

Petrological, geochemical and geodynamic evolution of the Wadi Al-Baroud granitoids, north Arabian-Nubian shield, Egypt

Bassam A. Abuamarah^a, Hassan Alzahrani^{a,*}, Marian J. Matta^b, Mokhles K. Azer^c, Paul D. Asimow^d, Mahmoud H. Darwish^b

^a Department of Geology and Geophysics, King Saud University, Riyadh, 11451, Saudi Arabia

^b Geology Department, Faculty of Science, New Valley University, El-Kharga, 72511, Egypt

^c Geological Sciences Department, National Research Centre, 12622, Dokki, Cairo, Egypt

^d Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA, 91125, USA

ARTICLE INFO

Handling Editor: M Mapeo

Keywords:

Arabian-Nubian Shield
Eastern Desert
Post-collisional magmatism
Lithospheric delamination
Nb-Ta oxide minerals
Granitoid compositions

ABSTRACT

The Wadi Al-Baroud area, in Egypt's Eastern Desert, exposes Neoproterozoic rocks of the Arabian-Nubian Shield (ANS), including both syntectonic granitoids (granodiorite and tonalite) and post-collisional granites. We present field work, petrographic study, mineral compositions, and whole-rock geochemistry results from these granitoids and discuss their petrogenesis, magmatic sources, evolution, and tectonic significance. The syntectonic granitoids show subduction affinity and an anomalous steep trend of K-enrichment that suggests assimilation of a granitic component during their evolution. The post-collisional granites form two plutons, on opposite sides of Wadi Al-Baroud, named here the Ras Baroud pluton (RBP) and the Abu Hawis pluton (AHP). They intruded the syntectonic granitoids with sharp intrusive contacts. The post-collisional plutons are devoid of mafic enclaves and are cut by very few dikes. They dominantly consist of biotite monzogranite that grades into muscovite monzogranite. The latter lithology hosts Nb-Ta oxide minerals (columbite, tantalite, and wadginite) displaying a variety of textural and compositional features. The cores are primary columbite-(Mn), whereas rims are overgrown or partly replaced by tantalite-(Fe) and wadginite due to late interactions with highly fractionated residual melt. The highly-evolved AHP and RBP granites are typical of the post-collisional granitoids of the ANS, including high concentrations of rare earth elements (REE), Ta, Hf, Nb, Zr, Y, and Rb; elevated ratios of Ga/Al; and low contents of Sr, CaO, and MgO. Their geochemistry suggests that the parental magma of both plutons formed from an I-type tonalitic source rock that underwent partial melting during the thermal disturbance that followed a lithospheric delamination event during the post-collisional stage of the East African Orogeny. The variations in major oxide and trace element contents among individual samples of the AHP and the RBP cannot be explained as a liquid line of descent due to fractional crystallization; rather we interpret them as sampling variable proportions of an evolved liquid and the solid crystals in equilibrium with that liquid.

1. Introduction

Along both sides of the Red Sea there are exposures of a basement complex of Neoproterozoic age known as the Arabian-Nubian Shield (ANS). On the Egyptian side, these rocks dominate the mountain chains of the Eastern Desert and southern Sinai. Together with the Mozambique Belt, the ANS forms the East African Orogen (Stern, 1994), where tectonic and magmatic events spanning about 300 million years of geologic time are recorded. The ANS segment of the orogen appears to be dominated by juvenile crust of Neoproterozoic age (Johnson et al., 2011;

Fritz et al., 2013).

This work focuses on an area near the conventional dividing line separating the north Eastern Desert from the central Eastern Desert, along an alluvial wash known as Wadi Al-Baroud. The basement geology, mineralization and structure of the area have been investigated several times (e.g., Sayyah et al., 1993; Surour et al., 2004; Al-Boghdady et al., 2005; Raslan et al., 2010; El-Bialy and Omar, 2015; Fawzy et al., 2020; Mahdy, 2021). Although it is known that the exposures in the area include rocks of both the “older” and the “younger” granites and the intrusive contacts between them, published studies are contradictory

* Corresponding author.

E-mail address: hsan@ksu.edu.sa (H. Alzahrani).

<https://doi.org/10.1016/j.jafrearsci.2023.105044>

Received 10 July 2023; Received in revised form 18 August 2023; Accepted 24 August 2023

Available online 30 August 2023

1464-343X/© 2023 Elsevier Ltd. All rights reserved.

and leave much uncertain about the origin of the granitoids. We carried out new studies of the granitoids and their country rocks, including field mapping, thin section petrography, mineral identification and chemical characterization, and whole-rock geochemistry. The intent is to integrate all the available geological, petrological, mineralogical, and

geochemical observations to decipher the petrogenesis, geodynamic significance, and mineralization associated with the post-collisional granites of Wadi Al-Baroud. We seek to identify the place of the studied granitoids in the context of the Neoproterozoic evolution of the northern ANS.

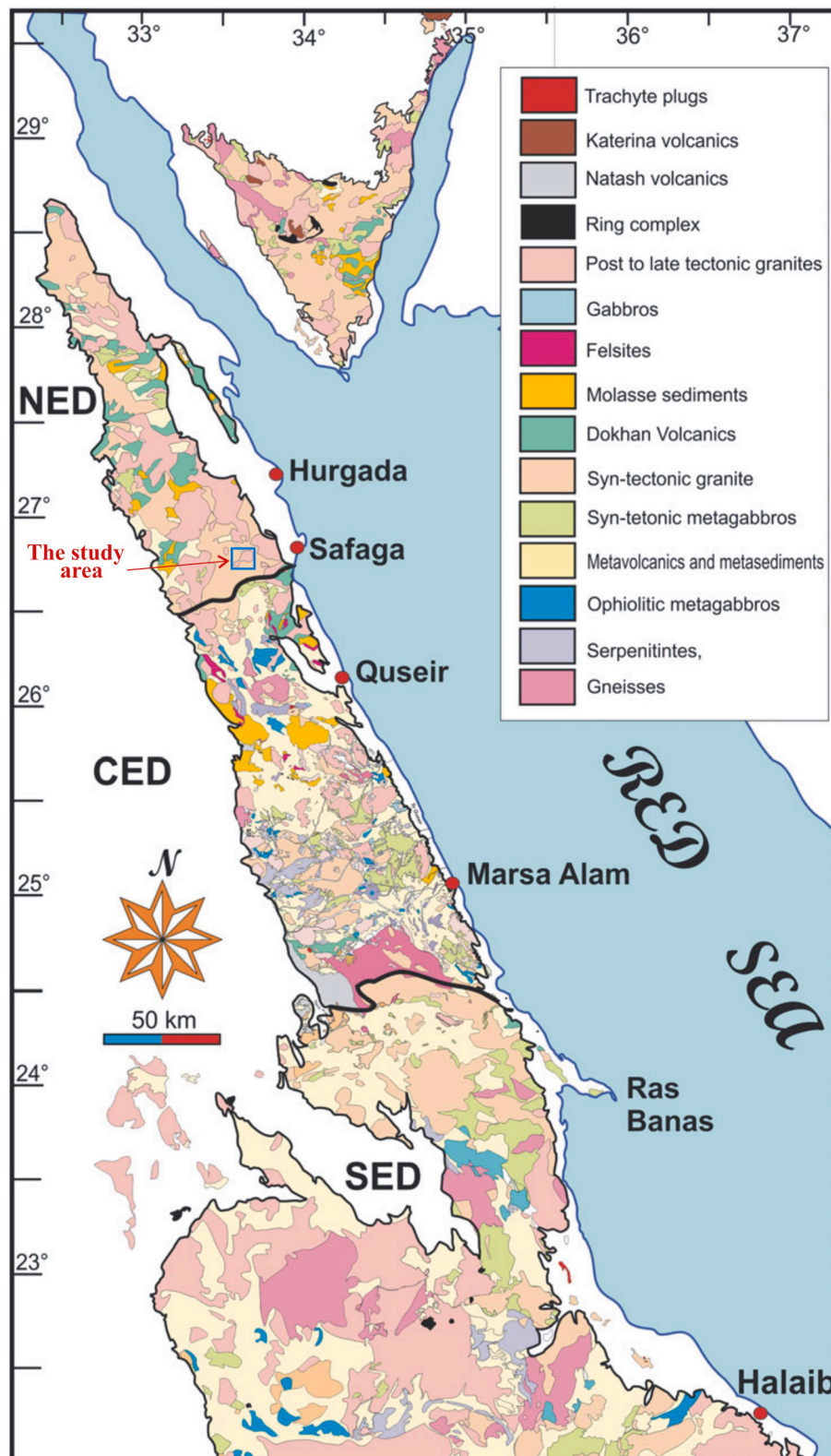


Fig. 1. Geological map of the Egyptian Nubian Shield showing the three tectono-lithologic domains of the Eastern Desert (after [Abd El-Wahed and Hamimi, 2021](#)). The location of the study area is indicated.

2. Geologic background

2.1. Regional geology

The tectonic and magmatic record in the ANS is separated into three phases (reviewed in [Azer and Asimow, 2021](#)): the pre-collisional (800–750 Ma), syn-collisional (720–630 Ma), and post-collisional

phases (620–580 Ma). The pre-collisional phase is marked by dismembered and highly altered ophiolite assemblages thrust over intra-oceanic island arcs (e.g., [Abdel-Karim et al., 2001, 2021a](#); [Azer and Stern, 2007](#); [Ali et al., 2010](#); [Azer et al., 2019a](#)). The syn-collisional stage records subduction (island arc successions and gabbro–diorite assemblages) and continental margin magmatism (calc-alkaline gabbros through granodiorites and associated volcanic units). The collisional stage ended when

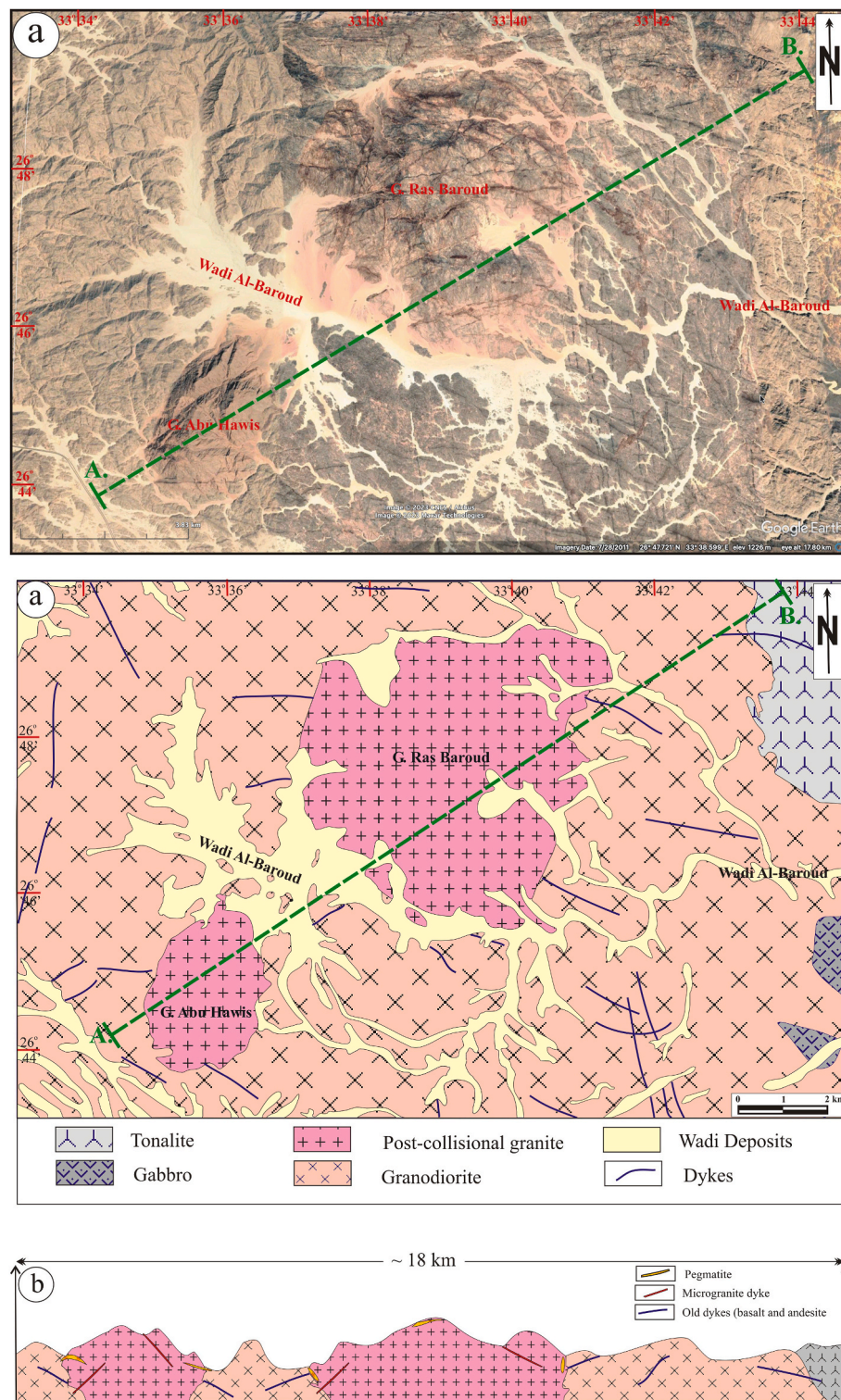


Fig. 2. (a) Satellite image (from Google Earth™) of the Wadi Al-Baroud area with the line of cross-section indicated. (b) Geologic map of the Wadi Al-Baroud area. (c) Schematic geological cross-section showing the inferred relationships between the post-collisional granites and their country rocks.

the merged East and West Gondwana blocks and the juvenile Neoproterozoic crust docked with the East Saharan Craton (Kröner et al., 1994). The post-collisional stage (Beyth et al., 1994; Eyal et al., 2010) is characterized by intra-crustal melting that generated calc-alkaline and alkaline plutonic and volcanic magmatism, with temporal overlap between the end of the calc-alkaline and alkaline phases of post-collisional magmatism (Be'eri-Shlevin et al., 2009a, 2011; Eyal et al., 2010). These post-collisional rocks constitute a detailed record of the sequence of events marking the end of orogenic activity and the onset of the post-orogenic period.

Stern et al. (1984) and El-Gaby et al. (1988) distinguished three tectono-lithologic domains that they labeled the south Eastern Desert, central Eastern Desert, and north Eastern Desert (SED, CED, and NED) (Fig. 1). Stern and Hedge (1985) noted a general younging trend along the orogen from the SED to the NED. The NED extends from the northern tip of the exposed basement southwards to the Qena-Safaga Road. This domain is characterized mainly by abundant and voluminous granitoids (especially A-type granites), Dokhan Volcanics, and associated Hammamat sediments. The NED typically lacks ophiolites, banded iron formation (BIF), or Najd fault-related deformation; gneisses are very scarce. The CED extends from the Qena-Safaga Road southwards to the Ras Banas-Aswan boundary. The basement of this domain is divided into the high-grade metamorphic “infrastructure unit,” structurally below the Pan-African “suprastructure unit” of low metamorphic grade rocks. Both units experienced syn-tectonic intrusion of mafic through felsic plutons and late-to post-tectonic granites accompanied by volcanic activity and volcanogenic sedimentation. The basement rocks of the SED resemble the CED, except that gneisses and migmatites are more abundant, and the ophiolitic ultramafics form more conspicuously transported nappes.

Granitoid intrusions are abundant in all three domains, representing around half of all the intrusive rocks by volume. They span a wide range of ages (~820–580 Ma), tectonic environment, and geochemical affinities (e.g., Bentor, 1985; Abdel-Karim and Arva-Sos, 1992; 2000; Azer, 2007; Khalil et al., 2018; Abdel-Karim et al., 2021b). *The post-collisional granites, in particular, are voluminous, compositionally diverse, and challenging to explain.* Many of these low-pressure A-type rocks are significantly enriched in metals of economic interest, including Nb, Ta, U, Th, Pb, Zr, Be, Mo, F and REE.

2.2. Geology of the Wadi Al-Baroud area

Wadi Al-Baroud lies at the southern end of the NED, close to the CED boundary (Fig. 1), ~35 km southwest of Safaga City. We examined the geology of an area of 227 km² bounded by 26° 43' to 26° 50' N and by 33° 34' to 33° 44' E. It is dissected by several faults and structurally controlled wadis, principally the main channel and tributaries of Wadi Al-Baroud. On the ground and in satellite imagery, the Neoproterozoic rocks stand out in light colors (Fig. 2a); they include syntectonic granitoids (granodiorite and tonalite), gabbros, and post-collisional granites (Fig. 2b). They form hills of moderate to high relief (980–1365 m above sea level). The rock units in the study area are indicated schematically in a NE-SW cross-section (Fig. 2c). The syntectonic granitoids have been dated by Rb-Sr isochron to 632.8 ± 4.6 Ma (Attawiya et al., 1996), whereas the post-collisional granitoids yield zircon U-Pb ages of ~595–605 Ma (Moussa et al., 2008).

The bulk of the map area is covered by granodiorite, forming huge exposures that extend beyond the limits of the present map. In a few exposures, it grades into tonalite. Granodiorite and tonalite are gray-colored with massive to gneissose textures. Their field appearance is quite similar and they grade into one another. They form gently-sloping low to moderate relief topography characterized by spheroidal weathering and exfoliation.

The most distinctive field characteristics of the granodiorite and tonalite are microgranular mafic enclaves and dikes. The enclaves of microdiorite and amphibolite are darker-colored than their host granitoids (Fig. 3a). Their shapes may be rounded, ellipsoidal, elongated, or irregular. They range from a few cm up to 1 m; their contacts with host granodiorite and tonalite may be either sharp or reactive. Both granodiorite and tonalite are cut by many dikes with compositions spanning rhyolite, andesite and basalt.

Small gabbroic masses are exposed in the southeastern corner of the map. The gabbro intruded the syntectonic granitoids with sharp intrusive contacts. Gabbro is dark green, medium-to coarse-grained, and mostly massive with blocky to bouldery appearance. It is neither deformed nor metamorphosed. A few dikes are observed cutting the gabbro mass but the majority of dikes that cut the granodiorite are truncated at the contact with the gabbro. Gabbro outcrops show

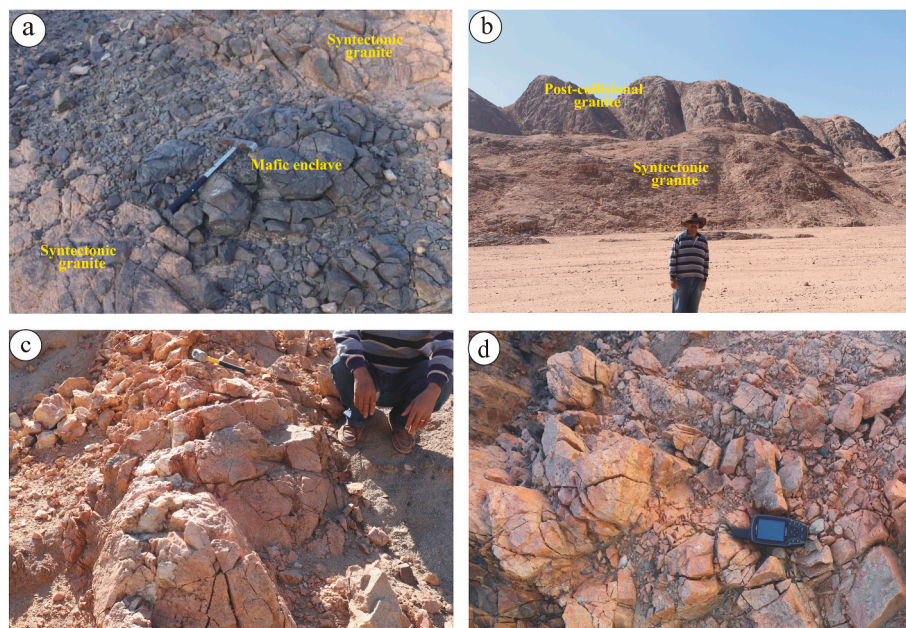


Fig. 3. Field photographs. (a) Mafic microgranular enclave of amphibolite in syntectonic granodiorite. (b) Post-collisional granite intruding syntectonic granitoids with sharp intrusive contacts. (c) Offshoot of the post-collisional Ras Baroud granite invading the syntectonic granodiorite. (d) Pockets of pegmatite at the margin of the Ras Baroud pluton.

intensive exfoliation and onion-like or spheroidal weathering.

The post-collisional granites (PCG) are highly resistant rocks and underlie high topographic features. There are sharp intrusive contacts between the PCG and syntectonic granitoids (Fig. 3b). There are two plutonic masses that represent the PCG in the area. To the northeast, the larger body is the Ras Baroud pluton (RBP) underlying Gabal Ras Baroud. To the southwest, the smaller body is the Abu Hawis pluton (AHP) underlying Gabal Abu Hawis. The RBP outcrop is $\sim 40 \text{ km}^2$ and has roughly circular shape. The AHP outcrops over a $\sim 8 \text{ km}^2$ ellipse. They contain no mafic enclaves and are cut by very few dikes.

The PCG are massive, pink to red, medium-to coarse-grained, and homogenous in appearance. They commonly show one or two sets of penetrative joints. Fine-grained granitic veinlets are present throughout the PCG. A few large granodiorite xenoliths occur along the RBP's margins. The marginal zones of the post-collisional granites also feature fine-grained chilled margins, tens of centimeters in width. The PCG bodies send offshoots and apophyses into the syntectonic granitoids (Fig. 3c). The marginal parts of the PCG experienced post-magmatic hydrothermal alteration, marked by areas enriched in silica, hematite, or kaolinite.

Coarse-grained pegmatitic pockets are observed at the margins of the AHP and especially of the RBP. They occur as plugs and dikes with sharp contacts (Fig. 3d) inside the pluton and along its boundaries. They are variable in shape (oval to lenticular) and size (0.4–30 m in diameter). The pegmatites are distinguished into albite-rich and K-feldspar-rich varieties. Some large pegmatitic bodies are zoned with quartz cores and micaceous feldspar rims. Many quartz veins, up to 0.5–1.5 m thick and 5–10 m long, are observed at the margins of the AHP, but are less common in the RBP. A few younger dikes of various compositions cut the PCG and extend to the country rocks. These dikes include felsic (microgranite and rhyolite), andesitic and mafic dikes.

3. Methodology

Mineral chemical analyses were collected with a CAMECA SX-5 electron microprobe at University of Vienna (Austria). The accelerating potential was 15 kV; the beam was focused; and on-peak counting times of 20 s were used for all analyses. Beam-sensitive minerals were analyzed with 20 nA beam current, whereas stable minerals were analyzed at 40 nA. Primary standards included both synthetic minerals and some well-characterized natural minerals. Raw X-ray counts were corrected for matrix effects using the PAP scheme.

Based on petrographic study, 31 samples were selected for chemical analysis. Crushing in an agate mortar and repeated quartering yielded suitable splits of coarse chips of each sample. Splits were further pulverized in an agate ring mill. Powders were sent to Northwest University, China, for whole-rock analysis. Powdered samples were heated at 1000°C for 50 min to determine Loss on ignition (L.O.I.). Samples were prepared for X-ray fluorescence (XRF, Rigaku RIX2100) by mixing 0.7 g of sample, 0.3 g LiF, 0.4 g NH_4NO_3 , 3.6 g $\text{Li}_2\text{B}_4\text{O}_7$, and 2–3 drops of 1.5% (w/w) LiBr solution. This mixture was melted in a non-wetting precious metal crucible and poured into a glass disk prior to analysis. Meanwhile, 50 mg of sample powder was digested using at 190°C for 48 h in mixed HClO_4 , HNO_3 and HF in steel bombs with polytetrafluoroethylene sleeves. After drying, residues were taken up in 80 mL of 2% HNO_3 with 10 ng/g of Rh as an internal standard. These solutions were analyzed by ICP-MS (Agilent 7500a) for trace elements and REE. The analytical protocol is standardized using international rock standards BCR-2, BHVO-1 and AGV-1. The analytical precision of this protocol, based on sample replicates, is better than 1% for major oxides and 5% for REE and trace elements.

4. Petrographic characteristics

The petrographic characteristics of each rock type collected from Wadi Al-Baroud area are described here. The post-collisional granites

are found to be biotite monzogranite that grades into muscovite monzogranite; samples were grouped according to which mica mineral is dominant. We also examined pegmatites and quartz veins associated with the post-collisional granites, as well as syntectonic granodiorite and tonalite. Forty-one samples were point-counted to obtain modal mineralogy (Tables 1 and 2). In the modal QAP ternary (Streckeisen, 1976), all the post-collisional AHP and RBP samples are classified as monzogranite, whereas the synorogenic granitoids are classified as granodiorite and tonalite (Fig. 4a).

4.1. Post collisional granites

4.1.1. Biotite monzogranite

Most samples of biotite monzogranite from the RBP and AHP are medium-to coarse-grained with allotriomorphic granular texture, although a few samples are sheared and strongly altered. Biotite monzogranite is composed of K-feldspars, plagioclase, quartz, biotite, and rare amphibole. Accessory phases include opaques, titanite, zircon, allanite, monazite, muscovite and apatite. Orthoclase and microcline together are 27–31 vol %. Orthoclase occurs as coarse anhedral grains containing albite lamellae forming different types of perthite including flame (Fig. 4b). Small subhedral plagioclase prisms are found as inclusions in the perthite. Microcline occurs as subhedral plates commonly characterized by crosshatching and perthitic textures enclosing small anhedral K-feldspar grains (Fig. 4c) or subhedral plagioclase. Plagioclase (24–30 vol%) occurs as subhedral stout prisms; some crystals exhibit alteration zoning with fresh rims surrounding cores extensively altered to sericite (Fig. 4d). Quartz (37–43 vol%) occurs as subhedral and anhedral interstitial grains and as inclusions of variable sizes and shapes. Undulose extinction and numerous fine inclusions of albite, microcline and zircon characterize the large quartz grains (Fig. 4e).

Biotite is the most abundant mafic mineral; amphibole is present but rare. The modal abundance of biotite is variable; it occurs as anhedral flakes and tabular prisms (Fig. 4f). Pleochroism is common from brown to yellowish-brown. Some biotite crystals are partly to extensively altered along cleavage planes to chlorite. Rare anhedral amphibole crystals are recorded in a few samples. The opaques, both Fe-Ti oxides and Nb-Ta oxides (1–4 vol%), occur as medium-sized anhedral grains enclosed in the biotite and plagioclase. Granular aggregates of Fe-Ti oxides are associated with mafic mineral alteration. The small subhedral crystals of Nb-Ta oxides vary from black to dark brown. The identity of these opaque phases was refined with electron microprobe data (see below).

Scarce anhedral grains of zircon are embedded in quartz and K-feldspars. Subhedral crystals of allanite are deep red-brown or black and associated with biotite (Fig. 4g). Titanite occurs as scarce anhedral grains. There are anhedral interstitial muscovite crystals (Fig. 4h), increasing in abundance towards areas of muscovite monzogranite. Minute tabular crystals of apatite are included in biotite (Fig. 4g). There are very fine anhedral crystals of monazite.

4.1.2. Muscovite monzogranite

Muscovite monzogranite is medium to coarse-grained. Marginal samples are mylonitized and sheared. Muscovite monzogranite is essentially composed of K-feldspars, plagioclase, quartz and muscovite with minor biotite and rare amphibole. The accessory minerals include opaques, zircon, fluorite, garnet, monazite, allanite, and apatite. There are secondary minerals such as sericite, epidote, and chlorite. K-feldspars (31–36 vol%) range from anhedral to subhedral; coarse anhedral crystals of orthoclase are dominant; they show simple twinning (Fig. 5a) and inclusions of plagioclase (Fig. 5b), quartz, and muscovite. Fe-stained turbid microcline is subordinate. Medium to coarse, anhedral, interstitial quartz (35–43 vol%) with scarce small inclusions of muscovite and plagioclase embays and corrodes the feldspars. Small euhedral plates and subhedral grains of plagioclase (21–28 vol%) display lamellar albite twins and minor sericite replacement.

Table 1

Modal composition (vol%) in the syntectonic granitoids of Ras Baroud area.

Rock type	Sample No.	Total counts	Quartz	K-Feldspars	Plagioclase	Mafics	Opaques
			%	%	%	%	%
Tonalite	B24T	1000	26.90	4.20	61.20	5.60	2.10
	B23T	1200	26.83	5.17	60.50	5.58	1.92
	B25T	1000	28.40	8.50	58.80	2.90	1.40
	B26T	1100	28.27	4.73	59.00	6.64	1.36
	B27T	1200	25.50	4.42	61.67	6.92	1.50
	B36T	1100	26.64	5.45	59.73	6.36	1.82
Granodiorite	B21	1200	32.33	13.17	46.00	6.17	2.33
	B22	1100	30.64	15.45	45.18	6.82	1.91
	B28	1100	29.91	17.64	43.36	7.00	2.09
	B29	1000	31.20	16.70	47.50	3.80	0.80
	B30	1200	32.00	16.25	46.33	3.58	1.83
	B31	1200	31.00	15.67	47.75	3.33	2.25
	B32	1000	27.30	17.10	47.30	4.80	3.50
	B33	1200	31.58	21.33	40.67	4.50	1.92
	B34	1100	27.91	12.73	51.36	5.64	2.36
	B35	1200	28.67	11.92	51.08	6.17	2.17
	B41	1200	31.00	15.50	45.58	5.75	2.17

Table 2

Modal composition (vol%) in the post-collisional granites of AHP and RBP.

Rock type	Sample No.	Total counts	Quartz	K-Feldspars	Plagioclase	Mafics	Opaques
			%	%	%	%	%
Ras Baroud granite	B3	1100	42.91	26.73	27.73	1.55	1.09
	B4	1000	42.30	27.40	27.90	1.30	1.10
	B5	1200	38.67	28.67	30.42	0.92	1.33
	B6	1200	36.92	29.67	28.83	3.33	1.25
	B7	1100	40.27	29.82	28.00	0.82	1.09
	B8	1100	40.18	31.36	26.27	1.36	0.82
	B14	1200	42.00	31.75	24.25	0.92	1.08
	B12	1200	38.58	31.00	28.17	0.67	1.58
	B37	1000	38.50	34.40	25.70	0.80	0.60
	B38	1100	37.36	32.82	27.91	0.91	1.00
	B39	1200	40.67	32.00	26.25	0.33	0.75
	B40	1200	37.67	33.42	27.25	1.00	0.67
	SB44	1200	39.75	30.67	27.17	1.25	1.17
Abu Hawis granite	H1	1000	39.60	28.10	26.80	1.30	4.20
	H2	1200	42.67	29.42	26.08	0.75	1.08
	H3	1200	41.00	28.75	26.08	1.67	2.50
	H4	1000	37.90	30.60	28.20	1.70	1.60
	H5	1100	42.91	31.27	24.00	0.91	0.91
	H6	1200	39.00	29.33	26.17	2.17	3.33
	H7	1000	41.10	35.50	20.70	1.40	1.30
	H9	1200	35.33	34.33	27.42	1.83	1.08
	H10	1199	36.03	33.69	26.36	2.50	1.42
	H13	1100	42.91	31.36	22.45	1.64	1.64
	H15	1160	40.26	30.95	25.52	1.98	1.29

Muscovite occurs as euhedral and subhedral large crystals and as anhedral small flakes replacing feldspars. The large muscovite crystals are characterized by perfect cleavage and high interference colors (Fig. 5c). Biotite occurs as small anhedral flakes, slightly altered along margins into chlorites and opaques (Fig. 5d). Very rare anhedral fine amphibole grains are noted. The opaques (0.6–1.5 vol%), mainly Nb-Ta and Fe-Ti oxides, are found both included in quartz and as anhedral to subhedral grains in replacement assemblages after mafic minerals. Columbite is the principal primary Nb-Ta oxide, while tantalite and wodginite are secondary phases. Tantalite occurs as overgrowths or replacement patches around primary columbite (Fig. 5e). Wodginite occurs as mineral inclusions in columbite, intergrowths with tantalite, or as individual single crystals. Scarce sphenoid-shaped euhedral titanite crystals are enclosed in feldspar. Scarce euhedral zircon crystals are associated with altered biotite. A few samples contain scarce anhedral small garnet crystals (Fig. 5f). Light brown, pleochroic, anhedral crystals of allanite have a crackly appearance. Monazite occurs as fine disseminated grains.

4.1.3. Pegmatites

There is a texturally and mineralogically diverse set of pegmatites associated with the post-collisional granites. Here we divide them by color and mineralogy into pink K-feldspar pegmatite and white albite pegmatite.

K-feldspar pegmatite is coarse to very coarse and visibly pink. It is volumetrically dominated by K-feldspars and quartz; albite, muscovite and mafic minerals are much less abundant. A variety of accessory minerals are present in K-feldspar pegmatite: opaques (both Nb-Ta oxides and Fe-Ti oxides), monazite, zircon, fergusonite, xenotime, fluorite, pyrochlore, bastnaesite and samarskite. Large subhedral to anhedral grains of both orthoclase and microcline are the essential minerals. Orthoclase contains perthitic lamellae of exsolved albite, while microcline shows tartan twinning. There are inclusions of albite, zircon, and Fe-Ti oxides in the large K-feldspar crystals. There are large anhedral quartz grains showing undulose extinction; quartz is also included in K-feldspars and muscovite. Muscovite crystals are large and subhedral to anhedral. Scarce amphibole crystals are anhedral (Fig. 5g).

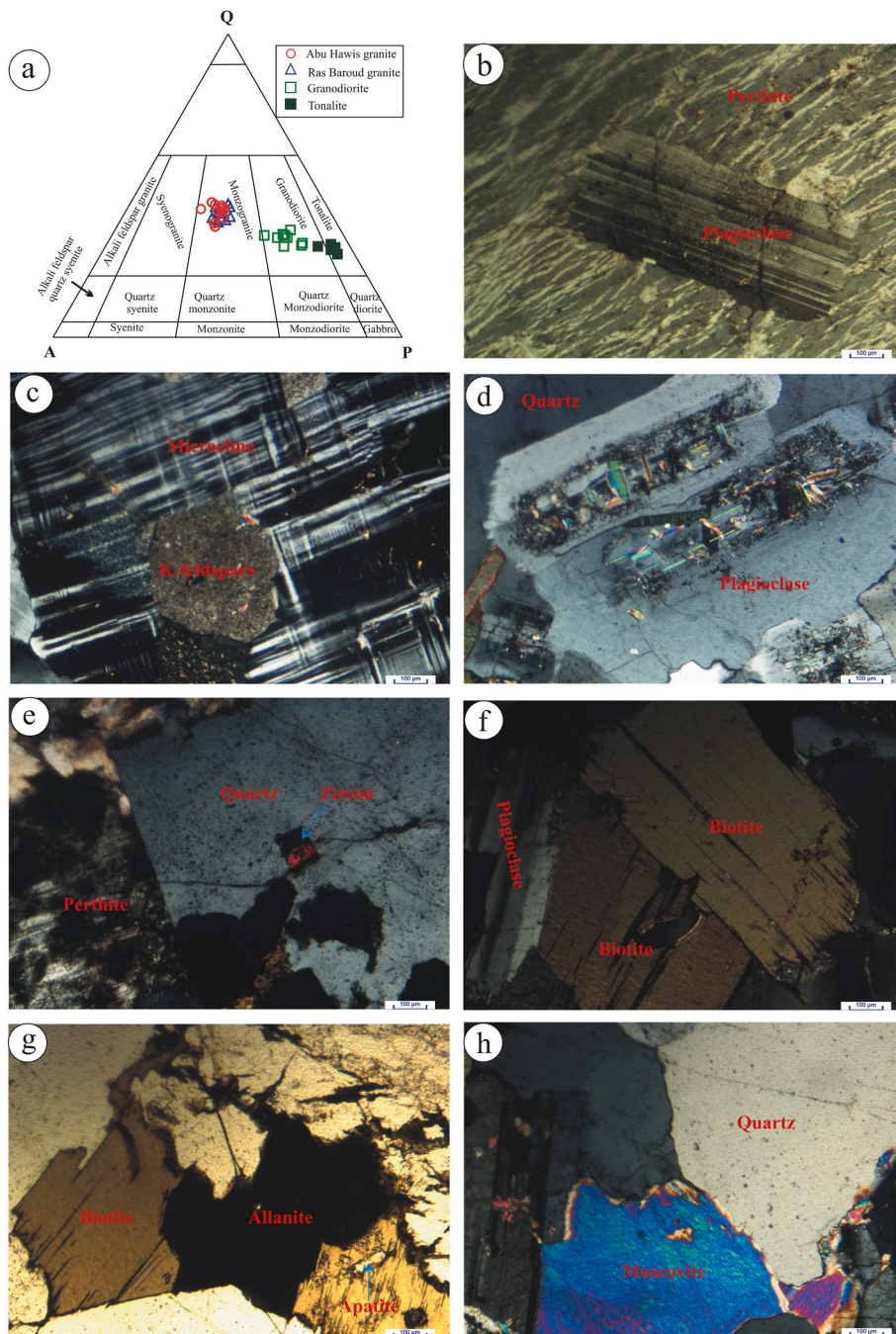


Fig. 4. (a) Ternary plot of modal quartz-alkali feldspar-plagioclase for granitoid rock classification (Streckeisen, 1976). Remaining panels are petrographic images of the biotite monzogranite (all in cross-polarized transmitted light): (b) plagioclase crystal in perthite, (c) crosshatching in microcline and K-feldspar inclusion, (d) highly altered cores of plagioclase crystals with fresh rims, (e) zircon crystal enclosed in quartz, (f) corroded tabular biotite crystals, (g) allanite crystal associated with biotite containing apatite inclusions, and (h) anhedral muscovite crystal.

Albite-rich pegmatite is medium-grained and white. It consists essentially of albite, quartz, K-feldspar, and micas (both muscovite and biotite). In addition to zircon and opaques, there is accessory fluorite. The abundant albite forms both euhedral prismatic and anhedral crystals. The polysynthetic twinning planes may be broken or bent, recording post-magmatic deformation. In places, a graphic texture of albite and quartz intergrowth is noted (Fig. 5h). Alteration of albite is common, including replacement by sericite, muscovite, and kaolinite, especially in crystal cores. K-feldspar, which displays both tartan twinning and perthitic lamellae, may contain small quartz and muscovite inclusions. Chlorite fibers and aggregates are found as an alteration product in biotite. There are small interstitial flakes of muscovite.

4.1.4. Quartz veins

Quartz veins are dominated by modal quartz accompanied by minor

muscovite and feldspars with accessory opaques (Fe-Ti oxides), fluorite, cassiterite, pyrochlore and zircon. The medium- to coarse-grained quartz crystals are subhedral and show wavy extinction. They show variable degrees of ductile deformation. The vein boundaries are marked by fine aggregates of sub-parallel needle-shaped quartz crystals. Numerous mineral fragments from the host rocks are disaggregated into the quartz veins.

4.2. Syntectonic granites

4.2.1. Granodiorite

The granodiorite is gray to whitish-gray. Its hypidiomorphic granular texture is made up of medium to coarse grains of plagioclase, quartz, K-feldspars and mafic minerals. Fe-Ti oxides, titanite, zircon and apatite are the main accessory phases. A few samples have a schistose texture.

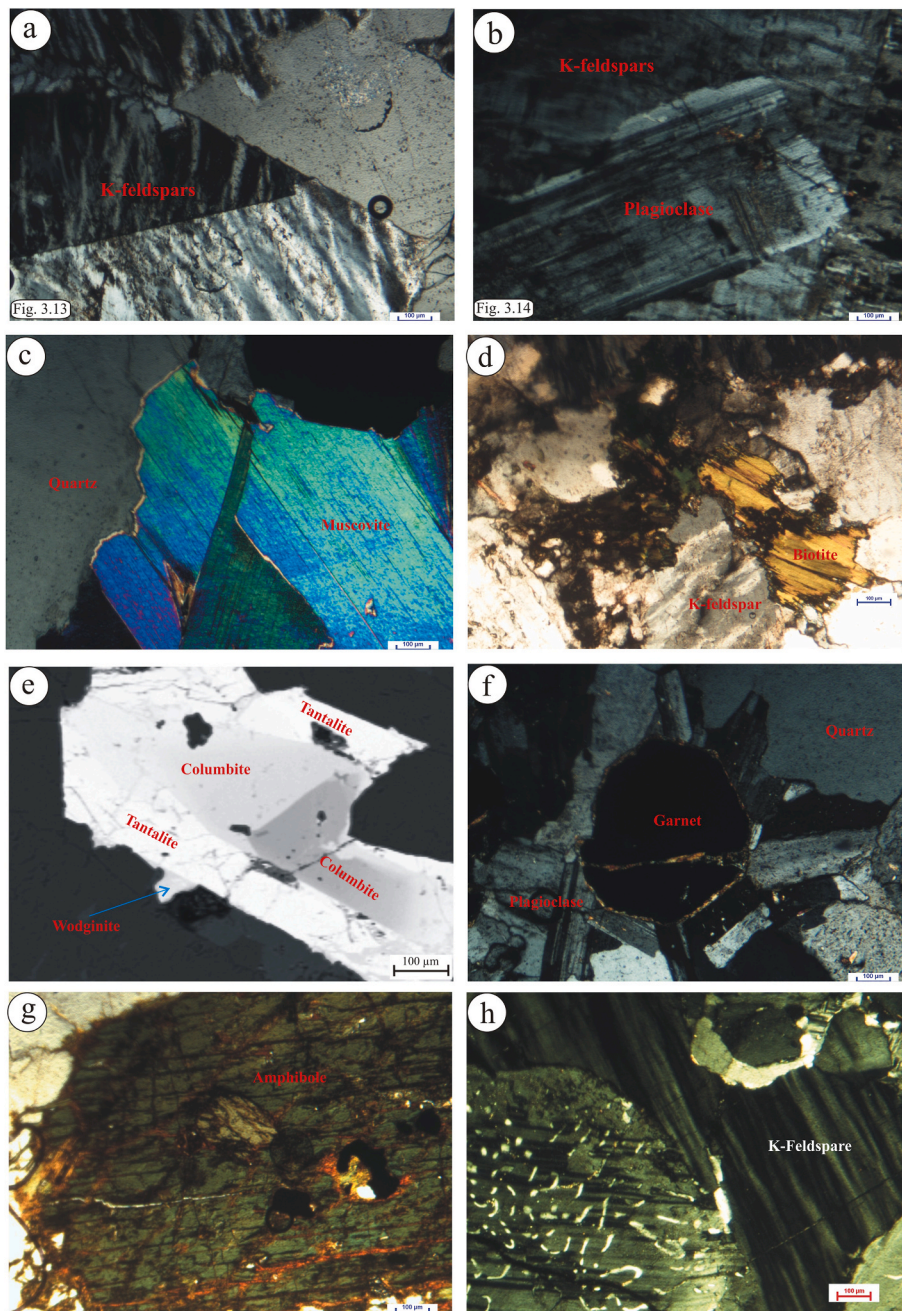


Fig. 5. Petrographic images of muscovite monzogranite (a, b, c, f, and h are in cross-polarized transmitted light, d and g are in plane-polarized light, e is in backscatter image): (a) orthoclase perthite showing simple twinning, (b) plagioclase within orthoclase perthite, (c) cracked muscovite crystal with perfect cleavages, (d) biotite altered along margins into chlorite and opaques, (e) overgrowth of tantalite around primary columbite, (f) garnet crystal, (g) amphibole crystal in pegmatite, and (h) micrographic intergrowth between quartz and K-feldspar.

Subhedral to anhedral plagioclase (41–52 vol%) is the most abundant mineral, variably altered to sericite and carbonates, especially in the cores. The large fresh plagioclase crystals show normal zoning. Quartz (27–33 vol%) forms anhedral crystals that corrode other minerals. K-feldspars (12–22 vol%) occur as anhedral interstitial crystals and include both orthoclase and microcline-microperthite.

Biotite and amphibole make up the mafic component (3–7 vol%). Yellow/brown pleochroic biotite is anhedral and is found in tabular, flake, and aggregate forms with inclusions of zircon and apatite. Alteration of biotite forms chlorite, muscovite, and crystallographically-controlled aggregates of iron oxide. Anhedral twinned tabular crystals of amphibole contain sparse Fe-Ti oxide and zircon inclusions along with minor replacement by Fe-Ti oxides and chlorite. The pleochroism of amphibole ranges from brownish green to pale yellow. The opaques (2–4 vol%) occur as small to medium anhedral grains enclosed in biotite and amphibole. Rhomb-shaped titanite grains associated with

amphibole are fairly abundant. Apatite occurs as numerous small prisms enclosed in biotite and amphibole.

4.2.2. Tonalite

Tonalite is uniformly gray. The grain size is medium to coarse and most samples show schistose texture. The essential minerals are plagioclase, quartz, K-feldspars, biotite and amphibole. Opaques, apatite, titanite and zircon are accessory phases. Tonalite closely resembles the associated granodiorite, but tonalite has more mafic minerals at the expense of less quartz and K-feldspar. The dominant plagioclase (57–62 vol%) forms mostly fresh, coarse, subhedral to anhedral prisms exhibiting lamellar twinning. The twin lamellae may be bent. Plagioclase rims are often corroded by quartz and K-feldspars. Where plagioclase cores are not obscured by alteration to sericite, normal zoning is evident. Anhedral to subhedral small crystals of K-feldspars (<10 vol%), both orthoclase and microcline, are interstitial.

The orthoclase is occasionally altered to kaolinite. Microcline is characterized by cross-hatch twinning and encloses scattered quartz grains having mostly corroded outlines. Coarse, anhedral quartz (25–29 vol%) is interstitial to plagioclase. It often displays undulose extinction. Some quartz crystals are cracked and others contain apatite inclusions.

Biotite forms both isolated subhedral crystals and aggregates with amphibole. Iron oxides decorate the cleavage plans and grain boundaries of most biotite crystals. The anhedral to subhedral amphibole grains display dark green to pale green pleochroism and simple twinning. Amphibole may be partly replaced by chlorite and opaques.

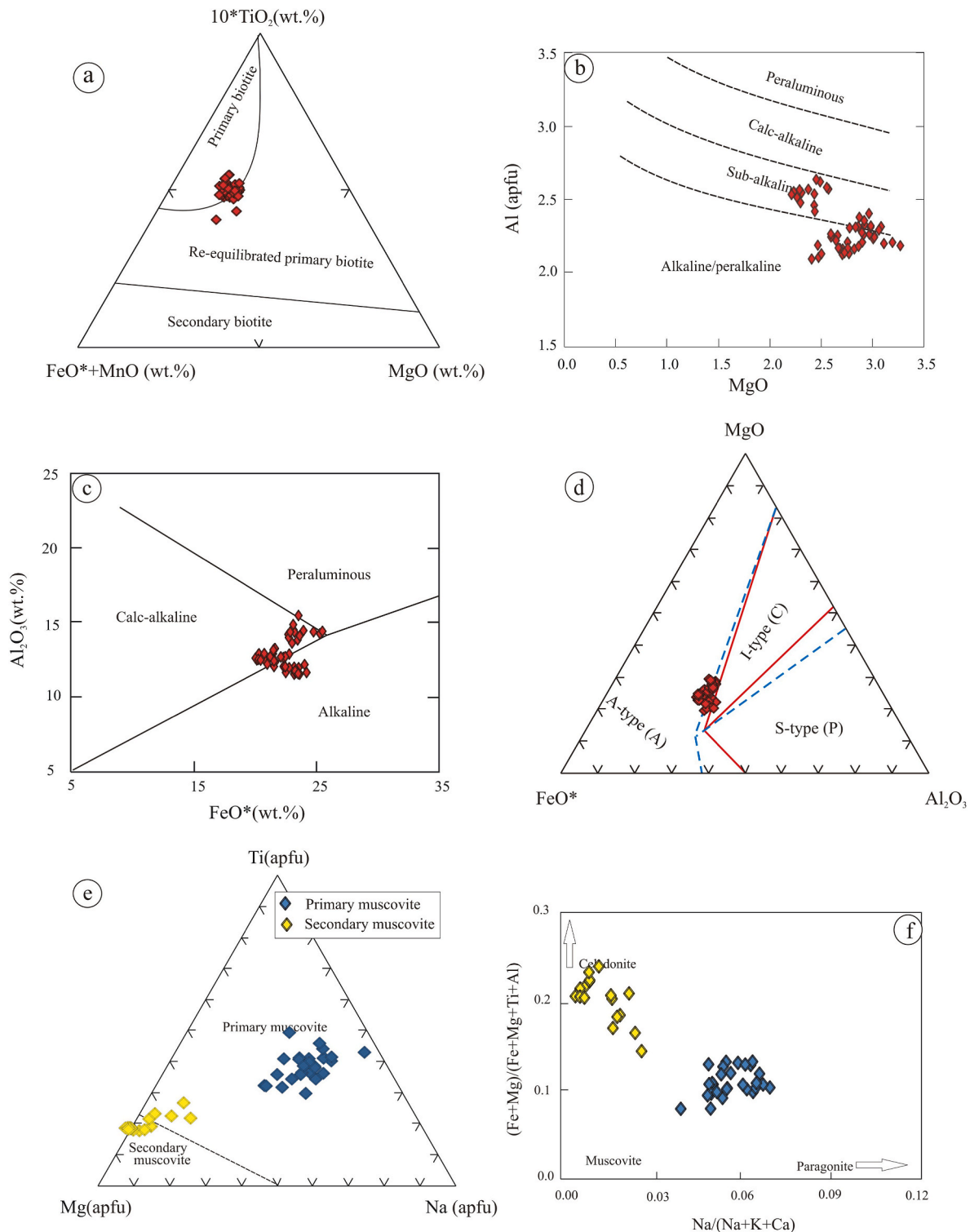


Fig. 6. Mineral chemistry plots: (a) $\text{TiO}_2\text{-FeO}^*\text{-MgO}$ ternary diagram for classification of biotite (Nachit et al., 2005); (b) MgO vs Al discrimination diagram for biotite after Nachit (1985); (c) FeO^* vs Al_2O_3 discrimination diagram for biotite (Abdel-Rahman, 1994). (d) $\text{MgO-FeO-Al}_2\text{O}_3$ discrimination diagram for biotite. Solid lines are divisions proposed by Gion et al. (2022) to separate A-type, I-type, and S-type fields. Dashed lines are the divisions determined by Abdel-Rahman (1994) for alkaline (A), calc-alkaline (C) and peraluminous (P) fields. (e) Mg-Ti-Na ternary diagram for the compositional fields of muscovite after (Miller et al., 1981). (f) $\text{Na}/(\text{Na} + \text{K} + \text{Ca})$ vs. $(\text{Fe} + \text{Mg})/(\text{Fe} + \text{Mg} + \text{Ti} + \text{Al})$ variation diagram of muscovite.

Opacques, principally Fe oxide, are alteration products after biotite and amphibole. There are apatite inclusions in plagioclase, biotite and amphibole. Titanite forms euhedral interstitial crystals and subhedral crystals associated with biotite. Euhedral or cracked zircon is commonly associated with amphibole.

5. Mineral composition

We refined the identity and compositions of the constituent minerals in the RBP and AHP samples by EPMA analysis. The analyzed minerals include silicates (feldspars, biotite, muscovite, amphibole, chlorite, and zircon) and selected non-silicate minerals (Nb-Ta oxides, Fe-Ti oxides, apatite and fluorite). Some accessory minerals (monazite, thorite, allanite and pyrochlore) were not suitable for EPMA analysis due to grain size limitations or to the limited number of elements included in practical EPMA protocols. Data, reported as oxide weight percents and calculated structural formulae, are reported in the Appendix (Tables SD1–SD17).

5.1. Silicate minerals

5.1.1. Feldspars

Feldspar analyses are divided by lithologic type (biotite and muscovite monzogranite), locality (AHP and RBP), and mineral group (K-feldspar, albite, and plagioclase) (Tables SD1, SD2 & SD3). K-feldspars were found in both biotite monzogranite and muscovite monzogranite. Each analyzed K-feldspar crystal (Table SD1) is homogenous, but there is a range among crystals from 13.3 to 16.3 wt % K₂O, corresponding to orthoclase proportions from Or₇₈ to Or₉₈.

The analyzed plagioclases include albite, oligoclase and andesine. Again, no zoning of individual crystals of plagioclase was found, suggesting crystallization close to equilibrium conditions. Albite (Ab_{90–99}, with An_{<5.5}) was found in both biotite monzogranite and muscovite monzogranite (Table SD2). Oligoclase was found in both biotite monzogranite and muscovite monzogranite, whereas andesine was only found in biotite monzogranite (Table SD3). The oligoclase is An₁₁ to An₂₇ with an average of An₁₅, while andesine is An₃₂ to An₃₈ with an average of An₃₄.

5.1.2. Biotite

Biotite is a main mineral in biotite monzogranite and a less common phase in muscovite monzogranite. The analyzed biotite (Table SD4) is mostly annite. Its FeO/MgO ratio ranges from 1.49 to 2.21 in biotite monzogranite and from 2.01 to 2.56 in muscovite monzogranite. The biotite in muscovite monzogranite is richer in Al₂O₃ (13.6–15.4 wt %) than that in biotite monzogranite (11.5–13.2 wt %). The ternary diagram of Nachit et al. (2005) places the biotite analyses either in the primary biotite field or straddling the boundary between with re-equilibrated primary biotite (Fig. 6a).

Biotite compositions form a continuous series in samples of both studied plutons, as expected if they share a common parental magma and crystallized under similar conditions. Biotite composition may be used to constrain the type of the parental magma (Nachit, 1985; Abdel-Rahman, 1994; Gion et al., 2022). The Nachit (1985) biotite discrimination diagram places the analyses across the sub-alkaline and alkaline fields (Fig. 6b). The Al₂O₃ vs. FeO* diagram of Abdel-Rahman (1994) places the analyses across the boundary between calc-alkaline and alkaline suites, approaching the edge of the peraluminous field (Fig. 6c). The ternary biotite composition diagram (Abdel-Rahman, 1994; Gion et al., 2022) shows compositions plotting in the A-type field but close to the I-type boundary (Fig. 6d).

5.1.3. Muscovite

Muscovite is abundant in muscovite monzogranite and occurs as an accessory mineral in biotite monzogranite (Table SD5). Petrographically, muscovite is divided into primary and secondary categories. The

chemical diversity of muscovite is consistent with this division, based on a modified Miller et al. (1981) discrimination diagram (Fig. 6e). The muscovite identified as primary has more TiO₂ (0.40–0.88 wt %), Al₂O₃ (29.4–32.2 wt %) and Na₂O (0.27–0.48 wt %), but less MgO (0.15–0.74 wt %) and FeO* (3.15–5.94 wt %) than secondary muscovite (0.04–0.31 wt % TiO₂, 27.0–30.5 wt % Al₂O₃, 0.03–0.19 wt % Na₂O, 0.98–2.33 wt % MgO and 5.47–8.09 wt % FeO*). TiO₂ > 0.4 wt % is considered a signature of magmatic muscovite (Anderson and Rowley, 1981; Zen, 1988). The elevated FeO* content in the secondary muscovite indicates the presence of a ferrous celadonite component, while elevated Na₂O content in the primary muscovite indicates solution towards paragonite component (Fig. 6f).

5.1.4. Amphibole

Electron microprobe analyses for amphibole from the PCG (Table SD6) were checked for stoichiometry, mapped to structural formulae, and assigned mineral species names according to current International Mineralogical Association recommendations (Hawthorne et al., 2012; Locock, 2014). The amphibole analyses are all calcic and range from mostly magnesio-ferri-hornblende in biotite monzogranite to mostly ferro-ferri-hornblende in muscovite monzogranite; that is, Fe²⁺/Mg is generally higher in amphibole in the muscovite monzogranite. There is a single analysis with higher Na than the others that classifies as hastingsite. Based on petrographic investigation and chemical composition, all the analyzed amphiboles are primary amphibole, with >0.1 Ti atoms per formula unit (Girardeau and Mevel, 1982) and a primary signature in Si vs. Ca + Na + K (Keeditse et al., 2016) (Fig. 7a).

5.1.5. Chlorite

Chlorite (Table SD7) is present as a replacement phase after biotite and amphibole. Chlorite in these samples shows a limited range of compositions; most analyses correspond to pycnochlorite with a few brunsvigite points (Hey, 1954) (Fig. 7b).

5.1.6. Zircon

Zircon occurs as an accessory mineral in all RBP and AHP monzogranite samples. The analytical totals of most zircon points (Table SD8) are low (96–98 wt %), presumably because accumulated damage in highly radioactive Neoproterozoic zircons leaves them mostly metamict. It is chemically pure (Zr, Hf)SiO₄ (the table reports up to 0.45 wt % P₂O₅ but this is likely due to imperfect correction for the interference between P K α and Zr L α X-rays). Zircon in biotite monzogranite contains less HfO₂ (avg. 2.99 wt %) than zircon in muscovite monzogranite (avg. 4.08 wt %).

5.2. Non-silicate minerals

5.2.1. Nb-Ta phases

The EPMA data were used to confirm and extend the petrographic identification of Nb-Ta phases. We found columbite (Table SD9), tantalite (SD10) and wodginite (SD11). Note that the SiO₂ reported in tantalite is likely due to imperfect correction for the interference of the X-ray lines of Si and Ta. The “columbite quadrilateral”, Ta/(Nb + Ta) vs. Mn/(Mn + Fe), organizes the analyses into columbite-(Mn), tantalite-(Fe), and wodginite (Fig. 7c). Columbite is present in both biotite and muscovite monzogranite samples. It displays a normal zoning trend from Nb-rich cores near Ta/(Nb + Ta) = 0.11 and Mn/(Mn + Fe) = 0.52 towards Ta- and Mn-enriched mantles reaching up to Ta/(Nb + Ta) = 0.31 and Mn/(Mn + Fe) = 0.79.

Tantalite-(Fe) is recorded only in the muscovite monzogranite as rims around columbite-(Mn). The ratios of Ta/(Nb + Ta) vary between 0.54 and 0.66; Mn/(Mn + Fe) spans 0.40 to 0.50 (plus a single outlier at Mn/(Mn + Fe) = 0.62). Contents of Fe and Mn in each tantalite rim are nearly constant. The formation of tantalite-(Fe) rims on primary columbite-(Mn) has previously been assigned to alteration processes

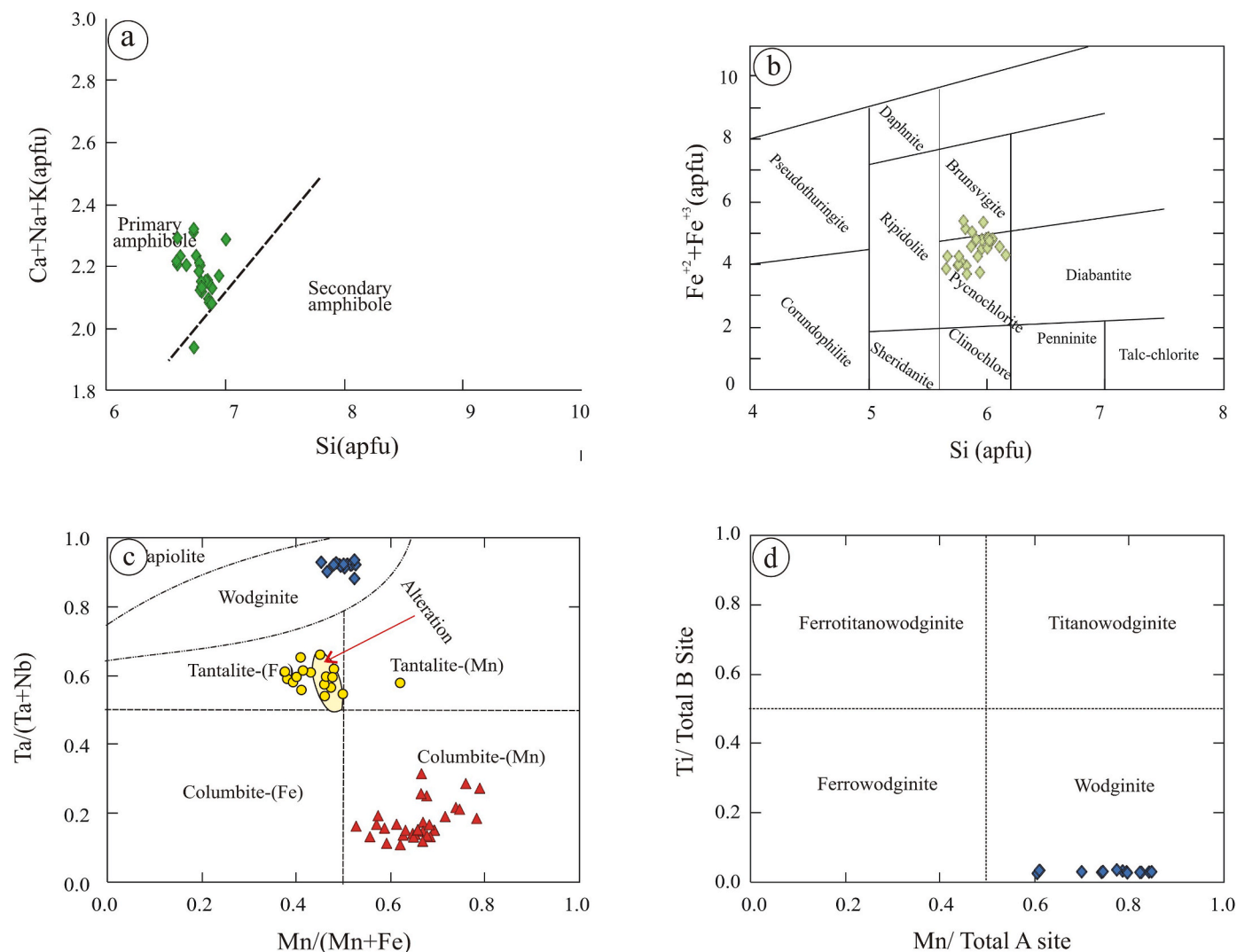


Fig. 7. More mineral chemistry plots: (a) discrimination diagram for primary and secondary amphiboles (after Keeditse et al., 2016), (b) chlorite nomenclature (after Hey, 1954), (c) chemical composition and nomenclature of the Ta-Nb oxides based on $\text{Ta}/(\text{Ta} + \text{Nb})$ vs $\text{Mn}/(\text{Mn} + \text{Fe})$ ratios, (d) classification quadrilateral for wodginite-group minerals based on $\text{Mn}/(\text{total A site})$ vs. $\text{Ti}/(\text{total B Site})$; modified after Tindle and Breaks (1998).

(Beurlen et al., 2008).

The wodginite end-member composition, $\text{MnSnTa}_2\text{O}_8$, is often diluted by extensive substitution, e.g. Fe^{2+} substituting for Mn, Ti substituting for Sn, and Nb substituting for Ta. The wodginite in the present samples displays complex textures and some variation in major and minor element compositions, likely due to growth under disequilibrium conditions as an alteration phase. Analytical totals are somewhat low (96.18–98.27 wt %), possibly because we did not analyze for fluorine. The wodginite analyses feature minor Nb_2O_5 (2.64–4.96 wt %) and very low Ti (0.27–0.48 wt %) alongside subsequent FeO^* (6.84–8.67 wt %) and MnO (6.18–8.82 wt %) contents. As with tantalite, apparent SiO_2 is likely due to interference between Ta and Si X-rays. The wodginite classification diagram $\text{Ti}/(\text{total B})$ vs. $\text{Mn}/(\text{total A site})$ places all analyses in the wodginite *sensu stricto* field (Fig. 7d).

The nomenclature for zoning of columbite-tantalite group minerals was adopted from Lahti (1987) and Tindle and Breaks (2000). Increasing $\text{Ta}/(\text{Nb} + \text{Ta})$ and $\text{Mn}/(\text{Mn} + \text{Fe})$ ratios from the core to the rim of a crystal defines normal zoning in this group, while reverse zoning has the opposite trend (Lahti, 1987). This behavior is expected because Ta/Nb and Mn/Fe typically increase during fractional crystallization in granites (Cerný and Ercit, 1985). The $\text{Ta}/(\text{Nb} + \text{Ta})$ trend is governed by early crystallization of Nb-rich columbite (Linnen and Keppler, 1997),

whereas there are a number of phases that contribute to the evolution of $\text{Mn}/(\text{Mn} + \text{Fe})$. Within the primary core-mantle regions, columbite-(Mn) in the current rocks exhibits such normal zoning trends. On the other hand, the overgrowth or partial replacement of columbite-(Mn) by tantalite-(Fe) indicates normal evolution with respect to $\text{Ta}/(\text{Nb} + \text{Ta})$ but reverse zoning with respect to $\text{Mn}/(\text{Mn} + \text{Fe})$. The late tantalite in crystal margins and along fractures has been interpreted as a record of partial resorption and reprecipitation (Lahti, 1987). Such transformation of columbite to tantalite might reflect interaction with supercritical vapour (e.g., Jahns and Burnham, 1969) or with peraluminous residual melt (e.g., London et al., 1990).

5.2.2. Fe-Ti oxide phases

We found magnetite (Table SD12), ilmenite (Table SD13), goethite (Table S14), and hematite (Table SD15). The compositions of magnetite in the biotite monzogranite and muscovite monzogranite are slightly different. All magnetite analyses in muscovite monzogranite are low-Ti magnetite ($\text{TiO}_2 \leq 0.68$ wt % and $\text{Ti apfu} \leq 0.02$), whereas biotite monzogranite contains both low-Ti magnetite ($\text{TiO}_2 \leq 1.16$ wt % and $\text{Ti apfu} \leq 0.03$) and titanomagnetite (up to 6.38 wt % TiO_2 and Ti apfu up to 0.19). Ulvöspinel contents, calculated according to the procedure of Stormer (1983), are from 0.90 up to 1.9 mol % in the muscovite granite

and from 1.4 up to 18.5 mol % in the biotite granite.

The rhombohedral oxide solid solution includes the end members ilmenite (FeTiO_3) and pyrophanite (MnTiO_3) (Deer et al., 1992). Ilmenite in the muscovite monzogranite contains more MnO (5.28–7.58 wt %; average 6.33) than that in biotite monzogranite (3.85–5.57 wt %; average 4.55). The calculated ilmenite content (Stormer, 1983) ranges between 92 and 99 mol % (average 95.2) in the biotite granite and between 93 and 99 mol % (average 96.2) in the muscovite granite.

Goethite and hematite appear as secondary alteration phases after the igneous Fe-Ti oxides. The analyses of goethite have low totals and substantial apparent SiO_2 because it is a hydrous, porous phase and likely intermixed at nanoscale with other minerals. Hematite contains up to 4.8 wt % TiO_2 and also shows somewhat low total, even with Fe reported as Fe_2O_3^* , probably due to partial hydration.

5.2.3. Apatite and fluorite

Apatite analyses (Table SD16) essentially serve to indicate only that an apatite phase is present; without F and Cl measurements they cannot be used to assign a detailed mineral name to this material. Oxides other than CaO and P_2O_5 occur in only minor amounts. Likewise, fluorite analyses (Table SD17) serve only to indicate that this mineral is present; without analysis of F, the only element present in detectable amounts is Ca.

6. Geochemistry

Whole-rock compositions allow us to confirm the nomenclature and to classify the chemical affinity and tectonic environment associated with each rock type. They also help to group samples into likely cogenetic cohorts and offer targets for testing hypotheses for their

petrological evolution. Samples of granite, granodiorite, and tonalite were selected for analysis on the basis of field and petrographic evidence indicating minimal alteration. The mylonitized and sheared granites were too strongly altered to analyze. Data for major oxides, trace elements and REE are reported for the AHP (8 samples), the RBP (13 samples), and their country rocks (4 tonalite samples and 6 granodiorite samples). The whole rock chemical analyses are divided by rock type and analytical method and presented in Tables 3–11.

6.1. Geochemical characteristics

The PCG have high silica contents (74.8–77.0 wt % SiO_2 in AHP and 73.1–77.2 wt % SiO_2 in RBP) and high differentiation index values (Thornton and Tuttle, 1960) (91.0–94.7 in AHP and 89.6 to 93.5 in RBP). By contrast, the syntectonic granites are less differentiated, with lower silica contents (64.6–66.9 wt % SiO_2 in tonalite and 67.8–70.9 wt % SiO_2 in granodiorite) and differentiation index values (57.1–63.8 in tonalite and 68.4–78.3 in granodiorite). Differences are also apparent in many other elemental concentrations: compared with the PCG, tonalite and granodiorite samples have higher TiO_2 , Fe_2O_3 , CaO, MgO, P_2O_5 , Sr, Ba, Co, Cr, Cu, V, Ni, and Zn but lower alkalis, Nb, Rb, Y, Ta, Hf, Th, U, Zr, Li and As.

6.2. Rock classification

Standard rock nomenclature is based on modal mineralogy (Fig. 4a), but we can also verify the nomenclature using whole-rock chemical classification schemes; the CIPW norms are given in Tables 3, 4 and 9. De la Roche et al. (1980) introduced a plot of R_1 [$4\text{Si}-11(\text{Na} + \text{K})-2(\text{Fe} + \text{Ti})$] vs. R_2 [$6\text{Ca}+2\text{Mg} + \text{Al}$] (Fig. 8a). On this plot, the PCG plot as

Table 3
Major oxides and normative compositions in the post-collisional granite of Ras Baroud.

Sample No	B3	B4	B5	B6	B7	B8	B12	B13	B14	B38	B39	B40	B41
Major oxides (wt.%)													
SiO_2	74.76	74.36	75.22	76.03	77.21	73.12	76.19	74.18	74.55	75.34	73.84	74.55	76.21
TiO_2	0.08	0.1	0.1	0.06	0.05	0.15	0.07	0.12	0.09	0.07	0.11	0.1	0.06
Al_2O_3	13.78	13.11	12.86	13.01	12.02	14.02	12.61	13.49	13.14	13.25	13.73	13.32	12.68
Fe_2O_3	0.88	1.28	1.06	0.84	0.75	1.63	0.67	1.06	1.03	0.99	1.21	1.04	0.75
MnO	0.05	0.09	0.08	0.04	0.02	0.1	0.02	0.08	0.06	0.05	0.08	0.07	0.03
MgO	0.34	0.38	0.31	0.29	0.26	0.42	0.29	0.35	0.31	0.32	0.37	0.32	0.28
CaO	1.33	1.46	1.34	1.16	1.16	1.52	1.05	1.51	1.26	1.21	1.57	1.44	1.23
Na ₂ O	4.08	4.15	3.93	3.96	3.41	4.62	3.89	4.04	4.23	3.65	4.22	3.96	3.75
K ₂ O	4.12	3.84	4.11	4.19	4.26	3.85	4.27	4.03	3.97	3.94	3.96	4.01	4.24
P_2O_5	0.07	0.1	0.08	0.05	0.04	0.12	0.04	0.08	0.06	0.07	0.09	0.07	0.04
LOI	0.71	0.5	0.35	0.27	0.85	0.32	0.92	0.85	1.01	0.83	0.6	0.76	0.68
Total	100.14	99.18	99.28	99.82	99.17	99.36	99.65	100.39	99.67	99.97	99.78	99.64	99.95
CIPW (normative composition)													
Quartz	31.81	31.96	33.46	33.89	38.37	27.38	34.78	31.57	31.8	36.04	30.18	32.64	35.24
Corundum	0.35	-	-	-	-	-	-	-	-	0.95	-	0.01	-
Orthoclase	24.49	22.98	24.53	24.87	25.4	22.88	25.48	24.09	23.79	23.56	23.62	23.98	25.25
Albite	34.72	35.55	33.59	33.65	29.11	39.32	33.23	34.58	36.29	31.26	36.04	33.92	31.98
Anorthite	6.18	5.86	5.35	5.36	4.94	6.17	4.36	6.84	5.2	5.61	6.87	6.77	5.27
Diopside	-	0.68	0.7	0.08	0.5	0.53	0.52	0.18	0.62	-	0.33	-	0.51
Hypersthene	1.89	2.2	1.7	1.7	1.29	2.72	1.22	2.03	1.71	2.02	2.21	2.05	1.33
Magnetite	0.22	0.33	0.27	0.21	0.18	0.41	0.17	0.28	0.26	0.25	0.31	0.27	0.18
Ilmenite	0.15	0.19	0.19	0.11	0.1	0.29	0.13	0.23	0.17	0.13	0.21	0.19	0.11
Apatite	0.15	0.22	0.18	0.11	0.09	0.26	0.09	0.18	0.13	0.15	0.2	0.15	0.09
Geochemical parameters													
Colour Index	2.27	3.4	2.87	2.1	2.07	3.95	2.04	2.72	2.76	2.4	3.07	2.51	2.15
Diff. Index	91.02	90.49	91.57	92.41	92.88	89.59	93.48	90.24	91.88	90.86	89.83	90.53	92.47
ANOR	20.1	20.3	17.9	17.7	16.3	21.2	14.6	22.1	17.9	19.2	22.5	22	17.3
Q	31.81	31.96	33.46	33.89	38.37	27.38	34.78	31.57	31.8	36.04	31.2	33.5	36.1
R1	2542	2546	2623	2654	2914	2284	2675	2533	2506	2773	2458	2591	2730
R2	429	432	411	394	373	458	374	444	408	405	455	431	395
AI	0.81	0.84	0.85	0.85	0.85	0.84	0.87	0.82	0.86	0.78	0.82	0.81	0.85
ASI	1.01	0.96	0.96	0.99	0.97	0.96	0.98	0.98	0.97	1.06	0.97	0.99	0.98
Ti	480	600	600	360	300	899	420	719	540	420	659	600	360
K	34201	31877	34118	34782	35364	31960	35447	33454	32956	32707	32873	33288	35198
P	306	436	349	218	175	524	175	349	262	306	393	306	175
AI = molar (Na + K)/Al AI = molar (Na + K)/Al $\text{ASI} = \text{molar Al}/(\text{Ca} + \text{Na} + \text{K})$ ANOR = $100 \times \text{An}/(\text{Or} + \text{An})$ $Q' = Q/(Q + \text{Or} + \text{Ab} + \text{An})$													

Table 4

Major oxides and normative compositions in the post-collisional granite of Abu Hawis.

Sample No	H2	H4	H5	H6	H7	H10	H11	H13
Major oxides (wt.%)								
SiO ₂	75.15	76.97	76.82	75.59	76.74	74.95	74.76	76.57
TiO ₂	0.08	0.04	0.03	0.09	0.06	0.1	0.09	0.04
Al ₂ O ₃	12.57	12.11	11.63	13.12	12.42	13.48	13.19	12.18
Fe ₂ O ₃	1.11	0.6	0.72	1.13	0.58	0.97	1.07	0.63
MnO	0.07	0.01	0.01	0.07	0.03	0.06	0.07	0.02
MgO	0.33	0.27	0.25	0.31	0.25	0.32	0.32	0.26
CaO	1.24	1.04	0.92	1.13	1.15	1.19	1.3	1.15
Na ₂ O	3.88	3.66	3.42	3.82	3.55	3.94	3.88	3.54
K ₂ O	4.19	4.41	4.61	3.86	4.37	4.22	4.09	4.46
P ₂ O ₅	0.08	0.02	0.01	0.07	0.04	0.07	0.07	0.02
LOI	0.93	1.17	1.01	0.83	0.94	0.74	0.83	1.04
Total	99.67	100.03	99.36	100.44	99.24	100.05	99.87	99.92
CIPW (normative composition)								
Quartz	33.72	36.56	37.56	35.61	36.74	32.79	33.3	36.51
Corundum	-	-	-	0.77	-	0.43	0.18	-
Orthoclase	25.11	26.3	27.7	23.02	26.05	25.13	24.47	26.67
Albite	33.29	31.26	29.42	32.62	30.3	33.6	33.24	30.31
Anorthite	4.56	3.61	2.8	5.2	5.08	5.49	6.07	4.21
Diopside	0.97	1.21	1.48	-	0.34	-	-	1.19
Hypersthene	1.72	0.78	0.78	2.15	1.13	1.93	2.11	0.82
Magnetite	0.28	0.14	0.17	0.28	0.15	0.25	0.27	0.15
Ilmenite	0.15	0.08	0.06	0.17	0.11	0.19	0.17	0.08
Apatite	0.18	0.04	0.02	0.15	0.09	0.15	0.15	0.04
Geochemical parameters								
Colour Index	3.12	2.21	2.49	2.61	1.73	2.37	2.55	2.24
Diff. Index	92.12	94.11	94.67	91.24	93.08	91.52	91.02	93.49
ANOR	15.4	12.1	9.2	18.4	16.3	17.9	19.9	13.6
Q	33.72	36.56	37.56	35.61	36.74	32.79	34.3	37.4
R1	2617	2779	2804	2744	2812	2578	2628	2780
R2	396	362	339	394	379	408	413	374
AI	0.87	0.89	0.91	0.80	0.85	0.82	0.82	0.87
ASI	0.95	0.95	0.95	1.05	0.98	1.02	1.00	0.96
Ti	480	240	180	540	360	600	540	240
K	34782	36609	38269	32043	36277	35031	33952	37024
P	349	87	44	306	175	306	306	87
AI = molar (Na + K)/Al								
ANOR = 100 × An/(Or + An)								
AI = molar (Na + K)/Al								
Q' = Q/(Q + Or + Ab + An)								
ASI = molar Al/(Ca + Na + K)								

normal granites, whereas the syntectonic granites plot as granodiorite and tonalite. Streckisen and Le Maitre (1979) defined a normative scheme for classifying oversaturated igneous rocks using the Q' - ANOR diagram. Here, Q' is defined as $100 \times Q / (Q + Or + Ab + An)$ and ANOR is defined as $100 \times An / (Or + An)$. On this plot (Fig. 8b), the PCG samples straddle the monzogranite/syenogranite boundary. On the same diagram, the syntectonic suite mostly plot in the tonalite and granodiorite fields.

6.3. Trace and rare earth element results

Trace elements in PCG samples are plotted in order from incompatible to compatible and normalized to the primitive mantle (PM) concentrations (Sun and McDonough, 1989) (Fig. 8c). The two plutons show broadly similar patterns; all samples are enriched in most large-ion lithophile elements (LILE), notably Rb, K, Th, and Pb, as well as high field strength elements (HFSE), notably Ta, Zr and Hf. There are obvious negative anomalies in Ba, Sr, P, and Ti. A-type granites typically show these features (Jahn et al., 2001; Wu et al., 2002). The elements showing negative anomalies are compatible in feldspar, apatite, and ilmenite. Hence their depletion is most easily explained either by fractional crystallization of these phases or by their presence in the residuum during partial melting. The absence of any Ta-Nb trough in these samples distinguishes them from typical subduction-related suites (Hollings and Wyman, 1999; Saunders et al., 1980). The syntectonic suite (tonalite and granodiorite, Fig. 8d) also yields a coherent set of trace element patterns in all samples, with obviously distinct character from the post-collisional group. The syntectonic samples are less enriched overall; are not depleted in Sr, P or Ti; and display prominent negative anomalies

in Ta-Nb and positive anomalies in Ba. These features are typical of subduction-related rocks (Hollings and Wyman, 1999; Saunders et al., 1980).

Patterns of REE concentration, normalized to CI chondrite values (Evensen et al., 1978), in the PCG samples are shown in Fig. 8e. The patterns are all similar and subparallel, with concentrations of all REE higher on average in AHP compared to RBP. Both plutons show moderate light REE (LREE) enrichment $[(La/Lu)_n = 2.63-6.02]$ and modest depletion of middle REE (MREE) compared to heavy REE (HREE) $[(Gd/Lu)_n = 0.68-0.83]$. There are striking negative Eu anomalies $(Eu/Eu^* = 0.36-0.57)$, generally considered a signature of plagioclase removal under moderately reducing conditions (Hanson, 1978; McKay, 1989) at some stage of evolution of the parental magma or its source, earlier than that sampled by the plutonic rocks. Possibilities include early plagioclase fractionation at a deeper level of the plumbing system, residual plagioclase in the source, or a source that had already inherited a negative Eu anomaly (Lee et al., 2013).

Corresponding patterns of the REE in the syntectonic suite are shown in Fig. 8f. Compared to the post-collisional granites ($\Sigma REE = 136-332 \mu g/g$), the syntectonic granites ($\Sigma REE = 48-102 \mu g/g$) have lower overall REE concentrations. All tonalite and granodiorite samples show nearly similar REE patterns, with concentrations increasing from tonalite (48–63 $\mu g/g$) to granodiorite (70–102 $\mu g/g$). The syntectonic granites are strongly enriched in ratios of LREE to HREE; $(La/Lu)_n$ ranges from 9.3 to 10.0. The uniform slope across the REE series continues with elevated MREE/HREE ratios $[(Gd/Yb)_N = 1.66-1.93]$. Eu anomalies are small and of either sign $(Eu/Eu^* = 0.76-1.22)$, which may indicate roles for both fractionation and assimilation of feldspars.

Table 5Trace element contents ($\mu\text{g/g}$) in the post-collisional granite of Ras Baroud.

Sample No	B3	B4	B5	B6	B7	B8	B12	B13	B14	B38	B39	B40	B41
Cr	4.26	7.15	4.92	3.19	1.98	7.65	1.98	7.09	6.22	3.77	6.51	5.73	2.55
Ni	5.17	5.47	4.07	1.47	1.22	6.87	1.99	5.33	4.12	3.01	6.23	4.89	1
Co	0.79	0.79	0.43	0.35	0.37	1.02	0.52	0.89	0.84	0.54	0.89	0.72	0.48
Sc	2.56	2.88	1.81	1.19	0.72	3.54	1.32	3.04	2.74	1.99	2.84	2.5	1.11
V	3.94	4.18	3.16	2.6	1.19	5.03	1.99	4.16	4.3	3.47	4.81	3.82	1.88
Cu	3.87	5.08	2.98	2.22	1.29	5.95	1.66	4.91	4.01	2.98	4.78	3.72	1.44
Pb	22.29	21.01	14.99	10.96	5.92	29.04	12.64	25.33	23.49	16.3	25.08	19.52	9.9
Zn	20.01	29.65	33.07	22.99	21.82	55.27	22.91	35.9	40.56	14.13	30.21	33.42	22.58
Bi	0.34	0.35	0.22	0.19	0.14	0.34	0.24	0.28	0.35	0.17	0.39	0.29	0.26
Cd	0.03	0.04			0.02	0.03	0.02	0.02			0.02		
Sn	2.07	3.06	3.77	3.47	3.28	2.56	4	2.49	3.08	2.99	2.29	2.83	2.58
W	0.33	0.47	0.63	0.9	0.56	0.36	0.49	0.33	0.56	0.46	0.39	0.46	0.67
Mo	1.37	1.42	2.77	2.58	3.43	1.28	2.73	2.11	1.74	3.03	1.35	2.31	3.45
As	1.08	1	1.46	1.9	1.81	0.91	1.53	0.7	0.76	1.21	0.94	0.76	1.3
Sb	0.08	0.04	0.03		0.04	0.05	0.03	0.03			0.04	0.01	
Ag	4.87	3.33	3.02	1.41	2.77	5.92	19.92	3.88	1.78	2.06	4.92	4.97	1.17
Au	0.1	0.05	0.07	0.07	0.11	0.1	0.1	0.1	0.03	0.08	0.07	0.02	0.02
Rb	127.49	137.57	132.96	209.45	303.4	98.61	208.83	116.9	124.99	170.09	99.98	118.01	229.59
Cs	0.37	0.23	0.59	0.94	1.31	0.15	0.84	0.21	0.28	0.79	0.2	0.42	0.89
Ba	310.53	306.93	239.42	182.85	77.69	342.82	192.04	342.84	314.59	239.5	331.8	301.32	126.24
Sr	54.56	53.78	47.89	35.95	27.48	62.47	38.75	55.51	51.58	41.77	58.36	48.39	34.14
Ga	22.82	17.86	24.83	26.38	36.41	18.67	25.71	18.89	19.87	21.41	18.92	21.81	30.39
Li	7.26	3.19	8.44	11.99	24.11	1.39	15.54	4.42	4.54	11.53	2.68	4.87	14.88
Ta	2.54	1.89	3.83	4.27	5.87	1.79	5.05	2.17	3.02	3.38	1.59	2.68	5.65
Nb	41.64	32.34	36.65	53.25	74.24	22.66	62.05	25.47	31.7	33.95	25.4	37.15	53.04
Hf	11.97	7.85	11.4	15.78	20.08	6.31	14.88	6.08	8.67	10.68	6.73	8.71	15.72
Zr	326.22	302.51	302.11	339.28	344.41	261.08	335.62	281.96	300.81	311.72	288.76	300.67	326.34
Y	45.76	40.45	52.55	51.94	59.66	24.92	52.59	31.8	39.59	42.12	35.76	41.23	53.51
Th	18.75	15.61	33.07	36.87	58.05	7.34	44.5	12.88	14.32	31.19	9.52	21.63	39.56
U	3.17	4.17	6.18	5.62	13.17	3.22	8.55	2.92	3.69	4.94	3.08	4.48	7.4
Be	2.98	5.69	5.62	5.32	2.98	3.26	3.98	1.99	3.57	4.02	4.98	3.8	4.09
Rb/Sr	2	3	3	6	11	2	5	2	2	4	2	2	7
Rb/Ba	0	0	1	1	4	0	1	0	0	1	0	0	2
K/Rb	268	232	257	166	117	324	170	286	264	192	329	282	153
K/Ba	110	104	143	190	455	93	185	98	105	137	99	110	279
Zr/Hf	27	39	27	22	17	41	23	46	35	29	43	35	21
Nb/Ta	16	17	10	12	13	13	12	12	10	10	16	14	9
TZr ($^{\circ}\text{C}$)	851	837	839	854	857	821	852	833	838	854	833	840	849

6.4. Variation diagrams

The concentrations of major oxides (Fig. 9) and trace elements (Fig. 10) in the various granitoid samples are plotted versus silica (Harker diagrams) to test whether they may be derived from a single source and to consider what petrological processes may explain their evolution. Samples of the two post-collisional plutons define a single smooth trend in every examined variation diagram; there are no resolvable differences aside from the sampling of a broader range of SiO_2 contents in the RBP suite compared to the AHP suite. In both plutons, with increasing SiO_2 we observe decreases in all other major oxides except K_2O , which is positively correlated with SiO_2 . Concerning trace elements, again in both plutons with increasing SiO_2 we observe decreasing Sr and Ba (as well as Ni, Co, Cu, Sc, V, Cr and Pb, not plotted). By contrast, Rb, Nb, Y, Th, U, and Ga (as well as Hf, Zr, Ta, Cs, Li, and As, not plotted) are positively correlated with SiO_2 . The other analyzed trace elements do not correlate with SiO_2 and their variation diagrams are not plotted.

The chemical compositions of the syntectonic tonalite and granodiorite samples also show continuous trends through both groups. All the major oxides except K_2O decrease with increasing SiO_2 , although in this case Na_2O is too scattered to define a trend. Those trace elements that show coherent variation with SiO_2 all trend in the same direction that they do in the post-collisional granites: with increasing silica, Ba and Sr decrease whereas Rb, Nb, Y, Th, U, and Ga decrease.

6.5. Magma type

The PCG show high-K character on the SiO_2 vs. K_2O diagram whereas the tonalite-granodiorite samples trace out an extremely anomalous steep trend that crosses from the low-K field to the high-K field (Fig. 11a). The series boundaries on the [Peccherillo and Taylor \(1976\)](#) plot were drawn to sort suites of samples related by conventional fractional crystallization processes into series and the boundaries therefore parallel typical fractionation paths. The steep paths of the tonalite-granodiorite suite is the first evidence presented herein that the bulk composition of these rocks, while they apparently form a coherent suite, cannot easily be explained as a series of liquid compositions along a liquid line of descent. We will return to this issue below.

The PCG samples cross the boundary between metaluminous and mildly peraluminous; their alumina saturation index [ASI, defined as the molar ratio $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$] values range from 0.95 to 1.06. An ASI of 1.06 is considered the maximum for I-type granites ([Chappell, 1974](#)). By contrast, all the samples of tonalite and granodiorite samples have $\text{ASI} < 1.0$ and classify as metaluminous. The peraluminous character in some PCG samples is confirmed by the presence of corundum in their norms (0.01–0.95%, [Tables 3 and 4](#)) and of muscovite in their modes. The agpaitic index [AI, defined as molar $(\text{Na} + \text{K})/\text{Al}$] of the PCG samples range from 0.78 to 0.91 with an average of 0.84. Values of $\text{AI} < 0.87$ are associated with calc-alkaline character ([Liégeois and Black, 1987](#); [Liégeois et al., 1998](#)). Indeed, all the tonalite and granodiorite samples have clear calc-alkaline character, with AI much less than 0.87

Table 6

Trace element contents (mg/g) in the post-collisional granite of Abu Hawis.

Sample No	H2	H4	H5	H6	H7	H10	H11	H13
Cr	5.42	2.04	1.98	3.01	2.42	4.97	5.7	2.81
Ni	3.21	1	1.43	2.79	1.56	3.93	4.33	1.14
Co	0.64	0.41	0.42	0.46	0.35	0.63	0.62	0.43
Sc	2.04	0.97	0.85	1.66	1.16	2.57	2.32	1.02
V	3.29	1.49	1.2	2.83	1.34	3.98	3.39	1.63
Cu	2.84	1.34	1.05	2.35	1.17	3.17	3.58	1.56
Pb	21.18	7.94	8.93	15.77	8.66	20.82	18.15	6.96
Zn	34.75	23.78	20.83	27.94	18.16	29.84	34.18	24.26
Bi	0.27	0.22	0.08	0.21	0.15	0.34	0.25	0.17
Cd	0.02		0.04	0.03	0.01	0.02	0.01	
Sn	2.5	4.29	3.17	3.17	2.6	2.68	3.95	3.36
W	0.74	0.86	0.63	0.69	0.73	0.41	0.58	0.57
Mo	2.45	2.81	3.43	3.17	2.54	2.37	2.33	3.59
As	1.02	2.52	1.79	1.31	1.24	1.29	0.76	1.85
Sb			0.03	0.01	0.1	0.4	0.13	0.02
Ag	2.11	1.87	1.84	3.22	1.32	6.84	6.61	2.19
Au	0.02	0.05	0.08	0.04	0.1	0.1	0.03	0.12
Rb	153.44	263.97	291.57	201	255.72	120.82	132.93	264.6
Cs	0.44	1.15	1.21	0.66	1.01	0.54	0.4	1
Ba	277.1	113.12	93.63	257.29	167.33	257.16	278.45	129.19
Sr	44.22	25.67	26.82	48.78	31.9	42.83	42.6	29.8
Ga	22.63	33.78	33.09	26.44	35.66	22.68	21.58	29.55
Li	10.63	18.44	20.7	11.85	16.92	7.12	5.57	17.11
Ta	3.48	6.54	6.87	2.76	5.18	3.6	2.76	6.85
Nb	48.55	72.01	72.49	40.24	65	38.59	31.44	67.04
Hf	9.82	18.86	19.63	13.4	17.15	11.82	9.68	17.93
Zr	312.74	341.35	357.4	308.3	348.21	323.35	307.15	339.62
Y	37.92	61.81	71.19	51.15	50.64	35.8	40.65	55.05
Th	27.84	49.97	55.91	37.5	46.08	25.81	22.41	48.71
U	6	9.87	12.46	6.95	9.54	5.96	4.78	7.88
Be	4.72	3.63	4.96	3.5	3.99	2.98	3.73	3.53
Rb/Sr	3	10	11	4	8	3	3	9
Rb/Ba	1	2	3	1	2	0	0	2
K/Rb	227	139	131	159	142	290	255	140
K/Ba	126	324	409	125	217	136	122	287
Zr/Hf	32	18	18	23	20	27	32	19
Nb/Ta	14	11	11	15	13	11	11	10
TZr (°C)	841	852	857	851	857	851	844	852

Table 7

Rare earth element contents (µg/g) in the post-collisional granite of Ras Baroud.

Sample No	B3	B4	B5	B6	B7	B8	B12	B13	B14	B38	B39	B40	B41
La	40.18	32.93	30.56	45.62	44.91	26.79	50.2	35.83	38.28	43.61	34.61	35.96	44.56
Ce	86.50	75.62	64.64	97.37	95.99	56.44	102.18	74.77	80.59	92.58	74.80	75.80	93.59
Pr	10.56	9.18	7.80	11.81	11.49	6.81	12.53	9.01	9.74	11.34	9.07	9.19	11.35
Nd	41.48	34.22	30.25	46.77	44.00	26.10	49.21	31.80	37.36	43.47	34.07	34.65	44.33
Sm	8.28	6.78	6.11	8.87	8.54	4.00	9.42	5.30	7.17	7.69	6.21	6.37	8.50
Eu	1.03	0.91	0.96	1.14	1.23	0.50	1.09	0.83	0.88	1.01	0.73	0.84	1.21
Gd	6.41	5.64	6.57	7.18	7.09	3.45	7.43	3.98	5.49	5.82	4.97	5.30	6.87
Tb	1.05	0.93	1.18	1.18	1.19	0.55	1.23	0.67	0.92	0.96	0.82	0.90	1.14
Dy	6.81	5.68	7.94	7.83	7.87	3.76	8.08	4.25	6.02	6.36	5.23	5.96	7.53
Ho	1.46	1.25	1.67	1.68	1.69	0.84	1.70	0.97	1.30	1.38	1.15	1.29	1.61
Er	4.51	3.78	5.23	5.19	5.21	2.61	5.47	3.03	4.07	4.26	3.55	4.02	5.03
Tm	0.79	0.72	0.90	0.88	0.90	0.44	0.89	0.51	0.69	0.72	0.63	0.68	0.85
Yb	5.94	5.34	6.69	6.51	6.72	3.14	6.61	3.85	5.10	5.36	4.66	5.09	6.28
Lu	0.98	0.98	1.19	1.08	1.13	0.52	1.12	0.61	0.84	0.89	0.79	0.86	1.05
Eu/Eu*	0.43	0.45	0.46	0.44	0.48	0.41	0.40	0.55	0.43	0.46	0.40	0.44	0.48
(La/Yb)n	4.57	4.17	3.09	4.74	4.52	5.77	5.14	6.29	5.08	5.50	5.02	4.78	4.80
(La/Sm)n	3.06	3.07	3.16	3.25	3.32	4.23	3.36	4.27	3.37	3.58	3.52	3.56	3.31
(Gd/Lu)n	0.80	0.71	0.68	0.81	0.77	0.81	0.81	0.80	0.80	0.80	0.77	0.76	0.80
(La/Lu)n	4.20	3.44	2.63	4.33	4.07	5.28	4.59	6.02	4.67	5.02	4.49	4.28	4.35

(0.39–0.45 in tonalite and 0.54–0.68 in granodiorite).

Sylvester (1989) used the ratios of $(\text{MgO} + \text{FeO}^* + \text{TiO}_2)/\text{SiO}_2$ and $(\text{Al}_2\text{O}_3 + \text{CaO})/(\text{FeO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})$ to construct a discrimination

diagram for use with granitic rocks containing more than 68 wt% SiO_2 (Fig. 11b). The PCG plots in the “highly fractionated granite” field, which does not distinguish clearly between alkaline and calc-alkaline

Table 8Rare earth element contents ($\mu\text{g/g}$) in the post-collisional granite of Abu Hawis.

Sample No	H2	H4	H5	H6	H7	H10	H11	H13
La	39.33	54.08	61.67	41.24	44.21	45.12	41.06	49.59
Ce	80.07	114.45	135.89	88.54	94.88	91.94	85.11	107.02
Pr	9.30	14.21	16.29	10.07	11.47	11.87	10.21	13.01
Nd	33.42	55.20	64.85	38.37	43.27	43.00	37.50	50.63
Sm	5.73	10.35	11.87	8.18	8.07	7.25	6.91	9.39
Eu	0.96	1.42	1.22	1.18	1.14	1.11	1.02	1.26
Gd	5.09	8.00	9.18	6.62	6.19	4.81	5.40	7.24
Tb	0.88	1.32	1.50	1.15	1.04	0.81	0.93	1.20
Dy	5.64	8.79	10.20	7.66	6.74	5.09	6.01	7.98
Ho	1.21	1.88	2.22	1.69	1.48	1.09	1.30	1.73
Er	3.59	5.76	6.65	5.30	4.55	3.44	4.03	5.26
Tm	0.62	1.00	1.13	0.89	0.78	0.58	0.68	0.90
Yb	4.86	7.31	8.33	6.43	5.83	4.58	5.18	6.66
Lu	0.83	1.18	1.36	1.07	0.98	0.78	0.88	1.09
Eu/Eu*	0.54	0.48	0.36	0.49	0.49	0.57	0.51	0.47
(La/Yb)n	5.47	5.00	5.01	4.34	5.13	6.66	5.36	5.04
(La/Sm)n	4.33	3.30	3.28	3.18	3.46	3.93	3.75	3.33
(Gd/Lu)n	0.75	0.83	0.83	0.76	0.77	0.76	0.75	0.81
(La/Lu)n	4.86	4.70	4.65	3.95	4.62	5.93	4.78	4.66

Table 9

Major oxides and normative compositions in the syntectonic granitoids of Ras Baroud area.

Rock type	Tonalite				Granodiorite					
Sample No	B23T	B24T	B25T	B26T	B21	B22	B27	B28	B30	B32
Major oxides (wt.%)										
SiO ₂	66.93	64.60	65.17	65.86	70.51	70.91	67.77	68.59	69.72	69.23
TiO ₂	0.95	1.22	1.13	1.05	0.68	0.64	1.02	0.84	0.62	0.77
Al ₂ O ₃	14.73	15.49	15.18	15.33	13.84	13.53	14.67	14.05	13.80	13.93
Fe ₂ O ₃	3.93	4.06	4.15	4.11	3.12	2.98	3.57	3.49	3.08	3.23
MnO	0.07	0.09	0.08	0.08	0.07	0.05	0.06	0.05	0.06	0.04
MgO	2.02	2.59	2.39	2.12	1.34	1.55	2.03	1.78	1.44	1.52
CaO	5.76	7.08	6.91	6.19	3.37	3.12	5.02	3.75	3.32	4.10
Na ₂ O	2.93	3.29	3.34	2.83	2.90	2.91	3.13	3.42	3.54	3.29
K ₂ O	1.71	0.55	0.63	1.17	3.48	4.13	2.62	2.69	3.24	2.82
P ₂ O ₅	0.17	0.21	0.20	0.20	0.12	0.10	0.14	0.16	0.10	0.13
LOI	1.00	1.13	1.00	1.02	0.70	0.59	0.75	0.79	0.70	0.80
Total	99.89	100.09	100.05	99.95	99.82	99.61	99.69	99.88	99.51	99.56
CIPW (normative composition)										
Quartz	28.48	25.61	26.21	28.79	30.78	29.06	26.28	27.82	27.64	28.75
Corundum	-	-	-	-	-	-	-	-	-	-
Orthoclase	10.22	3.29	3.77	7.01	20.73	24.48	15.52	16.13	19.4	16.87
Albite	25.08	28.16	28.59	24.28	24.74	24.7	26.55	29.37	30.36	28.18
Anorthite	22.23	26.16	24.84	26.02	14.57	11.68	18.27	15.25	12.35	15.08
Diopside	4.53	6.43	6.9	3.09	1.23	2.6	4.67	2.09	3.02	3.79
Hypersthene	6.19	6.29	5.83	7.13	5.49	5.19	5.38	6.34	4.95	4.63
Magnetite	1.08	1.18	1.18	1.16	0.85	0.8	1.02	0.97	0.83	0.89
Ilmenite	1.75	2.34	2.17	2.02	1.3	1.22	1.94	1.62	1.19	1.48
Apatite	0.38	0.46	0.44	0.44	0.26	0.22	0.31	0.35	0.22	0.29
Geochemical parameters										
Colour Index	13.55	16.25	16.08	13.4	8.87	9.81	13.02	11.02	9.99	10.79
Diff. Index	63.79	57.06	58.57	60.08	76.25	78.25	68.35	73.32	77.4	73.79
ANOR	69	89	87	79	41	32	54	49	39	47
Q	33	31	31	33	34	32	30	31	31	32
R1	2900	2872	2878	2977	2543	2640	2681	2623	2543	2689
R2	1005	1190	1156	1068	697	676	926	765	697	787
AI	0.45	0.39	0.41	0.39	0.62	0.68	0.54	0.61	0.68	0.61
ASI	0.86	0.82	0.81	0.89	0.94	0.91	0.86	0.91	0.90	0.88
Ti	5695	7314	6774	6295	4077	3837	6115	5036	3717	4616
K	14195	4566	5230	9713	28889	34284	21749	22330	26896	23410
P	742	917	873	873	524	436	611	698	436	567
Mg#	0.50	0.56	0.53	0.51	0.46	0.51	0.53	0.50	0.48	0.48
AI = molar (Na + K)/Al AI = molar (Na + K)/Al <u>ASI = molar Al/(Ca + Na + K)</u>										
ANOR = 100 × An/(Or + An) Q' = Q/(Q + Or + Ab + An)										

suites, since they converge for highly evolved rocks. In fact, extensive fractional crystallization of calc-alkaline (I-type) magma can ultimately lead to A-type residual liquids (e.g., Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987; King et al., 1997). Moreover, partial melting

of rocks with calc-alkaline (I-type) affinity can yield A-type anatectic products (e.g., Creaser et al., 1991; King et al., 1997). The more evolved syntectonic granodiorites have $\text{SiO}_2 > 68$ wt % and may be plotted in Fig. 11b; they plot well into the calc-alkaline field.

Table 10Trace element contents ($\mu\text{g/g}$) in the syntectonic granitoids of Ras Baroud area.

Rock type	Tonalite				Granodiorite					
Sample No	B23T	B24T	B25T	B26T	B21	B22	B27	B28	B30	B32
Cr	13.8	17.8	15.78	14.82	7.96	6.96	10.37	9.96	8.95	9.96
Ni	14.83	18.86	19.82	12.87	4.93	3.98	10.35	6.96	3.96	5.99
Co	6.97	10.93	9.93	8.94	3.97	4.97	6.96	5.98	5.93	5.95
Sc	6.95	7.96	6.94	7.94	2.47	2.98	5.95	4.98	3.97	2.98
V	61.59	57.65	49.52	47.81	34.79	28.74	50.65	41.69	33.47	37.73
Cu	10.9	14.94	11.89	12.95	4.99	3.49	8.97	7.95	6.96	6.9
Pb	4.98	1.99	5.96	3.98	5.93	6.96	5.47	3.98	5.95	3.97
Zn	53.73	24.88	53.68	44.82	45.49	43.74	50.75	44.73	42.61	44.69
Bi	0.04	0.1	0.11	0.08	0.04	0.4	0.04	0.04	0.04	0.04
Cd	0.04	0.03	0.04	0.04	0.07	0.03	0.05	0.07	0.05	0.03
Sn	0.8	0.7	0.8	0.5	0.59	0.7	0.75	0.4	0.3	0.6
W	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Mo	0.8	0.8	1.07	1	0.26	0.07	0.75	0.22	0.35	0.11
As	2.79	3.08	3.38	2.79	2.67	2.19	2.79	3.18	2.87	3.67
Sb	0.02	0.02	0.11	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ag	19.9	19.9	33.8	19.92	19.78	28.83	19.9	19.88	19.82	19.86
Au	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rb	30.85	22.89	23.86	29.88	38.57	39.76	30.78	33.83	40.63	39.76
Cs	0.5	0.4	0.4	0.4	0.49	0.7	0.45	0.3	0.59	0.4
Ba	618.64	776.31	586.06	570.71	465.16	436.37	481.63	447.03	384.07	410.52
Sr	499.99	618.89	646.1	537.3	385.45	317.76	468.17	433.07	372.75	382.74
Ga	11.66	10.54	11.02	11.89	14.91	14.8	11.9	13.3	13.02	12.6
Li	11.34	9.68	12.82	14.16	14.93	20.68	11.24	13.92	14.77	18.27
Ta	0.21	0.2	0.2	0.2	0.5	0.7	0.2	0.3	0.35	0.4
Nb	5.68	3.68	4.66	5.57	10.74	12.15	6.18	5.86	8.16	7.67
Hf	3.14	2.12	2.69	2.89	5.26	6.27	4.07	4.56	4.97	4.65
Zr	103.98	87.56	83.58	94.43	169.59	190	130.03	121.32	154.88	142.43
Y	7.55	5.57	6.97	5.95	10.93	11.95	7.96	9.95	11.03	10.46
Th	2.94	1.99	1.98	2.67	4.27	3.88	2.89	3.18	3.28	3.69
U	0.69	0.44	0.63	0.42	1.19	1.19	0.87	0.93	0.9	1.04
Be	0.86	0.72	0.99	0.71	0.77	0.99	0.64	0.92	1.02	0.81
ZrT ($^{\circ}\text{C}$)	721	698	694	717	777	782	738	743	762	752

Table 11Rare earth element contents ($\mu\text{g/g}$) in the syntectonic granitoids of Ras Baroud area.

Rock type	Tonalite				Granodiorite					
Sample No	B23T	B24T	B25T	B26T	B21	B22	B27	B28	B30	B32
La	12.44	9.53	11.81	10.51	17.61	19.72	13.59	14.11	14.54	16.38
Ce	25.78	19.24	23.55	22.51	37.75	41.69	28.78	30.76	31.61	34.6
Pr	3.39	2.44	3.12	2.68	4.67	5.29	3.58	3.75	3.99	4.34
Nd	12.33	9.31	11.68	10.25	18.18	20.02	13.79	15.11	16.05	16.79
Sm	2.39	1.96	2.38	2.08	3.78	4.25	2.76	2.84	3.04	3.34
Eu	0.8	0.6	0.72	0.7	0.8	0.99	0.78	0.82	0.95	0.97
Gd	1.87	1.37	1.77	1.49	2.73	3	2.02	2.17	2.37	2.48
Tb	0.29	0.21	0.27	0.23	0.4	0.43	0.31	0.34	0.35	0.38
Dy	1.68	1.15	1.53	1.3	2.39	2.54	1.77	1.92	1.99	2.16
Ho	0.34	0.25	0.32	0.28	0.46	0.5	0.36	0.38	0.4	0.44
Er	0.91	0.69	0.84	0.74	1.26	1.36	0.97	1.01	1.1	1.18
Tm	0.14	0.1	0.12	0.11	0.18	0.2	0.14	0.15	0.16	0.17
Yb	0.89	0.67	0.82	0.72	1.24	1.33	0.95	1	1.05	1.15
Lu	0.13	0.1	0.12	0.11	0.18	0.19	0.14	0.15	0.16	0.17
Eu/Eu*	1.16	1.12	1.07	1.22	0.76	0.85	1.01	1.01	1.08	1.03
(La/Yb)n	9.45	9.62	9.74	9.87	9.60	10.03	9.67	9.54	9.36	9.63
(La/Sm)n	3.29	3.07	3.13	3.19	2.94	2.93	3.11	3.14	3.02	3.10
(Gd/Lu)n	1.76	1.68	1.81	1.66	1.86	1.93	1.77	1.77	1.82	1.79
(La/Lu)n	9.80	9.76	10.08	9.79	10.02	10.63	9.95	9.64	9.31	9.87

The PCG contain a number of geochemical signatures that are common in A-type granites: elevated concentrations of Ga, Th, Hf, Y, Ta, and Nb together with low concentrations of P_2O_5 , CaO, and MgO (Bonin, 2007; Eby, 1990; Whalen et al., 1987). Especially diagnostic features include $10000 \times \text{Ga}/\text{Al}$ ratios mostly greater than 2.5 and elevated high field-strength elements compared to the other recognized granite types. This distinction can be illustrated on a Ga/Al vs. Nb diagram after

Whalen et al. (1987), where the Wadi Al-Baroud post-collisional granites plot in the A-type field whereas the syntectonic granitoids do not (Fig. 11c). However, this plot is also subject to error in highly fractionated liquids or small-degree partial melts, wherein concentration of incompatible Nb and Ga in small liquid fractions may yield an A-type liquid from an I-type parent (e.g., King et al., 1997).

Another useful discrimination diagram, suggested by Frost et al.

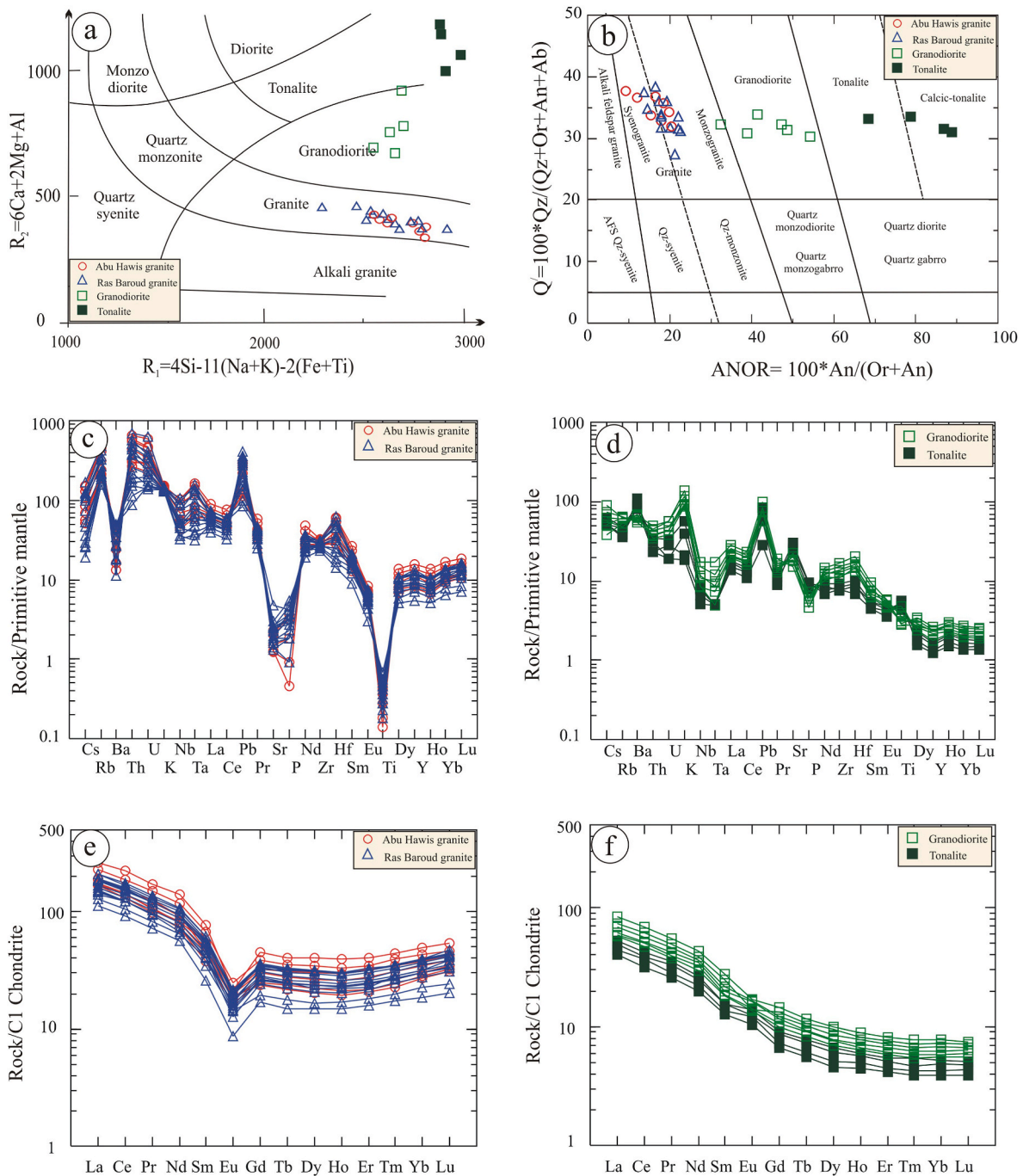


Fig. 8. (a) classification of granitoids using the $R_1 - R_2$ diagram (De la Roche et al., 1980), (b) normative $Q' - ANOR$ diagram for classification of granitoids (Streckeisen and Le Maitre, 1979), (c) primitive mantle-normalized spider diagram for the post-collisional granites of AHP and RBP, (d) primitive mantle-normalized spider diagram for the syntectonic granites, (e) chondrite-normalized REE patterns for the post-collisional granites of AHP and RBP, and (f) chondrite-normalized REE patterns for the syntectonic granites.

(2001), plots $Na_2O + K_2O + CaO$ vs. SiO_2 . Here, the PCG analyses plot towards the calcic edge of the field of A-type granites (Fig. 11d), whereas the syntectonic granitoids plot as I-type and again delineate an anomalously steep trend across the calcic field. Eby (1990) suggested a refinement of the A-type category, distinguishing subtypes A₁ and A₂ with distinct trace element signatures. The Rb/Nb vs. Y/Nb plot (Fig. 11e) places PCG samples on both sides of the A₁-A₂ boundary, precluding a clear use of the Eby (1990) taxonomy for tectonic assignment in this case. A compilation of REE data from plutonic rocks ranging in age from 635 to 590 Ma throughout the north ANS (Eyal et al., 2010) (Fig. 11f) shows again that the PCG samples have REE patterns matching

those of other recognized alkaline post-collisional granites and that the tonalite and granodiorite samples have REE patterns resembling recognized calc-alkaline granitoids throughout the ANS.

Finally, mineral chemistry, particularly of mafic minerals with complex solid solution behavior, permits assignment of tectonic environment for the rocks in which those minerals are found (Nachit, 1985; Abdel-Rahman, 1994 and many others). Nachit (1985), for example, sorted peraluminous, calc-alkaline, subalkaline, and alkaline-peralkaline granites using biotite compositions. Biotite analyses from the PCG samples lie in the alkaline and sub-alkaline fields (Fig. 6b). Another scheme for biotite classification, due to Abdel-Rahman (1994),

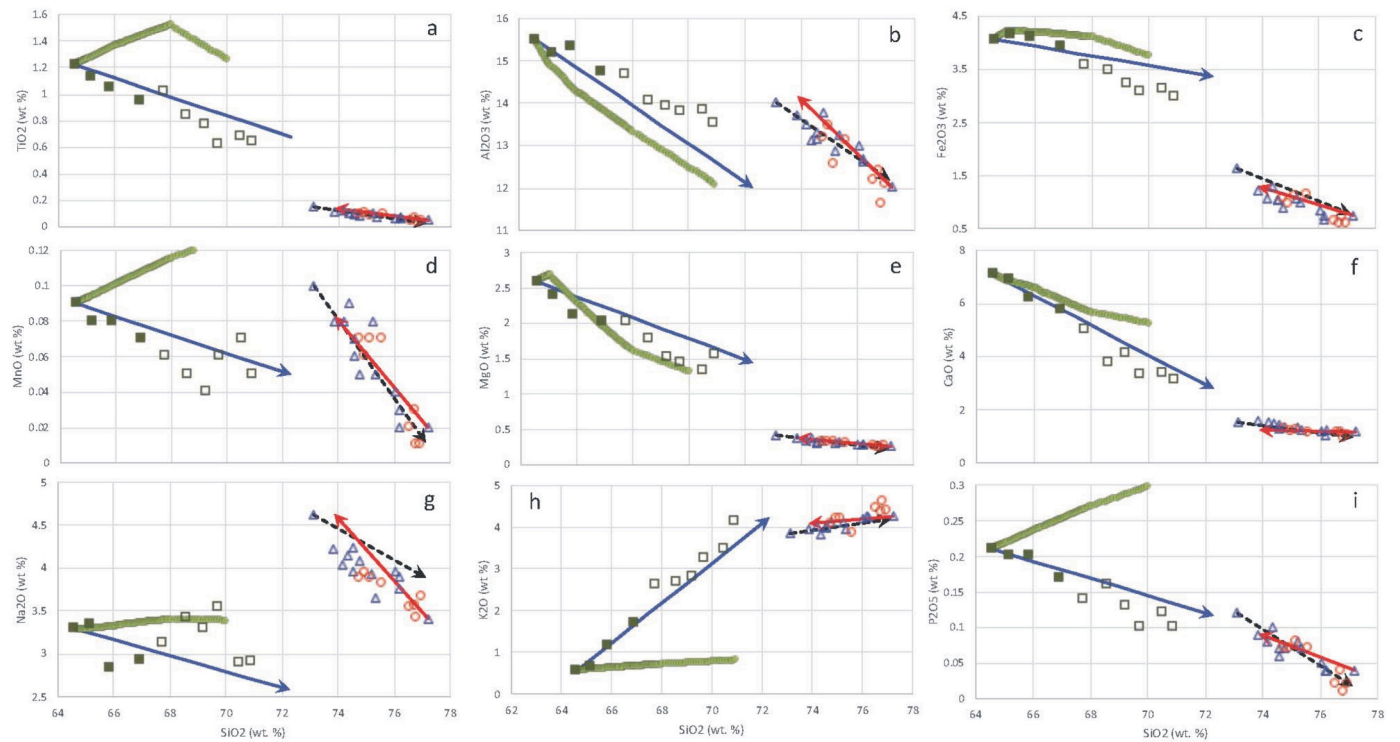


Fig. 9. Harker variations diagrams of major oxides vs. SiO_2 for the synkinematic tonalite-granodiorite and post-collisional monzogranite (RBP and AHP) suites of the Ras Al-Baroud area. Symbols as in Fig. 8. The green curves represent a rhyoliteMELTS model of the liquid line of descent obtained by fractionation of the most primitive tonalite. The blue arrows represent an assimilation-fractional crystallization trend proposed for the tonalite-granodiorite suite. The dashed black arrows indicate a fractional crystallization model for the RBP and AHP samples. The solid red arrows indicate a variable cumulate-liquid sampling model for the RBP and AHP samples. See text for explanation.

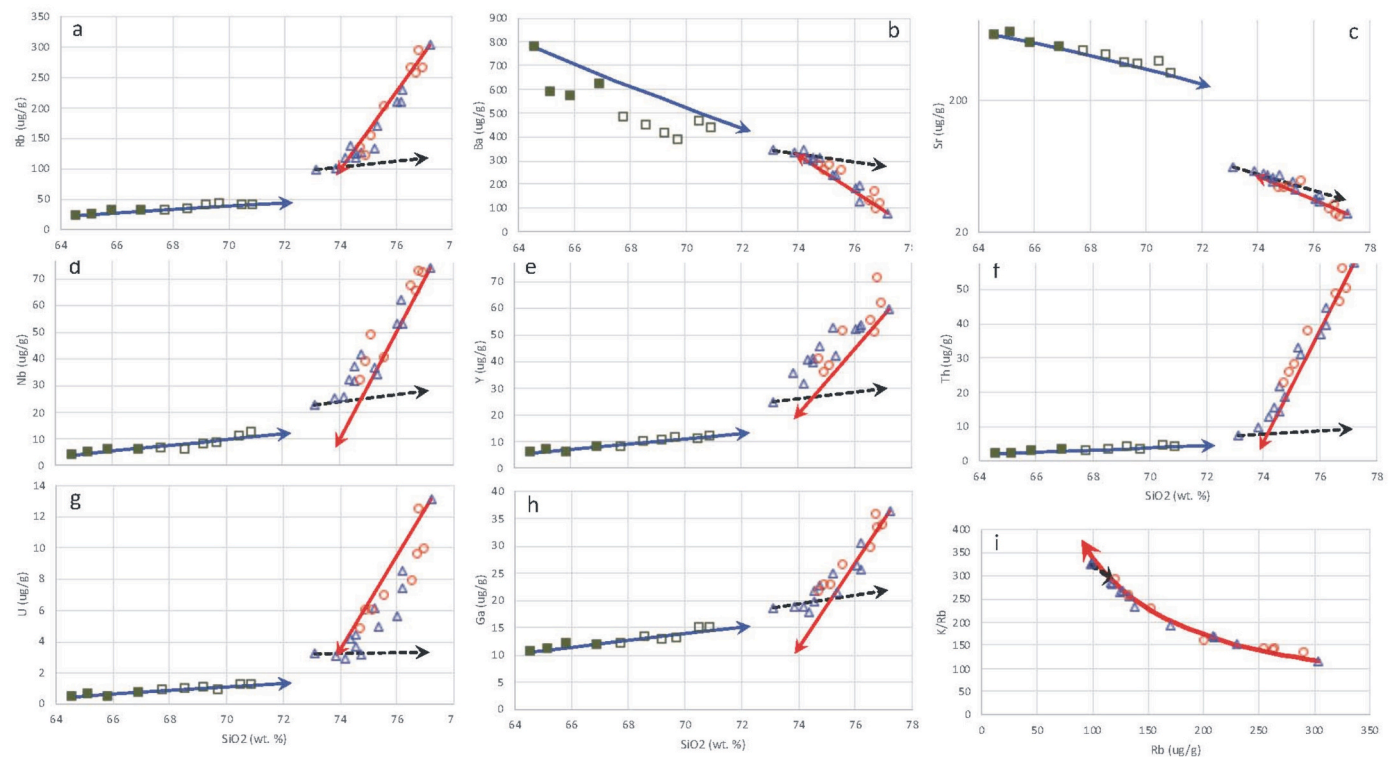


Fig. 10. Harker variation diagrams for selected whole-rock trace element concentrations vs. SiO_2 . See Fig. 9 for symbols and explanation.

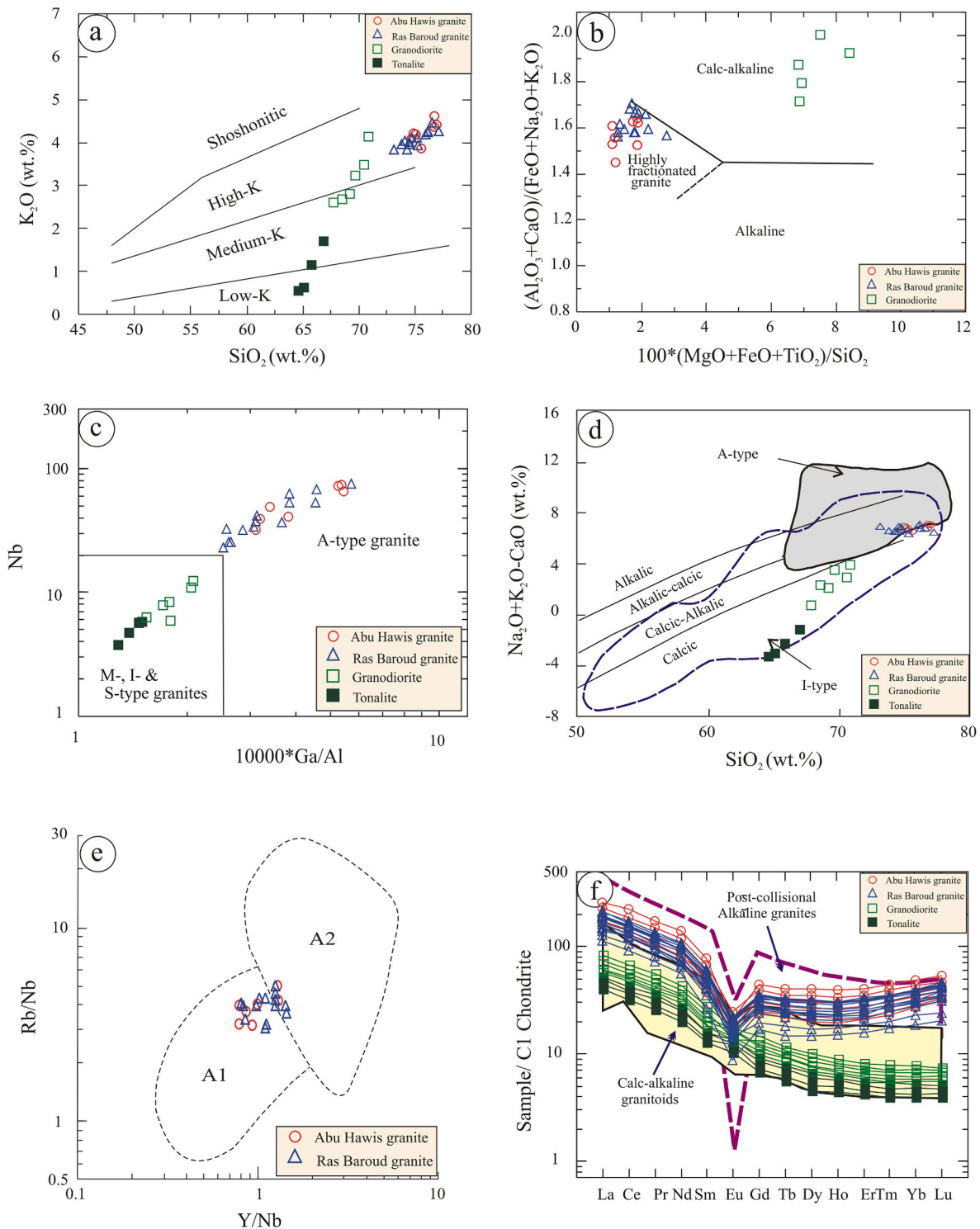


Fig. 11. Geochemical classification plots. (a) K_2O versus SiO_2 discrimination diagram of [Le Maitre et al. \(1989\)](#), (b) discrimination diagram of [Sylvester \(1989\)](#) for granitic rocks with >68 wt% SiO_2 , (c) Ga/Al vs. Nb for discrimination diagram for A-type granites ([Whalen et al. \(1987\)](#)), (d) SiO_2 vs. $Na_2O + K_2O - CaO$ after [Frost et al. \(2001\)](#), (e) Rb/Nb vs. Y/Nb diagram ([Eby, 1992](#)) and (f) Comparison of chondrite-normalized REE patterns for the present samples to fields of typical calc-alkaline and post-collisional alkaline granitoid suites in the ANS ([Eyal et al., 2010; Azer, 2013](#)).

uses a three-fold division. High FeO^* , low Al_2O_3 annite is a hallmark of alkaline (mostly anorogenic extension-related) suites. Moderate FeO^* and high Al_2O_3 (that is, high siderophyllite component) distinguishes biotite in peraluminous suites. Finally, high MgO (phlogopite component) marks biotite in subduction-related calc-alkaline orogenic suites. This classification yields apparently ambiguous results for the PCG biotite analyses, which straddle the alkaline (A-type) and calc-alkaline

(I-type) fields ([Fig. 6c and d](#)).

6.6. Tectonic setting

Previous authors have reached divergent conclusions concerning the tectonic setting of the AHP and the RBP. [Al-Boghdady et al. \(2005\)](#) concluded that partial melting of older I-type granites yielded an

alkaline parental magma that evolved to form the plutons. By contrast, [El-Bialy and Omar \(2015\)](#) favored partial melting of a pelitic or psammitic metasedimentary source and a high-K calc-alkaline parental magma. Here we consider whether the combination of our field, petrographic, mineralogical, and geochemical data resolve this controversy or suggest a different conclusion.

Field investigations clearly indicate that the AHP and RBP are post-collisional granites. Moreover, they are the youngest recorded magmatic products in the Wadi Al-Baroud area. They were emplaced at shallow levels into calc-alkaline granitoids associated with the subduction period of the Pan-African orogeny, after a period of unroofing and rapid uplift. As the Pan-African orogeny waned and calc-alkaline magmatism gave way to post-collisional and rift-related alkaline activity at ~620 Ma ([Harris, 1982](#); [Bentor, 1985](#)), the transitional period was accompanied in many parts of the ANS by a prodigious production of dike swarms, with compositions spanning basalt to rhyolite ([Friz-Töpfer, 1991](#); [Iacumin et al., 1998](#)). In the Wadi Al-Baroud area, our observations show that dikes intruded syntectonic granitoids, however the dikes are truncated by the post-collisional granites. There is no indication in the area that these dike swarms fed significant volcanic outpourings.

Post-collisional magmatism is considered to be an integral part of the waning stage of an orogeny and is neither strictly orogenic nor anorogenic, whereas rift-related magmatism is genuinely anorogenic. Intra-continental rifts, at least when fully developed, are associated with significant mafic and alkaline magmatism ([Black et al., 1985](#); [Wilson,](#)

[1994](#); [Menuge et al., 2002](#)). It is notable that the PCG are represented exclusively by oversaturated felsic rocks, with no associated intermediate or mafic rocks, which argues against a rifting model for these plutons.

The compositional characteristics of the PCG support the field observations indicating a post-collisional setting. Diagnostic geochemical features include, as noted above, low concentrations of Sr, CaO, MgO, alongside elevated alkali contents and marked enrichment in HFSE and REE ([Eby, 1990, 1992](#); [Whalen et al., 1987](#)). We may also apply a number of suitable tectonic discrimination diagrams. On the SiO_2 - Al_2O_3 discrimination plot proposed by [Maniar and Piccoli \(1989\)](#), the PCG plot in the POG (post-orogenic granitoid) field, which overlaps the boundary between other categories of granitoid on this plot ([Fig. 12a](#)). From the list of trace elements evaluated by [Pearce et al. \(1984\)](#) for tectonic discrimination among granites, [Rollinson \(1994\)](#) selected the elements Rb, Y and Nb as efficient discriminants. On a diagram of Rb vs. (Y + Nb) ([Fig. 12b](#)), samples from the PCG mostly fall in the within-plate field, whereas the tonalite and granodiorite suite is consistent with a volcanic-arc setting. On the same diagram, most of the PCG samples also plot in the post-collisional granite field that is superposed over the boundary between within-plate and volcanic-arc. A Rb-Hf-Ta diagram ([Harris et al., 1986](#)) also yields a within-plate setting for PCG samples, while the tonalite and granodiorite spread over the field of volcanic-arc associated rocks ([Fig. 12c](#)). The K_2O - Na_2O - CaO diagram ([Fig. 12d](#)) applied by [Azer et al. \(2020\)](#) places the PCG samples in field III with

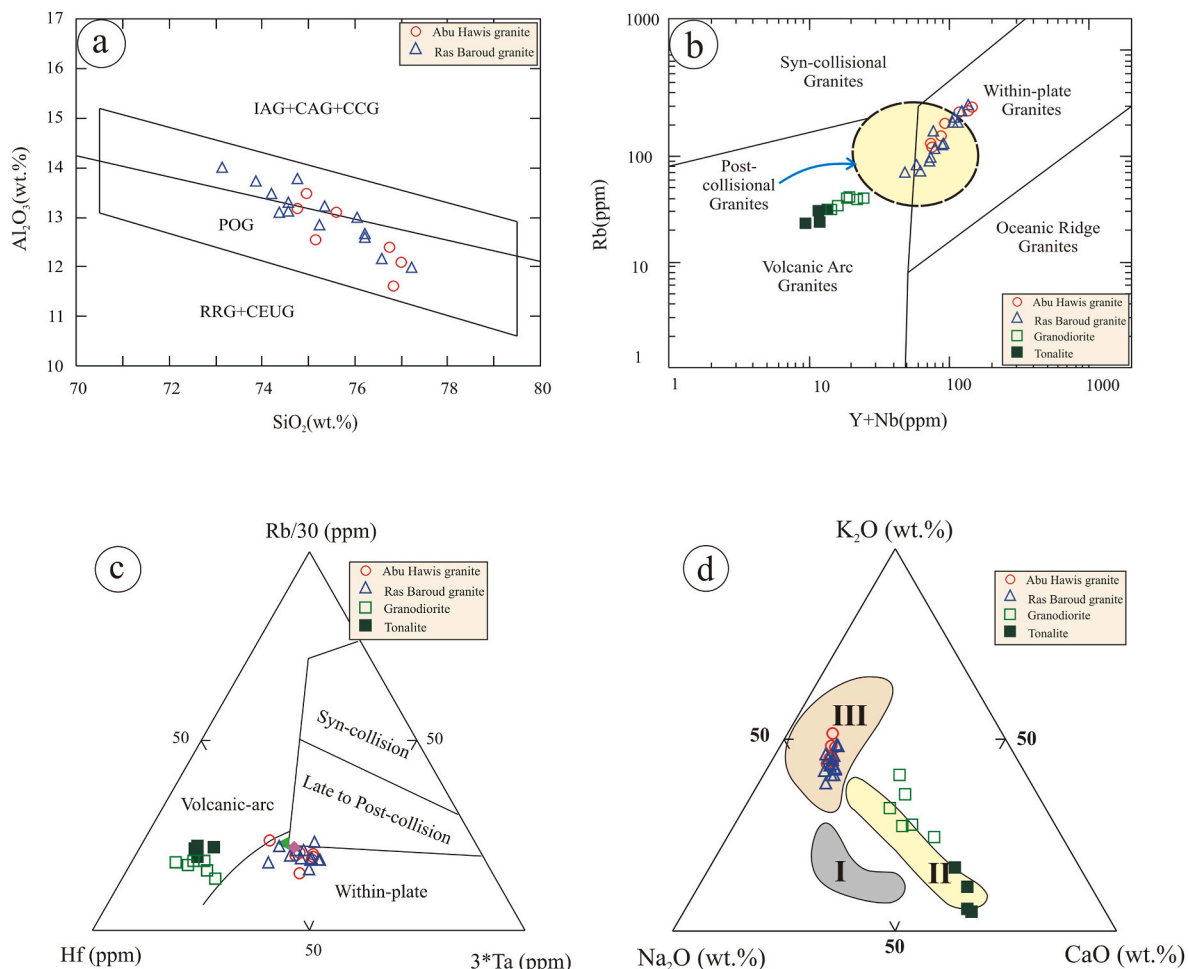


Fig. 12. Tectonic discrimination diagrams. (a) SiO_2 vs. Al_2O_3 diagram ([Maniar and Piccoli, 1989](#)); symbols are IAG, island arc granitoids; CAG, continental arc granitoids; CCG, continental collision granitoids; POG, post-orogenic granitoids; RRG, rift-related granitoids; and CEUG, continental epeirogenic uplift granitoids. (b) Rb vs. (Y + Nb) discrimination diagram for granites ([Pearce et al., 1984](#)). (c) Hf-Rb/30- 3^*Ta ternary diagram ([Harris et al., 1986](#)). (d) K_2O - Na_2O - CaO ternary diagram showing fields of the Egyptian granitoids ([Azer et al., 2019b](#)): I = old calc-alkaline phase, II = young calc-alkaline phase, III = young alkaline phase.

other Egyptian granites of the “younger” (late to post-collisional) group, whereas the synkinematic granitoids of Wadi Al-Baroud group with the early sub-phase of younger subduction-related granitoids of Egypt in field II.

7. Discussion

Determining the origin of the vast volumes of felsic post-collisional igneous rocks in the ANS is challenging, in part because there is unlikely to be a single answer. Such rocks can be (and likely were) the result of several different processes acting on several different sources (e.g., Abdel-Karim, 1997; Moussa et al., 2008; Ali, 2015; Ali et al., 2016; Azer and Asimow, 2021; Ghoneim et al., 2022), including mantle sources yielding mafic magma that underwent extensive fractional crystallization (El-Sayed et al., 2002; El-Nisr and El-Sayed, 2002; Maurice et al., 2013) and crustal sources that yielded more felsic primary magmas (Furnes et al., 1996; Moghazi, 1999, 2002; Farahat et al., 2007, 2011). The granitoid rocks of Wadi Al-Baroud area offer a significant new case study for this question, because they capture a temporal transition in the character and sources of ANS magmatism.

7.1. Magmatic sources

In this work, the felsic plutonic rocks along Wadi Al-Baroud have

been divided into two groups: post-collisional granites (monzogranite) and syntectonic granitoids (tonalite and granodiorite). We find no evidence for a petrogenetic relationship between these two groups. They had different magmatic sources and the monzogranite is not a product of fractional crystallization from the tonalite-granodiorite suite. This is shown by discontinuities in many variation diagrams as well as distinctly different normalized trace element and REE patterns (Figs. 8–10). Although each suite forms coherent geochemical trends, the two trends are distinct.

7.1.1. Source of syntectonic granites

In general, the subduction period of the Nubian Shield, which lasted from 670 to 630 Ma, is recorded by syntectonic granitoids with low-K to medium-K calc-alkaline character. These granitoids, often tonalites and granodiorites, may include rocks formed by melting of a range of sources (Azer and Asimow, 2021, and references therein). The syntectonic granitoids in the Wadi Al-Baroud area are metaluminous and calc-alkaline and indicate a subduction affinity. They define a single cogenetic suite with a common source. Their negative Nb-Ta anomalies and enrichment in LILE compared to HFSE are conventional signs of a mantle wedge source containing slab-derived components (e.g., Hawkesworth et al., 1993). However, direct derivation of these low-Mg# (0.46–0.56) rocks by evolution of mantle-derived magma would probably be accompanied by associated mafic rocks, which are not observed

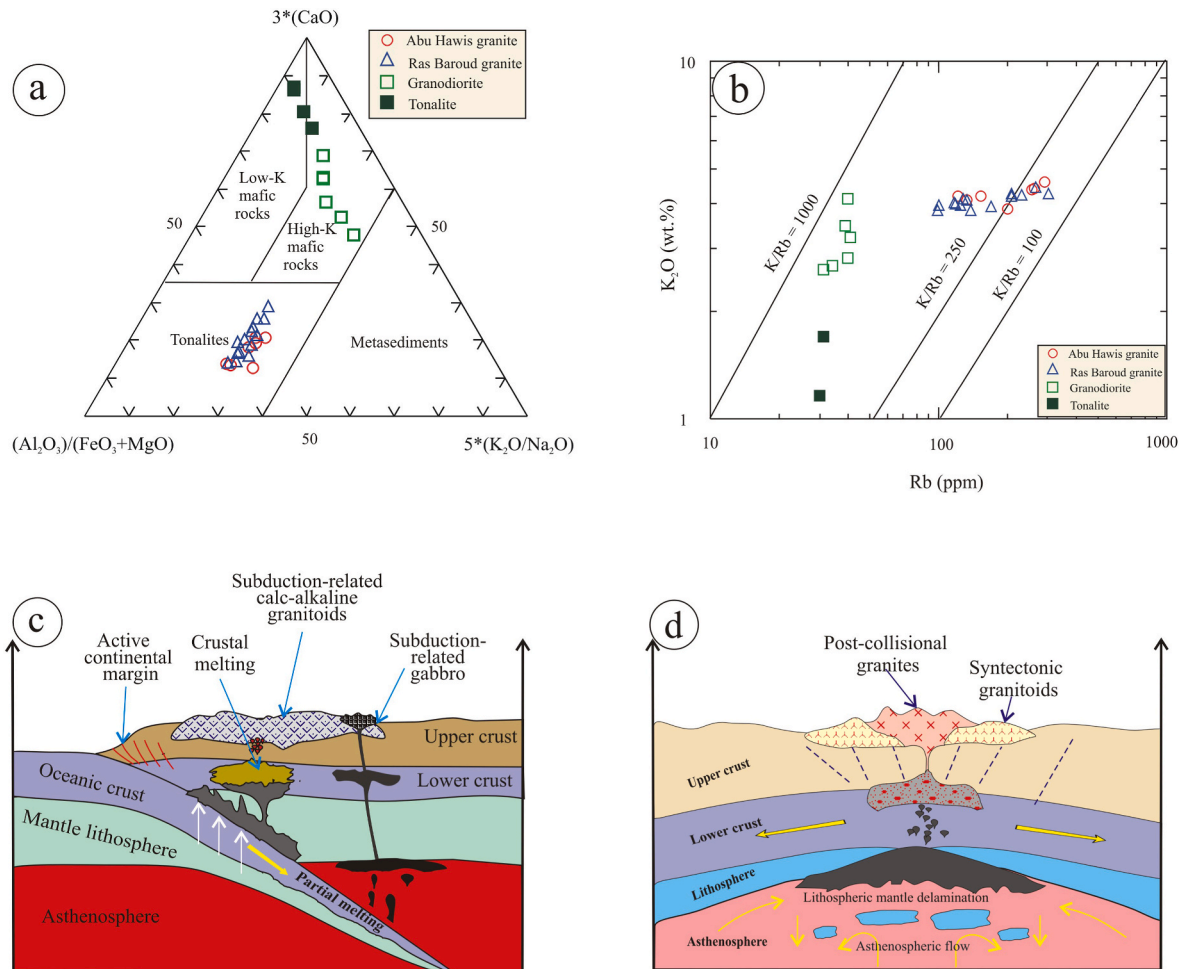


Fig. 13. (a) $\text{Al}_2\text{O}_3/(\text{FeO}^*+\text{MgO})$ – 3CaO – $5(\text{K}_2\text{O}/\text{Na}_2\text{O})$ petrogenetic discrimination diagram for the syntectonic granitoids and post-collisional granites at Wadi Al-Baroud area (Laurent et al., 2014), (b) Rb versus K_2O petrogenetic discrimination diagram for the syntectonic granitoids and post-collisional granites of Wadi Al-Baroud area (after Shaw, 1968), (c) the proposed model for the tectonomagmatic evolution of the Wadi Al-Baroud tonalite and granodiorite during the calc-alkaline subduction phase of the ANS, and (d) proposed model for the tectonomagmatic evolution of the granites of AHP and RBP during the post-collisional phase of the ANS.

(Turner and Langmuir, 2015). Rather, the subduction signature was likely added to the crust in a previous cycle of magmatism, stored for some time, and inherited by later magmatic cycles.

Laurent et al. (2014) summarized the results of numerous experimental studies with a source discrimination diagram (Fig. 13a) that points to mafic crustal sources and dehydration melting to form the tonalite and granodiorite. The subduction-related origin of the lower and middle (infrastructural) ANS crust explains the apparent affinity to juvenile arc rocks and how such a signature may be present in rocks that were emplaced after the end of active subduction (Petford and Gallagher, 2001; Beard and Lofgren, 1991). Such partial melting was likely the result of a geotherm elevated by underplating of mantle-derived magmas. In such a setting, although magmas sourced from lower-crust may be dominant, there can be mixing with liquids formed by fractionation of the mafic underplate magmas (Petford and Gallagher, 2001) as well as contamination during ascent through the upper crust (Halama et al., 2004; Chen et al., 2008; Hora et al., 2009).

The K/Rb ratios of the tonalite and granodiorite samples plot between values associated with mantle-derived (K/Rb = 1000) and crustal (K/Rb = 250) melts (Fig. 13b; Akinin et al., 2009). Moreover, there are sparse microgranular mafic enclaves (MMEs) in the synkinematic granitoids that point to magma mingling during their evolution. A hybridized intermediate magma, after continued evolution by fractionation and assimilation, would lead to the observed tonalite and granodiorite suite. We apply thermodynamic and mass conservation models below to sort out the balance between fractionation and assimilation in controlling the variation among the sampled compositions.

We propose a geodynamic model for the origin of the synkinematic granitoid suite (Fig. 13c). A protracted period of subduction first builds an arc-related continental crustal section. Dehydration of the subducting slab liberates fluids that, in turn, drive partial melting in the mantle wedge, yielding hydrous mafic melts. These rise and pond below the crust, where they supply sensible and latent heat able to elevate the crustal geotherm and promote crustal melting. Mingling of the melts resulting from fractionation of the underplate with the anatectic melts of the crust produces an intermediate hybrid magma. Finally, ascent, fractionation, and assimilation of upper crust transform this magma into tonalite and granodiorite, which are emplaced at relatively shallow crustal levels.

7.1.2. Source of post-collisional granites

The assembled data presented here demonstrate that the PCG were emplaced during the final, post-collisional stage of development of the ANS. Like other occurrences of post-collisional granites throughout the ANS (e.g., Abdel-Karim, 1997; Farahat and Azer, 2011; Ghoneim et al., 2022, and references therein), the AHP and the RBP have higher concentrations of Nb, Ta, Zr, Hf, Th and Y than do true subduction-related plutonic rocks. This causes them to plot as within-plate magmas on several discrimination diagrams (Fig. 12b–d) even though their agpaic index values (<0.87) suggests similarity to subduction-related rocks (Liégeois et al., 1998; Liégeois and Black, 1987).

The PCG share many features with a class of rocks known as highly fractionated I-type granites with A-type character. The existence of such rocks poses a challenge to the simple classification of granite types and to a simple assignment of each conventional granite type to a particular tectonic setting. There are several petrogenetic models that purport to explain such mixed-character granites. These include (1) tonalitic to granodioritic source rocks undergoing dehydration melting (Creaser et al., 1991); (2) mantle-derived mafic magma evolved via fractional crystallization (Haapala et al., 2007; Li et al., 2007; Wu et al., 2002); (3) extraction of I-type magmas followed by remelting of their residues (Collins et al., 1982; Whalen et al., 1987); (4) calc-alkaline source rocks melting under upper crustal conditions (Patiño Douce, 1997; Skjerlie and Johnston, 1993) and (5) hybridization of melts of mantle and crustal origin (Yang et al., 2006).

The diversity of theories for such granites in general is mirrored by

the diversity of sources and modes that have been proposed by those studying the post-collisional (620–600 Ma) period in the ANS (Azer, 2006; Be'eri-Shlevin et al., 2009a,b; Eyal et al., 2010; Bonin, 2004). Proposed models for the ANS post-collisional granitoids include hypothesis (2) above (fractionation of mantle-derived mafic magma; e.g., Stern and Voegeli, 1987; Beyth et al., 1994; Kessel et al., 1998; Mushkin et al., 2003; Jarrar et al., 2008), hypothesis (4) above (crustal source anatexis; e.g., Abdel-Rahman, 2006; Farahat et al., 2007; Ali et al., 2009) and hypothesis (5) above (mixed mantle and crustal sources; Azer, 2007; Be'eri-Shlevin et al., 2009b). Even more locally, as mentioned above, authors have disagreed about the petrogenesis of the PCG.

Derivation of evolved magmas by conventional fractional crystallization from a mafic primary magma requires that liquids passed through the intermediate compositional range (Kessel et al., 1998; Osman et al., 2023). The studied granites (AHP and RBP) are exclusively felsic, with no associated intermediate or mafic magmatic rocks. The absence of any enclaves or dikes in the intrusions argues against an origin by such conventional fractionation crystallization. The geochemical and isotopic argument against a simple model of fractionation from mantle-derived magma for post-collisional northern ANS granites was succinctly stated by Eyal et al. (2010). Rather, the available geochemical data for the PCG support the model of partial melting of juvenile crustal sources. For example, Smirnov and Beus (1983) demonstrated the elevation of Nb/Ta ratios in crustal melts compared to mantle melts. The PCG have notably greater concentrations of Nb (23–74 µg/g, av. 46 µg/g) than Ta (1–7 µg/g, av. 4 µg/g). Likewise, Akinin et al. (2009) noted that K/Rb differs between crustal and mantle melts and this ratio is notably lower than the mantle values in the PCG (Fig. 13b).

The Neoproterozoic crustal rocks that make up the mostly juvenile crustal section of the ANS would have been available to undergo partial melting at the time of emplacement of the PCG. Such older potential source rocks include I-type calc-alkaline plutonic suites, gabbro-diorite complexes, and metamorphic schists and gneisses. Among these, El-Bialy and Omar (2015) argued for metasedimentary (pelitic and psammitic) sources. However, the PCG are mildly metaluminous to mildly peraluminous. By contrast, pelitic to psammitic metasediments melt to highly peraluminous liquids (Montel and Vielzeuf, 1997). Patiño Douce (1997) showed that calc-alkaline tonalite, undergoing dehydration melting (e.g., at 0.4 GPa and 950 °C) is a plausible source for A-type parental liquids, from both major and trace element perspectives. Hence, like Al-Boghdady et al. (2005), we prefer an igneous source for the magma parental to the PCG. Unlike Al-Boghdady et al. (2005), though, we do not require that this melt be alkaline. Indeed, the observed rocks are consistent with tonalitic sources in the source discrimination system of Laurent et al. (2014) (Fig. 13a) and the evolved members of the suite resemble the small-degree experimental partial melts of tonalite obtained by Watkins and Clemens (2007).

Melting of the crust, however, requires special conditions. Either the crust must be thick enough for a normal crustal geotherm to continue to high enough pressure to encounter the solidus, or the geotherm must be steep enough to reach the solidus without crustal thickening. The thickness of the ANS crust when the PCG were emplaced was likely to have been relatively low. The eastern part of the Arabian Shield is underlain by up to 39 km of crust, but the central ANS along the Red Sea is underlain by only 23–25 km of crust (Al-Damegh et al., 2005). This is not sufficient to encounter melting without anomalous heating, which may have been the result of magmatic underplating, plausibly following a lithospheric delamination event. Moreover, the structural weaknesses and stress states in the crust likely control the ascent of melts into the upper crust in the post-collisional setting (Black et al., 1985; Brown, 1994). In the ANS, such a link is supported by regional associations between large-scale structural lineaments and post-collisional A-type rocks (e.g., Abdel-Rahman, 2006).

7.1.3. Geodynamic emplacement of post-collisional granites

Lithospheric delamination models for crustal evolution have been

invoked for all periods of Earth history (e.g. Foley et al., 2003; Goscombe et al., 2019; McLelland et al., 2010; Ueda et al., 2012; Moore and Wiltschko, 2004; Wang et al., 2022) and in numerous different tectonic situations (Göğüş et al., 2011; 2017; Liu et al., 2000). After foundering and convective removal of the lower mantle lithosphere, buoyant asthenosphere rises to replace it (Lee et al., 2001; Magni and Király, 2020). The sinking lithospheric mass may be heated and undergo partial melting. The rising asthenosphere may undergo decompression-driven melting. Finally, initial subsidence is followed by rapid uplift, which leads to erosion and decompression of crustal material. Together with underplating-driven heating of the crust, these events trigger the onset of crustal magmatism.

Delamination is not generally associated with the older calc-alkaline granitoids (720–650 Ma) but it is a common model for the post-collisional evolution of the ANS in the period from 620 to 590 Ma (numerous references following Avigad and Gvirtzman, 2009). Avigad and Gvirtzman (2009) presented a model of deformation associated with the East African Orogeny that may have yielded 50 km thick crust and 150 km thick, unstable lithosphere. Regional isostatic response to subsequent delamination caused major unroofing by removal of up to ~10 km of upper crust (Garfunkel, 1999), bringing formerly mid-crustal calc-alkaline granitoids like the tonalite-granodiorite suite of Wadi Al-Baroud up to shallow crustal levels. Post-collisional granites were then emplaced into these uplifted subduction-era granitoids. Extension associated with post-delamination doming is recorded in the Nubian Shield by dike swarms, normal faults and shear zones (Blasband et al., 2000) that affect the uplifted older granitoid sequence but predate post-collisional plutons (Stern et al., 1984; Stern, 1985; Greiling et al., 1994).

The scenario for emplacement of the PCG (Fig. 13d) calls for a collisional period of thickening of crust and lithosphere before lithospheric delamination and oceanic slab break-off. Delamination and slab break-off remove negative buoyancy, replacing it with positive dynamic topography, isostatic uplift, crustal doming and erosion. The delivery and underplating of mafic magma, together with erosion-driven decompression, promote lower-crustal partial melting. Despite their I-type sources, these magmas may acquire A-type character either by extraction of low-degree melts or by extensive fractionation in the middle crust.

7.2. Magmatic evolution

7.2.1. Crystallization conditions

Ions with equal charge and very similar ionic radius, sometimes

called “twin elements”, may be used to discriminate magmatic fractionation from hydrothermal processes. When the behavior of trace elements is controlled by mineral-melt partitioning, charge and ionic radius effectively predict the behavior of each element (CHARAC, or CHARGE-RADIUS Controlled behavior). Two good examples of such elemental twins are Y/Ho and Zr/Hf (Moussa et al., 2021). On the other hand, non-magmatic processes involving leaching or precipitation by hydrothermal fluids depend on aqueous complexes that do not follow CHARAC behavior. A plot of Y/Ho against Zr/Hf (Bau, 1996) indicates the PCG samples are consistent with dominantly CHARAC behavior (Fig. 14a), suggesting a dominantly magmatic origin for the chemical variations in the suite, and a limited role for exchange with hydrothermal solutions.

Emplacement of the PCG plutons likely occurred at low pressure in the upper crust. Petrographic observations reveal distinct coexisting K-feldspar and albite along with occasional perthite grains, pointing to subsolvus crystallization and minor subsequent exsolution (Abuamarah et al., 2022). Moreover, whole-rock compositions for the PCG plot near the minimum melt composition in the Ab-Or-Qz ternary for pressures of 0.1–0.4 GPa with <1% F (Fig. 14b). However, F was present to some extent, as indicated by the presence of magmatic fluorite. The presence of pegmatite veins with gradational contacts in the AHP and the RBP demonstrates fluid saturation, at least towards the end of the magmatic process (London, 2015; Wu et al., 2020).

Magmatic temperature may in some cases be estimated from zircon saturation thermometers (Watson and Harrison, 1983; Harrison and Watson, 1984; Ayers and Watson, 1991; Hoskin et al., 2000). The calibration of Watson and Harrison (1983) yields zircon saturation temperatures between 694 and 782 °C (average 738 °C; Table 10) for the syntectonic granitoids as opposed to 821–857 °C for the post-collisional granites (average 843 °C for the RBP and 851 °C for the AHP; Tables 5 and 6). The very high zircon saturation temperatures obtained for the post-collisional granites are implausible, given other evidence for their highly-evolved, fluid-saturated, F-bearing, low-pressure, sub-solvus character. It is critical to realize that the zircon thermometer assumes that the whole-rock composition is a liquid composition. A mix of cumulate crystals (including abundant zircons) and liquid in the whole-rock composition will naturally yield high and misleading zircon saturation temperature.

7.2.2. The synkinematic suite —fractional crystallization and assimilation

As discussed above, all the samples of the tonalite-granodiorite suite form a single coherent trend in variation diagrams for major oxides and

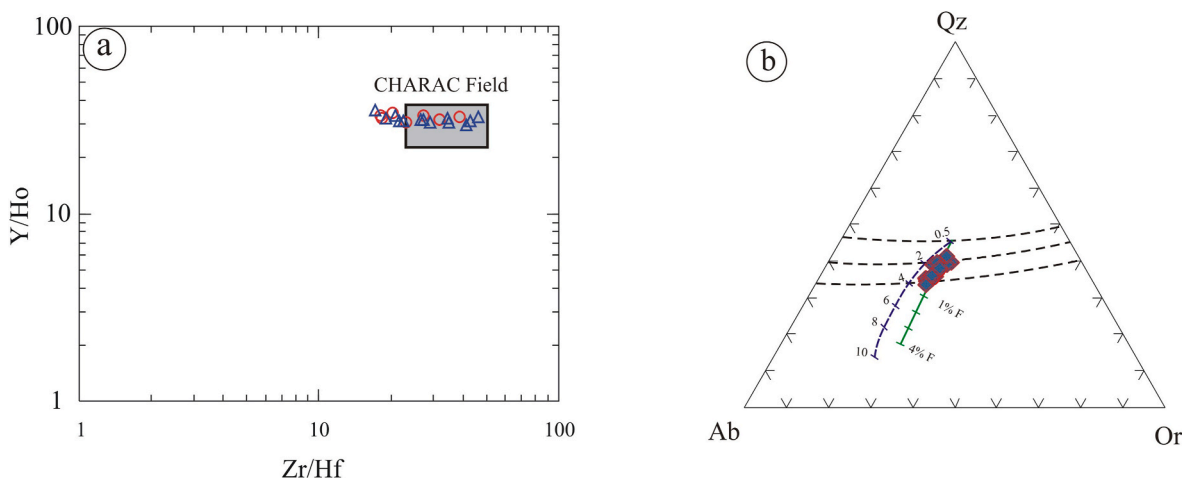


Fig. 14. (a) Zr/Hf vs. Y/Ho diagram (Bau, 1996), and (b) normative composition of the granites of AHP and RBP plotted in Qz-Ab-Or projection. Solid green line shows the trace of the minimum melt composition at 1 kbar with excess H₂O and increasing fluorine (F) content up to 4 wt% F (Manning, 1981). Dashed lines show the quartz-alkali feldspar cotectics and the trace of the water-saturated minimum melt compositions in the haplogranite system at total pressure ranging from 0.5 to 10 kbar (Holtz et al., 1992; Winkler et al., 1975).

trace elements, and on normalized multielement trace element and REE plots. They clearly represent a single cogenetic magmatic suite. In many ways they resemble a conventional fractional crystallization sequence and it is tempting to consider them as points along a liquid line of descent. However, as mentioned above, the suite features a highly anomalous trend of K enrichment, causing it to cross from low-K calc-alkaline character in the most primitive tonalite to high-K calc-alkaline character in the most evolved granodiorite. Fractional crystallization does not normally show this behavior. Indeed, we attempted to model the evolution of the suite as a liquid line of descent by applying the rhyoliteMELTS 1.0 model (Gualda et al., 2012) and the easyMELTS software (by Einari Suikkanen, available at <http://magmasource.caltech.edu>) to describe fractional crystallization of the most primitive tonalite, sample B24T. The result of a typical model run (50 MPa pressure, NNO buffer, H₂O-saturated) is shown by the green trends in Fig. 8. Other pressure, oxygen fugacity, and water content conditions do not change the conclusion significantly: the suite is not consistent with thermodynamic predictions of the crystallization sequence. The opposite slopes of the model fractionation trend and the tonalite-granodiorite suite data in TiO₂, Fe₂O₃, MnO, and P₂O₅ could be attributed to model errors in the stability of the minor phases ilmenite and apatite. However, the very large difference in the slope of the predicted trend in K₂O vs. SiO₂ is a fundamental problem, confirming the anomalous behavior of this suite in terms of K-enrichment.

The most plausible explanation for the K-enrichment trend in the suite of tonalite and granodiorite samples is assimilation accompanying fractional crystallization. The assimilated material may have been mixed into the evolving melt or simply incorporated as xenocrystic solids; the geochemical consequences for whole-rock chemistry will be similar. We modeled this process first by considering the extreme end member of pure assimilation with no fractionation. The assimilation of up to 50% of the original weight of tonalite of a mixture of 63% alkali feldspar (Or₆₅Ab₃₅), 35% quartz, and 2% magnetite generates a vector that matches the slope of the tonalite-granodiorite suite in every major element variation diagram. However, this model fails to account for some features of the trace element evolution, notably the severe depletion of Sr and Ba. Hence, we considered the likelihood of fractionation of plagioclase accompanying the assimilation. We found a solution whereby each 5 g of assimilation is matched by 1 g of removal of An₅₀Ab₅₀ plagioclase (which is the composition present in the tonalite); the modeled evolution vector is shown in Fig. 9. Finally, having satisfied all the major element constraints, we are able to compute the trace element content of the assimilant that is necessary to generate the trends in every trace element variation diagram (Fig. 10). The values are quite reasonable for an evolved granite magma or an assemblage of alkali feldspar, quartz, and magnetite. All the parameters of this model are given in Supplementary Table SD18.

7.2.3. The post-collisional plutons — variable sampling of liquid and cumulates

Numerous features of the AHP and RHP sample suites are nominally consistent with the relationship among their compositions being dominated by a simple fractional crystallization process. This includes the excellent correlations observed in the variation diagrams (Figs. 9 and 10); the gradual upward shift of parallel REE patterns (except Eu) with increasing SiO₂ (Fig. 8e); the large ranges in Zr/Hf (17–46), Rb/Sr (2–11) and Nb/Ta (9–17) ratios (Tables 5 and 6; Ballouard et al., 2016); and the major negative anomalies (Fig. 8c) in elements compatible in Fe-Ti oxide (Ti), apatite (P), and feldspar (Sr and Ba). However, all these features are permissive of a variety of evolution models for the suite. In fact, the trend on a diagram of Rb vs. K/Rb (Fig. 14c) suggests a process intermediate between crustal assimilation and closed-system fractional crystallization (Akinin et al., 2009; Miller and Snoke, 2009).

An acceptable quantitative model of the magmatic evolution must simultaneously satisfy the major and trace element data. We sought to find a fractional crystallization model that could generate the full PCG

suite as a liquid line of descent from the most primitive sample, B8. For all major elements, this can be realized by a fractionating assemblage of 83.9 wt% plagioclase (Ab₇₄An₁₈Or₈), 14 wt% biotite, 1.3 wt% ilmenite, and 0.8 wt% apatite (details in Supplementary Table SD18). This fractionation trend is shown by the black dashed arrows in Figs. 9 and 10. Although, by construction, it parallels the data in every major element variation diagram, it fails to explain any of the trace element trends. This result is inevitable because it requires only 22% mass fractionation for the composition to evolve from 73.1 to 77.2 wt% SiO₂. Yet we observe enrichment by a factor of 3.1 in Rb concentration, by a factor of 3.3 in Nb, 7.9 in Th, 4.1 in U, and ~2.3 in REEs. Even if the trace elements were perfectly incompatible, the most that they could be enriched in the residual liquid by 22% mass fractionation is 22%. Moreover, the Eu anomaly gets smaller from tonalite to granodiorite, which is not consistent with progressive fractionation of plagioclase. There is no reasonable combination of fractionating minerals that would reduce the “lever-arm” of fractionation enough to allow 87% mass removal across the observed range of compositions, which would be necessary to explain the Th enrichment by simple concentration into residual liquid.

Faced with the failure of a liquid line of descent fractional crystallization model to explain the major and trace element variations in the PCG, there are a few alternative hypotheses that could be entertained. One is to continue to treat the samples as liquid compositions but consider assimilation coupled to fractional crystallization, as we did in the previous section for the synkinematic rocks of Ras Al-Baroud. However, the PCG are so enriched compared to their country rocks that it is implausible to find a source of any assimilant that would be capable of enriching them further. Instead, we consider the “variable cumulate-liquid sampling” concept introduced by Osman et al. (2023). In the absence of clear evidence that a rock sample represents a liquid composition (e.g., an erupted glass, a quenched margin, etc.), one must consider the possibility that its bulk composition represents instead some mixture of crystals and liquid, along a spectrum from a pure cumulate (with no residual liquid) to a quenched liquid. In this case, perhaps the simplest model one can envision to explain the variations among samples of a given pluton is a complete equilibrium model wherein the most evolved sample represents the liquid composition and all other samples contain variable proportions of the solid minerals that are in equilibrium with that liquid. This model has the advantage, compared to the liquid line of descent models, that large ranges in concentrations of incompatible trace elements naturally arise.

We applied the variable cumulate-liquid sampling model to the PCG suite as follows. The most evolved sample, B7 with 77.2 wt% SiO₂, represents the liquid end member. The normative composition of the most primitive sample, B8 with 73.1 wt% SiO₂, shows that the sample can be composed of 45 wt% alkali feldspar (Ab₅₄An₄Or₄₂), 20.5 wt% plagioclase (Ab₇₄An₁₈Or₈), 28 wt% quartz, 4 wt% biotite, 0.3 wt% ilmenite, 0.15 wt% apatite, and 2% residual B7 liquid. Using the mineral compositions and partition coefficients given in Supplementary Table SD18, we find that mixing between the B7 liquid and the B8 solids satisfies the trend of the data in every major and trace element (red arrows in Figs. 9 and 10). Although the differences between the liquid line of descent model and the variable cumulate-liquid sampling model are modest in the major element variation diagrams, they are truly striking in the trace element variation diagrams. Fig. 10i shows that the variable cumulate-liquid sampling model explains the trend in K/Rb vs. Rb across a factor of 3 in Rb concentration, whereas the liquid line of descent model cannot, since it generates only 22% increase in Rb.

We emphasize that the use of the variable cumulate-liquid sampling model to explain the observed differences among sampled members of an emplaced pluton does not exclude the possibility that the liquid experienced fractional crystallization. As we have noted, the depletion of all PCG samples in P, Ti, Ba, and Sr suggests selective sequestration of apatite, ilmenite, and feldspar at an earlier stage of evolution, either as residual phases during melting of tonalite in the source, or by fractional

crystallization at deeper levels of the system not shown at the present depth of exposure.

7.3. Origin of Nb-Ta oxide minerals

The compositional and textural varieties of the Ta-Nb oxides from the studied granites preserve information about the evolution of the plutons. The progressive magmatic evolution from Nb to Ta endmembers (e.g., Cerny et al., 1985; London, 2008; Melcher et al., 2015; Fuchsloch et al., 2019; Chládek et al., 2020) has been associated with changes in alumina saturation index (ASI), parental melt composition, volatile components, and temperature as well as the different solubilities of Nb and Ta in melts (e.g., Linnen and Keppler, 1997; Chevychelov et al., 2010; McNeil, 2018; Bartels et al., 2010; Fiege et al., 2018). Lahti (1987) associated the same trend with a kinetic fractionation of slowly-diffusing Nb and Ta being incorporated into rapidly growing crystals, but Poonosamy et al. (2021) questions this concept. The coupled changes in Nb/Ta and in Mn/Fe reflect the crystallization of both the Nb-Ta oxide minerals and of competing minerals such as micas and Fe-Ti oxides (Stepanov et al., 2014; Van Lichtervelde et al., 2007; Novak and Cerny, 1998; Chládek et al., 2020).

A primary magmatic fractionation trend is observed in columbite in the PCG, with normal zoning towards increasing Mn/(Mn + Fe) and Ta/(Ta + Nb). However, the final crystallization of the muscovite granite member of each pluton involves formation of tantalite with a sharp decrease in Mn/(Mn + Fe). The patchy zonation in cores of crystals that have tantalite rims and wadginite overgrowths may reflect dissolution of primary columbite by late magmatic fluids. Metasomatic replacement is often associated with the occurrence of secondary tantalite and wadginite. Although the formation of these secondary minerals requires derivation of Ta, Fe and Sn from a fluid that was out of equilibrium with columbite (Wu et al., 2017), there is limited evidence of major changes in whole-rock composition associated with metasomatism. We associate the action of late magmatic hydrosilicate liquids with properties transitional between those of silicate melts and hydrothermal fluids (Smirnov et al., 2012) with small-scale element redistribution in these samples.

8. Conclusions

- The Wadi Al-Baroud area features two Neoproterozoic granitoid suites. The older syntectonic granitoids (granodiorite and tonalite) contain microgranular mafic enclaves and are cut by many dikes. The younger post-collisional granites (PCG), forming the Ras Baroud Pluton (RBP) and the Abu Hawis Pluton (AHP) on opposite sides of Wadi Al-Baroud, intruded the syntectonic granitoids with sharp intrusive contacts. They lack mafic enclaves and truncate most dikes.
- The RBP and AHP both consist of biotite monzogranite that grades into muscovite monzogranite. A variety of trace phases host their enriched trace-element budget, including Nb-Ta oxides. The Nb-Ta minerals are mostly primary, with overprinting by a Sn-bearing residual melt or fluid.
- The syntectonic granitoids form a coherent suite with subduction-influenced characteristics. They formed by dehydration melting of mafic arc-related crustal sources and they evolved by a combination of plagioclase fractionation and assimilation of a K-rich component that causes the suite to progressively transition from low-K to high-K calc-alkaline character.
- The post-collisional granites form a distinct coherent suite with within-plate geochemical characteristics. The highly evolved character and trace-element signatures of the PCG closely resemble numerous other post-collisional granites of the ANS. The PCG were derived from a parental melt that was the product of lithospheric delamination-driven partial melting of an I-type tonalitic crustal source.

- Despite evidence of selective early removal of feldspar, apatite, and ilmenite, the variations among the individual samples of the PCG are not consistent with compositions along a liquid line of descent but can instead represent variable mixtures of an evolved liquid with accumulation of the crystals in major- and trace-element equilibrium with that liquid.

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.

Data availability

All the data will be published with the manuscript

Acknowledgements

This work was supported by King Saud University (Researchers Supporting Project number RSP2023R425, covering all analytical costs in Vienna and China), and the US National Science Foundation (1947616). Also, this paper is based upon work supported by Science, Technology and Innovation Funding Authority (STDF) under grant number 45905. The present manuscript is a part of the M.Sc thesis of Marian J. Matta (third author). The authors are indebted to the editor (Prof. Read Mapeo) and the reviewer (Prof. Abdel-Aal M. Abdel-Karim) for their efforts and numerous helpful comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2023.105044>.

References

- Abd El-Wahed, M., Hamimi, Z., 2021. The Egyptian Nubian shield within the frame of the Arabian-Nubian shield. The Geology of the Egyptian Nubian Shield 15–51.
- Abdel-Karim, A.M., 1997. Mineralogy and petrochemistry of Abu tobil younger granites, East of el-tor, southern Sinai, Egypt. *J. Geol.* 41 (2B), 655–686.
- Abdel-Karim, A.M., 1992. Geology and K-Ar ages of some older and younger granites in southwestern Sinai. In: *Egypt. Proc. 3rd Conf. Geol. Sinai Develop.*, pp. 261–266 (Ismailia).
- Abdel-Karim, A.M., Arva-Sos, E., 2000. Geochemical characteristics and K-Ar ages dating of some granitoid rocks from southern Eastern Desert, Egypt. *Egypt. J. Geol.* 44/1, 305–318.
- Abdel-Karim, A.A., Azer, M., Sami, M., 2021b. Petrogenesis and tectonic implications of the Maladob ring complex in the South Eastern Desert, Egypt: New insights from mineral chemistry and whole-rock geochemistry. *International Journal of Earth Sciences* 110, 53–80.
- Abdel-Karim, A.M., El-Shafei, S.A., Azer, M.K., 2021a. The Neoproterozoic ophiolitic ultramafic rocks in Eastern Desert of Egypt: implications for petrogenesis and metasomatic processes. *International Geology Review* 63, 208–232.
- Abdel-Karim, A.M., Soliman, M.M., El-Kazzaz, Y., Mazhar, A.A., Abdel-Gawad, G.A., 2001. Geological and geochemical characteristics of the mafic-ultramafic rocks of Gabal Garf area, south Eastern Desert. *Egypt. Annals of Geological Survey of Egypt XXIV*, 193–218.
- Abdel-Rahman, A.F.M., 1994. Nature of biotites from alkaline, calc-alkaline, and peraluminous magmas. *J. Petrol.* 35 (2), 525–541.
- Abdel-Rahman, A.M., 1994. Nature of biotites from alkaline, calc-alkaline and peraluminous magmas. *J. Petrol.* 35, 525–541.
- Abdel-Rahman, A.M., 2006. Petrogenesis of anorogenic peralkaline granitic complexes from Eastern Egypt. *Mineral. Mag.* 70 (1), 27–50.
- Abuamarah, B.A., Azer, M.K., Seddik, A.M., Asimow, P.D., Guzman, P., Fultz, B.T., Wilner, M.J., Dalleska, N., Darwish, M.H., 2022. Magmatic and post-magmatic evolution of post-collisional rare-metal bearing granite: the neoproterozoic homrit Akarem granitic intrusion, south Eastern desert of Egypt, Arabian-Nubian shield. *Geochemistry* 82, 125840.
- Akinin, V.V., Miller, E.L., Wooden, J.L., 2009. Petrology and geochronology of crustal xenoliths from the Bering Strait Region: linking deep and shallow processes in extending continental crust. *The geological Society of America Special* 456.
- Al-boghdady, A.A., Omar, S.A., Bayoumi, M.M., 2005. Geological and petrological investigations on Gabal Abu Hawis area, central eastern Desert-Egypt. The 4th International Conference on the Geology of Africa (1), 267–287.

- Al-Damegh, K., Sandvol, E., Barazangi, M., 2005. Crustal structure of the Arabian plate: new constraints from the analysis of teleseismic receiver functions. *Earth Planet. Sci. Lett.* 231 (3–4), 177–196.
- Ali, B.H., 2015. SHRIMP U–Pb zircon geochronology: evidence for emplacement time of some granitoids north Eastern Desert, Egypt. *Arabian J. Geosci.* 8, 5465–5474.
- Ali, B.H., Wilde, S.A., Gabr, M.M.A., 2009. Granitoid evolution in Sinai, Egypt, based on precise SHRIMP U–Pb zircon geochronology. *Gondwana Res.* 15 (1), 38–48.
- Ali, K.A., Azer, M.K., Gahlan, H.A., Wilde, S.A., Samuel, M.D., Stern, R.J., 2010. Age constraints on the formation and emplacement of neoproterozoic ophiolites along the Allaqi suture, south Eastern desert, Egypt. *Gondwana Res.* 18, 583–595.
- Ali, K.A., Zoheir, B.A., Stern, R.J., Andresen, A., Whitehouse, M.J., Bishara, W.W., 2016. Lu–Hf and O isotopic compositions on single zircons from the north Eastern desert of Egypt, Arabian–Nubian shield: implications for crustal evolution. *Gondwana Res.* 32, 181–192.
- Anderson, J.L., Rowley, M.C., 1981. Synkinematic intrusion of peraluminous and associated metaluminous granitic magmas, Whipple Mountains, California. *Can. Mineral.* 19 (1), 83–101.
- Attawiya, M.Y., Nossair, L.M., Ragab, A.I., El Debeiky, S.A., 1996. Geology, petrography, geochemistry and geochronology of the old granite batholith between Qena and Safaga, Eastern Desert, Egypt. In: *Proceedings of the 6th Conference of Nuclear Sciences and Applications* (Cairo, Egypt).
- Avigad, D., Gvirtzman, Z., 2009. Late Neoproterozoic rise and fall of the northern Arabian–Nubian Shield: the role of lithospheric mantle delamination and subsequent thermal subsidence. *Tectonophysics* 477 (3–4), 217–228.
- Ayers, J.C., Watson, E.B., 1991. Solubility of apatite, monazite, zircon, and rutile in supercritical aqueous fluids with implications for subduction zone geochemistry. *Philos. Trans. R. Soc. London, Ser. A: Physical and Engineering Sciences* 335 (1638), 365–375.
- Azer, M.K., 2006. The petrogenesis of late Precambrian felsic alkaline magmatism in South Sinai, Egypt. *Acta Geol. Pol.* 56 (4), 463–484.
- Azer, M.K., 2007. Tectonic significance of late precambrian calc-alkaline and alkaline magmatism in saint katherine area, south sinai, Egypt. *Geol. Acta* 5 (issue 3), 255–272.
- Azer, M.K., 2013. Late Ediacaran (605–580 Ma) post-collisional alkaline magmatism in the Arabian–Nubian Shield: a case study of Serbal ring-shaped intrusion, southern Sinai, Egypt. *J. Asian Earth Sci.* 77, 203–223.
- Azer, M.K., Abdelfadil, K.M., Asimow, P.D., Khalil, A.E., 2020. Tracking the transition from subduction-related to post-collisional magmatism in the north Arabian–Nubian Shield: a case study from the Homrit Waggat area of the Eastern Desert of Egypt. *Geol. J.* 55 (6), 4426–4452.
- Azer, M.K., Abdelfadil, K.M., Ramadan, A.A., 2019b. Geochemistry and petrogenesis of Late Ediacaran rare-metal albite granite of the Nubian Shield: case study of Nuweibi intrusion, Eastern Desert, Egypt. *J. Geol.* 127 (6), 665–689.
- Azer, M.K., Asimow, P.D., 2021. Petrogenetic evolution of the Neoproterozoic igneous rocks of Egypt. In: *The Geology of the Egyptian Nubian Shield*. Springer, Cham, pp. 343–382.
- Azer, M.K., Gahlan, H.A., Asimow, P.D., Mubarak, H.S., Al-Kahtany, K.M., 2019a. Multiple stages of carbonation and element redistribution during formation of ultramafic-hosted magnesite in Neoproterozoic ophiolites of the Arabian–Nubian Shield, Egypt. *J. Geol.* 127 (1), 81–107.
- Azer, M.K., Stern, R.J., 2007. Neoproterozoic (835–720 Ma) serpentinites in the Eastern Desert, Egypt: fragments of forearc mantle. *J. Geol.* 115 (4), 457–472.
- Balouard, C., Poujol, M., Boulvais, P., Branquet, Y., Tartèse, R., Vigneresse, J.L., 2016. Nb–Ta fractionation in peraluminous granites: a marker of the magmatic–hydrothermal transition. *Geology* 44, 231–234.
- Bartels, A., Holtz, F., Linnen, R.L., 2010. Solubility of manganotantalite and manganocolumbite in pegmatite melts. *Am. Mineral.* 95, 537–544.
- Bau, M., 1996. Controls on the fractionation of isovalent trace elements in magmatic and aqueous systems: evidence from Y/Ho, Zr/Hf and lanthanides tetrad effect. *Contrib. Mineral. Petrol.* 123, 323–333.
- Be’eri-Shlevin, Y., Katzir, Y., Valley, J.W., 2009b. Crustal evolution and recycling in a juvenile continent: oxygen isotope ratio of zircon in the northern Arabian Nubian Shield. *Lithos* 107, 169–184.
- Be’eri-Shlevin, Y., Katzir, Y., Whitehouse, M., 2009a. Post-collisional tectonomagmatic evolution in the northern Arabian–Nubian Shield: time constraints from ion-probe U–Pb dating of zircon. *J. Geol.* Soc. 166 (1), 71–85.
- Be’eri-Shlevin, Y., Samuel, M.D., Azer, M.K., Rämö, O.T., Whitehouse, M.J., Moussa, H. E., 2011. The Ediacaran Ferani and Rutig volcano-sedimentary successions of the northernmost Arabian–Nubian Shield (ANS): new insights from zircon U–Pb geochronology, geochemistry and O–Nd isotope ratios. *Precambrian Res.* 188 (1–4), 21–44.
- Beard, J.S., Lofgren, G.E., 1991. Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites at 1, 3, and 6.9 kb. *J. Petrol.* 32 (2), 365–401.
- Bentor, Y.K., 1985. The crustal evolution of the Arabo–Nubian Massif with special reference to Sinai Peninsula. *Precambrian Res.* 28, 1–74.
- Beurlen, H., Da Silva, M.R.R., Thomas, R., Soares, D.R., Olivier, P., 2008. Nb–Ta–(Ti–Sn) oxide mineral chemistry as tracer of rare-element granitic pegmatite fractionation in the Borborema Province, Northeastern Brazil. *Miner. Deposita* 43, 207–228.
- Beyth, M., Stern, R.J., Altherr, R., Kröner, A., 1994. The late Precambrian Timna igneous complex Southern Israel: evidence for comagmatic-type sanukitoid monzodiorite and alkali granite magma. *Lithos* 31, 103–124.
- Black, R., Lameyre, J., Bonin, B., 1985. The structural setting of alkaline complexes. *J. Afr. Earth Sci.* 3 (1–2), 5–16, 1983.
- Blasband, B., White, S., Brooijmans, P., De Boorder, H., Visser, W., 2000. Late proterozoic extensional collapse in the Arabian–Nubian shield. *J. Geol. Soc.* 157 (3), 615–628.
- Bonin, B., 2004. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. *Lithos* 78 (1–2), 1–24.
- Bonin, B., 2007. A-type granites and related rocks: evolution of a concept, problems and prospects. *Lithos* 97 (1–2), 1–29.
- Brown, M., 1994. The generation, segregation, ascent and emplacement of granite magma: the migmatite to crustal-derived granite connection in thickened orogens. *Earth Science Review* 36, 83–130.
- Černý, P., Ercit, T.S., 1985. Some recent advances in the mineralogy and geochemistry of Nb and Ta in rare-element granitic pegmatites. *Bull. Mineral.* 108 (3), 499–532.
- Cerny, P., Meintzer, R.E., Anderson, A.J., 1985. Extreme fractionation in rare-element granitic pegmatites; selected examples of data and mechanisms. *Can. Mineral.* 23 (3), 381–421.
- Chappell, B.W., 1974. Two contrasting granite types. *Pac. Geol.* 8, 173–174.
- Chen, B., Tian, W., Jahn, B.M., Chen, Z.C., 2008. Zircon SHRIMP U–Pb ages and in-situ Hf isotopic analysis for the Mesozoic intrusions in South Taihang, North China craton: evidence for hybridization between mantle-derived magmas and crustal components. *Lithos* 102 (1–2), 118–137.
- Chevychelov, V.Y., Borodulin, G.P., Zarskiy, G.P., 2010. Solubility of columbite, (Mn, Fe)(Nb, Ta) O₆, in granitoid and alkaline melts at 650–850° C and 30–400 MPa: an experimental investigation. *Geochem. Int.* 48 (5), 456.
- Chládek, S., Uher, P., Novák, M., 2020. Compositional and textural variations of columbite-group minerals from beryl-columbite pegmatites in the Maršákov District, Bohemian Massif, Czech Republic: magmatic versus hydrothermal evolution. *Can. Mineral.* 58 (6), 767–783.
- Clemens, J., Holloway, J.R., White, A.J.R., 1986. Origin of A-type granite: experimental constraints. *Am. Mineral.* 71, 317–324.
- Collins, W.J., Beams, S.D., White, A.J.R., Chappell, B.W., 1982. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contrib. Mineral. Petrol.* 80, 189–200.
- Creaser, R.A., Price, R.C., Wormald, R.J., 1991. A-type granites revisited: assessment of a residual-source model. *Geology* 19 (2), 163–166.
- De la Roche, H., Leterrier, J., Grandclaude, P., Marchal, M., 1980. A classification of volcanic and plutonic rocks using R₁–R₂ diagrams and major-element analyses — its relationship with current nomenclature. *Chem. Geol.* 29, 183–210.
- Deer, W.A., Howie, R.A., Zussman, J., 1992. *An Introduction to the Rock Forming Minerals*, second ed. Longman Scientific and Technical, London, p. 696pp.
- Eby, G.N., 1990. The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos* 26 (1–2), 115–134.
- Eby, G.N., 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* 20 (7), 641–644.
- El-Bialy, M.Z., Omar, M.M., 2015. Spatial association of Neoproterozoic continental arc I-type and post-collision A-type granitoids in the Arabian–Nubian Shield: the Wadi Al-Baroud older and younger granites, north eastern desert, Egypt. *J. Afr. Earth Sci.* 103, 1–29.
- El-Gaby, S., List, F., Tehrani, R., 1988. Geology, evolution and metallogenesis of the Pan-African belt in Egypt. In: *El-Gaby, S., Greiling, R.O. (Eds.), The Pan-African Belt of Northeast Africa and Adjacent Areas*. Vieweg and Sohn, Weinbaden, pp. pp17–68.
- El-Nisr, S.A., El-Sayed, M.M., 2002. The role of fractional crystallization and assimilation in the evolution of the zoned Mukhattata pluton. Eastern Desert, Egypt. *Chemie der Erde* 62, 216–236.
- El-Sayed, M.M., Mohamed, F.H., Furnes, H., Kanisawa, S., 2002. Geochemistry and petrogenesis of the neoproterozoic granitoids in the central eastern desert. Egypt. *Chemie der Erde* 62, 317–346.
- Evensen, N.M., Hamilton, P.J., O’ Nions, R.K., 1978. Rare earth abundances in chondritic meteorites. *Geochem. Cosmochim. Acta* 42 (8), 1199–1212.
- Eyal, M., Litvinovsky, B., Jahn, B.M., Zanzilevich, A., Katzir, Y., 2010. Origin and evolution of post-collisional magmatism: coeval Neoproterozoic calc-alkaline and alkaline suites of the Sinai Peninsula. *Chem. Geol.* 269 (3–4), 153–179.
- Farahat, E.S., Azer, M.K., 2011. Post-collisional magmatism in the northern Arabian–Nubian Shield: the geotectonic evolution of the alkaline suite at Gebel Tarbush area, south Sinai, Egypt. *Chem. Erde* 71, 247–266.
- Farahat, E.S., Mohamed, H.A., Ahmed, A.F., El Mahallawi, M.M., 2007. Origin of I- and A-type granitoids from the Eastern Desert of Egypt: implications for crustal growth in the northern Arabian–Nubian shield. *J. Afr. Earth Sci.* 49, 43–58.
- Farahat, E.S., Zaki, R., Hauenberger, C., Sami, M., 2011. Neoproterozoic calc-alkaline peraluminous granitoids of the Deleihimmi pluton, Central Eastern Desert, Egypt: implications for transition from late-to post-collisional tectonomagmatic evolution in the northern Arabian–Nubian Shield. *Geol. J.* 46 (6), 544–560.
- Fawzy, M.M., Mahdy, N.M., Sami, M., 2020. Mineralogical characterization and physical upgrading of radioactive and rare metal minerals from Wadi Al-Baroud granitic pegmatite at the Central Eastern Desert of Egypt. *Arabian J. Geosci.* 13, 1–15.
- Fiege, A., Simon, A., Linsler, S.A., Bartels, A., Linnen, R.L., 2018. Experimental constraints on the effect of phosphorous and boron on Nb and Ta ore formation. *Ore Geol. Rev.* 94, 383–395.
- Foley, S.F., Buhre, S., Jacob, D.E., 2003. Evolution of the Archean crust by delamination and shallow subduction. *Nature* 421 (6920), 249–252.
- Fritz, H., Abdelsalam, M., Ali, K.A., Bingen, B., Collins, A.S., Fowler, A.R., Ghebreab, W., Hauenberger, C.A., Johnson, P.R., Kusky, T.M., Macey, P., 2013. Orogen styles in the East African orogen: a review of the neoproterozoic to cambrian tectonic evolution. *J. Afr. Earth Sci.* 86, 65–106.
- Friz-Töpfer, A., 1991. Geochemical characterization of Pan-African dyke swarms in southern Sinai: from continental margin to intraplate magmatism. *Precambrian Res.* 49 (3–4), 281–300.
- Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. *J. Petrol.* 42 (11), 2033–2048.

- Fuchsloch, W.C., Nex, P.A., Kinnaird, J.A., 2019. The geochemical evolution of Nb-Ta-Sn oxides from pegmatites of the Cape Cross-Uis pegmatite belt, Namibia. *Mineral. Mag.* 83 (2), 161–179.
- Furnes, H., El-Sayed, M.M., Khalil, S.O., Hassanen, M.A., 1996. Pan-african magmatism in the wadi el-imra district, central Eastern Desert, Egypt: geochemistry and tectonic environment. *J. Geol. Soc.* 153 (5), 705–718.
- Garfunkel, Z., 1999. History and paleogeography during the Pan-African orogen to stable platform transition: reappraisal of the evidence from the Elat area and the northern Arabian-Nubian Shield. *Isr. J. Earth Sci.* 48 (3), 135–157.
- Ghoneim, M.F., Abdel-Karim, A.M., Abu Anbar, M.M., Habib, A., El-Shafei, S.A., 2022. Petrogenesis of post-collisional high-K calc-alkaline and alkaline magmatism at Southern Sinai, Egypt: the role of crustal anatexis combined with convective diffusion. *J. Geol.* 130 (2), 111–132.
- Gion, A.M., Piccoli, P.M., Candela, P.A., 2022. Characterization of biotite and amphibole compositions in granites. *Contrib. Mineral. Petrol.* 177 (4), 1–15.
- Girardeau, J., Mevel, C., 1982. Amphibolitized sheared gabbros from ophiolites as indicators of the evolution of the oceanic crust: bay of Islands, Newfoundland. *Earth Planet Sci. Lett.* 61 (1), 151–165.
- Göğüş, O.H., Pysklywec, R.N., Corbi, F., Faccenna, C., 2011. The surface tectonics of mantle lithosphere delamination following ocean lithosphere subduction: insights from physical-scaled analogue experiments. *G-cubed* 12 (5), Q05004.
- Göğüş, O.H., Pysklywec, R.N., Faccenna, C., 2017. Geodynamical models for continental delamination and ocean lithosphere peel away in an orogenic setting. *Geophysical Monograph*, “Active global seismology: Neotectonics and earthquake potential of the eastern mediterranean region”. American Geophysical Union 225, 121–139.
- Goscombe, B., Foster, D.A., Blewett, R., Czarnota, K., Wade, B., Groenewald, B., Gray, D., 2019. Neoproterozoic metamorphic evolution of the Yilgarn Craton: a record of subduction, accretion, extension and lithospheric delamination. *Precambrian Res.* 335, 105441.
- Greiling, R.O., Abdeen, M.M., Dardir, A.A., El Akhal, H., El Ramly, M.F., El Din Kamal, G. M., Osman, A.F., Rashwan, A.A., Rice, A.H.N., Sadek, M.F., 1994. A structural synthesis of the proterozoic Arabian-Nubian shield in Egypt. *Geol. Rundsch.* 83, 484–501.
- Gualda, G.A., Ghiorso, M.S., Lemons, R.V., Carley, T.L., 2012. Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems. *J. Petrol.* 53 (5), 875–890.
- Haapala, I., Frindt, S., Kandra, J., 2007. Cretaceous Gross Spitzkoppe and Klein Spitzkoppe stocks in Namibia: topaz-bearing A-type granites related to continental rifting and mantle plume. *Lithos* 97 (1–2), 174–192.
- Halama, R., Marks, M., Brüggemann, G., Siebel, W., Wenzel, T., Markl, G., 2004. Crustal contamination of mafic magmas: evidence from a petrological, geochemical and Sr–Nd–Os–O isotopic study of the Proterozoic Isortoq dike swarm, South Greenland. *Lithos* 74 (3–4), 199–232.
- Hanson, G.N., 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth Planet Sci. Lett.* 38 (1), 26–43.
- Harris, N.B., Pearce, J.A., Tindle, A.G., 1986. Geochemical characteristics of collision-zone magmatism. In: Coward, M.P., Ries, A.C. (Eds.), *Collision Tectonics*, 19. Journal of Geological Society, London, Special Publication, pp. 67–81.
- Harris, N.B.W., 1982. The petrogenesis of alkaline intrusives from Arabia and Northeast Africa and their implications for within-plate magmatism. *Tectonophysics* 83, 243–258.
- Harrison, T.M., Watson, E.B., 1984. The behavior of apatite during crustal anatexis: equilibrium and kinetic considerations. *Geochem. Cosmochim. Acta* 48 (7), 1467–1477.
- Hawkesworth, C.J., Gallagher, K., Hergt, J.M., McDermott, F., 1993. Mantle and slab contributions in arc magmas. *Annu. Rev. Earth Planet Sci.* 21 (1), 175–204.
- Hawthorne, F.C., Oberti, R., Harlow, G.E., Maresch, W.V., Martin, R.F., Schumacher, J. C., Welch, M.D., 2012. Nomenclature of the amphibole supergroup. *Am. Mineral.* 97 (11–12), 2031–2048.
- Hey, M.H., 1954. A new review of the chlorites. *Mineral. Mag.* 30 (224), 277–292.
- Hollings, P., Wyman, D., 1999. Trace element and Sm–Nd systematics of volcanic and intrusive rocks from the 3 Ga Lundy Lake Greenstone belt, Superior Province: evidence for Archean plume–arc interaction. *Lithos* 46 (2), 189–213.
- Holtz, F., Behrens, H., Dingwell, D.B., Taylor, R.P., 1992. Water solubility in aluminosilicate melts of haplogranite composition at 2 kbar. *Chem. Geol.* 96, 289–302.
- Hora, J.M., Singer, B.S., Wörner, G., Beard, B.L., Jicha, B.R., Johnson, C.M., 2009. Shallow and deep crustal control on differentiation of calc-alkaline and tholeiitic magma. *Earth Planet Sci. Lett.* 285 (1–2), 75–86.
- Hoskin, P.W.O., Kinny, P.D., Wyborn, D., Chappell, B.W., 2000. Identifying accessory mineral saturation during differentiation in granitoid magmas: an integrated approach. *J. Petrol.* 41, 1365–1396.
- Iacumin, M., Marzoli, A., El-Metwally, A.A., Piccirillo, E.M., 1998. Neoproterozoic dyke swarms from southern Sinai (Egypt): geochemistry and petrogenetic aspects. *J. Afr. Earth Sci.* 26 (1), 49–64.
- Jahn, B.M., Wu, F., Capdevila, R., Martineau, F., Zhao, Z., Wang, Y., 2001. Highly evolved juvenile granites with tetrad REE patterns: the Woduhe and Baerzhe granites from the Great Xing'an Mountains in NE China. *Lithos* 59 (4), 171–198.
- Jahns, R.H., Burnham, C.W., 1969. Experimental studies of pegmatite genesis; I. A model for the derivation and crystallization of granitic pegmatites. *Econ. Geol.* 64 (8), 843–864.
- Jarrar, G.H., Manton, W.I., Stern, R.J., Zachmann, D., 2008. Late Neoproterozoic A-type granites in the northernmost Arabian-Nubian Shield formed by fractionation of basaltic melts. *Geochemistry* 68 (3), 295–312.
- Johnson, P.R., Andresen, A., Collins, A.S., Fowler, A.R., Fritz, H., Ghebreab, W., Kusky, T., Stern, R.J., 2011. Late Cryogenian–Ediacaran history of the Arabian–Nubian Shield: a review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. *J. Afr. Earth Sci.* 61 (3), 167–232.
- Keedite, M., Rajesh, H.M., Belyanin, G.A., Fukuyama, M., Tsunogae, T., 2016. Primary magmatic amphibole in Archean meta-pyroxenite from the central zone of the Limpopo Complex, South Africa. *S. Afr. J. Geol.* 119 (4), 607–622.
- Kessel, R., Stein, M., Navon, O., 1998. Petrogenesis of late neoproterozoic dikes in the northern Arabian–Nubian shield: implications for the origin of A-type granites. *Precambrian Res.* 92 (2), 195–213.
- Khalil, A.E.S., Obeid, M.A., Azer, M.K., Asimow, P.D., 2018. Geochemistry and petrogenesis of post-collisional alkaline and peralkaline granites of the Arabian-Nubian Shield: a case study from the southern tip of Sinai Peninsula, Egypt. *Int. Geol. Rev.* 60 (8), 998–1018.
- King, P.L., White, A.J.R., Chappel, B.W., Allen, C.M., 1997. Characterization and origin of aluminous A-type granites from the Lachlan Fold Belt, southeastern Australia. *J. Petrol.* 38, 371–391.
- Kröner, A., Krüger, J., Rashwan, A.E.A., 1994. Age and tectonic setting of granitoid gneisses in the Eastern Desert of Egypt and south-west Sinai. *Geol. Rundsch.* 83, 502–513.
- Lahti, S.L., 1987. Zoning in columbite-tantalite crystals from the granitic pegmatites of the Eräjärvi area, southern Finland. *Geochem. Cosmochim. Acta* 51 (3), 509–517.
- Laurent, O., Martin, H., Moyen, J.F., Doucelaine, R., 2014. The diversity and evolution of late-Archean granitoids: evidence for the onset of “modern-style” plate tectonics between 3.0 and 2.5 Ga. *Lithos* 205, 208–235.
- Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabine, P. A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R., 1989. A Classification of Igneous Rocks and Glossary of Terms. Recommendations of the IUGS Subcommittee on the Systematics of Igneous Rocks. Blackwell, Oxford, p. 193.
- Lee, C.T., Rudnick, R.L., Brimhall Jr., G.H., 2001. Deep lithospheric dynamics beneath the Sierra Nevada during the Mesozoic and Cenozoic as inferred from xenolith petrology. *G-cubed* 2 (12), 2001GC000152.
- Lee, S.-G., Asahara, Y., Tanaka, T., Lee, S.R., Lee, T., 2013. Geochemical Significance of the Rb–Sr, La–Ce and Sm–Nd Isotope Systems in A-type Rocks with REE Tetrad Patterns and Negative Eu and Ce Anomalies: the Cretaceous Muamsa and Weolaksan Granites. *Chemie Der Erde* 73, South Korea, pp. 75–88.
- Li, X.H., Li, Z.X., Li, W.X., Liu, Y., Yuan, C., Wei, G.J., Qi, C.S., 2007. U–Pb zircon, geochemical and Sr–Nd–Hf isotopic constraints on age and origin of Jurassic land A-type granites from central Guangdong, SE China: a major igneous event in response to foundering of a subducted flat-slab? *Lithos* 96 (1–2), 186–204.
- Liégeois, J.P., Black, R., 1987. Alkaline magmatism subsequent to collision in the Pan-African belt of the Adrar des Iforas. In: Fitton, J.G., Upton, B.G.J. (Eds.), *Alkaline Igneous Rocks*, 30. Geological Society, Special Publication, pp. 381–401.
- Liégeois, J.P., Navez, J., Hertogen, J., Black, R., 1998. Contrasting origin of post-collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline granitoids. The use of sliding normalization. *Lithos* 45, 1–28.
- Linnen, R.L., Keppler, H., 1997. Columbite solubility in granitic melts: consequences for the enrichment and fractionation of Nb and Ta in the Earth’s crust. *Contrib. Mineral. Petrol.* 128, 213–227.
- Liu, M., Shen, Y., Yang, Y., 2000. Gravitational collapse of orogenic crust: a preliminary three-dimensional finite element study. *J. Geophys. Res. Solid Earth* 105 (B2), 3159–3173.
- Locock, A.J., 2014. An Excel spreadsheet to classify chemical analyses of amphiboles following the IMA 2012 recommendations. *Comput. Geosci.* 62, 1–11.
- London, D., 2008. Pegmatites, 10. Canadian Mineralogist Special Publication, p. 347.
- London, D., 2015. Reading pegmatites: Part 1—what beryl says. *Rocks Miner.* 90 (2), 138–153.
- London, D., Stein, H.J., Hannah, J.L., 1990. Internal Differentiation of Rare-Element Pegmatites: a Synthesis of Recent Research, 246. Geological Society of America Special Paper, pp. 35–50.
- Magni, V., Király, A., 2020. Delamination. Reference module in Earth systems and environmental sciences. <https://doi.org/10.1016/B978-0-12-409548-9.09515-4>.
- Mahdy, N.M., 2021. Textural and chemical characteristics of zircon, monazite, and thorite, Wadi Al-Baroud area, Eastern Desert of Egypt: implication for rare metal pegmatite genesis. *Ore Geol. Rev.* 136, 104225.
- Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *Geol. Soc. Am. Bull.* 101 (5), 635–643.
- Manning, D.A.C., 1981. The effect of fluorine on liquidus phase relationships in the system Qz–Ab–Or with excess water at 1 kb. *Contrib. Mineral. Petrol.* 76, 206–215.
- Maurice, A.E., Bakht, B.R., Basta, F.F., Khiamy, A.A., 2013. Geochemistry of gabbros and granitoids (M- and I-types) from the Nubian Shield of Egypt: roots of Neoproterozoic intra-oceanic island arc. *Precambrian Res.* 224, 397–411.
- McKay, G.A., 1989. Partitioning of rare earth elements between major silicate minerals and basaltic melts. In: Lipin, B.R., McKay, G.A. (Eds.), *Geochemistry and Mineralogy of Rare Earth Elements*, 21. Mineralogical Society of America, pp. 45–77.
- McLelland, J.M., Selleck, B.W., Hamilton, M.A., Bickford, M.E., 2010. Late-to post-tectonic setting of some major Proterozoic anorthositic–mangerite–charnockite–granite (AMCG) suites. *Can. Mineral.* 48 (4), 729–750.
- McNeil, A.G., 2018. Crystallization Processes and Solubility of columbite-(Mn), tantalite-(Mn), Microcline, Pyrochlore, Wodginite and Titanowodginite in Highly Fluxed Haplogranitic Melts (Doctoral Dissertation). The University of Western Ontario (Canada).
- Melcher, F., Graupner, T., Gäbler, H.E., Sitnikova, M., Henjes-Kunst, F., Oberthür, T., Gerdes, A., Dewaele, S., 2015. Tantalum–niobium–tin mineralisation in African pegmatites and rare metal granites: constraints from Ta–Nb oxide mineralogy, geochemistry and U–Pb geochronology. *Ore Geol. Rev.* 64, 667–719.

- Menuge, J.F., Brewer, T.S., Seeger, C.M., 2002. Petrogenesis of metaluminous A-type rhyolites from the St Francois mountains, Missouri and the Mesoproterozoic evolution of the southern Laurentian margin. *Precambrian Res.* 113 (3–4), 269–291.
- Miller, C.F., Stoddard, E.F., Bradfish, L.J., Dollase, W.A., 1981. Composition of plutonic muscovite: genetic implications. *Can. Mineral.* 19 (1), 25–34.
- Miller, R.B., Snoke, A.W., 2009. Crustal Cross Section from the Western North American Cordillera and Elsewhere: Implications for Tectonic and Petrologic Processes. The Geological Society of America. Special Paper 456.
- Moghazi, A.K.M., 1999. Magma source and evolution of Late Neoproterozoic granitoids in the Gabal El-Urf area, Eastern Desert, Egypt: geochemical and Sr–Nd isotopic constraints. *Geol. Mag.* 136 (3), 285–300.
- Moghazi, A.M., 2002. Petrology and geochemistry of Pan-African granitoids, Kab Amiri area, Egypt—implications for tectonomagmatic stages in the Nubian Shield evolution. *Mineral. Petrol.* 75, 41–67.
- Montel, J.M., Vielzeuf, D., 1997. Partial melting of metagreywackes, Part II. Compositions of minerals and melts. *Contrib. Mineral. Petrol.* 128, 176–196.
- Moore, V.M., Witschko, D.V., 2004. Syncollisional delamination and tectonic wedge development in convergent orogens. *Tectonics* 23 (2), TC2005. <https://doi.org/10.1029/2002TC001430>.
- Moussa, E.M., Stern, R.J., Manton, W.I., Ali, K.A., 2008. SHRIMP zircon dating and Sm/Nd isotopic investigations of Neoproterozoic granitoids, Eastern Desert, Egypt. *Precambrian Res.* 160 (3–4), 341–356.
- Moussa, H.E., Asimow, P.D., Azer, M.K., Abou El Maaty, M.A., Akarish, A.I., Yanni, N.N., Mubarak, H.S., Wilner, M.J., Elsaheer, M.A., 2021. Magmatic and hydrothermal evolution of highly-fractionated rare-metal granites at Gabal Nuweibi, Eastern Desert, Egypt. *Lithos* 400, 106405.
- Mushkin, A., Navon, O., Halicz, L., Hartmann, G., Stein, M., 2003. The petrogenesis of A-type magmas from the Amram Massif, southern Israel. *J. Petrol.* 44 (5), 815–832.
- Nachit, H., 1985. Composition chimique des biotites et typologie magmatique des granitoids. *Comptes Rendus Hebdomadaires de l'Académie des Sciences* 301 (11), 813–818.
- Nachit, H., Ibhi, A., Abia, E.H., Ohoud, M.B., 2005. Discrimination between primary magmatic biotites, reequilibrated biotites and neoformed biotites. *Compt. Rendus Geosci.* 337, 1415–1420.
- Novak, M., Cerny, P., 1998. Niobium-tantalum oxide minerals from complex granitic pegmatites in the Moldanubicum, Czech Republic; primary versus secondary compositional trends. *Can. Mineral.* 36 (2), 659–672.
- Osman, M.S., Azer, M.K., Asimow, P.D., Price, J.B., Ibañez-Mejia, M., 2023. Mineralogy, Geochronology, and Geochemistry of the Calc-Alkaline Um Takha White Granite Pluton, South Sinai, Egypt, 107021. *Lithos*.
- Patino Douce, A.E., 1997. Generation of metaluminous A-type granites by low pressure melting of calc-alkaline granitoids. *Geology* 25 (8), 743–746.
- Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* 25, 956–983.
- Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contrib. Mineral. Petrol.* 58, 63–81.
- Petford, N., Gallagher, K., 2001. Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. *Earth Planet Sci. Lett.* 193 (3–4), 483–499.
- Poonosamy, J., Mahrous, M., Curti, E., Bosbach, D., Deissmann, G., Churakov, S.V., Geisler, T., Prasianakis, N., 2021. A lab-on-a-chip approach integrating in-situ characterization and reactive transport modelling diagnostics to unravel (Ba, Sr) SO₄ oscillatory zoning. *Sci. Rep.* 11 (1), 23678.
- Raslan, M.F., El-Shall, H.E., Omar, S.A., Daher, A.M., 2010. Mineralogy of polymetallic mineralized pegmatite of Ras Baroud granite, central Eastern Desert, Egypt. *J. Mineral. Petrol. Sci.* 105 (3), 123–134.
- Rollinson, H., 1994. Using Geochemical Data: Evaluation, Presentation, Interpretation. Longman Scientific & Technical – John Wiley & Sons Inc., New York, p. 352.
- Saunders, A.D., Tarney, J., Weaver, S.D., 1980. Transverse geochemical variations across the Antarctic Peninsula: implications for the genesis of calc-alkaline magmas. *Earth Planet Sci. Lett.* 46 (3), 344–360.
- Sayyah, T.A., Assaf, H.S., Abdel Kader, Z., Mahdy, M.A., Omar, S.A., 1993. New Nb-Ta occurrence in gebel Ras Baroud, central Eastern Desert. *Egyptian Mineralogist* 5, 41–55.
- Shaw, D.M., 1968. A review of K-Rb fractionation trends by covariance analysis. *Geochem. Cosmochim. Acta* 32 (6), 57.
- Skjerlie, K.P., Johnston, A.D., 1993. Fluid-absent melting behavior of an F-rich tonalitic gneiss at mid-crustal pressures: implications for the generation of an orogenic granites. *J. Petrol.* 34 (4), 785–815.
- Smirnov, S.Z., Thomas, V.G., Kamenetsky, V.S., Kozmenko, O.A., Large, R.R., 2012. Hydrosilicate liquids in the system Na₂O–SiO₂–H₂O with NaF, NaCl and Ta: evaluation of their role in ore and mineral formation at high T and P. *Petrology* 20, 271–285.
- Smirnov, V.I., Beus, A.A. (Eds.), 1983. *Studies of Mineral Deposits*. Mir publishers, Moscow.
- Stepanov, A., A Mavrogenes, J., Meffre, S., Davidson, P., 2014. The key role of mica during igneous concentration of tantalum. *Contrib. Mineral. Petrol.* 167, 1–8.
- Stern, R.J., 1985. The Najd fault system, Saudi Arabia and Egypt: a late Precambrian rift-related transform system? *Tectonics* 4 (5), 497–511.
- Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African orogen: implications for the consolidation of Gondwanaland. *Annu. Rev. Earth Planet Sci.* 22 (1), 319–351.
- Stern, R.J., Gottfried, D., Hedge, C.E., 1984. Late Precambrian rifting and crustal evolution in the northeastern desert of Egypt. *Geology* 12 (3), 168–172.
- Stern, R.J., Hedge, C.E., 1985. Geochronologic and isotopic constraints on late Precambrian crustal evolution in the Eastern Desert of Egypt. *Am. J. Sci.* 285 (2), 97–127.
- Stern, R.J., Voegeli, D.A., 1987. Geochemistry, geochronology, and petrogenesis of a late Precambrian (~ 590 Ma) composite dike from the north Eastern desert of Egypt. *Geol. Rundsch.* 76, 325–341.
- Stormer, J.C., 1983. The effects of recalculation on estimates of temperature and oxygen fugacity from analyses of multicomponent iron-titanium oxides. *Am. Mineral.* 68 (5–6), 586–594.
- Streckeisen, A., 1976. To each plutonic rock its proper name. *Earth Science Review* 12, 1–33.
- Streckeisen, A., Le Maitre, R.W., 1979. A Chemical Approximation to the Modal QAPP Classification of the Igneous Rocks.
- Sun, S., McDonough, W.F., 1989. Chemical and isotopic systematic of oceanic basalts: implications for mantle compositions and processes. In: Saunders, A.D., Norry, M.J. (Eds.), *Magmatism in the Ocean Basins*, 42. Geological Society of London, Special Publications, pp. 313–345.
- Surour, A.A., Omar, S.A., Zunic, T.B., 2004. Cation ordering and chemistry of cryptically zoned columbite from Ras Baroud rare-metal pegmatites, Central Eastern Desert, Egypt. In: 6th International Conference on Geochemistry. Alexandria University, Egypt, pp. 777–795.
- Sylvester, P.J., 1989. Post-collisional alkaline granites. *J. Geol.* 97 (3), 261–280.
- Thornton, C.P., Tuttle, O.F., 1960. Chemistry of igneous rocks—[Part] 1, Differentiation index. *Am. J. Sci.* 258 (9), 664–684.
- Tindle, A.G., Breaks, F.W., 1998. Oxide minerals of the separation rapids rare-element granitic pegmatite group, Northwestern Ontario. *Can. Mineral.* 36, 609–635.
- Tindle, A.G., Breaks, F.W., 2000. Columbite-tantalite mineral chemistry from rare-element granitic pegmatites: separation Lakeh area, NW Ontario, Canada. *Mineral. Petrol.* 70 (3/4), 165.
- Turner, S.J., Langmuir, C.H., 2015. The global chemical systematics of arc front stratovolcanoes: evaluating the role of crustal processes. *Earth Planet Sci. Lett.* 422, 182–193.
- Ueda, K., Gerya, T.V., Burg, J.P., 2012. Delamination in collisional orogens: thermomechanical modeling. *J. Geophys. Res. Solid Earth* 117 (B8), B08202.
- Van Lichtenvelde, M., Salvi, S., Beziat, D., Linnen, R.L., 2007. Textural features and chemical evolution in tantalum oxides: magmatic versus hydrothermal origins for Ta mineralization in the Tanco Lower Pegmatite, Manitoba, Canada. *Econ. Geol.* 102 (2), 257–276.
- Wang, Q., Zhao, J., Zhang, C., Yu, S., Ye, X., Liu, X., 2022. Paleozoic post-collisional magmatism and high-temperature granulite-facies metamorphism coupling with lithospheric delamination of the East Kunlun Orogenic Belt, NW China. *Geosci. Front.* 13 (1), 101271.
- Watkins, J.M., Clemens, J.D., 2007. Archean TTGs as sources of younger granitic magmas: melting of sodic metatonalites at 0.6–1.2 GPa. *Contrib. Mineral. Petrol.* 154 (1), 91–110.
- Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Planet Sci. Lett.* 64 (2), 295–304.
- Whalen, J.B., Currie, K.L., Chappel, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.* 95, 407–419.
- Wilson, M., 1994. *Igneous Petrogenesis*. Chapman & Hall, London, p. 466.
- Winkler, H.G.F., Boese, M., Marcopoulos, T., 1975. Low temperature granite melts. *Neues Jahrbuch Mineral. Monatsh.* 6, 245–268.
- Wu, F.Y., Liu, X.C., Liu, Z.C., Wang, R.C., Xie, L., Wang, J.M., Ji, W.Q., Yang, L., Liu, C., Khanal, G.P., He, S.X., 2020. Highly fractionated Himalayan leucogranites and associated rare-metal mineralization. *Lithos* 352–353, 105319.
- Wu, F.-Y., Sun, D.-y., Li, H., Jahn, B.-M., Wilde, S., 2002. A-type granites in northeastern China: age and geochemical constraints on their petrogenesis. *Chem. Geol.* 187, 143–173.
- Wu, M., Samson, I.M., Zhang, D., 2017. Textural and chemical constraints on the formation of disseminated granite-hosted W-Ta-Nb mineralization at the Dajishan deposit, Nanling Range, Southeastern China. *Econ. Geol.* 112 (4), 855–887.
- Yang, J.H., Wu, F.Y., Chung, S.L., Wilde, S.A., Chu, M.F., 2006. A hybrid origin for the Qianshan A-type granite, northeast China: geochemical and Sr–Nd–Hf isotopic evidence. *Lithos* 89 (1–2), 89–106.
- Zen, E.A., 1988. Phase relations of peraluminous granitic rocks and their petrogenetic implications. *Annu. Rev. Earth Planet Sci.* 16 (1), 21–51.