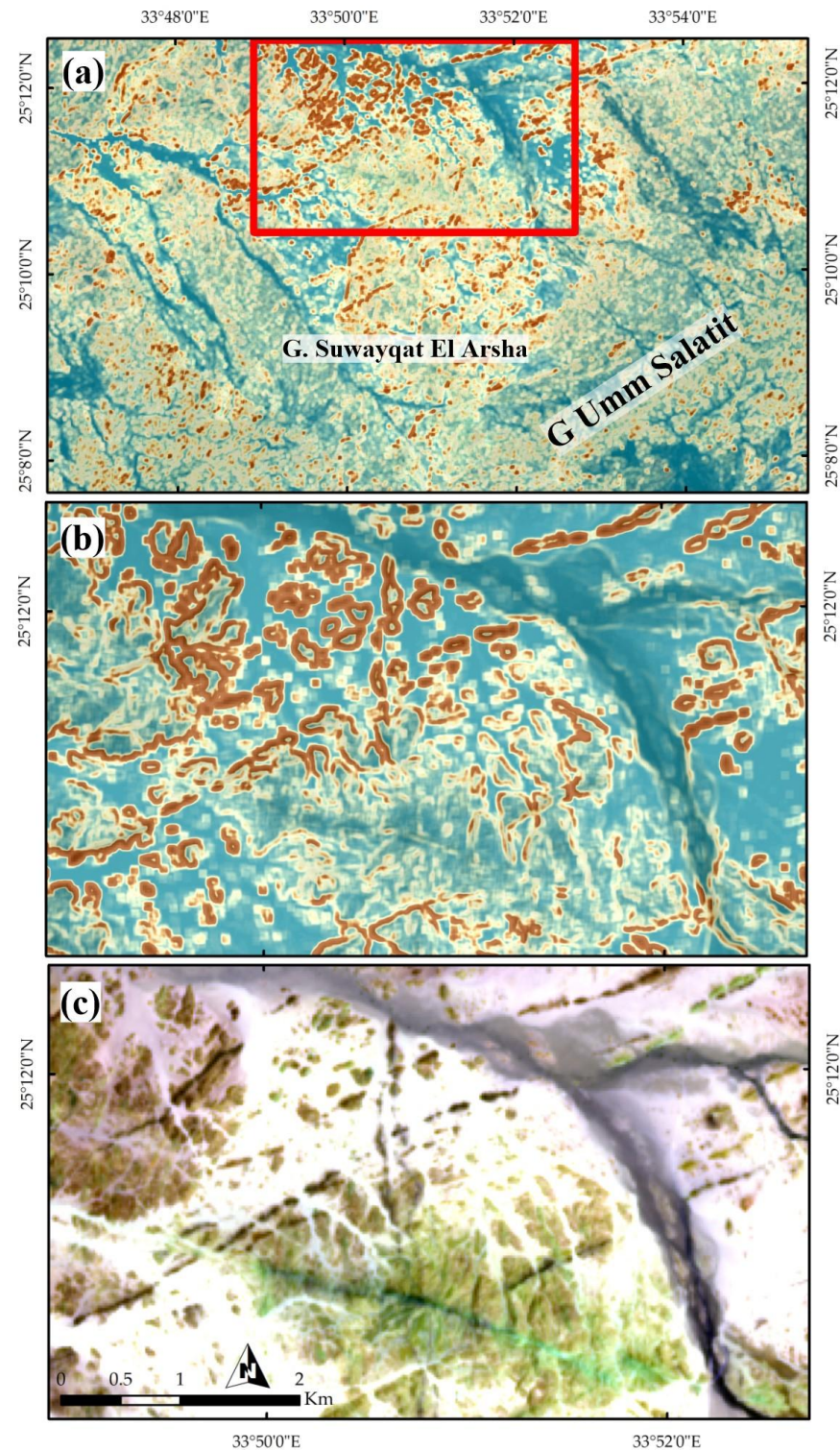


Figure 7. Sentinel-2 contrast analysis (a) highlighting dike patterns (brown) and their dominant NESW and N-S orientations. Close-up (b) and comparison with FCC image (c) demonstrate effective dike delineation. The red box shown the northern part of the area.

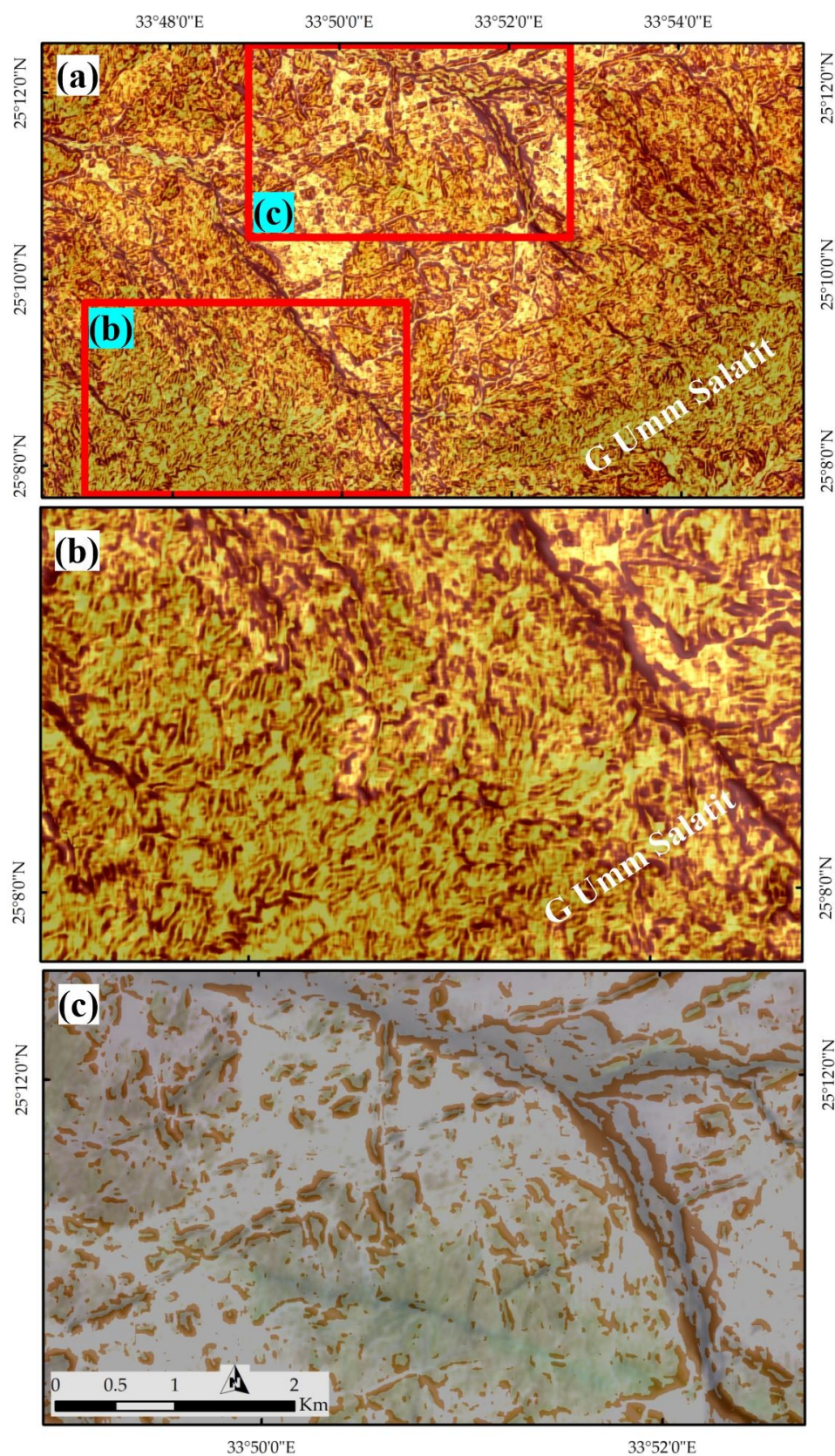


Figure 8. (a) Correlation analysis revealing linear relationship and structural trends (brown), including prominent NW–SE and NE–SW orientations. Close-up (b) and isolated high correlation values (red in (c)) emphasize dominant tectonic trends (NE–SW, N–S, and NW–SE).

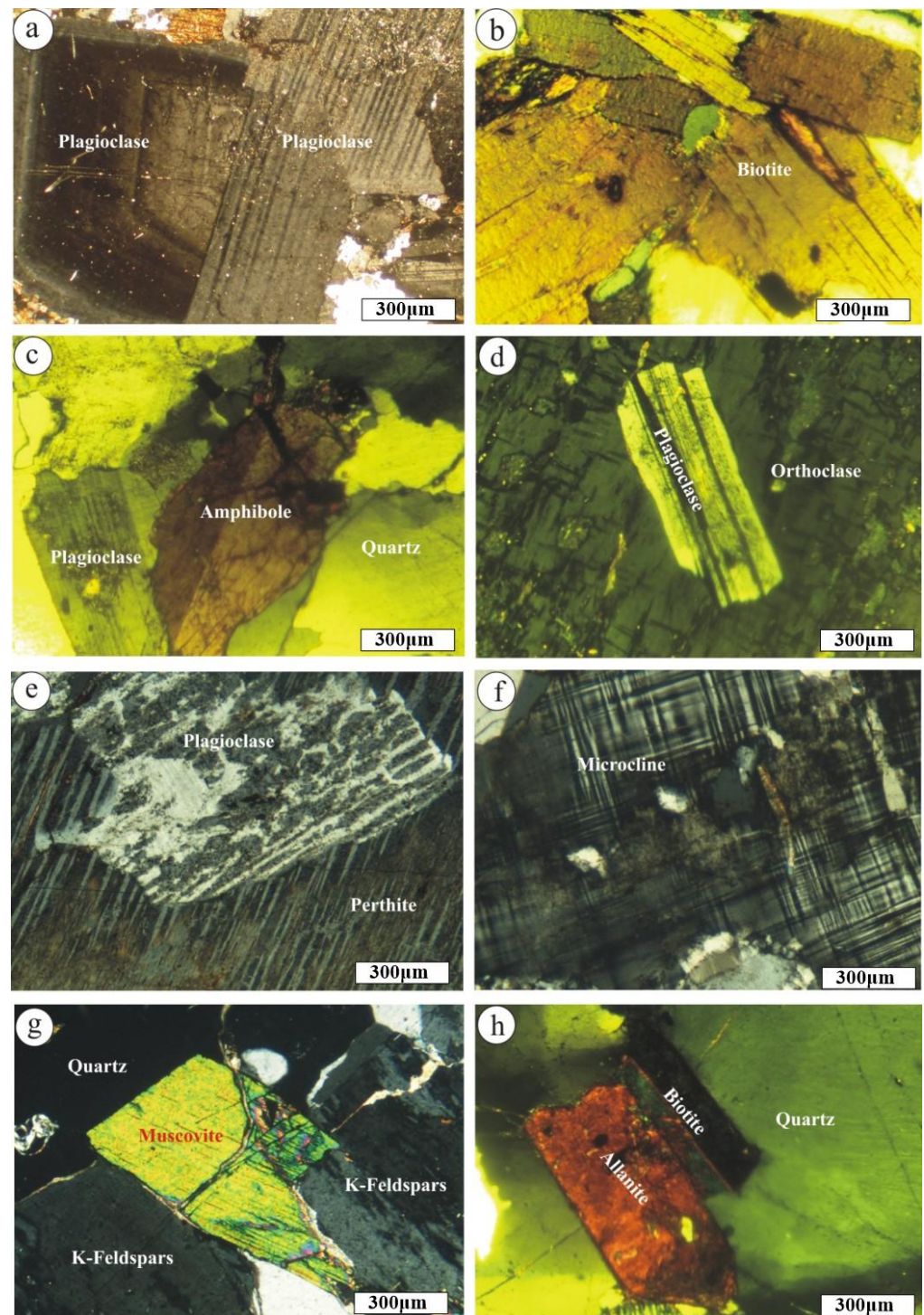


Figure 9. Photomicrographs of the Suwayqat El-Arsha granitoids ((a–c): granodiorite, (d–h): monzogranites) under cross-polarized light.

4.2.2. Monzogranite

Monzogranite is a coarse-grained, cream-colored two-mica granite mainly composed of quartz, plagioclase, K-feldspar, and minor biotite and muscovite, with accessory apatite, titanite, monazite, zircon, and opaque minerals. Secondary sericite and kaolinite are also found. K-feldspars (27–32 vol. %) are represented by orthoclase, microcline, and perthitic intergrowths with plagioclase. Orthoclase occurs as large subhedral crystals containing plagioclase inclusions up to 2 mm in length and 1.8 mm in width (Figure 9d).

Perthitic zones are platy in shape and show stringy and patchy perthite that contains inclusions of highly altered plagioclase (Figure 9e). Microcline is found to be subprismatic to platy crystals showing characteristic tartan twinning (Figure 9f). Some crystals of perthite and microcline are slightly kaolinitized. Plagioclase (25–32 vol. %) occurs as subhedral prismatic crystals showing albite twinning up to 2.6 mm in length and 1.4 mm in width. Most plagioclase crystals are fresh, while others are slightly sericitized. Small subhedral plagioclase prisms are found as inclusions in the perthite and microcline. Quartz (35–42 vol. %) occurs as anhedral interstitial crystals or as graphic intergrowths reaching up to 2.5 mm in length and 2 mm in width with K-feldspar and contains inclusions of variable sizes and shapes composed of feldspars and mafic minerals. Muscovite occurs as subhedral to euhedral crystals that saturated earlier in the melt history than K-feldspar and quartz (Figure 9g). Scarce anhedral crystals of zircon are included in K-feldspars and quartz. Allanite is deep red-brown in color and associated with biotite (Figure 9h). Titanite and monazite occur as anhedral crystals interstitial to other minerals, while apatite occurs as minute, disseminated crystals and as minute tabular crystals in biotite. The common alteration recorded in the studied granites is silicification, kaolinitization, sericitization, and chloritization.

4.3. Mineral Chemistry

Mineral composition of granodiorite and monzogranite was determined using an electron-probe micro-analyzer (EPMA), especially for plagioclase, albite, K-feldspar, amphibole, biotite, chlorite, muscovite, magnetite, ilmenite, apatite, and zircon crystals. Four samples were prepared for EPMA, two for granodiorite (SW32, SW55) and two for monzogranite (SW16, SW39). A similar number of probe spots were measured on each sample (Supplementary Tables S1–S11).

4.3.1. Silicate Minerals

Feldspars

Crystal chemistry of feldspars, including plagioclase, albite, and K-feldspars, was determined for granodiorite and monzogranite. Plagioclase ($n = 26$), albite ($n = 27$), and K-feldspar ($n = 26$) compositions were calculated based on eight oxygen atoms (Supplementary Tables S1–S3). Plagioclase crystals in granodiorite have a composition ranging from albite to andesine, whereas plagioclases in monzogranite are solely albite and oligoclase (Figure 10a). The average composition of plagioclase in granodiorite is $\text{Ab}_{68}\text{An}_{30}\text{Or}_3$, and $\text{Ab}_{84}\text{An}_{15}\text{Or}_2$ for monzogranite (Supplementary Table S1). In both granodiorite and monzogranite, the proportions of orthoclase and anorthite are lower than the albite content. The analysis of albite crystals revealed high Na_2O (10.67–11.82 wt.%) and low CaO (0.03–0.84 wt.%) concentrations, indicating high albite (94.93–99.37%) and very low anorthite (0.14–4.1 wt.%) contents. The K-feldspar analyses of the studied granodiorite and monzogranite have an average composition of $\text{Ab}_{8.3}\text{An}_{0.4}\text{Or}_{90.7}$ and $\text{Ab}_{5.2}\text{An}_{0.2}\text{Or}_{94.7}$, respectively. The analyses also indicate high K_2O contents in granodiorite (16.06%) and monzogranite (16.29%). According to the feldspar classification diagram [42], alkali feldspar falls in the microcline–orthoclase–sanidine field (Figure 10a).

Amphibole

Amphiboles represent one of the essential mafic minerals in the Suwayqat El-Arsha granitoids. The chemical composition and structural formula of amphibole ($n = 37$) is calculated based on 23 oxygen atoms (Supplementary Table S4). Structural formula of amphibole were calculated using Excel spreadsheet [43]. According to the Si versus $\text{Ca} + \text{Na} + \text{K}$ (apfu) discrimination [44] diagram, amphibole of granodiorite trends in its magmatic composition trending from magnesio-hornblende to tschermakitic hornblende (one grain is a true tscher-

makite), while monzogranite samples range widely in Mg# from magnesio-hornblende to ferro-hornblende to ferro-tschermakite having negligible Mg (Figure 10b). Despite the wide scatter, in general, monzogranite amphibole is more ferroan than granodiorite amphibole.

Biotite

Biotite is the essential ferromagnesian mineral of the Suwayqat El-Arsha granitoids and occurs in both granodiorite and monzogranite. Supplemental data Table S5 shows the chemical composition and structural formulae of the biotite ($n = 31$) using 22 oxygens. The FeO_t in biotite analyses of granodiorite range from 11.66 to 17.64 wt.%, MgO content from 12.91 to 17.33 wt.%, and K_2O from 8.48 to 9.89 wt.%. The investigated biotite crystals have Al_t concentrations ranging from 2.35 to 3 a.p.f.u. Based on the biotite discrimination diagram [45], the analyzed biotite falls in the re-equilibrated, primary biotite field (Figure 11a), as a result of some depletion in TiO_2 . Furthermore, the analyzed biotite from monzogranites plot mostly in the calc-alkaline biotite field (one sample in the peraluminous field), whereas the biotite in granodiorite has a calc-alkaline to peraluminous affinity [46] and noteworthy higher Mg (apfu) values (Figure 11b). According to FeO_t vs. Al_2O_3 diagram [47] for constraining magma composition based on biotite chemistry, the both studied granites are calc-alkaline in nature (Figure 11c). Modeled crystallization temperatures fall between 700 and 800 °C with the granodiorite showing a slightly higher temperature than the monzogranite. The decrease in modeled crystallization temperature correlates with lower TiO_2 concentrations (Figure 11d; [48]).

Muscovite

A few muscovite grains ($n = 9$) from the monzogranite were analyzed. The Supplementary Table S7 provides the chemical composition and structural formulas (based on 24 oxygens) of the analyzed muscovite from the monzogranite. Muscovite has high contents of SiO_2 , FeO^* , Al_2O_3 , and K_2O with averages of 45.66, 4.76, 31.10, and 9.8 wt.%, respectively. Magmatic muscovite is characterized by higher than 0.4 wt.% TiO_2 content [49–51].

Chlorite

The analyzed chlorite data ($n = 15$) is shown in Supplementary Table S6. It is characterized by relatively high values of SiO_2 , FeO^* , Al_2O_3 , and MgO with averages of 26.7, 30.55, 13.32, and 12.13 wt.%, respectively. Chlorite is a secondary alteration product of biotite and amphiboles. According to the chlorite classification of Hey [52], the granodiorite and monzogranite chlorites have a fairly small spread in the brunsvigite-pycnochlorite field (Figure 12a).

Zircon

The analyzed zircon ($n = 16$) is from both the granodiorite and monzogranite of the Suwayqat El-Arsha area, and its chemical composition is presented in Supplementary Table S8. It has high contents of ZrO_2 (28.95–32.04 wt.%), SiO_2 (58.94–64.17 wt.%), and HfO_2 (1.8–4.05 wt.%).

4.3.2. Non-Silicate Minerals

The non-silicate minerals comprise Fe-Ti oxides and apatite. The Fe-Ti oxides are magnetite, titanomagnetite, and ilmenite and their compositions are given in Supplementary Tables S9 and S10. The analyzed magnetite from granodiorite and monzogranite ($n = 22$) has high FeO_t content (81.11–93.58 wt.%) and low to moderate TiO_2 content (0.47–12.66 wt.%), indicating that some grains are titanomagnetite. Ilmenite ($n = 19$) is essentially composed of FeO_t (41.55–52.51 wt.%), TiO_2 (40.6 to 53.66 wt.%), and MnO (1.94–6.68 wt.%).

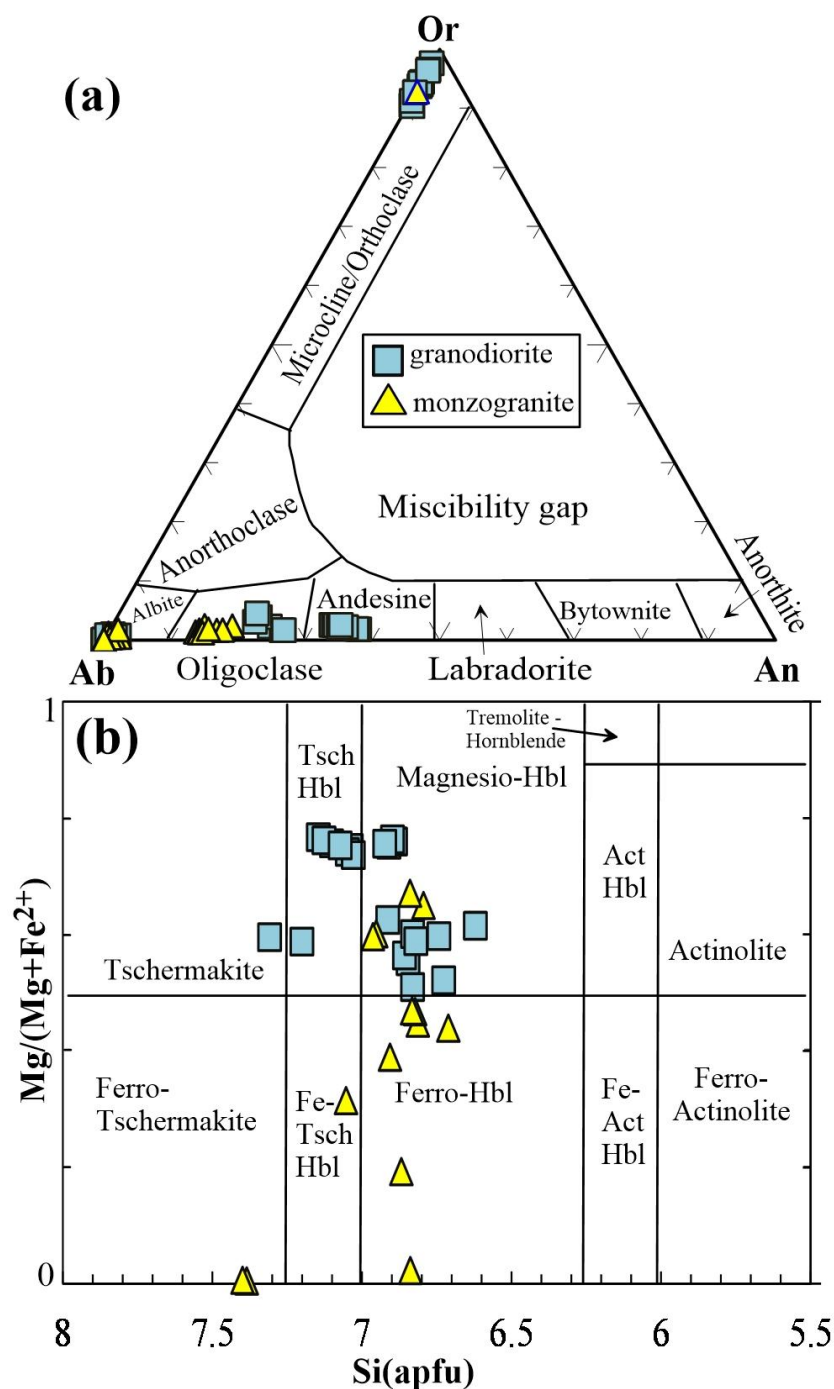


Figure 10. (a) Ab-Or-An classification diagram [42]. (b) Si versus. Mg# ($Mg/(Mg+Fe^{2+})$) discrimination diagrams for amphiboles [44].

Apatite, a significant accessory mineral in these magmatic rocks, was analyzed from the Suwayqat El-Arsha granodiorite and monzogranite ($n = 14$; Supplementary Table S11). Apatite has high CaO (53.25–55.2 wt.%) and P_2O_5 (38.99–41.28 wt.%) contents, and low average contents of Na_2O (1.2 wt.%), SiO_2 (0.4 wt.%), FeO (0.29 wt.%), MnO (0.25 wt.%), and MgO (0.02 wt.%). Based on the SiO_2 -FeO* binary diagram [53], most apatites are magmatic, but two grains, one from each rock type, fall into the hydrothermal apatite field (Figure 12b).

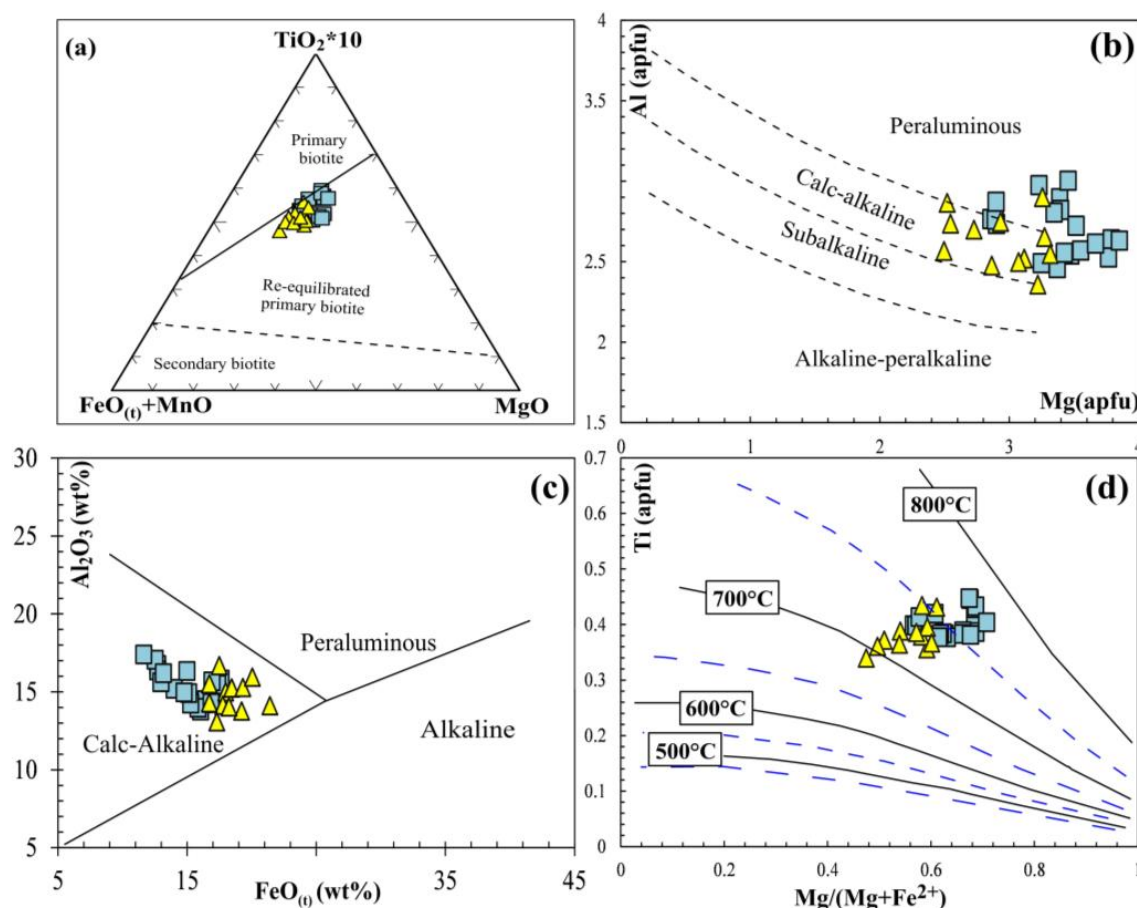


Figure 11. Chemical characteristics of the biotite crystals. (a) $\text{MgO}-10\times\text{TiO}_2-(\text{FeO}_t + \text{MnO})$ ternary diagram [45]. (b) Mg (apfu) vs. Al (apfu) for biotite (after [46]). (c) FeO_t vs. Al_2O_3 diagram (after [47]). (d) Ti vs. $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$, illustrating the biotite temperature [48]. The sign “*” referred to the multiplication process.

4.4. Geochemistry

Major, Trace, and Rare-Earth Element Data

Twenty-one fresh samples—12 samples of granodiorite and 9 samples of monzogranite—were analyzed for major, trace, and rare-earth elements (Table 1).

The SiO_2 content ranges from 68.21 to 71.44 wt.% for granodiorite and from 73.58 to 75.87 wt.% for monzogranite. On average, the granodiorite is enriched in Al_2O_3 (14.66 wt.%), Fe_2O_3 (2.61 wt.%), MgO (1.09 wt.%), CaO (2.89 wt.%), and TiO_2 (0.49 wt.%) compared to monzogranite. On the other hand, monzogranite samples are characterized by relatively high average SiO_2 (74.58 wt.%) and K_2O (4.51 wt.%) contents. The differentiation index for monzogranite ($\text{DI} = 89.53\text{--}95.84$, average = 92.01) is higher than that for granodiorite ($\text{DI} = 72.65\text{--}82.93$, average = 78.89, Table 1).

Table 1. Chemical composition (major oxides, and trace and rare-earth elements) and calculated normative mineralogy of granodiorite and monzogranite. REE were normalized to chondrite after Sun and McDonough [54] to calculate their ratios.

Sample No.	Granodiorite												Monzogranite								
	GD-SW29	GD-SW32	GD-SW35	GD-SW38	GD-SW41	GD-SW44	GD-SW47	GD-SW50	GD-SW52	GD-SW55	GD-SW59	GD-SW63	MZ-SW11	MZ-SW16	MZ-SW2	MZ-SW22	MZ-SW27	MZ-SW39	MZ-SW5	MZ-SW66	MZ-SW8
Major oxides (wt.%)																					
SiO ₂	68.21	68.84	69.82	70.16	70.65	68.58	71.69	71.37	70.26	71.44	71.32	69.42	75.87	73.78	73.58	74.49	75.38	74.66	74.3	73.98	75.24
TiO ₂	0.77	0.67	0.51	0.46	0.45	0.74	0.26	0.34	0.54	0.24	0.42	0.59	0.05	0.17	0.16	0.14	0.06	0.15	0.12	0.17	0.08
Al ₂ O ₃	14.88	14.38	14.73	14.9	14.7	14.61	14.71	14.56	14.81	14.92	14.49	14.29	12.11	13.59	13.48	13.16	12.56	13.41	13.27	13.54	12.89
Fe ₂ O ₃	3.32	2.92	2.68	2.48	2.44	3.26	1.99	2.31	2.6	2.12	2.38	2.89	0.81	1.47	1.65	1.28	0.78	1.31	1.25	1.55	1.04
MnO	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.02	0.05	0.05	0.06	0.03	0.05	0.07	0.06	0.07
MgO	1.56	1.23	1.03	0.89	0.88	1.53	0.92	0.89	1.06	0.95	0.91	1.25	0.27	0.36	0.39	0.32	0.27	0.31	0.33	0.33	0.32
CaO	3.87	3.33	2.89	2.77	2.59	3.73	2.37	2.34	2.97	2.42	2.41	3.07	0.82	1.17	1.41	1.06	0.91	1.03	1.36	1.13	1.16
Na ₂ O	3.56	3.63	3.67	3.84	3.63	3.56	4.09	3.66	3.63	3.95	3.75	3.54	3.96	3.87	3.82	3.67	4.14	3.79	3.95	3.63	3.82
K ₂ O	2.54	2.92	3.08	2.9	3.19	2.72	3.44	3.57	3.07	3.23	3.55	3.19	4.88	4.53	4.38	4.35	4.72	4.6	4.33	4.28	4.58
P ₂ O ₅	0.14	0.11	0.1	0.09	0.09	0.13	0.08	0.08	0.09	0.06	0.08	0.11	0.03	0.06	0.05	0.04	0.04	0.06	0.06	0.05	0.04
LOI	0.85	0.69	0.7	0.59	0.56	0.82	0.5	0.55	0.6	0.54	0.57	0.64	0.93	0.75	0.68	0.91	0.79	0.86	0.9	0.56	0.7
Total	99.76	98.78	99.28	99.15	99.25	99.75	100.1	99.76	99.7	99.9	99.94	99.06	99.68	99.8	99.65	99.48	99.68	100.23	99.94	99.28	99.94
R1	2581	2522	2546	2556	2597	2566	2461	2552	2593	2540	2517	2532	2484	2439	2474	2604	2425	2514	2498	2594	2555
R2	783	699	649	633	609	762	588	580	661	599	587	671	339	410	435	387	357	389	422	403	393
Quartz	26.9	27.68	28.57	29.13	30.12	27.04	27.69	29.53	28.96	28.83	28.82	27.99	32.7	30.65	30.64	33.72	31.49	32.09	31.33	33.39	32.55
Orthoclase	15.21	17.63	18.5	17.42	19.14	16.29	20.44	21.31	18.35	19.24	21.15	19.2	29.2	27.06	26.19	26.11	28.22	27.38	25.86	25.65	27.29
Albite	30.53	31.39	31.57	33.03	31.18	30.53	34.8	31.28	31.06	33.68	31.99	30.51	33.93	33.1	32.7	31.54	35.45	32.31	33.78	31.15	32.6
Corundum	-	-	0.34	0.63	0.79	-	0.14	0.61	0.33	0.67	0.28	-	-	0.34	0.01	0.59	-	0.47	-	1.01	-
Anorthite	17.34	14.62	13.91	13.37	12.45	16.05	11.3	11.2	14.31	11.7	11.53	13.92	0.85	5.47	6.75	5.08	1.76	4.75	5.74	5.35	4.52
Hypersthene	6.28	5.02	5.14	4.63	4.57	5.92	4.43	4.61	5.02	4.72	4.58	5.46	0.37	2.53	2.86	2.27	0.54	2.23	2.01	2.58	1.65
Magnetite	0.92	0.81	0.72	0.67	0.66	0.9	0.51	0.6	0.71	0.53	0.63	0.79	0.19	0.37	0.41	0.33	0.19	0.33	0.32	0.39	0.26
Ilmenite	1.48	1.3	0.98	0.89	0.87	1.42	0.5	0.65	1.04	0.46	0.8	1.14	0.1	0.33	0.31	0.27	0.12	0.29	0.23	0.33	0.15
Apatite	0.31	0.25	0.22	0.2	0.2	0.29	0.18	0.18	0.2	0.13	0.18	0.24	0.07	0.13	0.11	0.09	0.09	0.13	0.13	0.11	0.09
Trace elements (ppm)																					
Cr	8.84	7.79	5.95	5.4	5.04	8.87	3.91	4.14	5.76	4.42	4.62	7	2.14	2.74	3.41	3.23	2.46	2.87	3.34	3.55	2.37
Ni	6.95	5.18	3.72	4.21	3.46	6.2	3.73	3.03	4.67	3.61	3.86	4.2	1.16	2.84	3.15	2.92	1.54	2.51	2.59	2.87	2.43
Co	5.64	5.01	4.03	3.62	3.11	5.71	1.66	2.65	3.69	2.15	3.1	4.47	0.42	1.73	1.62	0.96	0.41	1.41	0.78	1.3	0.54
Sc	4.88	4.21	3.43	3.61	3.35	4.65	3.54	3.34	3.88	3.79	3.14	3.91	0.91	2.41	3.05	2.15	1.17	2.37	2.7	2.4	1.55
V	34.17	26.5	17.6	14.96	16.2	34	8.65	12.66	21.08	7.81	15.58	25.77	0.74	2.64	3.16	2.85	1.29	2.24	3.95	2.58	3.31
Cu	7.68	6.32	5.07	5.4	4.86	7.5	4.13	4.02	5.67	3.7	4.07	5.56	1.28	3.57	4.72	2.65	1.65	3.19	4.17	3.67	2.93
Pb	7.9	8.79	11.08	11.95	12.1	7.41	14.74	13.19	10.53	15.64	12.41	8.28	8.17	14.43	17	15.21	9.81	14.24	16.32	13.8	12.49
Zn	54	65.32	79.54	87.42	90.6	58.66	93.26	90.98	83.54	103.47	84.76	61.13	32.25	68.86	71.87	54.28	22.08	67.41	56.88	74.61	47.32
Cd	0.06	0.07	0.04	0.04	0.07	0.06	0.05	0.05	0.06	0.04	0.05	0.06	0.03	0.03	0.02	0.03	0.02	0.01	0.02	0.04	0.02
Sn	0.28	0.45	0.65	0.6	0.59	0.48	0.96	0.7	0.67	0.57	0.65	0.5	3.33	2.07	2.29	2.93	3.36	2.83	2.55	2.71	3.09
W	0.12	0.09	0.16	0.15	0.09	0.13	0.19	0.14	0.11	0.13	0.1	0.09	0.68	0.51	0.44	0.41	0.67	0.52	0.49	0.32	0.61
Mo	0.42	0.3	0.26	0.43	0.48	0.4	0.82	0.34	0.55	0.64	0.4	0.33	3.28	1.86	1.43	2.21	2.86	1.58	2.06	1.55	2.75
As	2.99	3.27	2.93	2.67	2.67	2.95	1.91	2.19	2.73	2.25	2.43	2.73	1.86	1.08	0.94	1.3	1.63	1.26	1.04	1	1.23
Sb	0.01	0.03	0.04	0.01	0.05	0.02	0.05	0.03	0.02	0.04	0.02	0.02	0.06	0.08	0.06	0.09	0.05	0.05	0.08	0.07	0.08

Table 1. Cont.

Sample No.	Granodiorite											Monzogranite									
	GD-SW29	GD-SW32	GD-SW35	GD-SW38	GD-SW41	GD-SW44	GD-SW47	GD-SW50	GD-SW52	GD-SW55	GD-SW59	GD-SW63	MZ-SW11	MZ-SW16	MZ-SW2	MZ-SW22	MZ-SW27	MZ-SW39	MZ-SW5	MZ-SW66	MZ-SW8
Trace elements (ppm)																					
Ag	19.89	17.84	19.35	19.86	19.78	19.87	15.92	18.83	19.84	17.89	20.31	18.08	4.91	7.87	8.92	5.03	6.21	8.97	5.09	6.33	7.4
Rb	49.17	60.58	67.38	76.03	73.79	49.57	107.64	75.65	59.52	90.7	72.2	60.56	272.67	154.7	150	192.09	238.31	179.1	181.18	180.8	210.2
Cs	1.3	1.95	1.14	1.62	1.95	1.61	1.75	1.39	1.41	2.2	1.79	2.08	1.87	1.91	1.65	2.18	2.71	1.98	2.41	2.03	2.1
Ba	528.63	437.8	525.0	467.7	468.8	462.4	440.04	476.3	481.7	460.76	468.7	490.3	252.67	403.4	410.8	321.86	267.85	394.19	311.96	378.63	252.0
Sr	371.61	322.1	259.2	242.52	253.9	371.9	181.26	226.4	284.0	173.41	251.9	317.5	38.53	100.7	119.9	78.78	44.1	108.08	79.9	119.79	44.63
Ga	10.15	14.43	13.16	16.69	17.14	12.87	18.08	17	16.21	15.42	16.96	15.44	28.42	20.75	19.53	23.05	25.33	21.25	20.11	18.74	22.96
Li	20.77	25.84	20.3	12.2	19.53	18.96	26.97	19.76	21.95	18.51	15.39	14.84	39.73	35.15	25.8	38.03	48.63	42.18	41.32	36.67	44.51
Ta	0.61	0.77	0.53	0.86	0.52	0.81	1.02	0.71	0.49	0.48	0.7	0.44	5.53	2.51	1.92	2.82	4.64	2.64	3.05	2.64	3.86
Nb	5.45	6.82	7.04	6.25	7.82	6.13	10.83	8.1	7.07	7.81	8.54	7.8	37.95	20.64	17.56	31.1	31.84	23.85	29.54	18.86	29.72
Hf	4.16	5.43	5.08	4.85	5.77	5.86	6.24	5.79	5.27	4.75	5.71	4.79	13.57	7.02	7.31	9.88	12.44	8.11	11.14	7.58	10.63
Zr	116.53	135.6	174.0	149.95	172.4	126.1	179.92	160.2	131.6	137.76	181.3	143.6	342.38	215.8	235.3	264.91	340.68	244.85	296.64	259.37	308.8
Y	8.15	8.66	9.62	9.57	12.08	8.87	14.98	11.02	10.69	12.88	9.96	8.83	61.54	31.61	30.42	37.81	52.56	36.03	37.35	28.55	44.2
Th	4.24	5.15	7.21	8.47	11.91	4	10.17	6.13	5.61	9.79	6.08	4.96	50.87	23.93	27.24	28.45	44.04	32.25	26.54	29.7	37.7
U	0.9	0.97	1.12	1.84	1.19	1.34	2.22	2.19	1.53	2.56	1.19	1.05	8.73	3.47	3.58	6.46	7.9	4.48	3.8	4.17	5.71
Be	1.09	1.13	1.88	1.43	1.37	1.58	2.03	1.46	1.56	1.87	1.39	1.18	3.92	2.55	3.22	3.84	4.21	3.34	3.1	3.33	4.79
Bi	0.16	0.12	0.22	0.15	0.18	0.14	0.34	0.34	0.12	0.27	0.22	0.19	0.18	0.34	0.39	0.28	0.19	0.29	0.29	0.35	0.22
REE (ppm)																					
La	12.27	14.685	15.05	16.262	17.87	13.53	20.261	18.43	15.70	19.52	15.24	15.16	51.305	32.49	28.56	38.507	47.405	38.584	36.39	32.91	37.83
Ce	25.482	28.58	29.52	32.528	35.53	28.45	41.229	36.15	32.56	37.263	31.70	29.86	109.98	69.26	62.06	80.767	100.36	81.905	76.157	68.583	79.09
Pr	3.106	3.363	3.54	3.878	4.196	3.503	5.035	4.243	3.965	4.303	3.83	3.546	13.335	8.527	7.636	9.86	12.205	10.461	9.653	8.497	9.48
Nd	11.029	12.435	13.13	14.428	15.61	13.63	19.141	15.54	15.26	16.073	14.86	13.15	52.095	32.14	28.87	36.92	47.47	39.162	37.553	33.17	35.71
Sm	2.293	2.423	2.667	2.858	3.12	2.63	3.697	3.1	3.018	2.86	2.837	2.624	9.815	5.953	5.515	7.04	8.938	7.715	6.96	6.133	6.51
Eu	0.607	0.615	0.617	0.658	0.678	0.535	0.763	0.677	0.753	0.721	0.787	0.63	1.27	0.87	0.927	1.1	1.158	1.033	0.981	0.943	1.077
Gd	1.933	1.975	2.11	2.306	2.56	2.043	2.813	2.55	2.305	2.76	2.223	2.076	7.785	5.513	5.035	5.65	7.361	6.793	5.89	5.287	6.118
Tb	0.29	0.285	0.3	0.34	0.382	0.305	0.451	0.377	0.337	0.43	0.33	0.3	1.288	0.887	0.808	0.95	1.221	1.11	0.966	0.857	1.077
Dy	1.633	1.585	1.713	1.95	2.228	1.723	2.558	2.16	1.933	2.597	1.86	1.688	8.598	5.53	4.941	6.057	8.04	7.328	6.241	5.433	6.793
Ho	0.327	0.323	0.34	0.388	0.44	0.345	0.538	0.427	0.383	0.51	0.377	0.338	1.85	1.113	1.009	1.287	1.73	1.566	1.239	1.103	1.414
Er	0.883	0.885	0.943	1.058	1.204	0.938	1.531	1.177	1.043	1.377	1.023	0.936	5.663	3.187	2.82	3.887	5.118	4.578	3.71	3.27	4.237
Tm	0.13	0.13	0.137	0.156	0.176	0.138	0.238	0.173	0.153	0.203	0.15	0.136	0.97	0.497	0.447	0.627	0.863	0.747	0.577	0.52	0.691
Yb	0.877	0.873	0.993	1.046	1.192	0.92	1.564	1.163	1.025	1.367	0.993	0.924	7.16	3.51	3.146	4.59	6.403	5.637	4.06	3.773	4.946
Lu	0.13	0.13	0.137	0.154	0.174	0.138	0.249	0.17	0.152	0.207	0.15	0.136	1.18	0.55	0.476	0.753	1.068	0.97	0.637	0.59	0.816
Eu/Eu*	0.88	0.86	0.79	0.78	0.73	0.71	0.72	0.74	0.87	0.78	0.96	0.82	0.44	0.46	0.54	0.53	0.44	0.44	0.47	0.51	0.52
(La/Yb) _N	9.46	11.38	10.25	10.51	10.14	9.94	8.76	10.72	10.36	9.66	10.38	11.10	4.85	6.26	6.14	5.67	5.01	4.63	6.06	5.90	5.17
(La/Sm) _N	3.38	3.83	3.56	3.59	3.62	3.25	3.46	3.75	3.28	4.31	3.39	3.65	3.30	3.44	3.27	3.45	3.35	3.16	3.30	3.39	3.67
(Gd/Lu) _N	1.82	1.86	1.89	1.84	1.80	1.81	1.38	1.84	1.86	1.63	1.82	1.87	0.81	1.23	1.30	0.92	0.84	0.86	1.13	1.10	0.92
(La/Lu) _N	9.67	11.57	11.26	10.82	10.52	10.05	8.34	11.11	10.59	9.66	10.41	11.42	4.45	6.05	6.15	5.24	4.55	4.08	5.85	5.72	4.75

$$\text{Eu}/\text{Eu}^* = \text{Eu}_N / (\text{Sm}_N \times \text{Gd}_N)^{0.5}.$$

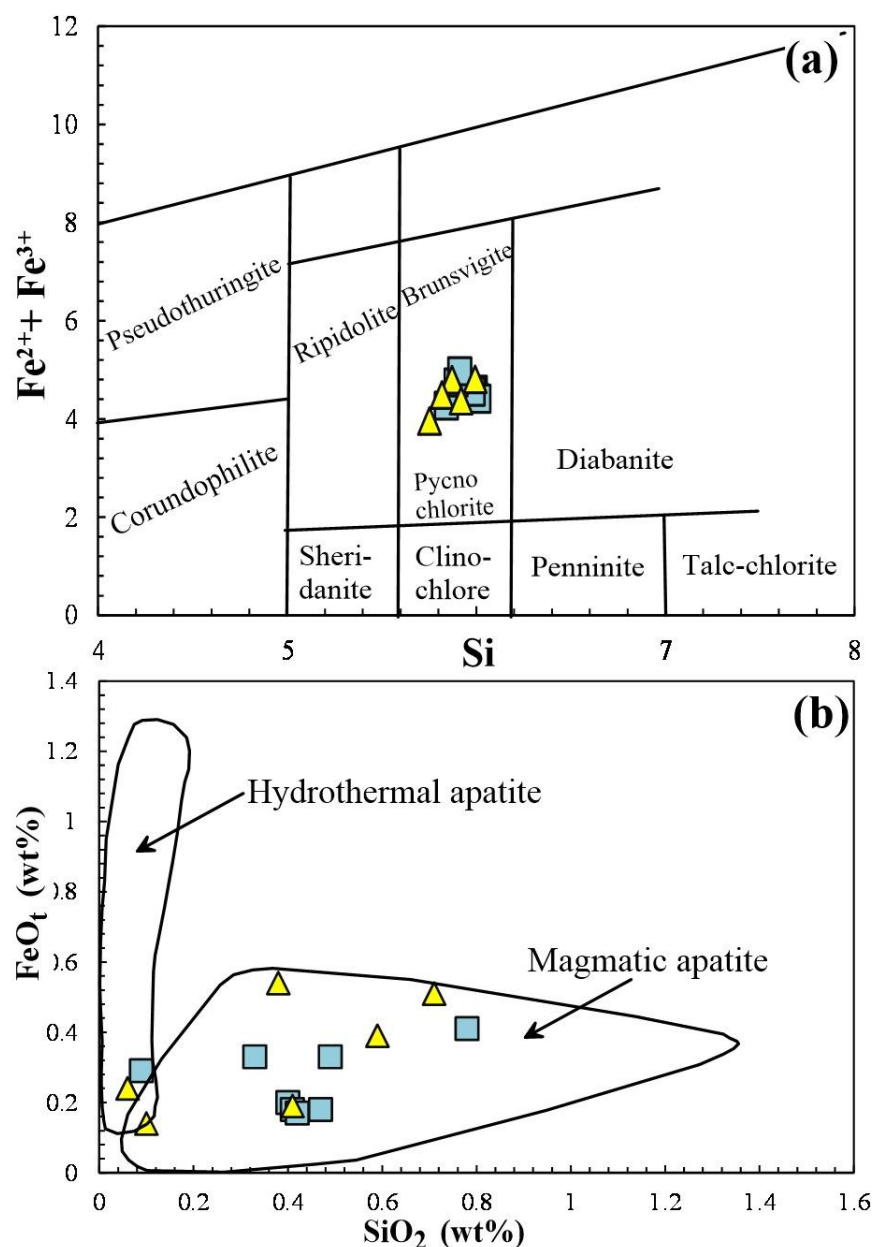


Figure 12. (a) Si vs. Fe (apfu) chlorite classification diagram [49]. (b) Compositional fields for magmatic and hydrothermal apatite [53].

Major oxide and trace element whole-rock compositions of the granitic rocks of Suwayqat El-Arsha are plotted on Harker variation diagrams (Figure 13). The high silica samples of Suwayqat El-Arsha reveal evolutionary trends within granitic rocks, indicating either fractional crystallization or magma mixing. For instance, the majority of samples in Harker variation diagrams for major oxides and trace elements exhibit near-linear trends (Figure 13). K_2O , Na_2O , Rb, Nb, Zr, Y, and Ga show positive correlation with SiO_2 (Figure 13a,b,j–m,r); whereas CaO , Al_2O_3 , MnO , P_2O_5 , MgO , Fe_2O_3 , TiO_2 , Ba, Sr, Cr, and V show negative correlation with SiO_2 (Figure 13c–i,n–q). The P_2O_5 content shows significant negative correlation with SiO_2 concentration in a Harker diagram, similar to an I-type granite trend (Figure 13f; [55,56]). For granodiorite, several elements exhibit invariant (slope = 0) to almost invariant (slightly positive slope) behavior with respect to SiO_2 , including Al_2O_3 , MnO , Nb, Zr, Y, and Ba, whereas only MgO and V exhibit similar, almost invariant (slightly negative slope) behavior for monzogranite (Figure 13).

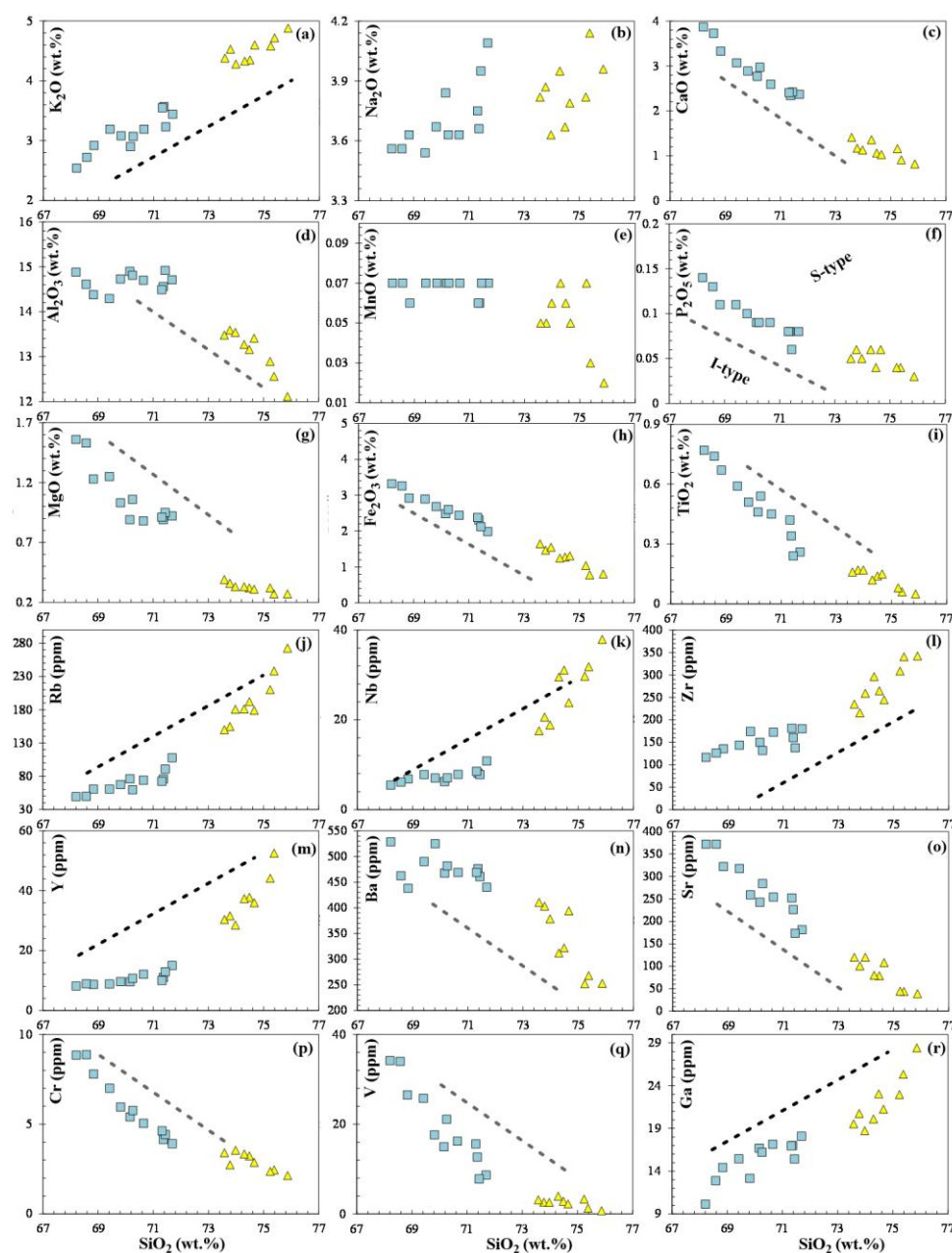


Figure 13. Harker diagrams of major (a–i) and trace (j–r) element concentrations vs. SiO_2 content for the Suwayqat El-Arsha granitoids. The dashed line indicates the direction of the gradient (increasing/decreasing). Trend lines are for visual reference only.

5. Discussion

5.1. Remote Sensing

The results of the remote sensing application showed good agreement with the field and petrographic studies and the lithographic map extracted from the remote. According to these results, Sentinel-2 data make full use of the differences in spectral sensitivities of distinct rock units, promoting new comprehensive lithological mapping.

Contrast values assess the internal variation among image pixels—coarser or more heterogeneous textures produce higher contrast, while uniform areas, with identical adjacent pixels, exhibit near-zero contrast. Consequently, variations in spectral signatures, often associated with different mineralogical compositions, can be effectively identified through higher contrast values.

As anticipated, higher contrast values correspond to more heterogeneous areas and distinctly highlight the dikes with their linear extensions, appearing in brown tones. Figure 7b provides a close-up view, clearly illustrating the linear shape of the dikes and revealing that NE–SW and N–S orientations are the dominant structural trends in the area. A comparison between Figure 7b (contrast image) and Figure 7c (FCC 12-11-2) further emphasizes how effectively the contrast analysis delineates dikes trending NE–SW and N–S from the surrounding host rocks.

5.2. Rock Classification and Magma Type

On the An–Or–Ab classification diagram [57], the Suwayqat El-Arsha granitoids plot in the ‘granodiorite’ and ‘granite’ fields (Figure 14a), which agrees with their petrography. On a Q’–ANOR classification diagram [58], granodiorite plots in the granodiorite field, stretching to the monzogranite–granodiorite joint, whereas the two-mica monzogranite plots in the monzogranite, syenogranite, and alkali feldspar granite fields (Figure 14b), suggesting more compositional variation for the monzogranite than for the granodiorite. On the FeO^* –($\text{Na}_2\text{O} + \text{K}_2\text{O}$)–MgO ternary diagram [59], the granodiorite plots in the calc-alkaline field, whereas the monzogranite plots near the total alkalis end-member, which indicates its alkaline nature (Figure 14c). On the other hand, based on alumina saturation ([60]; Figure 14d), the granodiorite is notably more aluminous than the monzogranite and plots in the peraluminous to metaluminous fields with elevated A/NK (1.4–1.8) and low A/CNK (0.95–1.05), whereas the monzogranite spans from peraluminous to metaluminous to slightly peralkaline (two samples) fields at similar A/CNK to those of granodiorite. The abundance of biotite and muscovite validates the peraluminous nature of these granitoids.

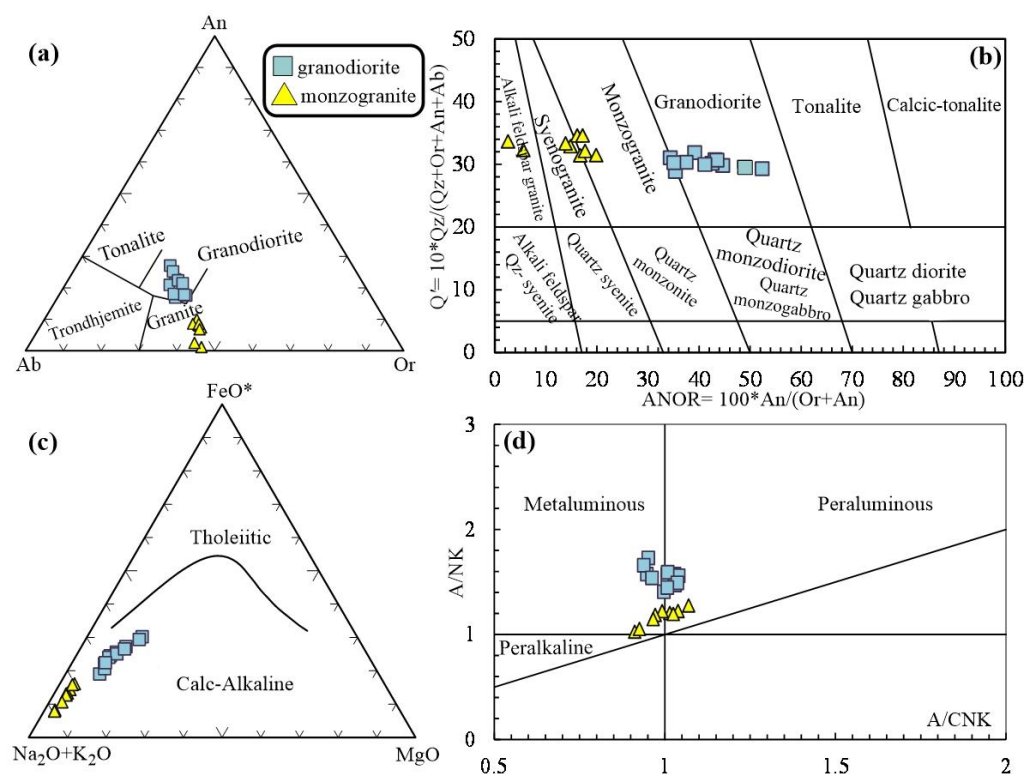


Figure 14. The classification diagrams of the present granitoids. (a) An–Or–Ab classification ternary diagram after [57]. (b) Q’–ANOR classification diagram after [58]. (c) FeO^* –($\text{Na}_2\text{O} + \text{K}_2\text{O}$)–MgO ternary classification diagram after [59]. (d) Molar $\text{Al}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. $\text{Al}_2\text{O}_3 / (\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ (aluminum saturation index; ASI) diagram after [60]. The sign “*” referred to the multiplication process.

Based on SiO_2 -alkali and SiO_2 - K_2O diagrams, the Suwayqat El-Arsha granitoids show calc-alkaline characteristics (Figure 15a,b; [61,62]); particularly, monzogranite is high-K alkali-calcic to calc-alkalic, and granodiorite is medium- to high-K calc-alkalic to calcic). Monzogranites are similar in composition to other Eastern Desert (ED) A-type granites, whereas granodiorites correspond to Eastern Desert (ED) I-type granites (Figure 15a).

Granitoids are commonly classified using the I-, S-, and A-types [63–66]. The studied granitoids were derived from two compositionally different, magmatic sources (Figure 15c). The $10^4 \times \text{Ga}/\text{Al}$ vs. $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram indicates that the granodiorite plots in the ‘I-type granite’ field, whereas the monzogranite falls into the ‘A-type granite’ field (Figure 15c; [67]). Ref. [67] inferred that A-type granites have high total alkali contents ($\text{K}_2\text{O} + \text{Na}_2\text{O} > 7.0$ wt.%) and 10,000 Ga/Al ratios (mostly > 2.6). The petrographic study shows that the granodiorite, characterized by typical I-type minerals (biotite and hornblende; Figure 15c), lacks aluminum-rich minerals (such as muscovite, garnet, and cordierite), indicating an I-type origin, whereas monzogranite has magmatic muscovite, indicating an S-type origin [68]. According to the Nb vs. SiO_2 tectonic discrimination diagram [69], the granodiorite plots in a ‘volcanic arc (orogenic)’ field, whereas the monzogranite falls in the ‘overlap’ field (Figure 15d).

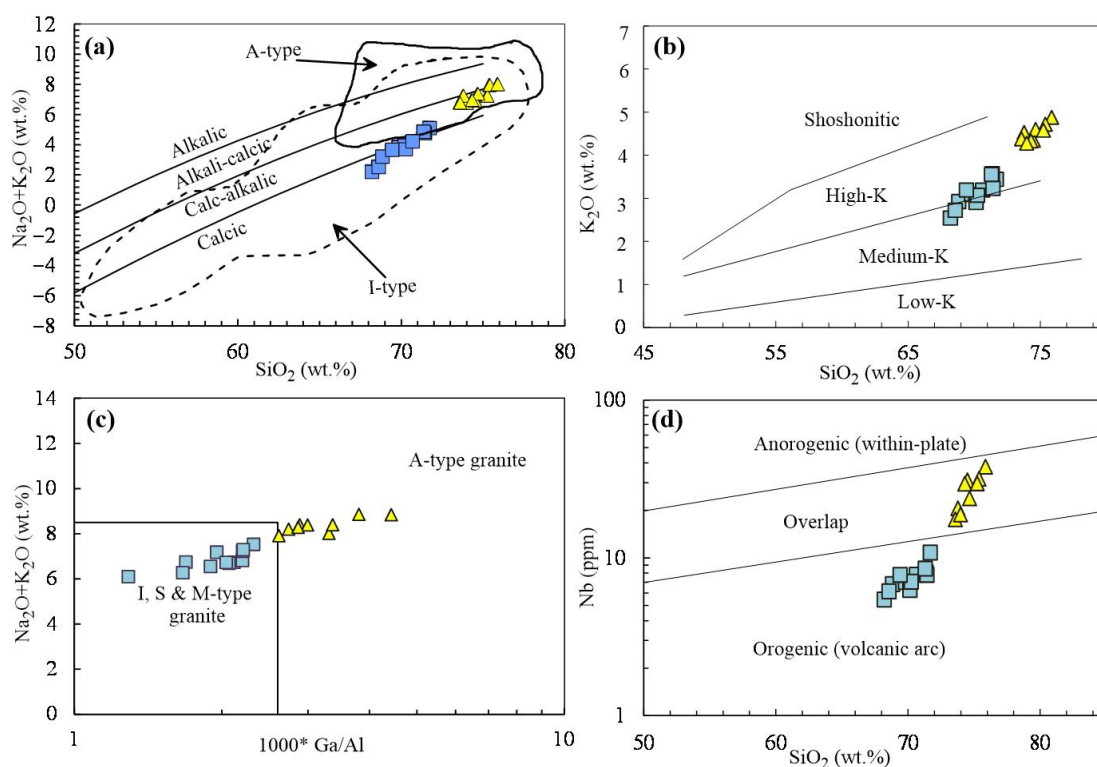


Figure 15. Tectonic classification diagrams of the studied granites. (a) $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs. SiO_2 discrimination diagram [61]. (b) SiO_2 vs. K_2O discrimination diagram [62]. (c) $10^4 \times \text{Ga}/\text{Al}$ vs. $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ after [67]. (d) SiO_2 vs. Nb diagram after [69]. The sign “*” referred to the multiplication process.

Ref. [70] utilized trace elements to differentiate granites from different tectonic settings, and according to their Ta vs. Yb (Figure 16a) and Rb vs. $(\text{Nb} + \text{Y})$ (Figure 16b) tectonic classification diagrams, the granodiorite plots in the ‘syn-collision granites’ (Figure 16a) and ‘volcanic-arc granites’ (Figure 16b) fields, whereas the monzogranite plots in the ‘within-plate granites’ (Figure 16a,b) and within the ‘post-collisional granite’ (Figure 16b) fields. On the Na_2O - K_2O - CaO ternary diagram ([71]; Figure 16c), the granodiorite samples plot in the ‘calc-alkaline, older granites’ field of the Neoproterozoic granites of the Arabian-Nubian

Shield, whereas the monzogranite plots in the ‘younger granites’ field. According to Rb/30–Hf–3Ta ternary diagram ([72]; Figure 16d), the granodiorite plots in the ‘volcanic-arc’ field, and monzogranite plots in the ‘late to post-collision’ field. According to CaO/Na₂O and Al₂O₃/TiO₂ batch-mixing ratios ([73]; Figure 16e), the granodiorite could be the product of approximately three mafic aliquot and seven pelite aliquot (30:70) mixture, but, interestingly, because of small Al₂O₃ range (Figure 13d), granodiorite drifts off the theoretical curve into low Al₂O₃/TiO₂ space. In contrast, monzogranite plots solely in the field of ‘strongly peraluminous granites’ derived from either mixing of one mafic aliquot and nineteen pelite aliquots (5:95 mixture) or an almost pure pelite source (1:99 mixture). Similarly to the granodiorite, monzogranite also drifts off the theoretical mixing curve, but to a high Al₂O₃/TiO₂ space, probably corresponding to the outlier alkali feldspar granite samples (Figure 14b).

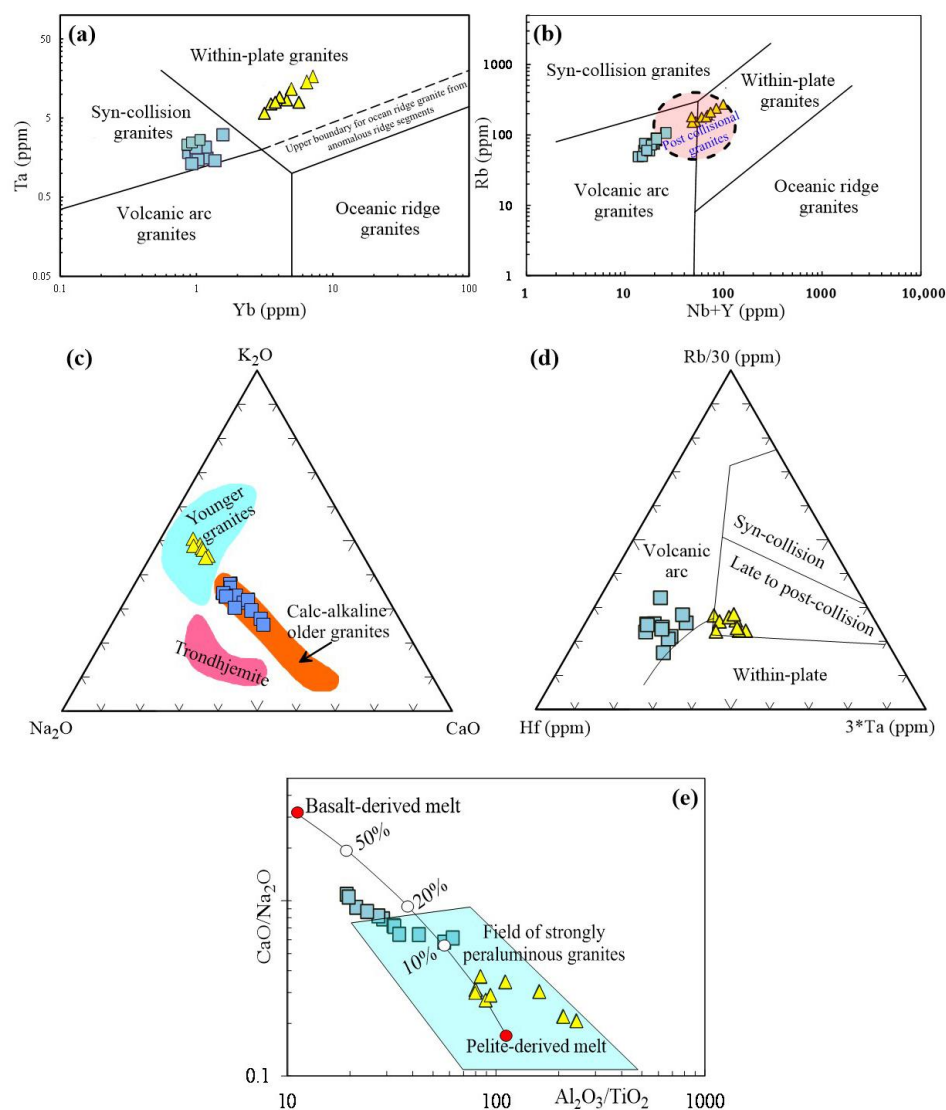


Figure 16. Tectonic affinities diagrams of the studied granites. (a) Ta vs. Yb tectonic setting diagram [70]. (b) (Nb + Y)-Rb tectonic discrimination diagram [70]. (c) K₂O-Na₂O-CaO ternary diagram showing literature data for the Egyptian granitoids [71] and data from this study. (d) Rb/30–Hf–3Ta ternary diagram [72]. (e) Al₂O₃/TiO₂ vs. CaO/Na₂O diagram [73].

Spider diagrams (Table 1; Figure 17a,b), based on the normalization values of Palme and O'Neill, 2013 [74], demonstrate a significant difference in magmatic evolution between the granodiorite and monzogranite. Some of the variations in incompatible elements in

granodiorite and monzogranites are primarily due to early fractionation of plagioclase, with negative Sr and Eu anomalies developed (Figure 17a; [75,76]). Sr in the monzogranite, in particular, is so depleted that a few of the measurements are only a factor of two greater than the primitive mantle (Figure 17a). Pb in the granodiorite is relatively enriched. The spider diagrams for both monzogranite and granodiorite are characterized by enrichment in large-ion lithophile elements (LILE) and flat high-field-strength element (HFSE) concentrations with depletions in Ba, Nb, Sr, Eu, and Sm. Extreme alkali feldspar fractionation is indicated by significant negative Eu anomalies, especially in the monzogranite, which are mostly associated with low contents of Ba and Sr. Granodiorite exhibits smaller Eu anomaly than monzogranite (Figure 17b).

The chondrite-normalized REE patterns [54] of the Suwayqat El-Arsha granitoids show moderately fractionated patterns ($(La/Yb)_N = 8.7\text{--}11.3$) and a negative Eu anomaly ($Eu/Eu^* = 0.70\text{--}0.95$), indicating the enrichment of HREE compared to LREE (Figure 17b). The most common equation to calculate the Eu anomaly is $Eu/Eu^* = Eu_N / (Sm_N \times Gd_N)^{0.5}$, where Eu_N , Sm_N , and Gd_N are the chondrite-normalized values for Europium, Samarium, and Gadolinium, respectively. The granodiorite shows low abundance of REE ($\Sigma REE = 60.85\text{--}100.13$ ppm) compared to the monzogranite ($\Sigma REE = 152.22\text{--}272.29$ ppm). The granodiorite exhibits LREE enrichment with respect to MREE ($(La/Sm)_N = 3.2\text{--}4.3$; average is 3.5) and flat HREE patterns ($(Gd/Lu)_N = 1.3\text{--}1.8$; average is 1.7), while the monzogranite is less enriched in LREE [$(La/Sm)_N = 3.1\text{--}3.6$; average is 3.4] and HREE [$(Gd/Lu)_N = 0.8\text{--}1.2$; average is 1.0].

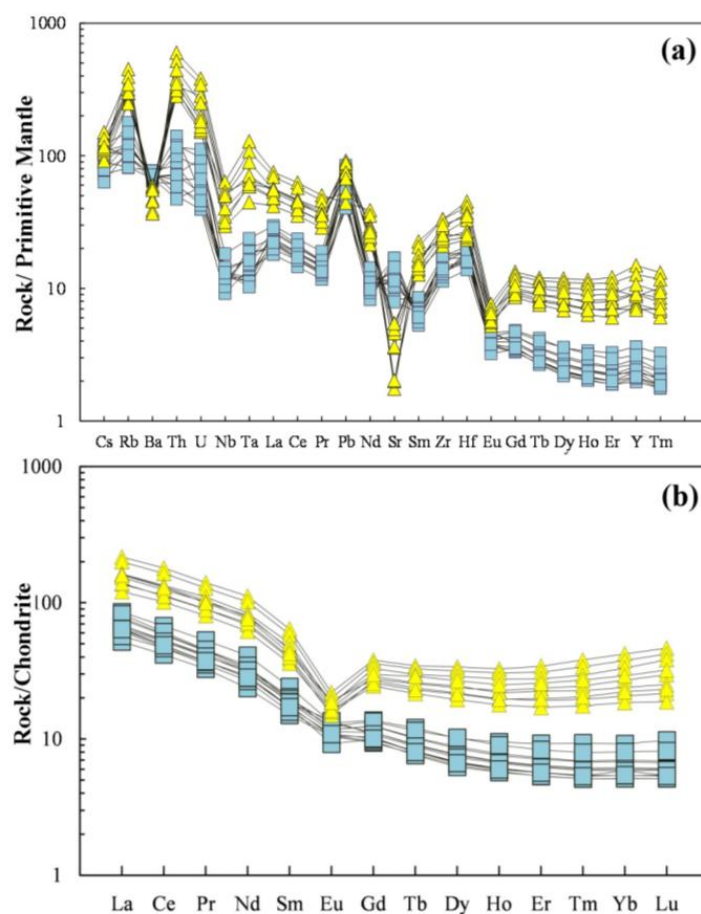


Figure 17. (a) Multi-element (extended trace and rare-earth elements) spider diagrams normalized to primitive mantle after [74]; (b) C1 chondrite after [54].

5.3. Magmatic Evolution and Petrogenesis

Systematic variations in the ratios and concentrations of compatible vs. incompatible elements can be utilized for recognizing partial melting and fractional crystallization processes [77,78]. On the La/Yb vs. La and Zr/Nb vs. Zr diagram, the monzogranite samples fall along a fractional crystallization trend during magma evolution (Figure 18a,b), while the granodiorite samples plot along the partial melting trend on Figure 18b. Plagioclase fractionation rose the Rb/Sr ratio and decreased Sr and Eu concentrations (Figure 18c). According to [79], crystallization trends in Figure 18d distinguish plagioclase and K-feldspar crystallization. The biotite ability to substitute K with Ba has led to a decrease in Ba content (Figure 18d).

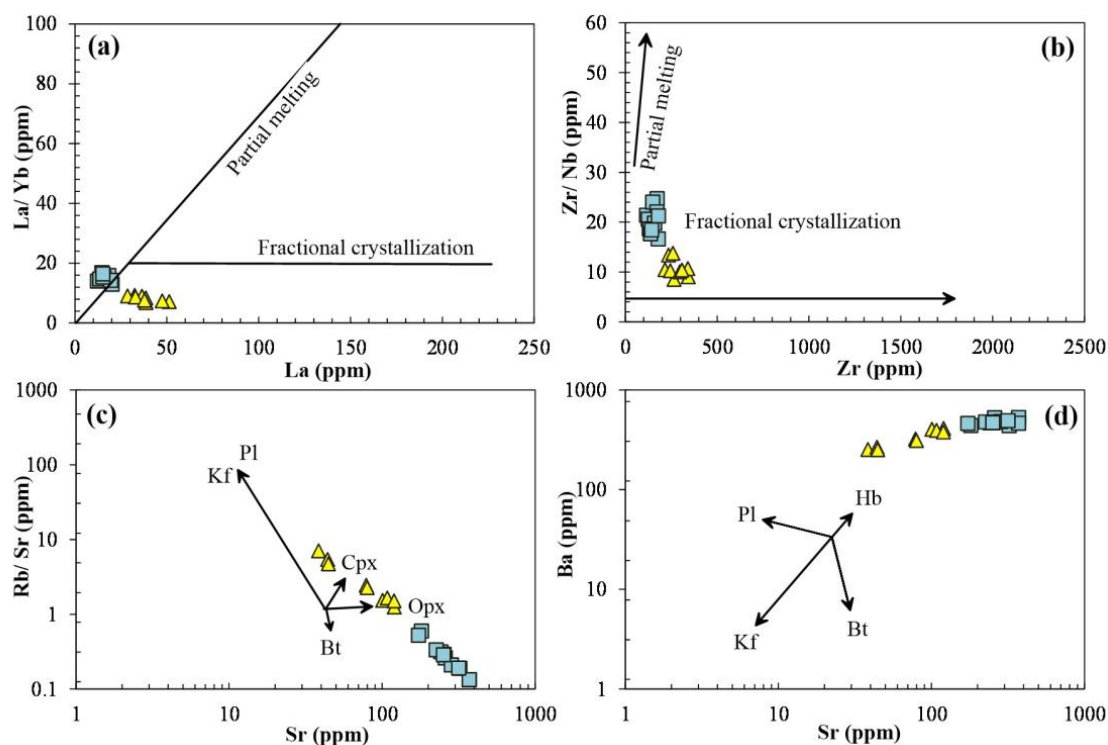


Figure 18. Trace element indicators of magmatic differentiation processes. (a) La/Yb vs. La, (b) Zr/Nb vs. Zr. (c,d). Diagrams showing patterns related to fractional crystallization of biotite (Bt), clinopyroxene (Cpx), hornblende (Hb), K-feldspar (Kf), orthopyroxene (Opx), and plagioclase (Pl); (c) Rb/Sr vs. Sr, (d) Ba vs. Sr.

Magmatic rocks are well developed in the Suwayqat El-Arsha district, such as metagabbro, metavolcanics, granodiorite, and monzogranite. Based on field studies and the previous mapping, the granite rocks dominate this area.

According to remote sensing studies (Sentinel-2, EnMap data), the magmatic rocks are well differentiated, using several tools such as FCC, MNF, and SMACC abundances, which allow the rocks to be easily distinguished from each other, especially granodiorite and monzogranite (Figures 4 and 5). Using Sentinel-2 and geological studies, a new geological map has been drawn (Figure 19). The new map is more accurate and better resolves the different geological units in the study area (Figure 19). Dike bearings highlight the tectonic fabrics in the area with the northwest–southeast, north–south, and northeast–southwest orientations. These patterns are well documented in the study area and are evident from the remote sensing analysis (Figures 7 and 8).

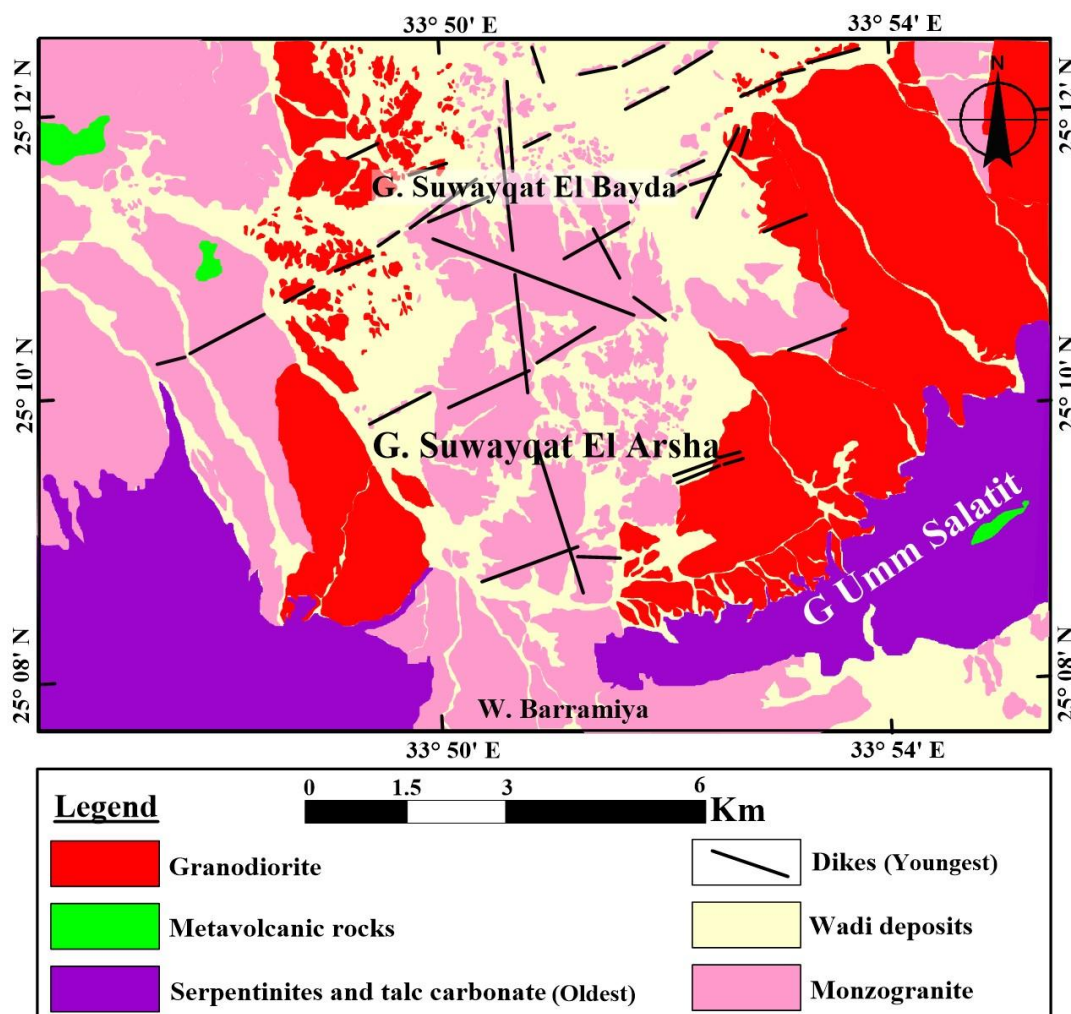


Figure 19. Revised geological map of the Suwayqat El-Arsha area modified after EGSM 1983, 1990 [20,21].

Granodiorites originated from metaluminous to peraluminous melts, based on their aluminum saturation index (ASI). In contrast, monzogranites exhibit a lower ASI, trending along the 0.8 slope line into the peralkaline field ([60]; Figure 14d). Both monzogranites and granodiorite trend towards high calc-alkaline-K magma, except for a few granodiorite samples.

According to [67] and Miller, 1985 [68], tectonic setting for the older granodiorite is likely a syn-orogenic, volcanic arc (Figure 16a,b,d). In contrast, the younger monzogranite exhibits a tectonic affinity to late- to post-orogenic and anorogenic (within-plate) granites. Magma composition evolved from the older granodiorite to younger monzogranite towards higher Nb (Figure 15d [69] or Figure 16b; [70]) and Yb (Figure 16a; [70]).

The older granodiorite and younger monzogranite exhibit REE patterns characterized by strong negative Eu anomalies, LREE depletion, and HREE enrichment (Figure 17b). These geochemical characteristics suggest that the granodiorite was derived from subduction-related melts such as high-K, mafic (basaltic) magmas. On the other hand, monzogranite was likely derived from peraluminous magma, formed as a result of anatexis and partial melting of the pelitic precursor ([73]; Figure 16e).

Importantly, we highlight that the Suwayqat El-Arsha granites are similar in origin to those in the Wadi El-Hima area south of Hafafit (Stage I collisional ~ 650–620 Ma; Stage II post-collisional, 630–590 Ma) [2,26], which are also characterized by a high degree of differentiation. Geochemical characteristics of granodiorites in both areas correspond to an I-

type, syn-collisional, volcanic-arc, consistent with an orogenic tectonic setting. Geochemical characteristics of monzogranites are consistent with an A-type, late- to post-collisional granite, indicating within-plate tectonic setting. Considering startling similarities between the two areas, such as tectonic setting, magma type, age (Stage I collisional ~ 650–620 Ma; Stage II post-collisional, 630–590 Ma) [2], and mineralogical composition (e.g., both areas contain two-mica granites), we infer that these intrusions belong to a large-size batholith composed of I- and A-type granites and stretches over a large area from north of Marsa Alam Road (Umm Salatit–Homrit Waggat) to Wadi El-Hima, south of Hafafit [26].

5.4. Crystal Mush Model for Granite Genesis

The clear gap in SiO₂ (68–71% vs. 74–76%) is the first-order signal for an origin as a crystal mush. The monzogranite represents the extracted, high-silica melt. The granodiorite represents the residual, locked crystalline framework from which that melt was expelled [80–82]. In the Residual Granodiorite: Enrichment in Al₂O₃, Fe₂O₃, MgO, CaO, TiO₂, P₂O₅ (elements compatible in plagioclase, amphibole, biotite, and accessory phases). This is because these elements are locked in the cumulus minerals of the mush (e.g., plagioclase, hornblende, biotite, magnetite, apatite). In the extracted monzogranite, enrichment in SiO₂ and K₂O occurs because SiO₂ is concentrated in the residual melt, while K₂O is highly incompatible, partitioning into the melt phase.

Granodiorite (Residue) is calc-alkaline, I-type, and metaluminous to weakly peraluminous in character, reflecting the dominant mineralogy of the residual mush: plagioclase + hornblende + biotite. Its “volcanic arc” tectonic signature is inherited from the source of the parent magma that formed the mush [81,82]. The monzogranite (extracted melt) shift towards alkaline/high-K, A-type, and more varied peraluminous-peralkaline chemistry is a direct consequence of melt extraction, along with other incompatible elements (Rb, Nb, etc.).

The high Ga/Al ratio and alkali content are hallmarks of highly evolved, residual melts. The presence of magmatic muscovite is critical. In the mush model, this is not an S-type indicator but a late-stage peraluminous mineral crystallizing from the extracted, hydrous, high-silica melt as it cools separately. It validates the melt’s high Al saturation post-extraction. Its “within-plate” tectonic affinity is a geochemical artifact of extreme differentiation, not necessarily an anorogenic setting. A-type chemistry can be generated by efficient extraction of interstitial melt from a calc-alkaline mush.

Reconciling the “A-type Tonalite” Contradiction is the most important interpretive leap. However, within the crystal mush paradigm, it makes sense as a process descriptor rather than a source descriptor. The “Tonalitic source” (or more accurately, granodiorite based on the present plots) is the residual crystal framework. It is not a frozen liquid. Its chemistry is controlled by the cumulus minerals (hence calc-alkaline, I-type). The monzogranite likely represents an extracted melt component from the crystal mush. If this hot, reactive, high-silica melt were to intrude or interact with the residual granodiorite of its own system or a similar one, it could hybridize it; a hybrid rock with a “tonalitic” modal composition (from the residue) but carrying an “A-type” geochemical overprint (from the infiltrating melt) could result.

These geneses include several reasons:

Mush Formation: A calc-alkaline, I-type parent magma (from a volcanic arc source) ascends and stalls in the upper crust, forming a large, crystal-rich mush (~50–70% crystals). The assemblage is dominated by plagioclase, hornblende, biotite, Fe-Ti oxides, and apatite.

Melt-Crystal Segregation: Tectonic triggers (e.g., renewed magmatism, faulting) or internal buoyancy forces cause the high-silica, volatile-rich interstitial melt to be extracted from the crystalline network. This is a critical differentiation event.

Solidification of Complementary Products: The residual, melt-depleted crystal framework solidifies in situ as the granodiorite unit. It is chemically buffered by its solid assemblage, explaining its restricted composition and I-type signature. The extracted melt ascends further, coalescing into separate batches. It solidifies as the monzogranite intrusions, exhibiting the full geochemical signature of an evolved, residual liquid (high SiO_2 , K_2O , Ga/Al, low P_2O_5 , A-type traits).

Potential Late Interaction: Local hybridization where the extracted melt intrudes back into its own residue could create ambiguous samples, potentially explaining any outliers.

6. Physicochemical Conditions of Crystallization

The pressure–temperature conditions and oxygen fugacity ($\log f_{\text{O}_2}$) of granite crystallization can be assessed based on whole-rock chemical data as well as chemical compositions of their primary minerals (amphibole, pyroxene, biotite, plagioclase, zircon, garnet, monazite, apatite and rutile, and Fe–Ti oxides) [83–88].

6.1. Biotite Thermobarometry

Biotite is sensitive to change in both chemistry and physicochemical conditions of crystallization, such as temperature (T), pressure (P), and oxygen fugacity (f_{O_2}); therefore, in some cases they can be used to simulate the P–T conditions of the magmatic system [89–93]. Henry et al. [48] found that Ti, Mg, and Fe contents in the biotite are particularly sensitive indicators of variations in crystallization temperature. Consequently, biotite crystallization temperature can be estimated based on its Ti content and Mg# value [$\text{Mg\#} = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$]. On the $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ vs. Ti diagram of [91], the primary biotites from the granodiorite give temperatures clustered between 725 and 775 °C, while the biotite of monzogranite gives temperatures between 675 and 750 °C (Figure 20). However, outlier data points for each rock type significantly overlap suggesting that a continuous evolution of melts is allowed by the biotite thermometry.

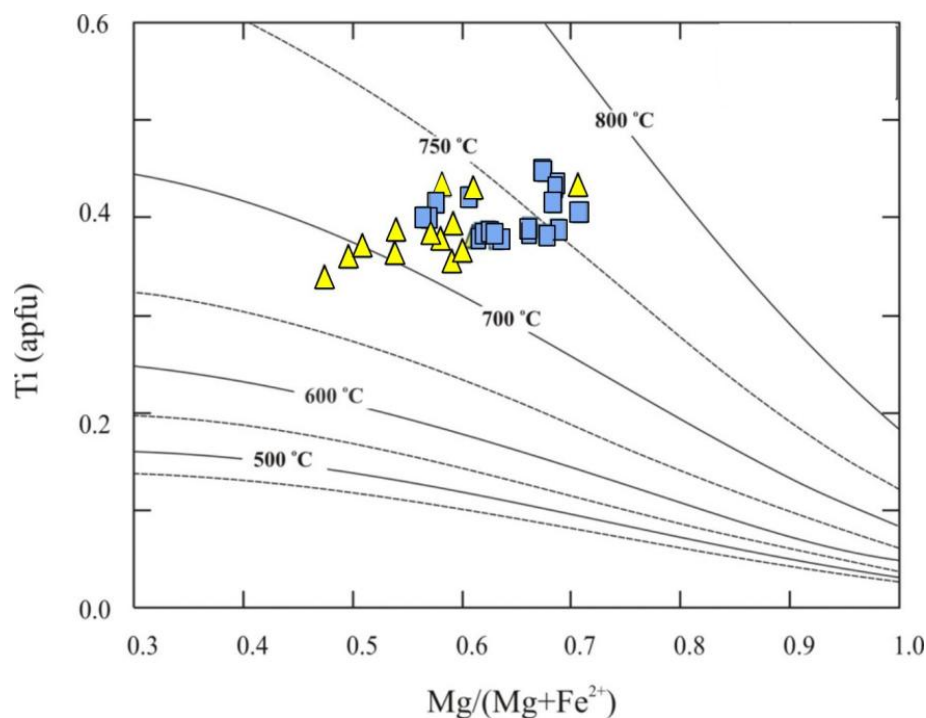


Figure 20. $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ vs. Ti diagram of biotite [91].

6.2. Hornblende Geothermometry and Oxygen Fugacity

Geothermometry and oxygen fugacity can be estimated using the concentration of Al IV coordination of primary hornblende [94–97]. Using the spreadsheet designed by [97], the estimated temperatures range between 742 °C and 813 °C (av. 780 °C) in granodiorite and 767 and 786 °C (av. 775 °C) in monzogranite. On the $\text{Fe}_{\text{t}}/(\text{Fe}_{\text{t}} + \text{Mg})$ vs. Al^{IV} discrimination diagram [98], the primary hornblende of the granodiorite and monzogranite fall in the field of intermediate and high $f\text{O}_2$ conditions (Figure 21).

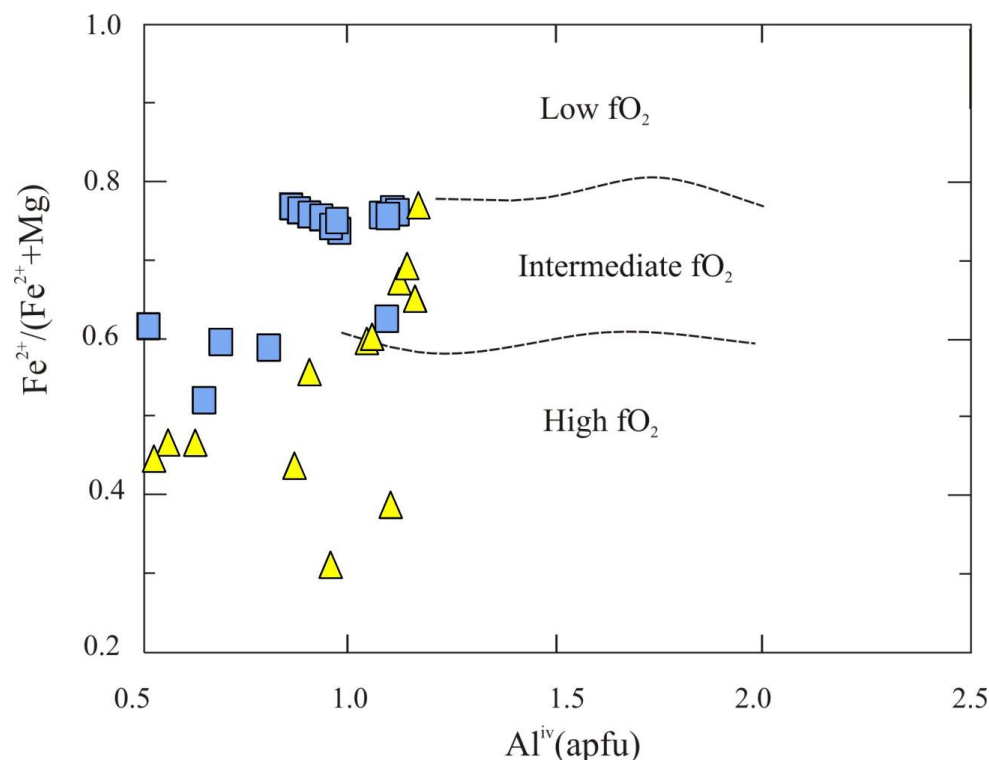


Figure 21. $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ vs. Al^{IV} diagram of amphibole [98].

7. Conclusions

- Our study provides a comprehensive discussion of the geological context, remote sensing, petrography, mineral chemistry, and geochemistry of the granites in the Gabal Suwayqat El-Arsha district of Eastern Desert, Egypt.
- The present lithological map (Sentinel-2 and EnMap hyperspectral data) introduced a well-defined distribution of the studied granites compared to all the previous studies over the study area. In addition, textural analysis of Sentinel-2 imagery was employed to highlight the dominant structural features, revealing prominent NE–SW, NW–SE, and N–S lineaments. These structural orientations are highlighted by dike orientations across the terrain.
- The granitic rocks comprise two distinct phases: an older granodiorite and a younger monzogranite. Both phases exhibit calc-alkaline affinities and range from peraluminous to metaluminous with medium- to high-K compositions. Geochemical signatures, including a pronounced negative Eu anomaly and extreme Sr depletion in the monzogranite, point to extensive early plagioclase fractionation within the magmatic system.
- Potential source magma is high-K, mafic subduction-related melts or a mixture of 75% pelite and 25% tholeiitic basalt for the granodiorite and 95% pelite and 5% tholeiitic basalt for monzogranite. The granodiorite was generated from an I-type magma at a collisional stage in a volcanic-arc setting, while the monzogranite was produced from an A-type magma in a late- to post-collisional tectonic setting. The statement

rather presents a sophisticated, multi-stage crustal evolution model. The granodiorite represents crust building during active collision, involving significant mantle input. The monzogranite represents crustal reworking during post-collisional collapse, melting the refractory residue left behind by the first event. The key to linking the “pelite source” to the “A-type” signature is understanding that the pelite was transformed into a granulitic residue by the time of the second melting event.

- The A-type geochemical signature in this province is interpreted as the product of efficient melt extraction from calc-alkaline crystal mushes, producing complementary I-type granodioritic residues and A-type monzogranitic leucosomes.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/geosciences16010037/s1>, Table S1: Electron microprobe analyses of plagioclase in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S2: Electron microprobe analyses of Albite in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S3: Electron microprobe analyses of K-feldspar in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S4: Electron microprobe analyses of amphibole in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S5: Electron microprobe analyses of biotite in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S6: Electron microprobe analyses of chlorite in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S7: Electron microprobe analyses of muscovite in monzogranite of the Suwayqat El-Arsha area; Table S8: Electron microprobe analyses of zircon in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S9: Electron microprobe analyses of magnetite in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S10: Electron microprobe analyses of ilmenite in granodiorite and monzogranite of the Suwayqat El-Arsha area; Table S11: Electron microprobe analyses of apatite in granodiorite and monzogranite of the Suwayqat El-Arsha area.

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References

1. Hashad, A.H. Present Status of Geochronological Data on the Egyptian Basement Complex. *Bull. Inst. Appl. Geol.* **1980**, *3*, 31–46.
2. Stern, R.J. Arc and continental crust genesis in the Pan-African orogeny: Evidence from Egypt and the Nubian Shield. *Tectonics* **1994**, *13*, 1504–1516.
3. Abdelsalam, M.G.; Stern, R.J. Evolution of the Egyptian basement and implications for the tectonics of the Eastern Desert and Sinai. *Geol. Soc. Am. Bull.* **1996**, *108*, 296–309.
4. EGSMA. *Geological Map of Marsa Shaab Quadrangle*; Egyptian Geological Survey: Cairo, Egypt, 2002.
5. Moore, M.M.; Wang, Z. Tectonic setting of Pan-African granites in Egypt. *Geol. Mag.* **2004**, *141*, 459–474.

6. Stern, R.J.; Ali, K. Crustal evolution of the Egyptian Precambrian rocks. In *The Geology of Egypt*; Springer International Publishing: Cham, Switzerland, 2019; pp. 131–151.
7. El-Bialy, M.Z. *Precambrian Basement Complex of Egypt*; Springer International Publishing: Cham, Switzerland, 2019; pp. 37–79.
8. Asran, A.M. Rock Succession in Egyptian Nubian Shield. In *The Geology of the Egyptian Nubian Shield*; Springer International Publishing: Cham, Switzerland, 2021; Volume 2020, pp. 53–81.
9. Moghazi, A.M. Petrology and geochemistry of pan-African granitoids, Kab Amiri area, Egypt-implications for tectonomagmatic stages of the Nubian Shield evolution. *Miner. Pet.* **2002**, *75*, 41–67. [\[CrossRef\]](#)
10. Moussa, E.M.M.; Stern, R.J.; Manton, W.I.; Ali, K.A. SHRIMP zircon dating and Sm/Nd isotopic investigations of Neoproterozoic granitoids, Eastern Desert, Egypt. *Precambrian Res.* **2008**, *160*, 341–356. [\[CrossRef\]](#)
11. Eliwa, H.A.; Bretkreuz, C.; Murata, M.; Khalaf, I.M.; Bühler, B.; Itaya, T.; Takahashi, T.; Hirahara, Y.; Miyazaki, T.; Kimura, J.I.; et al. SIMS zircon U-Pb and mica K–Ar geochronology, and Sr–Nd isotope geochemistry of Neoproterozoic granitoids and their bearing on the evolution of the northeastern Desert, Egypt. *Gondwana Res.* **2014**, *25*, 1570–1598. [\[CrossRef\]](#)
12. Ali, K.A.; Zoheir, B.A.; Stern, R.J.; Andresen, A.; Whitehouse, M.J.; Bishara, W.W. Lu–Hf and O isotopic compositions on single zircons from the North Eastern Desert of Egypt, Arabian–Nubian Shield: Implications for crustal evolution. *Gondwana Res.* **2016**, *32*, 181–192. [\[CrossRef\]](#)
13. Azer, M.K.; Abdelfadil, K.M.; Asimow, P.D.; Khalil, A.E. Tracking the transition from subduction-related to post-collisional magmatism in the north Arabian–Nubian Shield: A case study from the Homrit Waggat area of the Eastern Desert of Egypt. *Geol. J.* **2020**, *55*, 4426–4452. [\[CrossRef\]](#)
14. Lasheen, E.S.R.; Mohamed, W.H.; Ene, A.; Awad, H.A.; Azer, M.K. Implementation of petrographical and aeromagnetic data to determine depth and structural trend of Homrit Waggat Area, Central Eastern Desert, Egypt. *Appl. Sci.* **2022**, *12*, 8782. [\[CrossRef\]](#)
15. Abuamarah, B.A.; Azer, M.K.; Seddik, A.M.; Asimow, P.D.; Guzman, P.; Fultz, B.T.; Wilner, O.D.; Dalleska, N.; Darwish, M.H. Magmatic and post-magmatic evolution of post-collisional rare-metal bearing granite: The Neoproterozoic Homrit Akarem Granitic Intrusion, south Eastern Desert of Egypt, Arabian–Nubian Shield. *Geochemistry* **2022**, *82*, 125840. [\[CrossRef\]](#)
16. Khedr, M.Z.; Abo Khashaba, S.M.; El-Shibiny, N.H.; El-Arafy, R.A.; Takazawa, E.; Azer, M.K.; Palin, R.M. Remote sensing techniques and geochemical constraints on the formation of the Wadi El-Hima mineralized granites, Egypt: New insights into the genesis and accumulation of garnets. *Int. J. Earth Sci.* **2022**, *111*, 2409–2443. [\[CrossRef\]](#)
17. Hussein, A.A.; Aly, M.M.; El Ramly, M.F. A proposed new classification of the granites of Egypt. *J. Volcanol. Geotherm. Res.* **1982**, *14*, 187–198. [\[CrossRef\]](#)
18. El Gaby, S.; El Nady, O.; Khudeir, A. Tectonic evolution of the basement complex in the Central Eastern Desert of Egypt. *Geol. Rundsch.* **1984**, *73*, 1019–1036. [\[CrossRef\]](#)
19. Shebl, A.; Badawi, M.; Dawoud, M.; Abd El-Wahed, M.; El-Dokouny, H.A.; Csámer, Á. Novel comprehensions of lithological and structural features gleaned via Sentinel 2 texture analysis. *Ore Geol. Rev.* **2024**, *168*, 106068. [\[CrossRef\]](#)
20. Egyptian Geological Survey and Mining Authority (EGSMA). Metallogenic Map of the Aswan Quadrangle, 1983, Egypt. Scale 1:500,000. Available online: <https://www.scrip.org/reference/referencespapers?referenceid=2908716> (accessed on 5 January 2026).
21. Egyptian Geological Survey and Mining Authority (EGSMA). Basement Rocks of Manjam Al-Barramiyah Quadrangle, 1990, Egypt. Sheet NG 36 G2. Scale 1:100,000. Available online: https://books.google.com.sg/books/about/Basement_Rocks_of_Manjam_Al_Barramiyah_Q.html?id=Qha70QEACAAJ&redir_esc=y (accessed on 5 January 2026).
22. Mohamed, H.; Saibi, H.; Bersi, M.; Abdelnabi, S.; Geith, B.; Ismaeil, H.; Tindell, T.; Mizunaga, H. 3-D magnetic inversion and satellite imagery for the Um Salatit gold occurrence, Central Eastern Desert, Egypt. *Arab. J. Geosci.* **2018**, *11*, 674. [\[CrossRef\]](#)
23. Shackleton, R.M. Review of Late Proterozoic sutures, ophiolitic mélanges and tectonics of eastern Egypt and north-east Sudan. *Geol. Rundsch.* **1994**, *83*, 537–546. [\[CrossRef\]](#)
24. Conoco Coral Corporation and the Egyptian General Petroleum Corporation (EGPC). Geological Map of Egypt, Sheet NG 36 SE, Gebel HAMATA, 1987, Scale 1:500,000. Available online: <https://www.scrip.org/reference/referencespapers?referenceid=2908715> (accessed on 5 January 2026).
25. Hassaan, M.M.; Saleh, G.M.; El-Desoky, H.M.; Amer, R.M.; El-Kady, A.M. Lithological-structural setting of Homrit Waggat granites in Central Eastern Desert, Egypt: New contributions. *Int. J. Innov. Sci. Eng. Technol.* **2015**, *11*, 670–690.
26. Elnagar, M.E.; El-Desoky, H.M.; Ibrahim, G.; Abdel-Rahman, A.; Heikal, M. Petrology and geochemistry of granitic rocks at Gabal El-Magal El Harami and Wadi El-Hima district, Southeastern Desert, Egypt. *Egypt. J. Geol.* **2024**, *68*, 341–365. [\[CrossRef\]](#)
27. Abdel-Rahman, A.M.; Gahlan, H.A.; Latif, M.L.A.; Elyaseer, M.H.; Price, J.B.; Azer, M.K. Mineral chemistry, ASTER hydrothermal alteration mapping, and geotechnical characterization of granitic rocks of the Arabian–Nubian Shield; A case study from Wadi El-Hima, South Eastern Desert, Egypt. *J. Afr. Earth Sci.* **2025**, *229*, 105683. [\[CrossRef\]](#)
28. Shukri, N.M.; Lotfi, M. The geology of the north-western part of Gebel Siwiqat El Arsha area, Eastern Desert of Egypt. *Bull. Fac. Sci. Cairo* **1954**, *32*, 25–46.

29. Abdelkader, M.A.; Watanabe, Y.; Shebl, A.; El-Dokouny, H.A.; Dawoud, M.; Csámer, Á. Effective delineation of rare metal-bearing granites from remote sensing data using machine learning methods: A case study from the Umm Naggat Area, Central Eastern Desert, Egypt. *Ore Geol. Rev.* **2022**, *150*, 105184. [\[CrossRef\]](#)
30. Abdelkader, M.A.; Watanabe, Y.; Shebl, A.; Badawi, M.; Dawoud, M.; El-Dokouny, H.A.; Csámer, Á.; Abdellatif, M. Advanced exploration of rare metal mineralization through integrated remote sensing and geophysical analysis of structurally-controlled hydrothermal alterations. *J. Geochem. Explor.* **2024**, *267*, 107598. [\[CrossRef\]](#)
31. Shebl, A.; Abdellatif, M.; Hissen, M.; Abdelaziz, M.I.; Csámer, Á. Lithological mapping enhancement by integrating Sentinel 2 and gamma-ray data utilizing support vector machine: A case study from Egypt. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *105*, 102619. [\[CrossRef\]](#)
32. Drusch, M.; Del Bello, U.; Carlier, S.; Colin, O.; Fernandez, V.; Gascon, F.; Hoersch, B.; Isola, C.; Laberinti, P.; Martimort, P.; et al. Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services. *Remote Sens. Environ.* **2012**, *120*, 25–36. [\[CrossRef\]](#)
33. Lekka, C.; Petropoulos, G.P.; Detsikas, S.E. Appraisal of EnMAP hyperspectral imagery use in LULC mapping when combined with machine learning pixel-based classifiers. *Environ. Model. Softw.* **2024**, *173*, 105956. [\[CrossRef\]](#)
34. Storch, T.; Honold, H.P.; Chabrilat, S.; Habermeyer, M.; Tucker, P.; Brell, M.; Ohndorf, A.; Wirth, K.; Betz, M.; Kuchler, M.; et al. The EnMAP imaging spectroscopy mission towards operations. *Remote Sens. Environ.* **2023**, *294*, 113632. [\[CrossRef\]](#)
35. Shebl, A.; Csámer, Á. Lithological, structural and hydrothermal alteration mapping utilizing remote sensing datasets: A case study around Um Salim area, Egypt. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *942*, 012032. [\[CrossRef\]](#)
36. Harris, J.R.; Rogge, D.; Hitchcock, R.; Ijewliw, O.; Wright, D. Mapping lithology in Canada's Arctic: Application of hyperspectral data using the minimum noise fraction transformation and matched filtering. *Can. J. Earth Sci.* **2011**, *42*, 2173–2193. [\[CrossRef\]](#)
37. Luo, G.; Chen, G.; Tian, L.; Qin, K.; Qian, S.E. Minimum Noise Fraction versus Principal Component Analysis as a Preprocessing Step for Hyperspectral Imagery Denoising. *Can. J. Remote Sens.* **2016**, *42*, 106–116. [\[CrossRef\]](#)
38. Shebl, A.; Abdellatif, M.; Abriha, D.; Dawoud, M.; Ali, M.A.H.; Mahmoud, A.S.; Kristály, F.; Csámer, Á. EnMap hyperspectral data in geological investigations: Evaluation for lithological and hydrothermal alteration mapping in Neoproterozoic rocks. *Gondwana Res.* **2025**, *143*, 91–124. [\[CrossRef\]](#)
39. Aggarwal, A.; Garg, R.D. Systematic approach towards extracting endmember spectra from hyperspectral image using PPI and SMACC and its evaluation using spectral library. *Appl. Geomat.* **2015**, *7*, 37–48. [\[CrossRef\]](#)
40. Hall-Beyer, M. Practical guidelines for choosing GLCM textures to use in landscape classification tasks over a range of moderate spatial scales. *Int. J. Remote Sens.* **2017**, *38*, 1312–1338. [\[CrossRef\]](#)
41. Shebl, A.; Hamdy, M. Multiscale (microscopic to remote sensing) preliminary exploration of auriferous-uraniferous marbles: A case study from the Egyptian Nubian Shield. *Sci. Rep.* **2023**, *13*, 9173. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Deer, W.A.; Howie, R.; Zussman, J. *An Introduction to the Rock—Forming Minerals*, 2nd ed.; Pearson Education Limited: London, UK, 1992; pp. 1–712.
43. Locock, A.J. An Excel spreadsheet to classify chemical analyses of amphiboles following the IMA 2012 recommendations. *Comput. Geosci.* **2014**, *62*, 1–11. [\[CrossRef\]](#)
44. Leake, B.E.; Woolley, A.R.; Arps, C.E.; Birch, W.D.; Gilbert, M.C.; Grice, J.D.; Hawthorne, F.C.; Kato, A.; Kisch, H.J.; Krivovichev, V.G.; et al. Nomenclature of amphiboles; report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on new minerals and mineral names. *Mineral. Mag.* **1997**, *61*, 295–310. [\[CrossRef\]](#)
45. Nachit, H.; Ibhi, A.; Ohoud, M.B. Discrimination between primary magmatic biotites, reequilibrated biotites and neoformed biotites. *Comptes Rendus Géosci.* **2005**, *337*, 1415–1420. [\[CrossRef\]](#)
46. Stussi, J.M.; Cuney, M. Nature of biotites from alkaline, calc-alkaline and peraluminous magmas by Abdel-Fattah M. Abdel-Rahman: A comment. *J. Petrol.* **1996**, *37*, 1025–1029. [\[CrossRef\]](#)
47. Abdel-Rahman, A.F.M. Nature of biotites from alkaline, calcalkaline, and peraluminous magmas. *J. Petrol.* **1994**, *35*, 525–541. [\[CrossRef\]](#)
48. Henry, D.J.; Guidotti, C.V.; Thomson, J.A. The Ti-saturation surface for low-to-medium pressure metapelitic biotites: Implications for geothermometry and Ti-substitution mechanisms. *Am. Mineral.* **2005**, *90*, 316–328. [\[CrossRef\]](#)
49. Miller, C.F.; Stoddard, E.F.; Bradfish, L.J.; Dollase, W.A. Composition of plutonic muscovite: Genetic implications. *Can. Mineral.* **1981**, *19*, 25–34.
50. Zen, E.A. Phase relations of peraluminous granitic rocks and their petrogenetic implications. *Annu. Rev. Earth Planet. Sci.* **1988**, *16*, 21–51. [\[CrossRef\]](#)
51. Villa, I.M. Direct determination of ³⁹Ar recoil distance. *Geochim. Cosmochim. Acta* **1997**, *61*, 689–691. [\[CrossRef\]](#)
52. Hey, M.H. A new review of the chlorites. *Mineral. Mag.* **1954**, *30*, 277–292. [\[CrossRef\]](#)
53. Chen, L.; Yan, Z.; Wang, Z.Q.; Wang, K. Characteristics of Apatite from 160–140 Ma Cu (Mo) and Mo (W) Deposits in East Qinling. *Geol. Acta* **2017**, *91*, 1925–1941.

54. Sun, S.; McDonough, W. Chemical and isotopic systematic of oceanic basalts: Implications for mantle compositions and processes. Magmatism in the Ocean Basins. In *Geological Society of London*; Saunders, A.D., Norry, M.J., Eds.; Special Publications: London, UK, 1989; Volume 42, pp. 313–345.
55. Chappell, B.W. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* **1999**, *46*, 535–551. [[CrossRef](#)]
56. Li, X.H.; Li, Z.X.; Li, W.X.; Liu, Y.; Yuan, C.; Wei, G.J.; Qi, C.S. U-Pb zircon, geochemical and Sr–Nd–Hf isotopic constraints on age and origin of Jurassic I- and A-type granites from central Guangdong, SE China: A major igneous event in response to foundering of a subducted flat-slab? *Lithos* **2007**, *96*, 186–204. [[CrossRef](#)]
57. O’connor, J.T. A classification for quartz-rich igneous rocks based on feldspar ratios. *US Geol. Surv. Prof. Pap. B* **1965**, *525*, 79–84.
58. Streckeisen, A.; Le Maitre, R.W. A chemical approximation to the modal QAPF classification of the igneous rocks. *Neues Jahrb. Mineral. Abh* **1979**, *136*, 169–206.
59. Irvine, T.N.; Baragar, W.R.A.F. A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* **1971**, *8*, 523–548. [[CrossRef](#)]
60. Maniar, P.D.; Piccoli, P.M. Tectonic discrimination of granitoids. *Geol. Soc. Am. Bull.* **1989**, *101*, 635–643. [[CrossRef](#)]
61. Frost, B.R.; Barnes, C.G.; Collins, W.J.; Arculus, R.J.; Ellis, D.J.; Frost, C.D. A geochemical classification for granitic rocks. *J. Petrol.* **2001**, *42*, 2033–2048. [[CrossRef](#)]
62. Le Maitre, R.W.; Bateman, P.; Dudek, A.; Keller, J.; Lemeyre, J.; Le, B.M.J.; Sabine, P.A.; Schmid, R.; Sorensen, H.; Streckeisen, A.; et al. A Classification of Igneous Rocks and Glossary of Terms. 2002; Volume 193. Available online: www.cambridge.org/9780521662154 (accessed on 5 January 2026).
63. Peccerillo, A.; Taylor, S.R. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contrib. Mineral. Petrol.* **1976**, *58*, 63–81. [[CrossRef](#)]
64. Chappell, B.W.; White, A.J.R. Two contrasting granite types. *Pac. Geol.* **1974**, *8*, 173–174.
65. Chappell, B.W.; White, A.J.R. Two contrasting granite types: 25 years later. *Aust. J. Earth Sci.* **2001**, *48*, 489–499. [[CrossRef](#)]
66. Loiselle, M.C. Characteristics and Origin of Anorogenic Granites. *Geol. Soc. Am. Abstr. Programs* **1979**, *11*, 468.
67. Whalen, J.B.; Currie, K.L.; Chappell, B.W. A-type granites: Geochemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.* **1987**, *95*, 407–419. [[CrossRef](#)]
68. Miller, C.F. Are Strongly Peraluminous Magmas Derived from Pelitic Sedimentary Sources? *J. Geol.* **1985**, *93*, 673–689. [[CrossRef](#)]
69. Pearce, J.A.; Gale, G.H. Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks. *Geol. Soc. Lond. Spec. Publ.* **1977**, *7*, 14–24. [[CrossRef](#)]
70. Pearce, J.A.; Harris, N.B.W.; Tindle, A.G. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* **1984**, *25*, 956–983. [[CrossRef](#)]
71. Hassan, M.A.; Hashad, A.H. Precambrian of Egypt. In *The Geology of Egypt*; Said, R., Ed.; Balkema: Rotterdam, The Netherlands, 1990; pp. 201–245.
72. Harris, N.B.W.; Pearce, J.A.; Tindle, A.G. Geochemical characteristics of collision-zone magmatism. In *Collision Tectonics, Geological Society*; Coward, M.P., Ries, A.C., Eds.; Special Publications: London, UK, 1986; Volume 19, pp. 67–81. [[CrossRef](#)]
73. Sylvester, P.J. Post-collisional strongly peraluminous granites. *Lithos* **1998**, *45*, 29–44. [[CrossRef](#)]
74. Palme, H.; O’Neill, H.S.T.C. Cosmochemical estimates of mantle composition. In *Treatise on Geochemistry*; Elsevier: Amsterdam, The Netherlands, 2003.
75. Green, T.H. Island arc and continent-building magmatism—A review of petrogenic models based on experimental petrology and geochemistry. *Tectonophysics* **1980**, *63*, 367–385. [[CrossRef](#)]
76. Bevins, R.E.; Pharaoh, T.C.; Cope, J.C.W.; Brewer, T.S. Geochemical character of Neoproterozoic volcanic rocks in southwest Wales. *Geol. Mag.* **1995**, *132*, 339–349. [[CrossRef](#)]
77. Davidson, J.P.; Dungan, M.A.; Ferguson, K.M.; Colucci, M.T. Crust-magma interactions and the evolution of arc magmas: The San Pedro-Pellado Volcanic complex, southern Chilean Andes. *Geology* **1988**, *15*, 443–446. [[CrossRef](#)]
78. Schiano, P.; Monzier, M.; Eissen, J.P.; Martin, H.; Koga, K.T. Simple mixing as the major control of the evolution of volcanic suites in the Ecuadorian Andes. *Contrib. Mineral. Petrol.* **2010**, *160*, 297–312. [[CrossRef](#)]
79. Mingram, B.; Trumbull, R.B.; Littman, S.; Gerstenberger, H. A petrogenetic study of anorogenic felsic magmatism in the Cretaceous Paresis ring complex, Namibia: Evidence for mixing of crust and mantle-derived components. *Lithos* **2000**, *54*, 1–22. [[CrossRef](#)]
80. Bachmann, O.; Bergantz, G.W. On the origin of crystal-poor rhyolites: Extracted from batholithic crystal mushes. *J. Petrol.* **2004**, *45*, 1565–1582. [[CrossRef](#)]
81. Barnes, C.G.; Werts, K.; Memeti, V.; Ardill, K. Most granitoid rocks are cumulates: Deductions from hornblende compositions and zircon saturation. *J. Petrol.* **2019**, *60*, 2227–2240. [[CrossRef](#)]
82. Bohrsen, W.A.; Spera, F.J.; Ghiorso, M.S.; Brown, G.A.; Creamer, J.B.; Mayfield, A. Thermodynamic model for energy-constrained open-system evolution of crustal magma bodies. the magma chamber simulator. *J. Petrol.* **2014**, *55*, 1685–1717. [[CrossRef](#)]

83. Watson, E.B.; Harrison, T.M. Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types. *Earth Planet. Sci. Lett.* **1983**, *64*, 295–304. [[CrossRef](#)]
84. Harrison, T.M.; Watson, E.B. The behavior of apatite during crustal anatexis: Equilibrium and kinetic considerations. *Geochim. Cosmochim. Acta* **1984**, *48*, 1467–1477. [[CrossRef](#)]
85. Bea, F.; Fershtater, G.; Corretgé, L.G. The geochemistry of phosphorus in granite rocks and the effect of aluminium. *Lithos* **1992**, *29*, 43–56. [[CrossRef](#)]
86. Montel, J.M. A model for monazite/melt equilibrium and application to the generation of granitic magmas. *Chem. Geol.* **1993**, *110*, 127–146. [[CrossRef](#)]
87. Ryerson, F.J.; Watson, E.B. Rutile saturation in magmas: Implications for TiNbTa depletion in island-arc basalts. *Earth Planet. Sci. Lett.* **1987**, *86*, 225–239. [[CrossRef](#)]
88. Ayers, J.C.; Watson, E.B. Rutile solubility and mobility in supercritical aqueous fluids. *Contrib. Mineral. Petrol.* **1993**, *114*, 321–330. [[CrossRef](#)]
89. Luhr, J.F.; Carmichael, I.S.; Varekamp, J.C. The 1982 eruptions of El Chichón Volcano, Chiapas, Mexico: Mineralogy and petrology of the anhydritebearing pumices. *J. Volcanol. Geotherm. Res.* **1984**, *23*, 69–108. [[CrossRef](#)]
90. Wones, D.R. Significance of the assemblage titanite+ magnetite+ quartz in granitic rocks. *Am. Mineral.* **1989**, *74*, 744–749.
91. Hossain, I.; Tsunogae, T. Crystallization conditions and petrogenesis of the paleoproterozoic basement rocks in Bangladesh: An evaluation of biotite and coexisting amphibole mineral chemistry. *J. Earth Sci.* **2014**, *25*, 87–97. [[CrossRef](#)]
92. Moshefi, P.; Hosseinzadeh, M.R.; Moayyed, M.; Lentz, D.R. Comparative study of mineral chemistry of four biotite types as geochemical indicators of mineralized and barren intrusions in the Sungun Porphyry Cu-Mo deposit, northwestern Iran. *Ore Geol. Rev.* **2018**, *97*, 1–20. [[CrossRef](#)]
93. Uchida, E.; Endo, S.; Makino, M. Relationship between solidification depth of granitic rocks and formation of hydrothermal ore deposits. *Resour. Geol.* **2007**, *57*, 47–56. [[CrossRef](#)]
94. Schmidt, M.W. Amphibole composition in tonalite as a function of pressure: An experimental calibration of the Al-in-hornblende barometer. *Contrib. Mineral. Petrol.* **1992**, *110*, 304–310. [[CrossRef](#)]
95. Stein, E.; Dietl, C. Hornblende thermobarometry of granitoids from the Central Odenwald (Germany) and their implications for the geotectonic development of the Odenwald. *Mineral. Petrol.* **2001**, *72*, 185–207. [[CrossRef](#)]
96. Krawczynski, M.J.; Grove, T.L.; Behrens, H. Amphibole stability in primitive arc magmas: Effects of temperature, H₂O content, and oxygen fugacity. *Contrib. Mineral. Petrol.* **2012**, *164*, 317–339. [[CrossRef](#)]
97. Ridolfi, F.; Renzulli, A.; Puerini, M. Stability and chemical equilibrium of amphibole in calc-alkaline magmas: An overview, new thermobarometric formulations and application to subduction-related volcanoes. *Contrib. Mineral. Petrol.* **2010**, *160*, 45–66. [[CrossRef](#)]
98. Anderson, J.L.; Smith, D.R. The effects of temperature and fO₂ on the Al-in-hornblende barometer. *Am. Mineral.* **1995**, *80*, 549–559. [[CrossRef](#)]

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