

Original Article

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Geochemical insights, physico-mechanical properties and lithological enhancement using PRISMA hyperspectral data of intrusive rocks at Gabal Nikeiba area, South Eastern Desert, Egypt

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Abstract

This study presents an integrated study of remote sensing, fieldwork, petrographic, geochemical analyses and geotechnical properties of intrusive rocks in the Nikeiba area, South-Eastern Desert, Egypt. Gabal Nikeiba area is composed of Neoproterozoic rocks, including island-arc assemblages (mafic metavolcanics and metagabbro-diorite) and syn- (granodiorite and tonalite) to post-tectonic granitoids (syenogranite, alkali feldspar granite and quartz syenite), followed by post-granitic dikes of various compositions. PRISMA (PRecursore IperSpettrale della Missione Applicativa) hyperspectral data effectively delineated lithological units and structural features. The lithological discrimination serves as a spatial blueprint, ensuring that field sampling for geochemical analysis is optimized and geomechanical characterization is strategically targeted. The old magmatic phase is represented by a calc-alkaline series, typical of magmas formed in a subduction or continental collision setting. The post-collisional granites are subdivided into two magmatic phases, an older one including syenogranite and alkali feldspar granite, and a younger event includes quartz syenite. They have chemical signatures typical for A-type granites (i.e., high SiO₂, K₂O, Fe/Mg ratio, low CaO, MgO) which are associated with extensional tectonics, crustal melting and intraplate environments. Rare earth element (REE) patterns show light REE (LREE) enrichment and a distinct slope from LREEs to heavy REEs (HREEs). Bulk densities range from 2.48 to 2.7 g/cm³, with low porosity and water absorption, except for granodiorite. Quartz syenite and alkali feldspar granite exhibit superior physical properties and meet American Society for Testing and Materials (ASTM) C615 standards. Quartz syenite shows the highest mechanical strength and lowest abrasion, making it highly durable. Overall, quartz syenite is the most suitable candidate for dimensional stone applications.

1. Introduction

The geology of Egypt is predominantly defined by its complex Precambrian crystalline basement, a component of the Arabian-Nubian Shield (ANS). This shield represents the northern extension of the East African Orogen, formed during the Pan-African Orogeny (Akaad and Noweir 1969; Shackleton *et al.* 1980) that assembled Gondwana in the Neoproterozoic (900–550 Ma). During the peak of the Pan-African orogeny, the closure of the Mozambique Ocean led to the accretion of island arcs and micro-continents (Fritz *et al.* 1996, 2013; Ali *et al.* 2010). The magmatism in this phase produced the so-called ‘Older Granites’, which are predominantly I-type (igneous-derived). Their geochemistry is calc-alkaline, characterized by enrichment in large ion lithophile elements (LILEs) and depletion in high field strength elements (HFSEs), a signature typical of granitic suites formed at subduction zones and continental arcs (Abdel-Rahman and Martin 1990; Abuamarah *et al.* 2023). These granodiorites and tonalites (collectively called granitoids) formed from the partial melting of meta-igneous lower crust, with possible mantle wedge contributions, and were deformed during the ongoing tectonic compression (Abdel-Rahman and Martin 1990; Asran and Kamal El-Din 1997; El-Sayed 1998; Azer *et al.* 2020; Abuamarah *et al.* 2023; El-Bialy *et al.* 2025).

Following the main collisional event, the tectonic regime shifted to extensional or trans-tensional. This critical change led to the emplacement of the so-called ‘Younger Granites’. They are classified as A-type granites (Loiselle and Wones, 1979). They are alkaline to peralkaline, with high contents of silica, potassium, sodium, HFSE (e.g., Zr, Nb, Ga, Y) and high Fe/Mg ratios

(Ibrahim *et al.* 2015; Abd El-Fatah *et al.* 2023; Elsaygher *et al.* 2023). This composition is inconsistent with subduction and instead points to melting in a stable, within-plate tectonic setting (Cleary *et al.* 2017; Azer *et al.* 2024; Mubarak *et al.* 2025). The genesis of A-type magmas is often attributed to the high-temperature, anhydrous partial melting of a felsic granulitic lower crust that had been previously depleted by the extraction of the older I-type magmas (citations missing). The heat required for this melting is attributed to upwelling of the asthenospheric mantle (delamination of the lithospheric mantle or slab break-off) following the continental collision (citations missing).

Although previous geological investigations in the Egyptian Nubian Shield have successfully utilized multispectral sensors, such as Landsat and ASTER, these datasets often face limitations in distinguishing between lithological units with similar spectral signatures due to their broad and discontinuous bands especially if compared with hyperspectral data. Several studies (e.g., Shebl *et al.* 2024a; El Ghrabawy *et al.* 2019; Gad and Kusky 2007) demonstrate that although multispectral data is effective for regional mapping, it can struggle to resolve specific complicated lithological transitions.

The recent launch of the PRISMA (PRecursore IperSpettrale della Missione Applicativa) hyperspectral satellite provides new capabilities for Earth observation, as it captures radiance data across both the visible and near-infrared (VNIR) and shortwave infrared (SWIR) spectral ranges. A key characteristic of the sensor is its high signal-to-noise ratio (SNR), which is reported to exceed 200:1 in the VNIR and 100:1 in the SWIR. Preliminary investigations suggest that the combination of numerous spectral bands with these SNR levels is well suited for detailed lithological mapping (Mishra *et al.* 2022; Shebl *et al.* 2024b). Building upon this foundation, the present study aims to use PRISMA data to enhance lithological discrimination, marking the first such integrated application over the study area.

Granitic rocks from the Eastern Desert and Sinai Peninsula are a significant natural resource in Egypt, valued for their durability and aesthetic qualities, which make them highly suitable for both construction and decorative applications. Consequently, their geotechnical properties have been the focus of numerous studies aimed at evaluating their performance and quality for these purposes (Abd El-Ghafour *et al.* 2012; Osmanet *et al.* 2023; Rashwan *et al.* 2023; Gomah *et al.* 2024; Abdel-Rahman *et al.* 2025; Khedr *et al.* 2026).

This study has a dual objective: (1) to contribute to characterize and deepen the understanding of the petrogenesis and tectonic evolution of Egyptian Nubian Shield rocks, especially the Nikeiba area, using whole-rock geochemistry and PRISMA hyperspectral data, and (2) to apply this knowledge to evaluate their quality and suitability as dimension and ornamental stone.

The methodology of this study is designed as an integrated multidisciplinary workflow, utilizing remote sensing, geochemistry and geotechnical analysis to provide a holistic characterization of the Gabal Nikeiba intrusive rocks. The integration begins with the application of PRISMA hyperspectral data to achieve precise lithological and structural discrimination of the terrain. This remote sensing framework serves as the basis for targeted sampling, ensuring that the subsequent geochemical investigations and geotechnical characterizations are representative of the distinct rock units identified. By linking the lithological mapping, chemical composition and physico-mechanical properties, the study bridges the gap between surface observation and material behaviour, which is essential for both geological understanding and future engineering applications of these lithologies. This study aims to deepen the understanding of the petrogenesis and tectonic evolution of the

Egyptian Nubian Shield, with a specific focus on the Nikeiba area. By integrating PRISMA hyperspectral data, whole-rock geochemistry, we provide a robust geological framework to evaluate the quality and suitability of these intrusive units as dimension and ornamental stones.

2. Geological setting and field observations of Nikeiba area

Gabal Nikeiba area is among the most significant granitic intrusions in the Southeastern Desert of Egypt (Figure 1a) that recently has attracted the attention of researchers due to its economic potential (Eliwa *et al.*, 2018a, 2018b; Abdel Gawad *et al.* 2021, 2022; Hanfi *et al.* 2022; Hassan *et al.* 2024). The Nikeiba area belongs to the Northern ANS and is exposed between latitudes 23° 49' and 23° 53' N and longitudes 34° 18' and 34° 24' E (Figure 1b). It is located about 120 km east of Aswan city.

The Gabal Nikeiba area is covered mainly by Neoproterozoic rocks. The different rock units in the study area are evident both in the field and in the satellite images and include island-arc assemblages, syntectonic granitoids and post-collisional granites together with post-granitic dikes of various compositions (Abu Zeid 2014; Nady *et al.* 2019; Abdel-Gawad, 2011, 2021; Abdel-Gawad *et al.* 2022). The island-arc rocks represent the oldest rock unit in the mapped area and include mafic metavolcanics and a metagabbro-diorite complex. The syntectonic granitoids comprise granodiorite and tonalite, while post-collisional granites are made up by syenogranite, alkali feldspar granite and quartz syenite. Geochronological data regarding Gabal Nikeiba area is yet missing. The age relations between the different rock units in the study area have been established by their crosscutting relationships. In the field, the syntectonic granitoids and post-collisional granites share sharp intrusive contact against older mafic metavolcanics and metagabbro-diorite. On the other hand, syenogranite and alkali feldspar granite show gradational contacts, while quartz-syenite intruded them with sharp intrusive contacts. The granitic rocks were affected by several events of deformation and hydrothermal alteration and are dissected by structurally controlled wadis filled with alluvial deposits.

The metavolcanics of island-arc association are the most common rock type among island-arc associations. They occur as dark brown rocks intruded by the syenogranites, alkali feldspar granites, quartz syenites and syenites (Figure 2a and b). They include basic and intermediate varieties that are foliated and intercalated with volcanoclastics (tuffs and breccias). Metagabbro-diorites are always found in the form of small hillocks of variable heights (Figure 2b). Metagabbro is massive, but became sheared and foliated along the contacts with the metavolcanics. It shows rhythmic layering, where coarse-grained layers occur grade upwards into medium- and fine-grained layers.

Granodiorite bodies form low to moderate relief with gentle slopes and spheroidal weathering. The rock is grey in colour, medium- to coarse-grained rocks, highly fractured and speckled with black spots due to the presence of biotite and hornblende. It is characterized by cavernous, exfoliation and bouldery weathering especially along contacts with the post-collisional granites. Some outcrops of granodiorite occur as sharp contact with syenogranites. The most distinctive field characteristic of the granodiorite is the presence of microgranular mafic enclaves and xenoliths with dark-coloured, different shapes, sizes and compositions. Tonalite is less abundant and shows gradational contact with granodiorite (Figure 2c).

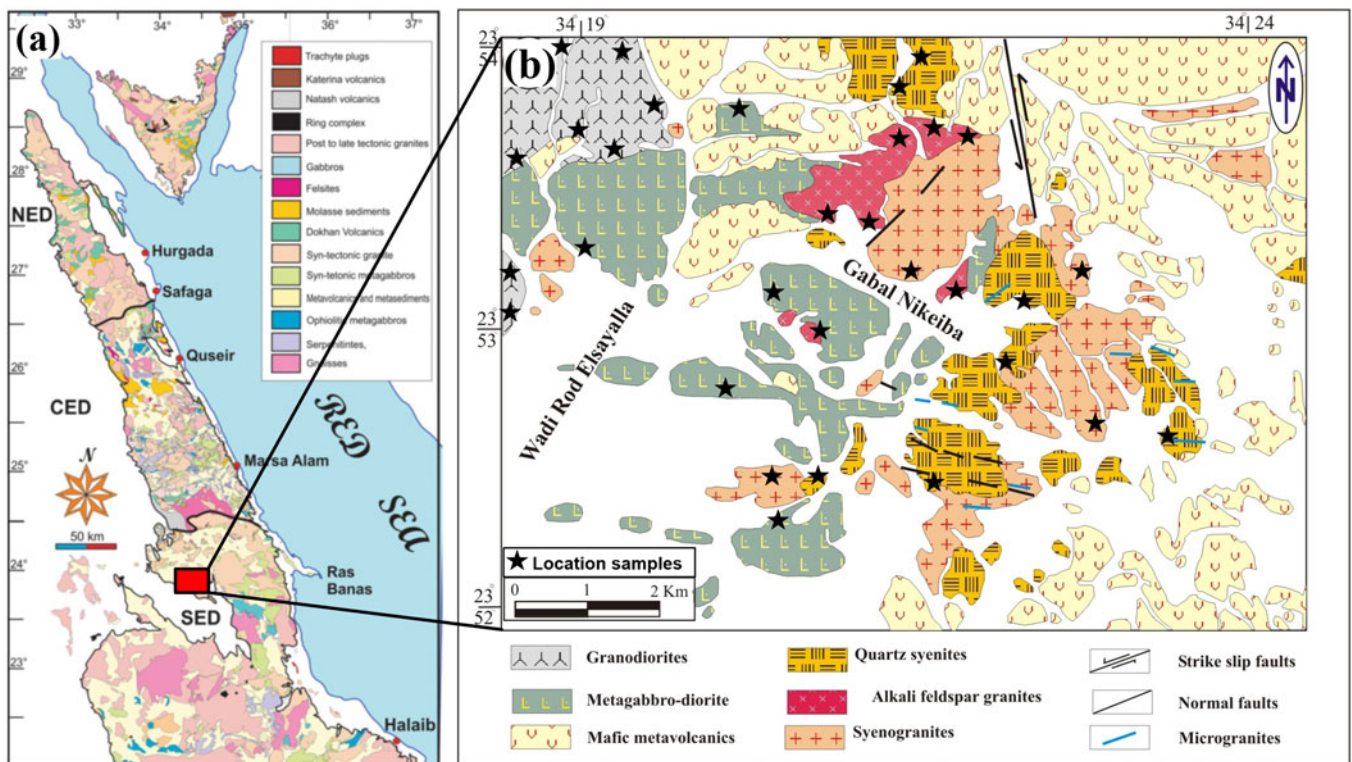


Figure 1. (a) Simplified geological map of the Egyptian Nubian Shield compiled from the Geological Map of Egypt (El-Ramly 1972) and the CONCO geological maps (Klitzch *et al.* 1987). Abbreviation; NED: North Eastern Desert, CED: Central Eastern Desert, SED: South eastern desert. (b) Geological map of the Gabal Nikeiba (modified after Abdel Gawad *et al.* 2022).

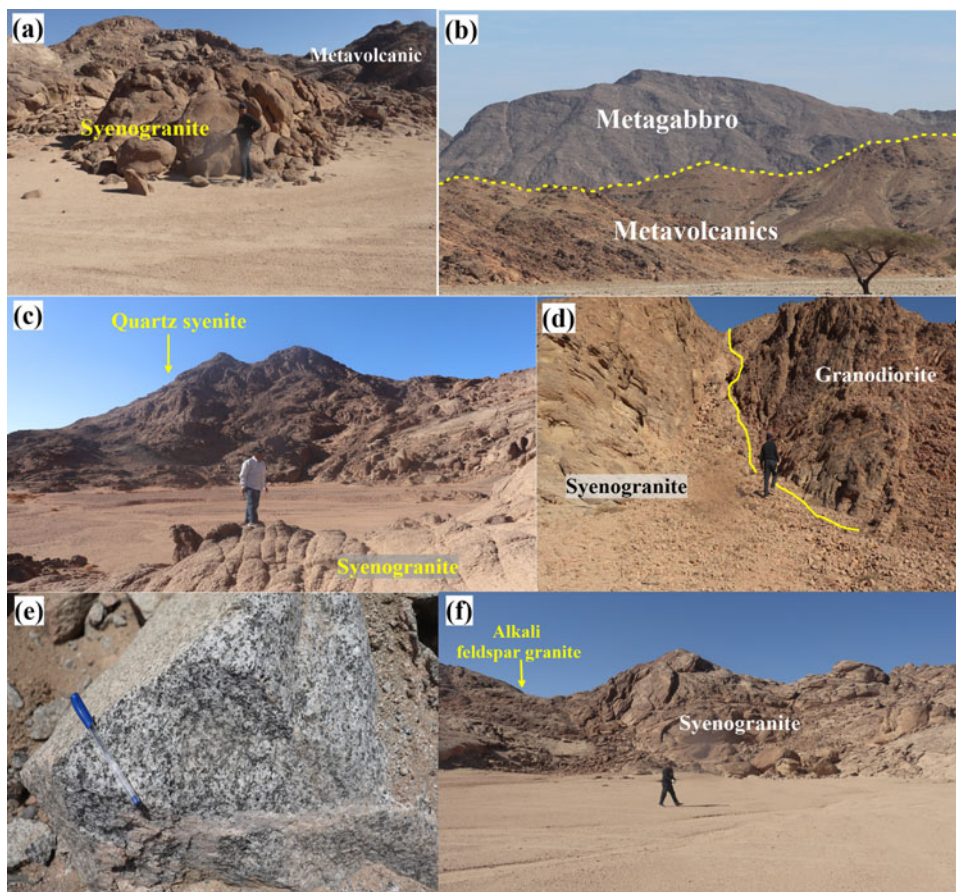


Figure 2. Photographs showing: (a) exfoliation and boulders of syenogranite in contact with metavolcanics; (b) close-up view of the sharp intrusive contact between metagabbro and metavolcanics; (c) tonalite blocks; (d) quartz syenite intruded the syenogranites, forming hills; (e) sharp intrusive contact between quartz syenite and alkali feldspar granite; and (f) panorama view of syenogranites intruded by alkali feldspar granites.

The post-collisional granites are distinguished in the field by differences in colour and texture. The contacts between post-collisional granites are seen in different places to be either sharp or gradational.

Syenogranite is the most common rock type among the A-type granitoids. It is medium- to coarse-grained, with colours ranging from whitish to pale pink, and reddish-brown (Figure 2d). Syenogranites form sharp intrusive contacts with mafic metavolcanics and quartz syenites. Few apophyses of syenogranite extend into the country rocks. The syenogranite is affected by significant alteration near contacts with the alkali feldspar granite, which is marked by enrichment in silica and Fe-oxides. Quartz syenite is medium- to coarse-grained with pale grey to pale pink colours. Syenite bodies are characterized by and moderate to high relief (Figure 2d and e).

Alkali feldspar granite is a medium- to coarse-grained holocrystalline equigranular rock, with whitish, and yellowish to pale white, colours. It displays sharp intrusive contacts with meta-gabbro-diorite and mafic metavolcanics. It intruded into the syenogranite with sharp intrusive contacts (Figure 2f). Apophyses of the alkali feldspar granite into the country rocks are structurally controlled. The granite is devoid of any foliation and/or xenoliths of country rocks. The outer parts of the alkali feldspar granites are highly tectonized with the development of alteration zones with a distinctive dissected appearance, cut by pegmatites and quartz veins reach to 7.5 km. The alteration zones are characterized by sericitization and silicification. Also, mylonitization and cataclasis are observed along these zones.

Dikes of different compositions cross-cut the island-arc assemblages and granodiorite but stop against post-collisional granites. They are more resistant to erosion, forming ridges cutting discordantly across the host rocks. The frequency of dikes in the granodiorites is noticeably higher than in the post-collisional granites.

3. Materials and methods

The following section summarizes the methodology, comprising remote sensing data, field and laboratory investigations.

3.a. Remote sensing data (PRISMA hyperspectral data)

Launched by the Italian Space Agency (ASI) on March 22, 2019, the PRISMA satellite is a cutting-edge hyperspectral system orbiting at 615 km in a low-Earth, Sun-synchronous path. It covers wavelengths 400–2500 nm across approximately 240 channels (with a 30 m spatial resolution and <10 nm spectral resolution), complemented by a 5 m pixel size panchromatic camera (400–700 nm) (Alawy *et al.* 2025; Candela *et al.* 2016; Daoud *et al.* 2025; El-Omairi *et al.* 2025; Loizzo *et al.* 2019; Shebl *et al.* 2023, 2024a). This push broom sensor, with a 30 km swath and internal calibration, provides highly detailed spectral information within VNIR (400–1100 nm, 66 channels) and SWIR (920–2500 nm, 174 channels) regions, boasting a spectral width ≤ 14 nm, ± 0.1 nm spectral calibration accuracy, and robust SNRs. Its advanced capabilities and 12-bit radiometric quantization make PRISMA data invaluable for various research applications. PRISMA data, including both archived and new acquisitions, are freely available to registered users, albeit with a daily usage quota to ensure equitable access.

The hyperspectral analysis was conducted using a PRISMA image acquired on 7 November 2023 (Product ID: PRS_L2D_STD_20231107082611_20231107082616_0001). To ensure the highest level of data fidelity for lithological discrimination, the

Level 2D (L2D) standard product was utilized. The L2D standard product was used, which provides orthorectified and atmospherically corrected surface reflectance data. Atmospheric correction was performed during the PRISMA L2D processing chain using the official PRISMA atmospheric correction module, which is based on radiative transfer modelling and accounts for molecular absorption, aerosol scattering, water vapour content and adjacency effects. This ensures conversion from top-of-atmosphere (TOA) radiance to bottom-of-atmosphere (BOA) reflectance suitable for quantitative spectral analysis. The atmospheric correction was performed via the PRISMA proprietary processor, which accounts for aerosol optical thickness and water vapour, thereby providing the precise spectral signatures necessary for subsequent structural mapping and lithological characterization.

Particularly with hyperspectral remote sensing data, it is crucial to ensure better selection of approaches that deliver the required information according to our goal. To achieve this, several image-processing methods were applied to PRISMA data. The goal was to enhance the distinction between exposed rock units. Our findings indicate that certain false colour combinations (FCCs) can offer good lithological discrimination. Furthermore, dimensionality-reduction techniques like principal component analysis (PCA) and minimum noise fraction (MNF) proved even more effective in providing clear diagnostic information for our target lithologies.

Selecting the best FCCs for this research was done considering the wavelengths of the data bands and the exposed rock units. The selection of band combinations was based on the spectral characteristics of the PRISMA dataset and the diagnostic absorption features of common rock-forming and alteration minerals. Specific FCCs used in this study include 30–20–9 (Red Green Blue) for general lithological visualization, 81–44–8 for enhanced VNIR–SWIR integration and 190–187–140 for SWIR-dominated discrimination of alteration-related spectral features. These combinations were selected to enhance lithological contrast by targeting key spectral responses of iron oxides and hydroxyl-bearing minerals.

FCC 30–20–9 (RGB) combination provides a quasi-natural colour composite for the rock units; the integration of VNIR and SWIR bands was critical for enhancing the contrast between the rock units. An effective FCC was produced by selecting spectral bands that maximize the distinction between lithological units (Badawi *et al.* 2022; Shebl *et al.* 2024b). The study carefully selected its RGB combinations based on the specific types of rock units present in the study area, and insights from previous research. This approach ensures that FCCs significantly enhance image visualization, thereby facilitating superior interpretation. Ultimately, a colour composite image is produced by choosing spectral properties that sharpen the distinction of both lithological. Four main FCCs were applied in the current research.

PCA and MNF were applied. In PCA, the initial principal components (PCs) were leveraged in the current investigation for the discerning delineation of rock units, the precise identification of lithologies and the charting of prominent geological structures. These components are employed to construct robust colour composites, thereby augmenting the visual interpretation of lithological distribution. This efficacy stems from the fact that the foremost PCs exhibit the maximum conceivable data dispersion and encapsulate the most considerable possible variance (Abd El-Wahed *et al.* 2021; Abdelkader *et al.* 2024; Loughlin 1991).

On the other hand, the MNF methodology itself constitutes an orthogonal transformation designed to arrange components based on an ascending order of random noise, differing from PCs, which are ordered by diminishing variance (Assiri 2016; Green *et al.*

1988). The initial MNF bands, which encompass the most substantial information content, were employed for the delineation of lithological units, in contrast to subsequent bands where the influence of noise incrementally escalates. Typically, MNF encompasses a dual-stage process of PCA rotations. The first stage involves the determination of the PCs derived from the noise covariance matrix, subsequently leading to the decorrelation and rescaling of noise within the dataset. The latter stage then proceeds with the extraction of PCs from this pre-processed, noise-whitened data.

To maximize the SNR and reduce data redundancy, PCA and MNF transformations were performed on the full hyperspectral cube (VNIR–SWIR). The first six PCs were retained for analysis, as they collectively accounted for the vast majority of the cumulative scene variance. Subsequent components were excluded due to a sharp decline in eigenvalues and a corresponding dominance of noise. The final combinations were generated by evaluating the decorrelation between leading components; specifically, combinations of PCs were selected that exhibited the highest contrast across lithological boundaries.

3.b. Field and laboratory investigations

Field investigations were conducted across the study area to obtain representative material from the principal lithological units. A total of 31 hand-specimen samples were collected from fresh outcrops, adhering to standard geological sampling protocols to minimize surficial weathering effects. The sampling locations, which encompass the range of identified rock types, are documented on the geological map of the study area (Figure 1). All 31 collected samples were subjected to whole-rock geochemical analysis to characterize the bulk composition of each lithological unit. For the suite of physicomachanical tests (including abrasion resistance, uniaxial compressive strength (UCS) and porosity), a targeted sub-selection of 23 samples was made from the original collection. This selection was guided by the following critical criteria to ensure the integrity and relevance of the test results: minimal post-formation alteration, macroscopic integrity and representativeness of fresh rock mass.

Samples exhibiting the lowest loss on ignition (LOI) values from the geochemical dataset were prioritized. A low LOI is a key indicator of minimal volatile content (e.g., H_2O , CO_2 from clays, carbonates or hydrated minerals), signifying negligible, secondary, low-temperature alteration and weathering. This ensures that the measured mechanical properties reflect the inherent characteristics of the primary rock fabric rather than the effects of subsequent alteration. Samples showing the least evidence of macroscopic weathering, such as discoloration, friable surfaces or visible fractures, were chosen. This was confirmed by detailed petrographic examination to exclude samples with significant micro-fracturing or pervasive hydrothermal mineral overprints. The subset was explicitly chosen to represent the competent, unweathered core of each rock unit, which is most relevant for engineering-geological applications and genetic interpretations of original rock strength.

Fieldwork focused on mapping and sampling of diorite, granite and syenite. Petrographic analysis of 31 thin sections of these rocks was performed using a polarized light microscope at the National Research Center in Dokki, Egypt.

Thirty-one samples (five samples of diorite, three of tonalite, five of granodiorite, seven samples of quartz syenite, four samples of syenogranite and seven of alkali feldspar samples) were subjected to chemical analysis at Northwest University in China. To calculate the LOI, powdered samples were heated for 50 minutes

at 1000°C and re-weighed. To prepare the samples for X-ray fluorescence (XRF, Rigaku RIX2100), 0.7 g of the sample powder was mixed with 0.3 g of LiF, 0.4 g of NH_4NO_3 , 3.6 g of $Li_2B_4O_7$ and two to three drops of 1.5% (w/w) LiBr solution. The sample mixture was first molten in a non-wetting precious metal crucible and cast into a glass disk. Concurrently, a 50 mg aliquot of powdered sample was digested for 48 hours at 190°C in a mixture of $HClO_4$, HNO_3 and HF within sealed steel bombs lined with polytetrafluoroethylene (PTFE) sleeves. The digested product was then dried, and the resulting residues were dissolved in 80 mL of a 2% HNO_3 solution containing 10 ng/g Rh as an internal standard. Trace element and rare earth element (REE) concentrations in these solutions were determined using an Agilent 7500a inductively coupled plasma mass spectrometry (ICP-MS). The analytical data were calibrated against international rock standards (BCR-2, BHVO-1 and AGV-1). Based on replicated samples, the analytical precision of this method is better than 1% for major oxides and 5% for REEs and other trace elements. Analytical results are provided in Table 1 (major elements in wt% and trace elements in ppm).

3.c. Geotechnical tests

The accurate evaluation of a rock's physico-mechanical behaviour, particularly for its suitability as dimension stone, depends critically on representative sampling. For this study 23 bulk samples from four lithological units (tonalite, granodiorite, quartz syenite and alkali feldspar granite) were collected, identified as high-priority targets for dimension stone exploration. The sampled units represent a range of plutonic bodies exhibiting diverse mineralogical, textural and petrographic features. In accordance with American Society for Testing and Materials (ASTM) standard C97/2018ASTM, cubical specimens ($5 \times 5 \times 5$ cm; Figure 3) were prepared from the collected rock samples for physical and mechanical testing at the Laboratory of Raw Building Materials and Processing Technology Research Institute, Housing and Building National Research Center (HBRC), Dokki, Egypt. The physical properties of density, water absorption and apparent porosity were measured according to ASTM, C20/2022, C97/2018a test methods. Mechanical properties, including compressive strength, modulus of rupture, flexural strength and abrasion resistance, were evaluated in accordance with the Standard Specification for Granite Dimension Stone (ASTM C615/2011, C170/2017, C99/2018b and C880/2018c). The abrasion resistance of the natural stone specimens was determined in accordance with EN 14157:2017 ('Böhme' method). The following technical parameters and instrument specifications define the test procedure. The Böhme Abrasion Testing Machine subjects a cubic stone specimen to abrasion under a defined load on a rotating cast iron grinding disk, using a standardized abrasive grit. The volume loss after a fixed grinding path is the measure of abrasion resistance. Abrasion resistance technical parameters, including drum/disk rotational speed (40 rpm for DIN; Deutsches Institut für Normung), applied vertical load/pressure (22N). The holder ensures the specimen projects 5.0 mm $\pm$ 0.5 mm below the holder's base to contact the grinding disk.

4. Results

4.a. Remote sensing

4.a.1. FCC-PCA composites for lithological enhancement

Our remote sensing analysis using PRISMA hyperspectral data clearly highlights the lithological variability and structural

Table 1. Chemical analyses of syn-collisional and post-collisional granitoids at Gabal Nikeiba area

Rock type Sample No.	Syn-collisional granitoids												
	Diorite					Tonalite			Granodiorite				
	NK7	NK9	NK10	NK45	NK63	NK15	NK19	NK21	NK1	NK14	NK17	NK20	NK23
Major oxides (wt.%)													
SiO ₂	54.9	55.2	56.4	57.7	58.5	62.2	63.8	65.2	66.3	67.89	68.5	69.9	70
TiO ₂	1.14	0.98	0.79	0.82	0.69	0.63	0.62	0.56	0.47	0.46	0.36	0.32	0.27
Al ₂ O ₃	17.18	17	16.2	15.8	16.5	15.5	15.8	15.7	16.1	16.39	16.1	15.96	15.25
Fe ₂ O ₃	8.62	8.81	8.62	7.76	7.32	6.88	6.01	5.32	5.16	4.4	3.97	3.99	3.62
MnO	0.13	0.1	0.12	0.12	0.1	0.1	0.04	0.08	0.06	0.07	0.07	0.11	0.07
MgO	4.68	4.36	3.92	3.95	3.75	2.19	1.83	1.92	1.29	1.14	0.93	0.84	0.72
CaO	7.18	6.93	6.63	6.84	5.85	4.76	4.58	4.36	3.92	3.11	2.94	2.63	2.22
Na ₂ O	3.52	3.7	3.73	3.59	2.98	4.12	4.04	3.85	3.23	3.41	3.22	3.37	3.25
K ₂ O	0.43	0.61	0.82	1	1.31	1.54	1.74	1.91	2.16	2.54	2.76	2.52	2.88
P ₂ O ₅	0.31	0.27	0.25	0.21	0.17	0.18	0.16	0.17	0.15	0.14	0.13	0.11	0.14
LOI	1.58	1.54	1.43	1.54	2.09	1.08	1.17	0.62	0.77	0.44	0.33	0.22	0.44
Total	99.67	99.5	98.91	99.33	99.26	99.18	99.79	99.69	99.61	99.99	99.31	99.97	98.86
Trace elements (ppm)													
Cs	0.37	0.68	0.24	0.55	0.34	0.41	0.47	0.77	0.67	0.78	1.24	1.76	2.11
Rb	7.09	9.87	10.27	12.88	16.17	27.79	24.88	39.43	35.09	53.14	56.57	61.24	65.64
Ba	190.31	259.6	217.4	242.38	209.72	365.08	352.87	429.27	357.57	400.01	416.27	361.78	392.98
Sr	712.23	469.08	444.79	421.46	358.77	392.37	389.63	346.82	307.64	299.47	238.32	284.69	311.08
Pb	6.54	7.5	5	6.64	4.64	17.18	17.85	16.26	14.14	6.44	7.61	4.44	6.17
Th	1.13	1.37	1.42	1.34	1.48	3.13	3.39	4.85	4.26	6.16	7.48	4.29	6.23
U	1.51	1.37	1.44	1.61	1.74	0.88	0.93	0.72	1.94	1.56	1.72	1.46	0.96
Zr	56	94.78	67.09	77.64	82.55	142.44	139.33	137.27	157.87	194.6	222.89	229.87	214.78
Hf	2.74	2.94	1.69	1.85	2.11	3.34	4.01	3.97	4.23	5.55	6.54	7.08	7.29
Ta	0.22	0.23	0.19	0.21	0.2	0.26	0.33	0.29	0.38	0.41	0.49	0.7	0.77
Y	12.61	13.11	10.09	11.14	9.56	18.08	16.56	14	20.19	23.77	21.94	25.34	27.46
Nb	3.44	4.16	4.74	5.47	5.22	6.54	6.89	7.77	8.47	9.84	9.99	10.45	11.14
Sc	20	21.14	18.56	19.88	17.21	15.09	12.24	11.37	6.57	4.17	2.54	3.17	2.57
Cr	105.59	95.69	102.55	92.97	86.27	17.66	19.93	16.94	18.08	14.86	12.31	15.79	14.32
Ni	47.25	51.38	51.34	25.65	31.05	16.45	15.08	11.45	6.49	5.97	4.65	4.11	3.47
V	132.03	139.09	127.06	117.18	113.29	39.58	41.24	42.46	37.57	36	41.03	35.46	34.97
W	0.21	0.31	0.26	0.37	0.35	0.57	0.61	0.74	0.67	0.82	0.79	0.94	1.05
Ga	18.97	19.08	14.33	12.11	13.14	14.13	15.74	16.57	17.24	16.88	17.37	18.08	18.78
Zn	88.45	79.14	71.54	69.57	80.91	61.1	52.64	53.58	54.52	11.28	49.82	102.46	56.4
Cu	119.87	90.55	101	88.34	78.99	63.88	49.88	46.38	45.5	35.88	38.5	38.5	23.63
Mo	4.56	4.41	5.07	4.38	3.59	4.17	5.21	4.88	5.61	5.24	5.77	5.74	6.01
Sn	4.02	3.74	3.36	3.58	2.84	3.56	3.11	4.14	4.57	4.08	5.67	6.46	6.87
Hf	3.01	2.95	3.86	3.16	3.59	3.67	4.41	4.37	4.65	6.11	7.19	7.79	8.02
REE (ppm)													
La	4.5	5.08	4.18	3.75	3.2	9.73	8.64	7.44	11.96	13.96	17.54	15.14	16.99
Ce	11.01	12.8	10.16	9.1	7.6	21.93	20.38	17.56	26.63	30.55	35.98	33.73	36.58
Pr	1.6	1.84	1.42	1.3	1.1	2.96	2.76	2.38	3.48	3.79	4.33	4.21	4.63

(Continued)

Table 1. (Continued)

Rock type	Syn-collisional granitoids																	
	Diorite					Tonalite			Granodiorite									
	Sample No.	NK7	NK9	NK10	NK45	NK63	NK15	NK19	NK21	NK1	NK14	NK17	NK20	NK23				
Nd	7.18	8.24	6.27	6.04	5.3	12.93	11.6	10.84	14.54	15.2	17.08	17.54	18.62					
Sm	2	2.24	1.72	1.7	1.4	3.2	2.99	2.58	3.28	3.47	3.77	4.06	4.43					
Eu	0.7	0.76	0.57	0.61	0.52	1.09	1.01	0.91	1.01	0.98	1.05	1.11	1.15					
Gd	2.24	2.56	1.84	2.04	1.7	3.43	3.19	2.92	3.85	4.13	4.13	4.51	5.01					
Tb	0.37	0.4	0.3	0.32	0.27	0.59	0.54	0.46	0.61	0.66	0.67	0.74	0.84					
Dy	2.2	2.42	1.88	1.93	1.68	3.51	3.26	2.84	3.82	4.14	4.05	4.57	5.25					
Ho	0.45	0.54	0.38	0.41	0.35	0.68	0.64	0.58	0.79	0.87	0.85	0.97	1.09					
Er	1.34	1.46	1.09	1.16	1.01	1.89	1.76	1.61	2.12	2.34	2.3	2.55	2.86					
Tm	0.2	0.23	0.16	0.18	0.15	0.27	0.26	0.23	0.31	0.36	0.35	0.38	0.42					
Yb	1.32	1.44	1.05	1.15	1.01	1.81	1.68	1.52	2.06	2.44	2.33	2.57	2.77					
Lu	0.2	0.22	0.16	0.18	0.15	0.27	0.25	0.23	0.31	0.38	0.35	0.39	0.43					
Post-collisional granitoids																		
Rock type	Quartz-syenite							Syenogranite				Alkali feldspar granite						
Sample No.	NK43	NK50	NK56	NK58	NK65	NK67	NK70	NK4	NK25	NK54	NK60	NK27	NK30	NK32	NK36	NK39	NK41	NK48
Major oxides (wt.%)																		
SiO ₂	65.53	66.41	66.51	67.45	67.81	68.68	68.96	70.96	71.22	71.73	72.44	71.54	72.31	72.36	73.17	73.41	74.03	75.2
TiO ₂	0.21	0.23	0.22	0.24	0.19	0.19	0.19	0.18	0.15	0.14	0.14	0.14	0.13	0.12	0.13	0.13	0.07	0.04
Al ₂ O ₃	16.51	15.82	15.79	15.51	15.36	14.88	14.94	14.15	14.04	13.88	13.62	13.79	13.67	13.58	13.77	13.8	12.69	12.39
Fe ₂ O ₃	3.04	3.47	3.12	3.82	3.06	3.36	2.71	2.75	2.36	2.3	2.16	2.19	2.26	1.95	2.26	2.16	1.6	1.22
MnO	0.07	0.1	0.11	0.11	0.09	0.07	0.07	0.06	0.04	0.03	0.03	0.03	0.03	0.04	0.03	0.02	0.02	0.02
MgO	0.07	0.09	0.13	0.07	0.12	0.06	0.1	0.09	0.05	0.06	0.03	0.14	0.03	0.07	0.04	0.05	0.01	0.02
CaO	1.02	1.19	1.27	0.88	1.07	0.74	0.87	0.8	0.64	0.63	0.66	1.04	0.64	0.7	0.66	0.61	0.57	0.32
Na ₂ O	5.63	5.78	5.68	5.36	5.5	5.18	5.25	4.9	4.75	4.54	4.57	4.3	4.45	4.45	4.18	4.04	4.04	4.22
K ₂ O	5.64	4.75	4.14	5.07	4.44	4.99	4.56	4.73	4.82	4.8	4.92	4.63	4.69	4.55	4.8	4.79	4.76	4.84
P ₂ O ₅	0.02	0.03	0.04	0.02	0.04	0.02	0.04	0.03	0.02	0.03	0.02	0.05	0.02	0.03	0.02	0.03	0.01	0.01
LOI	1.22	1.23	1.56	0.78	1.6	0.88	1.13	0.85	0.93	1.09	0.8	1.06	0.83	0.77	0.72	0.88	0.64	0.74
Total	98.96	99.1	98.57	99.31	99.28	99.05	98.82	99.46	99.02	99.23	99.39	98.91	99.06	98.62	99.78	99.92	98.44	99.02
Trace elements (ppm)																		
Cs	1.15	1.33	1.54	0.77	1.49	1.39	1.77	1.36	1.67	0.92	1.47	1.19	1.91	1.53	2.95	1.73	1.36	0.63
Rb	196.9	132.7	138.8	145.8	145	174.8	164.9	194.8	204.8	205.8	234.4	187.9	233.7	241.3	240.6	228.7	186.3	220.4
Ba	281.1	612.7	632.8	372.7	488.7	241.9	329.6	269.5	264.0	244.7	202.8	241.7	175.1	190.2	174.6	204.6	102.9	22.33
Sr	56	103.5	107.9	71.44	99.18	56.35	88.85	68.48	61.42	70.6	56.55	68.56	43.76	49.89	58.08	52.23	30.64	10.91
Pb	11.72	9.19	8.72	9.16	8.95	13.12	10.97	10.96	15.41	8.14	10.38	10.32	14.83	8.56	15.04	16.27	8.09	12.39
Th	27.56	25	23.33	30.6	24.66	28.53	27.19	29.88	28.69	33.51	36.73	33.9	30.91	35.06	31.25	36.42	39.63	19.51
U	6.76	5.15	5.2	6.05	5.84	7.02	7.41	8.45	7.6	9.12	11.73	8.39	10.95	11.24	9.1	10.52	11.62	5.72
Zr	410	706	700.4	806.2	666.8	622.2	617.4	656.8	480.5	310.5	328.1	259	421.3	285.6	387.2	287.6	235.8	174
Hf	11.95	17.05	16.78	19.75	16.67	16.77	16.25	17.56	13.56	9.55	10.83	8	12.48	9.4	10.97	9.73	9.29	7.29
Ta	13.82	10.68	8.87	10.2	9.83	12.84	10.89	15.07	13.72	14.3	15.15	9.66	13.46	14.53	14.62	15.85	16.09	9.99
Y	61.35	85.49	74.4	85.41	102.4	87.99	93.78	45.29	52.47	60.8	63.12	71.9	82.64	93.49	91.94	111.3	103.9	107.3
Nb	191.3	160.1	132.9	171.2	148.1	162.9	154.8	189.6	181.9	182.3	216.5	95.35	151.2	134.5	213.6	208.3	242.9	131.0
Sc	1.05	1.69	1.39	1.92	1.68	1	1.71	1.87	1.24	1.16	0.73	0.97	1.03	1.31	0.64	0.54	0.37	0.15

(Continued)

Table 1. (Continued)

Rock type	Post-collisional granitoids																	
	Quartz-syenite							Syenogranite				Alkali feldspar granite						
	Sample No.	NK43	NK50	NK56	NK58	NK65	NK67	NK70	NK4	NK25	NK54	NK60	NK27	NK30	NK32	NK36	NK39	NK41
Cr	7.64	4.52	5.26	2.77	4.14	7.14	6.67	5.17	5.97	3.19	3.1	3.51	4.22	3.52	4.04	3.55	1.47	7.24
Ni	3.87	3.99	2.95	2.91	5.06	4.63	4.46	2.74	3.65	0.79	2.69	2.09	3.01	3.41	4.17	3.15	2.8	6.34
V	4.09	4.86	5.31	5.02	5.31	5.9	5.59	5.78	5.33	8.68	9.33	9.1	9.04	6.93	7.05	6.81	3.7	7.4
W	5.4	0.97	1.15	1.52	1.2	4.71	308.5	291.4	1.68	3.36	265.5	5.58	2.02	264.4	3.83	2.35	179.2	0.45
Ga	31.15	25.62	24.99	25.95	24.83	27.59	27.36	26.6	25.81	20.83	23.19	19.69	25.79	22.22	25.36	21.99	23.59	25.66
Zn	109.9	153.0	154.9	125.5	148.5	144.3	128.7	127.7	113.7	50.63	77.72	24.3	127	49.29	107.7	79.9	91.29	130.1
Cu	6.23	3.61	3.27	5.35	3.98	5.22	9.3	7.55	4.91	4.95	2.73	5.97	4.14	2.38	5.02	3.29	3.95	8.54
Mo	4.42	2.75	1.79	4.92	3.37	3.47	2.87	3.77	2.7	2.22	5.18	1.05	1.68	6.82	0.67	1.15	0.19	0.52
Sn	6.43	5.07	5.36	6.89	6.28	32.58	9.8	12.15	9.95	6.71	6.64	7.76	9.84	5.13	11.14	6.85	3.96	4.84
Hf	13.75	18.83	18.26	21.84	18.81	19.15	18.4	19.73	15.67	11.05	12.75	9.25	14.54	11.09	12.77	11.65	11.82	9.16
REE (ppm)																		
La	72.5	81.61	87.81	99.89	120.85	132.84	153.18	17.85	22.04	29.31	33.77	39.77	34.26	50.26	47.46	61.18	57.14	64.22
Ce	156.5	168.9	185.75	200.92	251.85	267.51	313.32	44.05	54.22	63.79	76.59	86.14	73.75	109.52	99.63	121.67	112.48	142.85
Pr	19.23	21.02	22.92	25.48	29.99	32.18	35.85	5.82	7.55	8.89	9.23	11.72	9.88	14.49	13.13	16.45	15.18	17.66
Nd	69.79	75.88	83.78	91.85	107.04	118.63	124.31	23.85	31.79	37.67	36.13	48.21	40.41	57.4	52.18	61.62	58.17	69.84
Sm	12.49	14.58	16.73	17.52	19.08	20.71	21.9	6.14	7.18	8.26	8.74	10.28	9.37	13.75	12.38	13.98	12.54	16.16
Eu	1.29	1.94	1.94	2.14	2.78	2.69	2.91	0.67	0.75	0.79	0.82	0.89	0.92	0.96	1.04	1.15	1.22	1.08
Gd	11.22	15.72	12.79	14.45	17.78	16.54	19.38	5.92	8.11	9.01	9.54	10.29	11.2	12.69	13.9	16.11	14.37	15.22
Tb	1.75	2.44	2.08	2.3	2.82	2.59	2.91	1.08	1.33	1.5	1.5	1.67	1.95	2.17	2.29	2.9	2.48	2.72
Dy	11.28	15	12.46	14.19	17.95	15.68	17.37	7.56	8.82	9.93	9.9	11.33	13.08	14.49	15.77	19.24	16.72	18.23
Ho	2.3	3.05	2.78	3	3.67	3.3	3.52	1.64	1.92	2.14	2.1	2.41	2.78	3.19	3.44	4.22	3.56	3.85
Er	6.63	8.72	7.97	8.83	10.67	9.73	10	4.82	5.65	6.3	6.32	7.32	8.25	9.7	10.12	12.45	10.57	11.35
Tm	1.01	1.32	1.21	1.34	1.6	1.49	1.49	0.74	0.88	0.97	0.95	1.14	1.27	1.44	1.5	1.87	1.58	1.67
Yb	6.81	9.15	8.31	8.96	10.71	9.99	10.25	4.76	5.89	6.57	6.43	7.76	8.44	9.25	9.64	11.86	10.63	11.26
Lu	1.01	1.41	1.26	1.36	1.59	1.45	1.49	0.66	0.9	1	0.95	1.1	1.3	1.36	1.45	1.75	1.52	1.65

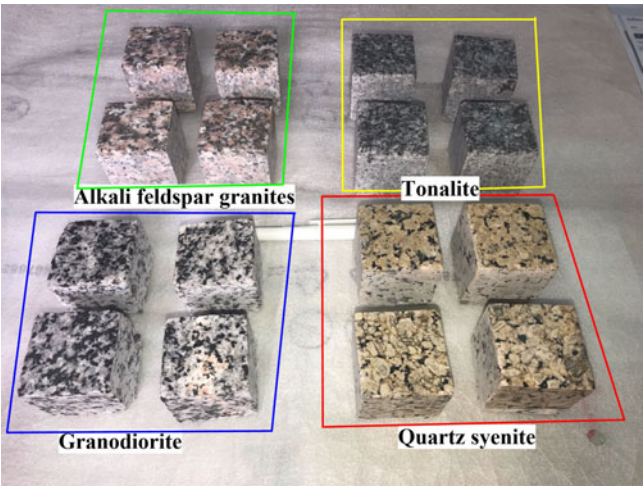


Figure 3. Photographs showing the cubic hand specimens of the studied rocks.

complexity within the study area. By applying widely accepted remote sensing techniques and leveraging the rich spectral detail provided by PRISMA, all major rock units and structural elements were effectively delineated.

FCCs of PRISMA data reasonably effectively highlight lithological distinctions. In one composite (bands 30-20-9), syenogranites and quartz syenites appear in brownish tones (Figure 4a), and metagabbro-diorite and mafic metavolcanics are darker. A second composite (bands 81-44-8) provides enhanced separation, with acidic rocks showing a pronounced yellowish hue, granodiorite in bright brown and metagabbro-diorite in dark brown (Figure 4c and b). Mafic metavolcanics are well mapped along the eastern flank and in scattered central and western exposures. To move closer to the main objective of this research, characterization of the granitic rocks, a tailored FCC using bands 39–92–127 (RGB) was applied. This combination (Figure 4c) successfully discriminates between syenogranites and quartz syenites, with the former appearing in turquoise and the latter in bright brown, exhibiting a clearly defined boundary

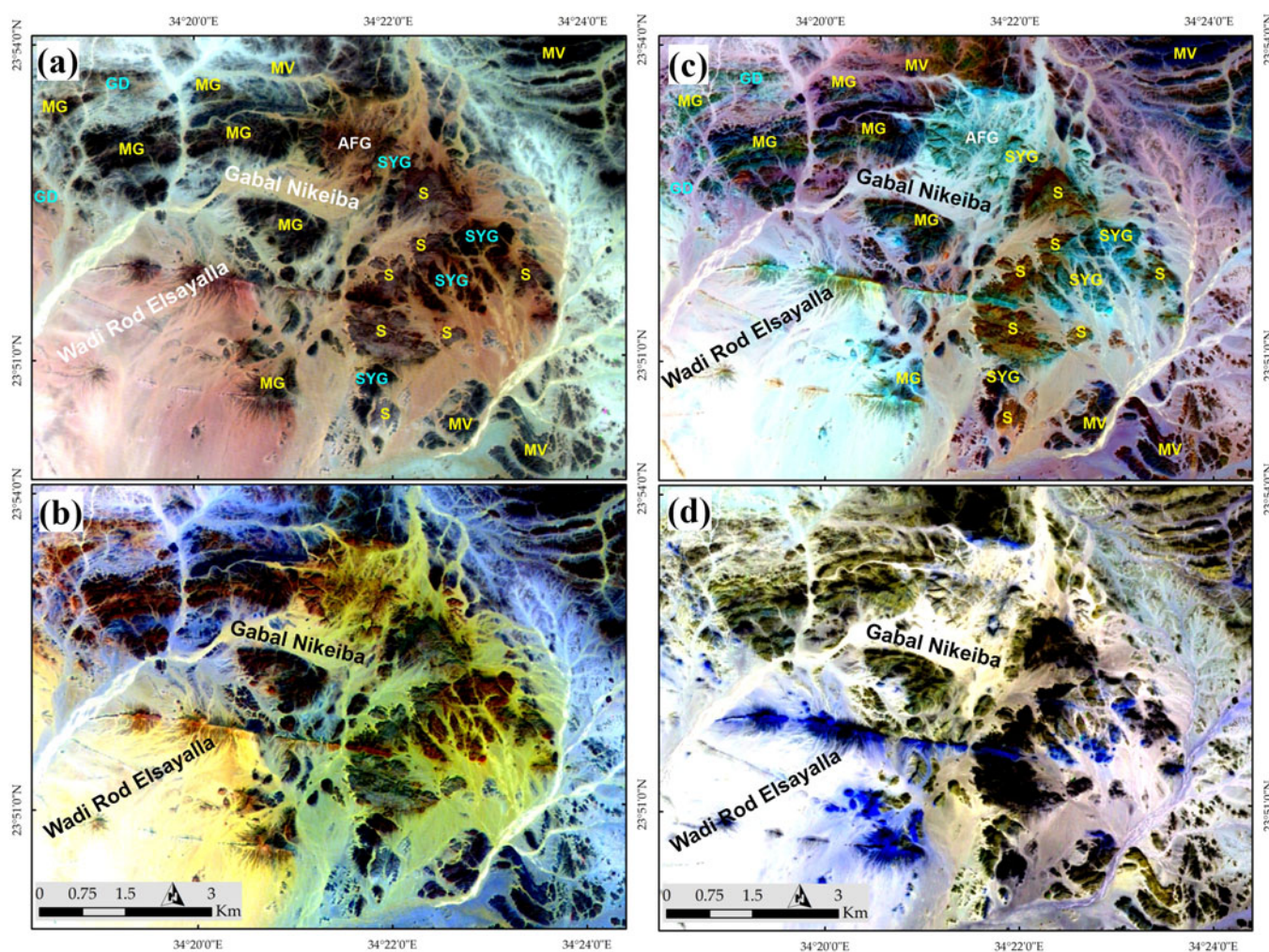


Figure 4. Lithological mapping using PRISMA data: (a) FCC 3020–9 (RGB) highlights syenogranites and quartz syenites in brownish tones, contrasting with darker metavolcanics and metagabbro–diorite; (b) FCC 81–44–8 (RGB) enhances the separation of acidic and mafic rocks, with granodiorite distinctly shown in brown tone at NW corner. (c) Discrimination of granitic units and quartz veins using PRISMA data FCC 39–92–127 (RGB) distinguishes syenogranites (turquoise) from quartz syenites (bright brown) and reveals heterogeneity in metagabbro–diorite. (d) FCC 190–187–140 (RGB) displays quartz veins in vivid blue cutting across granitic bodies. Abbreviations: MG; metagabbro–diorite, GD; granodiorite, S; quartz syenite, SYG; syenogranites, MV; metavolcanics, AFG; alkali feldspar granites.

between them. The FCC analysis further details rock distributions and internal variations. It identifies small rock blocks in the southern and eastern regions. In the northwest, granodiorite appears in a darker turquoise, reflecting its compositional affinity with syenogranites. The technique also reveals heterogeneity within the metagabbro–diorite units, displaying a foliated texture in dark green to olive tones that effectively distinguishes them from the heterogeneously brown-toned mafic metavolcanics to the east.

A more detailed view of quartz veining cutting across syenogranites and quartz syenites is shown in Figure 4d, using the FCC of bands 190–187–140 (RGB). Quartz veins are vividly displayed in bright blue, sharply contrasting with surrounding granitic rocks. To further support and validate the FCC-based interpretations, PCA and MNF techniques were employed. These methods reduce data dimensionality while enhancing spectral contrast among complex lithologies. Figure 5a illustrates the composite of PC1–PC2–PC3 (RGB), where syenogranites are distinctly shown in vivid yellow, separated from surrounding units. The heterogeneity of foliated mafic metavolcanics in the northwest and their folding features in the southeast are clearly observed,

confirming the effects of tectonic deformation. Additionally, granodiorite in the northwest corner is uniquely displayed in green, aiding its discrimination from other granitoids. Figure 5b presents a PC4–PC5–PC3 (RGB) combination, emphasizing quartz veins and microgranites in pinkish tones that cut through a background of acidic rocks (displayed in green). This visualization also underscores the dominance of E–W and NW–SE tectonic trends throughout the study area.

4.a.2. Structural complexity

Remote sensing data were employed to derive preliminary structural interpretations for the study area. The compositional and structural heterogeneity of the metavolcanic units is further reinforced in Figure 5c, using PC6–PC3–PC2 (RGB), where syenogranite blocks appear in red, forming a mega sigma-like structure. Figure 5d displays a pseudocolour ramp of MNF 7, effectively highlighting E–W trending quartz veins, as pinkish-white linear features concentrated in the central and southern zones.

Further refinement of structural interpretation was achieved using a pseudocolour ramp of MNF 11 (Figure 6a), which reveals folding and heterogeneity across various lithologies, features that

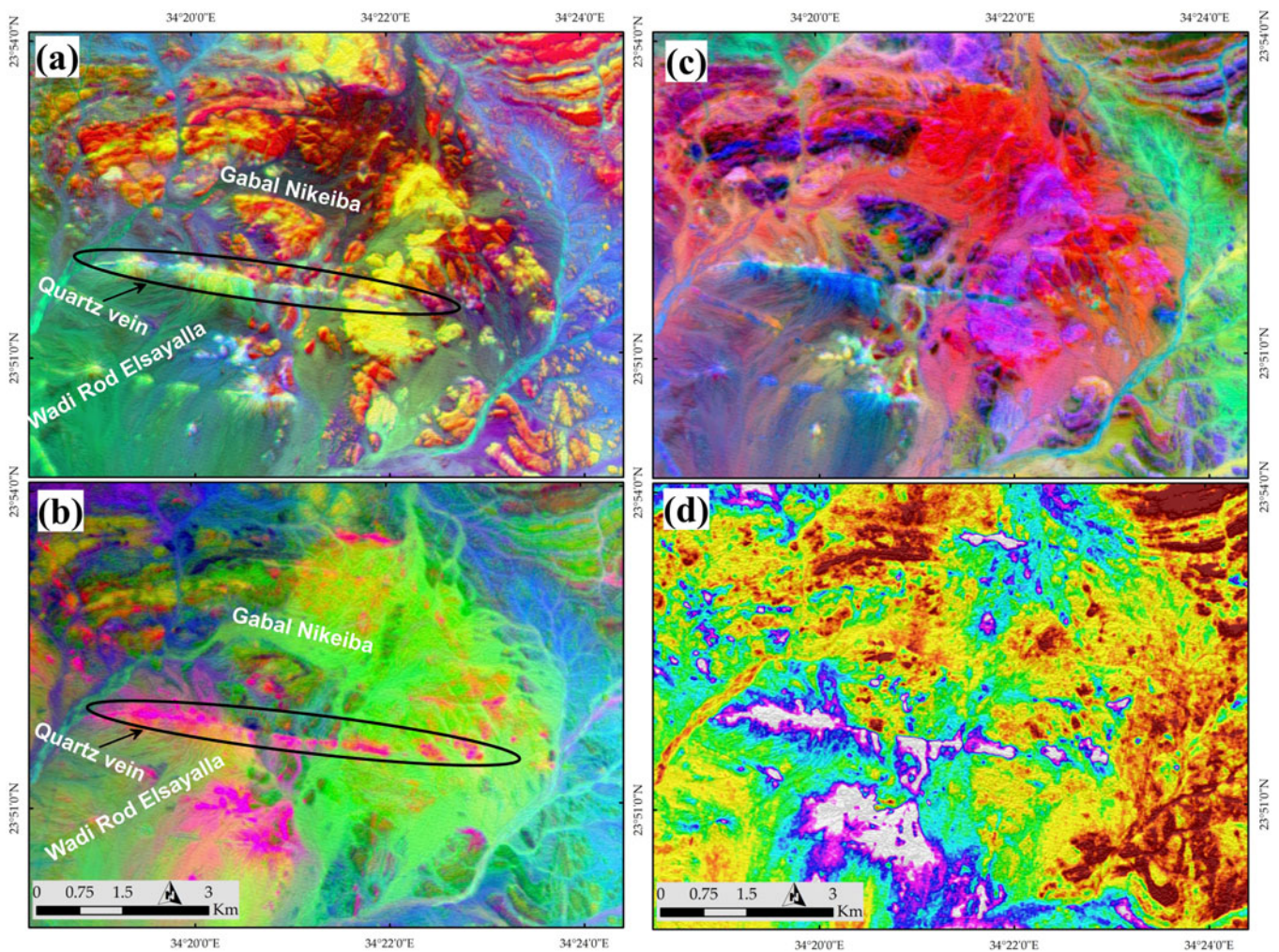


Figure 5. PCA composites for lithological enhancement: (a) PC1–PC2–PC3 (RGB) shows syenogranites in vivid yellow, metavolcanic folding in the southeast and granodiorite in yellowish green; (b) PC4–PC5–PC3 (RGB) highlights quartz veins and syenogranites in pinkish tones within a green acidic rock background. (c) Spectral and structural complexity revealed through PCA and MNF: PC6–PC3–PC2 (RGB) displays syenogranite deformation in red. (d) MNF 7 pseudocolour ramp highlights E–W trending quartz veins in pinkish white across central and southern zones.

are not as clearly visible in standard FCCs. A close-up view shown in Figure 6b confirms folding patterns within metagabbro–diorite, offering new insights into the tectonic history of the area.

To better visualize and interpret the structural framework of the study area, several detailed insets were prepared, each focusing on deformation features that reflect the impact of tectonic activity. The full extent of the area is shown in Figure 7a, where coloured rectangles highlight zones of structural significance. The area marked in red (Figure 7a) is expanded in Figure 7b, showing evidence of E–W trending strike-slip faulting, illustrated by the straightness of the wadis and the displacement of tributaries and lithological units. In the southern portion of the same Figure 7b, a well-defined trellis drainage pattern reflects strong structural control on surface hydrology. Just south of this region (Figure 7c; linked to the adjacent red rectangle in Figure 7a) captures severe dissection and rock deformation, revealed by the presence of perpendicular wadi intersections, displaced rock masses and parallel drainage alignments. In the northern part of the study area, Figure 7d (from the yellow box in Figure 7a) shows one of the clearest examples of structurally influenced drainage, with an N–S trending main wadi trunk intersected by E–W tributaries, a characteristic of trellis drainage formed within metagabbro–diorite rocks. Moving

to ductile deformation, Figure 7e (pink rectangle in Figure 7a) highlights folding within mafic metavolcanics, where foliation and compositional heterogeneity form a well-defined anticline–syncline pair, accentuated by erosion from wadis crossing the antiform axis.

To reinforce and expand upon these structural interpretations, a coloured pseudoramp of MNF 11 is shown in Figure 8a, with zoomed-in insets for detailed analysis. The red rectangle shown in Figure 8a is magnified in Figure 8b, where NW-trending lithological units appear dissected by NE–SW trending faults, paralleling those seen in Figure 7b. In the northeastern part of the map, the green rectangle leads to Figure 8c, which clearly depicts foliation, fault displacement and internal heterogeneity within mafic metavolcanics. Structural influence on quartz veins is especially evident in Figure 8d (yellow box in Figure 8a), where an E–W trending quartz vein is sharply delineated and intersected by perpendicular wadi tributaries and sediment deposits. Finally, Figure 8e (pink rectangle in Figure 8a) showcases a repetitive synform geometry, reflecting intense folding and the tectonic complexity of the region. Based on the above, these PRISMA-based remote sensing analyses provide critical insight into the tectonic architecture and geological evolution of the terrain.

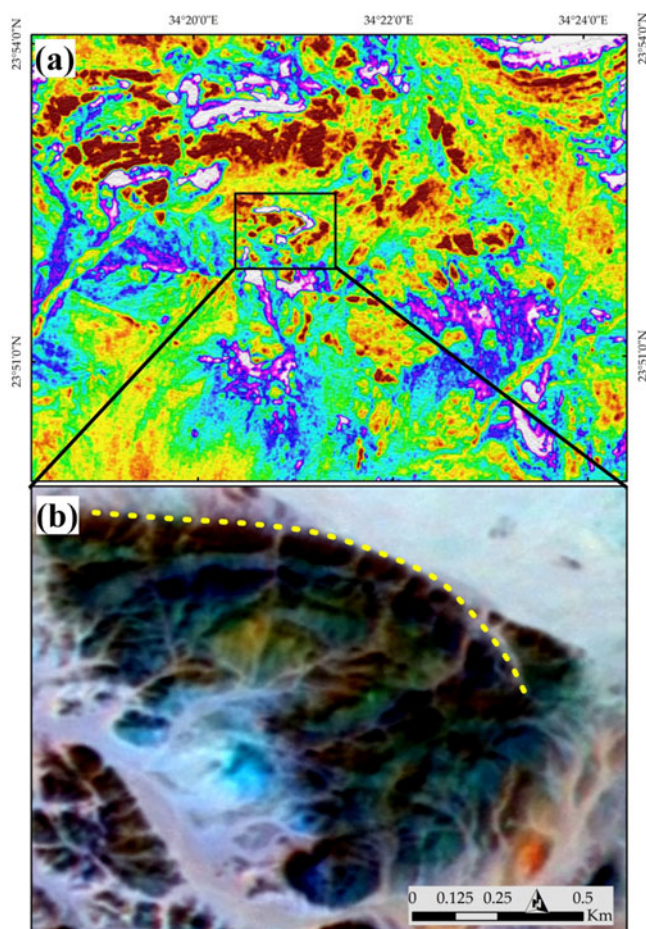


Figure 6. Preliminary structural features captured using MNF: (a) MNF 11 pseudo-colour ramp reveals subtle folding patterns and lithological complexity; (b) Close-up view emphasizes internal folding within metagabbro-diorite, aiding tectonic interpretation. Further field investigations are required for detailed confirmation of these structural features.

4.b. Petrographic characteristics of Nikeiba area

Petrographic descriptions of different rock units at Nikeiba area confirm the field identification. The rocks investigated include syn-collisional (diorite, tonalite and granodiorite) as well as post-col-lisional granitoids (quartz-syenite, syenogranite and alkali feldspar granite).

4.b.1. Syn-collisional granitoids

4.b.1.a. Diorite. Diorite is dark grey, medium-grained with hypidiomorphic granular texture. It is composed of plagioclase (55–65 vol. %) and mafic minerals (15–25 vol. %) with minor amounts of quartz (2–6 vol. %) and alkali feldspar (<10 vol. %). The accessory minerals include opaques, zircon, titanite and apatite. Plagioclase is the most common mineral and occurs as subhedral tabular crystals, which show normal and oscillatory zoning (Figure 9a). Some plagioclase crystals are marginally corroded and display saussuritization. Small quartz occurs as anhedral grains with sutured outlines and shows undulatory extinction. K-feldspar forms few subhedral to anhedral crystals between plagioclase. The mafic minerals include amphibole together with minor biotite and pyroxene. Amphibole occurs as subhedral prismatic crystals, usually fresh, and sometimes shows alterations along the margins into secondary amphibole and chlorite.

Amphibole forms short prisms, strongly pleochroic from pale yellow, green to brownish green. It contains inclusions of Fe-Ti oxides and zircons. Biotite forms discrete anhedral to subhedral crystals associated with or surrounding amphibole or as individual anhedral flakes. Pyroxene forms small subhedral crystals that exhibit alteration to tremolite. Opaques include small anhedral grains of Fe-Ti oxides distributed in the rock or as inclusions in the plagioclase and associated with mafic minerals. Titanite forms anhedral to euhedral crystals associated with hornblende and biotite. Apatite occurs as numerous minute crystals enclosed in mafic minerals and the plagioclase.

4.b.1.b. Tonalite. Tonalite is dark grey and medium-grained with hypidiomorphic granular texture. It is composed of plagioclase, quartz and mafic minerals together with accessory amounts of opaques and apatite. Secondary minerals include epidote, zoisite, chlorite and sericite. Plagioclase occurs as long subhedral plates, usually fresh, and exhibits lamellar twinning and zoning (Figure 9b). Few plagioclase crystals show bent twinning and are cracked due to deformation (Figure 9c), and others are highly saussuritized in the cores. The mafic minerals include amphibole and minor biotite. Amphibole forms anhedral short prisms, strongly pleochroic from pale yellow to green to brownish green. Some crystals are altered along margins into secondary amphibole and chlorite. Biotite occurs as tabular subhedral crystals or as anhedral flakes, occupying the interstitial spaces between the plagioclase. Quartz occurs as fine to coarse anhedral grains with wavy extinction occupying the interstitial spaces between the plagioclase crystals. Opaques comprise small anhedral Fe-Ti oxides distributed in the rock or as inclusions in the plagioclase and associated with mafic minerals. Apatite occurs as numerous minute crystals enclosed in mafic minerals and the plagioclase.

4.b.1.c. Granodiorite. The rock is coarse-grained and whitish grey spotted with dark grains. It consists of plagioclase, quartz, K-feldspars, mafic minerals and opaques. The accessory minerals include zircon, apatite and titanite. Plagioclase (40–45 vol. %) occurs as coarse subhedral to anhedral prisms, usually fresh and exhibit lamellar twinning; some crystals are zoned and others are highly altered to sericite and epidote (Figure 9d). Quartz (22–25 vol. %) forms anhedral and irregular crystals in between other minerals. It embays and corrodes the feldspars. K-feldspars (15–20 vol. %) are markedly less abundant than the plagioclase and occur as subhedral to anhedral crystals occupying the interstitial spaces between the plagioclase. They are turbid due to sericitization and stained by reddish iron oxides. They are represented mainly by orthoclase that contains inclusions of plagioclase in addition to quartz. The mafic minerals (4–7 vol. %) include biotite and amphibole. Biotite occurs as tabular crystals as well as anhedral flakes, strongly pleochroic from yellow to brown. Some biotite crystals are slightly altered to chlorite along the cracks, the margins and the cleavage planes (Figure 9e). Amphibole occurs as anhedral to subhedral short prisms that are moderately altered to chlorite and opaque minerals (Figure 9f). Opaques (4–5 vol. %) are represented by ilmenite and magnetite. Titanite forms euhedral crystals associated with mafic minerals. Apatite occurs as small inclusions in the plagioclase, biotite and amphibole. Zircon forms small euhedral crystals commonly associated with amphibole or as inclusions in biotite. Apatite occurs as small subhedral crystals and needles or as inclusions in the mafic minerals and plagioclase.

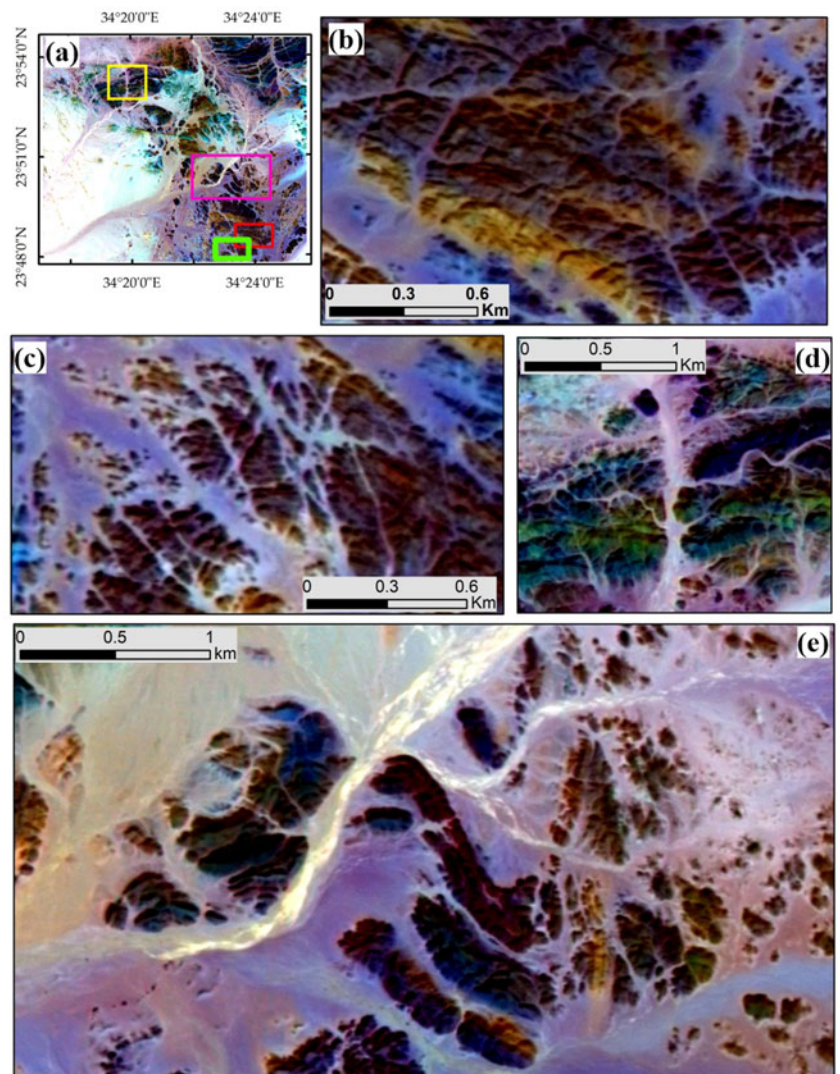


Figure 7. Preliminary structural interpretation using PRISMA-derived false colour composites: (a) overview map of the study area showing locations of structural insets; (b) strike-slip faulting along E-W trends with displaced tributaries and trellis drainage pattern; (c) evidence of intense deformation, wadi intersections and rock mass dislocation; (d) Trellis drainage in metagabbro-diorite rocks reflecting N-S and E-W tectonic trends; (e) well-defined anticline-syncline pair within mafic metavolcanics, emphasized by foliation and wadi incision in the anticline apex. Further field investigations are required for detailed confirmation of these structural features.

4.b.2. Post-collisional granitoids

4.b.2.a. Quartz-syenite. Quartz syenite is an inequigranular, medium-grained rock and rarely shows a porphyritic texture. It comprises of K-feldspars, quartz and mafic minerals with a small amount of plagioclase. Accessory minerals include zircon, allanite, fluorite, xenotime, pyrochlore, Nb-Ta oxides, muscovite, apatite and Fe-Ti oxides. K-feldspar (60–65 vol.%) is the essential mineral and occurs as subhedral tabular crystals of orthoclase that show simple twinning and exhibit string, patchy and flame perthitic intergrowths (Figure 10a). Most of the K-feldspar crystals are stained by iron oxide and occasionally fragmented with weak alteration to sericite. Albite (40–45 vol. %) forms subhedral prismatic crystals or fine inclusions in K-feldspars. Quartz (10–20 vol. %) occurs as interstitial anhedral crystals. The mafic minerals (5–10 vol. %) include biotite and amphiboles with minor pyroxene. Biotite is the dominant mafic mineral and occurs as subhedral to anhedral flakes, variably altered to chlorite, muscovite and iron oxides. Few inclusions of zircon, allanite and apatite are recorded within biotite crystals. Amphibole exists as subhedral prismatic crystals that show simple twinning (Figure 10b). Pyroxene is represented by small crystals of augite that are partially transformed into secondary amphiboles. Some anhedral crystals of Nb-Ta oxides, especially columbite, are observed in the quartz

syenite. Allanite occurs as pleochroic reddish-brown anhedral crystals (Figure 10c). Muscovite forms anhedral interstitial crystals. Pyrochlore forms yellow to reddish-yellow subhedral crystals, mostly associated with amphibole and Nb-Ta oxides. Fe-Ti oxides form granular aggregates associated with altered mafic. Apatite occurs as rod-like crystals scattered throughout the rock or associated with biotite.

4.b.2.b. Syenogranite. Syenogranite is medium- to coarse-grained and composed of quartz, K-feldspar and plagioclase with minor amounts of mafic minerals (2–5 vol. %). The accessory minerals include opaque phases, apatite, beryl, zircon, allanite, titanite, muscovite and monazite. K-feldspar (40–55 vol. %) occurs as platy crystals of orthoclase and microcline. Orthoclase shows string and patchy perthitic texture. Microcline is found as subprismatic to platy crystals with cross-hatching twinning (Figure 10d). Plagioclase (15–20 vol. %) forms subhedral prismatic crystals that are fresh or slightly sericitized. Small subhedral plagioclase inclusions occur in the orthoclase and microcline. Quartz (25–35 vol. %) occurs as anhedral interstitial crystals or forms a graphic intergrowth with K-feldspar (Figure 10e). It contains small inclusions of the feldspars and mafic minerals.

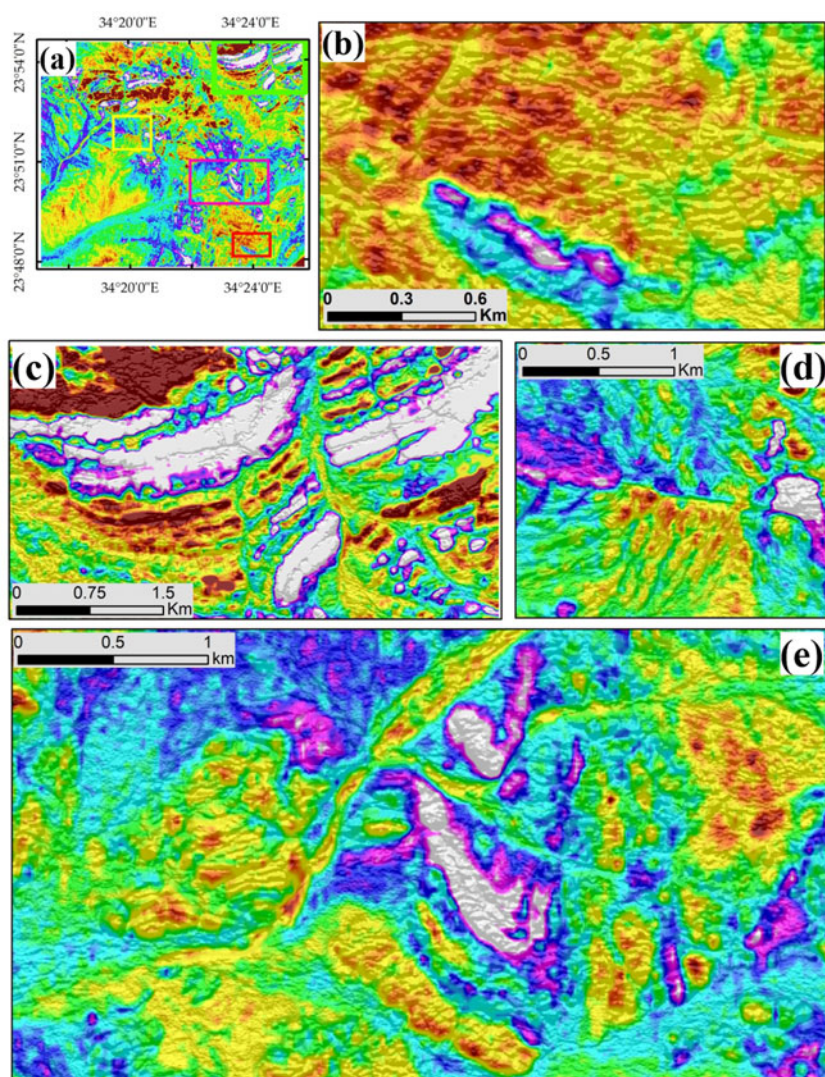


Figure 8. Preliminary structural mapping using MNF 11 pseudocolour ramp: (a) MNF 11 overview with highlighted structural zones; (b) NW-trending lithological units dissected by NE-SW faults, correlating with strike-slip zones; (c) foliation, displacement and lithological heterogeneity in mafic metavolcanics; (d) E-W trending quartz vein intersected by perpendicular wadi tributaries; (e) repetitive synform fold geometry reflecting ductile deformation complexity. Further field investigations are required for detailed confirmation of these structural features.

Mafic minerals include biotite and amphibole. Biotite occurs as an anhedral flakes and grain aggregates. Amphibole forms subhedral prismatic crystals that are partly altered to chlorite and opaques. Muscovite occurs as subhedral large crystals that are altered along its crystal margins into chlorite and fine aggregates of secondary muscovite (Figure 10f). Scarce anhedral crystals of zircon form individual crystals or occur as inclusions in quartz and K-feldspars. Allanite forms pleochroic reddish-brown anhedral crystals associated with biotite. Titanite occurs as a few sphenoid-shaped crystals enclosed in feldspar or associated with biotite. Monazite is found as anhedral crystals and as inclusions in the amphibole. Apatite occurs as minute tabular crystals in biotite, zircon as small prismatic crystals associated with biotite and amphibole.

4.b.2.c. Alkali feldspar granite. Alkali feldspar granite is medium- to coarse-grained. The main minerals are K-feldspar, quartz, plagioclase and mafic minerals. Zircon, apatite, Ta-Nb oxide, allanite, monazite, pyrochlore, beryl and Fe-Ti oxides are accessories. Alkali feldspars (50–60 %) are dusty in appearance and include both orthoclase and microcline. Orthoclase contains muscovite inclusions (Figure 10g). Microcline often exhibits micropertitic texture and cross-hatch twinning. Quartz (25–30 vol. %) is present as

fine to coarse anhedral grains with wavy extinction. Plagioclase (5–10 vol. %) occurs as isolated, corroded crystals showing simple albite twinning. Mafic minerals (2–3 vol. %) include biotite and amphibole (Figure 10h). Muscovite occurs as anhedral to subhedral interstitial crystals among other minerals. Zircon is the most common accessory mineral and forms disseminated crystals or inclusions in quartz and K-feldspars. Thorite occurs as subhedral crystals of reddish-black colour that are partially metamict and covered by amorphous blackish-brown rims. Columbite is the most common Ta-Nb oxide, occurring in various forms associated mainly with amphibole. A few columbite crystals exhibit colour variation suggestive of compositional zoning. Pyrochlore forms round yellowish-brown grains. Allanite is present as subhedral to anhedral reddish-brown to dark brown crystals, showing faint pleochroism. Fluorite occurs as anhedral to subhedral interstitial grains and as fillings of small veins.

4.c. Whole-rock geochemistry

This part deals with the geochemical characteristics of the granitoids from the Gabal Nikeiba area. The geochemical analyses of 31 samples include major oxides, trace and REE elements of the older granitoids (diorite, tonalite, granodiorite) and post-collisional

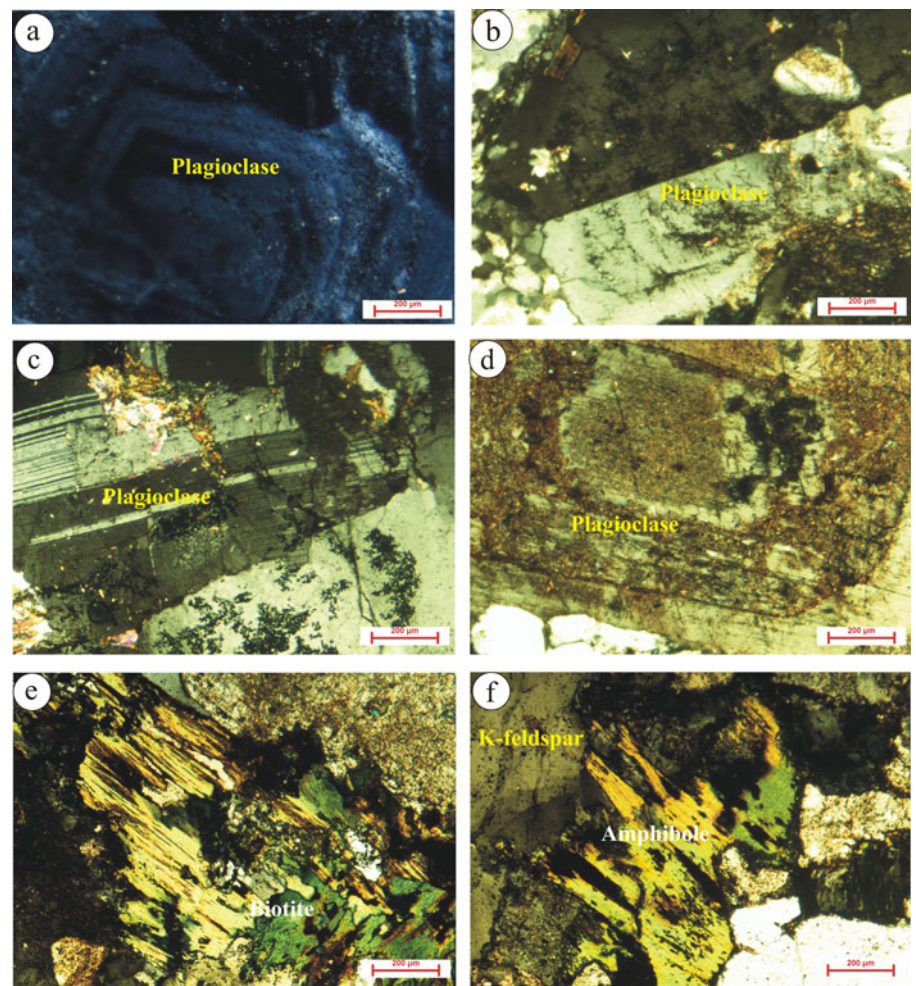


Figure 9. Petrographic features of the granitoids: (a) oscillatory zoning of plagioclase crystal in diorite; (b) carlsbad twinning of plagioclase in tonalite; (c) plagioclase crystals altered to a saussure in tonalite; (d) strong alteration of plagioclase to sericite and epidote in granodiorite; (e) coarse flakes of biotite altered to greenish chlorite in the granodiorite; (f) short prismatic crystals of amphibole in granodiorite.

granitoids (quartz syenite, syenogranites, alkali feldspar) are given in Table 1.

The older granitoids are characterized by lower contents of SiO_2 , Na_2O , K_2O , Rb, Ba, Th, U, Zr, Hf, Ta, Y, Nb and REE and higher contents of TiO_2 , Fe_2O_3 , MgO, CaO, Sc, Cr, Sr, Ni, Cu and V compared to the post-collisional granitoids (Table 1). The diorite samples are represented by low contents of SiO_2 (54.9–58.5 wt%), Na_2O (2.98–3.73 wt%), K_2O (0.43–1.31 wt%) and high concentrations of Al_2O_3 (15.8–17.18 wt%), Fe_2O_3 (7.32–8.81 wt%), MgO (3.75–4.68 wt%), CaO (5.85–7.18 wt%) and TiO_2 (0.69–1.14 wt%) when compared with the other older granitoid samples. The tonalite samples are characterized by comparably high SiO_2 (62.2–65.2 wt%), Na_2O (3.8–4.12 wt%) and K_2O (1.54–1.91 wt%), while the granodiorites are enriched in SiO_2 (66.3–70 wt%), Al_2O_3 (15.2–16.4 wt%), Na_2O (3.22–3.41 wt%) and K_2O (2.16–2.88 wt%).

Quartz syenite of the post-collisional granitoids is distinguished by its deviating contents of Al_2O_3 (14.88–16.51%), Fe_2O_3 (2.71–3.82 wt%), CaO (0.74–1.27 wt%), Na_2O (5.18–5.78 wt%), K_2O (4.14–5.64 wt%), Ba (241.91–632.88 wt%), Sr (56–107.95 wt%), Zr (2.71–3.82 wt%), and REE when compared with syenogranites and alkali feldspar granites.

The post-collisional granitoids are significantly enriched in total REE (ΣREE) compared with the older granitoids (e.g., La: 4.5 vs 153.18 ppm; Ce: 11 vs 313 ppm). Both suites are LREE enriched, but the post-collisional suite shows a much more pronounced enrichment. The trace elements and REEs of the investigated granitoid rocks (Table 1) were normalized to Mid Oceanic Ridge

Basalt (MORB), chondrite and primitive mantle values after Pearce (1983) and Sun and McDonough (1989).

4.c.1. Harker variation diagrams

Harker diagrams provide evidence for magmatic differentiation trends for both groups marked by increases in SiO_2 and K_2O associated with decreases in TiO_2 , Fe_2O_3 , MgO and CaO. K_2O is lower in the older granitoids (<2.9%) when compared with the post-collisional granitoids (>4.4%).

The geochemical trends of the major oxide constituents and trace elements of the granitic rocks of Gabal Nikeiba are illustrated in Harker variation diagrams (Figures 11 and 12). Most of the samples in show almost linear trends, which differ for the two granitoid groups (Figures 11 and 12). For all samples, incompatible elements (K_2O , Rb, Th, U, Nb, Zr) display positive correlations (Figures 11a, 12a, 12c–d, 12f–g), whereas major mafic-associated elements (Al_2O_3 , TiO_2 , MnO, CaO, Fe_2O_3 , MgO, P_2O_5) and compatible trace elements (Ba, Sr, V) show negative correlations (Figures 11b, 11d–i, 12b,e,h) with SiO_2 . The difference and similarity in elemental behaviour are due to the geochemical mineral association whereas elements such as potassium and sodium exhibit a positive orientation in granites, unlike magnesium, iron and calcium, which increase in mafic rocks.

High concentrations of Rb in the post-collisional granites indicate high degrees of fractional crystallization (FC), whereas low contents of Sr indicate extensive plagioclase fractionation. Nb (95–243 ppm) and Ta show extreme enrichment in the post-

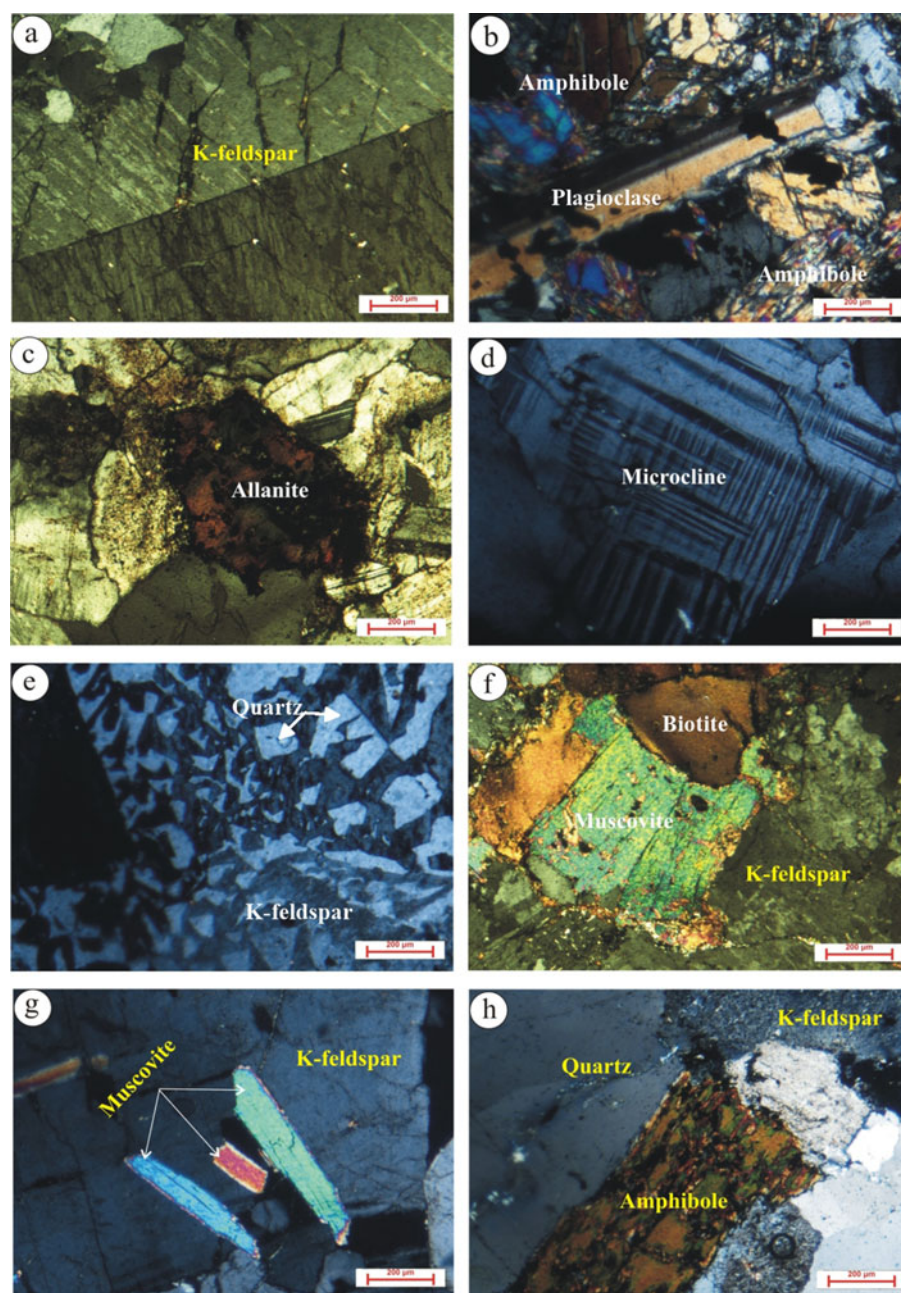


Figure 10. Petrographic features showing (a) simple twinning of K-feldspar (orthoclase) exhibiting string perthitic texture in quartz syenite; (b) subhedral prismatic crystals of amphibole next to plagioclase in quartz syenite; (c) allanite crystal associated with quartz and plagioclase in quartz syenite; (d) cross-hatched twinning of microcline in syenogranite; (e) coarse grains of graphic texture of K-feldspar and quartz in syenogranite; (f) biotite next to muscovite, which is altered to sericite along its margins in syenogranite; (g) high interference colours of muscovite flakes in alkali feldspar granite; (h) greenish brown colour of amphiboles in alkali feldspar granite.

collisional granites, which clearly distinguishes them from the older granitoid suite.

4.c.2. Geochemical classification

Using the classification diagrams of Streckeisen and Le Maitre (1979) and Bas *et al.* (1986) (Figure 13a and b), the studied samples of the older granitoid suite were identified as diorite, granodiorite and tonalite, whereas the post-collisional granitoids comprise syenite, alkali feldspar granite and syenogranite (Figures 12b and 13a). In the Q'-ANOR diagram (Streckeisen and Le Maitre 1979), these rocks plot in similar fields except for syenogranite samples, which extend towards the alkali feldspar granite field (Figure 13b).

According to the classification of Maniar and Piccoli (1989), the studied intrusive rocks range from metaluminous to peraluminous (Figure 13c). Hereby, granodiorite and alkali feldspar granite are more aluminous than the other rock types. The low Y and Ce

concentrations indicate an I-type origin for all rock sample (Figure 13). According to the magma series classification of Irvine and Baragar (1971), all of the present rocks are characterized by a calc-alkaline affinity (Figure 13e).

4.c.3. Tectonic setting

Geochemical discrimination using the Y versus Nb diagram (Pearce *et al.* 1984) reveals a clear tectonic distinction: the older granitoid suite (diorite, tonalite and granodiorite) plot in the volcanic-arc granite (syn-collision) field, whereas the post-collisional rocks (quartz syenites, syenogranites and alkali feldspar granites) classify as within-plate granites (Figure 14a).

These results are consistent with the Zr vs 10,000 Ga/Al diagram (Whalen *et al.* 1987; Figure 14b), where the older rock units plot within the S-, I-, and M-type granite fields. In contrast, the post-collisional rocks trend towards the A-type granite field. This

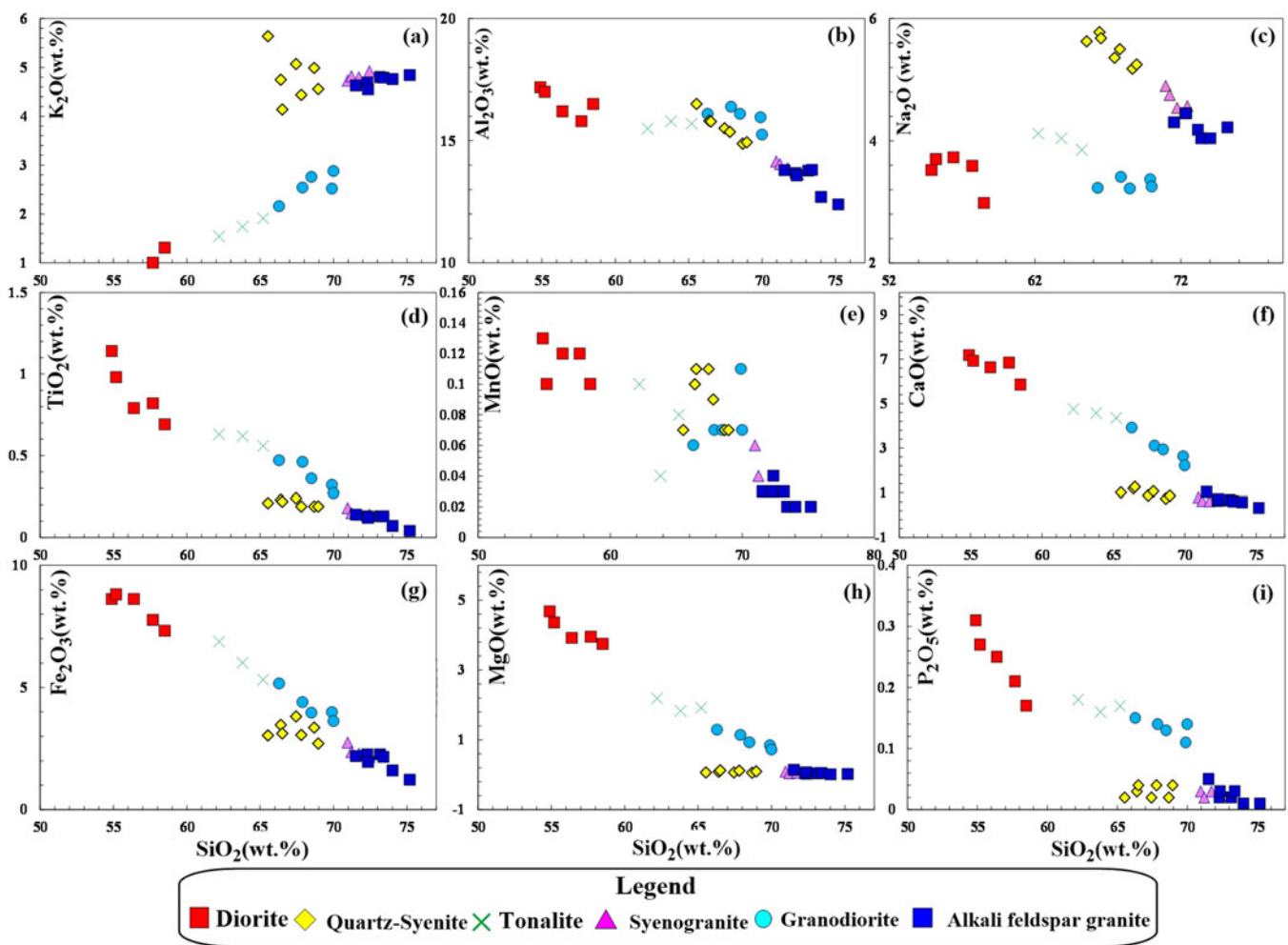


Figure 11. Harker variation diagrams illustrating trends of the major oxides against SiO₂.

A-type classification is further supported by their characteristic geochemical signature, which includes enrichment in Th, U, Zr, Hf, Rb, Ba and K, coupled with depletion in Sr, P, V and Ti (Wu *et al.* 2007).

The Nb vs SiO₂ diagram (Pearce and Gale 1977; Figure 14c) provides additional evidence for the tectonic discrimination. The older granitoid suite unequivocally plot in the orogenic (volcanic arc setting) field, thereby confirming their subduction related formation. The post-collisional granitoids reside in the anorogenic (within-plate) field. The subduction-related nature of the older granitoid suite is moreover delineated by the Nb/Zr vs Zr diagram of Pearce *et al.* (1984) (Figure 14d). The Na₂O–K₂O–CaO ternary diagram (Hassan and Hashad 1990) discriminates between different known Egyptian granitic suites. On this plot, the investigated older granitoids fall within the calc-alkaline older granites field, while the post-collisional granitoids plot within the Egyptian younger granites field (Figure 14e).

In general, the older granitoids represent a calc-alkaline series, most likely formed in a volcanic arc setting. Fractionation trend from diorite to granodiorite displays increasing SiO₂ and K₂O and decreasing MgO, CaO and Fe₂O₃. Moderate levels of compatible elements (Sr, Ba), low levels of incompatible elements (Rb, Nb, REE) and weak negative Eu anomalies are consistent with a mantle wedge source metasomatized by subducted sediments. Post-collisional granitoids (quartz syenite to alkali feldspar

granite) have signatures of A-type granites, which are associated with post-collisional extensional tectonics. The high temperatures and low water content allow for the enrichment of incompatible elements.

5. Discussion

5.a. Source and evolution of the granitic magmas

The discrimination between partial melting and FC processes can be achieved by analysing systematic variations in the ratios and concentrations of compatible versus incompatible elements (Davidson *et al.* 1987; Schiano *et al.* 2010). For the studied samples, the older phase units define trends consistent with partial melting on both La/Yb vs La and Zr/Nb vs Zr diagrams (Figure 15a, b). Conversely, the post-collisional granitoids exhibit a trend indicative of FC on the La/Yb vs La and Zr/Nb vs Zr diagrams (Figure 15a, b).

The petrogenesis of the granitic system was investigated using incompatible trace elements such as Sr and Ba. The significant depletions observed for these elements in all suites preclude an interpretation involving solely K-feldspar fractionation (El-Kammar *et al.* 2001; El-Sayed *et al.* 2003). Consequently, we conducted numerical trace element modelling following the fractionation law (Rollinson 2009) to evaluate whether the highly evolved alkali-feldspar granites could be derived from the granitic parent

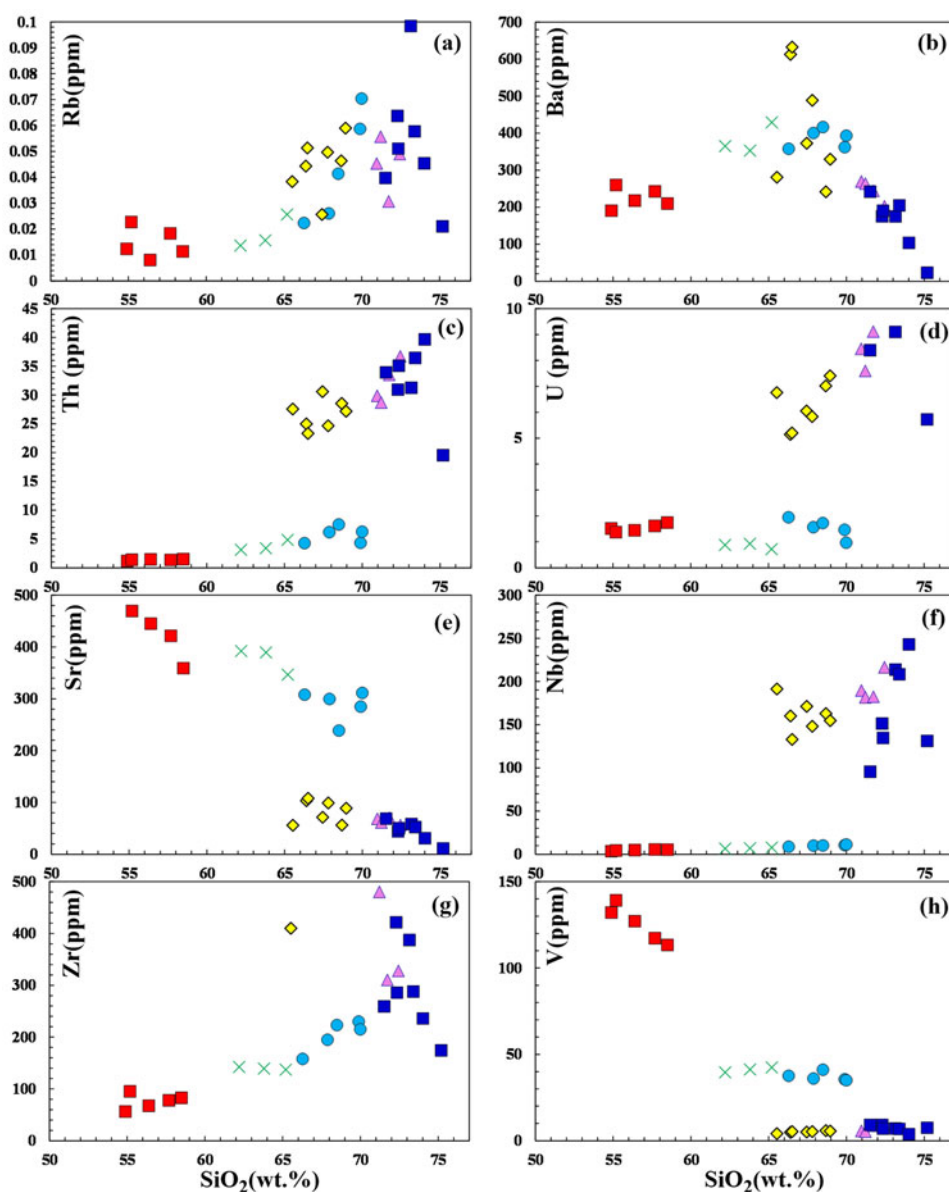


Figure 12. Harker variation diagrams illustrating trends of the trace elements against SiO_2 .

(Figure 15c). Results demonstrate that the observed geochemical signatures necessitate extensive FC, primarily involving K-feldspar and plagioclase. Based on the data shown in Figure 15, the granitic rocks originated mainly via FC or partial melting of their source.

The covariation of $(\text{La}/\text{Yb})_n$ with La is interpreted to reflect the separation of allanite and monazite during the crystallization. This process was a dominant mechanism responsible for the observed REE fractionation (Figure 15d).

According to the Ba/Rb variation diagram by Mason (1966), the older diorite, tonalite and granodiorite plot above the Ba/Rb ratio line of 4.4, reflecting significant Rb enrichment. In contrast, quartz syenite, syenogranite and alkali feldspar granites fall within the range between Ba/Rb ratios of 4.4×10^{-1} and 4.4×10^{-2} (Figure 16a). The Rb–Sr system serves primarily as a geochronological tool for determining the timing and cooling rates of geological events, including magmatic activity (Jenkin *et al.* 2001; El Bouseily and El Sokkary 1975). Condie (1973) proposed that the Rb–Sr relationship could also be used to infer the crustal depth at which granitic magmas originated. The Rb/Sr ratio acts as a proxy for magmatic

differentiation, typically increasing with higher degrees of fractionation. Based on the Rb–Sr binary diagram, all analysed intrusive rocks appear to have formed at depths ranging from approximately 20 to 30 km (Figure 16b). According to Figure 16b, the diorite samples show the strongest tendency towards Sr enrichment. The pronounced negative trend on the $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus TiO_2 diagram (Figure 16c) reflects progressive magmatic differentiation of the studied intrusive rocks (Sun and Nesbitt 1978). Altherr *et al.* (2000) introduced a binary diagram combining the molar ratios $\text{CaO}/(\text{MgO} + \text{FeO}^{\text{t}})$ and $\text{Al}_2\text{O}_3/(\text{MgO} + \text{FeO}^{\text{t}})$ to discriminate among different sources of granitic magmas. Using this diagram, the older syntectonic granitoid suite primarily plots in the partial-melt field indicative of a metabasaltic to metatonalitic source, whereas the post-collisional samples plot in fields consistent with partial melts derived from a metapelitic source (Figure 16d).

Petrogenetic models for subduction-related magmatism fall into two main categories. One view interprets these magmas as evolving from basaltic parental melts through FC or assimilation-plus-fractional-crystallization (AFC) processes (Bacon and Druiitt

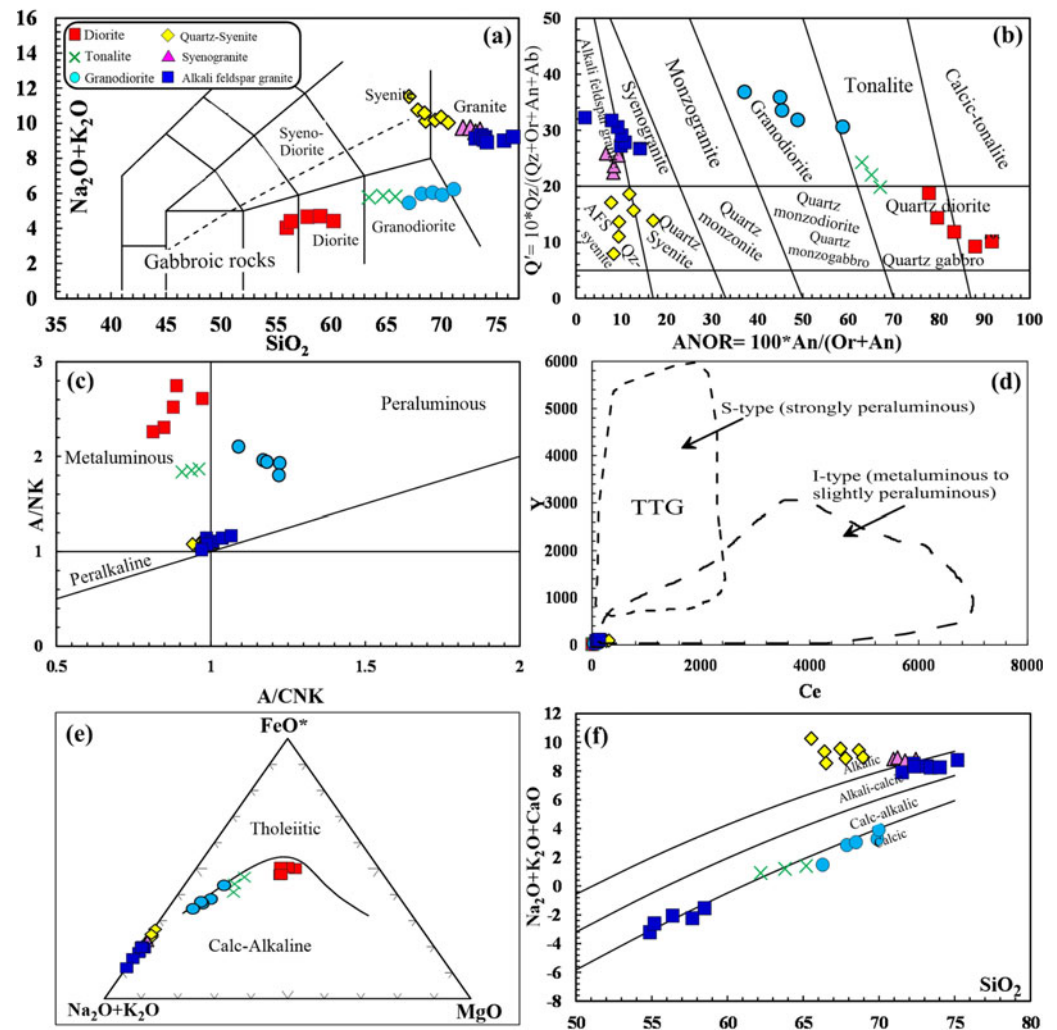


Figure 13. Geochemical classification and magmatic nature of the studied granites. (a) Total alkali vs silica diagram (TAS; Le Bas *et al.* 1986). (b) Q'-ANOR classification diagram of granitoids (Streckeisen and Le Maitre 1979). (c) ANK versus A/CNK diagram (Maniar and Piccoli 1989). (d) Ce versus Y diagram, modified after Sun *et al.* (2019). (e) AFM diagram (Irvine and Baragar 1971). (f) $(\text{Na}_2\text{O} + \text{K}_2\text{O})$ vs SiO_2 diagram (Frost *et al.* 2001).

1988). The alternative view considers them as products of lower-crust dehydration melting of mafic to intermediate meta-igneous rocks (Rapp and Watson 1995; Singh and Johannes 1996) or of metasedimentary sources (Patiño Douce and Beard 1996; Stevens *et al.* 1997). Experimental studies of dehydration melting on various crustal lithologies such as amphibolites, tonalitic gneisses, metagreywackes and metapelites under a range of conditions support the interpretation that high K felsic magmas commonly result from partial melting of crustal rocks (Altherr *et al.* 2000; Altherr and Siebel 2002). In Figure 16e, the compositions of the present rocks are broadly consistent with their derivation by partial melting of amphibolitic and metagreywacke sources.

5.b. Normalized multi-element diagrams and REE patterns

The spider normalized multi-element diagrams for the studied tonalite and granodiorite (Figure 17a) show relatively high concentrations of K, Rb, Ta and Hf, and conspicuous negative anomalies for Sr, Th, P, Rb and Ti, while the diorite samples show high values in Ba, Ta, P and low values in K, Rb, Th, Nb, Zr and Sm on continental crust-normalized spidergrams using normalization values after Pearce (1983) (Figure 17a).

Conversely, the post-collisional samples exhibit enrichment in elements such as K, Rb, Th, Ta, Zr, Hf, Sm, Y and Yb, while

showing depletion in Sr, Ba, P and Ti. This geochemical signature suggests significant crustal involvement (Harris 1983), which is indicative of intraplate granite characteristics (Pearce *et al.* 1984). Chondrite-normalized REE patterns reveal that the rocks are slightly enriched in LREEs (La, Ce, Pr, Nd, Sm) compared with heavy REEs (HREEs; Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). The REE patterns display steep negative slopes from the LREEs through the middle REEs (MREEs), transitioning to a mild positive slope that terminates at Lu (Figure 17c and d).

The enrichment of LREEs in the biotite granites is attributed to strong fractionation (El-Bahariya 2021). Quartz syenite, syenogranite and alkali feldspar granite share similar geochemical signatures, characterized by distinct negative Eu anomalies (Figure 17c and d), indicating extensive plagioclase fractionation.

5.c. Petrogenetic transition and source evolution

The geochemical transition from the older I-type to the younger A-type granitoids reflects a fundamental change in both melting conditions and source lithology. During the subduction stage, the input of aqueous fluids from the dehydrating slab lowered the solidus of the overlying mantle wedge, promoting basaltic underplating. The consequent hydrous melting of this juvenile metabasaltic-metatonalitic crust at moderate temperatures

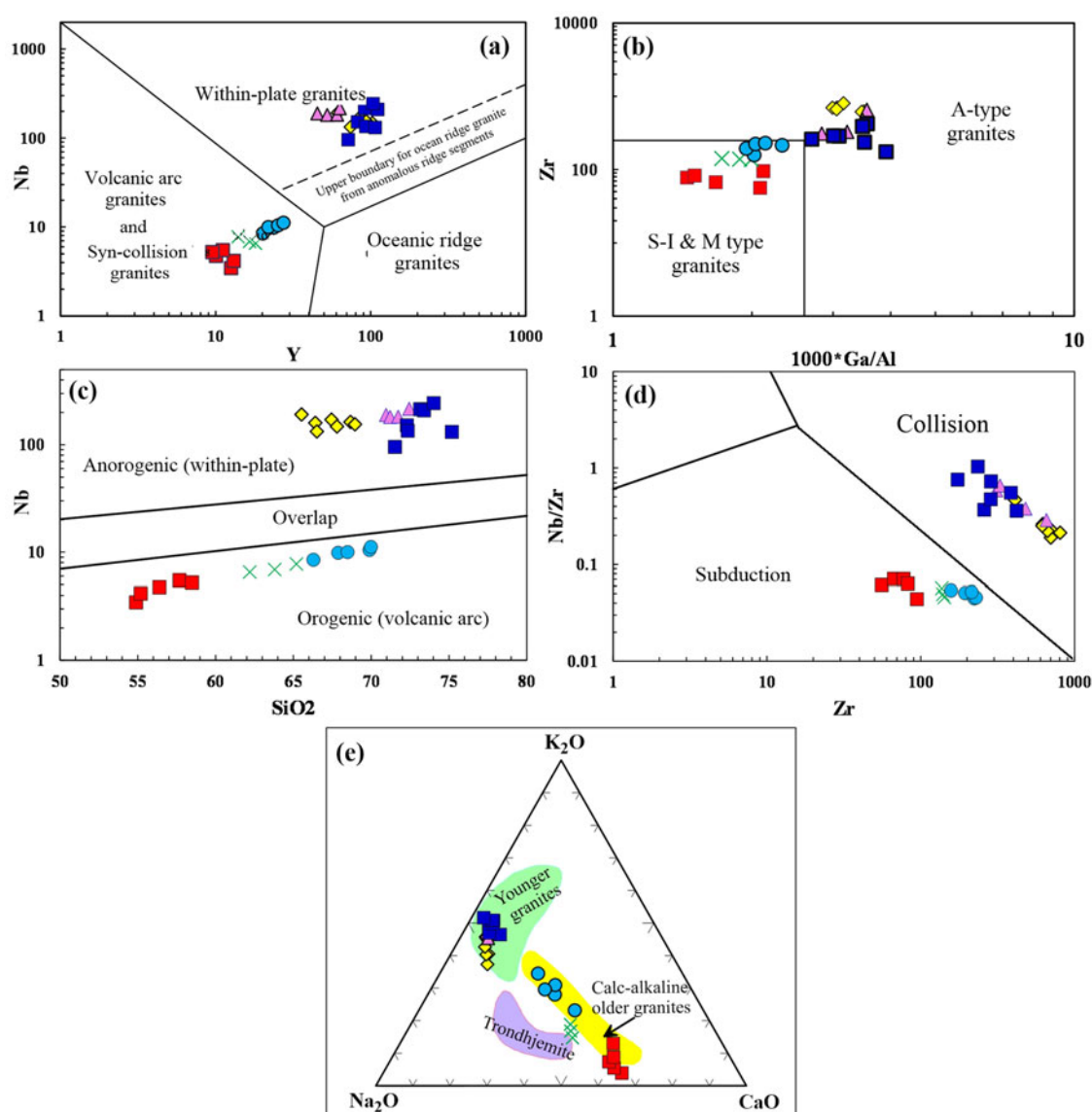


Figure 14. Tectonic setting of the investigated granitoid suites. (a) Nb versus Y diagram (Pearce *et al.* 1984). (b) $1000 \times \text{Ga} / \text{Al}$ against Zr diagram (Whalen *et al.* 1987). (c) SiO_2 vs Nb diagram (Pearce and Gale 1977). (d) Binary plot of Zr vs primitive mantle-normalized Nb/Zr (Pearce *et al.* 1984). (e) Na_2O - K_2O -CaO ternary diagram (Hassan and Hashad 1990), with fields of trondhjemites and calc-alkaline granitoids after Barker and Arth (1976).

(700–800 °C) produced magmas with elevated Sr/Y and depleted HREE, a characteristic of the older suites. In contrast, the switch to a post-collisional extensional regime induced a sharp rise in the geothermal gradient ($T > 850$ °C). Under these high-temperature, fluid-absent (dehydration) conditions, the rheologically weaker and more fertile meta-pelitic layers within the thickened orogenic root reached their solidus first. Because pelitic sources are enriched in K-feldspar and biotite and depleted in Ca-plagioclase relative to mafic sources, their partial melts are inherently enriched in K_2O , Rb and Ga, while depleted in Sr and Eu, faithfully reproducing the A-type signature observed in the younger granitoids.

The thermal and physical conditions necessary for this source shift are most plausibly supplied by lithospheric delamination or slab break-off. Following the cessation of subduction and continental collision, the dense lithospheric root or the detached oceanic slab founders into the asthenosphere. This process generates a steep thermal gradient due to upwelling of hot asthenospheric mantle. The resultant high heat flux not only promotes the

extensive dehydration melting of the overlying meta-pelitic middle crust but also drives regional-scale crustal extension. The associated pressure decrease further lowers the solidus of the quartz-feldspathic (pelitic) lithologies, facilitating the generation of large volumes of low-density, highly fractionated A-type magmas. Their subsequent rapid ascent along extensional shear zones effectively quenches their interaction with the mafic lower crust, preserving their distinct, crust-dominated geochemical fingerprint.

5.d. Geotechnical properties

Bulk density varies only slightly, ranging from 2.48 to 2.7 g/cm³ (Figure 18a). The higher water absorption observed in the granodiorite is a direct indicator of higher porosity (Figure 18b). This characteristic adversely affects the stone's durability by enhancing its susceptibility to weathering processes.

Deviations from the general trend were observed in specific samples. Granodiorite samples (NKB20) demonstrated a

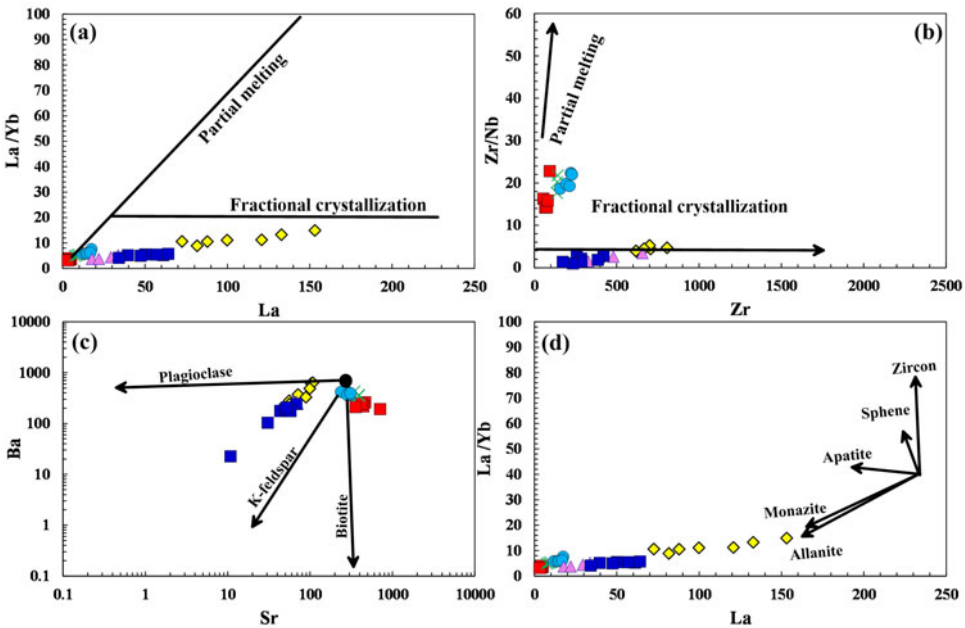


Figure 15. Trace-REE indicators of magmatic differentiation processes. (a) La/Yb vs La. (b) Zr/Nb vs Zr. (c) Ba vs Sr. (d) La/Yb vs La diagram with fractionation trends for the accessory minerals.

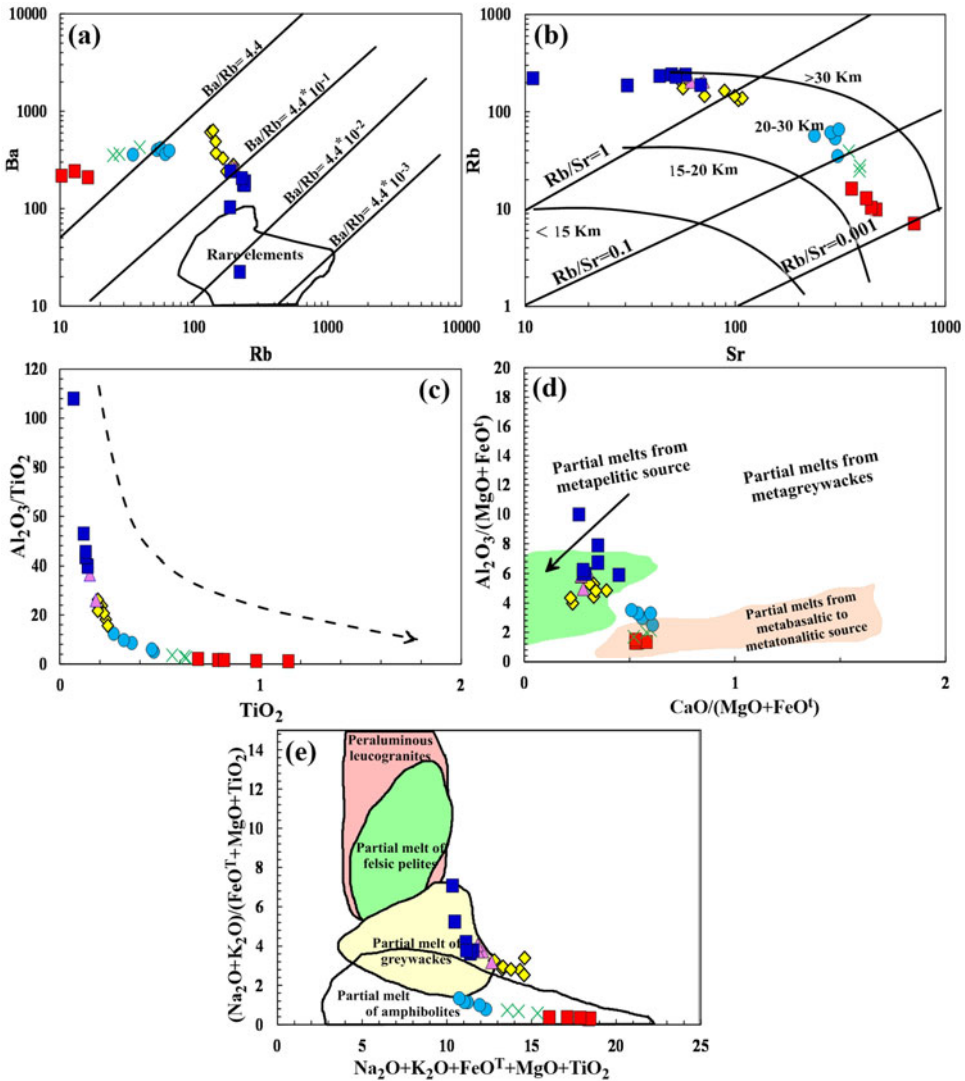


Figure 16. Petrogenesis and geotectonic discrimination diagrams of the studied rocks. (a) Ba vs Rb variation diagram after Mason (1966). (b) Sr vs Rb diagram of Condie (1973). (c) Al₂O₃/TiO₂ vs TiO₂ binary diagram after Sun and Nesbitt 1978. (d) Binary diagram showing granitic source after Altherr *et al.* 2000. (e) Na₂O + K₂O + FeO^T + MgO + TiO₂ vs (Na₂O + K₂O) / (FeO^T + MgO + TiO₂) binary diagram showing the genesis of granitic melts derived from felsic pelites, mafic pelites and greywackes (after Patiño Douce 1999).

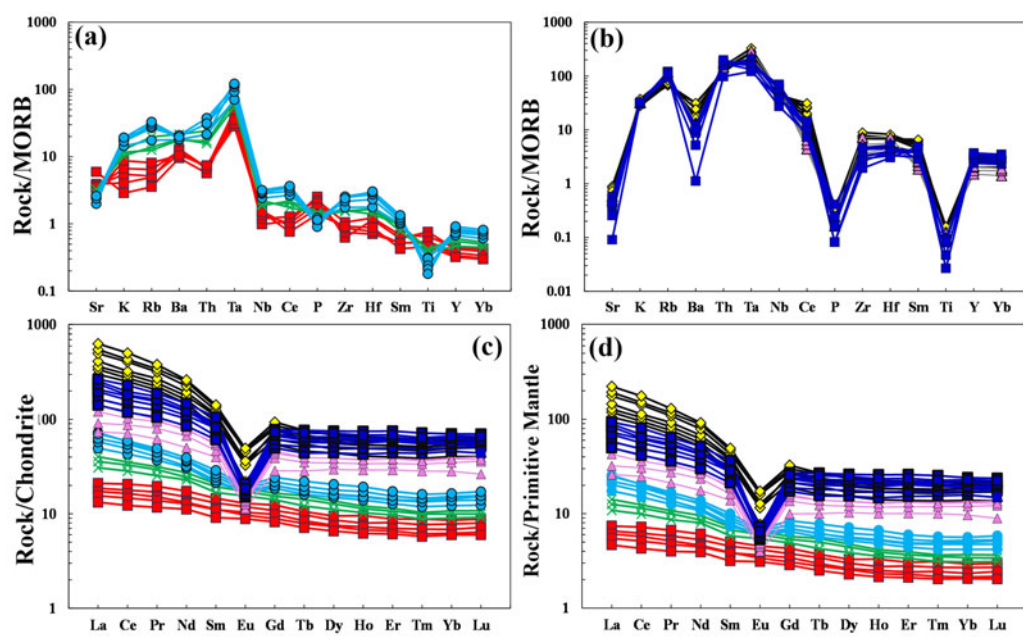


Figure 17. Trace and REE diagrams for the granitoid suites of (a) MORB-normalized spider diagrams of diorite, tonalite and granodiorite samples (Pearce 1983). (b) MORB-normalized spider diagrams for the post-collisional samples (Pearce 1983). (c) Chondrite-normalized REE patterns of (Sun and McDonough 1989). (d) Primitive-mantle-normalized REE patterns of Sun and McDonough (1989).

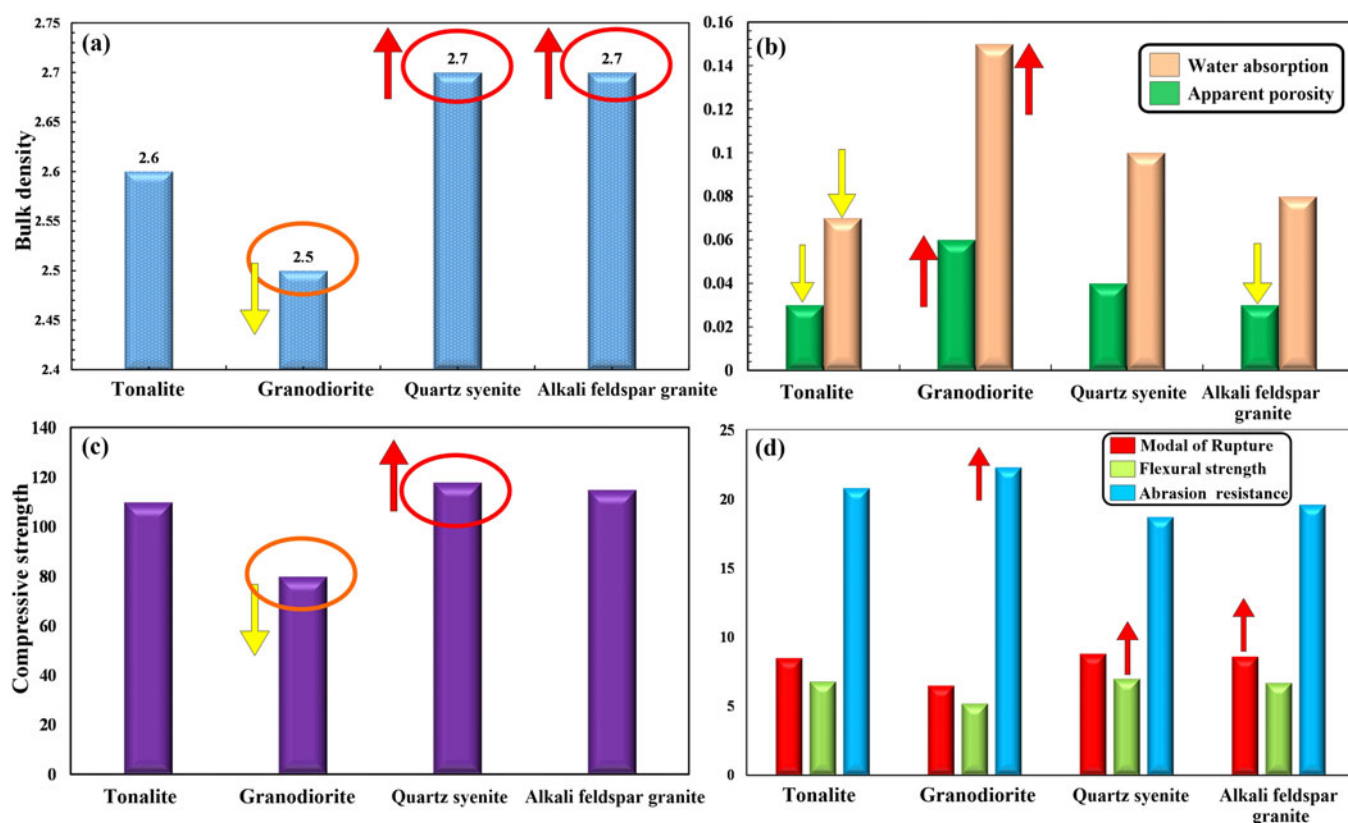


Figure 18. Histograms showing results of average (a) bulk density, (b) water absorption and apparent porosity, (c) uniaxial compressive strength and (d) modules of rupture, flexural strength and abrasion resistance.

relative decrease in bulk density, coupled with an increase in water absorption and apparent porosity. In contrast, quartz syenite (NKB25), and alkali feldspar granite (NKB30) samples were characterized by higher density and correspondingly lower absorption and porosity. It is noteworthy that all

measured physical properties for every sample fell within the acceptable range specified by ASTM C615;2011 for granite dimensional stone.

After presenting these results, it became clear that quartz syenite rock is the best rock that met the necessary criteria for dimensional

Table 2. Average of the physical and mechanical properties of the studied rocks

Rockunit	Abrasionresistance	Flexuralstrength	Modulus of rupture	Compressive strength	Apparent porosity	Water absorption	Bulk density
	(mm)	(MPa))	(MPa)	(MPa)	%	%	(g/cm ³)
Tonalite (N15)	20.8	6.8	8.5	110	0.07	0.03	2.5
Granodiorite (N20)	22.3	5.2	6.5	80	0.15	0.06	2.48
Quartz syenite (25N)	18.7	7	8.8	118	0.1	0.04	2.7
Alkali feldspar granite (30N)	19.6	6.7	8.6	115	0.08	0.03	2.7

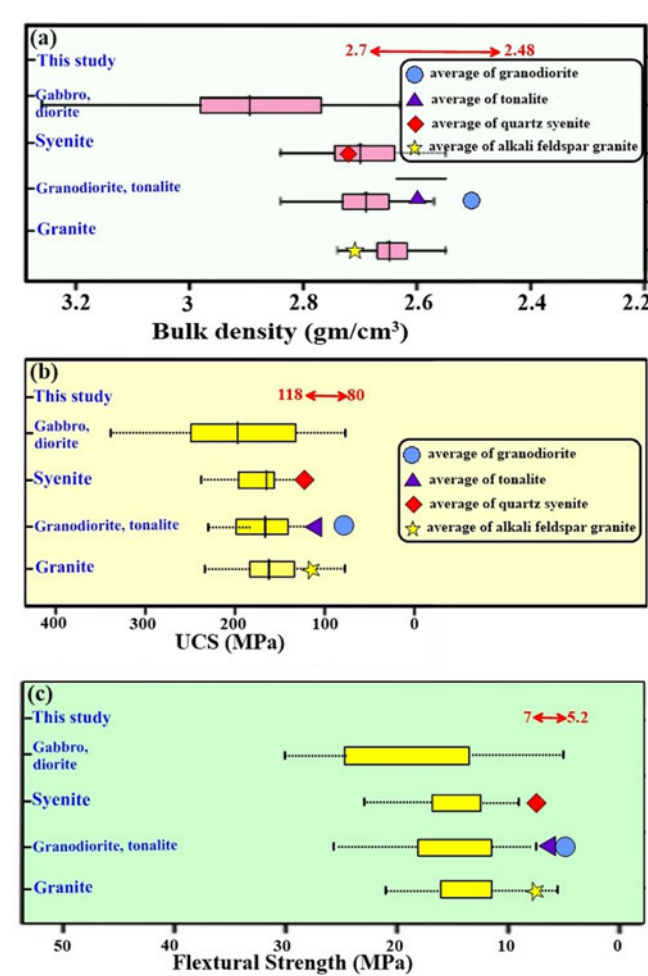


Figure 19. Boxplots average of the present results compared with global average according to Mosch (2009); (a) bulk density, (b) compressive strength, (c) flexural strength.

rocks, which were characterized by a significant increase in bulk density, compressive strength, modulus of rupture and flexural strength values with a decrease in water absorption and abrasion resistance compared with other rocks (Figure 18c and d; Table 2). The average bulk density values of quartz syenite, tonalite and alkali feldspar granite rocks are consistent with the global values according to Mosch (2009) and Mosch and Siegesmund (2007) (Figure 19a). Mosch and Siegesmund (2007) report that UCS in plutonic rocks ranges from 60 to 320 MPa. As shown in Figure 19b, the UCS values of quartz syenite, tonalite and alkali feldspar granite

typically cluster in the median quartile, exceeding 100 MPa. In contrast, the granodiorite samples fall below this threshold with a UCS of less than 100 MPa. In the Figure 19c, the flextural strength of the present samples is close to the global averages.

The primary factor behind the high UCS values is the elevated potassium feldspar (K-feldspar) content. K-feldspar is a competent' or 'strong' mineral with a high intrinsic strength and resistance to brittle fracture under load. In quartz syenite and alkali feldspar granite, K-feldspar typically forms a continuous, interlocking framework of crystals. This robust framework acts as the primary load-bearing component of the rock, effectively distributing stress and inhibiting the propagation of microcracks. Consequently, a higher proportion of this competent mineral directly translates to a greater overall resistance to compressive failure (Tugrul and Zarif 1999). It is noted that granodiorite samples are characterized by the lowest bulk density, compressive strength and flexural strength values, and this is due to their high water saturation, compared with other rocks.

The strength of a rock is not solely a function of its individual minerals but of their textural relationship. The interlocking, anhedral grains of K-feldspar in these rock types create a dense, cohesive fabric with minimal inherent planes of weakness. This contrasts with rocks containing higher proportions of sheet silicates such as micas or foliated minerals, which can act as internal planes of weakness, facilitating crack initiation and propagation under stress. The textural integrity provided by the K-feldspar network thus enhances the rock's overall cohesion and structural durability.

6. Conclusion

- This study presents an integrated assessment of the Nikeiba intrusive complex in South eastern desert, Egypt, combining PRISMA hyperspectral remote sensing with field, petrographic and geochemical investigations to elucidate its geology and evaluate its industrial potential. We conclude this work in the following lines.
- The remote sensing analysis using PRISMA hyperspectral data clearly determined the lithological mapping and structural complexity within the study area.
- Depending on the petrographical and geochemical studies, there are two distinct magmatic suits. The old phase (diorite-tonalite-granodiorite) represents a typical calc-alkaline suite formed in a collisional tectonic setting. The post collision phase (quartz-syenite-syenogranite-alkali granite) is a chemically distinct suite with A-type characteristics: high SiO₂, K₂O, Na₂O, Fe/Mg ratio and HFSEs (Nb, Ta, Zr, Y, REE).
- Chondrite-normalized REE patterns indicate that LREEs (La-Sm) are slightly enriched over HREEs (Eu-Lu). These

patterns show a steep negative slope from LREEs to MREEs), followed by a gentle positive slope towards Lu. During the FC of metaluminous granitic magmas, LREEs behave incompatibly, enriching the residual melt. In contrast, HREEs are compatible and are removed by crystallizing ferromagnesian minerals.

- The studied lithologies show consistent physical properties, with bulk density ranging from 2.48 to 2.7 g/cm³. Low water absorption and porosity values align with high density, except in granodiorite (NKB20), which exhibits higher absorption (0.06%) and porosity, reducing its durability. In contrast, quartz syenite (NKB25) and alkali feldspar granite (NKB30) show higher density and lower porosity.
- All samples meet ASTM C615:2011 standards for granite dimensional stone. Quartz syenite demonstrates superior mechanical properties with the highest compressive strength (118 MPa), modulus of rupture (8.8 MPa) and flexural strength (7 MPa) with the lowest abrasion value (18.7 mm), indicating high resistance. Granodiorite shows the weakest performance with lower strength and highest abrasion (22.3 mm). Compared with global benchmarks, quartz syenite, tonalite and alkali feldspar granite exceed 100 MPa in UCS and align with international flexural strength averages, making quartz syenite the most suitable dimensional stone.
- By definitively linking the post-collisional, A-type petrogenesis of the suite to its superior material properties, this work provides a genetic model for high-quality stone resources. Consequently, it contributes to the broader field by demonstrating a successful multidisciplinary methodology that bridges fundamental tectonic magmatism with applied remote sensing and industrial assessment, offering a reproducible framework for resource exploration in the Nubian Shield and similar arid terrains.

Data availability statement. All data have been included in the article.

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Competing interests. The authors declare no conflict of interest.

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