



Remote sensing and geochemistry of A-type granites, North Arabian-Nubian Shield: Insights into the origin and evolution of the granitic suites and processes responsible for rare metals enrichment

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ABSTRACT

The Nikeiba composite A-type magmatism of the South Eastern Desert of Egypt is subdivided into two magmatic phases, an older one including syenogranites and alkali feldspar granites, and a younger event characterized by the emplacement of quartz syenites. The older phase has nearly identical chemical composition with high silica contents ($\text{SiO}_2 = 70.7\text{--}73.6$ wt%), high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (1.0–1.33), Rb (196.66–241.36 ppm), and low Ba (60.182–279.23 ppm) compared to the younger phase ($\text{SiO}_2 = 65.7\text{--}69.5$ wt%), ($\text{K}_2\text{O}/\text{Na}_2\text{O} = 0.70\text{--}0.90$), Rb (123–172 ppm), Ba (294–717 ppm). These granitoids have elevated total alkalis (9.23–10.2 wt%), similar to alkaline ANS A-type granites characterized by higher concentrations of Zr (821 ppm), Y (135 ppm), Nb (267 ppm), Ga (22.3 ppm), and REEs (up to 639 ppm). They are considered metaluminous to slightly peraluminous post-collisional intraplate A₁-type granites, which crystallized from a mixed magma including calc-alkaline I-type tonalites-granodiorites and mantle material by fractional crystallization in the lower to middle crust after lithospheric delamination. The studied granites are rich in rare metals-bearing minerals, including zircon, fluorite, columbite, rutile, apatite, allanite, thorite, fergusonite, and bastnaesite which formed under hybrid conditions. To produce an accurate lithological map of the study area, machine learning algorithms like the Support Vector Machine (SVM) and Random Forest (RF) were applied to the Sentinel-2 data, including both the original bands and bands enhanced using Minimum Noise Fraction (MNF). The SVM applied to the MNF-Sentinel-2 dataset yielded the highest overall accuracy of 92.38 %. It shows excellent performance in the delineation of the studied granites, as verified by field investigations, petrographic, and geochemical data. Moreover, several hydrothermal alteration zones related to rare metals-bearing granitoids, such as sericitization, hematization of ferrous silicates, carbonatization, and kaolinitization, were identified from fused ASTER-Sentinel-2 data. Lineaments and spatial densities were extracted from the Sentinel-1B and ALOS PALSAR radar datasets. Based on the results of the structural analysis, the area is mainly controlled by NW-SE, N-S, and E-W trending fault sets, reflecting the pathways for rare metals enrichment. The cross-link between structural features, hydrothermal alteration zones, and higher density zones detected by combining field investigations, petrography, geochemistry, and remote sensing sheds new light on potentially mineralized zones and proposed exploration targets in the Nikeiba area and similar areas in the Arabian Nubian Shield.

1. Introduction

The Gabal Nikeiba area, located in the South Eastern Desert of Egypt, forms part of the northern segment of the Neoproterozoic (950–550 Ma;

Stern, 2002) Arabian-Nubian Shield (ANS) (Fig. 1a). This Neoproterozoic sector of the northern ANS, which encompasses the Eastern Desert of Egypt, Sinai, northwest Arabia, and Sudan, is primarily composed of ~ 50 % granitic rocks that host a variety of ore deposits (e.

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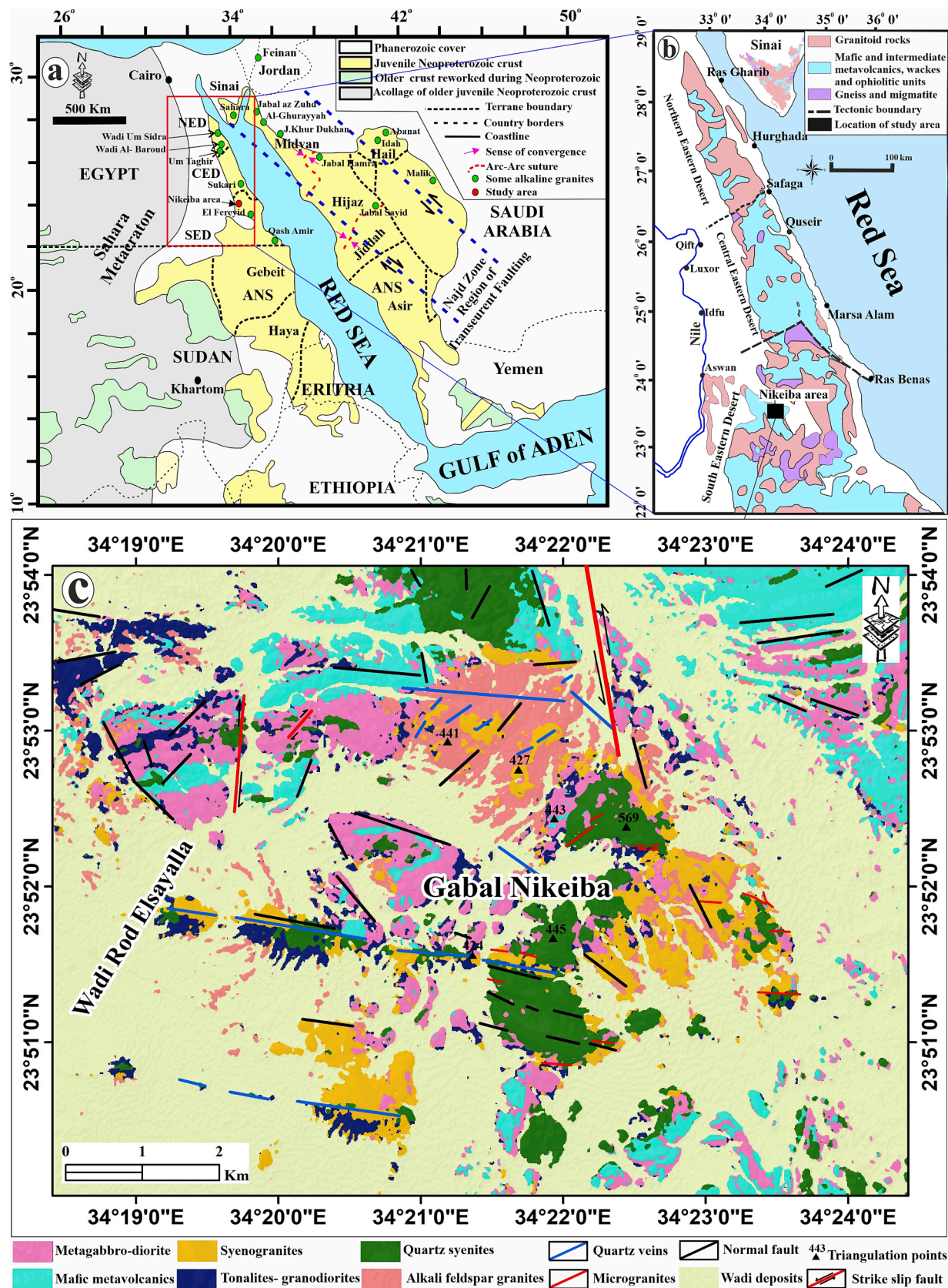


Fig. 1. (a) Location map of the Arabian Nubian Shield (ANS) showing the distribution of alkaline rare metal granites as well as the location of the Nikeiba area (modified after Johnson et al., 2011). (b) Geological map of the Eastern Desert of Egypt, including the study area (modified after Stern and Hedge, 1985). (c) Geological map of the Gabal Nikeiba area produced from integrated remote sensing (SVM-MNF-Sentinel-2), field observation, petrography, and geochemistry.

g., Hamimi et al., 2020). The ANS is composed of two post-collisional magmatic suites with significant temporal overlap. The first suite, composed of calc-alkaline rocks, was emplaced between 635 and 590 Ma, while the second suite, has an alkaline affinity, formed between 608 and 580 Ma (e.g., Eyal et al., 2010; Farahat and Azer, 2011; Azer et al., 2014; Moreno et al., 2014; Sami et al., 2017; Zoheir et al., 2020; Stern et al., 2024).

Post-collisional granites granitoids in the ANS, including those of the Nikeiba area, attract economic interest because they represent a significant source of strategic metals, such as rare earth elements (REEs), Li, F, Be, Bi, Cs, Zr, U, Th, Sn, W, Nb, and Ta (Supplementary 1) (e.g., Sami et al., 2017, 2018; Zoheir et al., 2020; Gahlan et al., 2022; Abuamarah et al., 2022; Abo Khashaba, 2022; Abdelkader et al., 2022; Khedr et al., 2022, 2023; Abo Khashaba et al., 2023; Stern et al., 2024). These elements are crucial in our life, especially the rare metals, because they are used for the manufacture of the latest high-technology equipment, as well as in the clean energy transitions, and have a high supply risk. The concentration of these metals in the granites is mainly controlled by many factors, including magma composition, temperature, pressure, degree of fractionation, and processes occurring during the magmatic-hydrothermal transition (e.g., Zoheir et al., 2020; Khedr et al., 2023; Stern et al., 2024). The emplacement of these granites is generally linked to significant fault systems, including the major NW-SE Najd fault system, along with conjugated NE-SW and E-W striking faults (e.g., Küster, 2009; Zoheir et al., 2020; Abo Khashaba et al., 2023; Khedr et al., 2023, 2024; Stern et al., 2024).

The Eastern Desert of Egypt shows great potential for mineral exploration, with abundant occurrences of mineralized granites and pegmatites, including those of the Nikeiba area (Supplementary 1). However, traditional exploration methods are limited in their ability to efficiently identify and map mineralized zones in this vast and challenging terrain (e.g., Gabr et al., 2015; Hassan et al., 2017, 2022, 2024; Abo Khashaba, 2022; Shebl et al., 2023; Khedr et al., 2022, 2023; Abo Khashaba et al., 2023). Moreover, there is still a lot of confusion about the origin, magma type, petrogenesis, and geodynamic evolution of ANS rare metal-bearing granites (e.g., Moghazi et al., 2015; Sami et al., 2017, 2018; Zoheir et al., 2020; Abuamarah et al., 2022; Khedr et al., 2023, 2024).

Remote sensing is a valuable tool for lithological discrimination and mineral exploration (e.g., Gabr et al., 2015; Hassan and Sadek, 2017; Ali-Bik and Hassan, 2022; Moghtaderi et al., 2022; Shebl et al., 2023; Khedr et al., 2022, 2023; Abo Khashaba, 2022; Abo Khashaba et al., 2023; Hassan et al., 2024). Examples of its relevance include the identification of hydrothermal alteration zones, structural lineaments, and various mineral deposits (e.g., uranium, gold, and REEs) (e.g., Gabr et al., 2015; Zimmermann et al., 2016; Salles et al., 2017; Hassan et al., 2022; Khedr et al., 2023; Abo Khashaba et al., 2023). Utilizing remote sensing for mineral exploration offers a cost-effective, time-efficient, and more successful approach for collecting data from hard-to-reach areas, such as high-elevation or rough terrains found in dry and semi-arid regions (e.g., Gabr et al., 2015; Hassan et al., 2017, 2022; Köhler et al., 2021; Abdelkader et al., 2022; Abo Khashaba et al., 2023).

Recently, advanced remote sensing techniques, such as machine learning and deep learning algorithms, have been applied to effectively delineate lithological and mineral mapping (e.g., De Boissieu et al., 2018; Sheykhoumoussa et al., 2020; Köhler et al., 2021; Costa et al., 2019; Wu et al., 2021; Santos et al., 2022; Xi et al., 2022; Abdelkader et al., 2022; Shebl et al., 2023; EL-Omairi and El Garouani, 2023; Lachaud et al., 2023; Hassan et al., 2024). These algorithms use statistical models to discern patterns and relationships within data, thereby improving efficiency and accuracy compared to traditional methods (e.g., Santos et al., 2022; Xi et al., 2022; Shebl et al., 2023; EL-Omairi and El Garouani, 2023). Algorithms like Random Forests (RF), Support Vector Machines (SVM), and Artificial Neural Networks (ANN) can be

employed in the mapping of lithological rock units, proving to be more effective, accurate, and efficient than conventional methods (e.g., Santos et al., 2022; Xi et al., 2022; Shebl et al., 2023; EL-Omairi and El Garouani, 2023).

In this work, we aim to shed light on the role of remote sensing in delineating different alteration zones associated with rare metal mineralizations in the Nikeiba area. In addition, radar data such as Sentinel-1 and ALOS PALSAR were applied to detect structural features, while machine learning algorithms were used to automatically identify the widely exposed lithological rock units. The main objective of this work is to investigate the geology, petrography, geochemistry, and mineralogy of the rare metals-bearing granites in the Nikeiba area, aiming to understand their magma types, tectonic settings, petrogenesis, and geodynamic evolution, as well as the origin of the rare metal mineralization. The cross-links of these datasets were proposed to help in detecting new exploration targets of rare metal mineralization in the northern Arabian Nubian Shield (e.g., the Nikeiba area).

2. Geological setting and field relations

The Nikeiba area is located in the South Eastern Desert of Egypt ~ 74 km south of the El-Sheikh Shadli area and ~ 120 km west of the Red Sea coast (Fig. 1). It lies between latitudes 23° 50' 03" N to 23° 54' 02" N and longitudes 34° 18' 26" E to 34° 24' 22" E (Fig. 1b, c). Based on different remote sensing techniques, such as decorrelation stretch (b12, b8, and b3 as RGB; Supplementary 1) of Sentinel-2B, machine learning algorithms like SVM and RFs (section 4.1), field investigation, petrography, and geochemistry, a detailed and accurate geological map of the Nikeiba area was constructed (Fig. 1c). The lithological rock units in the area are composed of mafic metavolcanics, metagabbro-diorite complex, tonalites-granodiorites, syenogranites, alkali feldspar granites, and quartz syenites crosscut by microgranites, quartz veins and small pegmatite veins (Fig. 1c). Structurally, the study area is cross-cut by numerous fault systems in different directions, such as NW-SE, N-S, and E-W (Fig. 1c).

The mafic metavolcanics occur as dark brown rocks and have sharp intrusive contacts with the metagabbro-diorite complex rocks (Fig. 1b, c). They were intruded by the syenogranites, alkali feldspar granites, and quartz syenites (Fig. 1c). Occasionally, the metagabbro-diorite complex hosts xenoliths of mafic metavolcanics along their contacts (Fig. 2a). Tonalites-granodiorites represent the old granitic rock unit in the area (Fig. 1c). In the northwestern part of the mapped area, they are exposed as gray colored, low-relief, isolated bodies and outcrops of variable aerial expansion (Fig. 1c).

Syenogranites are moderate to high relief terrains, up to 230 m in height, and cover an area of c. 5.257 km² (Fig. 1c). They are medium- to coarse-grained, whitish to pale pink, buff, or reddish brown in color (Fig. 2b, c). Syenogranites form sharp intrusive contacts with mafic metavolcanics, metagabbro-diorite complex rocks, and quartz syenites and show gradational contacts with alkali feldspar granites (Fig. 1c, 2b). They are crosscut by radioactive quartz veins at their periphery (Fig. 2c). Beryl was found in syenogranites as veins reaching c. 3 m in length and c. 0.5 m in width (Fig. 2d). Alkali feldspar granites are medium to coarse-grained, reddish to pink, and cover an area of c. 5.944 km² (Fig. 1c, 2b). They are moderate to high relief plutons, up to 300 m in height (Fig. 1c, 2b-d). Alkali feldspar granites have a markedly sharp intrusive contact with mafic metavolcanics and quartz syenites (Fig. 1c). Syenogranites and alkali feldspar granites are characterized by exfoliation structures (Fig. 2c). Quartz syenites have high relief trains, up to 350 m in height (Fig. 1c, 2e-g). They are medium to coarse-grained, vary in color from pale pink to dark grey, and cover an area of c. 8.961 km² (Fig. 1c, 2e-g). They are crosscut by numerous microgranite dykes in variable directions that reach c. 0.5 m in width and ~ 400 m in length and variable quartz veins (Fig. 1c, 2f). Pegmatites are represented by coarse-grained veins

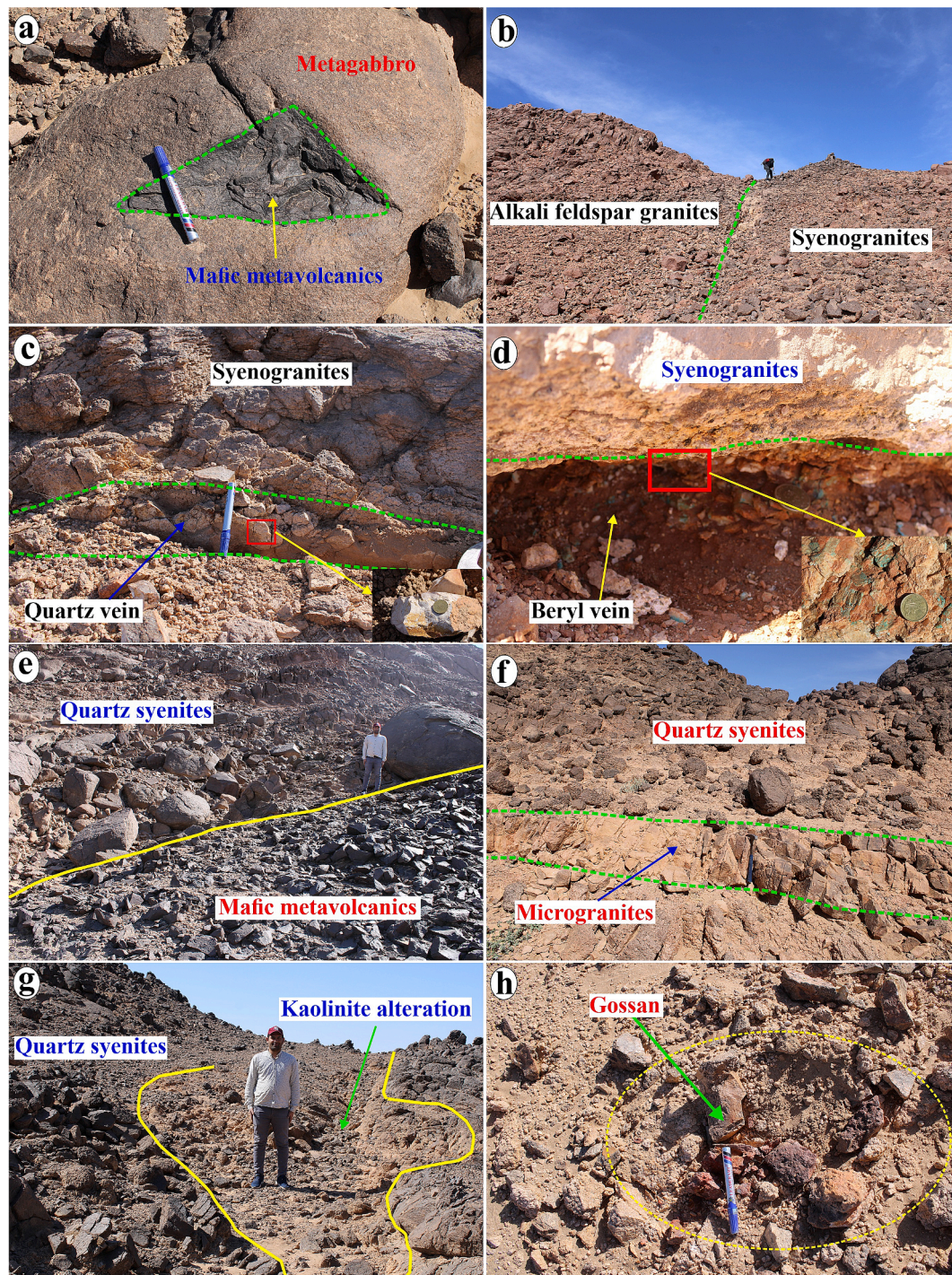


Fig. 2. Field observation of the Nikeiba area (a) Close-up view of the metavolcanics xenolith in metagabbro (b) Gradational contact between syenogranites and alkali feldspar granites (c) Radioactive quartz vein cut syenogranites (d) Beryl vein cut syenogranites (e) Sharp intrusive contact between metavolcanics and quartz syenites (f) Microgranite dyke cut quartz syenites (g) Large kaolinite alteration in quartz syenites (h) Close-up view of gossan alteration.

with pink color cutting the syenogranites and alkali feldspar granites.

The studied area is affected by several events of hydrothermal alteration, such as silicification, argillization, sericitization, kaolinitization, and gossan alteration (Fig. 2). Argillic alteration is mainly associated with quartz syenites, having c. 25 m length and c. 3 m width (Fig. 2g). Gossan zone was observed both in the northern part of quartz syenites and in the southern part of syenogranites (Fig. 2h). Hydrothermal alterations are possibly fault-related, being concentrated mainly in the NW-SE Najd fault system and conjugated E-W and NE-SW directions.

3. Materials and methods

3.1. Remotely sensed data

The Copernicus Sentinel-2 satellite platform is equipped with a Multi-Spectral Instrument (MSI) that captures imagery of the Earth's surface across a broad spectral range. The MSI sensor operates in the Visible Near Infrared (VNIR), as well as the Short Wave Infrared (SWIR) regions, covering the electromagnetic spectrum from 0.443 μm to 2.190 μm (Supplementary 2). The cloud-free Sentinel-2 imagery utilized in this

study was accessed through the European Space Agency's (ESA) Open Access Hub (accessed on 10 August 2023). The data was then atmospherically corrected using the Sentinel Application Platform (SNAP) software, followed by layer stacking, subsetting, and further processing conducted in the ENVI 5.6 software environment. Due to its higher spatial resolution (10 m), machine learning algorithms such as SVM and RF were used for better lithological discrimination of different rock units in the study area.

In this work, ASTER data (AST_L1B_00304142004083033) was acquired on 14 April 2004. The ASTER properties are described in [Supplementary 2](#). The ASTER Short Wave Infrared (SWIR) channels provide a significant improvement in the spectral characterisation of minerals and rock units of the Earth's surface (Rowan and Mars, 2003; Volesky et al., 2003; Hassan and Sadek, 2017; Abo Khashaba et al., 2023). ASTER data has been enhanced to 10 m using data fusion (Gram-Schmidt) with Sentinel-2B. The ASTER (VNIR) bands were fused with the corresponding VNIR bands of Sentinel-2B, while the ASTER (SWIR) data were combined with the SWIR bands of Sentinel-2B. This integrated dataset, comprising nine spectral bands of the electromagnetic spectrum, was employed to detect mineralized alteration zones potentially associated with rare metal occurrences in the Nikeiba area. Seven mineral indices were applied to the fused multispectral data to facilitate the identification and mapping of these altered zones.

This study utilizes Sentinel-1B and ALOS PALSAR radar datasets to map structural features in order to determine their role in rare metal distribution. Sentinel-1B data with Id (S1B_IW_GRDH_1SDV_20211220T154614_20211220T154639_030111_03986C_253A) was acquired on 20 December 2021, and the ALOS PALSAR data (ALPSRP133730460) on 28 July 2008. The two types of radar datasets were obtained from ASF Data Search Vertex <https://search.asf.alaska.edu/>. The widely used LINE module of Geomatica-PCI software was applied to perform automatic detection of lineament predominant directions in the Nikeiba area using a single cross-polarization (HV) of Sentinel-1 and ALOS-PALSAR datasets. Additionally, the rose diagrams were performed using the ROCKWOR software version 2018.

The portable TerraSpec Halo Mineral Identifier Spectrometer Device (ASD) was used for identifying the spectra of rock-forming minerals in rare metal-bearing granitic samples. For this study, twenty-two rock samples of different rock units in the Nikeiba area have been measured by the ASD device ([Supplementary 3](#)).

3.2. Fieldwork and petrography

In this study, a sampling of seventy-five rock samples from the different granitic varieties, country rocks, alteration zones, dykes, quartz, and beryl veins have been collected for laboratory work. Based on pre-field remote sensing studies, these samples were selected to represent different lithological units in the area. About fifty thin sections are prepared from the collected specimens as part of the petrographic investigation in order to describe the various hydrothermal alterations, textures, and mineral assemblages, as well as to identify ore minerals. The petrographic investigation was done at the Mineralogy and Petrology Department, Institute of Applied Geosciences, Karlsruhe Institute of Technology, Germany, and the Geology Department, Kafrelsheikh University, Egypt, using a polarizing microscope. We performed an SEM/EDS analysis using a TESCAN VEGA II scanning electron microscope in conjunction with an EDX INCA X-act from Oxford Instruments at the Karlsruhe Institute of Technology, Department of Mineralogy and Petrology, Germany ([Supplementary 4](#)).

3.3. Geochemistry

3.3.1. Mineral chemistry

The mineral chemical compositions of feldspars, biotites, amphiboles, chlorite, pyroxenes, zircon, apatite, and columbite in the syenogranites, alkali feldspar granites, and quartz syenites from the Nikeiba

area were determined through detailed electron microprobe analysis (EMPA) conducted at the Department of Earth Sciences, University of Western Ontario, Canada. A JEOL JXA-8530F field-emission electron microprobe was used for the analyses. Operating conditions were 20 kV probe current, 40–60 nA accelerating voltage, 1–2 μ m 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. Pure metal standards (serial 2AG-METM25-44, Astimex Standards Limited) were used for Mn, Th, Mn, Nb, Ta, Hf, Pb, Th, and U.

The chemical composition of the essential rock-forming minerals in the syenogranites, alkali feldspar granites, and quartz syenites of the Nikeiba area was determined through detailed EPMA analysis. Representative mineral crystals were selected for the analyses, which were conducted to provide insights into the tectono-magmatic affiliation of the studied rock units. [Tables 3–6](#) show the results of the representative microprobe analyses for the main mineral phases found in the Nikeiba area, and the full datasets of the mineral analyses are provided in [Supplementary 5](#).

3.3.2. Whole-rock chemistry

Based on the petrographic study, twenty-two representative samples of the Nikeiba area were selected for whole-rock major, trace, and REEs analyses. The powder was obtained by crushing them in an agate ball mill and then grinding them. We determined the concentrations of major and trace elements using an X-ray fluorescence spectrometer (ThermoARL XRF Spectrometer). An analysis surface was prepared by grinding, refusing, and polishing powdered samples on diamond laps after mixing in Di-lithium tetraborate flux (2:1 flux: rock) and fusing at 1000 °C in a muffle furnace. Calibration was performed using reference material 650 CC from GSP2. In most cases, XRF analyses have an analytical precision of better than 1 % for major elements and better than 5 % for trace elements (except for Ni, Cr, Sc, and V). After firing at 1000 °C, the weight difference is used to determine losses on ignition (LOI). In this study, the concentrations of REEs and trace elements were determined by ICP mass spectrometry (Agilent 7700 ICPMS). For each sample, 50 mg powder was dissolved in Teflon containers that had been washed in hot (250 °C) 3:1 nitric and hydrofluoric acid for at least eight hours. Blank fused beads and USGS standards AGV-2 and RGM2 were used to develop sensitivity curves for the detector. Quality control was performed using additional USGS standards, including DTS-2, BCR-1, and G-2. These analyses were performed at the GeoAnalytical Laboratory at Washington University, USA. The whole-rock geochemistry analyses for the Nikeiba rock units are presented in [Table 7](#) and [Supplementary 6](#).

This study was based on an integrated methodology of remote sensing techniques, field investigations, petrography, and geochemistry, as shown in [Fig. 3](#).

4. Remote sensing methods

4.1. Automatic lithological mapping based on machine learning algorithms

Machine learning algorithms have recently been used to identify and classify different rock types in a specific area. In the current study, object-based classification using a radial basis function (RBF) of support vector machine (SVM) and random forest (RF) algorithms has been applied to the Sentinel-2 dataset ([Fig. 4a](#)) for automatic lithological identification of the Nikeiba area. A 300 training sets were used to learn two types of Artificial Intelligence (AI) machine learning (SVM and RF) based on field observations of ground truth ASD spectral signatures of seven different classes ([Table 1](#); [Supplementary 3-1](#)). Additionally, semantic segmentation of the Sentinel-2 data (b12, b8, b3) was used to identify the label of each class ([Fig. 4b](#)). In order to enhance the accuracy of the lithological detections using both SVM and RF, the Minimum

Table 1

Confusion matrices, overall and class-based statistics for SVM and RFs based on MNF of Sentinel-2 data.

SVM	QS	AFG	SG	WD	MV	GD	Mgb	Sum	Precision%	Recall%	F1-score%
QS	2627	0	0	0	13	1	12	2653	99.02	99.39	99.21
AFG	0	1570	112	33	0	11	0	1726	90.96	81.18	85.79
SG	0	163	2178	0	0	73	7	2421	89.96	91.4	90.67
WD	0	182	0	6880	0	0	0	7062	97.42	99.48	98.44
MV	11	6	2	0	5011	15	252	5297	94.60	96.13	95.36
GD	0	8	82	3	16	1316	187	1612	81.64	74.35	77.82
Mgb	5	5	9	0	173	354	1447	1993	72.60	75.96	74.24
Sum	2643	1934	2383	6916	5213	1770	1905	22,764	OA = 92.38		
Overall Accuracy%									92.38		
Kappa Accuracy%									90.57		
Mean F1 Accuracy%									88.79		
RFs	QS	AFG	SG	WD	MV	GD	Mgb	Sum	Precision%	Recall%	F1-score%
QS	2603	0	0	0	22	0	28	2653	98.12	97.34	97.73
AFG	0	1542	153	23	0	8	0	1726	89.34	71.49	79.42
SG	0	270	2066	2	1	70	12	2421	85.34	88.67	86.97
WD	0	323	2	6238	499	0	0	7062	88.33	99.41	93.54
MV	10	6	6	0	4938	18	319	5297	93.22	87.37	90.2
GD	0	12	91	11	25	1291	182	1612	80.09	78.67	79.37
Mgb	61	4	12	1	167	254	1494	1993	74.96	73.42	74.18
Sum	2674	2157	2330	6275	5652	1641	2035	22,764	OA = 88.61		
Overall Accuracy%									88.61		
Kappa Accuracy%									85.98		
Mean F1 Accuracy%									85.92		

Table 2

Minerals detection of the exposed rock units in the Nikeiba area using TerraSpec Halo portable Mineral Identifier Device (ASD).

Sample	Rock name	Minerals detected	Wavelength of absorption features
NKB1	Syenogranites	Ferrihydrite, Chabazite, Gypsum, Kaolinite, Hematite	2211.22, "1.248", "889.892", "1.004"
NKB1		Hematite, Chabazite, Gypsum, Phengite, Kaolinite	,"2211.11", "1.246", "889.439", "0.287", "1.004"
NKB2		Riebeckite, Palygorskite	,"2347.43", "2210.12", "2307.5", "2347.43"
NKB2		Riebeckite, Palygorskite, Iron	,"2347.35", "2212.96", "2347.35"
NKB4		Phillipsite-Ca, Tourmaline	,"2210.93", "2210.93", "2295.99"
NKB16		Goethite, Chabazite, Gypsum, Aragonite, Hematite	1.185, "997.273"
NKB13		Chabazite, Kaolinite	2210.33, "0.999"
NKB14		Chabazite, Kaolinite	,"2211.38", "0.998"
NKB14		Hematite, Chabazite, Kaolinite	2211.57, "1.374", "934.972", "0.999"
NKB17		Kaolinite, Palygorskite, Muscovite	2211.13, "2211.13", "0.823", "1.006", "2385.01"
NKB17		Kaolinite, Palygorskite, Phengite	,"2210.95", "2210.95", "0.794", "1.007", "2386.95"
NKB18		Hematite, Montmorillonite, Dickite, Goethite	2211.16, "1.819", "896.974"
NKB18		Montmorillonite	2211.36
NKB19		Goethite, Montmorillonite, Hematite	2211.06, "1.695", "892.362"
NKB19		Goethite, Montmorillonite, Hematite	2210.73, "1.719", "893.866"
NKB20		Chabazite, Muscovite, Kaolinite	2209.45, "2209.45, 0.412, 1.004, 2357.68"
NKB20		Chabazite, Phengite, Fe-Chlorite	2209.7, 0.533
NKB21		Ferrihydrite, Chabazite, Phengite, Fe-Chlorite, Hematite	2208.92, "1.282", "975.111", "0.192"
NKB21		Chabazite, Tourmaline, Phengite	,"2207.69", "2207.69", "2258.76", "0.196"
NKB23	Quartz syenites	Ferrihydrite, Heulandite, Kaolinite, Muscovite, Gypsum, Hematite	2210.64, "2210.64", "1.525", "908.326", "0.457", "1.006", "2387.8"
NKB23		Goethite, Montmorillonite, Kaolinite, Hematite	2210.74, "1.61", "908.172", "1.009"
NKB5		Hematite, Chabazite	1.587, "916.202"
NKB5		Hematite, Laumontite	1.365, "932.426"
NKB6		Ferrihydrite, Chabazite, Gypsum, Strontianite, Hematite	1.172, "996.155"
NKB7		Hematite, Phillipsite-Ca, Tourmaline, Hornblende, Aragonite	2210.89, "2210.89", "1.258", "931.913", "2240.6"
NKB7		Hematite, Chabazite	1.282, "909.464"
NKB9		Ferrihydrite, Chabazite, Tourmaline, Hematite	2210.58, "2210.58", "1.165", "981.593", "2256.1"
NKB9		Ferrihydrite, Chabazite, Phengite, Hematite	2209.97, "1.233", "959.314", "0.383"
NKB10		Hematite, Chabazite, Gypsum, Smithsonite	1.322, "911.366"
NKB10		Hematite, Chabazite, Gypsum, Tourmaline	2209.04, "2209.04", "1.266", "943.255", "2256.89"
NKB11		Laumontite, Gypsum, Vermiculite	,"2215.52", "2337.49"
NKB11		Laumontite, Vermiculite, Gypsum	,"2205.8", "2336.82"
NKB12		Hematite, Phillipsite-Ca, Tourmaline	2210.56, "2210.56", "1.279", "932.031"
NKB12		Hematite, Phillipsite-Ca, Tourmaline, Dolomite, Coquimbite	2209.91, "2209.91", "1.326", "908.332", "2253.87"
NKB15		Hematite, Chabazite	1.287, "997.097"

Noise Fraction (MNF) transformation algorithm of the Sentinel-2 dataset was used instead of the original Sentinel-2 data (Table 1; Supplementary 3-1). The input datasets were split into 80 % for the training process and 20 % for the testing process in order to train the machine learning automatic lithological model as well as to calculate the accuracy assessment for each lithological unit class. Consequently, the SVM and RF algorithms were fed training areas for seven different lithological

classes in the Nikeiba area. For the Sentinel-2 dataset, a total of 22,764 pixels, representing the seven lithological units, were selected (Table 1; Supplementary 3-1). Accuracies were evaluated using the confusion matrix, precision, recall, F1-score, overall accuracy (OA), and kappa accuracy (Table 1; Supplementary 3-1).

Table 3

Representative EPMA analysis of feldspar in the Nikeiba granites, South Eastern Desert, Egypt.

Rock name	Syenogranites						Alkali feldspar granites						Quartz syenites			
Sample No.	NBK4		NBK4		NBK4		NBK22		NBK22		NBK22		NBK5		NBK5	
Mineral	K-feldspar		Albite		Plagioclase		K-feldspar		Albite		Plagioclase		K-feldspar		Albite	
Spot#	Kfs1	Kfs2	Abt1	Abt2	Plag1	Plag2	Kfs1	Kfs2	Abt1	Abt3	Plag1	Plag2	Kfs1	Kfs2	Abt1	Abt2
SiO ₂	64.61	64.58	67.07	67.59	62.99	57.78	64.86	64.32	68.18	68.20	63.16	62.81	64.45	64.37	68.20	68.32
TiO ₂	0.00	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.03	0.01	0.02	0.01	0.00	0.01
Al ₂ O ₃	18.11	17.88	20.14	18.69	22.79	26.42	17.76	18.10	18.95	19.44	22.62	22.86	18.07	17.78	19.26	19.01
Cr ₂ O ₃	0.02	0.01	0.00	0.02	0.20	0.02	0.02	0.01	0.00	0.01	0.19	0.05	0.02	0.00	0.02	0.01
FeO _t	0.23	0.24	0.10	0.43	0.14	0.36	0.35	0.45	0.50	0.24	0.23	0.09	0.19	0.34	0.48	0.20
MnO	0.02	0.00	0.00	0.00	0.00	0.02	0.04	0.00	0.00	0.02	0.01	0.01	0.00	0.02	0.00	0.00
MgO	0.00	0.01	0.00	0.00	0.01	0.04	0.05	0.02	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.01
CaO	0.02	0.02	0.84	0.02	4.39	9.34	0.03	0.02	0.01	0.21	4.17	4.47	0.01	0.02	0.02	0.13
Na ₂ O	0.25	0.32	11.54	11.64	9.09	5.95	0.29	0.37	11.86	11.90	9.21	9.05	0.32	0.30	11.75	11.55
K ₂ O	16.31	15.97	0.10	0.08	0.25	0.55	16.04	15.95	0.07	0.12	0.28	0.24	16.25	15.97	0.08	0.18
P ₂ O ₅	0.00	0.01	0.02	0.03	0.02	0.03	0.00	0.05	0.00	0.00	0.02	0.01	0.00	0.00	0.02	0.00
Total	99.56	99.05	99.82	98.50	99.88	100.53	99.45	99.32	99.59	100.16	99.94	99.61	99.33	98.81	99.82	99.43
Si	12.01	12.05	11.79	12.02	11.18	10.34	12.06	11.99	12.00	11.93	11.20	11.17	12.01	12.04	11.97	12.02
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	3.97	3.93	4.17	3.92	4.77	5.57	3.89	3.98	3.93	4.01	4.73	4.79	3.97	3.92	3.98	3.94
Cr	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00
Fe	0.04	0.04	0.01	0.06	0.02	0.05	0.05	0.07	0.07	0.04	0.03	0.01	0.03	0.05	0.07	0.03
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Ca	0.00	0.00	0.16	0.00	0.83	1.79	0.01	0.00	0.00	0.04	0.79	0.85	0.00	0.00	0.00	0.02
Na	0.09	0.12	3.93	4.01	3.13	2.06	0.10	0.13	4.05	4.04	3.17	3.12	0.12	0.11	4.00	3.94
K	3.87	3.80	0.02	0.02	0.06	0.13	3.80	3.79	0.02	0.03	0.06	0.05	3.86	3.81	0.02	0.04
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	19.98	19.94	20.10	20.04	20.01	19.96	19.95	19.98	20.07	20.09	20.03	20.02	19.99	19.95	20.04	20.00
Anorthite	0.10	0.10	3.85	0.09	20.77	44.99	0.15	0.10	0.05	0.96	19.70	21.15	0.05	0.10	0.09	0.61
Albite	2.27	2.95	95.61	99.46	77.82	51.86	2.67	3.40	99.57	98.39	78.73	77.50	2.90	2.77	99.46	98.38
Orthoclase	97.63	96.95	0.55	0.45	1.41	3.15	97.18	96.50	0.39	0.65	1.57	1.35	97.05	97.12	0.45	1.01

4.1.1. Support vector Machine (SVM)

SVM is a type of supervised machine-learning algorithm that is commonly used due to its potential and accuracy for mapping different rock types (Hassan and Sadek, 2017; Agrawal et al., 2022; Shebl et al., 2023; EL-Omairi and El Garouani, 2023). The accuracy of classification and the success of SVM training depend on the choice of kernel functions. Some of the often utilized kernel functions for the SVM are the sigmoid kernel (SIG), radial basis function (RBF) kernel, polynomial kernel (PL), and linear kernel (LN). Zhu et al. (2011) claim that the RBF has good interpolation capabilities. Therefore, we employed the RBF kernel function in this study.

Object-based image classification using the RBF-SVM technique includes the segmentation process of an image into homogeneous objects followed by both object analysis and the SVM classification process, which have been applied to both the original bands and enhanced MNF of sentinel-2 datasets (Fig. 4c, e) using QGIS software. It divides several data classes by identifying the best hyperplane. Choosing the greatest margin hyperplane is a crucial parameter for more accurate predictions and trustworthy classification outcomes, according to statistical learning theory (e.g., Shebl et al., 2023). The SVM method could potentially be trained on labeled data, which identifies several lithological classes in the context of lithological mapping. After having been taught, the SVM algorithm can recognize new data points and categorize them into distinct lithological groups according to their attributes.

In this study, we applied the SVM classifier algorithm to the Sentinel-2 dataset (Fig. 4c, e; Table 1; Supplementary 3-1). The results of SVM applied to the Sentinel-2 original bands showed that it has an overall classification accuracy (OA) of 88.6 % with a Kappa accuracy = 87.1 % and an F1-score value = 85.8 % (Fig. 4c; Table 1; Supplementary 3-1). The highest precision, recall, and F1-score values (> 80 %) were recorded in quartz syenites, mafic metavolcanics, wadi deposits, alkali feldspar granites, and syenogranites classes (Supplementary 3-1). While tonalites-granodiorites and metagabbro-diorite complex rocks have lower values (< 76 %) (Supplementary 3-1). The results of accuracy of

all classes are nearly the same as in the original bands, except in the alkali feldspar granites and syenogranites classes that show high performance with precision 88.2 %, 89.6 %, recall 81.2 %, 84.1 %, and F1-score 84.6 %, 86.8 %, respectively (Supplementary 3-1). The SVM classifier algorithm applied to the MNF-Sentinel-2 gives excellent overall accuracy (OA = 92.4 %), kappa coefficient 90.6 %, and Mean F1-score 88.8 values (Fig. 4e; Table 1; Supplementary 3-1). In this data, the SVM algorithm gives excellent precision ranging from 90 % to 99.0 %, recall from 81.2 % to 99.4 %, and F1-score 85.8 % to 99.2 % for quartz syenites, alkali feldspar granites, syenogranites, wadi deposits, and mafic metavolcanics classes (Fig. 4; Table 1; Supplementary 3-1). While it displays good to moderate performance in tonalites-granodiorites and metagabbro-diorite classes with precision, recall, and F1score values up to 81.6 %, 76 %, and 77.8 %, respectively (Fig. 4e; Table 1; Supplementary 3-1).

4.1.2. Random forest (RF)

Random Forest (RF) is one of the most popular no-parametric classifier algorithms used for lithological mapping using remote sensing datasets (e.g., Shebl et al., 2023; Khedr et al., 2024). RF is an ensemble learning method combining multiple decision trees to improve accuracy and robustness. In the context of lithological mapping, the RF algorithm can be trained on a labeled dataset and then used to classify new data points by aggregating the predictions from individual decision trees (Breiman, 2001).

In this study, RF has been applied to Sentinel-2 original bands and MNF-Sentinel-2 (Fig. 4d, f; Table 1; Supplementary 3-1). The results showed that the overall accuracy (OA = 88.9 %), Kappa coefficient (86.3 %), and mean F1-score (85.3 %) values of the original bands of Sentinel-2 and MNF-Sentinel-2 (OA = 88.6 %; kappa = 86 %, and F1-score = 86 %) are nearly similar (Supplementary 3-1). Quartz syenites, wadi deposits, and mafic metavolcanics display excellent performance values (> 90 %) in both two datasets (Table 1; Supplementary 3-1). On the other side, tonalites-granodiorites and metagabbro-diorite complex

Table 4
Representative EPMA analysis of biotite in the Nikeiba granites, South Eastern Desert, Egypt.

Rock name	Syenogranites						Alkali feldspar granites						Quartz syenites					
Sample No.	NBK4						NBK22						NBK5					
Spot#	Bi1	Bi2	Bi3	Bi4	Bi5	Bi6	Bi1	Bi2	Bi3	Bi4	Bi5	Bi6	Bi1	Bi2	Bi3	Bi4	Bi5	Bi6
SiO ₂	34.80	35.51	34.08	33.44	33.39	34.09	34.20	35.20	33.21	34.28	35.06	34.17	34.98	35.17	34.67	35.01	34.56	34.86
TiO ₂	2.17	2.14	3.58	2.69	2.76	2.47	2.30	2.78	2.99	2.18	2.99	2.67	2.10	1.97	1.93	1.85	2.57	2.16
Al ₂ O ₃	10.41	10.36	12.67	12.08	11.99	13.89	10.43	10.48	12.32	10.49	13.57	9.75	9.55	10.78	10.39	10.52	13.45	15.37
Cr ₂ O ₃	0.02	0.03	0.05	0.04	0.04	0.04	0.03	0.04	0.04	0.02	0.05	0.04		0.04	0.03	0.02	0.05	0.03
FeOt	36.51	35.54	32.21	33.52	33.30	31.22	35.68	36.49	32.63	35.74	31.04	35.84	36.53	35.68	36.87	36.76	31.47	30.47
MnO	0.34	0.40	0.38	0.56	0.57	0.32	0.31	0.36	0.51	0.32	0.23	0.34	0.40	0.33	0.39	0.39	0.49	0.42
MgO	0.83	0.83	1.58	1.84	1.80	1.88	0.32	0.26	1.81	0.32	2.29	0.72	0.91	0.30	0.28	0.28	1.64	1.51
CaO	0.09	0.10	0.14	0.20	0.21	0.21	0.08	0.08	0.21	0.06	0.14	0.06	0.06	0.12	0.06	0.06	0.32	0.17
Na ₂ O	0.10	0.16	0.22	0.14	0.17	0.14	0.10	0.11	0.18	0.09	0.09	0.06	0.05	0.12	0.08	0.09	0.13	0.19
K ₂ O	8.60	8.06	8.77	8.46	8.44	8.82	8.78	8.64	8.30	8.82	8.71	8.76	8.40	8.63	8.86	8.78	8.66	9.08
P ₂ O ₅	0.02	0.00	0.02	0.03	0.02	0.02	0.00	0.00	0.02	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.02	0.02
Total	93.89	93.13	93.70	93.00	92.69	93.10	92.23	94.44	92.22	92.32	94.17	92.45	92.98	93.14	93.56	93.76	93.36	94.28
Si	6.47	6.59	6.22	6.21	6.21	6.21	6.48	6.49	6.18	6.49	6.28	6.47	6.57	6.56	6.50	6.53	6.28	6.22
Ti	0.30	0.30	0.49	0.38	0.39	0.34	0.33	0.39	0.42	0.31	0.40	0.38	0.30	0.28	0.27	0.26	0.35	0.29
Al	2.28	2.27	2.72	2.64	2.63	2.98	2.33	2.28	2.70	2.34	2.86	2.18	2.12	2.37	2.30	2.31	2.88	3.23
Cr	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00
Fe	5.68	5.52	4.91	5.20	5.18	4.76	5.65	5.63	5.08	5.66	4.65	5.68	5.74	5.56	5.78	5.73	4.79	4.55
Mn	0.05	0.06	0.06	0.09	0.09	0.05	0.05	0.06	0.08	0.05	0.03	0.05	0.06	0.05	0.06	0.06	0.08	0.06
Mg	0.23	0.23	0.43	0.51	0.50	0.51	0.09	0.07	0.50	0.09	0.61	0.20	0.25	0.08	0.08	0.08	0.44	0.40
Ca	0.02	0.02	0.03	0.04	0.04	0.04	0.02	0.02	0.04	0.01	0.03	0.01	0.01	0.02	0.01	0.01	0.06	0.03
Na	0.04	0.06	0.08	0.05	0.06	0.05	0.04	0.04	0.06	0.03	0.03	0.02	0.02	0.04	0.03	0.03	0.05	0.07
K	2.04	1.91	2.04	2.00	2.00	2.05	2.12	2.03	1.97	2.13	1.99	2.12	2.01	2.05	2.12	2.09	2.01	2.07
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Total	17.12	16.96	16.99	17.12	17.12	17.00	17.11	17.01	17.06	17.11	16.89	17.13	17.09	17.03	17.15	17.11	16.95	16.94
Mg#	0.04	0.04	0.08	0.09	0.09	0.10	0.02	0.01	0.09	0.02	0.12	0.03	0.04	0.01	0.01	0.01	0.08	0.08
Fe#	0.96	0.96	0.92	0.91	0.91	0.90	0.98	0.99	0.91	0.98	0.88	0.97	0.96	0.99	0.99	0.99	0.92	0.92

Table 5
Rebrepresentative EPMA analysis of amphiboles in the Nikeiba granites, South Eastern Desert, Egypt.

Rock name	Syenogranites				Alkali feldspar granites								Quartz syenites							
Sample No	NBK4				NBK22								NBK5							
Mineral	Sodic-calcic (ferrorichterite)				Sodic-calcic (ferrorichterite)				Riebeckite		Arfvedsonite		Calcic amphibole (Ferrohornblede)				Arfvedsonite		Riebeckite	
SiO ₂	45.05	48.17	47.08	47.22	47.34	47.33	46.60	46.53	49.77	49.99	51.74	52.04	42.70	43.56	44.71	42.47	42.76	49.54	49.97	49.58
TiO ₂	1.84	1.91	1.88	1.95	0.97	0.96	1.06	1.02	0.19	0.12	1.13	1.13	1.20	1.25	1.19	1.22	1.08	0.20	0.25	0.64
Al ₂ O ₃	2.37	1.55	1.81	1.29	1.81	1.79	1.81	1.85	1.32	1.20	0.77	0.68	3.69	3.41	3.39	3.85	4.92	1.44	1.02	0.46
Cr ₂ O ₃	0.00	0.01	0.00	0.00	0.02	0.00	0.07	0.07	0.01	0.00	0.01	0.01	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.02
FeO [†]	33.51	33.40	33.34	33.67	34.99	34.99	34.29	34.33	35.92	36.31	24.90	24.60	34.73	33.79	33.56	33.73	34.18	35.83	36.16	35.83
MnO	0.88	0.82	0.84	0.85	1.23	1.27	1.22	1.20	0.52	0.41	1.04	1.02	1.09	1.07	1.10	1.04	0.89	0.46	0.52	0.72
MgO	0.89	0.91	1.03	0.73	0.04	0.04	0.06	0.06	0.02	0.02	6.34	6.59	0.52	0.57	0.60	0.56	0.47	0.02	0.03	1.03
CaO	5.24	4.10	4.40	3.89	3.20	3.26	3.21	3.22	0.12	0.08	0.77	0.89	8.19	7.78	8.06	8.50	8.99	0.19	0.79	1.34
Na ₂ O	5.08	5.58	5.38	5.75	5.00	5.10	4.91	4.99	7.11	6.82	8.27	8.20	2.28	2.58	2.54	2.22	1.80	7.07	6.08	6.49
K ₂ O	1.26	1.35	1.29	1.38	1.16	1.15	1.15	1.16	0.98	0.73	1.29	1.28	0.94	0.94	0.92	0.98	1.06	1.04	0.52	0.52
P ₂ O ₅	0.05	0.03	0.01	0.01	0.00	0.00	0.01	0.00	0.02	0.01	0.01	0.01	0.00	0.02	0.00	0.03	0.02	0.01	0.01	0.01
Total	96.17	97.83	97.06	96.74	95.76	95.89	94.39	94.43	95.98	95.69	96.27	96.45	95.34	94.99	96.07	94.62	96.18	95.80	95.35	96.64
Si	7.48	7.77	7.67	7.74	7.85	7.84	7.83	7.82	8.16	8.20	8.07	8.09	7.22	7.34	7.41	7.21	7.13	8.13	8.21	8.08
Ti	0.23	0.23	0.23	0.24	0.12	0.12	0.13	0.13	0.02	0.01	0.13	0.13	0.15	0.16	0.15	0.16	0.14	0.02	0.03	0.08
Al ^{IV}	0.46	0.23	0.33	0.25	0.15	0.16	0.17	0.18	0.00	0.00	0.00	0.00	0.78	0.66	0.59	0.79	0.87	0.00	0.00	0.00
Al ^{VI}	0.00	0.06	0.02	0.00	0.20	0.19	0.19	0.19	0.25	0.23	0.14	0.12	0.00	0.01	0.07	0.00	0.09	0.28	0.20	0.09
Al ^(total)	0.46	0.29	0.35	0.25	0.35	0.35	0.36	0.37	0.25	0.23	0.14	0.12	0.78	0.68	0.66	0.79	0.97	0.28	0.20	0.09
Fe ⁺²	4.00	4.00	3.91	4.05	3.52	3.56	3.53	3.56	3.31	3.18	2.47	2.44	3.77	3.87	3.99	3.94	3.86	3.34	3.17	3.12
Fe ⁺³	0.60	0.46	0.58	0.52	1.23	1.19	1.19	1.18	1.50	1.68	0.74	0.72	1.05	0.82	0.61	0.78	0.84	1.48	1.68	1.65
Mn	0.12	0.11	0.12	0.12	0.17	0.18	0.17	0.17	0.07	0.06	0.14	0.13	0.16	0.15	0.15	0.15	0.13	0.06	0.07	0.10
Mg	0.22	0.22	0.25	0.18	0.01	0.01	0.02	0.02	0.00	0.00	1.48	1.53	0.13	0.14	0.15	0.14	0.12	0.00	0.01	0.25
Ca	0.93	0.71	0.77	0.68	0.57	0.58	0.58	0.58	0.02	0.01	0.13	0.15	1.48	1.40	1.43	1.55	1.61	0.03	0.14	0.23
Na	1.64	1.74	1.70	1.83	1.61	1.64	1.60	1.63	2.26	2.17	2.50	2.47	0.75	0.84	0.82	0.73	0.58	2.25	1.94	2.05
K	0.27	0.28	0.27	0.29	0.25	0.24	0.25	0.25	0.20	0.15	0.26	0.25	0.20	0.20	0.19	0.21	0.23	0.22	0.11	0.11
CaB	0.93	0.71	0.77	0.68	0.57	0.58	0.58	0.58	0.02	0.01	0.13	0.15	1.48	1.40	1.43	1.55	1.61	0.03	0.14	0.23
NaB	0.90	1.16	1.07	1.17	1.08	1.08	1.08	1.08	1.55	1.50	1.66	1.65	0.22	0.36	0.40	0.23	0.16	1.54	1.37	1.29
(Ca + Na)B	1.83	1.87	1.84	1.85	1.65	1.66	1.66	1.66	1.57	1.51	1.79	1.80	1.70	1.77	1.83	1.78	1.76	1.57	1.51	1.52
Na/(Na + K)	0.86	0.86	0.86	0.86	0.87	0.87	0.87	0.87	0.92	0.93	0.91	0.91	0.79	0.81	0.81	0.77	0.72	0.91	0.95	0.95
(Na + K)A	1.00	0.86	0.90	0.94	0.77	0.80	0.77	0.79	0.92	0.82	1.10	1.07	0.73	0.68	0.61	0.71	0.65	0.93	0.67	0.87
(Ca + Na)B	1.83	1.87	1.84	1.85	1.65	1.66	1.66	1.66	1.57	1.51	1.79	1.80	1.70	1.77	1.83	1.78	1.76	1.57	1.51	1.52
P _{kbar}	2.57	1.63	1.91	1.41	1.94	1.92	1.97	2.01	1.44	1.33	0.96	0.89	5.03	4.13	4.01	5.07	6.79	1.56	1.18	0.77
depth (km)	6.93	4.40	5.15	3.82	5.24	5.18	5.31	5.43	3.88	3.60	2.58	2.41	13.59	11.15	10.82	13.70	18.34	4.21	3.19	2.07

Table 6

Representative EPMA analysis of zircon and columbite in the Nikeiba granites, South Eastern Desert, Egypt.

Mineral	Zircon																	Columbite						
Rock	Syenogranites						Alkali feldspar granites				Quartz syenites							Alkali feldspar granites						
Sample	NBK4						NBK22				NBK5							NBK22						
SiO ₂	32.38	32.35	31.35	30.71	32.53	30.62	32.31	31.44	32.83	32.41	32.01	32.74	30.99	31.91	32.71	31.73	31.07	0.04	0.14	0.06	0.05	0.14	0.14	0.05
TiO ₂	0.00	0.00	0.03	0.00	0.00	0.03	0.43	0.00	0.02	0.00	0.01	0.01	0.03	0.01	0.00	0.02	0.00	0.73	0.61	0.85	0.58	0.70	0.67	0.65
Al ₂ O ₃	0.00	0.10	0.27	0.00	0.00	0.33	0.10	0.00	0.00	0.00	0.00	0.04	0.21	0.00	0.04	0.23	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.02
FeOt	0.22	0.41	0.14	0.42	0.24	0.74	0.66	0.72	0.08	0.22	0.26	0.49	0.38	0.37	0.36	0.59	0.52	17.15	16.72	16.46	16.46	16.96	16.65	16.46
MnO	0.00	0.00	0.16	0.00	0.00	0.16	0.05	0.00	0.00	0.00	0.00	0.00	0.12	0.03	0.00	0.14	0.02	3.25	3.38	3.81	3.91	3.06	3.48	3.89
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01
CaO	0.00	0.06	0.37	0.00	0.03	0.48	0.06	0.05	0.01	0.01	0.13	0.14	0.07	0.21	0.02	0.22	0.07	0.03	0.02	0.02	0.03	0.02	0.02	0.03
Na ₂ O	0.00	0.05	0.05	0.00	0.00	0.07	0.05	0.00	0.00	0.00	0.00	0.00	0.07	0.18	0.00	0.06	0.00	0.02	0.03	0.01	0.02	0.04	0.03	0.02
K ₂ O	0.00	0.03	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.36	0.00	0.07	0.05	0.02	0.04	0.01	0.01	0.02	0.01	0.02	0.02
P ₂ O ₅	0.00	0.15	0.09	0.02	0.06	0.07	0.15	0.00	0.00	0.00	0.00	0.02	0.16	0.02	0.02	0.21	0.10	0.02	0.02	0.00	0.03	0.00	0.00	0.01
ZrO ₂	64.49	63.29	63.82	64.95	62.39	63.90	63.55	63.54	64.01	63.10	64.32	62.29	62.69	63.94	63.33	62.81	63.71	—	—	—	—	—	—	—
HfO ₂	0.88	1.43	1.29	2.24	2.80	1.25	1.41	2.87	1.66	1.70	1.53	2.79	2.97	1.79	1.87	2.35	2.32	—	—	—	—	—	—	—
Nb ₂ O ₅	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	66.65	64.75	64.70	66.02	64.40	65.02	65.69
Ta ₂ O ₅	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	10.30	13.27	13.37	11.73	14.05	13.10	12.14
Total	97.97	97.86	97.59	98.33	98.06	97.65	98.81	98.63	98.63	97.44	98.26	98.53	98.17	98.46	98.42	98.43	97.83	98.23	98.96	99.30	98.85	99.40	99.13	98.99
Si	1.01	1.01	0.99	0.97	1.02	0.97	1.00	0.99	1.02	1.02	1.00	1.02	0.98	1.00	1.02	0.99	0.98	0.00	0.01	0.00	0.00	0.01	0.01	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.04	0.03	0.03	0.03	0.03
Al	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.01	0.01	0.00	0.01	0.01	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.91	0.90	0.88	0.88	0.92	0.89	0.88
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.18	0.21	0.21	0.17	0.19	0.21
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zr	0.98	0.96	0.98	1.00	0.95	0.98	0.96	0.97	0.97	0.96	0.98	0.94	0.97	0.97	0.96	0.96	0.98	—	—	—	—	—	—	—
Hf	0.01	0.01	0.01	0.02	0.03	0.01	0.01	0.03	0.02	0.02	0.01	0.03	0.03	0.02	0.02	0.02	0.02	—	—	—	—	—	—	—
Nb	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.95	0.94	0.94	0.95	0.94	0.94	0.95
Ta	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.09	0.12	0.12	0.10	0.12	0.11	0.11
Total	2.00	2.01	2.01	2.00	2.00	2.02	2.01	2.01	2.00	2.00	2.00	2.01	2.02	2.01	2.01	2.02	2.01	2.16	2.19	2.20	2.18	2.20	2.19	2.18

Table 7
Representative whole rock chemistry (major, trace, and REE) analysis of the Nikeiba area, South Eastern Desert, Egypt.

Rcock name	Syenogranites					Alkali feldspar granites								Quartz syenites								
Sample No.	NBK1	NBK4	NBK16	NBK20	NBK21	NBK2	NBK13	NBK14	NBK17	NBK18	NBK19	NBK22	NBK23	NBK5	NBK6	NBK7	NBK8	NBK9	NBK10	NBK11	NBK12	NBK15
SiO ₂	71.86	72.31	70.74	71.95	71.59	72.99	73.56	72.49	72.11	72.52	71.49	70.86	72.11	67.47	67.29	67.76	66.53	68.50	68.19	65.71	69.54	68.84
TiO ₂	0.14	0.13	0.16	0.15	0.13	0.11	0.11	0.13	0.15	0.15	0.14	0.17	0.14	0.21	0.21	0.19	0.22	0.19	0.18	0.22	0.18	0.20
Al ₂ O ₃	14.02	13.57	14.22	13.97	13.87	13.33	13.42	13.32	13.96	13.96	13.97	13.96	13.80	15.26	16.09	15.54	15.67	15.23	15.29	15.61	14.87	14.73
FeO ⁱ	2.24	2.08	2.47	2.44	2.42	2.11	1.97	2.16	2.26	2.23	2.31	2.54	2.17	3.24	2.89	3.06	3.36	2.92	2.88	3.11	2.55	2.67
MnO	0.03	0.03	0.05	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.04	0.03	0.12	0.11	0.09	0.12	0.07	0.07	0.11	0.06	0.09
MgO	0.04	0.02	0.04	0.06	0.08	0.03	0.05	0.04	0.05	0.04	0.07	0.05	0.04	0.13	0.12	0.14	0.13	0.12	0.09	0.15	0.08	0.11
CaO	0.72	0.76	0.73	0.63	0.64	0.63	0.57	0.62	0.55	0.61	0.72	0.79	0.53	1.30	1.11	0.96	1.21	0.99	0.94	1.50	0.77	0.85
Na ₂ O	4.78	4.74	4.89	4.29	4.61	4.38	4.09	4.37	4.15	4.59	4.49	5.01	4.52	5.65	5.49	5.44	5.83	5.31	5.40	5.71	5.29	5.15
K ₂ O	5.13	4.92	4.76	5.49	4.85	5.29	5.22	4.91	5.52	4.94	4.74	4.92	4.81	4.24	4.15	4.33	4.09	4.47	4.76	4.18	4.58	4.63
P ₂ O ₅	0.02	0.02	0.01	0.02	0.04	0.01	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.04	0.05	0.04	0.03	0.04	0.04	0.05	0.04	0.04
LOI	0.62	0.55	1.04	0.88	0.92	0.66	0.92	0.97	1.11	0.88	1.37	0.83	0.99	1.73	1.63	1.65	1.21	0.73	1.41	1.85	0.89	1.76
Total	99.60	99.13	99.11	99.91	99.18	99.56	99.96	99.06	99.91	99.96	99.35	99.19	99.17	99.39	99.14	99.20	98.40	98.57	99.25	98.20	98.85	99.07
Cs	2.84	2.19	2.75	1.52	1.47	4.50	2.11	1.76	0.23	0.46	0.58	0.73	0.70	0.77	1.79	1.47	1.28	2.19	2.23	1.55	1.01	2.10
Rb	229.41	235.58	210.27	230.51	196.66	261.89	241.36	239.58	215.35	228.17	204.74	201.68	216.10	123.47	150.38	154.94	134.07	172.20	156.69	132.11	169.11	153.57
Ba	203.18	119.01	249.84	260.66	238.04	60.18	159.25	210.35	251.58	279.23	226.53	273.11	269.68	531.94	717.14	588.38	613.59	368.66	346.03	567.92	326.00	294.19
Sr	47.87	48.31	83.30	69.39	64.04	56.97	44.55	53.16	64.26	68.19	72.25	59.39	75.51	97.99	115.15	103.20	107.66	93.43	96.34	101.03	83.40	89.73
Pb	20.15	17.36	26.04	16.85	8.95	15.92	8.93	10.23	27.71	8.55	9.64	11.61	8.72	13.10	9.53	8.93	9.43	11.34	9.14	10.31	12.70	13.18
Th	36.61	37.71	25.25	34.40	26.50	19.68	41.56	36.03	29.87	34.11	38.14	20.11	33.70	21.51	23.07	26.81	23.60	26.33	22.99	19.45	25.20	27.57
U	8.75	12.05	6.91	8.98	7.61	9.56	11.82	13.41	10.99	9.72	8.57	5.44	11.19	4.73	4.64	5.44	5.77	7.12	7.34	5.20	7.13	7.97
Zr	330.61	442.09	572.40	256.20	255.15	574.94	274.76	281.97	257.70	260.30	265.76	637.95	410.58	821.36	551.55	653.34	797.74	541.46	525.94	751.92	547.58	763.44
Hf	12.84	17.36	17.68	9.27	9.01	16.21	12.17	11.44	9.93	9.46	9.47	17.59	14.67	21.88	13.91	18.32	21.20	16.67	16.24	19.66	17.19	21.33
Ta	15.18	15.28	12.53	13.53	12.78	15.14	17.61	16.05	14.75	14.11	13.47	13.47	16.66	9.75	8.54	9.66	9.26	10.87	10.07	8.80	10.61	11.20
Y	102.52	134.50	89.02	91.67	90.57	129.63	101.44	95.13	100.06	88.74	83.47	92.08	80.36	74.85	65.06	71.21	60.83	72.87	71.13	67.32	78.57	81.91
Nb	240.48	266.76	181.48	196.13	182.29	204.47	198.16	203.00	186.37	179.84	167.63	182.70	197.24	141.41	137.17	156.46	120.53	143.62	146.63	141.18	155.60	165.23
Sc	0.27	1.27	1.60	1.34	0.59	0.88	1.35	0.92	0.25	0.00	–	1.25	1.73	1.49	0.98	1.66	2.62	0.60	1.88	0.58	3.10	1.43
Cr	0.48	0.61	1.54	7.08	0.61	4.57	4.58	–	5.58	5.59	2.84	15.82	6.12	8.82	1.88	2.12	5.24	5.59	1.48	8.67	2.24	12.18
Ni	3.99	3.61	2.58	4.70	0.14	3.82	3.87	1.14	1.60	3.31	1.43	4.12	–	4.29	2.89	5.07	3.69	5.55	5.81	2.27	2.42	5.41
V	2.26	9.45	4.71	9.51	9.40	9.37	9.08	9.13	9.08	9.40	8.38	4.92	8.27	4.11	3.26	5.95	6.13	7.69	5.88	6.53	5.58	3.50
W	0.90	1.57	1.53	9.98	5.50	0.60	3.59	788.64	2.57	6.29	1.27	0.86	3.32	1.31	1.09	0.92	0.55	1.25	1.36	1.82	922.43	1.87
Ga	19.03	22.13	20.34	15.17	13.90	23.42	16.11	16.00	14.85	14.57	15.69	20.09	17.75	19.52	19.51	18.50	20.12	19.96	18.40	17.15	19.79	22.43
Zn	130.40	170.19	133.47	28.64	23.00	164.07	43.02	40.04	66.27	22.94	21.25	131.46	107.63	236.58	122.13	101.21	152.27	106.13	107.96	190.47	104.80	175.31
Cu	4.26	5.09	6.64	6.93	4.93	3.87	1.86	1.16	3.75	1.93	6.05	2.81	3.86	6.72	1.98	2.01	3.71	2.82	3.20	4.12	22.38	2.70
Mo	0.19	0.42	3.07	1.34	0.76	0.48	2.31	13.75	0.95	1.37	1.04	3.10	4.85	4.03	1.05	4.02	1.90	2.64	2.05	2.41	2.63	3.35
Sn	7.38	8.67	17.41	7.68	8.84	18.35	5.37	5.93	7.81	5.31	6.77	7.70	4.51	0.15	4.43	6.84	8.87	8.78	11.85	2.78	11.46	9.17
La	57.48	36.54	23.62	70.36	31.86	86.24	51.27	38.81	42.02	43.96	26.75	20.46	70.36	119.57	101.08	84.23	115.49	62.48	50.57	60.10	81.20	141.71
Ce	124.28	78.77	53.87	157.46	68.55	194.44	108.86	84.36	95.42	95.28	59.27	45.23	63.56	253.94	212.06	183.44	226.54	133.26	111.90	126.52	160.58	280.21
Pr	16.54	10.91	7.42	18.87	9.62	23.47	14.33	11.58	12.59	12.66	8.12	6.31	8.93	30.51	26.04	22.58	25.20	16.99	14.39	15.16	18.51	30.69
Nd	64.96	46.18	31.53	77.29	40.72	90.58	57.92	45.81	49.31	52.65	35.06	26.60	37.24	110.11	93.55	78.64	90.02	60.24	56.12	56.04	68.18	110.13
Sm	15.08	9.66	6.95	17.85	8.61	20.95	13.60	9.92	12.58	11.25	7.89	6.32	8.28	18.52	15.41	13.05	15.89	11.87	12.26	11.59	13.80	19.83
Eu	1.03	0.74	0.75	0.93	0.79	1.78	1.50	1.16	1.13	0.85	0.73	0.63	0.86	3.40	3.22	2.43	3.03	1.49	1.43	2.72	1.83	1.76
Gd	16.37	10.34	7.86	19.47	8.68	21.87	14.01	12.02	11.32	10.92	9.17	7.29	9.19	15.32	14.16	13.17	18.19	10.62	12.51	11.21	13.53	15.64
Tb	2.71	1.71	1.25	3.25	1.37	3.80	2.47	1.92	2.14	1.68	1.57	1.17	1.57	2.30	2.11	2.08	2.76	1.81	1.97	1.82	2.13	2.38
Dy	18.27	11.23	8.24	21.88	9.45	25.17	15.46	12.99	13.58	11.44	9.85	7.74	10.49	13.64	12.24	12.67	16.80	11.27	12.82	11.82	13.57	14.23
Ho	3.70	2.46	1.82	4.69	1.97	5.42	3.22	2.71	2.93	2.42	2.24	1.72	2.21	2.69	2.42	2.57	3.43	2.51	2.69	2.48	2.84	2.91
Er	10.95	7.05	5.36	13.																		

Table 7 (continued)

(La/Yb)N*	3.59	3.43	2.91	3.57	3.53	3.66	3.68	3.17	3.35	4.02	2.74	2.66	6.93	9.68	7.21	7.54	5.42	4.21	5.73	6.79	10.49	11.11
(La/Sm)N*	2.39	2.37	2.13	2.47	2.32	2.58	2.36	2.45	2.09	2.45	2.12	2.03	5.32	4.11	4.04	4.55	3.3	2.58	3.25	3.69	4.05	4.48
(Gd/Yb)N*	1.22	1.16	1.15	1.18	1.14	1.10	1.20	1.17	1.07	1.19	1.12	1.13	1.08	1.61	1.34	1.42	1.10	1.24	1.27	1.35	1.60	1.46
(Ce/Yb)N*	3.01	2.86	2.57	3.09	2.93	3.19	3.02	2.67	2.94	3.37	2.35	2.27	2.42	7.85	6.07	5.72	4.47	3.60	4.67	5.19	8.61	8.50
Na ₂ O + K ₂ O	9.91	9.66	9.65	9.78	9.46	9.67	9.31	9.28	9.67	9.53	9.23	9.93	9.33	9.89	9.64	9.77	9.92	9.78	10.16	9.89	9.87	9.78
K ₂ O/Na ₂ O	1.07	1.04	0.97	1.28	1.05	1.21	1.28	1.12	1.33	1.08	1.06	0.98	1.06	0.75	0.76	0.80	0.70	0.84	0.88	0.73	0.87	0.90
K/Rb	185.64	173.37	187.93	197.71	204.73	167.68	179.54	170.13	212.79	179.73	192.19	202.52	184.78	285.08	229.09	232.00	253.25	215.49	252.19	262.66	224.83	250.28
Rb/Sr	4.79	4.88	2.52	3.32	3.07	4.60	5.42	4.51	3.35	3.35	2.83	3.40	2.86	1.26	1.31	1.50	1.25	1.84	1.63	1.31	2.03	1.71
Rb/Ba	1.13	1.98	0.84	0.88	0.83	4.35	1.52	1.14	0.86	0.82	0.90	0.74	0.80	0.23	0.21	0.26	0.22	0.47	0.45	0.23	0.52	0.52
Ba/Rb	0.89	0.51	1.19	1.13	1.21	0.23	0.66	0.88	1.17	1.22	1.11	1.35	1.25	4.31	4.77	3.80	4.58	2.14	2.21	4.30	1.93	1.92
Zr/Hf	25.75	25.47	32.38	27.64	28.32	35.47	22.58	24.65	25.95	27.52	28.06	36.27	27.99	37.54	39.65	35.66	37.63	32.48	32.39	38.25	31.85	35.79
Nb/Ta	15.84	17.46	14.48	14.50	14.26	13.51	11.25	12.65	12.64	12.75	12.44	13.56	11.84	14.50	16.06	16.20	13.02	13.21	14.56	16.04	14.67	14.75
Th/U	4.18	3.13	3.65	3.83	3.48	2.06	3.52	2.69	2.72	3.51	4.45	3.70	3.01	4.55	4.97	4.93	4.09	3.70	3.13	3.74	3.53	3.46
Th/Ta	2.41	2.47	2.02	2.54	2.07	1.30	2.36	2.24	2.03	2.42	2.83	1.49	2.02	2.21	2.70	2.78	2.55	2.42	2.28	2.21	2.38	2.46
Y/Nb	0.43	0.50	0.49	0.47	0.50	0.63	0.51	0.47	0.54	0.49	0.50	0.50	0.41	0.53	0.47	0.46	0.50	0.51	0.49	0.48	0.50	0.50
Y/Ho	27.71	54.67	48.91	19.55	45.97	23.92	31.50	35.10	34.15	36.67	37.26	53.53	36.36	27.83	26.88	27.71	17.73	29.03	26.44	27.15	27.67	28.15
Ba/Nb	0.84	0.45	1.38	1.33	1.31	0.29	0.80	1.04	1.35	1.55	1.35	1.49	1.37	3.76	5.23	3.76	5.09	2.57	2.36	4.02	2.10	1.78
Zr/Rb	1.44	1.88	2.72	1.11	1.30	2.20	1.14	1.18	1.20	1.14	1.30	3.16	1.90	6.65	3.67	4.22	5.95	3.14	3.36	5.69	3.24	4.97
Ce/Nb	0.52	0.30	0.30	0.80	0.38	0.95	0.55	0.42	0.51	0.53	0.35	0.25	0.32	1.80	1.55	1.17	1.88	0.93	0.76	0.90	1.03	1.70
10 ⁴ *Ga/Al	2.56	3.08	2.70	2.05	1.89	3.32	2.27	2.27	2.01	1.97	2.12	2.72	2.43	2.42	2.29	2.25	2.43	2.48	2.27	2.08	2.51	2.88
A/CNK	0.96	0.94	0.98	0.99	1.00	0.95	1.01	0.98	1.02	1.00	1.01	0.93	1.02	0.94	1.04	1.02	0.97	1.00	0.98	0.94	0.99	0.99
T _{Zr}	796.70	829.20	867.50	776.50	776.90	866.60	791.20	788.40	782.60	781.00	785.40	869.00	838.10	892.80	863.80	882.00	893.30	855.30	845.70	876.60	859.10	900.50
T _{Al}	797.70	784.10	716.90	780.50	834.10	739.10	828.90	785.90	814.80	786.20	776.00	769.60	814.80	791.40	809.30	794.50	756.70	802.40	799.10	791.90	813.30	806.00
P(Kbar)	9.97	7.01	10.70	7.87	6.70	5.02	3.65	4.59	5.96	6.13	5.61		5.21	26.40	21.76	21.38	32.05	18.50	23.95	34.37	15.49	15.74
Depth (Km)	26.92	19.90	28.89	21.25	18.10	15.20	9.80	12.40	16.10	16.50	15.20		14.20	71.30	58.80	57.70	86.50	50.00	64.70	92.80	41.80	42.50
logfO ₂	-13.17	-12.49	-11.77	-13.68	-13.68	-11.76	-13.41	-13.43	-13.57	-13.59	-13.55	-11.65	-12.40	-11.26	-12.17	-11.51	-11.24	-12.02	-12.13	-11.57	-11.90	-11.14
Quartz	23.26	24.83	22.65	24.68	24.85	26.40	28.58	27.10	25.68	25.61	25.64	21.77	26.30	16.04	17.06	17.39	14.54	18.35	16.74	13.74	19.64	19.41
Plagioclase	42.09	41.33	44.17	38.95	41.84	38.15	37.24	39.20	37.65	41.73	41.43	43.46	40.68	51.56	51.63	50.53	53.84	49.45	49.11	52.93	48.06	46.98
Albite	40.45	40.11	41.38	36.30	39.01	37.06	34.61	36.98	35.12	38.84	37.99	42.39	38.25	47.81	46.45	46.03	49.33	44.93	45.69	48.32	44.76	43.58
Orthoclase	1.65	1.22	2.79	2.65	2.83	1.09	2.63	2.23	2.53	2.90	3.44	1.07	2.43	3.75	5.18	4.50	4.51	4.52	3.42	4.62	3.30	3.40
Orthoclase	30.32	29.08	28.13	32.44	28.66	31.26	30.85	29.02	32.62	29.19	28.01	29.08	28.43	25.06	24.52	25.59	24.17	26.42	28.13	24.70	27.07	27.36
Corundum						0.08			0.23	0.001	0.20		0.27		0.69	0.26						
Diopside	1.61	2.19	0.69	0.31	0.08	1.77	0.00	0.65	0.00	0.00	0.00	2.45	0.00	2.20	0.00	0.00	1.18	0.12	0.89	2.29	0.23	0.50
Hypersthene	2.14	1.59	2.98	3.14	3.34	1.89	2.68	2.58	3.02	2.94	3.20	2.13	2.92	3.55	4.19	4.47	4.27	4.11	3.59	3.41	3.43	3.58
Ilmenite	0.27	0.25	0.31	0.29	0.25	0.21	0.21	0.25	0.29	0.29	0.27	0.33	0.27	0.41	0.41	0.37	0.43	0.37	0.35	0.43	0.35	0.39
Magnetite	0.39	0.37	0.44	0.43	0.43	0.37	0.35	0.38	0.40	0.39	0.41	0.45	0.39	0.58	0.52	0.55	0.60	0.52	0.51	0.56	0.45	0.48
Apatite	0.05	0.05	0.02	0.05	0.10	0.02	0.07	0.05	0.07	0.05	0.05	0.05	0.07	0.10	0.12	0.10	0.07	0.10	0.10	0.12	0.10	0.10
D.I	94.03	94.01	92.16	93.42	92.52	94.72	94.04	93.10	93.41	93.64	91.65	93.23	92.97	88.90	88.04	89.01	88.05	89.69	90.56	86.76	91.47	90.35
Agpaitic Index	0.96	0.97	0.93	0.93	0.93	0.97	0.92	0.94	0.92	0.92	0.90	0.97	0.92	0.91	0.84	0.88	0.89	0.89	0.92	0.89	0.92	0.92
Mg#	12.40	7.08	11.37	16.31	20.76	10.13	16.74	12.80	14.92	12.45	19.36	13.49	12.75	24.12	24.76	26.61	23.47	24.57	19.85	27.65	19.91	24.61
R1	1829.971	1927.436	1796.51	1920.552	1933.475	2013.829	2174.574	2071.087	1978.401	1985.732	1997.609	1722.531	2015.398	1409.933	1484.53	1487.773	1315.233	1553.996	1434.93	1288.474	1614.166	1602.069
R2	354.029	348.49	359.022	344.411	344.512	330.369	326.707	329.599	335.159	341.083	354.537	360.838	329.385	444.876	440.332	414.486	443.289	410.623	404.961	474.133	378.037	385.34

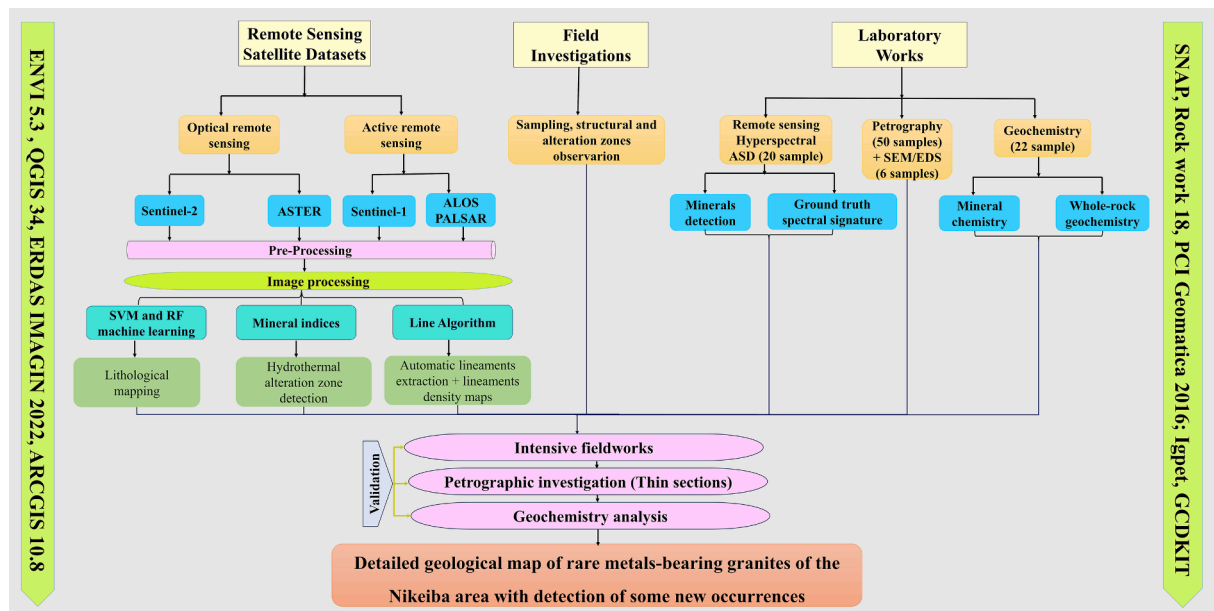


Fig. 3. Flow chart of the proposed methodology used in this study.

rocks show good to moderate performance with precision up to 80.1 %, recall = 78.7 %, and F1-score = 79.4 % in the MNF-Sentinel-2 data (Table 1; Supplementary 3-1). The performance of alkali feldspar granites and syenogranites in random forest algorithms are variables between the two input datasets with precision ranging from 85.3 % to 91.6 %, recall = 79 % to 91.6 %, and F1-score = 84.9 % to 90.7 % (Table 1; Supplementary 3-1).

4.2. Alteration zones and mineral mapping

Using remote sensing data from ASTER satellite imagery, we can determine the mineral content of Earth's materials (e.g., Hassan and Sadek, 2017; Hassan et al., 2022; Abo Khashaba et al., 2023; Khedr et al., 2022, 2023). This study employs ASTER mineral indices to detect minerals indicative of specific alteration zones. ASTER band ratio (b4/b5) effectively distinguishes alteration zones, highlighted by light white pixels (Fig. 5a) (e.g., Volesky et al., 2003). Phyllic alteration minerals, such as sericite, muscovite, and illite, were identified using the band ratio (b5 + b7/b6), represented in yellow (Fig. 5b) (e.g., Rowan and Mars, 2003; Van der Meer et al., 2012). ASTER index (b5/b4) has been used to identify ferrous silicate alteration minerals (Fig. 5c). The pure pixels-rich ferrous silicate alteration minerals (biotite, chlorite, and amphibole) have been detected with blue color (Fig. 5c). Additionally, the ASTER index (b7 + b9/b8) highlighted alteration zones associated with carbonate and mafic minerals (e.g., epidote and chlorite) in the Nikeiba area, depicted in magenta (Fig. 5d) (e.g., Rowan and Mars, 2003; Van der Meer et al., 2012). Kaolinite and hydroxyl alteration minerals were detected using the indices (b4/b5) × (b8/b6) and (b7/b6) × (b4/b6), shown in orange and light green, respectively (Fig. 5e, f) (e.g., Rowan and Mars, 2003; Van der Meer et al., 2012). Finally, the ASTER indices (b4/b2) and (b5/b3) emphasized the gossan and ferrous iron alteration zones with red and tourmaline green colors, respectively (e.g., Van der Meer et al., 2012; Volesky et al., 2003).

The present study utilized an Analytical Spectral Device (ASD) to acquire reflectance spectra of twenty rock samples that represent a variety of lithological rock units in the Nikeiba area (Table 2). Using the ASD-TerraSpec Halo near-infrared (NIR) hyperspectral instrument, the field-collected samples of the study area were used to extract the implemented spectra of the lithological units (syenogranites, alkali feldspar granites, and quartz syenites; Supplementary 3-2).

4.3. Automated structural lineaments extraction

The geological structures can be identified through various spatial data (e.g., Hagag et al., 2019; Javhar et al., 2019; Abo Khashaba et al., 2023) as crucial in determining the formation of ore deposits. In this study, the lineament extraction algorithm (LINE) is used to extract lineaments from Sentinel-1B and ALOS PALSAR images. There were certain parameters used to extract lineaments from both datasets, including 1) Filter Radius (RADI) = 10; 2) Edge Gradient Threshold (GTHR) = 100; 3) Length Threshold (LTHR) = 30; 4) Fitting Error Threshold (FTHR) = 3; 5) Angular Difference Threshold (ATHR) = 15 and 6) Linking Distance Threshold (DTHR) = 20.

The results of automatic lineament extraction in both datasets are shown in Fig. 6a, b. In both datasets, spatial density analysis is done by interpolating the extracted lineament vector data using ArcGIS version 10.8 to determine the frequency of the lineaments per unit area (number/km²) (e.g., Hagag et al., 2019; Abo Khashaba et al., 2023; Khedr et al., 2023). The density maps of the extracted lineaments show that they are extremely concentrated at the contact between quartz syenites and syenogranites in the south of the study area (Fig. 6c, d). Additionally, they are concentrated at contacts between the alkali feldspar granites, quartz syenites, and metavolcanics in the north of the mapped area (Fig. 6c, d), as well as the contacts between metavolcanics and syenogranites in the northeast of the area (Fig. 6c, d).

5. Petrography

The petrographical description of the different rock types of the Nikeiba area, including syenogranites, alkali feldspar granites, quartz syenites, and pegmatites, are given in the following sections. In this study, the identification of accessory minerals was done by scanning electron microscopy (SEM)-energy dispersive X-Ray spectroscopy (EDS) with petrographic description and mineral chemistry. These accessory minerals include Fe-Ti oxides, zircon [ZrSiO₄], fluorite [CaF₂], columbite [(Fe, Mn)(Nb₂O₆)], rutile [TiO₂], apatite [Ca₁₀(PO₄)₆F₂], fergusonite [(REE,Y)NbO₄], allanite [(Ce,Ca,Y,La)₂(Al,Fe⁺³)₃(SiO₄)₃(OH)], thorite [ThSiO₄], and bastnaesite-(Ce) [(La, Ce, Nd)CO₃F] (Supplementary 4).

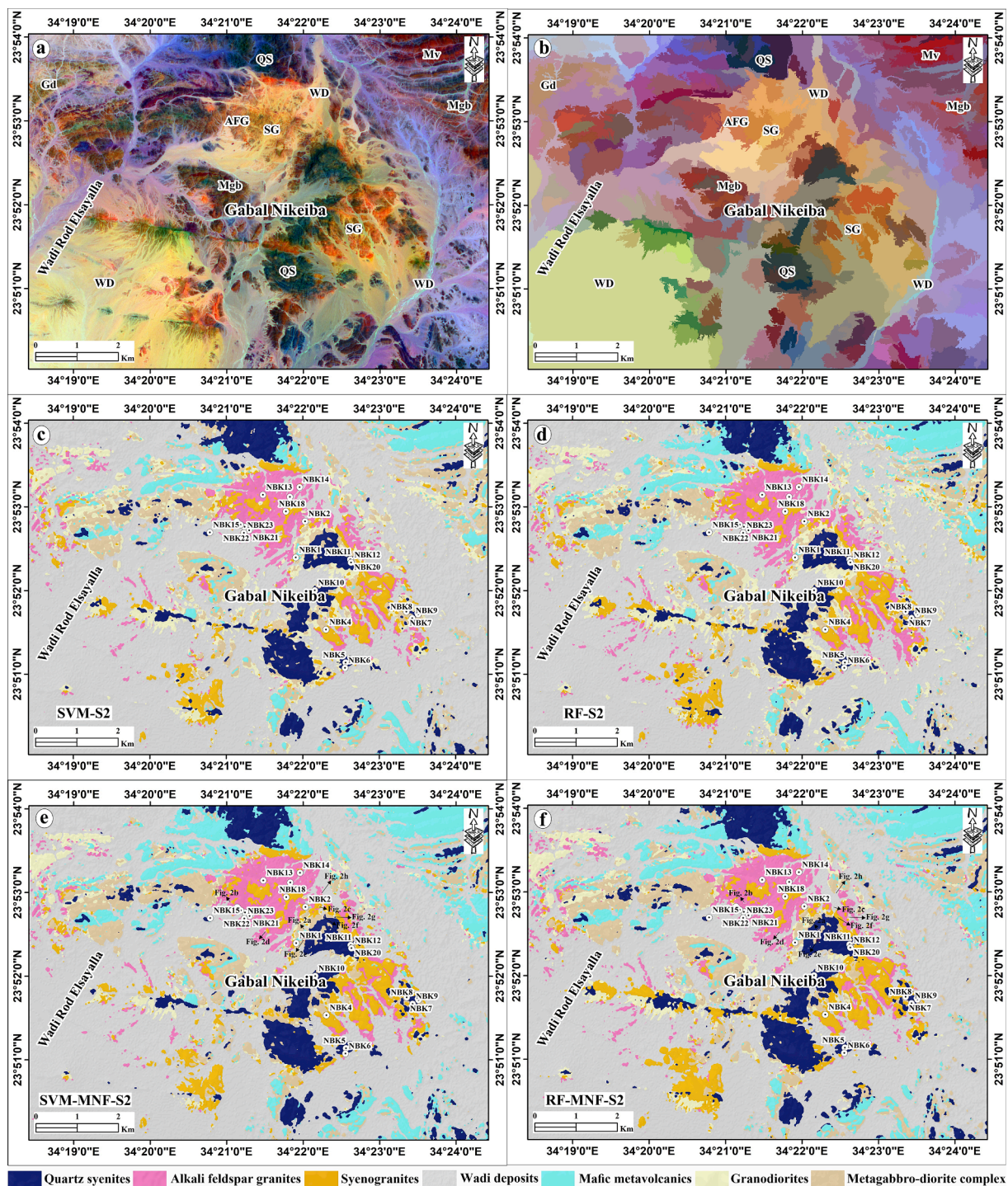


Fig. 4. (a) Sentinel-2 decorrelation stretch (b12, b8, b3) as RGB. (b) Semantic segmentation of the Sentinel-2 data. Automatic lithological detection using machine learning classification algorithms (c) RBF support vector machine applied to original bands of Sentinel-2. (d) Random forest applied to original bands of Sentinel-2. (e) SVM applied to MNF-Sentinel-2. (f) Random forest applied to MNF-Sentinel-2. Abbreviations: Mv; mafic metavolcanics, Mgb; metagabbro-diorite complex rocks, Gd; Tonalites-granodiorites, SG; syenogranites, AFG; alkali feldspar granites, QS; quartz syenites, WD; wadi deposits.

5.1. Syenogranites

Syenogranites are medium- to coarse-grained rocks characterized by a hypidiomorphic granular texture (Fig. 7a-d). The primary mineral composition includes K-feldspar (55–60 vol%), quartz (22–28 vol%), plagioclase (10–15 vol%), and biotite (3–5 vol%), with subordinate amounts of amphiboles and muscovite (<1 vol%) (Fig. 7a-d). Key alteration products consist of chlorite (~1 vol%), sericite, calcite, kaolinite, and epidote (Fig. 7a-d). Accessory minerals present include

Fe-Ti oxides, zircon, fluorite, allanite, garnet, apatite, rutile, columbite, thorite, fergusonite, and bastnaesite (Figs. 7a-d and 8). K-feldspar appears as subhedral to anhedral crystals of orthoclase and microperthite, exhibiting simple twinning and perthitic intergrowths with quartz, plagioclase, and biotite inclusions (Fig. 7a-c). Subhedral microcline crystals with cross-hatched twinning are also observed (Fig. 7b). Quartz occurs as anhedral crystals that fill the spaces between other minerals (Fig. 7b, c). Plagioclase is found as subhedral to euhedral tabular crystals, with some exhibiting significant sericitization in their cores, while

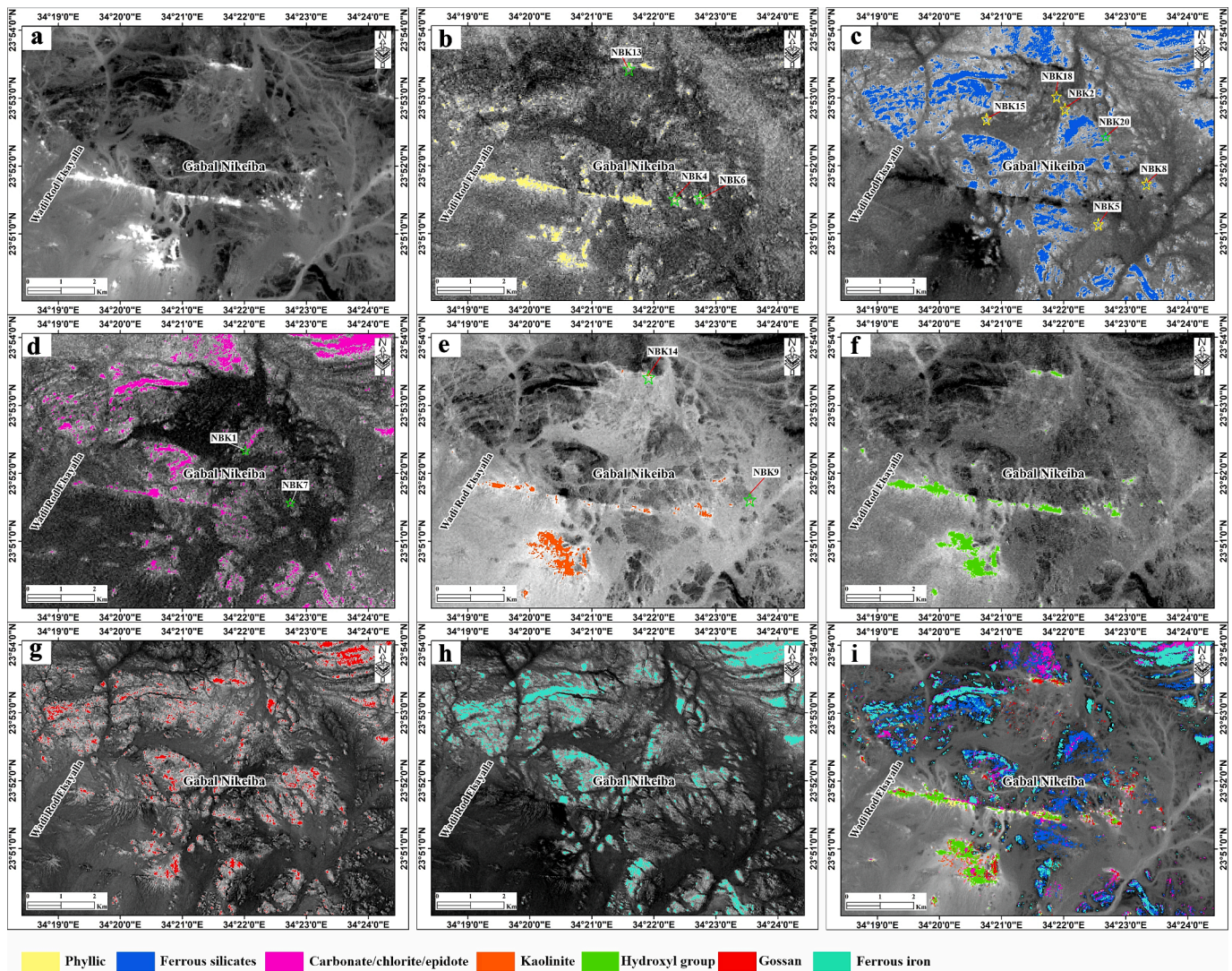


Fig. 5. Greyscale ASTER-Sentinel-2 alteration indices in the Nikeiba area. (a) Greyscale ASTER alteration index (b4/b5) emphasizes the different alteration zones with white pixels. (b) The phyllic alteration index (b5 + b7/b6) emphasizes the different alteration zones with a yellow color. (c) The ferrous alteration index (b5/b4) emphasizes the different alteration zones with a blue color. (d) Greyscale ASTER carbonate/chlorite/epidote index (b7 + b9/b8) emphasizes the different alteration zones with a magenta color. (e) Kaolinite alteration index (b4/b5) × (b8/b6) detecting the different alteration zones with orange color. (f) Hydroxyl alteration index (b7xb6) × (b4xb6) emphasizes the different alteration zones with green color. (g) ASTER alteration index (b4/b2) detecting gossan with red color. (h) ASTER index (b5/b3) emphasizing the ferrous iron alteration zones with tourmaline green. (i) ASTER mineral indices, showing seven types of alterations (phyllic, ferrous, carbonate/epidote/chlorite, kaolinite, hydroxyl group) of the in the Nikeiba area over the greyscale ASTER index (b4/b5). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

others remain as relics within K-feldspar (Fig. 7b). Biotite manifests as subhedral tabular crystals situated between quartz and plagioclase, or as interstitial flakes among quartz and K-feldspar or at the edges of garnet (Fig. 7c, d). It is frequently partially altered to chlorite and muscovite. Plagioclase and mafic silicates (such as amphibole and biotite) are primarily replaced by illite. K-metasomatism is indicated by the conversion of plagioclase and albite to microcline and orthoclase (Fig. 7a, b).

5.2. Alkali feldspar granites

Alkali feldspar granites exhibit medium- to coarse-grained crystals with an equigranular hypidiomorphic texture, and some samples display micrographic texture (Fig. 7e-h). The main mineral constituents are K-feldspar (60–65 vol%), quartz (24–30 vol%), plagioclase (4–6 vol%), biotite (~2 vol%), and subordinate sodic amphiboles (Fig. 7e-h). Minor amounts of muscovite are present as interstitial flakes between feldspars and quartz (Fig. 7f, j). Accessory minerals include zircon, fluorite, Fe-Ti oxides, beryl, apatite, columbite, and rutile, while chlorite and sericite

are the alteration products of biotite and feldspar, respectively (Fig. 7j, k, 8). The K-feldspar is the dominant mineral and occurs as euhedral to subhedral tabular orthoclase-perthite (string, flame, and braided) and microcline (Fig. 7e-k). Quartz forms subhedral to anhedral crystals (Fig. 7e-k). Plagioclase exhibits subhedral to euhedral elongate crystals with sharp contacts with alkali feldspar, some of which are altered in the core to sericite (Fig. 7j). Biotite appears as tabular to subhedral flakes with pale brownish to dark brown colors, and it is partially altered to chlorite and muscovite (Fig. 7f, j). Sodic amphiboles, including arfvedsonite and riebeckite, are rare and occur as subhedral to anhedral crystals (Fig. 7e). Euhedral, prismatic, and wedge-shaped zircon crystals are enclosed in K-feldspar and quartz (Fig. 7g, i, k, 8b), and euhedral to subhedral apatite crystals are also present (Fig. 7k). Fluorite occurs as large to moderate subhedral crystals in the interstices between quartz and k-feldspar (Fig. 7h, i, 8a). Fe-Ti oxides are represented by ilmenite, magnetite, and minor goethite (Fig. 7i, k). Columbite occurs as prismatic crystals, and some crystals are zoned (Fig. 8d).

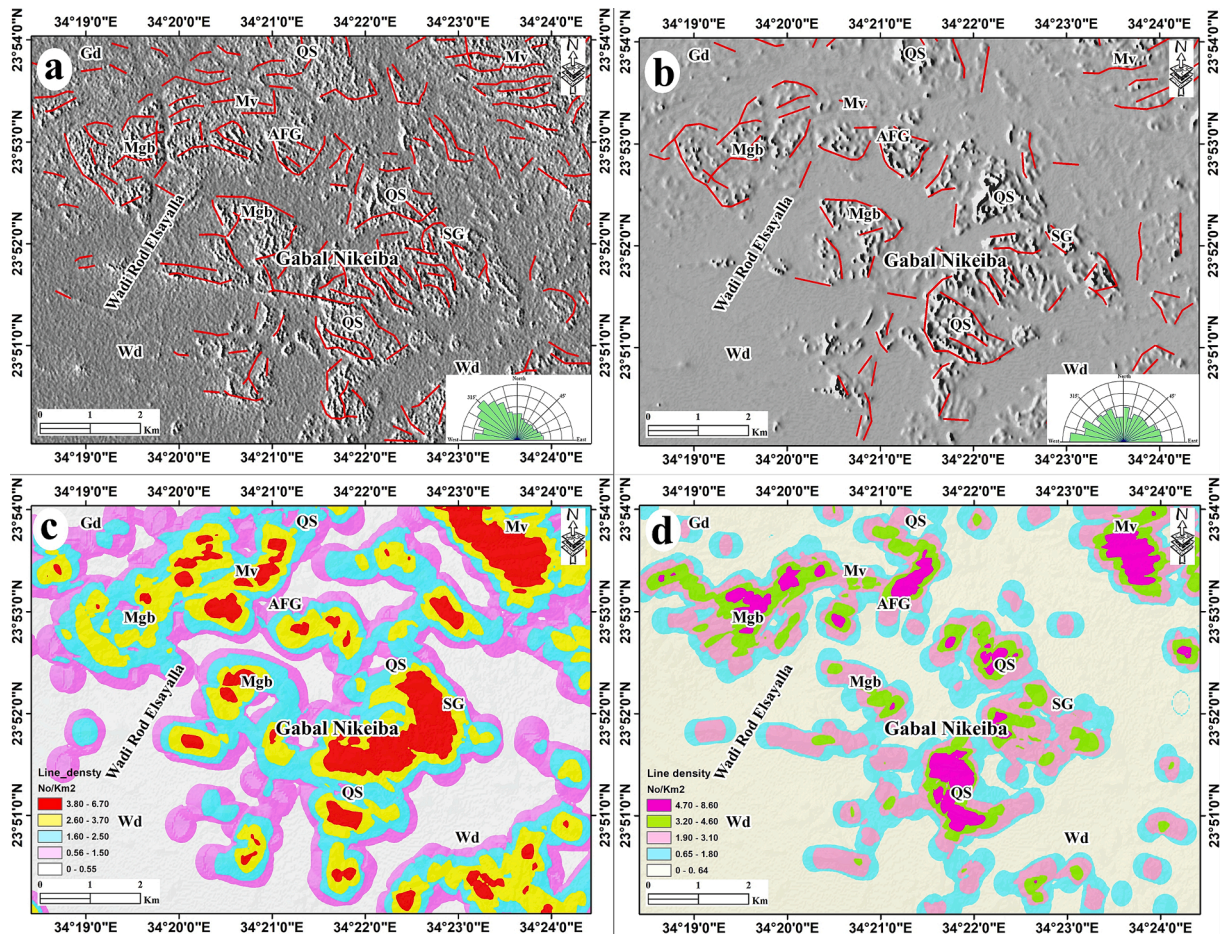


Fig. 6. (a, b) Lineaments extraction and rose diagrams based on Sentinel-1B and ALOS PALSAR, respectively. (c, d) Lineaments density map of Sentinel-1B and ALOS PALSAR, respectively. The highest concentration in quartz syenites, syenogranites, and alkali feldspar granites, respectively. For abbreviations see Fig. 4.

5.3. Quartz syenites

Quartz syenites are medium- to coarse-grained, pale pink rocks with a hypidiomorphic granular texture (Fig. 71-o). They are composed of K-feldspar (65–70 vol%), quartz (15–18 vol%), sodic amphiboles (arfvedsonite, riebeckite) (~6 vol%), biotite (~4 vol%) with a minor amount of plagioclase and pyroxenes (Fig. 71-o). Accessory minerals include zircon, Fe-Ti oxides, apatite, rutile, allanite, and fergusonite, while the alteration products are muscovite, chlorite, sericite, epidote, and carbonates (Fig. 71-o, 8). Perthitic orthoclase is the most abundant alkali feldspar, occurring as tabular subhedral crystals with a variety of textural features, such as string, flame, and braided, and is invaded by numerous accessory minerals along cleavage (Fig. 71, o). Quartz appears as large anhedral crystals or as tiny vein-filling aggregates, often containing inclusions of zircon and opaque phases (Fig. 71, o). Plagioclase is rare and marked by polysynthetic twinning lamella. The amphiboles, primarily arfvedsonite, and riebeckite, are the dominant mafic minerals, occurring as interstitial acicular crystals (Fig. 7n). Riebeckite is characterized by a distinctive blue color, while arfvedsonite exhibits brown to greenish colors, and both contain numerous inclusions of zircon, apatite, and Fe-Ti oxide minerals. Biotite appears as brown flakes or greenish-brown tabular crystals, reflecting its partial replacement to chlorite during hydrothermal alteration (Fig. 7m). Zircon is the main accessory phase, occurring as wedge-shaped and forming small prismatic crystals (Fig. 7o). Zircon is enclosed by other minerals such as perthite, quartz, amphiboles, and biotite (Fig. 8c). Allanite is also recorded in some samples (Fig. 7m, 8f). Pyroxene is found as

clinopyroxene and orthopyroxene. Apatite is associated with zircon and occurs as an inclusion in quartz (Fig. 8c).

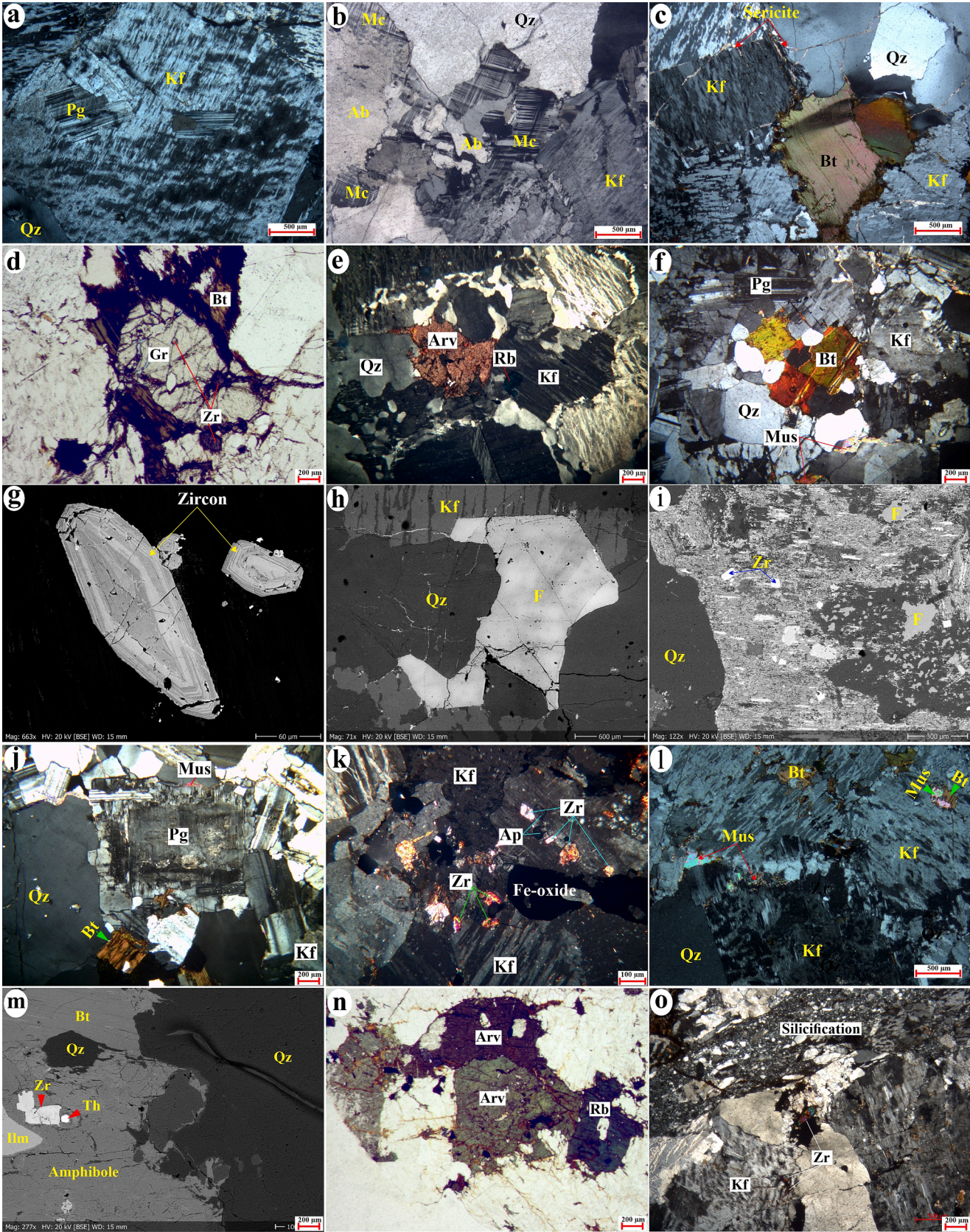
5.4. Pegmatites

The petrographic study revealed that the studied pegmatites consist of K-feldspars, quartz, plagioclase, biotite, muscovite, beryl, and Fe-Ti oxides. Pegmatites are very coarse-grained and show a hypidiomorphic equigranular texture.

6. Mineral chemistry

6.1. Feldspars

Representative chemical composition, structural formulae, and end-member formula of plagioclase (22 points), albite (35 points), and K-feldspar (41 points) in the Nikeiba granites are given in Table 3 and Supplementary 5. In the Nikeiba granites, plagioclase has a wide variation in anorthite contents and ranges in composition from oligoclase (An₂₀₋₂₃) to andesine (An₄₁₋₄₆) (Fig. 9a; Table 3 and Supplementary 5). It has high Al₂O₃ (22.62–26.93 wt%), Na₂O (5.85–9.21 wt%), and CaO (4.17–9.54 wt%) contents (Table 3 and Supplementary 5). Albite has limited compositions (Ab_{95.76-99.72}) close to the end-member NaAlSi₃O₈ with low Al₂O₃ (18.19–20.14 wt%), CaO (0–0.84 wt%) and high Na₂O (11.42–12.0 wt%) contents compared to the plagioclase (Fig. 9a; Table 3 and Supplementary 5). The K-feldspars from the Nikeiba granites have a homogenous composition near the end-member KAlSi₃O₈, with low



(caption on next page)

Fig. 7. Photomicrographs and Scanning Electron Microscopy images (SEM) images from different granitic rocks of the Nikeiba area showing mineralogical and textural variations. (a) Subhedral plagioclase (Pg) enclosed in coarse perthitic orthoclase (Kf) (b) microcline perthite (Mc) showing cross-hatching twinning, (c) subhedral crystals of biotite (Bt) between the interstices of Qz (quartz) and Kf (K-feldspar) and small tiny sericite, and (d) subhedral garnet (Gr) crystals rimmed with biotite (Bt) in syenogranites. (e) Large arfvedsonite (Arv) crystals associated with small riebeckite (Rb) crystal between the interstices of Qz (quartz) and Kf (K-feldspar), (f) coarse subhedral plated biotite (Bt) associated with tiny secondary muscovite (Mus), (g) well-developed oscillatory zoned zircon (Zr) crystals, (h) discrete crystal of fluorite (F) in the interstice between other minerals, (i) Several dissiminated subhedral to euhedral zircon (Zr) crystals, (j) coarse zoned plagioclase crystal, and (k) disseminated zircon (Zr) and apatite (Ap) in K-feldspar crystals (Kf) in alkali feldspar granites. (l) Coexisting biotite and muscovite in K-feldspar, (m) small thorite (Th) in the rim of subhedral zircon and both exist as inclusion in amphibole, (n) coarse crystals of green to brown arfvedsonite (Arv) and blue riebeckite, (o) large quartz vein (silicification) in quartz syenites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

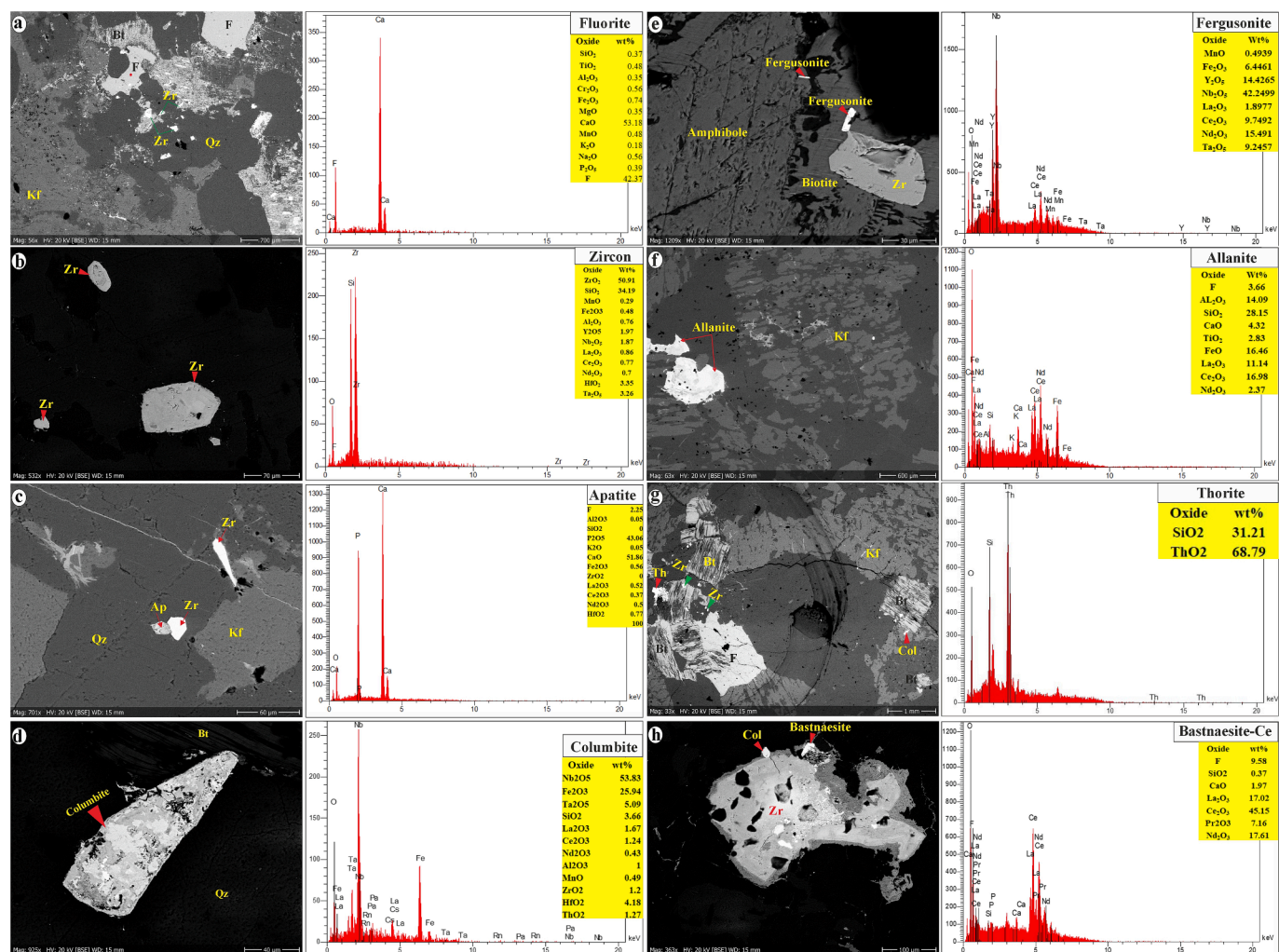


Fig. 8. Scanning Electron Microscopy images (SEM) images with EDS spectrum analysis of rare-metal minerals in the Nikeiba area. (a) Anhedral to subhedral fluorite (F) between the rock-forming minerals quartz (Qz) and K-feldspar (Kf) in alkali feldspar granites. (b) Euhedral to subhedral zoned zircon (Zr) in alkali feldspar granites. (c) Euhedral apatite (Ap) adjacent to Zr (zircon) crystal, and both occur as inclusion in quartz (Qz) in quartz syenites. (d) Subhedral columbite (Col) crystals in the constituent between biotite (Bt) and Qz (quartz) in alkali feldspar granites. (e) Small fergusonite crystals at the rim of large zircon (Zr) crystal and both as inclusion in biotite in quartz syenites. (f) Anhedral allanite crystals in quartz syenites. (g) Anhedral thorite (Th) crystal at the rim of biotite (Bt) in alkali feldspar granites. (h) Small bastnaesite crystal at the rim of zircon (Zr) in syenogranites.

Na₂O (< 0.65 wt%) and CaO (<0.37 wt%) contents and an average composition of (An_{0.18} Ab_{2.87} Or_{96.95}) (Fig. 9a; Table 4 and Supplementary 5).

6.2. Biotites

The chemical analysis of the biotites from all of the studied granites of the Nikeiba area and their structural formulae are given in Table 3 and Supplementary 5. The biotite minerals exhibit a range of Al₂O₃ contents, from 9.48 wt% to 15.37 wt%, reflecting subtle variations in

their aluminous character (Table 4; Supplementary 5). Similarly, the FeO^I content varies considerably, between 29.98 wt% and 36.87 wt%, while the MgO and K₂O concentrations range from 0.26 wt% to 2.73 wt% and 8.06 wt% to 9.06 wt%, respectively (Table 4; Supplementary 5). The biotite crystals (Table 4; Supplementary 5) are mostly iron-rich siliceous varieties (i.e., annite). These geochemical attributes are consistent with the characteristics of primary igneous biotite, as evidenced by the biotite composition plot in Fig. 9b. Further classification of the biotite samples, using the FeO^I versus Al₂O₃ discrimination diagram proposed by Abdel-Rahman (1994), clearly positions the analyzed

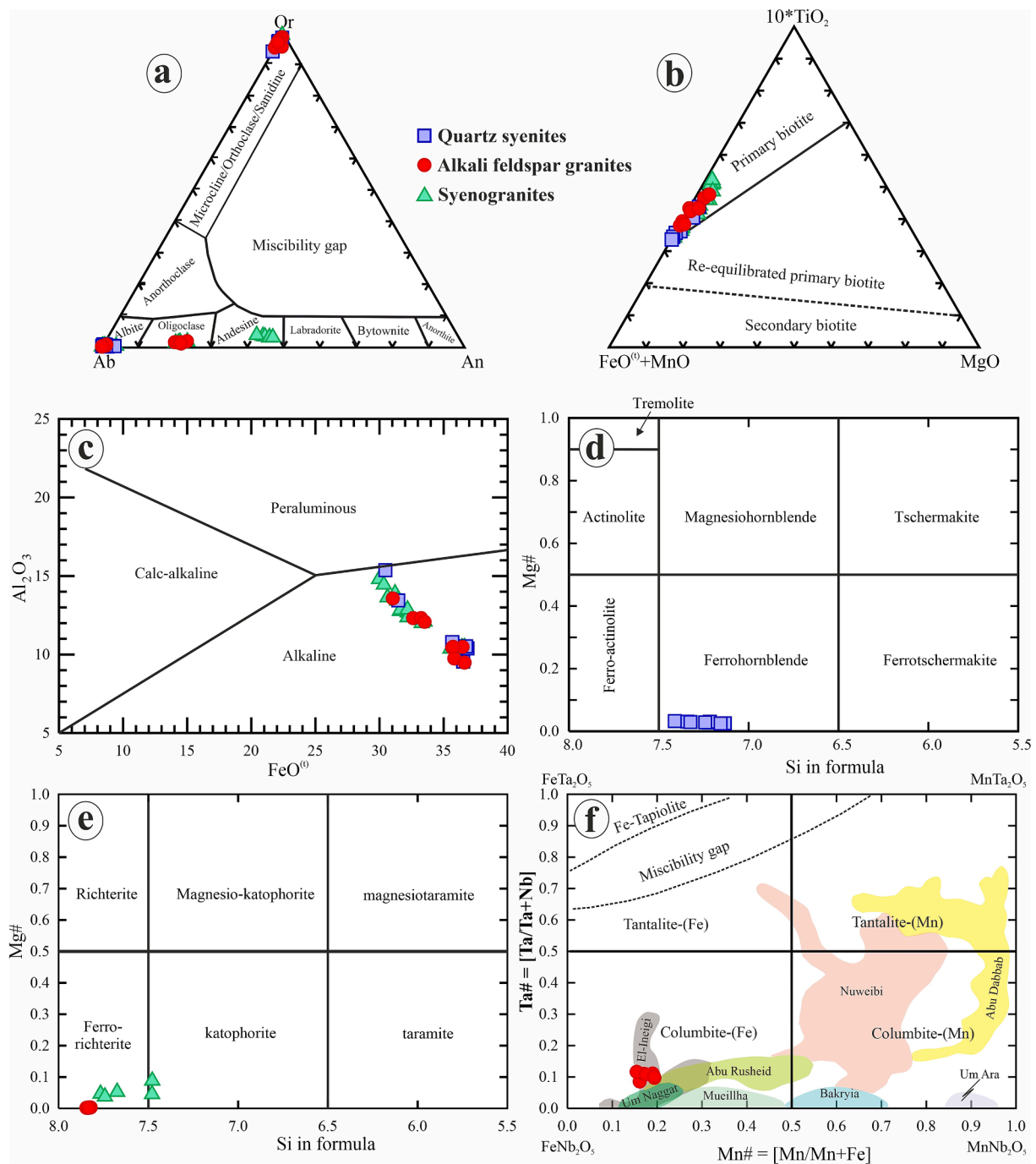


Fig. 9. (a) Feldspar composition in the An-Ab-Or diagram. (b) TiO_2 -($\text{FeO} + \text{MnO}$)- MgO ternary diagram for classification of biotite (after Nachit et al., 2005). (c) FeO^{I} versus Al_2O_3 discrimination diagram for biotite (Abdel-Rahman, 1994). (d, e) Classification of the analyzed amphiboles (after Leake et al., 1997). (f) A plot of $\text{Ta\#} = [\text{Ta}/(\text{Ta} + \text{Nb})]$ versus $\text{Mn\#} = [\text{Mn}/(\text{Mn} + \text{Fe})]$ ratios of columbite group minerals from the Nikeiba granites in comparison with others from rare metal granitoids the Eastern Desert of Egypt (data from Abdalla et al., 1998; Melcher et al., 2015).

biotite crystals within the alkaline field (Fig. 9c). This emphasizes the affinity of the host granitic intrusions to an alkaline magmatic suite.

6.3. Amphiboles

The detailed geochemical analysis of the amphibole minerals found in the granitic rock units of the Nikeiba has demonstrated their unique distribution and compositional features. Amphibole is found to be a more common mineral phase in the quartz syenites, with subordinate occurrences in the syenogranites and alkali feldspar granites (Fig. 7; Table 5; Supplementary 5). The detailed chemical analyses of the

amphibole minerals, along with their calculated structural formulae, are presented in Table 5 and Supplementary 5. These amphiboles are predominantly primary in origin ($\text{Ti}(\text{apfu}) > 0.1$), exhibiting a wide compositional range from calcic-amphiboles to sodic-rich varieties Table 5 and Supplementary 5. The calcic amphiboles are exclusively restricted to the quartz syenites (Table 5 and Supplementary 5) and are classified as ferrohornblende (Fig. 9d) based on the amphibole classification diagram of Leake et al. (1997). In contrast, the sodic-calcic amphiboles are observed in the syenogranites and alkali feldspar granites (Table 5 and Supplementary 5). They are classified as ferrichterite (Fig. 9e) according to the classification diagram of Leake et al. (1997).

Moreover, the sodic amphiboles are found in the quartz syenites and alkali feldspar granites (Table 5 and Supplementary 5), and are predominantly classified as riebeckite and arfvedsonite based on the Leake et al. (1997) amphibole nomenclature (Table 5 and Supplementary 5).

6.4. Chlorite

The major element compositions of chlorite (12 points) and its structure formula, are given in Supplementary 5. Chlorite from the Nikeiba granites has a total value ranging from 85.7 wt% to 89.0 % Supplementary 5. It shows a wide range of SiO₂, FeO^t, Al₂O₃, and MgO that vary from 25.1 wt% to 31.4 wt%, 33.5 wt% to 55 wt%, 8.6 wt% to 18.5 wt%, 2.7 wt% to 7.5 wt%, respectively (Supplementary 5). In the classification diagram (Al)–Mg–Fe of Zane and Weiss (1998), chlorite is plotted in the field of chamosite (Supplementary 5).

6.5. Pyroxenes

The representative chemical analysis of some pyroxene crystals (16 points) from the quartz syenites is listed in Supplementary 5. Quartz syenites have two types of pyroxenes, including clinopyroxene and orthopyroxene Supplementary 5. Clinopyroxene has high contents of CaO (21.4 – 22.0 wt%), SiO₂ (51.8–52.8 wt%), moderate MgO (14.2–14.8 wt%), and FeO^t (8.5–8.8 wt%), and low Al₂O₃ (1.11–1.25 wt%) Supplementary 5. On the other side, orthopyroxene has a high content of MgO (24.0–28.6 wt%), SiO₂ (52.9–54.7 wt%), and FeO^t (13.8–19.6 wt%), and low CaO (0.89–0.99 wt%), and Al₂O₃ (0.39–0.61 wt%) (Supplementary 5). According to the classification diagram of Deer et al. (1992), the analyzed clinopyroxene crystals are classified as diopside, while orthopyroxene is plotting in the field of clinoenstatite (Supplementary 5).

6.6. Fe-Ti oxides

The Fe–Ti oxide minerals (magnetite = 20 points; ilmenite = 16 points, goethite = 7 points) were analyzed in the syenogranites, alkali feldspar granites, and quartz syenites. The chemical composition of the Fe–Ti oxide minerals of the Nikeiba granites are listed in Supplementary 5. The ilmenite has an average content of TiO₂ = 51.15 wt% and FeO^t = 43.19 wt% Supplementary 5. Moreover, it has a high MnO content ranging from 1.04 to 2.9 wt% in the syenogranites, 1.23 to 3.21 wt% in the quartz syenites, and 3.74 to 8.71 wt% in alkali feldspar granites (Supplementary 5). This results in the presence of considerable MnTiO₃ component of the ilmenites of up to 19.97 wt% in quartz syenites (Supplementary 5). According to Deer et al. (1992), the pyrophanite (MnTiO₃) component may increase in ilmenite through simple substitution of Mn for Fe²⁺ with increasing oxygen fugacity under magmatic conditions. The magnetite crystals contain a noticeably high TiO₂ of up to 12.25 wt%, 4.28 wt%, and 20.86 wt% in syenogranites, alkali feldspar granites, and quartz syenites, respectively, and a low amount of MnO (<1.82 wt%) (Supplementary 5).

6.7. Accessory minerals

The Nikeiba granites include wide variations of accessory minerals, such as zircon, columbite, apatite, and rutile (Supplementary 5).

Representative EPMA analyses of zircon and its structural formula are given in Table 6. It shows limited variations in compositions with ZrO₂ ranging from 62.3 wt% to 65.0 wt%, SiO₂ of 30.6 wt% to 32.8 wt%, and HfO₂ from 0.88 wt% to 3.0 wt% (Table 6; Supplementary 5).

The major oxides in the analyzed columbite are Nb₂O₅ (64.70–66.65 wt%), Ta₂O₅ (10.30–14.05 wt%) and FeO^t (16.46–17.15 wt%) with subordinate MnO (3.06–3.89 wt%) (Supplementary 5). Columbite has Ta/(Nb + Ta) ratios between 0.08 and 0.12 and Mn/(Mn + Fe) ratios between 0.15 and 0.19; accordingly, they are classified as columbite-(Fe) (Fig. 9f; Supplementary 5).

The chemical analysis of the analyzed apatite from the studied granites shows that it has limited variation in composition with CaO contents ranging from 54.0 wt% to 55.7 wt%, P₂O₅ from 38.8 wt% to 41.6 wt%, and F from 2.02 wt% to 3.23 wt% (Supplementary 5). Rutile has an average content of TiO₂ (up to 93.4 wt%), and FeO^t (2.81 wt%) (Supplementary 5).

7. Whole-rock chemistry

7.1. Geochemical characteristics

The concentrations of major oxides, selected trace elements, and REEs of the Nikeiba area (22 samples) are listed in Table 7 and Supplementary 6. The Nikeiba rocks show a wide range of silica contents (SiO₂ = 65.7–73.6 wt%) (Table 7; Supplementary 6). Their differentiation index (D.I: normative Q + Or + Ab; Thornton and Tuttle, 1960) ranges from 92.2 to 93.6 for syenogranites, 91.6–94.0 for alkali feldspar granites, and 86.8–91.5 for quartz syenites (Table 7; Supplementary 6). The studied syenogranites and alkali feldspar granites have nearly similar chemical compositions with high silica contents (SiO₂ = 70.7–73.6 wt%), high K₂O/Na₂O ratios (1.0–1.33), Rb (197–241 ppm), and low Ba (60–279 ppm) compared to quartz syenites (SiO₂ = 65.7–69.5 wt%), (K₂O/Na₂O = 0.70–0.90), Rb (123–172 ppm), and Ba (294–717 ppm) (Table 7; Supplementary 6). The Nikeiba granites have elevated total alkalis (9.2–10.2 wt%), CaO (0.53 – 1.50 wt%), and FeO^t (1.97–3.36 wt%), similar to other ANS granites (e.g., El-Bialy and Streck, 2009a; Moreno et al., 2014; Azer et al., 2014; Sami et al., 2017; Khedr et al., 2023) (Table 7; Supplementary 6). Moreover, they are characterized by high contents of the REEs (total REE up to 639 ppm), Zr (821 ppm), Y (135 ppm), Nb (267 ppm), and Ga (22.4 ppm) (Table 7; Supplementary 6).

In Harker variation diagrams, the Nikeiba granitic rocks show regular differentiation trends with a distinct compositional gap between quartz syenites and more felsic granitic rocks (syenogranites and alkali feldspar granites) (Supplementary 7–1, 2). With increasing SiO₂ concentration, contents of TiO₂, Al₂O₃, MgO, FeO^t, CaO, Na₂O, MnO, Sr, and Ba are decreasing while K₂O, Rb, Y, U, Th, Nb, and Ta increase in the same direction (Supplementary 7–1, 2).

In the classification diagram of De la Roche et al. (1980), the studied syenogranites and alkali feldspar granites lie in the field of alkali feldspar granites, while quartz syenites mainly plot in the field of quartz syenites (Fig. 10a). When classified based on the petrographic modal contents (determined via point counting), the syenogranites, alkali feldspar granites, and quartz syenites plot in the field of syenogranites, alkali feldspar granites, and quartz syenites, respectively (Fig. 10b).

In chondrite normalized REEs pattern (using normalization factors of Sun and McDonough (1989), the studied granites show enrichment of light rare earth elements (LREEs) over heavy rare earth elements (HREEs) and strongly negative Eu anomalies of syenogranites and alkali feldspar granites (Eu/Eu* = 0.15 – 0.33) when compared to quartz syenites (Eu/Eu* = 0.30 – 0.73) (Fig. 11a, b). Quartz syenites show strongly LREE-enriched more fractionated REE patterns (La_N/Yb_N = 4.21–11.11; La/Sm_N = 2.58–4.55) compared to syenogranites and alkali feldspar granites (La/Yb_N = 2.74–6.93; La/Sm_N = 2.09–5.32) (Table 7; Supplementary 6). A tetrad effect (TE₁₋₃; Table 7; Supplementary 6) > 1, according to the quantification method of Irber (1999) and splitting the REE patterns into four rounded segments, is found for most samples. Regarding their compositional characteristics, the Nikeiba granites are similar to other alkaline A-type granites of ANS (El-Bialy and Streck, 2009b) (Fig. 11a, b). Primitive mantle normalized trace-element patterns (using normalization factors of Sun and McDonough, 1989) clearly display positive Rb anomalies in syenogranites and alkali feldspar granites and strongly negative anomalies of Ba, Sr, P, and Ti in all granitoids investigated (Fig. 11c, d), reflecting the fractionation of feldspar, apatite, and Fe-Ti oxides, respectively.

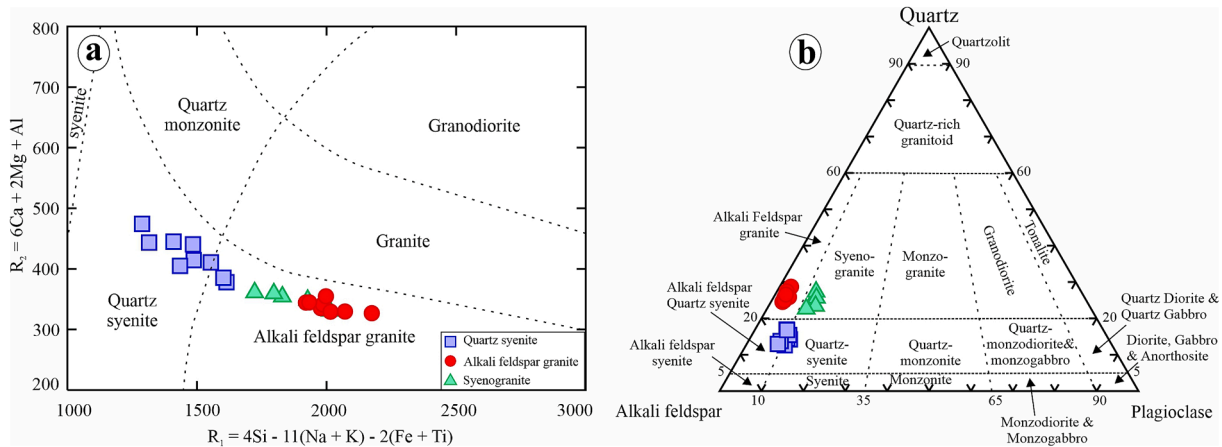


Fig. 10. (a) Nomenclature of the plutonic rocks using the R_1 - R_2 diagram (De la Roche et al., 1980). (b) Quartz-alkali feldspar-plagioclase (QAP) classification diagram (Streckeisen, 1976).

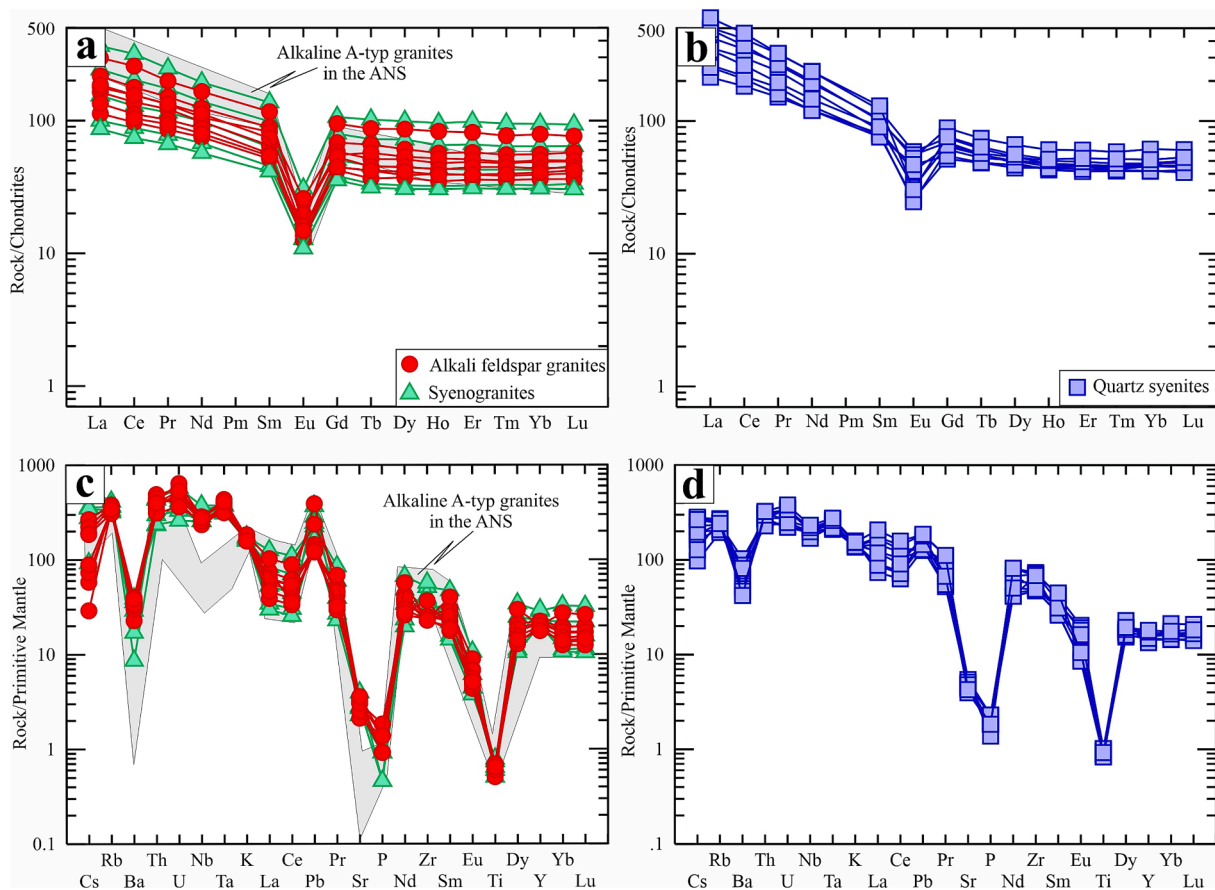


Fig. 11. Normalized multi-trace element diagrams for whole-rock chemistry. Chondrite-normalized REE patterns of syenogranites and alkali feldspar granites (a) and quartz syenites (b) of the Nikeiba area. Primitive mantle-normalized trace elements plots of syenogranites and alkali feldspar granites (c) and quartz syenites (d). Chondrite values from Sun and McDonough (1989). Fields of ANS A-type granites (El-Bialy and Streck, 2009).

7.2. Magma type and tectonic setting

Utilizing different geochemical classifications and discrimination diagrams for granitic rocks, the studied granites are critically evaluated. According to the major element classification diagram ($\text{SiO}_2 > 68\%$) of Sylvester (1989), the Nikeiba granites have an alkaline affinity (Fig. 12a). In general, these granites show very high alkali contents ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 9.23$ to 10.2 wt%; Table 7; Supplementary 6), and most

of them plot in the alkalic to alkali-calcic fields of Frost et al. (2001) (Fig. 12b). They have metaluminous to slightly peraluminous characteristics (molar A/CNK : $(\text{Al}_2\text{O}_3/\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}) = 0.93$ – 1.04) (Fig. 12c). The peraluminous character is confirmed by the calculated normative corundum (up to 0.69% ; Table 7; Supplementary 6) and the presence of muscovite in thin sections (Fig. 7f). The samples group as ferroan A-type granites (Fig. 12d) on the $\text{FeO}^{\text{T}}/(\text{FeO} + \text{MgO})$ vs. SiO_2 diagram (Frost et al., 2001).

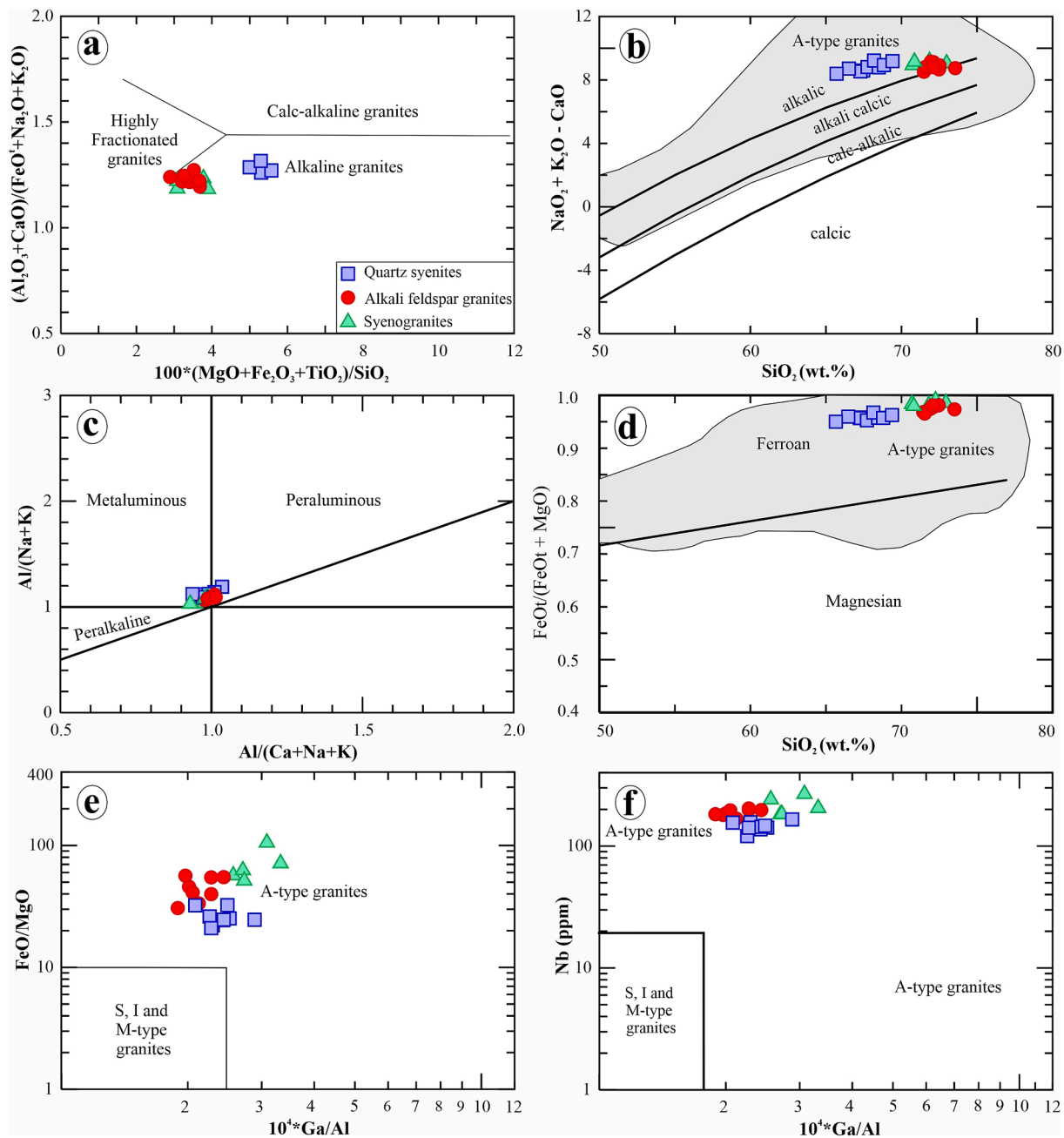


Fig. 12. (a) Major element classification diagram ($\text{SiO}_2 > 68\%$), showing the fields of alkaline, calc-alkaline, and highly fractionated calc-alkaline rocks (Sylvester, 1989). (b) Chemical classification diagram using SiO_2 versus $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ (Frost et al., 2001). (c) A/NK (molar $\text{Al}_2\text{O}_3/\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus A/CNK (molar $\text{Al}_2\text{O}_3/\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}$) (Maniar and Piccoli, 1989). (d) SiO_2 versus $\text{FeO}^\dagger/\text{FeO}^\dagger + \text{MgO}$ binary diagram showing that Nikeiba granitoids are ferroan (Frost et al., 2001). $10^4 \times \text{Ga}/\text{Al}$ against $\text{FeO}^\dagger/\text{MgO}$ (e) and Nb (f) for distinguishing between I, S, M, and A-type granites (Whalen et al., 1987).

The term A-type granites is used to distinguish within-plate or anorogenic granites from those originating in other tectonic settings (Loiselle and Wones, 1979). In this work, numerous characteristic features, such as metaluminous to weakly peraluminous nature, high $10^4 \times \text{Ga}/\text{Al}$ ratios (1.89–3.32), and $\text{FeO}^\dagger/(\text{FeO}^\dagger + \text{MgO})$ ratios (0.95–0.99), ΣREEs (135–639 ppm), Zr (up to 821.4 ppm), Th, and higher alkali contents, with substantial depletion in MgO and CaO, reflect the alkaline A-type affinity of the Nikeiba granites (e.g., Whalen et al., 1987; Eby, 1992; El-Bialy and Streck, 2009b; Khedr et al., 2023, 2024). Concomitantly, in discrimination diagrams of FeO/MgO vs. $10^4 \times \text{Ga}/\text{Al}$ and Zr vs. $10^4 \times \text{Ga}/\text{Al}$ (Whalen et al., 1987), the studied granites lie in the field of A-type granites (Fig. 12e, f). Moreover, the alkaline A-type character of the

granites is supported by their enrichment in large ion lithophile elements (LILE) like Rb, Cs, and K, and in high field strength elements (HFSE) like Ga (up to 22.4 ppm), Zn (237 ppm), Y (135 ppm), Ta (17.6 ppm), and Nb (267 ppm), as well as their strong depletion in Ba, Sr, Ti, and P (Fig. 11c, d; Table 7; Supplementary 6).

The tectonic setting of the studied granites can be determined by various geochemical discrimination diagrams. In the tectonic discrimination diagram Rb versus Y + Nb of Whalen et al. (1987), the studied syenogranites, alkali feldspar granites, and quartz syenites plot in the field of A-type granites of within-plate setting (Fig. 13a). This is confirmed by the Rb/30-Hf-3*Ta ternary diagram of Harris et al. (1986) (Fig. 13b). The Rb/Sr vs. K/Rb diagram (Fig. 13c) was found to be a

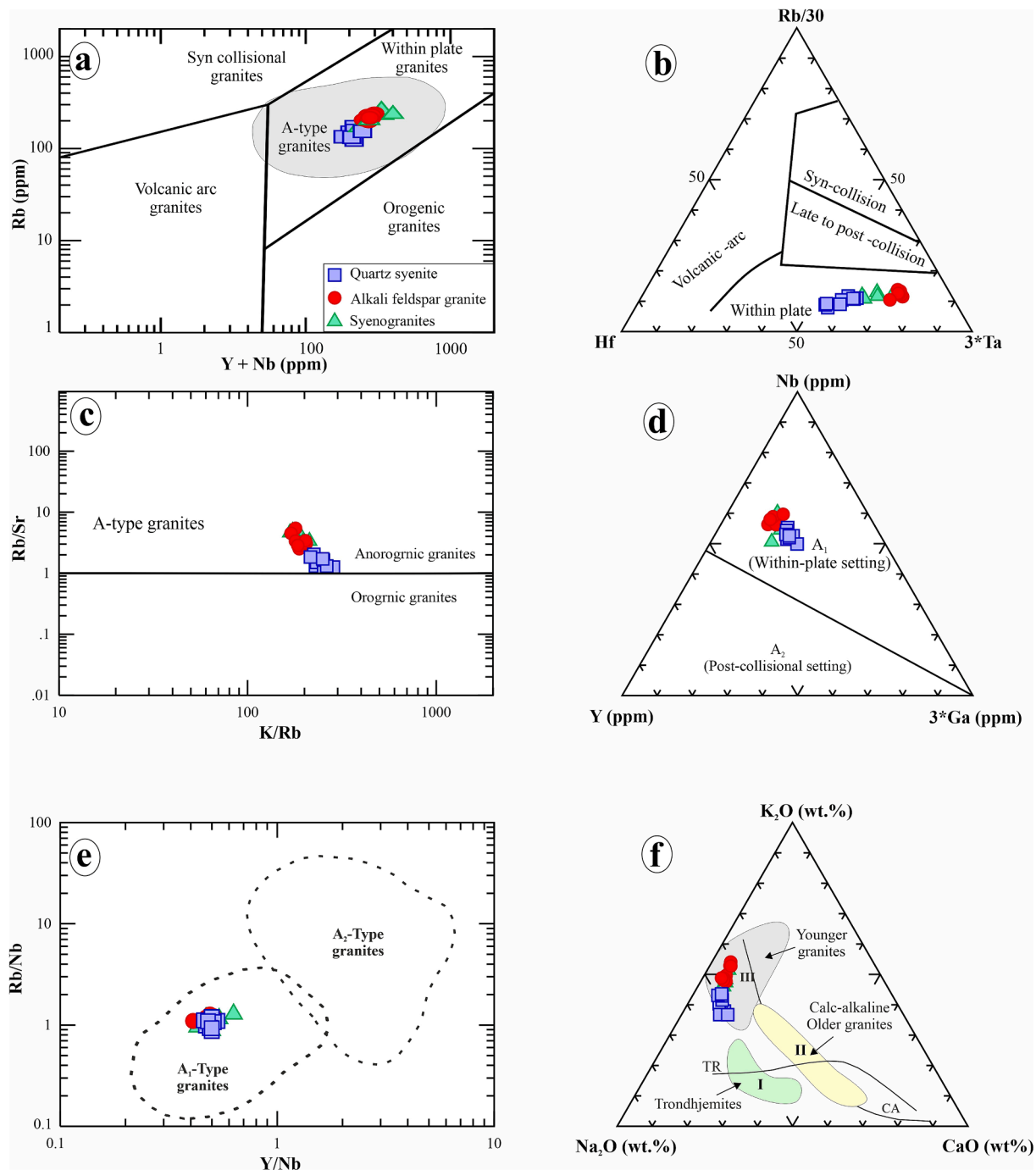


Fig. 13. (a) Y + Nb versus Rb tectonic discrimination diagram of Pearce et al. (1984). Fields for post-collision granites after Pearce (1996) and A-type granites after Whalen et al. (1987). (b) Hf-Rb/30–3*Ta ternary diagram (after Harris et al., 1986). (c) K/Rb versus Rb/Sr binary diagram. Y-Nb-Ga*3 ternary diagram (d) and Rb/Nb versus Y/Nb binary diagram (e) of Eby (1992) to distinguish between A₁ and A₂ granitoids; A₁ is anorogenic A-type granite with mantle signature whereas A₂ is post-collisional A-type granite with crustal source. (f) Na₂O–K₂O–CaO ternary diagram of Egyptian granitoids (Hassan and Hashad, 1990; Sami et al., 2017; Khedr et al., 2022, 2023). Trondjemites and calc-alkaline fields are after Barker and Arth (1976).

useful discriminant between orogenic and anorogenic granites (Abdel-Rahman and El-Kibbi, 2001). The Rb/Sr ratio of the Nikeiba granites is greater than one (Rb/Sr = 1.25–5.42; Table 7; Supplementary 6), suggesting an anorogenic setting. Based on the Nb–Y–3*Ga and Y/Nb versus Rb/Nb discrimination diagrams of Eby (1992), the Nikeiba granites plot in the field of A₁-type granites, again suggesting a within plate tectonic setting (Fig. 13d, e). Compared to other Egyptian granitoids, the studied granites, resemble younger granites of late to post-collisional settings (Fig. 13f).

8. Discussion

8.1. Machine learning-based lithological mapping

In this work, we used object-based machine learning algorithms, such as RBF-SVM and RF, to enhance the objectivity of image allocation in the Nikeiba area (Fig. 4; Supplementary 3–1). The performance of both algorithms applied to original bands and MNF was evaluated using a confusion matrix and compared to each other (Table 1; Supplementary 3–1). SVM applied to MNF-Sentinel-2 exhibited superior performance

(OA = 92.38 %, Kappa = 90.57 %, F1-score = 88.79 %), effectively differentiating lithological units, compared to the original bands of Sentinel-2 data (OA = 89.54 %, F1-score = 85.84 %) (Table 1; Supplementary 3–1). These high accuracies are related to many reasons, such as the high spatial resolution of Sentinel-2, high radiometric resolution with 16-bit, precise training sets, and the performance of machine learning algorithms that were used. These results have been validated based on several methods, including intensive fieldwork, petrography, and geochemistry data analysis (Figs. 2, 7–10).

Despite the studied granites (syenogranites, alkali feldspar granites, and quartz syenites) being nearly similar in mineral composition, the RBF-SVM classifier applied to MNF- Sentinel-2 imagery was able to accurately classify them with F1-scores of 90.67 %, 85.79 %, and 99.21 %, respectively (Fig. 4; Table 1; Supplementary 3–1). These high accuracy values indicate a strong agreement between the classified data and the ground truth observations. The results of machine learning classification were successful in not only producing an accurately discriminated lithological map but also identifying a new distribution of granitic rocks of the Nikeiba area (Fig. 4). These detailed mapping identifications of granitic rocks are very important because they have high concentration of rare earth elements (up to REEs = 639 ppm; Table 7; Supplementary 6) and other economically important rare metals. These results demonstrate the potential of using machine learning for automatic lithological identification, especially when using the Sentinel-2-MNF enhanced image with improved classification accuracy. So, it would be of great interest to geologists for lithological mapping and mineral exploration, particularly for selecting appropriate machine learning-based techniques to be implemented in similar areas.

8.2. Crystallization conditions of the Nikeiba granites

Accessory minerals like zircon and apatite play a crucial role in the estimation of their crystallization temperatures (Harrison and Watson, 1984). The Nikeiba granites have a high content of zirconium (syenogranites: Zr = 255–572 ppm), (Alkali feldspar granites: Zr = 258 – 638 ppm), and quartz syenites; Zr = 526 – 821 ppm) similar to Wadi El-Baroud granites (El-Bialy and Omar, 2015). On the other side, these contents are high when compared to other granitic rocks in the Eastern Desert of Egypt (e.g., Umm Naggat, Homrit Waggat, Abu Diab, and El-Ineigi) (Table 7; Supplementary 6) (e.g., Khedr et al., 2023, 2024; Azer et al., 2020; Sami et al., 2017). Zircon crystallizes in granitic magmas during an early stage, and the temperature of the magmas has a major influence on the Zr partition behavior of zircon. In order to determine zircon saturation temperatures (T_{Zr}), we used the equation developed by Boehnke et al. (2013). It is found that, for the syenogranites, alkali feldspar granites, and quartz syenites, the T_{Zr} are c. 809 °C, 813 °C, and 874 °C, respectively (Table 7; Supplementary 6). The apatite saturation temperature (T_{Ap}) has been used to determine similar temperatures (Harrison and Watson, 1984) with an average T_{Ap} value of c. 783 °C, 789 °C, and 796 °C (Table 7; Supplementary 6) for syenogranites, alkali feldspar granites, and quartz syenites, respectively. These temperatures are consistent with the saturation temperatures of zircon (750–876 °C), and apatite (750–866 °C) observed in other A-type granites in the ANS (e.g., El-Bialy and Omar, 2015; Sami et al., 2017; Khedr et al., 2023).

It is important to understand that pressure influences the crystallization conditions and depth. So, the Al-content in the amphibole was used to determine the pressure of the studied granites based on the calibration equation of Mutch et al. (2016): $P \text{ (kbar)} = 0.5 + 0.331(8) \times Al^{tot} + 0.995(4) \times (Al^{tot})^2$, where Al^{tot} is the total amphibole Al content in apfu. The result of the calculated pressure of syenogranites ranges from 1.41 kbar to 2.70 kbar, alkali feldspar granites from 0.89 kbar to 1.54 kbar, and quartz syenites from 0.77 kbar to 6.79 kbar (Table 5; Supplementary 5). These results indicate that the average intrusion depth of syenogranites, alkali feldspar granites, and quartz syenites is 5.52 km, 4.01 km, and 10.9 km, respectively (Table 5; Supplementary 5).

8.3. Petrogenesis and geodynamic evolution of the Nikeiba granites

It has been found that A-type granites form in a variety of within-plate and late-to post-orogenic environments (e.g., Whalen et al., 1987; Sylvester, 1989; Eby, 1992). Our results indicate that the Nikeiba A-type granites were emplaced during the late post-collisional stage of the ANS development. The studied granites have higher concentrations of Nb, Ta, Zr, Hf, Th, and Y than subduction-related plutonic rocks, and they are compositionally similar to other post-collisional granites found throughout the ANS (e.g., Abuamarah et al., 2022; Farahat and Azer, 2011; Khedr et al., 2023, 2024). According to recent geochronological U–Pb zircon dating, the post-collisional calc-alkaline and alkaline A-type granites of the ANS formed between 635 Ma and 590 Ma (e.g., Eyal et al., 2010; Johnson et al., 2011; Farahat and Azer, 2011; Ali et al., 2012; Azer et al., 2014; Moreno et al., 2014; Sami et al., 2017; Zoheir et al., 2020; Stern et al., 2024). In order to explain the origin of these A-type granites, several petrogenetic models have been proposed. These models include: (1) partial melting of tonalitic to granodioritic source rocks (e.g., Creaser et al., 1991; King et al., 1997; Sami et al., 2017; Khedr et al., 2022); (2) mantle-derived mafic magma evolving through fractional crystallization (e.g., Li et al., 2007; Akinin et al., 2009); (3) extraction of I-type magmas followed by remelting of their residues (e.g., Collins et al., 1982; Whalen et al., 1987); (4) melting of calc-alkaline source rocks under upper crustal conditions (e.g., Patino Douce, 1997; Farahat et al., 2007; Khedr et al., 2023); and (5) hybridization of melts of mantle and crustal origin (e.g., Yang et al., 2006; Azer, 2007).

In this study, we used certain trace element ratios to indicate the degree of crustal or mantle involvement in the parental melt. Mantle-derived melts typically have higher Nb/Ta values (>17.5), whereas the typical continental crust is characterized by a ratio of c. 11–12 (Rudnick and Fountain, 1995; Khedr et al., 2022). The Nikeiba A-type granites (quartz syenites and syenogranites-alkali feldspar granites) have Nb/Ta ratios that range from 11 to 17.5, suggesting crystallization from a crustally derived magma (Table 7; Supplementary 6). For Th/Ta ratios, on the other hand, values of c. 2 are typical for the mantle, whereas the lower crust shows values of c. 7.9 and the upper crust of c. 6.9. For the syenogranites, alkali feldspar granites, and quartz syenites, average values of 2.15, 2.18, and 2.44 are calculated, respectively, reflecting a considerable involvement of mantle materials in the melt (Table 7; Supplementary 6). Moreover, all studied granites are classified as A₁-type granites (Fig. 13d, e), which form in anorogenic tectonic settings and have a mantle affinity (Eby, 1992). Mantle-derived melts have very low Rb/Sr and Y/Nb ratios (Rb/Sr < 0.1; Y/Nb < 1.2), while continental crust has high ratios (Rb/Sr > 0.12; Rudnick and Fountain, 1995) and (Y/Nb > 1.2; Eby 1992). The value of the Rb/Sr ratio of all the Nikeiba granites ranges from 1.25 to 5.42 (Table 7; Supplementary 6), similar to that of the continental crust, whereas their Y/Nb ratios are very low (Y/Nb = 0.41 – 0.63; Table 7; Supplementary 6), suggesting that their parental magmas formed from partial melting of mantle sources. Contribution of magmas from enriched mantle sources during magma formation also fits to the relatively high average T_{Zr} of 810°C, 812°C, and 874°C for syenogranites, alkali feldspar granites and quartz syenites, respectively (Table 7; Supplementary 6; Gudelius et al., 2020). According to the source discrimination diagram of Laurent et al. (2014), the Nikeiba A-type granites plot in the field of tonalitic and metasedimentary source rocks (Fig. 14a). The K/Rb ratios of Nikeiba A-type granites (K/Rb = 168–285) are lower than mantle values (K/Rb = 1000) and close to those of crustal melts (K/Rb = 250) (Fig. 14b; Akinin et al., 2009).

The observed trends of major and trace element concentrations and elemental ratios (Nb/Rb, Y/Nb, Rb/Sr; Table 7; Supplementary 6) of the studied granitoids (Fig. 11) suggest that quartz syenites and syenogranites-alkali feldspar granites experienced magmatic differentiation. This is marked by decreases of Mg# from quartz syenites (average = 24) to syenogranites-alkali feldspar granite (Mg#:14) (Table 7; Supplementary 6) and the K/Rb vs. Rb diagram of Akinin et al. (2009),

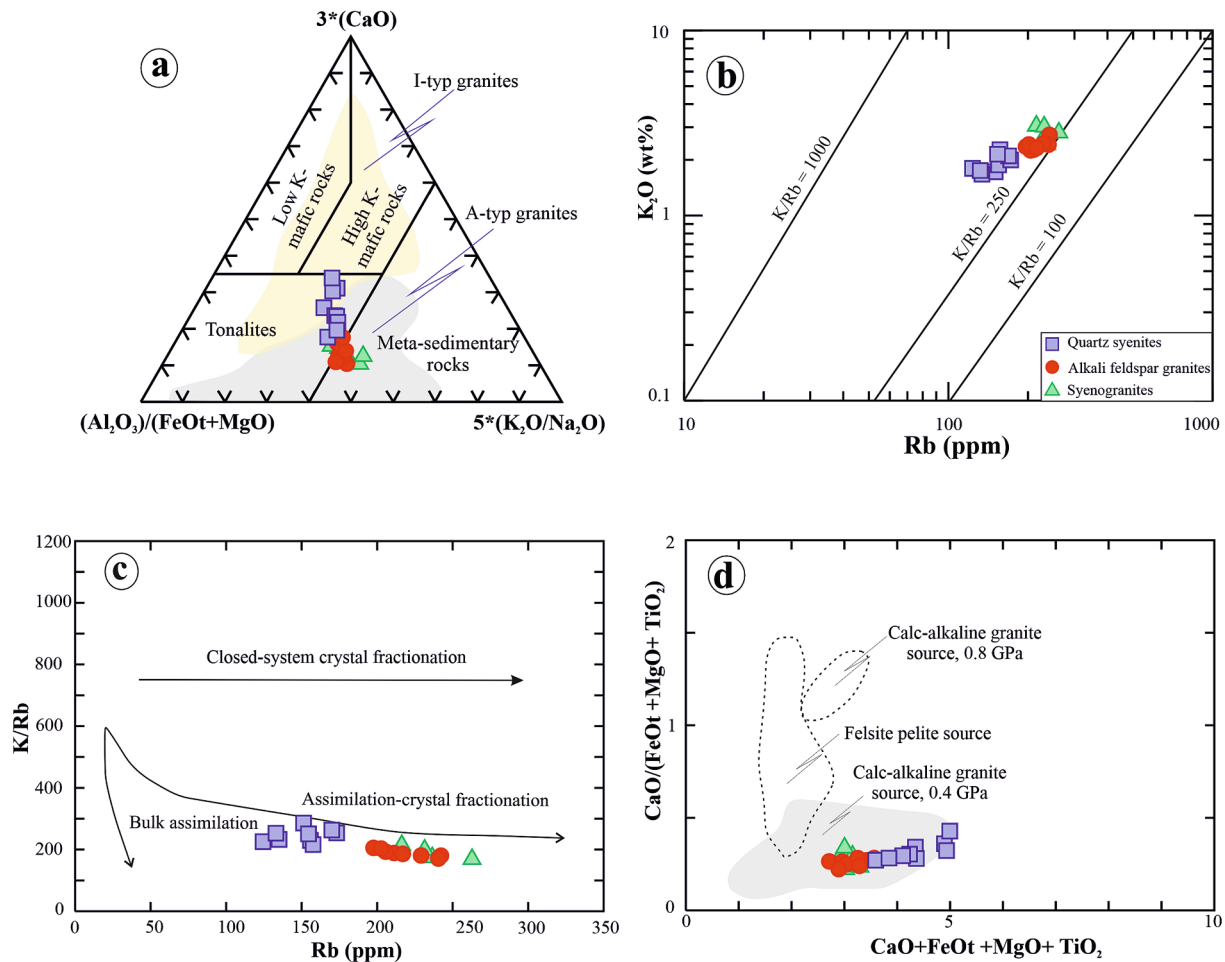


Fig. 14. (a) Petrogenetic discrimination $Al_2O_3/(FeO^t + MgO) - 3 \times CaO - 5 \times (K_2O/Na_2O)$ ternary diagram for the Nikeiba A-type granites (Laurent et al., 2014). (b) Rb vs. K_2O diagram (after Shaw, 1968). (c) Rb versus K/Rb diagram (Akinin et al., 2009). (d) Compositions of the Nikeiba A-type granites compared to melts produced by experimental dehydration-melting of various lithologies (Patino Douce, 1997).

where the two studied suites (quartz syenites and syenogranites-alkali feldspar granites) display intermediate assimilation and fractional crystallization trends (Fig. 14c). In the granitoids, concentrations of CaO, K_2O , Sr, Ba, and Rb are predominantly controlled by fractional crystallization of K-feldspar, plagioclase, and biotite (Fig. 15a, b). It is evident that extreme feldspar fractionation occurs in the syenogranites-alkali feldspar granites as indicated by the correlation of Eu anomalies with Ba and Sr concentrations and the Rb versus K/Rb diagram (Fig. 15c-e; Mao et al., 2015; Azer et al., 2020; Khedr et al., 2023, 2024). In the quartz syenites, where Eu anomalies are weak, plagioclase fractionation plays a limited role in their evolution. Based on plots of Sr versus Ba and Rb/Ba versus Rb/Sr (Fig. 15b, f), plagioclase segregated from the melts throughout the evolution of both suites. A gradual increase in K_2O with increasing SiO_2 in the Nikeiba granites (Supplementary 6–1 g) suggests that abundant alkali feldspar is not removed as a fractionating phase. However, decreasing Na_2O and CaO with increasing SiO_2 is consistent with plagioclase fractionation (Supplementary 6-1e, f).

Comparing the compositional trends of the Nikeiba granites with fractionation vectors for different phases from literature confirms that fractionation of both K-feldspar and plagioclase was important in the evolution of the granites, especially for the older suites (syenogranites and alkali feldspar granites) (Fig. 15a, b). Fe-bearing minerals (e.g., biotite, ilmenite, and titanite) may have also played a role, as suggested by the negative correlation between SiO_2 and FeO^t (Supplementary 6-1c). It has to be kept in mind, however, that an additional critical factor affecting the composition of the primitive parental magma and

assimilated crustal materials is the amount relative rate of assimilation of crustal material.

At the time of emplacement, the Neoproterozoic crustal rocks that comprise the majority of the ANS's juvenile crust would have been available for partial melting (e.g., El-Bialy and Omar, 2015; El Hadek et al., 2016; Khedr et al., 2023, 2024). These earlier plausible source rocks include metamorphic schists and gneisses, gabbro-diorite complexes, and I-type calc-alkaline plutonic suites (tonalites-granodiorites). The metaluminous to slightly peraluminous nature of the Nikeiba granites points to an igneous source rather than a metasedimentary one (Fig. 12c, 1a, Table 7; Supplementary 6). In the Patino Douce (1997) diagram, the Nikeiba granites group in the field of a calc-alkaline granite source (0.4 GPa), which is considered a plausible source rock for the parental magma of the A-type granites from both major and trace element perspectives. Hence, like for other plutonic rocks of the ANS, e.g., Umm Naggat, Homrit Waggat, and Ras Baroud (e.g., El Hadek et al., 2016; Abuamarah et al., 2022; Khedr et al., 2023, 2024), we prefer an igneous source (tonalites-granodiorites) for the magma parental to the first-stage granites of the Nikeiba area with considerable involvement of mantle materials. As a result of plagioclase fractionation and/or partial melting of crustal rocks with high K_2O , both granitic suites are characterized by high K_2O concentrations (4.1–5.5 wt%; Table 7; Supplementary 6). Based on field observations, remote sensing, petrography, and geochemistry, the syenogranites and alkali feldspar granites were emplaced simultaneously (Fig. 2b) and are similar regarding their chemical composition and texture (Figs. 4, 7a-h; Table 7; Supplementary 6), suggesting derivation from the same parental magmas. The latter

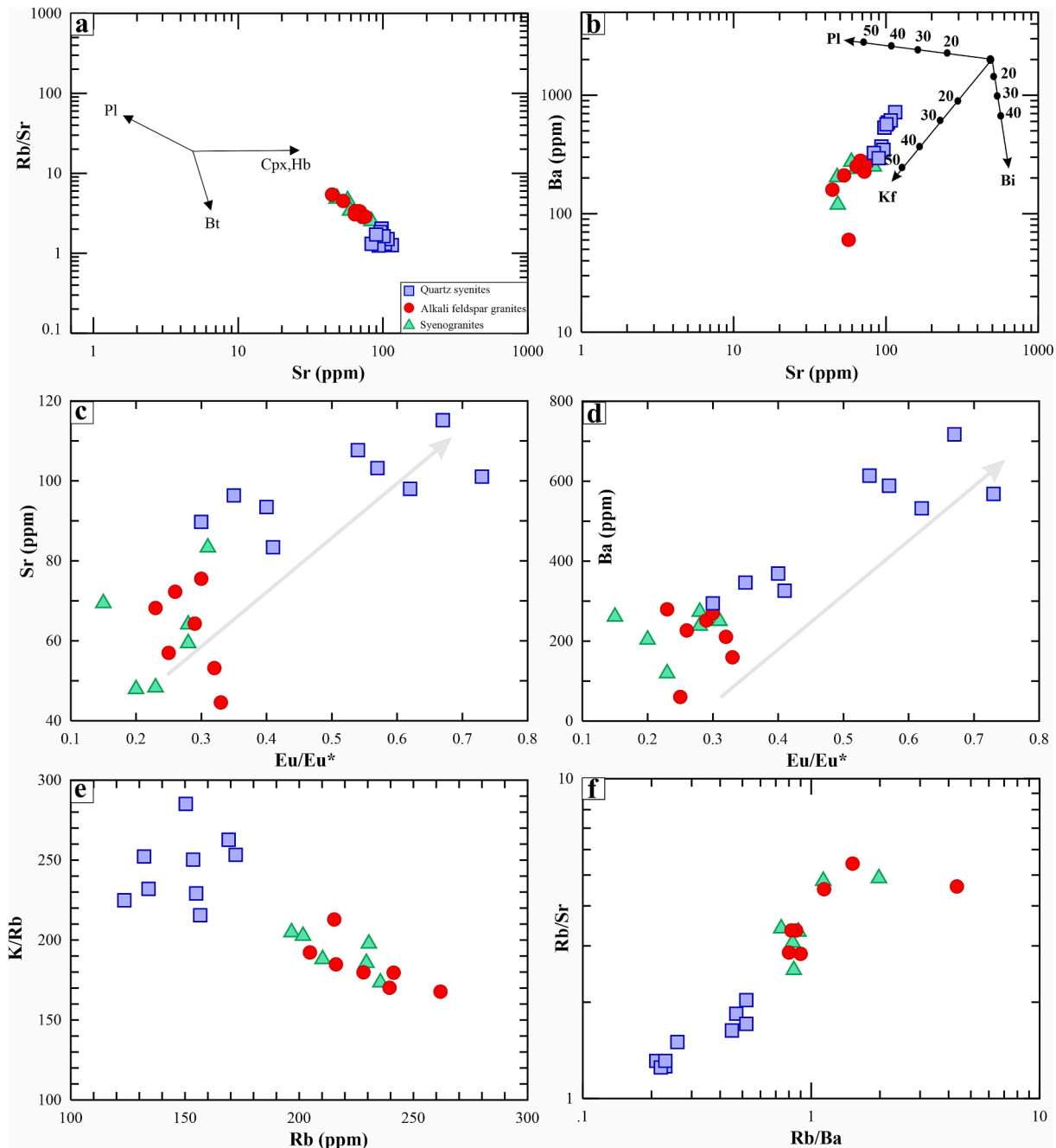


Fig. 15. Variation diagrams of Sr versus Rb/Sr (a), and Ba (b), showing that the fractionation of K-feldspar and plagioclase played an important role in the evolution of the Nikeiba A-type granites (partition coefficients of Sr and Ba are from [Arth \(1976\)](#)). Variation diagrams of Eu/Eu* versus Sr (c) and Ba (d). (e) Rb versus K/Rb. (f) Rb/Ba versus Rb/Sr.

formed by partial melting of calc-alkaline I-type tonalite-granodiorite with considerable involvement of a mantle component, like also suggested for other A-type granites of the ANS (e.g., [El Hadek et al., 2016](#); [Abuamarah et al., 2022](#); [Khedr et al., 2023, 2024](#); [Stern et al., 2024](#)). However, the younger rock suite (quartz syenites) is separated from syenogranites and alkali feldspar granites by a compositional gap (i.e., SiO_2) in Harker diagrams. Nonetheless, according to other chemical classification and discrimination, they have the same magma type (A-type, alkaline), tectonic setting (within plate), and source rocks (mixed mantle and calc-alkaline tonalite-granodiorite source) (Figs. 12–14; Table 7; Supplementary 4, 5). Accordingly, we suggest that the quartz syenites have originated from the same parental magma (tonalites-granodiorites), but they are less fractionated than syenogranites-alkali

feldspar granites ($\text{SiO}_2 = 65.7 - 69.5$ wt%; Table 7; Supplementary 6,7). In the source diagram of [Laurent et al. \(2014\)](#), the quartz syenites plot at the boundary between the I-type granite and high K-mafic rock source fields (Fig. 15a).

The following geodynamic model can be assumed for the origin of the alkaline A-type granites in the Nikeiba area, based on literature data and our own observations (Fig. 16). Lithospheric delamination is commonly assumed to characterize the post-collisional evolution of the ANS calc-alkaline granites and alkaline granites emplaced at c. 635 to 590 Ma and 608 Ma to 580 Ma, respectively (e.g., [Avigad and Gvirtzman, 2009](#); [Eyal et al., 2010](#); [Eliwa et al., 2014](#); [Farahat and Azer, 2011](#); [Moreno et al., 2014](#); [Azer et al., 2014](#); [Sami et al., 2017](#); [Azer et al., 2020](#); [Abuamarah et al., 2022](#); [Khedr et al., 2022, 2023, 2024](#); [Stern](#)

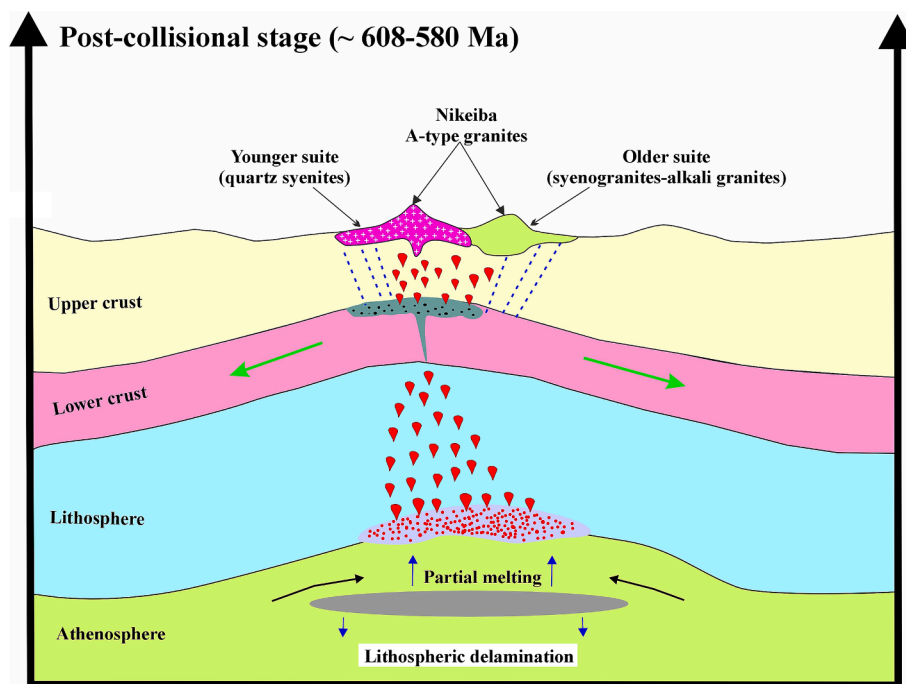


Fig. 16. A simplified model for the geodynamic evolution of the Nikeiba post-collisional alkaline A-type granites, showing the two phases of granites, lithospheric delamination that caused an upwelling of the asthenospheric mantle, partial melting of the lower crust, generation of A-type granitic magma, and finally erosional removal of cover to expose the top of the pluton.

et al., 2024). According to this scenario, there a collisional period of crustal thickening was pre-dating the lithospheric delamination and slab break-off. Negative buoyancy is eliminated by delamination and slab break-off and is replaced by positive dynamic topography, isostatic uplift, crustal doming, and erosion. Shield dike swarms, normal faults, and shear zones reflect extension related to post-delamination doming, affecting the uplifted older granitoid series but pre-dating the post-collisional plutons (e.g., Stern et al., 1984; Stern, 1985; Greiling et al., 1994; Sami et al., 2017; Azer et al., 2020; Abuamarah et al., 2022; Khedr et al., 2022, 2023, 2024). Preexisting tonalites and metasediments in the lower crust underwent partial melting at the lower crust's surface by erosion-driven decompression and the uprise and underplating of mafic magma (e.g., Abuamarah et al., 2022; Abo Khashaba, 2022; Khedr et al., 2022, 2023, 2024). Despite the igneous source rocks have an I-type character, the anatexic melts can become A-type either through significant fractionation in the middle crust or low-degree melt extraction. The Nikeiba alkaline granites comprise two granitic suites, separated by a compositional gap: (1) syenogranites and alkali feldspar granites and (2) quartz syenites. The first granitic suite is characterized by extensive fractional crystallization trends and alteration by fluid interaction, while the younger suite shows only minor evidence for fractional crystallization and may have crystallized in the late post-collisional stage.

8.4. Origin and enrichment of rare metals in the Nikeiba granites

In this section, we will shed light on the origin of rare metals-bearing minerals in the Nikeiba granites. There is strong evidence for a magmatic origin of the Nikeiba granites, despite their overprint by later hydrothermal processes. These evidence includes (1) sharp intrusive contacts between the Nikeiba granites and country rocks (Fig. 2e; Abo Khashaba et al., 2023; Gahlan et al., 2023; Khedr et al., 2023); (2) the presence of subhedral to anhedral primary feldspar, biotite, amphiboles, Fe-Ti oxides, and rutile (e.g., Abo Khashaba et al., 2023; Gahlan et al., 2023); (3) coexistence of fluorite between mineral constituents like k-feldspar and biotite (Fig. 7h, i, 8a); and (4) well-developed oscillatory

zoning subhedral to euhedral zircon and columbite (Fig. 7g, i, o 8b, d).

The hydrothermal effects are clearly observed in the marginal zones of the Nikeiba granites, where extensive replacement of the magmatic assemblage by alteration zones rich in secondary minerals was observed (Fig. 2g, 5, 8). This may be attributed to the fluids (released during the emplacement and cooling of the younger quartz syenites into the contact zones between and fractures transecting the different granitoids, also including the older syenogranites and alkali feldspar granites. These evidence includes: (1) development of quartz veins in fractures (Fig. 2c); (2) pronounced alteration of feldspar to sericite and muscovite as well biotite to chlorite in the alteration zones (Fig. 7c, f); (3) formation kaolinite-rich alteration zones within quartz syenites (Fig. 2g); (4) In the quartz syenites and syenogranites, silicification is considered an important sign of metasomatic alteration (Fig. 2c, 7o), which is also assumed to be the process responsible for secondary albite formation at the expense of k-feldspar and quartz; and (5) Part of the observed alteration processes are also revealed by the ASTER alteration mineral indices, which identify several types of alteration in the Nikeiba granites (Fig. 5; Abo Khashaba et al., 2023; Khedr et al., 2023);

In Egypt, rare metal-bearing mineral deposits are an important current subject of research. Several theories are proposed for their origin, including (1) a metasomatic origin associated with post-magmatic high temperatures (e.g., Kamel and El Tabbal, 1979; El Galy et al., 2016); (2) magmatic origins (e.g., Abou El Maaty and Ali-Bik, 2000; Sami et al., 2017); and (3) an origin involving both magmatic and post-magmatic processes (hybrid) (e.g., Zoheir et al., 2020; Abuamarah et al., 2022; Abo Khashaba, 2022; Abo Khashaba et al., 2023; Khedr et al., 2023, 2024). According to our petrographic investigation combined with SEM-EDS, and EPMA analyses, we found that the Nikeiba granites are rich in several rare metals-bearing minerals like fluorite, zircon, apatite, columbite, allanite, thorite, fergusonite, and bastnaesite (Figs. 7, 8; Supplementary 4, 5).

In our granite samples, fluorite [CaF₂] occurs as anhedral to subhedral crystals between the constituent minerals (quartz, k-feldspar, and biotite), suggesting its magmatic origin (Fig. 7h, i, 8a; Supplementary 4) (e.g., Sami et al., 2017; Khedr et al., 2023). BSE images show that it

contains tiny inclusions of zircon (Fig. 8a).

In the studied Nikeiba granites, zircon varies in shape from subhedral to euhedral. Wedge-shaped crystals with well-developed oscillatory magmatic zonation are present in all the studied granites (Fig. 7g, 8b), reflecting their magmatic origin (Fig. 7k, o). Moreover, it is free from any inclusions (Fig. 7g, k, o, 8b). The magmatic zircons in the Nikeiba area show very limited variations in their chemical compositions with ZrO_2 of 62.3 to 65.0 wt%, SiO_2 of 30.6 to 32.8 wt%, and low HfO_2 of 0.88 to 2.97 wt% with high electron probe analytical totals (97.44–98.81 wt%) (Table 6; Supplementary 5). Abdalla (2009) show that zircons from rare metal-bearing granites from the Eastern Desert of Egypt exhibit different evolutionary trends. However, in the HfO_2 versus ZrO_2 binary diagram (Abdalla, 2009), the Nikeiba zircons plot in the field of normal zircon from granitic rocks, similar to zircons from many granitic plutons in the Eastern Desert of Egypt (Supplementary 7–4).

Apatite [CaP_2O_5] in the studied granites occurs as small crystals associated with zircon, reflecting its magmatic formation (Fig. 7k, 8c; Sami et al., 2020). Due to its rare occurrence, along with other accessory minerals, it likely crystallized from remnant melt pockets caught in the space between early crystallizing main minerals (Fig. 7k, 8c). As common for igneous apatite, where the F concentration increases with differentiation, the apatite found in the Nikeiba granites is a fluorapatite with an F content of 2.02–3.23 wt% (Supplementary 5; Nash, 1984; Sami et al., 2020).

The studied columbite [(Fe, Mn) Nb_2O_5] is homogenous in composition (Table 6; Supplementary 5), crystallized in between quartz and magmatic biotite (Fig. 8d), reflecting its magmatic origin. Some columbite crystals show a weak normal zoning, which is associated with an increase in the Ta_2O_5 content towards the rim (Table 6; Supplementary 5), indicating a magmatic increase in Ta. Magmatic enrichment of Ta and Nb is demonstrated by the positive correlation of Nb and Ta in the corresponding whole-rocks with SiO_2 (Supplementary 7–2 g, h). In the studied granites, columbite and primary biotite are associated (Fig. 8d), which indicates that both phases crystallized in the late-magmatic stage from volatile-rich melts (e.g., Gahlan et al., 2023 and references therein).

Fergusonite [(REE, Y) NbO_4] is a common accessory mineral in rare metals-bearing granites and pegmatites. In this study, it is found in quartz syenites (Fig. 8e). The EDS analysis of fergusonite indicates high contents of Nb_2O_5 (up to 42.7 wt%), Y_2O_3 (20.1 wt%), REE (total REEs = 27.1 wt%), Ta_2O_5 (9.3 wt%), and Fe_2O_3 (6.50 wt%) (Fig. 8e; Supplementary 4). The oxide occurs as homogenous euhedral crystals in the rock matrix or at the margin of zircon, reflecting its (late) magmatic to secondary origin (Fig. 8e; Sami et al., 2017).

The hydrothermal rare metals-bearing minerals in the Nikeiba granites are restricted to three minerals, including allanite, thorite, and bastnaesite. They were found as fine to medium-grained crystals found along the grain margins of primary minerals or in fractures. Allanite [(Ce, Ca, Y, La) $_2(\text{Al}, \text{Fe}^{+3})_3(\text{SiO}_4)_3(\text{OH})$] occurs in quartz syenites as anhedral crystals, indicating that some allanite crystals may have a secondary origin (Fig. 8f; Abo Khashaba et al., 2023). According to the EDS analysis of allanite, it contains significant average contents of SiO_2 (35.0 wt%), LREE (22.3 wt%), Al_2O_3 (11.4 wt%), Fe_2O_3 (16.5 wt%), CaO (3.4 wt%), TiO_2 (4.8 wt%), and F (1.28 wt%) (Fig. 8f; Supplementary 4). In alkali feldspar granites and syenogranites, thorite [ThSiO_4] can be found as tiny anhedral crystals forming rims on zircon and along biotite cleavages (Fig. 8g). The presence of thorite next to zircon indicates fluid-rock interaction (e.g., Sami et al. 2017; Khedr et al., 2023). It has been indicated that REEs have been introduced into the Nikeiba area by hydrothermal fluids during alteration and are found in fluorocarbonate minerals such as bastnaesite. The formation of bastnaesite-(Ce) [(La, Ce, Nd) CO_3F] at the expense of allanite in syenogranites (Fig. 8h) suggests that it precipitates from the alteration of F-rich fluids. Bastnaesite shows high contents of LREEs (~ 87 wt%), and F (9 wt%), and minor content of CaO (1.97 wt%) (Fig. 8h; Supplementary 4).

8.5. Alteration zones and structure control of mineralization

Alteration minerals can be detected via remote sensing mainly by their spectral characteristics, including their spectral absorption features properties in the near-infrared (VNIR) and shortwave infrared (SWIR) ranges. In this study, the field samples collected from the Nikeiba area were spectrally measured using an ASD Halo device (350–2500 nm) in order to collect more precise alteration minerals information about the rare metal-bearing granitic rocks (Table 2; Supplementary 3.2–3.6). This provided the opportunity to collect spectral information on rock-forming minerals in the area that is more suited to the alteration minerals (Table 2; Supplementary 3.2–3.6).

We detected seven alteration types using ASTER mineral indices, including phyllic, hematization of ferrous silicates, carbonatization, kaolinitization, hydroxyl, gossan, and ferrous iron (Fig. 5). In this section, we will focus on the main alteration types related to rare metals concentration in the study area. The phyllic alteration is considered to be a crucial indicator of potential mineralization, including porphyry copper, rare earth elements, and gold deposits (Abo Khashaba et al., 2023; Khedr et al., 2023; El-Arafy et al., 2024). In this study, phyllic alteration zones that were especially emphasized using the ASTER phyllic index are well-distributed in the southern part of the study area at the contact between quartz syenites and syenogranites and in the northern part between alkali feldspar granites and syenogranites (Fig. 5b). Also, they are observed around the quartz veins crosscutting the metagabbro-diorite, syenogranites, and quartz syenites in the southern part of the study area (Fig. 5b). This is confirmed by the ASD measurements (Table 2; Supplementary 3.2–3.6). As a result of the circulation of hydrothermal fluids present in the granite, feldspar minerals are transformed into altered products (e.g., sericite and illite) (Figs. 5, 7c; Table 2; Supplementary 3.2). We found that this alteration zone is associated by an increase in REE contents ($\Sigma\text{REEs} = 205$ ppm) in the syenogranites (NBK4), ($\Sigma\text{REEs} = 305$ ppm) in the alkali feldspar granites (NBK13), and ($\Sigma\text{REEs} = 498$ ppm) in quartz syenites (NBK6) (Fig. 5b, 12a; Table 7; Supplementary 6). Also, it is associated with increases in the concentration of Zr (442 ppm), Nb (267 ppm), Y (135 ppm), and Th (38 ppm), fractionated in co-crystallizing phases like zircon (Fig. 17a; Table 7; Supplementary 6).

The ASTER ferrous silicate minerals index successfully discriminated the rock units in the Nikeiba area that are rich in biotite, chlorite, and amphibole minerals (Fig. 5c). Replacement of biotite and amphibole by chlorite is frequently observed in all rock units and associated with an increase in the ferrous silicate content. Using the ASD device, chlorite (as the only alteration mineral mentioned above) can be clearly identified because it exhibits unique absorption characteristics at 900 nm (VNIR region) (Table 2; Supplementary 3.3–3.6). We found that the ferrous silicates-rich zones are associated with an increase in the concentration of REE in quartz syenites samples NBK5, NBK8, and NBK15 with percentages of 587 ppm, 541 ppm, and 639 ppm, respectively (Fig. 5c, 7k; Table 7; Supplementary 6). Likewise, in the syenogranites NBK2 and NBK20, the concentration of ΣREEs are 511 ppm and 420 ppm, respectively, while the alkali feldspar granites NBK18 recorded the concentration of $\Sigma\text{REEs} = 260$ ppm (Fig. 5c, 17b; Table 7; Supplementary 6). Additionally, this zone is rich in Zr (798 ppm), Nb (205 ppm), and Y (130 ppm) (Fig. 12b; Table 7; Supplementary 6), similar to other rare metals-bearing granites in the ANS (Abo Khashaba, 2022; Khedr et al., 2023). The concentration of REEs and Zr increases gradually from alkali feldspar granites to quartz syenites (Fig. 17b). Whereas Nb and Y are highly concentrated in syenogranites, alkali feldspar granites, and quartz syenites, respectively (Fig. 17b; Table 7; Supplementary 6).

In the Nikeiba area, the ASTER carbonate and epidote alteration index well emphasize lithological units rich in secondary mafic minerals and carbonates (Fig. 5d). This alteration type is mainly observed in the metavolcanics and at the contact between metavolcanics and quartz syenites, and alkali feldspar granites (Fig. 5d). Ca-rich minerals (pyroxenes, amphiboles, plagioclase) that could release calcium into

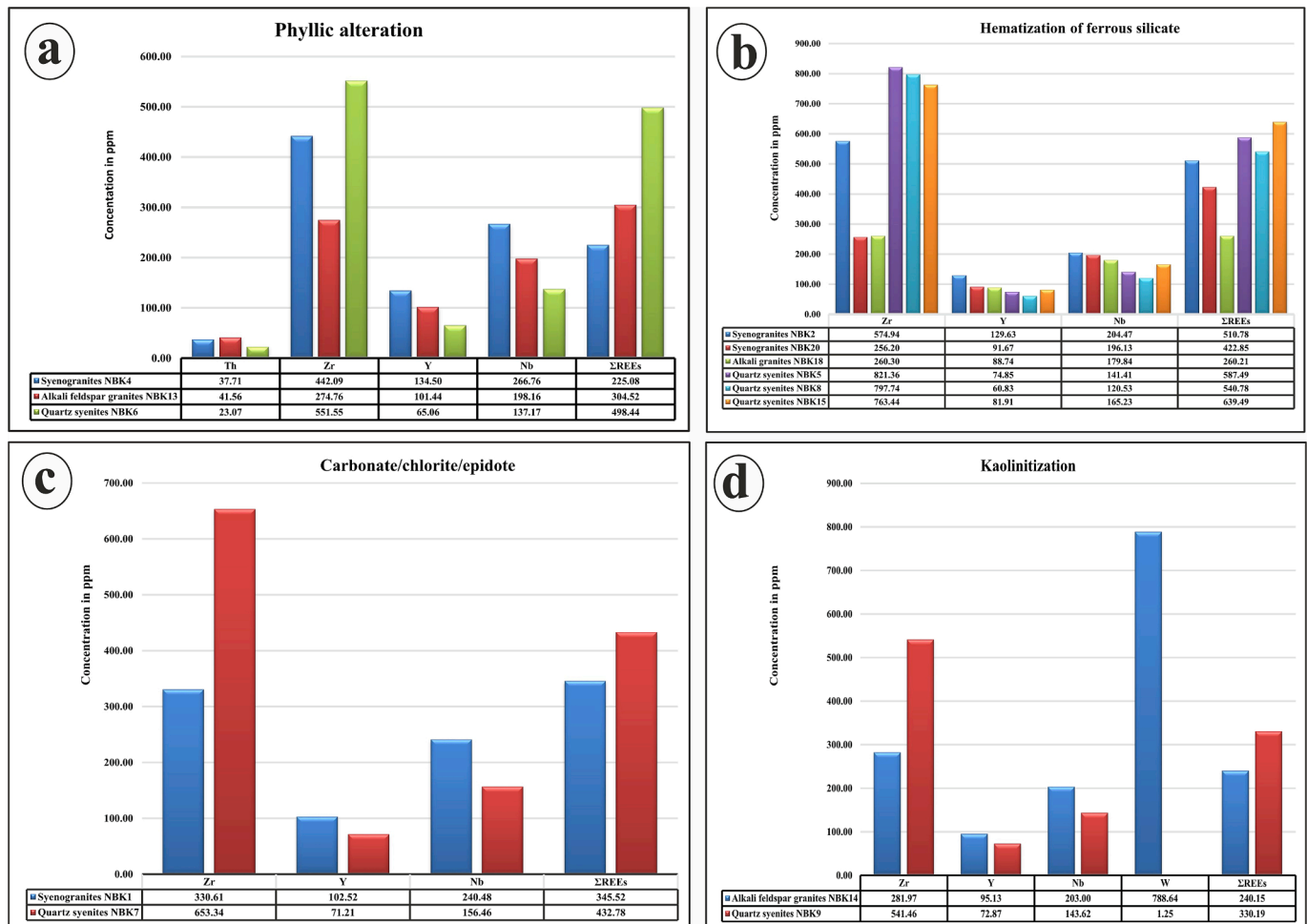


Fig. 17. Important ASTER alteration indices related to the increase in the concentration of rare metals in the Nikeiba area. (a, b) These diagrams show that in the phyllic alteration zone and hematization of ferrous silicates, quartz syenites have the highest concentration in REEs and Zr and the lowest concentration in Nb, Y, and Th compared to syenogranites and alkali feldspar granites. (c) In the carbonate/chlorite/epidote alteration zone, quartz syenites have the highest concentration in REEs and Zr compared to syenogranites that have high concentrations in Nb and Y. (d) In kaolinitization, quartz syenites have the highest concentration in REEs and Zr, while alkali feldspar granites have high contents of W, Nb, and Y. This figure shows that quartz syenites are highly mineralized in all types of alteration and have the highest contents of REEs, and Zr and lowest Nb, Y, Th, and W compared to syenogranites and alkali feldspar granites.

hydrothermal fluids are abundant in metavolcanics (e.g., Abo Khashaba, 2022; Abo Khashaba et al., 2023; Khedr et al., 2023), explaining the close spatial association of carbonate and epidote alteration zones with the volcanics. In the Nikeiba area, the carbonate and epidote alteration zones provide a likely source of calcium and REE for the formation of calcite and fluorocarbonate minerals such as cerite and parisite in the neighboring altered granitic rocks (e.g., Schmandt et al., 2017; Abo Khashaba, 2022; Abo Khashaba et al., 2023; Khedr et al., 2023). Carbonate and epidote alteration is prominent in many quartz syenites and syenogranites, also leading to increased REE contents, like those of samples NBK7 and NBK1 with ΣREEs = 433 ppm and 346 ppm, respectively (Fig. 4d, 17c; Table 7; Supplementary 6). These high REE contents are likely related to the co-precipitation of REE carbonates together with calcite and epidote during the alteration of these rocks.

In this study, the argillic ASTER alteration, mainly characterized by the formation of kaolinite at the expense of the feldspars, was successfully determined in quartz syenites, syenogranites, and alkali feldspar granites (Fig. 2g, 5e). As a result of argillic alteration, some metals can become enriched, like molybdenum, silver, gold, and rare earth elements (e.g., Abo Khashaba et al., 2023; Khedr et al., 2023; El-Arafy et al., 2024). In order to validate the results, spectral signatures using ASD hyperspectral data measurements were performed on different granitic rocks in the Nikeiba area (Table 2; Supplementary 3.2–3.6). The results

show strong absorption at 1900 nm (SWIR region), reflecting the presence of clay minerals or kaolinitization (Table 2; Supplementary 3.2–3.6). During kaolinitization in granitic rock units in the Nikeiba area, the concentration of REEs also increases (e.g., NBK9; ΣREEs = 330 ppm, NBK14; ΣREEs = 240 ppm), as well as that of Zr (up to 541 ppm), Y (95 ppm), Mo (14 ppm), W (789 ppm), and Nb (203 ppm) (Fig. 17d; Table 7; Supplementary 6).

In this study, the automatic lineament extraction has been extracted using ALOS PALSAR and Sentinel-1B radar data (Fig. 6a, b). Four distinct predominant structural feature directions have been detected such as northwest-southeast (NW–SE), north–south (N–S), east–west (E–W), and northeast-southwest (NE–SW) (Fig. 6a, b). Most of these trends are compatible with major strike-slip faults in the study area, providing pathways for hydrothermal fluids related to rare metals mineralization (e.g., Gabr et al., 2015; Hagag et al., 2019; Abo Khashaba et al., 2023; Khedr et al., 2023, 2024). The extracted lineament density maps well-emphasized the structural features in quartz syenites, syenogranites, and alkali feldspar granites, highlighting the high-density zones associated with mineralization (Fig. 6c, d).

Several types of mineralization, including garnet (e.g., Khedr et al., 2022), rare metals (e.g., Abo Khashaba et al., 2023; Khedr et al., 2023, 2024), and gold (e.g., Gabr et al., 2015; Hassan and Ramadan, 2015), are associated with different structural features concentration in the Eastern

Desert of Egypt. These lineaments and fractures are regarded as important channels for hydrothermal fluid migration and associated mineral mineralization (e.g., Abo Khashaba et al., 2023; Khedr et al., 2022, 2023). The potential for rare metals mineralization in the Nikeiba area is high due to the observed high density of lineaments and fractures, which are likely linked with hydrothermal alteration zones. This is clearly observed at the contacts between quartz syenites and syenogranites in the southern part of the study area and those between alkali feldspar granites and metavolcanics in the northern part of the study area, where the rocks experienced a strong alteration with resulting high concentrations of selected valuable elements (Fig. 6c, d).

Finally, the analyses revealed that samples showing significant hematization of ferrous silicates and phyllic alteration zones, which are related to structural features like fractures and faults, were found to have the highest REE contents. This finding was validated by the petrographic and geochemical data analyses (Figs. 5–8; Table 7; Supplementary 6).

9. Conclusions

- 1) Machine learning algorithms like SVM and MF were applied to Sentinel-2 data to produce an accurate geological map of the Nikeiba area. The results indicate that SVM applied to enhanced MNF-Sentinel-2 gives accurate discrimination with an overall accuracy of 92.38 %. This leads to accurate discrimination of rare metals-bearing granites in the study area and sheds light on new targets for exploration.
- 2) Based on the fused ASTER-Sentinel-2 data, seven alteration zones were delineated in the Nikeiba area. The hematization of ferrous silicate is considered the main alteration type related to the enrichment of rare metals in the study area, with ΣREEs content reaching 511 ppm, 798 ppm Zr, 205 ppm Nb, and 130 ppm Y. These alteration zones and rare metals mineralization in the area are structurally controlled mainly by NW-SE, N-S, and E-W trends
- 3) High concentrations of REE, Zr, Nb, W, Sn, and Y are generally recorded for the Nikeiba granites, which are alkaline metaluminous to slightly peraluminous A-type granitoids. They have an affinity with post-collisional intra-plate A-type granites in the ANS. These granitic magmas were formed by partial melting of crustal rocks followed by fractional crystallization of the magma. The involvement of mantle materials is evident in most samples
- 4) The texture and geochemistry data reveal that the rare metals-bearing minerals in the studied granites are mainly magmatic and subordinately hydrothermal in origin. Magmatic minerals include zircon, fluorite, columbite, rutile, apatite, and fergusonite, whereas allanite, thorite, and bastnasite are of a secondary origin

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.oregeorev.2024.106391>.

Data availability

Data will be made available on request.

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