



Article The Geochemistry, Petrogenesis, and Rare-Metal Mineralization of the Peralkaline Granites and Related Pegmatites in the Arabian Shield: A Case Study of the Jabal Sayid and Dayheen Ring Complexes, Central Saudi Arabia

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Abstract: The Neoproterozoic period in the Jabal Sayid and Dayheen areas is characterized by three distinct magmatic phases: an early magmatic phase of granodiorite-diorite association, a transitional magmatic phase of monzogranites, and a highly evolved magmatic phase of peralkaline granites and associated pegmatites. The presence of various accessory minerals in the peralkaline granites and pegmatites, such as synchysite, bastnaesite, xenotime, monazite, allanite, pyrochlore, samarskite, and zircon, plays an important role as contributors of REEs, Zr, Y, Nb, Th, and U. The geochemical characteristics indicate that the concentration of these elements occurred primarily during the crystallization and differentiation of the parent magma, with no significant contributions from post-magmatic hydrothermal processes. The obtained geochemical data shed light on the changing nature of magmas during the orogenic cycle, transitioning from subduction-related granodiorite-diorite compositions to collision-related monzogranites and post-collisional peralkaline suites. The granodiorite-diorite association is thought to be derived from the partial melting of predominantly metabasaltic sources, whereas the monzogranites are derived from metatonalite and metagraywacke sources. The peralkaline granites and associated pegmatites are thought to originate from the continental crust. It is assumed that these rocks are formed by the partial melting of metapelitic rocks that are enriched with rare metals. The final peralkaline phase of magmatic evolution is characterized by the enrichment of the residual melt with alkalis (such as sodium and potassium), silica, water, and fluorine. The presence of liquid-saturated melt plays a decisive role in the formation of pegmatites.

Keywords: whole-rock geochemistry; petrogenesis; Jabal Sayid and Dayheen; rare-metal mineralization; Jeddah terrane; Arabian Shield

1. Introduction

Many peralkaline granites are considered specialized granites due to their distinct geochemical properties, including high concentrations of rare earth elements (REEs) and other elements such as Nb, Ta, Zr, Y, U, and Th [1,2]. The composition of the parental magma is a crucial factor for the subsequent enrichment of rare metals in peralkaline granites and related pegmatites. In addition, the degree and type of magmatic differentiation and the transition from magmatic to hydrothermal processes can significantly influence the final enrichment of rare metals in the resulting magma. The study of alkaline/peralkaline granites and related pegmatites with rare metals is important because it provides valuable insights into the behavior of rare metals during late magmatic processes. These studies help scientists to understand the processes that control the concentration and dispersion of rare metals in igneous rocks.

The origin and formation of the rare-metal alkaline and peralkaline granites in the Arabian Shield (AS) have been the subject of investigation in several studies [2–10]. Al-Ghurayyah, Jabal Hamara, Umm Al-Birak, Jabal Tawlah, Jabal Sayid, and the Hadb Ad



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Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Dayheen ring complex (referred to herein as the Dayheen intrusion) are indeed significant occurrences of rare metals in the AS (Figure 1). Both Jabal Sayid and Dayheen plutons were described earlier as A-type peralkaline granite that was produced in a within-plate tectonic setting [7,8].



Figure 1. A simplified geological map of the ANS (modified after [11–13]) with the sites of the study areas and other rare-metal alkaline granites in the AS (red circles).

The granitic rocks and related pegmatites in Jabal Sayid and the Dayheen areas are characterized by the high content of certain elements, including Zr, Nb, U, Th, and REEs. In both areas, the final stages of magmatic evolution played an important role in the concentration of rare metals. The study by [4] proposes that the Dayheen peralkaline granite was formed through the partial melting of the juvenile lower crust. This melting event is thought to have occurred after the collision between the East and West Gondwana supercontinents during the final stages of the AS evolution. Ref. [6] discussed the U-Pb zircon dating and Nd-Hf-O isotopic analyses of the Dayheen ring complex. These findings suggest that the complex was primarily derived from juvenile crust formed during the Neoproterozoic period. Ref. [8] concluded that the variations in rare-metal mineralization between Jabal Sayid and Dayheen primarily occur from a magmatic to a hydrothermal stage, suggesting the influence of hydrothermal processes on mineralization. Similarly, ref. [9] concluded that both magmatic and hydrothermal processes contributed to the

formation of mineralization in the Dayheen complex. The study by [10] suggests that part of the Dayheen granitic rocks developed during an extension stage.

Overall, these previous studies propose that the tectonic evolution of post-collision alkaline and peralkaline granites is closely linked to the assembly of the Arabian-Nubian Shield (ANS). The specific tectonic setting and processes that led to the emplacement of these granites are still subjects of ongoing study and debate among geologists and researchers in the field. To contribute to the understanding of the origin of rare-metal granites and pegmatites, the present authors conducted investigations on the Jabal Sayid and Dayheen plutons in the Jeddah terrane (Figure 1). These plutons are known to host the significant mineralization of Nb, Zr, REEs, U, and Th. This article aims to address several fundamental questions concerning the evolution of rare-metal granite–pegmatite systems based on petrological and geochemical data. Here are the key questions that could be presented:

- (1) What are the specific mechanisms involved in the petrogenesis of the peralkaline granites and related pegmatites in the Jabal Sayid and Dayheen areas?
- (2) What are the geochemical similarities or differences among the peralkaline granites and related pegmatites in the Jabal Sayid and Dayheen areas?
- (3) What is the significance of the rare metal data in terms of the granitic evolution in both the Jabal Sayid and Dayheen areas? The researchers aim to understand how rare metals, including REEs, Zr, Y, Nb, U, and Th, are concentrated and fractionated during the late-stage magmatic processes that have influenced the evolution of the granitic systems in these areas.
- (4) What is the role of crystallization, partial melting, and the nature of the source protolith in shaping the rare-metal granitic systems in the Jabal Sayid and Dayheen areas?

2. Geological Settings

2.1. Dayheen Ring Complex

The Dayheen ring complex is situated approximately 30 km south of the Jabal Sayid rare-metal granites (Figure 1). The rocks found in the Dayheen complex exhibit a distinct variety of granite rocks. In the central part of the complex, there are monzogranites, which represent a remnant of the original block and have undergone significant weathering processes, resulting in low topography. These rocks are then followed by hornblende-biotite granites as one moves outward. At the outermost part of the Dayheen complex, there are aegirine–riebeckite granites (Figure 2a). These granites intrude into older rocks, specifically the granodiorite–diorite association. The granites within the Dayheen complex demonstrate notable variations in composition, color, and texture. This suggests that different processes and conditions have influenced the formation and evolution of these rocks. The grain size of the monzogranite ranges from medium- to coarse-grained. In terms of color, it exhibits a transition from pink to pinkish gray. The hornblende–biotite granite as well as the aegirine–riebeckite granite constitutes the primary rock units within the circular complex. In some areas, these main rock units are intruded by fine-grained granites.

During field observations, distinct and well-defined boundaries were observed between the aegirine–riebeckite granite and the other granite types within the complex. These contacts between different granitic units exhibit clear and sharp transitions (Figure 3a). Within the aegirine–riebeckite granites, dykes of pegmatite and quartz veins are commonly observed. These pegmatite dykes display irregular topography, varying in both width and length (Figure 3b). Their dimensions can range from a few centimeters to one meter in width and length, and in some cases, they can extend beyond 30 m. The concentration of pegmatite dykes is particularly notable in the southern part of the Dayheen area.



Figure 2. A geological map of (**a**) the Dayheen area (modified after [14]) and (**b**) the Jabal Sayed area (modified after [15]). Sample locations are also shown.



Figure 3. (a) Sharp intrusive contact between diorite and peralkaline granite in the Dayheen area. (b) A pegmatite dyke within the Dayheen peralkaline granite. (c,d) Photomicrographs showing the major minerals in the Dayheen hornblende–biotite granite. (e) A photomicrograph showing a blue subhedral crystal of riebeckite within the Dayheen aegirine–riebeckite granite. (f) A photomicrograph showing the slender prismatic shape of aegirine within the Dayheen aegirine–riebeckite granite. (g) A prismatic crystal of zircon within the Dayheen pegmatite. (h) Zoned allanite crystals within the Dayheen pegmatite. Mineral abbreviations according [16].

2.2. Jabal Sayid

The Jabal Sayid mineralization is recognized as a significant rare-metal deposit within the AS, primarily owing to its economic importance. The Jabal Sayid area falls within the Jeddah terrane and is situated near the Bir Umq suture zone (Figure 1). The Bir Umq suture zone represents a boundary or contact zone between two distinct terranes, namely the Hijaz and Jeddah terranes. The Jeddah terrane is geographically situated in the western part of the AS. It is bounded by several other tectonic units: the Hijaz terrane to the north, the Afif terrane to the east, the Asir terrane to the south, and the Red Sea coastal plain to the west. The Jabal Sayid peralkaline granite is a component of the larger Jabal Sayid complex, which is primarily covered by volcano-sedimentary rocks belonging to the Mahd Group (Figure 2b). The Mahd Group is a geological formation composed of volcano-sedimentary rocks. These rocks typically include volcanic types such as basalt, andesite, dacite, rhyolite, and pyroclastic rocks. Additionally, sedimentary rocks such as sandstone, siltstone, and conglomerate are included. Insignificant limestone is also present within the Mahd Group.

The Jabal Sayid peralkaline granites have been dated using different isotopic dating methods, yielding slightly different ages. According to [17], the Rb/Sr age of the Jabal Sayid peralkaline granites is reported as 584 ± 26 Ma. On the other hand, ref. [7] conducted zircon U-Pb isotopic dating on peralkaline granites and reported an age of 593 Ma. The similarity of the Ediacaran age of the peralkaline granites in the Jabal Sayid pluton to other alkaline granites found in the ANS suggests a regional geodynamic event or tectonic process that influenced the formation of these granites. This similarity in age implies a broader geologic event that affected a larger region rather than being isolated to a specific locality. According to [8], the mineralization in the peralkaline granite of Jabel Sayid occurred in two distinct stages, namely a magmatic stage and a hydrothermal stage. During the magmatic stage, several minerals crystallized within the peralkaline granite. These minerals include zircon 1, quartz, hematite, and fresh aegirine. The crystallization of these minerals during the magmatic stage suggests that they formed directly from the cooling and solidification of the magma that gave rise to the peralkaline granite. In the hydrothermal stage, further mineralization occurred due to hydrothermal fluids interacting with the existing rock.

According to [18], the Jabal Sayid pegmatite is described as a sheet-like body with a width ranging from approximately 5 to 13 m. It extends for a significant strike length of about 2 km. The northern margin of the Jabal Sayid complex, where the pegmatite is situated, likely represents an area of interest for exploration and mining activities targeting the rare-metal mineralization associated with the pegmatite. The internal structure of the pegmatite is layered, and its composition exhibits variation [15]. The layers within the pegmatite are reported to be 0.3 to 5.0 m thick. These layers include coarse pegmatite, which contains crystals that can reach up to 3 cm in length. Additionally, micropegmatite and aplite are present within the layers. According to [15], there is a sharp contact between the peralkaline granite and the pegmatite (Figure 4a). Below this contact, dykes and veins are observed intruding joints and fractures that are parallel to the contact. This observation suggests that the emplacement of the pegmatite occurred at a later stage. The rocks within the pegmatite exhibit different colors, which can vary based on their iron oxide content. The color variations range from pink to brown varieties. Additionally, there are a few occurrences of black-colored rocks within the pegmatite.



Figure 4. (a) A photo of the pegmatite sheets showing the contact with the Jabal Sayid peralkaline granite. (b) A photo of the oxidized granite within the Jabal Sayid peralkaline granite. (c,d) Photomicrographs showing the deep-blue crystal of riebeckite and the euhedral crystal of aegirine within the Jabal Sayid peralkaline granite. (e,f) Photomicrographs showing major mineral constituents of the Jabal Sayid pegmatite. Mineral abbreviations according to [16].

Uranyl mineralization has been discovered within the pegmatite of Jabel Sayid through radiological surveys conducted by [19]. Following the discovery, several test wells were drilled by [20] to further identify and characterize uranyl mineralization in the area. This mineralization is related to the high content of Nb and REEs, as reported by [21]. Fluorite is a common mineral throughout the pegmatite, but it becomes particularly abundant in the alteration zones. Kasolite, which is a secondary uranium mineral, occurs mainly as cavity fillings and encrustations on quartz veins and along their contacts with the pegmatite [22].

To the south of the pegmatite sheets in the Jabal Sayid area, there is an oxidized peralkaline granite (Figure 4b). This granite has undergone varying degrees of hematization.

3. Analytical Techniques

The collection of 40 samples from various locations within the Dayheen and Jabal Sayid areas provides a representative dataset for studying the spatial variability of the granitic rocks in the region. These samples were prepared for petrographic examination in the "Laboratory for Rock and Thin Section Preparation" at King Abdulaziz University. To prepare the samples for petrographic examination, a flat face of rock was glued to a microscope slide and polished to achieve the desired thickness to be examined under a microscope. This thin section allows for a detailed examination of the rock's mineral composition, texture, and other petrographic features under a petrographic microscope. The selected samples were prepared for major, trace, and rare earth element analyses at the ACME Analytical Laboratories in Vancouver, Canada. The major oxides were measured by X-ray Fluorescence (XRF), with an accuracy of ± 0.01 wt.%. In addition, the number of volatiles in the form of Loss On Ignition (LOI) was measured with an accuracy of 0.01%. Trace and REEs were measured by the inductively coupled plasma mass spectrometer (ICP-MS) method, with an accuracy of 0.01 ppm to 1 ppm.

4. Petrography

4.1. Dayheen Ring Complex

4.1.1. Peralkaline Granites

Petrographically, the peralkaline granites in the Dayheen complex can be classified into two main types: hornblende–biotite granite and aegirine–riebeckite granite. The hornblende–biotite granite is primarily composed of quartz (28–35%), alkali feldspar (32–38%), plagioclase (20–30%), and 5–10% hornblende and biotite (Figure 3c,d). It exhibits a dark-gray to reddish-brown color and has a porphyritic texture. Poikilitic inclusions are common within granite and consist of plagioclase laths and hornblende. In some areas, quartz forms a myrmekitic texture with K-feldspar. Perthite and minor microcline represent the main K-feldspar minerals. Locally, perthite may be partially replaced by sericite. Plagioclase occurs as tabular crystals and exhibits simple albite twinning. It occasionally contains irregular fluorite crystals. Locally, plagioclase may undergo alteration to sericite and epidote. Subhedral prismatic crystals of dark blueish-green hornblende are present (Figure 3d). It shows pleochroism and contains inclusions of magnetite and titanite. The biotite crystals have a pale reddish-brown color and weak pleochroism. The granite contains several accessory minerals, including apatite, zircon, allanite, magnetite, and titanite.

The aegirine–riebeckite granite within the Dayheen complex is primarily composed of quartz (35–40%), K-feldspars (20–30%), albite (25–30%), and 7 to 10% aegirine and amphibole. It exhibits a porphyritic texture, where the phenocrysts consist of microcline, quartz, riebeckite, aegirine, and biotite. In the groundmass, the major minerals present are quartz and plagioclase. Quartz occurs as large, anhedral rounded grains within the rock. These quartz grains contain numerous inclusions of fine laths of albite, aegirine, and riebeckite. Albite is present as subhedral crystals in the groundmass of the rock. The K-feldspar crystals are primarily microclines and occur as microphenocrysts. Occasionally, the microcline crystals may have a rim of lath-shaped albite. In some instances, subhedral crystals of riebeckite can also be observed. They are characterized by their deep-blue color and exhibit varying degrees of pleochroism (Figure 3e). Aegirine is present as subhedral to euhedral prismatic crystals (Figure 3f). The color of the aegirine ranges from deep-green to pale olive-green. The accessory minerals mainly include apatite, zircon, fluorite, allanite, pyrochlore, samarskite, and hematite.

4.1.2. Monzogranite

The monzogranite in the Dayheen complex exhibits a grayish-white color, and in some instances, it displays a porphyritic texture. Monzogranite is primarily composed

of several minerals, including plagioclase, quartz, K-feldspar, and biotite. In addition to the main minerals, zircon, titanite, magnetite, apatite, allanite, and fluorite are present as accessory minerals. In certain areas of the monzogranite, chlorite alteration can be identified. Plagioclase is the dominant mineral, accounting for approximately 30–35% of the rock's volume. Its crystals are euhedral to subhedral and typically display tabular morphology. They often exhibit zoning, which is characterized by distinct compositional variations within individual crystals. The plagioclase crystals may also show signs of corrosion or resorption, indicating partial dissolution and reprecipitation during the rock's formation. In certain areas, plagioclase is altered into secondary minerals such as sericite and epidote. Quartz crystals (25–30%) are typically anhedral to subhedral. They occupy the spaces between the feldspar crystals or form intergrowths with K-feldspar known as graphic and myrmekitic textures. K-feldspar, constituting approximately 20–25% of the rock's volume, occurs as large anhedral crystals of microcline. It commonly displays Carlsbad twinning. Biotite forms subhedral flakes and elongated aggregates within the rock. It exhibits strong pleochroism from straw yellow to deep brown.

4.1.3. Pegmatite

The pegmatite within the Dayheen complex consists of large grains of quartz and K-feldspar minerals and minor mafic minerals. Pegmatitic rocks show a high content of radiation because they contain minerals rich in uranium and thorium, such as monazite, zircon (Figure 3g), allanite (Figure 3h), fluorite, pyrochlore, and thorite. Orthoclase and microcline are the two types of K-feldspars present. Microcline is characterized by a cross-hatched pattern and is occasionally intergrown with albite, forming patchy perthite. Riebeckite, which is the dominant mafic mineral, is blue in color. Aegirine occurs as needle-like crystals, and some are partially altered to hematite.

4.2. Jabal Sayed

4.2.1. Peralkaline Granite

The peralkaline granite in the Jabel Sayid area exhibits a porphyritic texture, characterized by the presence of large crystals embedded in a finer-grained groundmass. The major mineral constituents are quartz, which comprises approximately 35–40% of the rock, and K-feldspars, which make up about 30–40%. Albite, plagioclase is present in smaller amounts, around 8–10%. The mafic minerals, aegirine and riebeckite, account for 5 to 10% of the rock's composition (Figure 4c,d). The rare-metal minerals identified in the peralkaline granite include zircon, bastnaesite, monazite, and xenotime. These minerals are valuable due to their content of REEs and other economically significant metals. In addition to the primary minerals, secondary minerals such as hematite and fluorite are also present (Figure 5a). Quartz presents as anhedral crystals that fill the spaces between other mineral grains and is intergrown with K-feldspars, forming a graphic texture. The alkali feldspars, orthoclase and microcline, form subhedral to anhedral tabular to equant crystals. Some albite crystals are present in the groundmass, but they are rare and occur as fine-grained laths surrounding perthite and microcline grains. Aegirine occurs as subhedral to euhedral prismatic or needle-like crystals (Figure 4c). It exhibits pleochroism ranging from grass- or gray-green to brownish green. Riebeckite occurs as subhedral grains, less than 3 mm in size (Figure 4d). It is found interstitially between perthite and quartz grains.







4.2.2. Pegmatite

The pegmatite in the Jabel Sayid area is characterized by its coarse-grained nature and pink to pinkish-white coloration. The major mineral constituents of the pegmatite are K-feldspar and quartz, with minor amounts of plagioclase (Figure 4e,f). Additionally, minor biotite is present in the pegmatite. Accessory minerals include zircon, bastnasite, pyrochlore, xenotime, synchysite, and thorite (Figure 5b,c). These minerals are of interest due to their potential content of rare earth elements and other valuable metals. Quartz is the dominant mineral in the pegmatite and shows undulose extinction. The alkali feldspars are orthoclase and microcline. Orthoclase exhibits Carlsbad twinning, while microcline is characterized by cross-hatched patterns. Microcline commonly appears intergrown with albite, forming patchy perthite textures. Plagioclase laths display perfect lamellae twinning. Biotite occurs as flaky or tabular brown crystals and exhibits pleochroism from pale brown to dark brown. Chlorite is present as a secondary mineral in pegmatite.

From above, the accessory minerals found in the Jabal Sayid and Dayheen peralkaline granites and related pegmatites can be grouped into four main compositional categories: (a) the REEs-Ti-Zr association, which includes minerals such as synchysite, bastnaesite, titanite, and zircon in Jabal Sayid and zircon and titanite in Dayheen; (b) the REEs-Ca-P association, which includes minerals like xenotime and monazite in Jabal Sayid and apatite, allanite, and monazite in Dayheen; (c) the REEs-Y-Nb association, which is represented by minerals such as pyrochlore in Jabal Sayid and pyrochlore and samarskite in Dayheen; and (d) the Th-U-Pb association, which includes minerals like thorite and kasolite in Jabal Sayid and thorite in the Dayheen area. These mineral associations are enriched with incompatible elements, such as Light Rare Earth elements (LREEs), Zr, Y, Nb, Th, and U (Table 1).

Table 1. The names and generalized chemical formulae of REEs, Zr Y, Nb, Th, and U-bearing minerals known in the Dayheen and Jabal Sayid peralkaline intrusion and related pegmatites.

Accessory Mineral		Dayheen	J	abal Sayid
Group	Mineral Name	Formula	Mineral Name	Formula
REEs-Ti-Zr association	Zircon Titanite	ZrSiO ₄ CaTiSiO ₅	Synchysite Bastnaesite Titanite Zircon	(Ca, Ce(CO ₃) ₂ F (Ca, La)(CO ₃)F CaTiSiO ₅ ZrSiO ₄
REEs-Ca-P association	Apatite Allanite Monazite	Ca ₅ (PO4) ₃ (OH,F,Cl) (Ce,Ca) ₂ (Al, Fe ³⁺) ₃ (SiO ₃) ₃ (OH) (La,Ce,Nd,Th)PO ₄	Xenotime Monazite	(Y, Yb)(PO ₄) (La,Ce,Nd,Th)PO ₄
REEs-Y-Nb association	Pyrochlore Samarskite	(Na,Ca) ₂ Nb ₂ O ₆ (OH,F) (Y-Yb) Fe ³⁺ Nb ₂ O ₈	Pyrochlore	(Na,Ca) ₂ Nb ₂ O ₆ (OH,F)
Th-U-Pb minerals	thorite	ThSiO ₄	Thorite Kasolite	ThSiO₄ Pb(UO₂)(SiO₄)∙H₂O

5. Geochemistry

5.1. Major and Trace Element Characteristics

Granitoids are classified into different types based on various criteria such as mineral assemblages, field and petrographical features, and chemical and isotopic characteristics [23]. Major, trace, and REE analyses of the granites and related pegmatites from the Jabal Sayid and Dayheen areas are listed in Tables 2 and 3. In harmony with the field and petrographic studies, most of the peralkaline granites in Jabal Sayid and Dayheen are classified as peralkaline granites based on the R1-R2 geochemical diagram of [24]. The samples that are petrographically assigned to the Dayheen monzogranite plot as expected in the monzogranite field, whereas the granodiorite–diorite samples plot in the granodiorite and diorite fields (Figure 6).

Rock		Peralkaline Granites Pegmatites Monzogranit													itac	Crana	طنمينامم	Dia							
Туре	DL *		A	egirine–	Riebeck	ite Gran	ite			Horn	blende–I	Biotite G	Granite			regn	antes		IVIO	lizografi	nies	Grano	ulorites	Dior	ittes
Sample		GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	PG1	PG2	PG3	PG4	MZ1	MZ2	MZ3	GD1	GD2	Dio1	Dio2
											Majc	or elemei	nts (wt%	.)											
SiO ₂	0.1	73.2	71.5	71.8	73.0	71.3	72.5	75.9	70.5	72.5	74.1	74.2	71.8	72.1	69.7	66.3	72.6	71.9	73.6	73.0	72.7	69.9	62.5	56.9	58.8
TiO ₂	0.01	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.8	0.9	0.2	0.5	0.2	0.2	0.2	0.4	0.5	0.6	1.0
Al_2O_3	0.01	11.6	14.2	12.9	12.5	12.8	11.6	9.6	11.0	12.3	11.2	11.3	12.7	10.6	7.8	9.6	10.5	10.0	12.6	13.0	14.0	14.7	15.7	16.3	16.8
Fe ₂ O ₃ **	0.01	4.2	3.1	3.1	3.8	3.8	4.5	5.3	5.0	3.4	4.1	3.7	4.5	5.0	9.4	7.7	6.0	5.4	2.0	1.6	1.5	3.3	5.5	5.9	6.4
MnO	0.01	0.02	0.02	0.04	0.04	0.04	0.05	0.04	0.07	0.04	0.05	0.04	0.02	0.06	0.09	0.06	0.09	0.06	0.05	0.04	0.04	0.07	0.10	0.10	0.12
MgO	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.01	0.04	0.01	0.05	0.03	0.01	0.04	0.24	0.22	0.19	0.15	0.29	0.49	0.55	1.02	2.60	2.76	2.03
CaO	0.01	0.3	0.3	0.2	0.3	0.3	0.1	0.1	1.7	0.7	0.1	0.5	0.2	1.0	0.7	1.1	0.7	0.8	2.1	1.8	1.5	2.8	5.6	8.3	6.1
Na ₂ O	0.01	5.5	6.7	5.8	6.2	6.5	6.0	4.9	5.0	5.5	5.5	5.8	4.6	5.4	3.9	9.0	4.3	3.8	4.3	4.4	4.7	4.5	3.8	4.4	4.5
K ₂ O	0.01	4.2	3.5	4.7	4.3	4.0	3.9	3.5	4.1	4.4	3.9	3.6	4.9	4.4	0.8	0.6	2.2	2.7	3.2	3.6	3.4	2.6	1.9	0.7	0.9
P_2O_5	0.01	0.01	0.01	0.01	0.01	0.06	0.05	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.05	0.05	3.00	0.05	0.02	0.03	0.10	0.12	0.15	0.31	0.01
Cr ₂ O ₃	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
LOI	-5.11	0.2	0.2	0.3	0.3	0.3	0.2	0.4	1.7	0.7	0.1	0.4	0.2	0.9	1.3	0.9	0.7	1.0	1.8	1.1	1.3	1.0	1.7	4.2	2.8
SUM		99.4	99.7	99.0	100.6	99.2	99.0	100.0	99.2	99.7	99.2	99.7	99.1	99.6	94.8	96.4	100.5	96.4	100.2	99.3	100.0	100.4	100.1	100.5	99.5
												REEs (p	pm)												
La	0.1	82.4	27.7	161	106	62.3	120	360	108	94.2	89.2	38.9	204	109	907.6	759.0	361.0	337	22.2	25.5	18.9	36.8	11.6	10.8	15.7
Ce	0.1	187	59.0	358	227	146	273	870	191	195	196	93.4	385	247	2316	1731	848.7	779	46.2	34.5	50.2	70.2	26.4	20.8	34.6
Pr	0.02	24.1	7.9	48.2	29.8	20.1	37.6	99.2	21.7	25.7	26.0	12.1	48.5	30.5	300.5	219.0	110.5	101	6.0	5.7	5.0	7.9	3.6	2.5	4.7
Nd	0.3	101	32.6	206	126	87.2	154	334	89.3	109	111	49.3	194	119	1215	719.0	430.1	416	23.9	24.5	27.9	30.4	16.3	11.1	21.2
Sm	0.05	24.0	6.8	45.9	25.9	20.7	38.4	91.4	20.6	20.8	22.2	12.1	38.9	27.2	345.7	172.0	120.1	101	6.2	5.2	5.1	5.0	3.8	2.7	5.6
Eu	0.02	1.1	0.3	1.9	1.1	1.0	1.9	4.5	1.2	0.9	0.9	0.6	1.7	1.3	17.2	8.8	6.8	4.9	0.6	0.6	0.6	0.9	0.8	0.7	1.3
Gd	0.05	23.5	5.9	40.2	21.0	19.3	39.4	96.1	27.3	16.2	19.1	11.7	31.9	28.3	372.5	166.9	139.1	131	6.8	4.3	4.0	4.3	3.7	3.6	5.4
Tb	0.01	3.1	0.7	5.3	2.3	2.7	6.3	17.9	5.6	2.0	2.7	1.9	4.0	5.3	64.7	37.9	29.0	26.0	1.3	1.0	0.9	0.7	0.6	0.7	1.2
Dy	0.05	15.5	3.3	25.9	9.7	15.0	36.9	107	43.4	9.8	14.4	10.4	17.9	35.0	378.5	302.9	191.0	163	9.3	3.6	4.5	4.2	3.7	4.9	7.1
Но	0.02	2.9	0.5	4.2	1.3	2.9	7.4	22.5	11.8	1.9	2.7	2.1	2.7	8.2	79.6	81.9	38.6	36.1	2.1	0.9	1.9	0.8	0.7	1.1	1.6
Er	0.03	6.7	1.1	9.3	2.4	7.8	19.5	57.6	39.5	4.6	7.2	5.3	5.3	24.6	209.6	278.9	112.0	106	6.5	2.7	3.9	2.5	1.9	2.8	4.3
Tm	0.01	0.9	0.2	1.4	0.3	1.2	2.8	7.4	7.0	0.7	1.2	0.8	0.7	3.9	31.2	46.9	16.3	15.0	1.2	0.3	0.2	0.4	0.3	0.4	0.6
Yb	0.05	5.4	1.1	7.9	1.7	8.3	15.2	36.5	49.0	4.6	7.5	4.3	3.5	23.6	196.2	313.9	118.3	103	7.7	2.2	1.9	2.3	1.9	2.0	3.5
Lu	0.01	0.7	0.2	1.2	0.3	1.3	2.2	4.7	8.1	0.7	1.3	0.7	0.4	3.9	29.5	47.0	19.8	17.0	1.2	0.4	0.2	0.4	0.3	0.3	0.5

 Table 2. Major (wt%), trace (ppm), and rare earth elements (ppm) of selected granitoids and related pegmatites from the Dayheen area, Jeddah Terrane, Saudi Arabia.

Table	2.	Cont.

Rock							Peralk	aline G	ranites							Dear	- 121		М			6	1,	D.	•.
Туре	DL *		A	egirine–	Riebeck	ite Gran	ite			Horn	blende–I	Biotite C	Granite		-	regm	attites		IVIC	nzograf	intes	Grano	alorites	D101	ittes
Sample		GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	PG1	PG2	PG3	PG4	MZ1	MZ2	MZ3	GD1	GD2	Dio1	Dio2
											Trace	e elemer	nts (ppm)											
Y	0.1	73.6	18.5	103	33.6	76.5	192	640	314	55.8	68.2	59.4	79.2	223	185.7	2399	1461	974	66.3	45.3	29.2	23.2	19.5	27.5	42.5
Hf	0.1	19.5	5.5	30.4	3.7	23.5	44.5	41.7	258	11.7	31.6	8.9	3.6	80.6	617.7	531.0	360.0	131	6.1	5.5	4.3	4.0	3.1	2.1	4.8
Nb	0.1	64.0	9.4	58.0	32.3	121	115	579	141	42.6	40.7	60.5	360	136	2129	659.0	1639	1351	16.9	14.0	21.0	6.2	2.4	4.7	6.6
Ta	0.1	5.3	1.1	4.0	2.5	8.5	8.9	28.8	13.1	3.1	3.0	4.1	40.7	11.6	163.8	81.6	96.6	94.7	2.0	1.5	2.1	0.9	0.5	0.4	0.6
Th	0.2	7.4	2.1	18.0	1.2	4.5	13.1	91.7	21.3	3.1	10.5	7.2	267	22.2	263.8	2201	601.2	222	7.4	6.0	6.2	9.5	2.5	5.3	5.8
Zn	1	86.0	32.0	17.0	20.0	38.0	65.0	630	26.0	13.0	20.0	14.0	62.0	69.0	1653	255	381.8	503	42.0	61.0	52.0	51.0	43.0	53.0	63.0
Со	0.2	4.4	4.7	39.9	4.8	4.5	5.7	7.7	3.5	4.8	5.2	2.4	2.3	22.3	13.0	6.0	5.0	9.1	5.2	5.0	4.0	7.4	16.6	16.9	15.9
Ni	0.1	1.7	2.6	3.2	2.5	1.2	3.0	3.7	3.1	2.8	2.1	1.4	2.3	6.2	6.8	4.0	8.0	5.1	4.5	8.0	5.0	6.6	10.6	28.7	13.9
Ва	0.01	4.0	12.0	14.0	9.0	10.0	16.0	12.0	11.0	6.0	5.0	7.0	12.0	16.0	155.0	61.0	229.9	137	256	193	189	565	727	171	178
V	8	8.0	10.0	9.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	53.0	13.0	19.0	18.0	9.0	8.0	3.0	36.0	145	158	156
Cu	0.1	2.9	1.9	3.3	2.5	2.6	2.7	15.2	6.1	3.2	1.3	3.1	4.3	6.8	9.0	8.5	17.9	17.0	3.4	3.3	2.8	21.8	89.3	60.8	73.8
Sr	0.5	13.5	8.6	5.7	5.9	8.2	12.0	20.3	21.5	21.2	3.6	6.8	16.7	13.2	53.7	59.0	56.0	12.0	92.6	120	290	331	531	440	615
Zr	0.1	642	175	1115	101	918	1622	1563	9295	409	1157	311	102	2936	24,596	20,950	15,020	2392	149	180	156	152	121	73	149
Rb	0.1	441	349	444	438	429	385	390	530	372	314.1	329.8	599.2	540.4	96.6	11.0	373.0	373	77.9	125	144	43.7	32.0	13.6	16.0
As	0.5	0.6	1.8	0.6	0.9	1.6	0.2	3.8	1.4	0.8	0.6	5.0	5.4	4.9	0.4	0.2	0.2	0.5	0.9	0.6	0.5	1.3	1.2	5.6	2.6
Be	1	6.0	7.0	13.0	13.0	11.0	6.0	11.0	12.0	3.0	5.0	2.0	9.0	11.0	108.0	92.0	88.2	95.2	5.0	6.0	3.0	4.0	1.0	<1	5.0
Sb	0.1	0.2	0.1	0.1	0.1	0.3	< 0.1	0.6	0.1	0.1	0.1	0.3	0.9	0.2	0.5	0.4	0.1	0.6	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sn	1	20.0	14.0	15.0	16.0	18.0	25.0	39.0	35.0	8.0	13.0	14.0	25.0	34.0	202.0	269.0	130.2	124	8.0	4.0	2.0	4.0	1.0	<1	<1
U	0.1	8.0	1.0	6.6	3.4	7.4	9.4	68.2	28.5	4.3	4.8	4.8	12.1	15.8	287.8	251.0	139.7	101	2.6	2.0	1.9	1.6	0.9	1.4	1.3
W	0.5	48.1	38.2	408	43.4	47.6	54.5	88.5	38.0	48.1	50.5	21.9	21.0	228.7	103.7	97.1	92.3	67.0	35.0	40.1	38.0	17.6	20.8	11.4	23.8
Cd	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	< 0.1	0.2	1.6	1.0	1.0	1.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cs	0.1	1.3	0.9	1.2	1.9	1.9	1.5	1.9	1.4	1.4	1.0	2.1	2.0	1.9	1.0	1.1	10.9	11.1	1.6	3.5	5.7	1.9	1.1	0.4	0.2
Ga	0.5	51.7	64.6	56.4	55.8	59.5	51.4	39.3	48.2	52.0	47.2	46.7	58.8	48.0	45.5	57.2	29.2	38.5	16.1	24.0	28.0	13.8	15.5	15.7	15.0
Мо	0.1	0.5	1.6	0.5	1.0	0.6	1.5	1.1	0.7	0.5	1.2	0.4	1.4	1.0	0.8	0.8	1.1	98.2	0.7	0.5	0.7	0.7	0.9	0.6	0.8
Pb	0.1	30.0	11.1	34.8	10.4	29.6	74.7	258	147	11.6	15.6	25.1	37.0	19.5	414	101	261.5	243	5.2	7.0	4.0	6.3	2.7	1.8	2.5
Au	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.4	0.4	9.7	0.9	0.4
Bi	0.1	3.4	1.3	2.4	1.4	3.2	2.7	0.5	0.6	2.0	1.3	0.8	2.0	1.1	1.3	1.0	1.2	1.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Se	0.2	0.4	0.4	0.7	1.1	0.3	1.4	2.9	0.3	0.2	0.2	0.4	0.6	0.4	11.9	7.7	8.2	10.5	0.4	0.2	0.3	0.4	0.4	0.4	0.4

Table	2	Cont
Induic	<u></u>	Com.

Rock							Peralk	aline G	ranites							D	- 121		M			6	1	р:	
Туре	DL *		Aegirine–Riebeckite Granite Hornblende–Biotite Granite									Pegm	atites		NIC	nzogran	ites	Grano	aiorites	D101	rites				
Sample		GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	PG1	PG2	PG3	PG4	MZ1	MZ2	MZ3	GD1	GD2	Dio1	Dio2
Eu/Eu *		0.14	0.16	0.14	0.14	0.15	0.15	0.15	0.16	0.15	0.14	0.14	0.14	0.14	0.15	0.16	0.16	0.13	0.29	0.36	0.41	0.58	0.66	0.64	0.72
(La/Yb) _N		14.34	23.06	19.07	57.27	7.06	7.40	9.49	2.07	19.12	11.16	8.45	54.96	4.34	4.36	2.28	2.87	3.09	2.70	11.02	9.32	15.19	5.64	5.04	4.26
Y/Nb		1.15	1.97	1.78	1.04	0.63	1.67	1.11	2.23	1.31	1.68	0.98	0.22	1.64	0.09	3.64	0.89	0.72	3.92	3.24	1.39	3.74	8.13	5.85	6.44
Nb/Ta		12.08	8.55	14.50	12.92	14.21	12.93	20.11	10.78	13.74	13.57	14.76	8.85	11.76	13.00	8.08	16.97	14.27	8.45	9.33	10.00	6.89	4.80	11.75	11.00
Rb/Sr		32.6	40.6	77.9	74.3	52.3	32.1	19.2	24.6	17.5	87.3	48.5	35.9	40.9	1.8	0.186	6.659	31.05	0.8	1.042	0.497	0.1	0.1	0.031	0.026

* ACME laboratory detection limits. ** Total iron is calculated as Fe₂O₃.

Table 3. Major (wt%), trace (ppm), and rare earth elements (ppm) of selected granitoids and related pegmatites from the Jabal Sayid area, Jeddah Terrane, Saudi Arabia.

Rock Type	DL *					Peralkalin	e Granites							Pegm	atites		
Sample		SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SDPG1	SDPG2	SDPG3	SDPG4	SDPG5	SDPG6
								Major elem	ents (wt%)								
SiO ₂	0.1	73.9	74.8	74.3	74.0	74.9	74.2	75.3	74.9	75.0	74.8	74.6	73.7	71.8	73.8	70.0	71.6
TiO ₂	0.01	11.03	11.01	11.22	10.89	10.92	11.09	10.44	10.40	10.88	11.20	9.28	7.25	7.53	7.37	6.65	6.14
Al ₂ O ₃	0.01	0.10	0.16	0.07	0.10	0.07	0.20	0.21	0.17	0.05	0.18	0.40	1.75	1.33	0.62	0.88	0.45
Fe ₂ O ₃ **	0.01	3.97	3.55	3.71	3.98	3.97	4.01	4.74	3.33	3.10	3.21	4.15	4.09	2.93	5.01	4.84	7.22
MnO	0.01	0.03	0.06	0.05	0.05	0.04	0.15	0.12	0.15	0.07	0.05	0.50	< 0.01	< 0.01	0.11	< 0.01	0.34
MgO	0.01	0.21	0.03	0.09	0.11	0.02	0.13	0.12	0.03	0.07	0.04	0.44	0.44	0.28	0.14	0.08	0.17
CaO	0.01	0.91	0.71	0.50	0.66	0.19	0.32	0.25	0.28	1.12	0.19	1.06	1.20	2.82	0.81	4.21	1.91
Na ₂ O	0.01	4.66	4.86	5.56	5.51	4.96	5.30	4.13	5.11	4.58	5.51	4.19	0.61	0.54	0.32	0.26	0.37
K ₂ O	0.01	3.99	3.97	3.39	3.88	3.94	4.02	3.98	4.34	3.82	3.98	3.34	5.26	5.09	5.07	4.41	4.53
P ₂ O ₅	0.01	< 0.01	0.01	< 0.01	0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.31	< 0.01	0.12	0.13
Cr ₂ O ₃	0.01	0.018	0.022	0.017	0.010	0.019	0.112	0.123	0.107	0.005	0.003	0.320	0.420	0.239	0.142	0.027	0.161
LOI	-5.11	0.78	0.57	0.78	0.76	0.41	0.38	0.50	0.44	0.99	0.21	1.28	1.83	3.58	1.86	4.02	2.60
SUM		99.60	99.75	99.69	99.95	99.47	99.91	99.91	99.26	99.69	99.38	99.56	96.55	96.45	95.25	95.50	95.65

Table 3.	Cont.
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Rock Type	DL *					Peralkalin	e Granites				Pegm	atites					
Sample	22	SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SDPG1	SDPG2	SDPG3	SDPG4	SDPG5	SDPG6
								REEs	(ppm)								
La	0.1	65.1	110.0	79.2	54.6	72.80	93.6	135.4	63.9	61.3	85.7	334.6	745.4	2008.6	415.4	1775.6	1241.2
Ce	0.1	144.9	271.1	185.0	131.0	181.70	224.9	323.0	156.8	150.3	181.6	828.3	1731.9	2881.0	971.2	2742.2	2580.5
Pr	0.02	19.02	35.00	22.00	15.82	19.84	29.03	40.76	21.13	18.86	22.70	103.03	230.28	269.47	121.73	288.12	339.20
Nd	0.3	83.0	134.1	82.0	63.9	82.30	116.3	167.9	86.4	78.6	89.7	409.4	927.0	852.1	470.8	1024.1	1530.1
Sm	0.05	22.00	45.00	22.10	16.03	22.32	31.98	41.18	25.90	18.99	19.34	131.72	310.82	282.40	180.75	409.61	700.37
Eu	0.02	1.00	2.08	1.06	0.80	0.29	1.45	2.15	1.80	1.14	0.90	7.33	18.20	18.29	11.94	28.26	42.57
Gd	0.05	23.93	57.11	25.01	16.79	26.29	30.96	43.62	31.70	18.55	19.95	179.61	432.22	500.88	299.01	736.33	1138.77
Tb	0.01	3.83	11.04	4.80	2.69	4.67	4.40	8.01	6.27	3.42	3.47	39.64	99.02	130.52	79.94	176.13	241.11
Dy	0.05	22.97	76.00	29.01	14.49	35.43	23.57	46.38	37.09	19.13	19.70	244.81	661.31	945.39	612.56	1223.14	1496.99
Но	0.02	3.67	15.92	5.47	2.90	7.49	4.73	8.78	8.77	4.71	4.15	52.80	154.65	238.82	155.56	284.26	324.01
Er	0.03	12.99	44.81	12.99	7.19	22.74	11.95	21.86	26.49	13.21	11.04	135.24	424.68	695.71	473.31	767.08	774.31
Tm	0.01	1.80	7.74	1.67	0.98	2.63	1.89	3.31	4.59	2.24	1.79	18.16	55.61	97.60	77.07	109.79	90.12
Yb	0.05	11.10	31.04	7.99	5.22	18.88	11.47	19.83	27.42	12.15	10.43	87.79	303.28	549.87	470.88	609.28	399.70
Lu	0.01	1.95	3.79	0.99	0.84	2.08	1.76	3.39	4.92	2.44	1.79	10.45	46.08	78.33	66.31	77.77	46.67
								Trace elem	ents (ppm)								
Y	0.1	1229.7	443.9	149.0	76.1	210.20	123.5	223.9	229.2	121.3	107.1	1322.5	3626.7	5764.3	3445.5	7049.0	7905.0
Hf	0.1	29.9	48.0	23.0	23.0	15.50	28.5	57.7	68.6	28.8	32.1	45.2	414.3	271.7	369.7	278.0	111.6
Nb	0.1	87.3	167.1	55.0	119.0	113.70	123.6	219.0	121.0	104.5	63.7	912.7	1107.7	928.0	1480.5	618.6	1386.2
Та	0.1	6.0	12.6	3.4	23.9	8.60	8.1	14.7	10.8	8.0	5.0	67.2	92.0	107.3	131.8	61.4	94.0
Th	0.2	25.1	56.0	45.5	11.7	79.60	34.2	86.1	5.1	27.9	31.9	236.1	163.0	2224.7	1628.0	1886.8	2617.1
Zn	1	81	277	42	25	84.10	25	249	36	93	50	1583	181	171	424	509	3873
Со	0.2	9.7	7.0	4.9	6.1	5.30	6.0	7.2	7.8	6.4	50.2	5.1	6.6	4.7	5.4	5.3	4.0
Ni	0.1	12.8	6.0	5.9	4.7	3.60	2.3	6.6	2.9	4.6	3.9	3.7	6.5	6.5	6.2	5.0	4.5
Ba	0.01	21	25	14	19	9.10	14	16	6	15	9	76	26	80	41	28	47
V	8	35	<8	8	<8	<8	<8	<8	<8	<8	15	23	16	14	12	13	11
Cu	0.1	10.5	6.6	47.0	8.3	3.10	2.9	7.8	3.0	3.7	2.1	17.3	29.7	24.9	30.3	9.8	43.0
Sr	0.5	26.0	18.1	14.6	13.0	5.90	17.1	6.9	13.5	12.0	6.7	35.7	27.6	55.7	27.6	622.8	317.5

Rock Type	DL *					Peralkalin	e Granites						Pegm	atites			
Sample		SD1	SD2	SD3	SD4	SD5	SD6	SD7	SD8	SD9	SD10	SDPG1	SDPG2	SDPG3	SDPG4	SDPG5	SDPG6
Zr	0.1	11,310	2015	769	788	731.6	1120	2261	2712	1079	1064	2342	19,962	14,577	19,914	15,867	5846
Rb	0.1	243.0	323.2	221.1	225.0	248.30	345.7	320.0	309.3	242.0	214.6	227.6	650.4	748.7	598.4	622.3	696.8
As	0.5	6.1	1.0	2.1	1.0	4.40	21.1	1.1	5.8	4.5	6.2	< 0.5	< 0.5	1.8	0.5	10.2	12.2
Be	1	5	8	19	6	14.10	10	4	17	11	14	9	25	25	14	10	18
Sb	0.1	0.7	0.2	0.4	0.2	0.40	0.3	0.7	0.8	0.7	0.5	0.1	1.3	1.3	1.5	0.3	0.6
Sn	1	12	20	13	12	13.10	17	38	15	10	12	63	180	132	154	77	182
U	0.1	9.0	19.9	11.9	12.0	16.20	9.4	25.1	13.5	11.4	11.7	87.8	139.6	357.6	319.6	252.1	552.8
W	0.5	67.4	61.0	55.6	51.0	60.30	55.4	60.8	77.8	56.8	550.7	37.6	69.3	40.8	49.7	38.4	32.7
Cd	0.1	< 0.1	0.4	0.1	< 0.1	< 0.1	< 0.1	0.7	0.5	0.4	0.2	2.2	0.4	2.3	1.3	2.9	5.5
Cs	0.1	2.1	1.5	1.4	1.6	1.00	2.8	1.0	2.3	1.9	2.3	1.0	4.2	4.6	4.0	3.9	4.6
Ga	0.5	37.9	40.0	41.2	36.2	36.60	42.8	40.8	38.8	39.1	35.8	39.6	31.9	32.1	40.1	34.2	32.1
Мо	0.1	2.5	1.2	0.9	1.2	0.00	0.7	1.9	0.9	1.0	0.6	1.0	3.0	1.7	2.2	1.5	2.1
Pb	0.1	27.3	38.3	37.6	9.0	48.30	29.7	112.9	29.3	14.2	20.3	63.9	146.4	320.5	847.5	139.9	284.9
Au	0.3	1.3	2.1	< 0.5	< 0.5	< 0.5	< 0.5	2.1	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	31.2	< 0.5	< 0.5	< 0.5
Bi	0.1	0.5	< 0.1	0.5	0.2	0.50	0.6	0.5	0.8	0.6	0.3	0.1	0.1	<0.1	0.4	<0.1	0.3
Se	0.2	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	0.7	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Eu/Eu *		0.13	0.13	0.14	0.15	0.04	0.14	0.16	0.19	0.19	0.14	0.15	0.15	0.15	0.16	0.16	0.15
(La/Yb) _N		5.53	3.34	9.34	9.86	3.63	7.69	6.43	2.20	4.75	7.74	3.59	2.32	3.44	0.83	2.75	2.93
Y/Nb		14.09	2.66	2.71	0.64	1.85	1.00	1.02	1.89	1.16	1.68	1.45	3.27	6.21	2.33	11.40	5.70
Nb/Ta		14.55	13.26	16.18	4.98	13.22	15.26	14.90	11.20	13.06	12.74	13.58	12.04	8.65	11.23	10.07	14.74
Rb/Sr		9.3	17.9	15.1	17.3	42.08	20.2	46.4	22.9	20.2	32.0	6.4	23.6	13.4	21.7	1.0	2.2

Table	2	Cont
Table	J.	Com.

* ACME laboratory detection limits. ** Total iron is calculated as Fe₂O₃.



Figure 6. The classification of the studied granitic samples according to the R1-R2 diagram [24].

In the classification based on the ACNK versus ANK diagram [25], the peralkaline granites from Jabal Sayid and Dayheen are classified as peralkaline granites (Figure 7a). Conversely, monzogranite and granodiorite-diorite samples fall within a metaluminous field. The plotting of the studied granites on the alkalinity ratio (AR) against the SiO_2 diagram of [26] indicates that the peralkaline granite samples from Jabal Sayid and Dayheen are plotted within the alkaline and peralkaline fields (Figure 7b), while the Dayheen monzogranites fall within the alkaline field. This suggests that they have a slightly lower alkali content compared to the peralkaline granites, but they still exhibit alkaline characteristics. The alkaline/peralkaline character of the Jabal Sayid and Dayheen peralkaline granites is in agreement with the presence of aegirine and riebeckite as deduced from a petrographical study (Figures 3e,f and 4c,d). On the other hand, the Dayheen granodiorite–diorite samples are placed in the calc-alkaline field (Figure 7b). This indicates that these rocks have a different geochemical composition compared to the peralkaline granites and monzogranites. The change in alkalinity observed from calc-alkaline through alkaline to peralkaline in these rocks suggests a variation in the source of the magma and the tectonic setting in which they formed.

In the K_2O vs. SiO₂ diagram of [27], the peralkaline granite samples from Jabal Sayid and Dayheen, as well as the monzogranite samples from Dayheen, are plotted within the fields of the high-K calc-alkaline and shoshonite series (Figure 7c). However, it is also mentioned that granodiorite–diorite samples fall within the medium-K calc-alkaline. The change in magma composition from medium-K calc-alkaline to high-K calc-alkaline and shoshonite series indicates a progressive evolution of the magmas. This evolution can involve fractional crystallization, the assimilation of crustal rocks, or mixing between different magma sources. These processes can modify the chemical composition of the magma and result in observed variations in potassium content.



Figure 7. Magma-type diagrams of Jabal Sayid and Dayheen granites. (a) A/CNK vs. A/NK diagram [25], (b) AR vs. SiO₂ diagram [26], AR (Alkalinity Ratio) = $[Al_2O_3 + CaO + (Na_2O + K_2O)]/[Al_2O_3 + CaO - (Na_2O + K_2O)]$, (c) K₂O vs. SiO₂ diagram [27], and (d) FeO_t/(FeO_t + MgO) vs. SiO₂ diagram of [28]. Symbols as in Figure 6.

The FeO_t/(FeO_t + MgO) versus SiO₂ diagram of [28] provides insights into the composition and characteristics of the studied granitoids (Figure 7d). Samples of the peralkaline granites from Jabal Sayid and Dayheen fall within the ferroan field, whereas the monzogranite and granodiorite–diorite samples fall within the magnesian field. The ferroan nature of the peralkaline granites, similar to most of the rare-metal A-type granite in the ANS, suggests a higher iron content compared to magnesium. On the other hand, the positioning of the monzogranite and granodiorite–diorite samples within the magnesian field may be indicative of different source materials or differentiation processes that favor the incorporation of magnesium-rich minerals. The change from the magnesian field to the ferroan field can indicate a transition in the source rocks or the conditions under which these granitoids formed.

The trace element profiles of the peralkaline granites and their related pegmatites from Jabal Sayid and Dayheen exhibit similar patterns, as normalized to the ocean ridge granite (ORG, [29]). In general, these rocks are enriched in most trace elements (Figure 8a,b), except for Ba, which is depleted and exhibits values lower than one, specifically in the peralkaline granites. However, there are a few samples where the concentrations of Zr, Sm, Y, and Yb are lower than one. The enrichment of most trace elements suggests a significant contribution from crustal materials to the composition of these granites and related pegmatites. Figure 8c illustrates that the trace elements in monzogranites can be divided into two distinct groups based on their concentrations. The first group includes elements such as K, Rb, Ba, Th, Ta, Nb, Sr, and Ce, which are enriched relative to the values of ORG. The second group comprises elements like Zr, Sm, Y, and Yb, which have concentrations lower than one. The trace element patterns observed in the monzogranites align with those typically found in monzogranites associated with island or continental arc settings in the ANS context. In Figure 8d, a typical saw-tooth pattern of magma related to



subduction is observed in the granodiorite–diorite association, where elements such as K, Rb, Ba, and Th are enriched in these rocks compared to the values of ORG. On the other hand, elements like Ta, Nb, Sr, Ce, Zr, Sm, Y, and Yb show depletion.

Figure 8. The ocean ridge granite normalized spider diagram of trace elements [29] for (**a**) the Dayheen peralkaline granites and pegmatites; (**b**) the Jabal Sayid peralkaline granites and pegmatites; (**c**) the Dayheen monzogranites; and (**d**) the Dayheen granodiorite–diorite association. Symbols as in Figure 6.

5.2. REEs Characteristics

The Dayheen granodiorite-diorite association has the lowest total REE contents (103 ppm, on average, Table 2), followed by monzogranites with slightly higher total REE contents (126 ppm, on average). The Jabal Sayid and Dayheen pegmatites show the highest total REE contents (4056 and 7313 ppm, on average, respectively, Tables 2 and 3). The Jabal Sayid and Dayheen peralkaline granites have lower total REE contents (541 and 678 ppm, on average, respectively) compared to the related pegmatites. Chondritenormalized REE patterns (using the chondrite values of [30]) are presented in Figure 9. The REE profiles of the peralkaline granites and their related pegmatites from Jabal Sayid and Dayheen exhibit a close similarity in shape. Both profiles display a gentle sloping LREE subprofile and a relatively flat Heavy Rare Earth element (HREE) subprofile (Figure 9a,b). This suggests that the peralkaline granites and their related pegmatites share a common geochemical signature, characterized by a consistent distribution pattern of REEs. Another prominent feature in the REE profiles of both the peralkaline granite and pegmatites is the presence of a negative Eu anomaly. The presence of this anomaly and the strong overall REE enrichment in pegmatites further support the notion of distinct mineralogical and chemical processes that differentiate pegmatites from the parental peralkaline granites. In Dayheen peralkaline granites and related pegmatites, REE compositions are highly variable, with $(La/Yb)_N$ ratios ranging from 2.07 to 57.27 and negative Eu anomalies (Eu/Eu^{*}) from 0.13 to 0.16 (Table 2). Meanwhile, in the Jabal Sayid peralkaline granites and related pegmatites, REE compositions are less variable, with $(La/Yb)_N$ ratios ranging from 0.83 to 9.86 and comparable negative Eu anomalies (Eu/Eu^{*}) from 0.13 to 0.19. Chondrite-normalized REE patterns of the monzogranite and granodiorite–diorite association are also shown in Figure 9c,d. They are distinguished by LREE enrichment and small negative Eu anomalies (Eu/Eu^{*} = 0.29–0.41 for monzogranite, and 0.58–0.72 for the granodiorite–diorite association) with variable La/Yb ratios (2.7–11.02 for monzogranite, and 4.26–15.9 for the granodiorite–diorite association).



Figure 9. Chondrite-normalized REE patterns [30] for (**a**) the Dayheen peralkaline granites and pegmatites; (**b**) the Jabal Sayid peralkaline granites and pegmatites; (**c**) the Dayheen monzogranites; and (**d**) the Dayheen granodiorite–diorite association. Symbols as in Figure 6.

5.3. Rare Metal Contents

The comparison between Jabal Sayid and Dayheen in terms of their rare metal contents, as shown in Figure 10, reveals some distinct variations in the composition of their pegmatites and peralkaline granites. Jabal Sayid pegmatites show the highest average contents of LREEs (4494 ppm), HRREs (2819 ppm), Y (4852 ppm), Th (1459 ppm), U (285 ppm), and Zn (1124 ppm) compared to Dayheen pegmatites. Dayheen pegmatites show the highest average contents of Zr (15,937 ppm), Nb (1445 ppm), and Ta (109 ppm). Furthermore, the Dayheen peralkaline granites have a higher average content of LREEs (581 ppm) and Nb (135 ppm) and lower contents of HREEs (98 ppm), Zr (1565 ppm), and Y (149 ppm) compared to the Jabal Sayid peralkaline granites. Th, U, Ta, and Zn contents are comparable between the peralkaline granites of both locations. The enrichment of these elements in the peralkaline granites and related pegmatites can be attributed to the presence of various mineral associations, as shown in Table 1.



Figure 10. The histogram shows a comparison between Jabal Sayid and Dayheen in terms of their rare metal contents.

6. Discussion

6.1. Tectonic Setting

The R1-R2 tectonic setting discrimination diagram developed by [24] and the tectonic setting fields based on [31] can be used to classify different types of granitoids based on their geochemical signatures and relate them to specific tectonic environments (Figure 11a): (1) Subduction-related granitoids that are represented by the granodiorite–diorite association. These granitoids are typically related to an early stage in the orogenic cycle, characterized by subduction or pre-plate collision magmatism; (2) collision-related granitoids that are represented by monzogranites. The presence of monzogranites in the studied granitoids indicates a transitional stage in the orogenic cycle, where the tectonic collision has occurred, leading to the generation of collision-related magmas; (3) post-orogenic/Anorogenic granitoids that are represented by peralkaline granites. The presence of these rocks suggests a late stage in the orogenic cycle, characterized by post-orogenic or anorogenic magmatism. These observations support the idea that the granitoids in the Jabal Sayid and Dayheen areas may represent different stages within a single orogenic cycle, reflecting the evolving tectonic processes that occurred during their formation (blue dashed lines with arrows in Figure 11a).



Figure 11. (a) The R1-R2 tectonic setting discrimination diagram of [24], with tectonic setting fields based on [31]. The blue dashed line with arrows reflects different stages within a single orogenic cycle. (b) Y + Nb vs. Rb discrimination diagram [29], post-collisional field (red dashed circle) after Pearce (1996). VAG = volcanic arc granite, SYN-COLG = syn-collision granite, ORG = ocean ridge granite, and WPG = within-plate granite. Symbols as in Figure 6.

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Dayheen peralkaline granite samples fall within the within-plate field. This indicates that these samples have geochemical characteristics consistent with an intraplate tectonic setting. In contrast, the Dayheen granodiorite–diorite samples fall within the volcanic-arc granite field. This suggests that these samples have geochemical characteristics similar to those of subduction-related granitoids. Furthermore, the Dayheen monzogranite samples fall within the post-collisional field as defined [32]. This indicates that these samples have geochemical characteristics.

The chemical characteristics described for the Jabal Sayid and Dayheen peralkaline granites suggest a within-plate tectonic setting. These characteristics include significant depletions in CaO, MgO, Sr, and transition metals, along with high alkali contents and notable enrichments in High-Field-Strength Elements (HFSEs) such as Zr, Nb, Ta, and rare earth elements (REEs). The pronounced negative Eu anomalies in the REE patterns of the granites (Figure 9a,b) indicate the involvement of plagioclase feldspar fractionation in their petrogenesis, where the preferential removal of Eu²⁺ from the melt leads to the relative depletion of Eu compared to the other REEs. Overall, the described geochemical features are consistent with the within-plate tectonic setting of the Jabal Sayid and Dayheen peralkaline granites, indicating their formation in an intraplate environment away from plate boundaries [33–35].

6.2. The Petrogenesis of the Jabal Sayid and Dayheen Granitoids

6.2.1. Subduction-Related Granitoids

During an orogenic cycle, which encompasses the development of a mountain belt, the character of magmas can change as different tectonic processes occur. Regionally, this cycle is characterized by a transition in the nature of magmatism. It starts with typical subduction-related calc-alkaline compositions, followed by late-orogenic calc-alkaline rocks, and finally culminates in post-collisional peralkaline suites. As mentioned above, the Dayheen granodiorite–diorite association exhibits characteristics consistent with I-type granitoids. These characteristics include the following: high LREE/HREE ratios (7.47, on average) with nearly flat patterns for HREEs; small negative Eu anomalies; HFSE (Nb, Ta, and Ti) depletion; and Sr and Ba enrichment. This implies that these rocks were possibly derived from the partial melting of a subducted oceanic crust, with subsequent interaction with fluids and/or melts from the subduction zone. Geochemically, these granites yield lower Rb/Zr than that of S-type granitoids (Figure 12a, [36]). Moreover, they have lower $(Na_2O + K_2O)/CaO$ and Zr + Nb + Ce + Y than A-type granitoids (Figure 12b, [35]). The positioning of the Dayheen granodiorite-diorite rocks in the low-K mafic rocks field (Figure 12d) further supports their classification as I-type granitoids (Figure 12c, [37]). The Dayheen granodiorite–diorite association, as indicated by Figure 12e, is characterized by being Sr- and Ba-rich and Rb-poor. This implies that the generation of these magmas occurred in a subduction-like setting [38]. Additionally, the CaO/(MgO + FeO_{total}) vs. $Al_2O_3/(MgO + FeO_{total})$ diagram (Figure 12f) provides insights into the probable magma sources for the considered granitoids. The diagram suggests that most of the granodioritediorite association was developed by the melting of a mainly metabasaltic source. The composition of the lower crust in the AS, where the study areas are located, is consistent with the nature of this source.



Figure 12. (a) Rb/Zr vs. SiO₂ (after [36]). (b) Zr + Nb + Ce + Y (ppm) vs. $(Na_2O + K_2O)/CaO$ (after [35]). (c) The Zr vs. SiO₂ discrimination diagram for I- and A-type granitoid rocks [37]. (d) The ternary diagram of $Al_2O_3/(Fe_2O_3 + MgO)$ -3CaO-5(K_2O/Na_2O) (after [38]). The different fields represent the compositions of melts derived from a range of potential sources (tonalites, metasediments, and low- and high-K mafic rocks), determined by major element compositions of partial melts in experimental studies. (e) The Sr–Rb–Ba ternary plot for the studied granites (modified after [39]). (f) Molar CaO/(MgO + FeO_{total}) vs. $Al_2O_3/(MgO + FeO_{total})$ (after [40]). Symbols as in Figure 6.

6.2.2. Collision-Related Granitoids

In the discrimination diagram by [35] (Figure 12b), the Dayheen monzogranites plot as unfractionated S-, I-, and M-type granite. Furthermore, in the Zr vs. SiO₂ discrimination diagram of [37], the high-K calc-alkaline Dayheen monzogranites fall within the I-type field (Figure 12c). This observation aligns with the idea that the monzogranites have an intrusion-related origin, as I-type granites, and are typically related to magmatic arcs and subduction zones. However, the presence of a sedimentary component in the magma sources of the monzogranites is indicated in Figure 12f, where the samples fall within the overlapping partial melts of metatonalites and metagraywackes. This sedimentary component could have been derived from the descending slab during subduction and collision processes. Additionally, Figure 12d proposes that the monzogranite samples plot in the field of the melting of high-K mafic rocks to tonalitic rocks. This further supports the interpretation that the Dayheen monzogranites have a complex origin involving the melting of mafic rocks, potentially related to subduction processes. It is worth noting that the lower (Na₂O + K₂O)/CaO values observed in the Dayheen monzogranites indicate a relatively lower alkali content compared to the calcium content. This can be indicative of a more calc-alkaline nature, which is commonly related to S-type granites that form during collision events. The presence of S-type characteristics in the monzogranites could be related to specific geological conditions and processes occurring during their formation.

The composition of the Dayheen monzogranites suggests a mixing or hybridization process involving different source materials or a combination of magmas derived from different sources. After a collision event and crustal thickening, melting occurs in the mantle wedge due to the fractionation of an amphibole-dominated phase [41]. These melts then intrude on the base of the already hot and thickened crust, which promotes the further melting of the thickened lower crust [42]. As the magmas ascend towards the surface, they interact with the overlying continental crust, which is composed of older and more felsic rocks. This interaction leads to the assimilation of continental crustal material into the ascending magmas. The findings of [43] provide an alternative explanation for the formation of I-type granitoids, highlighting the importance of sedimentary materials in the process, i.e., how the interaction between mantle-derived magmas and sedimentary materials can lead to the formation of I-type granitoids. This suggests that the composition of the monzogranites may be influenced by the addition of sedimentary components during their formation. Collision-related magmas, such as the Dayheen monzogranites, are often characterized by their intermediate-to-felsic compositions. This composition reflects the complex processes of crustal thickening, mantle melting, and interaction with the continental crust, resulting in the generation of hybridized magmas with intermediate compositions.

6.2.3. Post-Orogenic or Anorogenic Granitoids

After a collision, significant amounts of high-K calc-alkaline granitoids are often emplaced, primarily as batholiths [44]. The isotopic ratios of Nd are often used as tracers to identify the sources of magmatic rocks. However, in the case of the ANS, the possible crustal materials for post-orogenic or anorogenic magmatism were themselves relatively young and had not undergone enough geological processes to develop distinctively crustal Nd isotope signatures, making it difficult to apply Nd isotope ratios as a reliable tracer in this context [45,46]. In that case, we can go to other evidence to identify the source of the Jabal Sayid and Dayheen parental peralkaline magmas. The Nb/Ta ratio and Y/Nb ratio are geochemical signatures that can provide valuable information about the source of magmas. These ratios are particularly useful in differentiating between mantle-derived and crustal-derived magmas. The Nb/Ta ratios in the Jabal Sayid and Dayheen peralkaline granites and pegmatites propose that these rocks crystallized from magmas derived from crustal sources rather than mantle-derived sources. The average Nb/Ta ratios are 12.94 for peralkaline granites and 11.72 for pegmatites in the case of Jabal Sayid and 12.98 for peralkaline granites and 13.08 for pegmatites in the case of Dayheen (Tables 2 and 3). These values fall within the range typically observed for crustal materials, which is generally lower than the Nb/Ta ratios observed in mantle-derived rocks. The typical Nb/Ta ratios for the continental crust range from 8 to 14, as reported by Stepanov and Hermann (2013). In contrast, the chondritic ratio, which represents the composition of the Earth's primitive mantle, is approximately 19.9 ± 0.6 [47]. Moreover, the Nb/Ta ratios in ocean island basalts typically fall around 15.9 ± 0.6 [48].

The Y/Nb ratio is another geochemical parameter commonly used to distinguish between different sources of magma. The average Y/Nb ratios reported for the peralkaline granites and pegmatites of Jabal Sayid (2.87 and 5.06, respectively, Table 3) and the peralkaline granites and pegmatites of Dayheen (1.34 and 1.33, respectively, Table 2) are higher than the typical Y/Nb ratios observed in mantle-derived sources, which are often less than 1.2 [33]. In terms of Rb/Sr ratios, mantle-derived materials typically have low Rb/Sr ratios, ranging from 0.1 to 0.01 [49], whereas lower and middle continental crust tends to be enriched in Rb relative to Sr [50]. Based on the Rb/Sr ratios observed in the studied granitoids, it is reasonable to conclude that the granodiorite–diorite association was formed from mantle material where lower Rb/Sr ratios between 0.03 and 0.1 were observed (Figure 13a). However, the higher Rb/Sr ratios in the monzogranites and peralkaline granites compared to typical mantle values suggest a significant contribution from sources other than the mantle, such as crustal materials.



Figure 13. (a) Rb/Sr ranges of the studied granitoid and associated pegmatites. (b) The Nb-Y-3Ga ternary diagram of [33]. Symbols as in Figure 6.

The use of the ternary discrimination diagram developed by [38] provides further evidence supporting the conclusion that the Jabal Sayid and Dayheen peralkaline granites

have a metasedimentary source (Figure 12d). Similarly, most of the Jabal Sayid and Dayheen peralkaline granites are plotted in the metapelitic source field, indicating a continental crustal source (Figure 12f). This further supports the idea that the peralkaline granitoids in the study area have a continental crustal source and are consistent with the broader geological context of the ANS. This is in agreement with the highest rubidium values and the lowest strontium and barium contents of the Jabal Sayid and Dayheen peralkaline granites (Figure 12e). The petrographical study indicating that the Jabal Sayid and Dayheen peralkaline granites are high in K-feldspar content is consistent with the observed variations in the Sr, Ba, and Rb contents in these rocks.

In the Zr + Nb + Ce + Y vs. $(Na_2O + K_2O)/CaO$ diagram of [35], the Jabal Sayid and Dayheen peralkaline granites fall within the A-type field (Figure 12b). When plotted on the discrimination diagram of [33], the Jabal Sayid and Dayheen granitoid samples overlap the boundary between the A1 and A2 subgroups (Figure 13b). The A1 subgroup is associated with rare-metal-bearing granitoids, similar to the Al-Ghurayyah granitoids in Saudi Arabia. On the other hand, the A2 subgroup aligns with the overall assumption of peralkaline granites in the ANS, where many peralkaline granites of crustal origin have been recognized, such as Al-Hamra granites, Saudi Arabia [51]; Feinan granites, Jordan [52]; and Um Taghir granites, Egypt [53].

6.3. Genesis of Rare Metals

The pie charts presented in Figure 14 provide information on the relative proportions of different rare metals in the Jabal Sayid and Dayheen peralkaline granites as well as in the related pegmatites from these locations. Based on the charts, the following observations can be made: (1) Jabal Sayid peralkaline granites have higher proportions of Zr and Y and lower proportions of LREEs, HREEs, and Nb compared to Dayheen peralkaline granites; (2) the Dayheen pegmatites have higher proportions of Zr and Nb and lower proportions of LREEs, HREEs, and Y compared to Jabal Sayid pegmatites. The variations in rare metal proportions in peralkaline granites and related pegmatites in Jabal Sayid and Dayheen can be related to different geological processes, such as the following: (1) different sources of magmatic material that contributed to the formation of these rocks; (2) fractional crystallization process, where different minerals can selectively incorporate or exclude certain elements, leading to variations in rare metal proportions; (3) late-stage hydrothermal alteration processes that can significantly affect the rare metal contents in these rocks; and (4) surficial weathering processes that can lead to the alteration and breakdown of rocks and minerals, resulting in the release, redistribution, and concentration of elements, including rare metals. Based on the present petrological and geochemical data, the investigation of these alternatives will be covered in the following sections.



Figure 14. Cont.



Figure 14. Pie charts illustrating the proportions of HREEs (Gd to Lu), LREEs (La to Sm), Zr, Y, and Nb in rare-metal peralkaline granites and related pegmatite in the Jabal Sayid and Dayheen areas.

The remarkably similar chondrite-normalized REE patterns (Figure 9a,b), as well as the trace element profiles (Figure 8a,b) of the peralkaline granites and related pegmatites from Jabal Sayid and Dayheen, support the idea of a common origin. This indicates that the variations in rare metal proportions are less likely to be attributed to differences in the source material. Instead, it suggests that the source material for these rocks had a consistent composition, contributing to the similar rare metal signatures observed in both areas. The correlations between the contents of rare metals (Zr, Y, Ta, U, Th, Pb, Hf, LREEs, and HREEs) and Nb as a measure of magma fractionation, as shown in Figure 15, offer meaningful information about the processes involved in the formation of rare-metal granitic and pegmatitic rocks. The choice of these elements, which are progressively increased in the residual melt of fractionating magma regardless of its composition, allows for a better understanding of the enrichment mechanisms that control the formation of these rare-metal-bearing rocks.



Figure 15. Correlations between the contents of rare metals and Nb as an indicator of magma fractionation. The open diamond symbols represent the Dayheen pegmatites, closed diamond symbols represent the Jabal Sayid pegmatites, and other symbols as in Figure 6.

The strong positive correlation coefficients (>0.9) between Nb and Ta in granitic rocks and related pegmatites from Jabal Sayid and Dayheen indicate their genetic links and derivation from common sources. The fact that Nb and Ta have a tendency to be higher in peralkaline granites and related pegmatites compared to monzogranites, granodiorites, and diorites (as shown in Figure 15a) is consistent with their behavior as incompatible elements during magmatic differentiation.

The elements Pb, U, Zr, and Hf exhibit moderate to strong correlations with Nb (R > 0.7) in the studied magmatic systems. This correlation suggests a common genetic origin and shared processes influencing their behavior. In the early magmatic phases, such as the granodiorite–diorite association, the concentrations of Pb, Zr, and Hf tend to be relatively low. This could be attributed to the fact that these elements are not significantly enriched during the initial stages of magmatic differentiation. The early magmatic phases may have undergone more extensive fractionation, resulting in the preferential loss or limited incorporation of Pb, Zr, and Hf. On the other hand, in the late magmatic phases, such as peralkaline granites and related pegmatites, the concentrations of Pb, U, Zr, and Hf are generally higher. This indicates that these elements become more enriched as the magmatic system evolves. The late-stage magmas may have experienced different processes, such as fractional crystallization or magma mixing, that promote the concentration and incorporation of Pb, U, Zr, and Hf. The correlation coefficients (R) between Nb and LREEs (La to Eu), HREEs (Gd to Lu), Y, and Th are generally weak and range from 0.55 to 0.65. Although these values can still be statistically significant and provide valuable insights, other factors or variables, such as magma mixing or late-stage hydrothermal alteration, may influence the relationship between Nb and LREEs, HREEs, Y, and Th.

The low values of the chemical index of alteration (CIA), chemical index of weathering (CIW), and plagioclase index of alteration (PIA) in the Jabal Sayed peralkaline granites and related pegmatites indicate that these rocks have experienced limited weathering and alteration [54]. This means that the chemical composition of these rocks has been relatively stable and has not undergone significant changes due to surficial weathering processes.

From above, it is suggested that the Jabal Sayid and Hadb Adh Dayheen peralkaline granites, along with their associated pegmatites, share a common parental magma and have formed primarily through fractional crystallization processes. The rare metal signature present in these rocks is believed to have been preserved during their formation. The previous age dating from Dayheen supports the idea that the rare-metal-bearing rocks in this region developed in a post-orogenic setting. Additionally, assessments of the published Sm-Nd isotopes for Jabal Sayid and Dayheen indicate that they have the same source [6–8,55]. This suggests that these granites and pegmatites share a common origin and were derived from a melt that underwent magmatic processes. The extreme levels of evolution that the melt experienced during its magmatic evolution likely contributed to the concentration of rare metals in the Jabal Sayid and Hadb Adh Dayheen peralkaline granites. This extreme evolution could have involved processes such as fractional crystallization, where certain minerals and elements become concentrated in the residual melt as it cools and solidifies. The higher concentrations of rare metals observed in the pegmatites can be interpreted by the influence of fractional crystallization. If the pegmatites formed from residual magma batches derived from the precursor granites, the concentrations of rare metals in the pegmatites could have been influenced by the fractionation process that occurred in the precursor granites. This process could have resulted in the enrichment of rare metals in the residual magmas that eventually formed the pegmatites. The presence of various accessory minerals in the Jabal Sayid and Dayheen peralkaline granites and related pegmatites, as listed in Table 1, is significant in controlling the behavior of rare metals in these rocks. The minerals synchysite, bastnaesite, xenotime, monazite, allanite, pyrochlore, samarskite, and zircon are recognized petrographically as important contributors of REEs, Y, Nb, and Zr in these rocks. Additionally, other minerals such as titanite, thorite, kasolite, apatite, and fluorite have been identified from petrographic studies. These minerals are typically enriched in elements such as Ti, Th, U, Pb, and F. Their presence further expands

the mineralogical inventory of the Jabal Sayid and Dayheen intrusions and suggests the potential involvement of these minerals in controlling the behavior of these specific elements. Fluids, such as aqueous solutions or volatile-rich gases, can play a crucial role in the formation of highly fractionated pegmatites with high concentrations of the rare metals Zr, Y, Nb, REEs, U, and Th and result in the formation of economically significant mineral deposits.

6.4. Genetic Model

Overall, the evolution of the ANS during the Pan-African period was marked by intense tectonic activity, magmatic intrusions, metamorphism, and the formation of various geological structures. These processes played a crucial role in shaping the distinctive geological features observed in the AS today and contributed to the formation of mineralized granitic rocks that exhibit significant enrichments of rare metals.

The geodynamic transition observed in the Jabal Sayid and Dayheen areas, from subduction-related granodiorite–diorite association to collision-related monzogranite and finally to post-collision or anorogenic peralkaline granites and related pegmatites, can be successfully modeled by considering three distinct magmatic stages:

- (a) Subduction-related magmatism: During this stage, the early mafic magma produced subduction-related granodiorite-diorite in the early stage of underplating. This mafic magma, likely derived from the subducting oceanic lithosphere, interacted with the overlying continental crust. The interaction resulted in the production of subduction-related granodiorite-diorite (Figure 16A). This stage represents the initial phase of magmatic activity related to subduction. Slab breakoff can lead to a change in subduction dynamics and the cessation of subduction-related magmatism. Subduction initiation and the formation of arc terranes occurred between 870 and 620 Ma [10].
- (b) Collision-related magmatism: As the tectonic processes continued, crustal thickening occurred in the region, and consequently the subducted oceanic slab broke off (Figure 16B). The deeper portions of the overlying crust, composed of metatonalites and graywackes, were subjected to increased pressure and temperature conditions. These conditions brought these rocks above their solidus temperatures, leading to partial melting. The resulting melt contributed to the early mafic magma, giving rise to a new generation of intermediate magma that produced monzogranites. Ref. [6] reported zircon U-Pb ages of 625 \pm 11 Ma for the hornblende–biotite granite and 613 ± 4 Ma for the monzogranite in the core of the Dayheen ring complex. These ages suggest that the monzogranite is younger than the rimmed hornblende-biotite granite. This age relationship contradicts the interpretation based on the present geochemical results, which suggest that the monzogranite is related to the collision stage, while the hornblende-biotite granite formed later in a post-collision stage. This implies that the monzogranite in the core of the ring complex is indeed older than the peralkaline rocks in the rim, consistent with the geological fact that the monzogranite was emplaced earlier than the rimmed granitic rocks, as stated by [56].
- (c) Post-collision magmatism: The geochemistry and previous geochronology show that the Dayheen and Jabal Sayid rare-metal-bearing peralkaline granites and related pegmatites were probably generated in a post-collision extensional setting. During this stage, anatexis, or partial melting, took place in the crustal material, leading to the generation of a new magma, which produced peralkaline granites and related pegmatites (Figure 16C). The magma composition was likely influenced by progressive chemical fractionation processes, which caused the development of peralkaline A-type granites and related pegmatites. The development of the Najd fault system is believed to have facilitated the ascent of magmas and the formation of peralkaline granitoids within the AS [9,57–61]. This fault system provided pathways for the upward migration of magmas from deeper levels to shallower crustal levels, where they eventually crystallized and formed peralkaline granitoids. The extensive crystal-

lization and differentiation processes that occur during the emplacement and cooling of post-collision granite magma can lead to the enrichment of rare metals and other related elements in the Jabal Sayid and Dayheen areas.



(A) Subduction-Related Magmatism (870-620 Ma)

(C) Post-collisional Magmatism (613-584 Ma)



Figure 16. A simplified model for the tectonomagmatic evolution of the juvenile crust in the Jabal Sayid and Dayheen areas, the western AS of Saudi Arabia. (**A**) The subduction of the oceanic crust, ophiolite detachment, and thrusting along the Bir Umq suture zone with the arc volcanism and arc-related plutonism of the granodiorite–diorite association. (**B**) The collisional phase, crustal anatexis, and monzogranite intrusions. (**C**) The partial melting of the crustal material leads to the generation of peralkaline granites and related pegmatites in post-collisional extension settings. The crust and mantle thickness are not to scale.

The reported ages of the peralkaline granites in Jabal Sayid and Dayheen are in agreement with the broader post-orogenic or anorogenic plutonic activity that occurred in the Arabian-Nubian Shield (AS) between 680 and 550 Ma, as documented by [62]. Ref. [63] reported a whole-rock Rb-Sr isochron age of 584 ± 26 Ma for the Dayheen ring complex, indicating the timing of granite emplacement in that area. This age aligns with the estimated age of zircon from the alkali granite at Jabal Sayid, which is reported as 593 ± 2.4 Ma, according to [7]. Furthermore, ref. [10] reported zircon U-Pb ages for various granitic rocks in the Dayheen area, including the hornblende–biotite granite, microgranite, and aegirine–riebeckite granites. These ages range from 613.3 ± 8.1 Ma to 596 ± 5.6 Ma. The ages reported by [7,10] are in close agreement, indicating that the emplacement of peralkaline granites in the Dayheen and Jabal Sayid areas occurred between 613 and 584 Ma.

The ε Nd values of the Jabal Sayid and Dayheen plutons are positive and relatively uniform, demonstrating similarity to the Jabal Sayid and Dayheen plutons in the Jeddah Terrane. The initial εNd for the alkaline granite in Jabal Sayid is +4.9 to 5.3 [7], while that of the Dayheen monzogranite, hornblende–biotite granite, and aegirine granite is +4.1 to 5.3 [6]. The observed similarity in isotopic composition between the Jabal Sayid and Dayheen peralkaline granites suggests a homogeneous isotopic signature in the source region. This similarity implies that these granites and their associated pegmatites were likely derived from the partial melting of the lower part of the juvenile AS crust. It is possible that the melting process involved the lower crust with or without direct contributions from upper mantle materials. This interpretation aligns with the findings of [10], who concluded that the granitic rocks in the Dayheen ring complex primarily originated from the juvenile crust, although there may have been some involvement of mantle-derived materials. Ref. [64] concluded that the S-type two-mica granitoids in the Bafoussam area of western Cameroon had heterogeneous isotopic signatures, which they attributed to anatectic melts of the upper continental crust with variable contributions from the lower continental crust or mantle melts. It is worth mentioning that the present geochemical data do not support a hybridized source for the formation of the Jabal Sayid and Dayheen peralkaline granites. If hybridization had occurred, it would likely result in scattered isotope signatures of Sm-Nd. However, the restricted ɛNd values observed in Jabal Sayid and Dayheen suggest a more homogeneous source without significant hybridization.

7. Conclusions

The Jabal Sayid and Dayheen ring complexes provide valuable insights into the geological processes that govern the enrichment and segregation of rare metals, particularly in highly evolved peralkaline granites and associated pegmatites. In the Dayheen ring complex, the central part of the complex consists predominantly of monzogranites. Towards the outermost part of the complex, there is a transition to hornblende–biotite granites, followed by aegirine–riebeckite granite. This zonation of granitic rock types indicates variations in the chemical composition and evolution of the magmatic system within the complex. The Jabal Sayid granites, on the other hand, intrude into the Late Proterozoic volcano-sedimentary unit of the Mahd Group. The granites in this area are primarily peralkaline and are accompanied by a sheet-like pegmatite body.

The evolution from an early granodiorite–diorite association to intermediate monzogranites and peralkaline granites with associated pegmatites can be successfully explained by the involvement of three different magma generations. During the early phase of underplating, which took place between 870 and 620 Ma, the first mafic magma was generated. This mafic magma led to the formation of the granodiorite–diorite association. This stage represents the first phase of magmatic activity associated with subduction. As tectonic processes continued, crustal thickening occurred, and the subducted oceanic plate broke away, leading to collisional magmatism (625–613 Ma). The deep parts of the overlying crust partially melted, and monzogranites were formed. During the post-collisional phase, which took place between 613 and 584 Ma, the crustal material underwent anatexis, i.e., the partial melting of the pre-existing rocks due to increased heat and pressure. This anatexis led to the formation of magmas that produced peralkaline granites and associated pegmatites through progressive chemical fractionation. This process can result in the enrichment of certain elements, including rare metals such as Zr, Y, Nb, REEs, U, and Th, in the residual melt. As the peralkaline granitic magmas underwent progressive chemical fractionation, they became increasingly enriched in these rare metals. The ascent of these magmas from deeper levels to shallower depths was likely facilitated by the Najd fault system. The interaction of the ascending magmas with surrounding rocks and fluids further influenced their composition and mineralogy. Fluids, such as aqueous solutions or volatile-rich gases, can contribute to the formation of highly fractionated pegmatites. These fluids can interact with the evolving magmas, causing further chemical differentiation and promoting the crystallization of rare-metal-bearing minerals within the pegmatites. The enrichment of rare metals within the Jabal Sayid and Dayheen peralkaline granites and related pegmatites can lead to the development of economically significant mineral deposits, making them of interest for mineral exploration and extraction.

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