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Magmatic and hydrothermal evolution of highly-fractionated rare-metal granites at Gabal Nuweibi, Eastern Desert, Egypt

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Abstract

The Nuweibi intrusion was emplaced during the final tectono-magmatic stage of Arabian-Nubian Shield development (ANS). Two cogenetic phases of intrusion can be recognized in the field: the early phase is represented by porphyritic albite granite and the final phase by non-porphyritic albite granite. Mineralogically, both phases are essentially composed of albite, quartz, and K-feldspars with subordinate muscovite. Accessory minerals include fluorite, zircon, Nb-Ta oxides, cassiterite, beryl, topaz, and garnet. Geochemically, the Nuweibi intrusion consists of extensively fractionated rare-metal granite with low contents of TiO₂, FeO_t, CaO, MgO, P₂O₅, Sr, and Ba in contrast to elevated concentrations of alkalis, Rb, Nb, Ta, and Hf. Their peraluminous (molar Al₂O₃/[CaO+Na₂O+K₂O] = 1.06-1.15) and low-P (P₂O₅ < 0.008 wt.%) character identify them as highly fractionated I-type granites. The primary magma of the Nuweibi intrusion was most likely generated by partial melting of the juvenile crust of the ANS. We document numerous lines of evidence that the Nuweibi albite granite was formed by extensive fractional crystallization

followed by interaction with magmatically-derived, F-rich hydrothermal solutions. The REE patterns of the Nuweibi albite granite show marked negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.01\text{--}0.15$) as well as prominent M-type tetrad effects ($\text{TE}_{1,3} = 1.332\text{--}3.536$), typically seen in highly differentiated granites and attributed to exchange with hydrothermal fluid. Anomalous ratios of isovalent “twin” elements such as Nb/Ta, Zr/Hf, and Y/Ho likewise indicate exchange with hydrothermal fluid. The primary rare-metal accessory minerals are restricted to the Mn-rich part of the columbite-tantalite series; this manganoan trend is characteristic of highly fractionated granites. Likewise, the presence of wodginite, a Sn-bearing mineral, is a unique fingerprint of highly evolved rare-metal granites. Late-stage hydrothermal overprint of the primary rare-metal mineralization is preserved by rims of fluorcalciomicrocline partly replacing columbite-(Mn) and tantalite-(Mn). Accumulation of residual volatile-rich melt and exsolved fluids in the upper part of the magma chamber produced stockwork pegmatite, greisen, and quartz veins that cut the peripheries of the Nuweibi intrusion and the surrounding country rocks.

Keywords: Arabian-Nubian Shield, Nuweibi intrusion, Rare-metal granite, Nb-Ta oxides, tetrad effect.

1. Introduction

Granitoid rocks are the most abundant intrusive members of the Egyptian basement complex. They were emplaced throughout the formation of the Nubian Shield (~ 820 to 570 Ma), evolving in major and trace-element composition as the ANS developed through various tectonic settings (e.g., Azer and Asimow, 2021). The wide distribution of post-orogenic granitoids is one of the most striking features of the basement rocks of Egypt. Generally, post-orogenic granites

evolved from calc-alkaline (630-600 Ma) to alkaline (610-590 Ma) character, with some overlap in their ages (Ali et al., 2009; Eliwa et al., 2014). They include a number of discrete, shallowly-emplaced A-type and highly fractionated I-type igneous complexes, with significant enrichment in some ores (Helba et al., 1997; Abou El Maaty and Ali Bik, 2000; El Hadek et al., 2016; Abu El-Rus et al., 2017; Sami et al., 2017, 2018; Heikal et al., 2019; Azer et al., 2019, 2020; Seddik et al., 2020, Abuamarah et al., 2021). The abundance of these post-orogenic granites is of geodynamic interest, as they represent a significant addition of material into the juvenile crust of the ANS over a relatively short time interval. These highly-fractionated granites and associated pegmatites also host important mineral deposits, with anomalously elevated concentrations of critical elements including Li, Be, F, Zr, Nb, Mo, Sn, Ta, W, Pb, Th, U, and rare earth elements (REE) (Sabet et al., 1976; Linnen et al 2012). In the Eastern Desert of Egypt, these granites are called rare-metal granites.

The Nuweibi intrusion, the target of the present work, is one of the most outstanding examples of rare-metal bearing granite in the ANS. It contains the largest ore reserve of Nb-Ta oxide minerals in the Eastern Desert of Egypt. The published works about this intrusion are sparse and contradictory (e.g., Sabet and Tsogoev, 1973; Hassanen and Harraz, 1996; Naim et al., 1996; Helba et al., 1997; Gippsland Limited, 2013; Emam et al., 2018; Azer et al., 2019), and no unique petrogenetic model has been proposed to explain the features of the intrusion. Therefore, the present work integrates field observations, petrography, mineral chemistry and whole-rock chemical analyses for the Nuweibi intrusion in order to examine its origin and mode of formation as well as to distinguish between magmatic and metasomatic stages in the evolution of the pluton. Also, this study offers a good opportunity to understand the formation of mineralized post-collisional granites throughout the ANS and elsewhere.

2. Geologic Setting

The Egyptian granites (*sensu lato*) are traditionally divided into two main groups, the older and younger “granites” (Hussein et al. 1982). El-Gaby et al. (1988) defined the older granites as grey, calc-alkaline, syn-tectonic, I-type granitoids. They range in composition from diorite to granodiorite and rarely to true granite. By contrast, the younger “granites” are defined as pink to red, calc-alkaline to alkaline, late to post-tectonic, I- and A-type granitoids. Azer and Asimow (2021) suggested a three-fold petrological classification scheme for the Egyptian granitoids which may be more informative. In this breakdown, the three main groups of Egyptian granitoids are: (1) synorogenic calc-alkaline granitoids, (2) late- to post-orogenic calc-alkaline granitoids and (3) post-orogenic alkaline granitoids.

The post-collisional granites in Eastern Desert of Egypt include several instances of rare-metal albite granite (e.g., Abou El Moustafa and Ali Bik 2000; El Hadek et al. 2016; Azer et al., 2019; 2020; Seddik et al., 2020; Abuamarah et al., 2021). Our study focuses on the Nuweibi albite granite intrusion, in the central part of the Eastern Desert (**Fig. 1**). Sabet and Tsogoev (1973) studied the Nuweibi granites and considered them to be apogranites, formed by metasomatic enrichment in rare metals and sodium derived from leaching of large underlying bodies of biotite granite. Concerning the age of these rare-metal granites, Hassanen and Harraz (1996) obtained a Rb/Sr age of 490 ± 27 Ma. Using $^{207}\text{Pb}/^{206}\text{Pb}$ zircon evaporation dating, Helba et al. (1997) found widely scattered ages of 600-450 Ma that constrain only that the pluton is late- or post-orogenic with respect to the Pan-African orogeny. Emam et al. (2018) concluded that the zircons are too disturbed to yield accurate dates, whereas U-Pb dating of columbite from two samples gives ~ 620 Ma. In the context of ages of other I-type post-collisional magmatism in

the Eastern Desert, the Proterozoic 620 Ma age is much more plausible than the Paleozoic Rb/Sr result.

The study area lies between latitudes $25^{\circ}11'20''$ and $25^{\circ}12'20''$ N and longitudes $34^{\circ}28'55''$ and $34^{\circ}30'05''$ E (**Fig. 2**). The Nuweibi albite granite occurs as a small, isolated pluton and exhibits a domal shape, elongated from east to west with an area of $\sim 1.8 \text{ km}^2$. A N-S sinistral strike-slip fault, roughly parallel to the regional structure of the Red Sea Coast, divides the Nuweibi intrusion into western and eastern parts along Wadi Nuweibi, with a displacement of $\sim 0.6 \text{ km}$.

Azer et al. (2019) classified the Nuweibi granites into two phases: an older porphyritic phase and a relatively younger nonporphyritic phase, both attributed to partial melting of the juvenile Nubian Shield crust, followed by extensive fractionation and a late-magmatic hydrothermal overprint. The western Nuweibi albite granite is non-porphyritic, nearly equigranular, and medium- to coarse-grained, whereas the eastern part exhibits porphyritic texture. In the northern part of the mapped area, a small serpentinite mass is thrust over the metasedimentary and metavolcanic rocks and then intruded by granodiorite-tonalite and Nuweibi granites. The eastern albite granite intruded into serpentinite, metagabbro-diorite, metasedimentary and metavolcanic country rocks, while the western albite granite intruded into granodiorite. The eastern, porphyritic phase is considered to represent the uppermost part of the intrusion.

Where the contact between the albite granite and country rocks is exposed, especially in the eastern part, stockscheider pegmatite stocks and veins are present. Pegmatite zones range in thickness from a few centimeters to several meters across. Along the fault zone, the albite granite shows brittle deformation with grinding and fracturing of grains. These fractures are filled with

green secondary minerals. Locally, the Nuweibi albite granite is stained brown or black due to the presence of manganese minerals; these are most common in the eastern part. The manganese minerals occur as dendritic clusters, rounded patches, and fillings along joint planes. Hassanen and Harraz (1996) indicated that these patches represent mixtures of Nb-Ta bearing minerals with Fe-Mn oxides, concentrated by density toward the bottom of the eastern phase of the pluton. Azer et al. (2019) confirmed this vertical zonation. A few pods and veins of greisen and quartz cut the albite granite and the surrounding country rocks.

3. Petrography

Petrographic examination reveals that the highly fractionated granites are holocrystalline, medium-grained, and leucocratic, with white to pale grey colours and very low abundances of mafic minerals. The textures of these granites can help to differentiate them into a porphyritic type, occurring in the eastern part of the Nuweibi pluton, and a non-porphyritic type, characteristic of the western part. The porphyritic phase is richer in modal albite than the non-porphyritic phase. A transitional texture can be observed between the eastern and western parts of the pluton, although much of this contact is obscured by faulting and wadi deposits.

The porphyritic samples are leucogranites, composed mainly of large phenocrysts of albite, quartz, and K-feldspars with subordinate muscovite. The groundmass consists of small laths of albite with subordinate fine-grained quartz and K-feldspars. Accessory minerals include garnet, zircon, beryl, columbite-tantalite, fluorite, and cassiterite. Albite occurs as large, subhedral to euhedral, unzoned crystals exhibiting Carlsbad twinning, as well as small laths in the groundmass. Quartz occurs in two generations: snowball phenocrysts (**Fig. 3a**) followed by

fine grains scattered in the groundmass. Some snowball quartz phenocrysts occur as subhedral crystals, ranging in diameter from 1-3 mm and containing poikilitic inclusions of albite in laths oriented parallel to the phenocryst outlines. Reports in the literature differ on the question of whether such snowball texture is magmatic (Pollard, 1989; Schwartz, 1992; Helba et al., 1997) or metasomatic (Beus, 1982) in origin. Recently, Wang et al. (2019) concluded that snowball quartz phenocrysts crystallize in fluid-enriched magma, where magmatic flow led to mineral rotation and rounded to sub-rounded quartz grains. K-feldspars are mainly orthoclase with minor microcline. They occur as subhedral to euhedral phenocrysts that exhibit simple twinning, as well as small anhedral crystals in the groundmass. Muscovite occurs as anhedral to subhedral flakes interstitial between albite and quartz and, rarely, as inclusions in quartz phenocrysts.

Nb-Ta oxides are common in the porphyritic samples of Nuweibi granite. They occur as anhedral and subhedral crystals and show variation in color from black to deep brown. Some crystals are zoned, exhibiting irregular patterns in the columbite-(Mn) to tantalite-(Mn) cores as well as rims of mottled or patchy fluorocalciomicrocline and wodginite or, rarely, tantalite-(Fe) (**Fig. 3c, d**). The rim zone may include tiny grains of cassiterite as well. The mineral names in the backscatter images are based on microprobe and SEM analyses (see section 5. Mineral chemistry).

The non-porphyritic samples are also leucogranites and exhibit a medium-grained hypidiomorphic texture. They are composed mainly of quartz, albite, and K-feldspars. The accessory minerals are beryl, garnet, zircon, fluorite, columbite–tantalite, cassiterite, wurtzite and topaz. Quartz occurs as anhedral to subhedral crystals that exhibit undulose extinction. Albite occurs as fresh subhedral crystals, up to 2 mm in length, that exhibit lamellar twinning. Orthoclase occurs as cloudy subhedral crystals, 2-3 mm long. Occasionally, orthoclase crystals

contain small microcline patches. Muscovite occurs as colourless to pale green subhedral plates and exhibits one set of cleavages. Rare anhedral biotite flakes are present. Nb-Ta oxides in the non-porphyratic samples occur as very fine anhedral crystals interstitial to feldspar (**Fig. 3d**).

A marginal zone of stockscheider pegmatite occurs at the upper boundary of the eastern part of the Nuweibi pluton. It is coarse-grained with a pinkish colour. The pegmatite is essentially composed of K-feldspars, quartz, albite, biotite, and topaz.

Greisen exhibits light colours and it is mainly composed of quartz grains and anhedral muscovite flakes, with minor fluorite and topaz and a few relics of albite and K-feldspars.

4. Analytical techniques

Back-scattered electron images (BSE), energy-dispersive compositional analyses, and X-ray maps were collected on carbon-coated polished thin-sections with a Zeiss 1550VP scanning electron microscope (SEM) housed at the Division of Geological and Planetary Sciences (GPS), California Institute of Technology (Caltech), USA. An accelerating potential of 25 kV was used to resolve high-energy lines of heavy elements. Deadtime was maintained below 60% and spectra were integrated for 60 s of live time. The EDS detector is a Si-drift type 80 mm² active area Oxford Max and data were processed with Oxford's AZTec software, using factory standards for quantification.

Spot chemical analyses were obtained using Caltech GPS' five-spectrometer JEOL JXA-8200 electron microprobe. Operating conditions were 15 kV accelerating voltage, 25 nA beam current, a focused beam (~1 µm diameter), and 20 s on-peak counting times. An expanded set of elements (F, Na, Mg, Al, Si, S, K, Ca, Ti, Cr, Mn, Fe, Ni, As, Nb, Sn, and Ta) was acquired using a mix of natural and synthetic mineral standards for calibration. Synthetic standards were

forsterite (Mg), fayalite (Fe), Mn-olivine (Mn), anorthite (Ca, Al, and Si), TiO₂ (Ti), Cr₂O₃ (Cr), fluorophlogopite (F), NiO (Ni), NbO (Nb), Sn metal, and Ta metal. Natural standards were Amelia albite (Na), Asbestos microcline (K), and pyrite (S). The mean atomic number background correction method and the CITZAF matrix correction routine were used. Calculations of cations and structural formulae normalized to appropriate numbers of oxygens per formula unit were carried out using either home-made Microsoft Excel spreadsheets or Minpet (Richard, 1995).

The major oxides, trace elements and rare-earth elements were analyzed at Caltech. Whole-rock compositions of major and minor elements (Si, Ti, Al, Fe, Mg, Ca, Na, K, P, and Mn expressed as oxide wt.%; V, Cr, Co, Zn, Rb, Sr, Y, Zr, Nb, Ba, and Pb expressed as elemental µg/g) were determined using a Panalytical Zetium XRF system. Sample powders were ground in a WC jaw crusher and an agate ball mill. Loss on ignition (LOI) was determined by weighing before and after firing in air for 1 hour at 1000 °C, and fused-glass beads were prepared from fired powders by mixing with 9 times their weight in 66.67% Li₂B₄O₇-32.83% LiBO₂-0.50% LiI flux and fusing at 1200 °C. The analytical protocol is standardized against a large number of USGS standard rock powders, and USGS standards AGV-2, BCR-2, and GSP-2 are analyzed before and after every group of unknowns for quality control. After the XRF measurements, 25±1 mg chips of the fused-glass beads are dissolved in new polypropylene tubes and refluxed in hot (100 °C) 3:1 nitric and hydrofluoric acid for at least 8 hours. After dilution with milli-Q distilled water to 30 mL total volume, the rare-earth elements (REE) and some trace elements (Sc, V, Co, Ni, Cu, Zn, Rb, Y, Zr, Nb, Mo, Cs, Hf, Ta, W, Tl, Pb, Th, and U) were determined using an Agilent Technologies 8800 triple quadrupole ICP-MS. A working curve for instrument sensitivity was developed using a blank fused bead from the same batch of flux as used to

prepare the unknowns along with the USGS standards AGV-2 and RGM-2. For quality control, additional USGS standards (BCR-2, GSP-2) were analyzed as unknowns. For those elements determined by both methods, the ICP-MS data are generally preferred, except for V, Sr, and Ba, which yielded much lower detection limits by XRF.

5. Mineral Chemistry

5.1 Silicate Minerals

Albite: The chemical compositions and structural formulae of plagioclase analyses are given in **Table 1S**. Plagioclase is almost pure end-member albite in composition, with a small variation in An content between 0.08 and 1.31 %. The average composition of albite in the sample of the eastern, porphyritic phase is $\text{Ab}_{99.05}\text{An}_{0.40}\text{Or}_{0.55}$ whereas the average in the western, non-porphyritic phase is $\text{Ab}_{98.80}\text{An}_{0.52}\text{Or}_{0.68}$; the difference in average An content is not statistically significant at the 95% confidence level.

K-feldspar: The chemical compositions and structural formulae of K-feldspar analyses are given in **Table 2S**. Composition is almost mostly close to pure end-member orthoclase, with maximum Ab contents of 4.2 % in the porphyritic sample and 6.6 % in the non-porphyritic sample. An contents are <0.50 % in both samples. The average composition of K-feldspar in the sample of the eastern, porphyritic phase is $\text{Ab}_{2.48}\text{An}_{0.13}\text{Or}_{97.40}$ whereas the average in the western, non-porphyritic phase is $\text{Ab}_{2.82}\text{An}_{0.19}\text{Or}_{96.98}$; the difference in average Ab content is not statistically significant at the 95% confidence level.

Muscovite: The chemical compositions and structural formulae of muscovite analyses are given in **Table 3S**. Generally, the studied muscovite is poor in TiO_2 (≤ 0.36 wt.%), Na_2O (0.11-0.32 wt.%), and MgO (0.07-0.84 wt.%), but contains significant FeO_t (4.59-9.55 wt.%). Plotting the muscovite analyses on the Ti-Na-Mg ternary diagram of Miller et al. (1981), their very low Ti contents place them all in the field of secondary muscovite (**Fig. 4a**), associated with subsolidus hydrothermal alteration rather than magmatic crystallization (Miller et al. 1981). The elevated FeO_t content corresponds to significant solid solution towards a ferrous celadonite component (**Fig. 4b**). The muscovite compositions in the porphyritic and non-porphyritic phases are notably different, with the porphyritic sample featuring lower Ti, Fe, Mg, Ca, and Na and hence being generally closer to stoichiometric muscovite. A few muscovite points in the porphyritic sample have measurable apparent Nb and Ta, probably indicating unresolved inclusions of columbite-tantalite in the analytical volume.

5.2. Nb-Ta Oxide minerals

The identification of the Nb-Ta oxide minerals under the microscope was refined and supported by EPMA analyses and SEM/EDS. Some high-resolution field-emission SEM electron images and charts with energy-dispersive X-ray spectra given in **Figures 5 and 6**.

Columbite-tantalite series: The chemical analyses and structural formula of the $(\text{Mn,Fe})(\text{Nb,Ta})_2\text{O}_6$ analyses are given in **Table 4S**. Plotting the analyzed samples on the “columbite quadrilateral” diagram reveals that most points are on the Mn-dominant side of the series, plotting along a single main trend from columbite-(Mn) to tantalite-(Mn) compositions (**Fig. 7a**). This “manganoan” trend (Beurlen et al., 2008) is commonly observed in columbite-tantalite in highly fractionated granitic pegmatites. A few analyses, found exclusively in the

western, non-porphyritic sample, lie off the main manganoan trend, clustering in an anomalous field of tantalite-(Fe) associated with alteration by Beurlen et al. (2008). The main trend indicates correlated enrichment in Ta/(Nb+Ta) and in Mn/(Mn+Fe). In peraluminous granite melts, early crystallization of lower-solubility Nb-rich columbite group members leads to progressive enrichment in the Ta/Nb ratio of residual melts and a zoned fractionation sequence towards Ta-rich compositions (Linnen and Keppler, 1997). However, the same explanation does not predict the coupled increase in Mn/(Mn+Fe), because the solubility of Fe-rich columbite is larger than that of Mn-rich columbite (Linnen, 2004). Instead, the enrichment of Mn/(Mn+Fe) with progressive fractionation must be controlled by other co-precipitating and more abundant Fe-bearing minerals (London et al., 2001), in this case most likely Fe-bearing muscovite (Van Lichtenvelde et al., 2007).

Wodginite: The chemical compositions and structural formulae of wodginite analyses are given in **Table 5S**. Wodginite is nominally $\text{MnSnTa}_2\text{O}_8$, but the wodginite structure accommodates several solid solutions, principally $(\text{Fe}^{2+}, \text{Mn}, \text{Li}, \square)^{\text{A}}(\text{Sn}, \text{Fe}^{3+}, \text{Ti}, \text{Ta})^{\text{C}}(\text{Nb}, \text{Ta})^{\text{B}}_2\text{O}_8$. Plotting the present analyses on a Ti/(total B site) vs. Mn/(total A site) diagram reveals that the extents of Ti and Fe^{2+} substitution are limited and that all the analyses lie in the field of wodginite *sensu stricto* (**Fig. 7b**). Again, there is a distinct difference between the mineral chemistry in the two phases of the intrusion: wodginite in the porphyritic phase is closer to nominal end-member composition, with average $\text{Ta}/(\text{Ta}+\text{Nb}) = 0.888$ and average $\text{Mn}/(\text{Mn}+\text{Fe}) = 0.875$, vs. $\text{Ta}/(\text{Ta}+\text{Nb}) = 0.802$ and $\text{Mn}/(\text{Mn}+\text{Fe}) = 0.698$ in the non-porphyritic phase (Table 5S). SnO_2 contents average 13.4 wt.% in the porphyritic sample and 11.4 wt.% in the non-porphyritic sample.

Fluorcalciomicrolite: Fluorcalciomicrolite was found and analyzed only in the porphyritic sample. The chemical compositions and structural formula of microlite-group analyses are given in **Table 6S**. Ta-dominant members of the pyrochlore supergroup form the microlite group, which includes 13 named mineral species that accommodate several substitutions. The present analyses — with Ta/(Ta+Nb) from 0.852 to 0.927, Ca from 1.14 to 1.27 atoms per formula unit, and F > 1 atom per formula unit — are all classified as fluorcalciomicrolite. This material hosts 11.8 to 13.7 wt.% CaO, 3.7 to 6.0 wt.% SnO₂, 62.5 to 69.3 wt.% Ta₂O₅, and 3.9 to 5.2 wt.% F.

6. Whole-rock chemistry

6.1. Major and trace elements

Twenty-one samples of Nuweibi albite granite and four samples of the country rocks were analyzed for major oxides (**Table 1**), trace elements (**Table 2**), and REEs (**Table 3**). The albite granite samples are characterized by high SiO₂ (71.6-78.8 wt.%), Al₂O₃ (12.0-16.8 wt.%), Na₂O (3.5-7.6 wt.%), and K₂O (2.3-5.2 wt.%) and very low TiO₂ (<0.008 wt.%), Fe₂O_{3t} (0.09-0.85 wt.%), MgO (≤0.05 wt.%), CaO (≤0.39 wt.%), and P₂O₅ (≤0.008 wt.%). The very low P₂O₅ contents observed are consistent with the absence of apatite or any other phosphate minerals, such as monazite and xenotime. The two phases of the intrusion fully overlap in major-oxide composition, but the non-porphyritic samples are notably homogeneous, fitting entirely within the limits of the ranges of porphyritic samples in all oxides with the exception of one high-K₂O non-porphyritic sample. The granodiorite country rocks are clearly distinct from and less fractionated than the Nuweibi pluton, with 70.1-72.1 wt.% SiO₂, 0.3-0.4 wt.% TiO₂, 2.5-3.7 wt.% Fe₂O_{3t}, 0.83-1.2 wt.% MgO, 1.4-2.4 wt.% K₂O, and 0.08-0.13 wt.% P₂O₅.

On a R_1 - R_2 diagram (De la Roche et al., 1980), the Nuweibi albite granites lie in the alkali-granite field, except one which lies in the field of quartz syenite. The country rocks lie in the granodiorite field (**Fig. 8a**).

The Nuweibi albite granites are strongly peraluminous ($ASI = \text{molecular } Al_2O_3 / (CaO + Na_2O + K_2O) = 1.06\text{--}1.15$); all the analyzed samples lie in the peraluminous field and essentially on the 1:1 line (given the extremely low CaO content) of the A/NK versus A/CNK diagram (**Fig. 8b**). The peraluminous character of the whole rock analysis is also reflected in normative corundum contents (0.38–2.63 wt.%, Table 1) and in the presence of modally significant muscovite and accessory garnet. The studied samples plot in the non-alkaline field on a SiO_2 versus $Na_2O + K_2O$ diagram, except for a few samples that lie in the transalkaline field (**Fig. 8c**). The Nuweibi albite granites lie in the field of highly fractionated calc-alkaline granites on a $(Al_2O_3 + CaO) / (FeO + Na_2O + K_2O)$ versus $100^* (MgO + FeO_t + TiO_2) / SiO_2$ diagram, as described by Sylvester (1989) (**Fig. 8d**). The country rocks are also peraluminous, with $ASI = 1.07\text{--}1.20$.

The primitive mantle normalized trace element patterns of the Nuweibi albite granite samples (**Fig. 9a**) are characterized by high concentrations of some high field-strength elements (HFSE; e.g., Nb, Ta, Zr, and Hf) and some large ion lithophile elements (Cs, Rb, Pb, U, and Th) alongside low concentrations of Sr, Ba, Ni, Co and V. The very low concentrations of Sr and Ba (Sr ranging from 14.8 to 23.3 $\mu\text{g/g}$ and Ba ranging from 9.8 to 23.7 $\mu\text{g/g}$) in the analyzed samples can be explained by extensive fractionation of feldspars, both plagioclase and K-feldspar, which sequesters these elements from the residual melt. On the other hand, Rb is incompatible in feldspars and accumulates significantly in the residual melt during such fractionation. The resulting high Rb content is characteristic of extremely fractionated granite.

Note that the alternative hypothesis for Sr and Ba depletion, namely leaching and extraction by hydrothermal fluids, would also remove other fluid-mobile elements, notably Cs, Rb, and Pb. Hence the main features of the trace element pattern seem more consistent with a magmatic fractionation model. The granodiorite country rocks have different, less fractionated trace element patterns, with lower Rb, Nb, Ta, and Hf alongside higher Cr, Co, Ni, V, Sr, and Ba.

Low Zr/Hf, Nb/Ta and K/Rb ratios are characteristic of highly fractionated, rare-metal granites (Raimbault et al., 1995). Breiter et al. (2007) suggested a division among common granites ($\text{Zr/Hf} > 55$), moderately evolved granites ($25 < \text{Zr/Hf} < 55$), and highly evolved granites ($\text{Zr/Hf} < 25$). The Zr/Hf ratios of the Nuweibi albite granite are exceptionally low (0.15 to 5.21), well into the highly evolved category. The low Zr/Hf ratios most likely reflect extensive fractionation of zircon, which selectively sequesters Zr and leaves residual melts comparatively enriched in Hf (Zaraisky et al., 2009). Breiter et al. (2007) noted that granites with Zr/Hf values lower than 25 are promising for prospecting Sn, W, Mo, and Be, whereas the formation of Ta deposits requires Zr/Hf values lower than 10. Indeed, the Nuweibi pluton has $\text{Zr/Hf} < 10$ and is a world-class Ta-Nb ore reserve.

Nb/Ta ratios can be lowered by fractionation of early columbite with Nb/Ta ratios higher than coexisting melt or by sub-solidus hydrothermal alteration. Ballourad et al. (2016) suggested that a Nb/Ta value of ~ 5 is a fingerprint of the magmatic–hydrothermal transition in peraluminous granites and may be used to distinguish between mineralized and barren peraluminous granites. Plotting the Nuweibi samples on a Nb/Ta vs. Zr/Hf diagram (after Ballourad et al., 2016), they lie at low Nb/Ta and low Zr/Hf, in the field of plutons that host Nb-Ta-Sn-Li-Cs-W ore deposits (**Fig. 9b**). Finally, most of the Nuweibi samples have $\text{K/Rb} < 150$, which is characteristic of pegmatite-hydrothermal evolution (Shaw, 1968). On the Y+Nb vs. Rb

discrimination diagram (Pearce et al., 1984), the Nuweibi samples straddle the boundary between the fields of syn-collisional and within-plate granites (**Fig. 9c**), while the granitic country rocks plot in the volcanic-arc field.

In pure magmatic fractionation, the isovalent element ratios Y/Ho and Zr/Hf behave coherently and generally remain close to chondritic ratios, because mineral-melt fractionation is dominated by ionic substitution in mineral lattice sites, for which ionic charge and radius are the principal determining factors. Evolution controlled by these parameters has been labeled CHARAC (CHARGE-RADIUS Controlled) behavior. On the other hand, solubility in aqueous solutions is affected by different chemical properties of the elements, such that leaching or precipitation by fluids leads to non-CHARAC behavior and loss of coherence between isovalent “twin” elements. Highly evolved magmas rich in H₂O, Li, F, B, and Cl are found to display exotic, non-CHARAC Y/Ho and Zr/Hf ratios (Bau, 1996; Irber, 1999). Nuweibi albite granite samples have low Y/Ho (4.3-18.7 except for one sample, compared to the chondritic ratio of 27.7; McDonough and Sun, 1995) and Zr/Hf ratios (3.0-6.8, compared to chondritic ratio of 36.3; McDonough and Sun, 1995). Plotting the Nuweibi samples on a Y/Ho vs. Zr/Hf diagram (Bau, 1996), they lie outside the field of CHARAC behavior (**Fig. 9d**), indicating that even their conventionally fluid-immobile elements were likely modified by interaction with hydrothermal solutions. Similar non-CHARAC behavior has been noted in other highly evolved rare-metal granitoids, such as the Abu Dabbab albite granite (Bau, 1996; Abuaramah et al., 2021).

6.2. Rare Earth Elements

The Nuweibi albite granites are characterized by low abundances of rare earth elements ($\Sigma\text{REE} = 9.4\text{-}116.6$ mg/g). The chondrite-normalized REE patterns are complex, although mostly

coherent across the sample suite except for scattered anomalously low La concentrations, below detection limits in some cases (**Fig. 10**). All patterns display strong negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.01\text{-}0.15$) and exhibit some enrichment of HREE relative to LREE [$(\text{La}/\text{Lu})_n$ from ≤ 0.01 to 0.51). Excepting the La anomalies, the LREE slopes vary from moderately negative to moderately positive [$(\text{Ce}/\text{Sm})_n$ from 0.5 to 2.8] while HREE slopes are uniformly positive [$(\text{Gd}/\text{Lu})_n$ from 0.03 to 0.24]. The strongly negative Eu anomalies, like the low concentrations of Sr and Ba noted above, imply extensive fractionation of feldspars while furthermore requiring conditions sufficiently reducing to stabilize some Eu^{2+} .

Whereas magmatic CHARAC behavior of REEs generates smooth normalized patterns (except for polyvalent Eu and sometimes Ce), irregular patterns may indicate non-CHARAC behavior and hence non-magmatic effects (Bru, 1996). One notable non-CHARAC pattern results from the tetrad effect, a quantum mechanical extra stability of quarter-, half-, three-quarter- and fully-filled 4f electron shells. Tetrad effects break the 15 lanthanide-series elements into four segments of four elements each (the 2nd and 3rd tetrads overlap at Gd) and, depending on whether the outer pair of elements in each tetrad are enriched or depleted in the preserved material relative to the center pair of elements, result in either convex-up “M-type” or concave-up “W-type” chondrite-normalized REE patterns (Monecke et al., 2002). The transport of coexisting fluids out of peraluminous rocks result in M-shaped tetrads in the residual rock and in W-shaped tetrads in the extracted fluids and materials metasomatized by those fluids (Masuda et al., 1987). Visual examination of the Nuweibi albite granite REE patterns reveals prominent M-shaped tetrad groups, especially in the 3rd (Gd-Ho) and 4th (Er-Lu) tetrads (**Fig. 10**). The 2nd tetrad is difficult to observe because Pm has no stable isotopes and Eu anomalies due to valence are larger than tetrad anomalies. In the present data the 1st tetrad is complicated in several

samples by La below detection limits (note, though, that anomalously low La relative to Ce is in fact expected for an M-shaped 1st tetrad).

We apply the procedure of Irber (1999) to quantify the intensity of the tetrad effect in the studied samples. In this method, only the tetrad effect values of the first tetrad ($t_1 \equiv \sqrt{(Ce_n \times Pr_n)/(La_n \times Nd_n)}$), and the third tetrad ($t_3 \equiv \sqrt{(Tb_n \times Dy_n)/(Gd_n \times Ho_n)}$) are considered, as well as the total tetrad effect ($TE_{1,3} \equiv \sqrt{t_1 \times t_3}$). Values of these tetrad parameters larger than unity indicate M-type tetrads; less than unity indicates W-type. Irber (1999) indicated that the tetrad effect becomes significantly visible at $TE_{1,3} > 1.10$. Of the 15 samples with a quantified La measurement, 13 have t_1 values significantly greater than unity (1.36 to 4.46) while only two samples display low t_1 values (0.59 and 0.52). All 21 analyzed samples yield t_3 values significantly greater than unity (1.23 to 1.56). Taking both tetrads together, of the 15 samples where $TE_{1,3}$ can be calculated, 13 show significant M-type values from 1.34 to 3.53. This is a clear manifestation of the M-type tetrad effect in the Nuweibi albite granite. In fact, the visually obvious M-type shape of the 4th tetrad in all these samples is unusually strong; Irber (1999) note that the effect is not usually visible in the 4th tetrad. Clear M-type tetrad patterns are a typical feature of highly fractionated volatile-rich granites that have undergone significant modification by hydrothermal activity (Jahn et al., 2001; Monecke et al., 2002; Broika, and Kubis, 2018).

7. Discussion

One of the most striking features of the Eastern Desert of Egypt, the northwestern segment of the ANS, is the abundance of post-collisional felsic plutons (Azer et al., 2019, 2020; Seddik et al., 2020; Abuamarah et al., 2021). The evolution of the Nuweibi intrusion is discussed here in light of the current data and post-collisional magmatism in the northern ANS.

7.1. Geodynamic setting and magma sources

The field relationships, mineralogy and geochemistry data help to define the geodynamic setting of the Nuweibi intrusion. The present study shows that the Nuweibi intrusion is undeformed and unmetamorphosed. It represents the youngest igneous activity in the study area and intruded the subduction-related granitoids. The dyke swarms that cut the subduction-related calc-alkaline rocks are, in turn, truncated by the Nuweibi intrusion. These criteria indicate a post-collisional setting for the Nuweibi intrusion. Also, the chemical characteristics of the Nuweibi intrusion are consistent with a post-collisional tectonic setting: marked depletion in Sr, MgO, CaO, and transition metals, primitive-mantle-normalized patterns (Fig. 9a) enriched in both LILE and HFSE, and no depletion (quite the opposite, in fact) in Nb or Ta.

A complete spectrum of petrogenetic models from entirely mantle-dominated to entirely crust-dominated have been proposed for post-collisional granites in the ANS (Jarrar et al., 2008; Be'eri-Shlevin et al., 2009; Eyal et al., 2010; Moghazi et al., 2011), but no single model has been suggested that satisfactorily explains all their chemical features. The Nuweibi intrusion shares geochemical characteristics common in intraplate, post-collisional magmas on the ANS: high SiO₂, Na₂O+K₂O, Ta, Nb and Hf along with low CaO, MgO, Ba and Sr. Unsurprisingly, then, all the categories of genetic hypothesis that have been proposed for such magmas in the ANS have been applied specifically to the genesis of the Nuweibi intrusion. These genetic hypotheses have included: (1) metasomatic origin (Sabet et al. 1976; El-Taball 1979; Raid, 1979), (2) magmatic origin (Abou El-Maaty and Ali Bik 2000) and (3) a combination of metasomatic and magmatic origins (Mohamed, 2013; Azer et al., 2019).

The present work indicates that all the granitic rocks of the Nuweibi intrusion were cogenetic and formed from the same magma. The two main rock types of the Nuweibi intrusion

represent different pulses of magma separated from the magma chamber and emplaced at different levels. Magmatic evolution is consistent with simple fractional crystallization, leading to fluid saturation of the residual melt as it became enriched in water, alkalis, and fluorine. The resulting exsolved fluid was buoyant; it segregated and escaped upwards, becoming a metasomatic fluid that caused hydrofracturing and alteration of early-emplaced phases of the overlying granite. The formation of greisen, stockscheider pegmatites, and quartz veins is attributed to action of this magmatically-derived fluid phase, which accumulated in the upper part of the magma chamber and then migrated into fractures at the contact between the albite granite and its country rocks.

The absence of mafic lithologies argues against an origin by extensive fractional crystallization of mantle-derived mafic magma. The peraluminous character of the rocks support the hypothesis that the primary melt was generated by partial melting of a juvenile crustal source, followed by extensive fractional crystallization and fluid interaction to produce the albite granite. The emplacement of the Nuweibi intrusion most probably occurred along Pan-African fractures re-activated by relaxation after the termination of the Pan-African orogeny. This is supported by the distribution of rare-metal granites in the Eastern Desert of Egypt along major faults and shear zones (e.g., Abdel-Rahman 2006).

7.3. Magmatic evolution and mineralization

The observation of very low phosphorus content in the Nuweibi pluton identifies the pluton as a highly fractionated, peraluminous, I-type granite. The $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ (A/CNK) values of the analyzed samples confirm the peraluminous character of the Nuweibi intrusion (Fig. 8b). The low P_2O_5 content of such rocks accentuates the incompatible behavior of elements like Th, U, Y, and REEs, which in higher- P_2O_5 systems are often retained in accessory

phosphate minerals (Alfonso et al., 2018). The highly fractionated affinity of the investigated granites can be confirmed with the granite classification diagram of Sylvester (1989) (Fig. 8d).

The MORB-normalized spider diagram for the Nuweibi granites (Fig. 9a) indicates steadily growing negative anomalies in Sr, Ba, P and Ti alongside increasingly negative Eu anomalies (Fig. 10). The Sr, Ba, and Eu anomalies seem consistent with plagioclase fractionation. P and Ti anomalies most likely reflect fractionation of apatite and Fe-Ti oxides, respectively. The investigated granites have a hypersolvus nature that indicates low water pressure and high temperatures of crystallization (King et al., 2007). The presence of fluorine decreases the solubility of water in melts while simultaneously lowering the crystallization temperature and the viscosity of granitic magmas (Dirghejell, 1985), which may have promoted faster migration of melt and allowed emplacement at shallow levels (Hannah and Stein, 1990).

The Nuweibi intrusion is characterized by the presence of muscovite, low Nb/Ta ratios (0.46-2.94), low TiO_2 (average 0.005 wt %), low Zr (68-146 $\mu\text{g/g}$), low LREE concentrations, and high Ta (15-169 $\mu\text{g/g}$). Stepanov et al. (2014) associated all these characteristics with fractionated leucogranites that yield economic concentrations of Ta. Mechanistically, fractionation of muscovite and columbite from peraluminous magma increase the Ta/Nb ratio, decrease the titanium content, and lead to a residual liquid rich in tantalum (Alfonso et al. 2018).

The low values of Y/Ho, Nb/Ta, and Zr/Hf and obvious M-type tetrad modification of the REE patterns of the rocks represent non-CHARAC behavior that testifies to substantial modification of magmatic trace element abundances by fluid-melt interaction (Bau, 1996). Although fluid-melt interaction in the later stages of fractional crystallization is the most common model for the origin of the REE tetrad effect in granite (e.g., Zhenhua et al., 2002), alternative hypotheses have been offered. Peretyazhko and Savina (2010), for example,

suggested that M-type tetrad effects in rare-metal granites are caused by fluoride-silicate liquid immiscibility, because extracted fluoride melts with strong W-type tetrad patterns leave behind residual silicate melt with M-type patterns. However, Peretyazhko and Savina's (2010) assertion that hydrothermal activity creates only W-type patterns considers only the leaching of REEs by fluids at high temperature; in the magmatic cupola, at low temperature, the M-type pattern in REEs transported upwards by fluids may be redeposited into the evolved high-level magma.

Our findings suggest a major role for hydrothermal activity in shaping the geochemistry of the Nuweibi albite granite. Evidence for such activity includes: (1) K/Rb ratios of 62-101; in felsic granites, $K/Rb < 150$ (Irber, 1999) or < 100 (Claire, 1992) is considered evidence of interaction with an aqueous fluid phase during mineral growth, (2) interstitial crystallization of fluorite and topaz among muscovite and albite indicate the involvement of hydrothermal solutions rich in F at a late stage of crystallization; the texture does not suggest an immiscible fluoride melt, (3) the presence of a strong M-type lanthanide tetrad effect (Jahn et al. 2001), (4) non-CHARAC behaviour of Y/Ho, Hf/Zr, and Nb/Ta ratios (Bau, 1996; Irber, 1999), and (5) alteration overgrowths on the Nb-Ta oxide minerals, as discussed in the next paragraph.

Nb and Ta are hosted by primary columbite-(Mn) and tantalite-(Mn), as well as secondary tantalite-(Fe), wodginite, and fluorcalciomicrolite. The manganoan trend of primary columbite-tantalite series mineralization (Beurlen et al. 2008) and the presence of Sn-rich wodginite (Černý and Ercit, 1989; Van Lichtenvelde et al., 2007) are characteristic of F-rich, highly fractionated granites. The coupled trend towards Mn and Ta enrichment in the columbite-tantalite series indicates progressive magmatic evolution by crystallization of early columbite and Fe-bearing muscovite. However, overgrowth by Ta-dominant fluorcalciomicrolite marks a hydrothermal overprint of the solidified granites (Uher et al., 1998; De Vito et al., 2006). During

the transition from the magmatic stage to the hydrothermal stage, an increase in F activity is associated with further enrichment in Ta/(Ta+Nb), recorded most strongly in the wodginite and fluorcalciomicrocline in the more heavily altered porphyritic phase of the intrusion (Černý et al., 1986; Tindle and Bickle, 1998).

Snowball texture, similar to that seen at Nuweibi intrusion, is observed also in the Mueilha intrusion in the Eastern Desert of Egypt (Abou El Maaty and Ali Bik, 2000; Seddik et al., 2020). The origin of snowball texture has been variously attributed to both metasomatic (Müller and Seltnann, 1999; Wu et al., 2018), and magmatic processes (e.g., Müller and Seltnann, 1999; Li et al., 2000). In the present case, the snowball texture is attributed to magmatic origins on the basis of numerous lines of evidence, including: (1) the albite crystals included in snowball quartz show concentric arrangement with euhedral to subhedral habit; (2) the snowball quartz crystals are uniform in size with subhedral to euhedral outlines and (3) no fractures along which post-magmatic replacement might have occurred are observed within the snowball quartz.

8. Conclusions

- The Nuweibi albite granite is one of the most important occurrences of rare-metal granite in the central Eastern Desert of Egypt. Although it is a small, isolated pluton, it contains the largest known ore reserve of Nb-Ta oxide minerals in the region. The intrusion is distinguished into an older porphyritic phase exposed in the east and a relatively younger nonporphyritic phase exposed to the west. A marginal zone of stockscheider pegmatite and greisen occurs at the upper boundary of the eastern part of the Nuweibi pluton.

- The Nuweibi albite granite is a highly fractionated, peraluminous, I-type, calc-alkaline granite. It features high concentrations of some high field-strength elements (Nb, Ta, Zr, and Hf) and some large ion lithophile elements (Cs, Rb, Pb, U, and Th) alongside low concentrations of Sr, Ba, Ni, Co, V, and REE (especially Eu).
- The fractionated ratios of isovalent trace elements and a very prominent M-type REE tetrad effect demonstrate significant modification of the composition of the Nuweibi pluton by fluid interactions.
- Nb-Ta oxides are common in the porphyritic samples of Nuweibi granite. They occur as composite grains of primary zoned columbite-(Mn) to tantalite-(Mn), overgrown by secondary fluorcalciomicrocline, wodginite, tantalite-(Te), and cassiterite. The presence of wodginite, a Sn-bearing mineral, is a unique fingerprint of highly evolved rare-metal granites.
- The Nuweibi intrusion was generated via partial melting of a juvenile crustal source, followed by extensive fractional crystallization to produce albite granite, leading to saturation with a magmatically-derived, F-rich fluid phase that migrated upwards and most extensively overprinted the early, porphyritic phase of the intrusion.

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Declaration of interests

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.

Supplementary data

Supplementary material

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Figure 1. Regional geological map showing the distribution of late Neoproterozoic basement rocks in the central Eastern Desert of Egypt (modified after Shackleton, 1994), the dividing line between central and southern portions of the Nubian Shield is after Stern and Hedge (1985). Distribution of the most important rare-metal bearing granite intrusions in the central and south Eastern Desert of Egypt: (1) Umm Naggat, (2) Umm Samra, (3) Abu Labbab, (4) Nuweibi, (5) Ineiga, (6) Homrit Waggat, (7) Igla, (8) Zabara, (9) Muweilha, (10) Nugrus, (11) El-Gharabiya, (12) Nikeiba, (13) Homrit Akarem, (14) Um Hibal, and (15) Um Ara.

Figure 2. Geologic map of the Gabal Nuweibi area (modified after Helba et al., 1997).

Figure 3. Selected photomicrographs from the Nuweibi albite granite: image (a) in cross-polarized transmitted light; images (b, c and d) are backscattered electron images. (a) snowball texture in the porphyritic albite granite, (b) columbite altered along margins into

wodginite in the porphyritic albite granite, (c) zoned columbite altered along margins into wodginite, fluorcalciomicrocline and tantalite in the porphyritic albite granite, (d) columbite interstitial to feldspars altered along margins into tantalite. The mineral abbreviations are: Ab = albite, Kfs = K-feldspar, Col = columbite, Ta = tantalite, Wdg = wodginite, Fcm = fluorcalciomicrocline.

Figure 4. Mineral chemistry of muscovite in the Nuweibi intrusion samples. (a) Compositional fields for primary and secondary muscovite in the ternary diagram of Miller et al. (1981), and (b) $\text{Na}/(\text{Na}+\text{K}+\text{Ca})$ vs. $(\text{Fe}+\text{Mg})/(\text{Fe}+\text{Mg}+\text{Ti}+\text{Al})$ variation diagram of muscovite.

Figure 5. Main image: layered image (brightness = backscattered electron contrast, colors = intensity of characteristic X-rays of elements indicated by color scale) of composite heavy mineral cluster in porphyritic sample. Insets: EDS spectra of the four main minerals present, with mineral identification and key mineral chemical indicators.

Figure 6. Main image: layered image (brightness = backscattered electron contrast, colors = intensity of characteristic X-rays of elements indicated by color scale) of composite heavy mineral cluster in porphyritic sample. Insets: EDS spectra of the four main minerals present, with mineral identification and key mineral chemical indicators.

Figure 7. Mineral chemistry of Nb-Ta oxides in Nuweibi intrusion samples: (a) chemical composition and nomenclature of the columbite-tantalite group minerals based on $\text{Ta}/(\text{Ta} + \text{Nb})$ vs. $\text{Mn}/(\text{Mn} + \text{Fe})$ ratios and (b) chemical composition and nomenclature of wodginite-group minerals based on $\text{Mn}/(\text{total A site})$ vs. $\text{Ti}/(\text{total B Site})$.

Figure 8. (a) Classification of the granitoid rocks in the Gabal Nuweibi area using the $\text{R}_1\text{-R}_2$ diagram of De la Roche et al. (1980), (b) Molar $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ versus $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O}+\text{K}_2\text{O})$ for granitoid rocks (after Maniar and Piccoli, 1989), (c) SiO_2 vs.

Na₂O+K₂O diagram of Middlemost (1991), and (d) discrimination diagram of Sylvester (1989) for rocks with > 68 wt.% SiO₂.

Figure 9. (a) Normalized extended trace element diagram; normalization values from Pearce (1983). (b) Zr/Hf vs. Nb/Ta diagram (Ballourad et al. (2016). (c) Y+Nb vs. Rb discrimination diagram (Pearce et al., 1984). (d) Zr/Hf vs. Y/Ho diagram (Bau, 1996).

Figure 10. Chondrite-normalized REE patterns for the Nuweibi granites. Normalization values from Evensen et al. (1978).

Table 1. Major oxide concentrations (wt.%) and CIPW norms of Nuweibi albite granites and their granodioritic country rocks.

Sample No	Porphyritic albite granite										Non-porphyritic albite granite			
	7N W	10N W	11N W	15N W	16N W	17N W	24N W	32N W	35N W	38N W	8N W	13N W	20N W	21N W
SiO ₂	78.80	71.61	72.39	74.15	73.25	72.80	75.86	75.94	73.31	77.40	78.54	78.26	78.23	76.58
TiO ₂	0.01	0.00	0.00	0.00	<d.l.	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00
Al ₂ O ₃	11.98	16.75	16.21	15.16	15.32	16.03	13.59	13.95	15.64	12.79	12.43	12.86	12.93	13.05
Fe ₂ O ₃	0.85	0.16	0.23	0.14	0.05	0.23	0.58	0.11	0.18	0.13	0.51	0.34	0.50	0.51
MgO	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	0.05	<d.l.	<d.l.	<d.l.	<d.l.
CaO	0.01	0.06	0.04	0.08	0.05	0.04	0.13	0.03	0.05	0.39	0.04	0.03	0.01	0.11
Na ₂ O	3.51	7.61	6.53	5.86	6.12	6.35	4.67	5.36	6.32	4.39	4.36	4.67	5.31	3.95
K ₂ O	4.28	2.82	3.49	3.97	3.94	3.67	4.22	3.89	3.43	3.78	3.73	3.30	2.82	5.17
P ₂ O ₅	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.23	0.01	0.05	0.02	0.01	0.03	0.10	<d.l.	0.01	0.00	0.12	0.05	0.08	0.06
LOI	0.33	0.15	0.28	0.21	0.33	0.27	0.28	0.19	0.27	0.72	0.24	0.26	0.24	0.25
Total	99.99	99.18	99.19	99.62	99.15	99.44	99.44	99.48	99.22	99.66	99.97	99.78	100.14	99.69
Quartz	31.75	26.8	28.72	22.26	35.67	35.54	31.63	29.87	23.29	36.75	39.43	30.8	35.76	32.99
Corundum	1.69	1.6	0.57	0.98	0.38	0.75	1.12	0.86	1.45	0.8	1.1	0.75	1.11	0.76
Orthoclase	8.11	23.39	23.03	21.04	23.33	22.07	25.02	23.15	20.44	22.54	26.2	25.81	16.62	30.57
Albite	35.97	47.4	45.29	54.89	38.08	39.96	39.7	45.62	54	37.46	30.5	40.2	44.8	33.51
Anorthite	11.98	0.32	0.79	0.21	1.98	0.22	0.6	0.14	0.22	1.91	0.01	0.6	0.05	0.51
Hypersthene	8.33	0.29	1.25	0.41	0.36	1.11	1.62	0.27	0.48	0.45	2.24	1.45	1.39	1.39
Magnetite	1.27	0.08	0.24	0.09	0.07	0.22	0.28	0.05	0.08	0.06	0.41	0.27	0.24	0.24

Ilmenite	0.68	0.09	0.09	0.09	0.1	0.1	0.01	0.01	0.01	0.02	0.09	0.1	0.01	0.01
Apatite	0.18	0.02	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0	0.01	0.01	0.01
ASI	1.14 8	1.068	1.111	1.074	1.057	1.106	1.089	1.065	1.101	1.065	1.10 1	1.137	1.094	1.062

Table 1. Cont.

Sample No	Non-porphyritic albite granite								Country rocks			
	23NW	34NW	40NW	45NW	46NW	48NW	449NW	50NW	5NW	7NW	19NW	29NW
SiO ₂	75.34	76.40	77.69	77.55	78.00	76.10	76.36	75.75	71.88	70.10	70.27	72.10
TiO ₂	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.32	0.40	0.38	0.30
Al ₂ O ₃	13.94	13.40	12.68	12.64	12.45	13.69	13.36	13.77	14.87	15.16	15.02	14.84
Fe ₂ O ₃	0.51	0.49	0.46	0.51	0.59	0.42	0.47	0.55	2.89	3.65	3.14	2.51
MgO	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	0.00	0.01	0.83	1.24	0.83	0.91
CaO	0.16	0.05	0.05	0.17	0.13	0.11	0.14	0.02	2.49	3.22	2.93	2.31
Na ₂ O	5.27	4.75	4.65	4.18	4.35	4.93	5.06	4.87	4.18	3.28	3.79	3.41
K ₂ O	3.78	4.04	3.59	4.12	3.63	4.19	3.65	3.98	1.35	1.67	2.26	2.40
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.10	0.13	0.10
MnO	0.08	0.02	0.06	0.07	0.08	0.03	0.01	0.07	0.05	0.06	0.06	0.04
LOI	0.32	0.41	0.20	0.38	0.38	0.36	0.42	0.41	0.70	0.71	0.72	0.77
Total	99.40	99.57	99.39	99.63	99.61	99.75	99.41	99.48	99.65	99.61	99.52	99.68
Quartz	29.42	32.77	36.39	36.52	35.22	36.65	31.83	30.66	31.75	30.97	28.17	33.29
Corundum	0.9	1.13	1.06	0.92	0.5	0.65	0.53	1.04	1.69	1.83	0.9	2.14
Orthoclase	22.43	23.99	21.31	21.42	25.35	22.05	22.46	24.46	8.11	9.98	13.45	14.41
Albite	44.79	40.36	39.5	35.48	36.45	38.2	43.05	42.08	35.97	28	32.21	29.26
Anorthite	0.78	0.21	0.24	0.85	0.87	0.63	0.69	0.04	11.98	15.48	13.88	11.19
Hypersthene	1.42	1.3	1.26	1.41	1.28	1.43	1.1	1.33	8.33	11.06	8.9	7.7
Magnetite	0.24	0.22	0.22	0.24	0.24	0.27	0.21	0.26	1.27	1.62	1.4	1.12
Ilmenite	0.01	0.01	0.01	0	0.08	0.09	0.09	0.11	0.68	0.83	0.79	0.64
Apatite	0.01	0.01	0.01	0.01	0	0	0	0.01	0.18	0.21	0.28	0.21
ASI	1.068	1.091	1.090	1.085	1.100	1.074	1.074	1.117	1.155	1.161	1.072	1.197

Table 2: Trace elements concentration (µg/g) of Nuweibi albite granite and their granodioritic country rocks

Element	Met hod *	d. l.	Porphyritic albite granite										Non- porphyritic albite granite			
			7 N	10 N	11 N	15 N	16 N	17 N	24 N	33 N	35 N	38 N	8NW	13 N	20 N	21 N

			W	W	W	W	W	W	W	W	W	W		W	W	W
Sc	IC P- MS	0.4	0.79	0.75	0.43	1.01	0.84	0.71	0.67	0.81	0.94	0.58	1.00	1.19	0.93	0.67
V	ICP - MS	8.0	<d. .1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.
	XR F	1.8	11. .0 5	15. 11	14. 92	12. 82	16. 51	14. 71	13. 90	13. 04	14. 19	13. 47	16.53	14. 49	9.8 9	17. 41
Cr	XR F	2.0	56. .0 4	20. 04	28. 72	21. 69	77. 80	13 0.3 8	34. 76	42. 34	31. 84	43. 62	37.57	39. 97	27. 71	13 0.8 2
Co	IC P- MS	0.4	0.83	0.58	0.56	0.54	0.95	1.24	0.66	0.57	0.68	0.55	0.63	0.64	0.50	1.24
	XR F	1.6	<d. .1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.
Ni	IC P- MS	3.0	33. .5 2	<d. 1.	<d. 1.	<d. 1.	76. 36	15 5.2 6	19. 57	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	13 4.2 2
Cu	IC P- MS	0.1	<d. .1.	0.08	<d. 1.	19. 96	4.7 2	<d. 1.	4.3 4	<d. 1.	3. 2	4.0 7	17.51	0.8 4	<d. 1.	1.4 0
Zn	IC P- MS	1.0	57. 8. 42	11. 92	68. 64	18. 33	26. 18	10 6.6 5	57. 55	11. 01	34. 94	45. 16	359.46	56. 49	28 0.2 4	12 4.2 1
	XR F	1.0	69. 4. 04	16. 04	79. 74	15. 72	27. 65	80 96	59. 55	13 7.1 1	31. 52	72. 32	419.58	62. 61	32 9.4 9	14 8.1 7
Rb	IC P- MS	1.0	64. 8. 27	73. 7.3 4	42. 9.8 2	30. 2.2 9	41. 5.5 6	43. 4.1 2	31. 4.1 2	43. 2.0 1	41. 3.3 3	42. 1.9 0	508.39	39. 8.7 5	32 6.0 6	32 0.8 5
	XR F	1.0	73. 0. 24	36. 8.8 9	49. 9.9 4	35. 4.6 8	46. 5.4 0	52. 5.9 9	36. 9.3 4	50. 6.9 6	48. 0.9 1	53. 5.5 1	579.91	46. 5.0 2	37 0.6 0	36 8.8 1
Sr	ICP - MS	25.0	<d. .1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.
	XR F	0.8	25. .2 7	31. 25	28. 78	30. 74	32. 05	29. 40	27. 22	27. 98	29. 73	35. 98	25.93	31. 76	25. 99	32. 43
Y	IC P- MS	1.0	3. 6	2.4 5	2.8 0	3.1 6	2.5 1	2.7 2	3.1 9	4.3 9	3.3 9	3.4 8	3.92	3.1 9	8.3 2	15. 77
	XR F	1.2	<d. 1.	<d. 1.	<d. 1.	1.9 2	<d. 1.	<d. 1.	1.8 5	1.2 8	<d. 1.	<d. 1.	<d.l.	<d. 1.	8.3 0	16. 33
Zr	IC P- MS	1.0	82. .2 7	52. 29	44. 64	42. 96	40. 54	42. 38	65. 37	83. 19	49. 56	60. 98	85.63	44. 33	10 4.1 3	74. 91
	XR F	0.7	71. .1 1	47. 51	43. 34	35. 30	36. 18	39. 06	55. 97	74. 72	39. 81	62. 57	75.52	39. 84	95. 17	69. 22
Nb	IC P- MS	0.4	15. 4. 91	59. 73	57. 22	69. 68	57. 11	55. 27	83. 81	11 3.1 2	53. 30	95. 98	113.61	73. 26	40. 78	11. 73
	XR F	0.9	16. 6. 65	63. 13	62. 11	75. 06	60. 07	62. 57	91. 46	12 4.9 0	55. 56	11 6.6 0	123.70	81. 03	43. 05	10. 78
Mo	IC P- MS	0.01	0.61	0.85	0.29	1.63	1.77	2.58	0.76	1.01	0.64	<d. 1.	0.20	2.0 9	0.0 1	2.0 3
Cs	IC P- MS	1.0	8.06	0.77	1.13	0.69	0.64	1.16	0.79	1.57	1.31	1.77	4.70	1.4 4	3.6 3	1.2 5
Ba	ICP - MS	25.0	<d. .1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.

	XR F	9. 0	<d .1	23. 35	13. 05	18. 41	13. 16	9.7 2	<d. 1.	<d. 1.	<d. 1.	12. 74	<d.l.	32. 80	<d. 1.	11. 60
Hf	IC P- MS	0. 5	21. .5 9	23. 17	22. 36	21. 86	20. 97	18. 83	17. 51	19. 85	22. 38	19. 84	22.33	21. 78	20. 00	12. 47
Ta	IC P- MS	0. 1	55. .5 6	53. 71	52. 28	13 9.5 6	13 0.3 0	56. 65	46. 95	49. 07	11 6.2 2	45. 38	39.41	16 8.5 3	13. 35	8.6 8
W	IC P- MS	0. 1	0. 78	0.2 8	<d. 1.	0.4 3	0.6 6	0.8 1	0.3 5	0.5 0	0.3 4	<d. 1.	0.20	0.8 2	<d. 1.	0.0 9
Tl	IC P- MS	0. 1	2. 34	1.1 6	1.7 3	1.1 5	1.3 9	1.5 7	1.2 3	1.9 1	1.4 6	1.8 9	1.91	1.4 7	1.0 5	1.1 3
Pb	IC P- MS	1. 5	40 .1 2	41. 68	52. 50	44. 71	38. 28	45. 46	24. 97	28. 55	36. 53	35. 17	56.04	61. 97	43. 83	45. 63
	XR F	1. 6	36 .8 7	31. 88	49. 45	36. 99	32. 67	48. 37	18. 41	24. 95	23. 85	37. 02	63.11	66. 86	47. 64	52. 19
Th	IC P- MS	1. 0	29 .4 1	17. 88	16. 24	19. 01	17. 88	16. 19	22. 52	27. 65	20. 53	23. 83	26.50	19. 86	26. 01	21. 71
	XR F	2. 1	20 .1 3	15. 64	16. 47	14. 12	20. 50	19. 22	18. 55	24. 77	19. 64	18. 80	20.22	22. 54	25. 52	20. 00
U	IC P- MS	1. 0	3. 35	4.2 7	4.6 8	4.0 8	4.6 6	4.2 3	3.7 9	3.8 0	4.4 1	4.6 1	3.22	6.0 4	2.7 0	4.1 5
Nb/Ta			3. 00	1.1 8	1.1 9	0.5 4	0.4 5	1.1 0	1.9 5	2.5 5	0.4 8	2.5 7	3.14	0.4 8	3.2 3	1.2 4
Zr/Hf			3. 29	2.0 5	1.9 4	1.5 1	1.7 3	2.0 7	3.2 0	3.7 6	1.7 8	3.1 5	3.38	1.8 3	4.7 6	5.5 5
Y/Ho			4. 28	9.0 9	18. 67	15. 04	17. 90	6.5 3	26. 97	13. 05	6.4 5	5.8 5	14.46	16. 38	11. 20	12. 20
K/Rb			51 .3 3	69. 26	67. 29	99. 14	72. 63	62. 67	95. 09	70. 14	63. 98	62. 94	56.36	62. 71	68. 53	11 6.3 0
*: Preferred method for each element shown in boldface .																

Table 2. Cont.

Element	Met hod *	d. l.	Non- porphyritic albite granite								Country rocks			
			23 N W	34 N W	40NW	45 N W	46 N W	48 N W	449 N W	50 N W	5N W	7N W	19 N W	29 N W
Sc	ICP -MS	0. 4	1.0 5	0.7 7	1.03	1.0 2	1.1 5	0.8 7	1.37	1.1 6	6.8 0	7.9 5	6.3 2	5.9 2
V	ICP -MS	8. 0	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	35. 47	43. 19	45. 14	36. 59
	XR F	1. 8	16. 12	14. 41	9.86	12. 82	11. 65	14. 64	14.1 3	14. 21	46. 57	58. 08	55. 66	49. 21
Cr	XR F	2. 0	20. 22	45. 63	23.14	18. 85	57. 45	23. 17	18.7 0	45. 54	94. 18	36. 57	32. 24	81. 41
Co	ICP -MS	0. 4	0.5 6	0.5 9	0.61	0.6 0	0.6 2	0.5 6	0.55	1.2 9	5.0 9	6.1 6	4.5 8	4.8 6
	XR F	1. 6	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.	4.6 4	3.3 7
Ni	ICP -MS	3. 0	<d. 1.	<d. 1.	<d.l.	<d. 1.	<d. 1.	<d. 1.	<d.l.	<d. 1.	88. 21	9.8 7	<d. 1.	64. 36

Cu	ICP-MS	0.1	5.27	8.27	6.88	3.44	11.23	<d.l.	<d.l.	11.89	28.22	18.03	18.05	1.20
Zn	ICP-MS	1.0	283.11	299.77	129.91	328.46	436.02	126.11	135.78	256.23	51.92	64.56	44.71	37.07
	XR F	1.0	312.31	356.06	156.38	350.30	349.39	147.51	160.53	295.33	46.71	72.26	58.71	47.28
Rb	ICP-MS	1.0	429.85	450.53	342.50	467.34	428.56	331.69	299.75	408.60	40.12	49.27	44.21	52.51
	XR F	1.0	489.69	533.98	397.91	503.85	476.04	370.63	328.84	450.45	46.57	54.64	50.62	61.56
Sr	ICP-MS	25.0	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	274.62	226.43	270.54	222.97
	XR F	8.8	30.78	30.57	27.58	27.90	28.61	27.02	28.95	27.46	318.59	258.37	311.85	270.98
Y	ICP-MS	1.0	11.45	8.04	5.68	11.05	11.27	11.19	19.62	12.81	11.03	33.45	17.04	12.31
	XR F	1.2	9.87	6.34	3.47	8.71	9.71	12.00	19.82	10.72	14.22	38.97	21.68	16.82
Zr	ICP-MS	1.0	124.50	88.24	91.41	102.41	108.57	88.78	122.31	123.68	112.56	224.03	128.86	94.81
	XR F	0.7	108.68	81.88	79.66	85.27	93.21	77.24	105.26	104.08	138.14	219.99	151.82	117.64
Nb	ICP-MS	0.4	39.91	65.10	129.58	101.57	112.13	38.78	48.17	54.68	4.80	6.34	4.49	5.35
	XR F	0.9	39.90	72.80	145.19	104.20	119.37	40.47	49.68	54.57	4.76	7.41	5.71	5.95
Mo	ICP-MS	0.01	0.07	0.02	0.21	0.22	0.21	0.35	0.95	0.22	1.89	1.22	0.46	2.24
Cs	ICP-MS	1.0	4.52	4.66	3.56	3.55	3.66	3.27	1.46	3.57	1.59	1.79	0.97	1.54
Ba	ICP-MS	25.0	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	354.66	472.41	383.81	459.69
	XR F	9.0	13.01	<d.l.	<d.l.	<d.l.	<d.l.	14.47	9.58	<d.l.	407.60	493.08	434.57	512.35
Hf	ICP-MS	0.5	21.40	17.63	24.58	20.95	23.23	17.53	21.00	22.18	3.37	6.02	3.63	2.82
Ta	ICP-MS	0.1	21.50	31.70	55.43	33.82	42.32	30.83	14.77	19.19	0.56	0.55	0.50	0.63
W	ICP-MS	0.1	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	0.82	0.21	0.86	0.78	0.94	0.14	0.33
Tl	ICP-MS	0.1	1.42	1.70	1.37	1.76	1.55	1.22	1.15	1.91	0.16	0.27	0.17	0.26
Pb	ICP-MS	1.5	54.46	54.10	29.97	63.78	54.23	52.09	48.67	59.00	6.19	6.52	6.07	12.15
	XR F	1.6	52.08	62.91	24.35	55.99	56.06	48.03	45.41	63.81	<d.l.	<d.l.	<d.l.	6.14
Th	ICP-MS	1.0	30.66	24.28	26.27	32.55	27.92	26.81	29.59	28.78	3.14	4.20	3.12	4.99
	XR F	2.1	24.85	22.54	23.83	26.57	23.47	19.61	25.59	26.62	7.47	11.78	9.77	10.72
U	ICP-MS	1.0	4.44	3.15	3.62	3.48	4.34	4.67	5.23	4.69	1.45	1.81	0.89	1.36
Nb/Ta			1.45	2.30	2.62	3.08	2.82	1.31	3.36	2.84	8.49	13.45	11.34	9.45
Zr/Hf			4.64	4.64	3.24	4.08	4.04	4.41	5.01	4.69	40.98	36.53	41.77	41.75
Y/Ho			12.22	13.09	5.56	9.28	10.77	14.90	13.14	9.60	10.77	14.90	13.14	9.60
K/Rb			68.37	69.76	80.60	72.09	67.83	97.71	99.84	78.42	27.94	28.20	424.85	379.01

												6	7		
*: Preferred method for each element shown in boldface .															

Table 3: Rare Earth element concentrations ($\mu\text{g/g}$) of Nuweibi albite granites and their granodioritic country rocks

Sample No	Porphyritic albite granite										Non-porphyritic albite granite			
	7N W	10N W	11N W	15N W	16N W	17N W	24N W	33N W	35N W	38N W	8N W	13N W	20N W	21N W
La	2.65	<d.l.	<d.l.	<d.l.	0.06	<d.l.	<d.l.	<d.l.	0.25	1.68	5.12	0.41	6.40	4.36
Ce	12.34	2.47	1.94	5.59	4.04	3.71	<d.l.	3.48	6.20	7.02	17.15	10.08	20.41	15.64
Pr	1.88	0.47	0.66	0.58	0.83	0.56	0.14	0.16	1.23	1.22	3.17	1.43	4.93	3.22
Nd	4.34	1.36	1.68	1.34	1.97	1.61	0.61	0.61	2.91	2.92	7.40	3.38	16.14	11.07
Sm	1.45	0.76	0.93	0.81	0.89	1.00	0.59	0.51	1.51	1.09	2.19	1.57	5.42	3.88
Eu	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Gd	0.79	0.47	0.54	0.47	0.46	0.57	0.50	0.46	0.77	0.51	1.12	0.74	3.20	2.31
Tb	0.31	0.20	0.27	0.26	0.21	0.27	0.18	0.20	0.33	0.25	0.39	0.35	0.90	0.68
Dy	2.73	1.73	2.43	2.28	1.87	2.27	1.37	2.03	2.79	2.39	3.12	2.84	6.05	5.25
Ho	0.57	0.36	0.46	0.43	0.38	0.42	0.29	0.49	0.52	0.55	0.62	0.55	1.08	1.18
Er	2.61	1.54	1.88	1.82	1.67	1.67	1.15	2.47	2.11	2.80	2.77	2.45	4.17	5.23
Tm	0.83	0.51	0.60	0.58	0.55	0.55	0.34	0.84	0.64	0.97	0.90	0.81	1.11	1.45
Yb	9.09	5.46	6.64	6.13	6.02	5.96	3.64	9.00	6.96	11.42	9.99	8.92	10.71	14.49
Lu	1.41	0.84	1.00	0.92	0.85	0.86	0.62	1.43	1.02	1.83	1.64	1.31	1.63	2.47
ΣREE	41.04	16.19	19.05	21.24	19.22	19.46	9.44	21.70	27.29	34.74	55.62	34.85	82.18	71.28
Eu/Eu*	0.09	0.15	0.10	0.11	0.12	0.10	0.14	0.15	0.09	0.11	0.06	0.08	0.02	0.03
(La/Yb) _n	0.20				0.01				0.02	0.10	0.35	0.03	0.41	0.20
(La/Sm) _n	1.14				0.04				0.10	0.96	1.46	0.16	0.74	0.70
(Gd/Lu) _n	0.07	0.07	0.07	0.06	0.07	0.08	0.10	0.04	0.09	0.03	0.08	0.07	0.24	0.12
(La/Lu) _n	0.19				0.01				0.03	0.10	0.32	0.03	0.41	0.18
(Ce/Sm) _n	2.05	0.78	0.50	1.66	1.10	0.90		1.66	0.99	1.56	1.89	1.56	0.91	0.97
t ₁	1.960				7.519				4.436	1.871	1.653	4.458	1.363	1.410
t ₃	1.518	1.600	1.803	1.879	1.654	1.780	1.473	1.477	1.686	1.628	1.465	1.723	1.388	1.265
TE _{1,3}	1.725				3.527				2.735	1.745	1.556	2.771	1.375	1.336

Table 3. Cont.

Sample No	Non-porphyritic albite granite									Country rocks			
	23NW	34NW	40NW	45NW	46NW	48NW	449NW	50NW	5NW	7NW	19NW	29NW	

La	3.71	2.04	2.90	12.29	2.80	7.74	13.78	3.19	11.12	19.17	10.81	16.54
Ce	12.69	13.88	12.55	33.62	11.13	10.90	8.16	23.56	21.19	41.41	22.37	30.36
Pr	3.33	1.93	1.95	6.95	3.21	4.87	8.79	2.11	2.51	5.18	2.89	3.49
Nd	10.83	5.86	4.46	19.96	10.87	15.52	28.45	5.80	9.57	21.08	11.86	12.61
Sm	4.04	1.86	1.32	5.77	4.02	4.51	8.87	2.05	2.10	4.68	2.66	2.48
Eu	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.78	1.05	0.76	0.73
Gd	2.50	1.03	0.76	3.02	2.51	2.56	5.08	1.54	1.96	4.97	2.65	2.29
Tb	0.79	0.36	0.35	0.81	0.75	0.70	1.26	0.63	0.33	0.84	0.44	0.36
Dy	5.66	2.96	3.58	5.47	5.75	5.20	7.94	5.95	1.96	5.49	2.82	2.06
Ho	1.11	0.71	0.86	1.04	1.17	1.15	1.52	1.40	0.38	1.12	0.57	0.40
Er	4.82	3.59	4.33	4.32	5.27	5.62	6.61	7.11	1.13	3.40	1.68	1.21
Tm	1.46	1.22	1.43	1.29	1.62	1.66	1.91	2.09	0.19	0.53	0.27	0.19
Yb	15.70	13.42	16.38	14.22	18.10	17.16	20.56	20.50	1.34	3.57	1.79	1.37
Lu	2.61	2.26	2.63	2.47	3.15	2.91	3.67	3.38	0.21	0.54	0.27	0.21
ΣREE	69.28	51.14	53.52	111.27	70.39	80.52	116.53	79.29	54.76	113.04	61.83	74.30
Eu/Eu*	0.03	0.06	0.08	0.03	0.03	0.03	0.03	0.05	1.17	0.66	0.87	0.93
(La/Yb) _n	0.16	0.10	0.12	0.59	0.11	0.31	0.46	0.11	5.63	3.65	4.11	8.18
(La/Sm) _n	0.57	0.68	1.37	1.33	0.44	1.07	0.97	0.97	3.31	2.56	2.54	4.16
(Gd/Lu) _n	0.12	0.06	0.04	0.15	0.15	0.11	0.17	0.06	1.14	1.13	1.23	1.33
(La/Lu) _n	0.15	0.09	0.11	0.52	0.05	0.28	0.39	0.10	5.45	3.67	4.21	8.07
(Ce/Sm) _n	0.76	1.80	2.30	1.41	0.67	0.58	0.22	2.78	2.44	2.14	2.03	2.96
t ₁	1.415	2.065	1.899	1.346	1.495	0.918	0.590	2.260	0.975	1.005	0.979	0.984
t ₃	1.406	1.331	1.536	1.312	1.344	1.229	1.258	1.462	1.020	1.006	1.003	0.996
TE _{1,3}	1.410	1.658	1.708	1.329	1.417	1.062	0.862	1.818	0.997	1.006	0.991	0.990

Graphical Abstract

Highlights

- Nuweibi intrusion is a prime example of the rare-metal granites of Egypt
- It contains cogenetic porphyritic and non-porphyritic albite granites
- It is extensively fractionated rare-metal granite with peraluminous character
- REE patterns show prominent M-type tetrad effects due to hydrothermal activity
- Primary magma was a partial melt of the juvenile continental crust