Pan-African rare metals bearing pegmatites in Wadi Ghadir, South Eastern desert, Egypt: the geochemical evolution and implications for mineralization

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Abstract

Quartz-diorites, monzogranites and pegmatites are the main rock units in the studied area. The pegmatites occur as zoned pockets within monzogranites with zonal arrangement: border, wall, intermediate, and core zones. The wall zone have enrichment of radioactive and RREs-bearing minerals. K-feldspar, plagioclase and quartz are essential minerals, whereas uranophane, columbite, zircon, xenotime, monazite, sphalerite and pyrite are accessories. Geochemically, the pegmatites of W. Ghadir have peraluminous character, ferroan with alkalic–calcic affinity and emplaced in within plate setting. These pegmatites revealed Li-bearing variety and high level of rare earth elements mineralization. The studied pegmatites exhibit high contents of Li, Nb, Cu, Ta, U, Th, Pb, Zr, Zn and Ga, can be from the previous data, the studied pegmatites can be classified as a Niobium–Yttrium–Fluorine (NYF) pegmatite or rare metal pegmatite. The trace elements ratio supports a low degree of fractionation and metasomatism in the evolutionary history of the pegmatites, and the very low Cs values (2.2–4.3 ppm) indicate paucity of alkali metal fractionation. Spectrometric investigation revealed that monzogranites are not uraniferous, while the radioactive anomaly is confined to the pegmatites. Applying the U mobilization equation proved that pegmatite samples have been originated from a late magmatic phase of magma very rich in radioelements, and the pegmatites affected with hydrothermal solutions rich in uranium than thorium which indicates uranium addition. Radioactive and important heavy minerals are represented by uranophane, columbite, zircon, monazite, xenotime, sphalerite and pyrite.

Keywords Rare Metals Pegmatite · Geochemistry · W. Ghadir · Eastern Desert · Uranium · Egypt

1 Introduction

Pegmatites define as a case of highly evolved granitic melts which result of protracted fractional crystallization [41] and are of scientific interest as they display complex and diverse textures, mineralogy, structures, and petrogenetic relationships, with evolved geochemical signatures, which have challenged petrologists in terms of the origin and processes of formation.

Pegmatites represent an important source of rare metals, such as Li, Rb, Cs and Ta. In addition, they have been considered a potential source of other rare metals, such

as Ga, Be, Sn, U, Nb, Hf, among others [38]. Pegmatites are, in addition, a source for high-quality industrial minerals (mainly feldspars, kaolinite, quartz, micas, and spodumene for ceramics) or gemstones such as topaz, tourmaline, aquamarine, spodumene, among others [41].

C`erny' [14] defined the 'pegmatite group' as the basic genetic unit of association among individual pegmatite bodies. Differentiation seen in a group of pegmatite dikes is thought to originate from differentiation of a common source pluton, such that continuous or episodic melt extraction, coupled with continuous crystallization, produces the regional zonation toward more fractionated,

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distal pegmatites (e.g., Trueman and Cerný [62]; Černý [15]).

Cerný and Ercit [13] classified the pegmatites based on the work of Ginsburg et al. [24] into three families considers a combination of emplacement, depth, metamorphic grade, and minor element contents: (I) Lithium–Cesium–Tantalum (LCT) pegmatites, (II) Niobium–Yttrium–Fluorine (NYF) pegmatites and (III) Mixed LCT–NYF pegmatites. The high-field-strength element (W, Zr, Nb, Ta, Ti, Sn, Hf, Th, and U) oxides found in pegmatites are of particular interest in industry owing to their use in high-tech commodities, and to scientists, as recorders of pegmatite evolution. However, the investigations are generally focused on the most evolved granitic pegmatites of LCT geochemical signature, especially in the REL–Li subclass [23].

Most of radioactive occurrences in the basement rocks of Egypt are located in the younger granites and related pegmatites. The latter have been considered as favorable uranium and thorium mineralization environments [50]. Many localities in the Eastern Desert of Egypt have a radioactive pegmatites, e.g., the pegmatitic bodies of the Gabal Ras Baroud younger granites [53] uranium and columbite mineralization in the pegmatites related to the Gabal Abu Dob younger granites [27], and radioactive pegmatites related to the Gabal El-Sibai alkali feldspar granites [2]. Anomalous pegmatites associated with granitic rocks have also been reported in the southern part of the Eastern Desert [3, 28], Abdel Warith et al. [1]. The high level of radioactivity of these rocks is attributed to the presence of accessory minerals such as zircon, monazite, thorite, uranothorite and allanite [57]. Uranium and thorium are generally enriched in the youngest, most felsic and most potassic members of comagmatic suites of igneous rocks [54].

The study of Nb–Ta minerals is of great interest from both economic and scientific point of view. New high technologies [38] and 2014), especially those for the manufacture of electronic devices of small dimensions, have caused an increase in the need for tantalum [42] and [48]. Columbite-group minerals with a chemical formula $(\text{Fe,Mn})(\text{Nb,Ta})_2\text{O}_6$ are the most important minerals in which Nb and Ta are major components. They commonly occur in pegmatites and highly evolved granites Cerný and Ercit [12, 20]. Recent studies show that the chemistry of columbite-group minerals possibly reflects the chemistry of magma sources and pegmatite melts [46]. These compositional variations of columbite-group minerals can potentially reveal fractionation of pegmatite melts as well as hydrothermal evolution of pegmatites [4].

Columbite-tantalite minerals commonly have a broad range of U contents that may reach several thousand ppm and may substitute Fe and Mn in their crystal lattice,

but for high U-contents may form phases of its own (e.g., uraninite, [55]). Rare metal pegmatites are small and chemically highly evolved portions of much larger composite granite intrusions which themselves form granite provinces and reflect episodes of partial melting in the lower continental crust (Cerný 1982). Pegmatite melts are enriched in volatile and incompatible components (incompatible with respect to the main granitic mineral phases) and may move along fractures up to several kilometers away from their igneous parent intrusions due to low viscosity and low density [33].

The present study aims to describe the geology, petrography, and geochemistry of rare-metal-bearing pegmatites in W. Ghadir, south Eastern Desert, Egypt, and focuses on geochemical evolution and mineralization.

2 Geological setting

El-Sharkawy and El-Bayoumi [19] classified the rocks that crop out along the eastern Ghadir as granites belonging to the older and younger (Gattarian) granites. Takla et al. [59] classified the granitoids of W. Ghadir as (a) diorites and granodiorites, which have similar characteristics to the older granites and (b) the younger granites that have similar characteristics to alkali and other anorogenic granitic suits. Ibrahim and Ali [29] subdivided the granitoid rocks in the Ghadir area according to their field relationships, petrography and geochemical characteristics into two types—the first one includes quartz diorite and gneissose granodiorite. They have a metaluminous characteristic and were emplaced during pre-plate collision under high water–vapor pressure and the second one is represented by perthitic leucogranite and muscovite–biotite granite. They were emplaced during syn-collision at moderate water–vapor pressure. Kamar [35] classified the pegmatites in W. Ghadir into zoned pockets and zoned lenses (fractured). The zoned pegmatite pockets have gradational contacts with its host monzogranite and have the following zonal arrangement: border, intermediate, and core zones. They can be considered as anomalous granites. The zoned pegmatite lenses are structurally controlled as they are arranged in more or less one trend along the fracture with a major fault striking NE–SW. They have intermediate and core zones. He also classified the heavy minerals into several groups according to its anion groups: (1) silicate (thorite), (2) carbonate (bastnäsite), (3) fluoride (fluorite), (4) oxides (columbite and hematite), (5) sulfide (pyrite), and (6) hydroxide (goethite and illite). Mahmoud et al. [43] classified the granitoid rocks to granodiorites and syenogranites. They recorded monazite, pseudo-autunite, goethite, hematite, pyrite, cinnabar, wulfenite, galena, natro-jarosite, titanite, and anatase in the stream

sediments. Khaleal et al. [36] studied the granitoid rocks north W. Ghadir and classified them into, quartz-diorite, granodiorite and monzogranite. The fresh monzogranite suffered alteration processes and rich in sulfides. The propylitic alteration as well as the K-metasomatism is the main alteration types in the altered monzogranite, while plagioclase destructed and formed epidote. The identified heavy minerals are mostly pyrite, sphalerite, galena, monazite, hematite and goethite EPMA analyses proved that pyrite mineral is rich in Co and Se and low values of Mn and Cu.

The studied area is nearly located at the middle part of W. Ghadir, lying at about 30 km south of Marsa Alam

City between latitudes $24^{\circ} 48' 09''$ and $24^{\circ} 49' 33''$ N and longitudes $34^{\circ} 52' 05''$ and $34^{\circ} 54' 05''$ E (Fig. 1).

This area was previously mapped by Takla et al. [58, 59], and they interpreted its geologic history as the following: (1) Old metamorphic rocks, composed of biotite granodiorite gneisses, migmatitic granite gneisses, granite mobilizates and amphibolite enclaves, (2) Ophiolitic mélange and (3) Intrusive granitoids that composed of diorites, granodiorites and granites.

The studied area (Fig. 1) is characterized by low-to-moderate relief and consists of older and younger

Fig. 1 **a** Location and **b** detailed geological maps of W. Ghadir area, SED, Egypt (modified after [58])

granitic rocks. These rocks are classified into quartz-diorite, monzogranites and pegmatites.

The quartz diorites are dark greenish gray color and medium- to coarse-grained. These rocks are cavernous, exfoliated, jointed, faulted and dissected by basic dykes. They are intruded by monzogranites with sharp intrusive contacts. The monzogranites are medium-to coarse-grained with a pink color forming moderate relief mountain terrains. They attain cavernous weathering, exfoliation and joints (Fig. 2a) and also dissected by basic dykes. Many of these joints are filled by copper mineralization and/or pegmatite veins. Some fractures exhibit alteration products represented by hematization and silicification and record high radioactivity rather than the surrounding fresh monzogranites.

The pegmatites occur as zoned pockets within the monzogranites. These pockets range in dimension from 4 to 30 m in width and from 10 to 50 m in long. They have gradational contacts with its host monzogranites, and also dissected by basic dykes (Fig. 2b and c). The pegmatite pockets have the following zonal arrangement: border, wall, intermediate, and core zones (Fig. 2d). Border zones consist of a thin fine-grained granitic rock at the contact with host rock. Inward from the border, the wall zone is marked by an abrupt increase in crystal size and characterized by the presence of significant mineralization. The intermediate zone forms gradational contacts with wall zone and larger in crystal size, where intergrowths resulting in K-feldspar and quartz of large crystal size. The core zone formed only from pure quartz or/and K-feldspars. Sometimes quartz is highly shearing specially at the fault zone (Fig. 2e). The wall zone is characterized by visible columbite mineral (Fig. 2f).

3 Methodology

Ten representative pegmatite samples were analyzed for their major, trace elements and rare earth elements at the ACME Analytical Laboratory, Vancouver, Canada. Major element contents were determined by ICP-ES (inductively coupled plasma emission spectrometry). Trace elements (including REEs) were also determined by ICP-MS (inductively coupled plasma mass spectrometry). The LOI (loss on ignition) values were measured on the basis of weighting the samples before and after one hour of heating at 1000 °C. The data of the analytical samples are tabulated in supplementary Tables (Tables 1, 2 and 3).

Field ground γ -ray spectrometry survey has been done using γ -ray spectrometric multichannel analyzer instrument model RS-230 Canadian Type. Ground γ -ray spectrometric survey can detect dose rate (D.R.) in unit (nanosieverts per hour (nSvh^{-1})), potassium (K%), equivalent

uranium content (eU ppm), and equivalent thorium content (eTh ppm).

The selected samples of pegmatites have been crushed to –60 mesh size followed the quartering of crushed sample to obtain representative sample of about 100 g for each one. Bromoform (sp. gr. = 2.89) were used to separate heavy minerals. The magnetite was separated from each heavy fraction by using a hand magnet. The magnetite free fractions were fractionated using the Frantz isodynamic separator at 0.08, 0.2, 0.5, 1.0 and 1.5A. This was followed by hand picking under binocular microscope in order to obtain pure mineral separates. Thin polished sections and separated grains were identified by Scanning Electron Microscope (SEM) back-scattered images supported by energy-dispersive spectrometer (EDS) unit (model Philips XL 30 SEM) at the laboratory of the Nuclear Materials Authority (NMA) of Egypt.

4 Results

4.1 Petrography

Petrographically, the monzogranite is essentially composed of quartz, k-feldspar, plagioclases and biotite. Opaques and zircon are accessory minerals. Chlorite, epidote and sericite are secondary minerals. Quartz occur as anhedral crystals of various shape and size, showing moderate to strong undulose extinction but sometimes show uniform extinction due to secondary quartz. Quartz crystals sometimes show evidence of ductile and brittle deformation and displacement as strike slip faults along fault planes (Fig. 3a). K-feldspar is represented by microcline perthite with some minor amount of orthoclase perthite, showing simple twinnings. They are corroded with secondary quartz crystals along their peripheries. Plagioclases occur as subhedral to anhedral tabular crystals of albite-oligoclase in composition. They are cloudy crystals due to partial alteration to sericite and secondary muscovite exhibiting certain twin lamellae at the core of crystals. Sometimes, they enclose zircon, opaques and anhedral quartz as inclusions. Biotite occurs as subhedral to anhedral tabular or flaky crystals, show slight altered to pale green chlorite and iron oxides along their cleavage planes. Opaque minerals occur as irregular patches related to biotite, scattered between essential minerals. Zircon (Fig. 3b) and epidote occur as subhedral crystals enclosed within biotite and feldspars.

The pegmatite (wall zone) shows evidence of post-crystallization hydrothermal alteration in thin section, especially along joint planes which filled by radioactive-bearing minerals and opaques. The pegmatite is essentially composed of K-feldspar, which is mostly represented by

Fig. 2 **a** Sub-vertical jointing in monzogranites, W. Ghadir, SED, Egypt. Looking NE **b** and **c**: Gradational contact between pegmatite body and its hosting monzogranites, W. Ghadir, SED, Egypt. And Notice, a basic dyke is cutting both of them and affected by a left lateral strike-slip fault. **d** Sketch showing zonation order in pegmatite pockets and its relation with hosting rock, W. Ghadir, SED, Egypt. **e** Pegmatite pocket mainly composed of K-feldspar and quartz (sheared qz), W. Ghadir, SED, Egypt. **f** Visible columbite in K-feldspar of pegmatite pocket, W. Ghadir, SED, Egypt

Table 1 Major oxides and CIPW norm for the studied granitic pegmatite, W. Ghadir area, SED, Egypt

S. no	GP1	GP2	GP3	GP4	GP5	GP6	GP7	GP8	GP9	GP10
SiO ₂	72.6	72.2	69.3	72.5	72.8	73.4	73.1	72.9	72.1	73.2
TiO ₂	0.06	0.05	0.11	0.07	0.09	0.08	0.07	0.04	0.08	0.06
Al ₂ O ₃	14.25	13.87	15.34	13.81	13.60	13.66	12.81	13.59	14.11	12.85
Fe ₂ O ₃ ^t	3.50	3.87	4.95	2.87	3.20	2.80	5.22	3.63	3.02	3.06
MgO	0.13	0.15	0.27	0.18	0.23	0.17	0.18	0.10	0.18	0.15
MnO	0.07	0.06	0.16	0.06	0.08	0.08	0.23	0.11	0.05	0.03
CaO	0.35	0.41	0.55	0.57	0.45	0.50	0.84	0.38	0.53	0.42
K ₂ O	3.65	3.58	3.94	4.32	4.28	4.25	3.76	3.60	3.59	4.26
Na ₂ O	4.80	5.32	4.81	5.03	4.62	4.82	2.97	5.11	5.56	4.27
P ₂ O ₅	0.02	0.04	0.04	0.02	0.02	0.02	0.03	0.02	0.04	0.02
LOI	0.7	0.4	0.6	0.5	0.7	0.4	0.8	0.5	0.7	0.9
total	100.13	99.95	100.05	99.95	100.07	100.18	100.01	99.98	99.96	99.22
CIPW-norm										
Q	29.84	26.60	24.72	25.36	28.35	27.83	39.49	28.48	24.74	30.97
C	1.81	0.607	2.28	0	0.62	0.258	2.41	0.641	0.21	0.48
Or	21.57	21.14	23.28	25.56	25.27	25.13	22.21	21.29	21.21	25.20
Ab	40.85	45.008	40.67	42.52	39.066	40.78	25.09	43.28	47.016	36.13
An	1.63	1.74	2.44	2.36	2.07	2.38	3.97	1.73	2.40	1.98
Di	0.00	0	0	0.26	0	0	0	0	0	0
Hy	0.33	0.37	0.66	0.33	0.58	0.41	0.45	0.25	0.45	0.37
Mt	0.05	0.044	0.206	0	0	0.05	0.545	0.25	0	0
Il	0.12	0.10	0.20	0.13	0.17	0.15	0.14	0.07	0.12	0.07
Hm	3.47	3.845	4.805	2.87	3.203	2.77	4.84	3.46	3.02	3.06
Tn	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ru	0.00	0	0	0	0.001	0	0	0	0.016	0.027
Ap	0.04	0.10	0.10	0.05	0.05	0.04	0.07	0.05	0.09	0.04

Fe₂O₃^t = total iron as Fe₂O₃

both orthoclase and orthoclase microperthite. Orthoclase occurs as euhedral to subhedral crystals and shows simple twinning. The microperthite are slightly altered to kaolinite. Quartz occurs as subhedral to anhedral crystals, with some crystals showing undulose extinction and irregular boundaries. Plagioclase exists as euhedral to subhedral crystals and has albite (An_{6–10}) composition. It exhibits albite and Carlsbad twinning and sometimes forms antiperthite texture. Partial alteration to kaolinite and sericite is developed. Local strain affecting pegmatites results in distortion of twinning in plagioclase crystals (Fig. 3c). Biotite occurs as subhedral flakey crystals and engulfing opaque minerals. Muscovite forms subhedral to anhedral flakey crystals and mostly filling the interstitial spaces between the major constituents especially plagioclase (Fig. 3d and e). Titanite forms subhedral to anhedral rhombic crystals and are associated with biotite. Opaques occur as subhedral to anhedral crystals usually filling the fractures and joints planes especially in plagioclases (Fig. 3f).

The doleritic dyke is fine- to medium-grained with dark green to light green colors. They are mainly composed of plagioclases, pyroxene, hornblende and opaque minerals. Plagioclases occurs as fine- to medium-grained subhedral to anhedral crystals of andesine to labradorite (An_{46–58}) in composition. They exhibit albite and albite/Carlsbad twinning and shows partial to complete alteration to saussurite and calcite (Fig. 3g). Pyroxene is represented by augite (Fig. 3h) and occurs as subhedral to anhedral crystals. It shows alteration to tremolite and actinolite due to deuteric effects. Hornblende exists as subhedral to anhedral crystals and shows partial to complete alteration to chlorite especially along the cleavage planes and crystal boundaries. Opaque minerals occur as anhedral crystals and associated with the mafic constituents. Titanite forms anhedral crystals associated with plagioclases and ferromagnesian minerals.

Table 2 Trace elements concentration (ppm) and geochemical parameters for granitic pegmatite of W. Ghadir area, SED, Egypt

S. no	GP1	GP2	GP3	GP4	GP5	GP6	GP7	GP8	GP9	GP10
Mo	11.97	6.3	26.88	9.49	8.21	5.16	87.17	14.3	6.22	5.15
Cu	419.2	122.2	212.8	73.3	157.6	46.3	695.9	153.6	95.4	49.4
Pb	2978.24	133.75	891.66	220.54	411.43	111.41	4902.89	336.44	185.69	44.72
Zn	900.4	1225	694.2	496.5	4847.7	249.3	2169.3	725.2	620.2	447.8
Ni	4	4.2	7.5	5.6	17	4.6	11	3.4	5.9	4.4
Co	1.9	2.3	3.8	3.3	4.6	3.4	3.4	1	3.5	2.9
As	2115	5.5	4.2	12.2	17.5	3.2	270	64.9	5.6	3.8
U	1120.7	114.7	118.4	85.5	245.8	79.8	933.1	82.9	156.2	71.7
Th	470.8	4000	1942.9	265.2	359.5	300	902.2	2551.9	2787.5	154.9
Sr	77	32	45	43	34	33	67	40	38	32
Bi	32.12	34.18	46.3	10.5	15.68	13.05	107.28	17.8	24.68	15.64
V	7	4	9	6	7	6	7	3	5	5
Cr	17	7	17	17	19	7	53	21	8	7
Ba	176	84	102	87	105	85	122	91	91	87
W	18.2	16.1	18.8	14.5	20	10	19	13.1	11.3	9.8
Zr	242.4	423.6	403.4	428.4	513.3	360.1	657	392.3	425.2	332.2
Sn	53.6	22	19	23.3	19.6	19.8	192.8	70.3	18.6	14
Be	7	162	5	8	8	9	15	32	100	7
Sc	1.7	2.3	1.7	1.5	1.5	1.5	3.7	2.2	2	1.4
Y	396.2	319.5	179.6	125.5	176.8	98.1	738.9	237	264	80.6
Hf	18.09	23.63	30.61	30.1	36.66	27.04	44.53	26.34	28.69	20.4
Li	139.2	905.5	292.2	103.1	284.9	576.6	492	552.7	547.1	111.8
Rb	452.9	539.9	489.3	488.3	602.6	677.1	706.6	615.1	340.7	471.5
Ta	114.3	73.6	132	97.4	81.4	61.7	150.5	100.7	78.4	50.9
Nb	797.72	533.56	903.57	708.79	631.56	544.2	1341.9	783.21	786.2	417.64
Cs	2.2	4.3	3.2	3.2	3	2.8	2.4	3.9	2.6	3.3
Ga	62.91	69.61	64.83	64.26	66.39	60.48	61.56	71.31	68.32	55.96
Geochemical parameters										
Nb/Ta	6.98	7.25	6.845	7.277	7.759	8.82	8.92	7.78	10.03	8.205108
Zr/Hf	13.40	17.93	13.18	14.23	14.0	13.32	14.75	14.89	14.82	16.28431
K/Cs	16,590.45	8320.06	12,309.37	13,513.96	14,254.28	15,186.4	15,659.63	9235.17	13,806.42	12,921.93
K ₂ O/Rb	0.008	0.0066	0.008	0.0089	0.0071	0.0063	0.0053	0.0059	0.011	0.009044
K/Rb	80.59	66.26	80.50	88.56	70.96	62.80	53.19	58.55	105.36	90.43983
K/Ba	207.38	425.91	386.18	497.07	407.27	500.26	308.06	395.79	394.47	490.14
Rb/Sr	5.88	16.87	10.87	11.36	17.72	20.52	10.55	15.38	8.97	14.73
Th/U	0.42	34.87	16.41	3.10	1.46	3.76	0.97	30.78	17.85	2.16
Y/Ho	22.13	21.73	18.14	17.93	18.61	18.17	20.87	19.92	22.76	18.74

5 Geochemistry of pegmatite

5.1 Geochemical characteristics of major oxides and selected trace elements

The whole-rock major and trace element compositions for W. Ghadir pegmatites are presented in Tables 1 and 2. Based on the R_1 – R_2 discrimination diagram of De La Roche et al. [18], the studied pegmatites plot in alkali feldspar granites field (Fig. 4a). The studied pegmatites are peraluminous magma type on Shand's index diagram (Fig. 4b).

Pearce et al. [51] discriminated between the different tectonic settings of the granitic rocks by plotting Y + Nb versus Rb (Fig. 4c). The figure reveals that the studied pegmatite samples plot in the within plate granite field.

According to the binary relation between $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{MgO})$ vs. SiO_2 , pegmatite samples fall in ferroan field (Fig. 4d, [22], Frost and Frost [21]). This is attributed to the variable amounts of biotite, ilmenite and magnetite with various degrees of hematization. Using the SiO_2 vs. $(\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO})$ diagram reveals that most of the studied pegmatites plot in the alkalic–calcic field (Fig. 4e [22]).

Table 3 Rare earth elements concentration (ppm) for granitic pegmatite of W. Ghadir area, SED, Egypt

S. no	GP1	GP2	GP3	GP4	GP5	GP6	GP7	GP8	GP9	GP10
La	28.9	45.2	23.9	9.4	15.7	10.2	45	25.1	38.8	8.2
Ce	91.24	217.47	170.57	55.61	82.49	46.75	201.92	175.56	170.03	36.76
Pr	16.7	24.8	7.6	4.7	8.4	4.2	30.9	13.4	19.6	3
Nd	43	54	17.8	11.6	20	11.3	76.9	31.4	45.4	9.3
Sm	22.2	23.1	7.3	5.3	8.4	4.1	36.9	13.5	18.7	2.9
Eu	0.5	0.3	0.2	0.2	0.3	0.3	0.8	0.2	0.4	0.2
Gd	23.6	18.7	7.3	6	8.9	4.8	36.1	12	15.4	4.1
Tb	9.3	7.6	3.9	2.6	4.2	2.1	16.6	5.5	6	1.7
Dy	69.9	58.2	36	24.5	35	18.1	134.8	45.6	46.6	14.6
Ho	17.9	14.7	9.9	7	9.5	5.4	35.4	11.9	11.6	4.3
Er	64.2	50.6	40.5	28.7	37.1	22.2	128.6	45.2	43.2	17.1
Tm	13.8	11.4	11.1	7.1	9.2	5.8	31.5	11.2	9.9	4
Yb	91.1	89.2	92.8	55	71	44.2	231.9	80.5	73	29.6
Lu	14.2	14.4	15.8	9	11	7.5	35.8	14.3	11.2	5.2
ΣREEs	506.54	629.67	444.67	226.71	321.19	186.95	1043.12	485.36	509.83	140.96
ΣLREEs	202.04	364.57	227.17	86.61	134.99	76.55	391.62	258.96	292.53	60.16
ΣHREEs	304.5	265.1	217.5	140.1	186.2	110.4	651.5	226.4	217.3	80.8
L/H	0.66	1.38	1.04	0.62	0.72	0.69	0.60	1.14	1.35	0.74
Eu/Eu*	0.07	0.04	0.08	0.11	0.11	0.21	0.07	0.05	0.07	0.18
Eu/Sm	0.023	0.013	0.027	0.038	0.036	0.073	0.022	0.015	0.021	0.069
TE _{1,3}	1.443	1.69	1.92	1.7	1.72	1.55	1.64	1.86	1.62	1.47

Normalized REEs after Boynton [8]. $\text{Eu}/\text{Eu}^* = \text{Eu}_N / [(\text{Sm}_N) \cdot (\text{Gd}_N)]^{0.5}$ according to Taylor and McLennan [60]

The studied pegmatites have moderate to high concentration of U, Th, Li, Nb, Ta (Nb^{Ta}), Zr, Ga, Pb, Zn, Y, Be. From the previous data, the studied pegmatites can be classified as a Niobium–Yttrium–Fluorine (NYF) pegmatite or rare metal pegmatite (Fig. 6b). The Nb/Ta ratio in the studied pegmatites ranges from 6.85 to 10.03, which refers to the decisive increase in the Ta due to effect of hydrothermal solution. Magmatic rocks of continental crust origin generally have low Nb/Ta ratio (11–12) [64]. The Zr/Hf ratio ranges from 13.18 to 17.93, suggesting significant change in the crystal chemistry of zircon toward increasing contents of Hf. The Th/U ratio ranges from 0.42 to 34.87 and K/Rb ratio ranges from 53.19 to 105.36, indicating a wide range of variation due to the leaching of uranium and accordingly enrichment in thorium as well as potassium. Bau et al. [6] suggest the complexation with fluorine as major cause for Y/Ho values > 28, while the complexing with bicarbonate is assumed to generate values < 28. The Y/Ho ratio in the studied granitic pegmatite ranges from 17.93 to 22.76, suggesting complexing with bicarbonate.

The plotting K/Rb ratio vs. Cs, the studied pegmatite samples fall in barren field and muscovite class according to Cerny and Burt [11], due to the depletion of Cs content (Fig. 5a). Ta vs. Ga and Ta vs. K/Cs plots (Fig. 5b and c) reveal that nearly all samples have high level of rare elements mineralization, based on the line of mineralization

proposed by Beus [7] and a little of them above base line of mineralization proposed by Gordiyenko [25]. Ta vs. Cs + Rb plots also reveal a moderate to high level of rare element mineralization (Fig. 5d), based on the line of mineralization proposed by Beus [7] and Gordiyenko [25].

The plots of Na_2O against K/Cs ratio (Fig. 6a) reveal that all the pegmatite samples fall in Li-bearing pegmatite field (1b) according to Gordiyenko [25] except one sample fall on mica field. The plots of Li against K/Rb ratio (Fig. 6b) reveal that samples spread in muscovite class pegmatite and in rare element class pegmatite.

The SiO_2 (wt%) form positive correlation with U (ppm) and negative correlation with Th (ppm), whereas Th/U ratio form negative correlation with Zr and Hf. This indicates that the increase in uranium is directly proportional with SiO_2 , Zr and Hf (Fig. 7a–d).

5.2 Rare earth elements

REEs analyses of Represented samples of pegmatites are listed in Table 3. The total REEs ranging from 140.96 to 629.67 ppm, where ΣLREEs range from 60.16 to 364.57 ppm and ΣHREEs range from 80.8 to 304.5 ppm. The high content of REEs in sample no. GP7 is due to the enrichment by xenotime and monazite minerals. The studied pegmatites reveal a small negative Eu anomaly (Eu/

Eu* = 0.04 to 0.21) pattern. It has an average Eu/Sm = 0.034 and LREEs/ HREEs = 0.9.

Chondrite-normalized REEs patterns (Fig. 8a), of the studied pegmatites are characterized by strong (Σ LREEs)_n and (Σ HREEs)_n enrichment due to the presence of some accessory minerals-bearing REEs, e.g., monazite, xenotime, and zircon. The pattern denotes moderate REEs fractionation in both LREEs and HREEs with positive Ce anomaly. The tetrad effect has been progressively recognized particularly for the granitic rocks which have undergone a high degree of fractional crystallization, hydrothermal alteration, and mineralization [5, 30, 32, 37, 66]. Masuda et al. [44] classified the tetrad effects into two different types, M and W-type (M-type in solid sample as residues and W-type in the interacting fluids as extract). The tetrad effect in the studied pegmatites was calculated according to Irber Eqs. (1999):

$$t_1 = \left(\frac{\text{Ce}/\text{Ce}^t \times \text{Pr}/\text{Pr}^t}{\text{Pr}/\text{Pr}^t} \right)^{0.5}, \quad t_3 = \left(\frac{\text{Tb}/\text{Tb}^t \times \text{Dy}/\text{Dy}^t}{\text{Dy}/\text{Dy}^t} \right)^{0.5}$$

$$\text{and } TE_{1,3} = (t_1 \times t_3)^{0.5}, \text{ when } TE_{1,3}$$

The studied rock have $TE_{1,3}$ values (1.44–1.92) more than 1.1, so they show tetrad effect (Table 3). The fractionation of elements with similar ionic radius and charge is regarded to be sensitive to change in the melt composition during magma differentiation [5, 31].

Spider diagram of normalized element data of average pegmatites concentration relative to average continental crust by Weaver and Tarney [65] is shown as in Fig. 8b.

It can be observed that, the elements have four behaviors; the first is strong enrichment (Rb, Th, U, Nb, Hf, Tb, Y, Tm and Yb) which is a characteristic of dominated crustal material in the parent magma [51]. The second is slight enrichment (K and Zr). The third behavior is depletion (Ba, Sr, P and Ti) and the fourth is the distribution of the elements around up/down the unity (La, Ce, Nd and Sm).

5.3 Spectrometric investigation

Uranium mobilization (eUm) in the studied rock types can be calculated as follows: the uranium mobilization is calculated by the difference between the measured eU and the expected original uranium, which is calculated by dividing the measured eTh by the average eTh/eU ratio in the crustal acidic rocks (original uranium = eTh/3.5 according to [17] to give the leaching values of uranium (eUm = eU – eTh/3.5). The result of the uranium mobilization equation (eUm = eU – eTh/3.5) is the hypothetical uranium distribution [10]. It is helpful in defining the trends of

uranium migration. Positive values indicate uranium addition by mobilization, whereas negative values indicated migration of uranium by leaching.

5.4 Monzogranite radiometric investigation

The D.R., K%, eU, eTh and eUm values in the monzogranites are illustrated in Table 4. The average eU content in the monzogranites (4.71 ppm) is less than twice their Clark value (4 ppm), this indicates that the eU in monzogranites are agreed with the average content of the crust and this monzogranites are not uraniferous.

The binary relations of D.R. versus, eU and eTh, are illustrated in Fig. 9a, b. They show positive relation. The plot of eU versus eTh illustrates that there are positive relations ($r=0.51$) between the variants indicating their magmatic origin (Fig. 9c). Weak negative relation ($r=-0.03$) exist between eTh and eTh/eU (Fig. 9d). Strong negative relation ($r=0.85$) exist between U vs. eTh/eU ratio (Fig. 9e). The migration equation for the studied monzogranites indicates uranium leached from parts and added in another parts (Fig. 9f).

5.5 Pegmatites radiometric investigation

The radioactive anomaly in the study area is confined to the pegmatites. The D.R. content ranges between 456.4 and 942 nSv h⁻¹ with an average of 699.17 nSv h⁻¹, whereas the average (eTh/eU) ratio is 0.98 ppm (Table 5, Fig. 10). The eU content ranges between 39 and 96.2 ppm with an average of 65.16 ppm, and the eTh content ranges between 41.2 and 83 ppm with an average of 61.66 ppm.

The binary relations of D.R., eU, eTh, and eTh/eU are illustrated in Fig. 10. These relations may provide an indicator of the geochemical behavior of U and Th in the studied pegmatites. Strong positive relations exist between D.R. and eU ($r=0.98$) and also with eTh ($r=0.98$) (Fig. 10a, b). The plot of eU versus eTh illustrates that there are very strong positive relations ($r=0.97$) between the variants indicating their magmatic origin (Fig. 10c). Strong negative relation ($r=0.85$) between eU versus eTh/eU, while weak negative relation ($r=-0.03$) exist between eTh and eTh/eU as shown in Fig. 10d, e). Result of the equation eU – (eTh/3.5) revealed that some of the measurements lie under the zero line, and this means that these samples have been originated from a late magmatic phase of magma very rich in radioelements with thorium concentration more than uranium. On the other side, the majority of measurements lie above the zero line indicating that the pegmatites affected with hydrothermal solutions rich in uranium than thorium which indicates uranium addition (Fig. 10f).

◀**Fig. 3** Photomicrograph of monzogranites showing; **a** Quartz crystal affected by ductile and brittle deformation with displacement as strike slip faults, Crossed Nicols (C.N.), **b** Zircon crystal enclosed within biotite and feldspars,; **c** Plagioclase crystal form twins and has two or more parts is differently orientated due to strain effect, (C.N.) **d** Fan-shape muscovite, **e** elongated muscovite filling fractures of plagioclase and associated with opaques, (C.N.) and **f** Opaques filling fractures, (C.N.); **g** and **h** Partiality to completely alteration of plagioclase to saussurite and pyroxene to actinolite and also alteration of hornblende to chlorite, (C.N.)

5.6 Mineralogical investigations

The mineralogical study aim to detect the radioactive minerals within studied pegmatites, which shows that the most common radioactive and important minerals of the studied pegmatites are represented by uranothorite, columbite, zircon, monazite, xenotime, sphalerite and pyrite. The morphological features and their percentage contents are attached for each mineral (Figs. 11, 12, 13, 14, 15, 16 and 17).

5.7 Uranothorite [(Th,U)SiO₄]

It is usually metamict and contains REEs in a few percent with Ce earths usually dominant and contains uranium and yttrium. EDX techniques revealed that it contains 49.48% Th, 29.62% U, 18.96% Si and 1.94% Al (Fig. 11).

5.8 Columbite (Fe, Mn)(Nb,Ta)₂O₆

It occurs as well-developed orthorhombic crystals in pegmatite exhibiting black color and shiny luster. Columbite is always associated with tantalite because Nb⁺⁵ and Ta⁺⁵ are closely associated and are always found together. Heinrich [26] concluded that some columbite might be radioactive because of the presence of uranium and thorium in its structure, or from inclusion, veinlets, or coatings of strongly radioactive minerals. Tischendorf [61] concluded that columbite–tantalite mineralization is genetically associated with post-orogenic geochemically distinct granitoids. EDX analysis of selected crystals from the pegmatites revealed that they have 21.79% Nb, 23.09% Ti, 15.75% U, 15.29% Y, 6.49% Pb, 4.83% Fe, 4.22% Si and 2.47% Ta (Fig. 12).

5.9 Zircon [ZrSiO₄]

It occurs as euhedral six-sided or eight-sided form with clusters of opaque inclusions. It is mainly colorless to pale yellow color. Rankama and Sahama [52] stated that thorite is isomorphic with zircon and it is evident that a large part of thorium is incorporated in the zircon structure. The ionic size of zirconium and thorium are not too unlike and

therefore thorium is able to enter the zircon structure in which it replaces. EDX analysis for separated mineral grains of pegmatite proved that they comprise Zr, Si, Hf, Ti, U and Th (Fig. 13).

5.10 Monazite [(Ce, REE) PO₄]

It occurs as very fine subhedral to anhedral grains in pegmatite samples. It exhibits transparent lemon yellow, honey yellow and reddish yellow with resinous luster. Monazite have a wide range of LREE and is iso-structural with cheralite (RE,Th,Ca,U)(P,Si)O₄ and with huttonite (ThSiO₄), both of which have highly cerium REE distributions [9, 49]. Thorium is usually existing in monazite in substitution for the REE. Jensen [34] concluded that the monazite structure would accept REE ions with ionic radii between those of La and Eu. It is confirmed by SEM–EDX technique and contains Ce, La, P, Nd, Pr, U and Th (Fig. 14).

5.11 Xenotime [YPO₄]

It exhibits translucent yellowish red to reddish brown colors with resinous luster. It is a tetragonal mineral iso-structural with zircon, ZrSiO₄. Besides Y, other rare earth elements (REE), predominantly heavy rare earth elements (HREE), and the actinide elements U and Th, are incorporated preferentially at the eight-fold lattice site in the xenotime-(Y) structure [47, 63]. It is confirmed by SEM–EDX technique and contains Y, P, Yb, Er and Si (Fig. 15).

5.12 Sphalerite [(Zn,Fe)S]

It is commonly associated with other sulfide minerals, such as galena and pyrite. It is confirmed by SEM–EDX technique and contains Zn, S and Fe (Fig. 16).

5.13 Pyrite [FeS₂]

It occurs as cubes, octahedral showing a brown color with metallic luster. The oxidized form of pyrite is unstable and decomposed into insoluble iron hydroxide and free sulfuric acid which passes into solution. It is confirmed by SEM–EDX analysis for separated mineral grains of pegmatite and contains Fe and S (Fig. 17).

6 Discussion

Many rare metals used today are derived from granitic pegmatites, but debate continues about the origin of these rocks. Since the studied pegmatites have classified as a Niobium–Yttrium–Fluorine (NYF) pegmatite or rare metal pegmatite. The following discussion aims to

Fig. 4 **a** R1–R2 diagram for the pegmatites of W. Ghadir, SED, Egypt, after De La Roch et al. [18]. **b** Shand's index diagram for the pegmatites of W. Ghadir, SED, Egypt, after Clarke [16]. **c** Rb vs. Y + Nb diagram for the pegmatites of W. Ghadir, SED, Egypt, [51]. **d** Fig. 4e: SiO₂ vs. Fe₂O₃/(Fe₂O₃ + MgO) diagram showing the bound-

ary between ferroan and magnesian intrusions of the pegmatites of W. Ghadir, SED, Egypt, Frost et al. [22]. **e** SiO₂ vs. Na₂O + K₂O–CaO diagram [22] showing the approximate range for the alkalic, alkali-calcic, calcic-alkalic, and calcic series of the pegmatites of W. Ghadir, SED, Egypt

Fig. 5 **a** Cs vs. K/Rb, **b** Ga vs. Ta, **c** K/Cs vs. Ta, **d** Cs + Rb vs. Ta for the studied granitic pegmatite of W. Ghadir, SED, Egypt. The discrimination lines according to Cerny and Burt [11]

Fig. 6 **a** Na₂O vs. K/Cs for the studied granitic pegmatite of W. Ghadir, SED, Egypt. (2=mica bearing, 1a=Cs bearing and 1b=Li bearing), according to Gordiyenko [25] as presented in Trueman and Cerny [62]

understand the classification and suggested origin of pegmatites. Cerny and Ercit [13] introduced a revised petrogenetic classification in which three families are distinguished: “an NYF family with progressive accumulation of Nb, Y and F (besides Be, REE, Sc, Ti, Zr, Th and U), fractionated from subaluminous to metaluminous A- and I-granites that are generated by a variety of processes involving depleted crust and/or mantle

contribution; a peraluminous LCT family marked by prominent accumulation of Li, Cs and Ta (besides Rb, Be, Sn, B, P and F) derived mainly from S-granites, less commonly from I-granites; and a mixed NYF + LCT family of diverse origins (e.g., NYF plutons contaminated by digestion of undepleted supracrustals)”. Martin and De Vito [45] contend that the depth zone classification cannot account for the two main geochemical categories of

Fig. 7 SiO_2 (wt%) vs. **a** U and **b** Th for the studied granitic pegmatite, W. Ghadir, SED, Egypt, Th/U ratio vs. **c** Zr and **d** Hf for the studied granitic pegmatite, W. Ghadir, SED, Egypt

Fig. 8 **a** Rare earth elements distribution pattern for the pegmatites, W. Ghadir, south Eastern Desert, Egypt. Normalized to Chondrite of Boynton [8], **b** Spiderdiagram of normalized element data

for the pegmatites, W. Ghadir, south Eastern Desert, Egypt. Normalized values refer to average continental crust of Weaver and Tarney [65]

pegmatites: LCT and NYF. They propose that the tectonic setting determines the nature of the parent magma and the derivative rare-element-enriched magmas. Thus, LCT pegmatites are generated in compressional tectonic

settings (orogenic suites) and NYF from extensional tectonic settings (anorogenic suites). Mixed NYF and LCT are proposed to be the result of contamination, either at the magmatic or postmagmatic stage, in which the evolved

Table 4 Field radiometric measurements of the monzogranites, Wadi Ghadir area, SED, Egypt

Serial no	D.R. (nSvh-1)	K%	eU (ppm)	eTh (ppm)	eTh/eU	eUm
1	103.9	3.1	4	9	2.25	1.43
2	114.5	4	2.4	11	4.58	-0.74
3	143.3	3.8	6.2	13	2.10	2.49
4	118.9	4	2.6	12	4.62	-0.83
5	105.2	3.4	4.2	9.5	2.26	1.49
6	110.5	4.2	3.8	12.1	3.18	0.34
7	106.5	3.8	2.9	11	3.79	-0.24
8	112.6	4.1	3.5	11.5	3.29	0.21
9	115.4	4.2	4.6	11.8	2.57	1.23
10	117.2	3.7	5.2	10.8	2.08	2.11
11	129.7	3.6	5.8	11.7	2.01	2.47
12	142.1	3.5	6.9	13.5	1.96	3.03
13	107.3	3.8	4.2	8.9	2.12	1.66
14	145.6	4.2	7.5	13.8	1.84	3.56
15	110.8	4	3.6	12.8	3.56	-0.06
16	132.3	4.2	5.8	12.6	2.17	2.20
17	130.2	3.8	5.5	12.2	2.22	2.01
18	126.5	3.5	5.2	11.2	2.15	2.00
19	128.5	3.6	5.6	12.1	2.16	2.14
Min	103.9	3.1	2.4	8.9	1.84	-0.14
Max	145.6	4.2	7.5	13.8	4.62	3.56
Average	121.11	3.82	4.71	11.61	2.68	1.39

NYF rocks get “soaked” with a fluid bringing in not only Li and B, but also Ca and Mg from the host rock. They also propose that pegmatites may form by anatexis from both crustal and mantle rocks, which may have been previously metasomatically altered. There are currently two hypotheses that aim to explain how pegmatite-forming melts are generated: (1) extended fractional crystallization of a granitic magma at the scale of a pluton, and (2) direct formation by low-degree partial melting of crustal rocks, typically in the presence of fluids [40, 45]. In practice, these hypotheses represent two end-members and many pegmatites may be formed by a combination of crustal melting and subsequent fractionation of small magmatic bodies.

It is clear that a trend toward a petrogenetic classification is emerging. We feel that a petrogenetic classification that can relate pegmatites to tectonic regimes and the related magma generating processes is ultimately essential in order to advance our understanding of pegmatite genesis within the larger-scale earth processes. This is an area for much needed future research.

7 Conclusions

The studied area is covered by quartz-diorites, monzogranites and pegmatites. The monzogranites are medium to coarse grained with a pinkish color forming medium relief mountain terrains. They attain cavernous weathering, exfoliation, joints, and fractures and also dissected by basic dykes. The pegmatites occur as zoned pockets within monzogranites with gradational contacts and dissected by basic dykes. The pegmatite pockets have the following zonal arrangement: border, wall, intermediate, and core zones. The wall zone have enrichment of radioactive and RREs-bearing minerals.

Geochemically, the pegmatites of W. Ghadir have per-aluminous character, ferroan with alkalic–calcic affinity and emplaced in within plate setting. The pegmatites indicate a narrow range of variation between Nb/Ta, Zr/Hf ratios, while it shows a wide range of variation in Th/U, K/Rb ratios. These pegmatites revealed high level of rare earth elements mineralization. The pegmatites of W. Ghadir are Li-bearing pegmatite. The binary variation

Fig. 9 D.R. versus **a** K%, **b** eU, **c** eTh, **d** eTh versus eU, **e** eTh versus eTh/eU, **f** eU versus eU-eTh/3.5 for the studied monzogranites, W. Ghadir, SED, Egypt

diagrams between SiO_2 (wt%), U, Th and Th/U ratio indicates the increase in uranium directly proportional with SiO_2 , Zr and Hf. The major oxides composition (MnO , MgO , CaO , Na_2O , TiO_2 , and P_2O_5) of the pegmatites of W. Ghadir are mostly not different from those of rare-metal-bearing pegmatites of Egypt. The trace elements analysis shows that the pegmatites documents relatively medium- to high contents of trace elements and rare metals. The studied pegmatites exhibit high contents of Li, Nb, Cu, Ta, U, Th, Pb, Zr, Zn and Ga, which are the

major mineralization indices for pegmatites bodies in the Egyptian basements. Thus, the studied pegmatites can be classified as a Niobium–Yttrium–Fluorine (NYF) pegmatite or rare metal pegmatite. The trace elements ratio supports a low degree of fractionation and metasomatism in the evolutionary history of the pegmatites, and the very low Cs values (2.2–4.3 ppm) recorded for the pegmatites indicate paucity of alkali metal fractionation. These features agree with the weak negative Ce signature and strong negative Eu anomaly REE pattern

Table 5 Field radiometric measurements of the granitic pegmatites, Wadi Ghadir area, SED, Egypt

Serial no	D.R. (nSvh-1)	K%	eU (ppm)	eTh (ppm)	eTh/eU	eUm
1	942	3.9	93	83	0.89	69.29
2	456.4	4	40	41.2	1.03	28.23
3	459	3.2	39.3	46.1	1.17	26.13
4	937.4	3.2	96.2	78.2	0.81	73.86
5	470	4.7	39	43	1.10	26.71
6	922	3.8	85	77	0.91	63.00
7	875	3.9	82.5	78	0.95	60.21
8	755	4.1	70.2	60.5	0.86	52.91
9	700.5	4.1	65.6	56.2	0.86	49.54
10	520.3	4.2	42.5	47	1.11	29.07
11	590.5	4.3	45.8	50.2	1.10	31.46
12	632.5	3.9	60.3	56.8	0.94	44.07
13	720.3	3.8	66.8	62.5	0.94	48.94
14	825.3	3.6	88.2	75.4	0.85	66.66
15	890.5	3.8	85.6	82.1	0.96	62.14
16	490	3.5	42.5	49.3	1.16	28.41
Min	456.4	3.2	39	41.2	0.81	27.23
Max	942	4.7	96.2	83	1.17	72.49
Average	699.17	3.88	65.16	61.66	0.98	47.54

exhibited by mostly the bulk rock pegmatites. The overall geochemical signatures of pegmatites of W. Ghadir, generally indicate low fractionation, and medium- to high-level of rare metal mineralization potential, like the rare-metal-bearing pegmatites in the basement complex of Egypt.

Spectrometric investigation using binary diagrams revealed that monzogranites are not uraniferous, while the radioactive anomaly in the study area is confined to the pegmatites. The binary relations of D.R., eU, eTh, and eTh/eU in pegmatites show Strong positive relations exist with U and Th indicating their magmatic origin.

Meanwhile, the result of mobilization equation proved that pegmatite samples have been originated from a late magmatic phase of magma very rich in radioelements, also the majority of measurements lie above the zero line indicating that the pegmatites affected with hydro-thermal solutions rich in uranium than thorium which indicates uranium addition.

The mineralogical investigation were done on separated heavy minerals shows that the radioactive and important heavy minerals content of the studied pegmatites are represented by uranothorite, columbite, zircon, monazite, xenotime, sphalerite and pyrite.

Fig. 10 D.R. versus **a** K%, **b** eU, **c** eTh, **d** eTh versus eU, **e** eTh versus eTh/eU, **f** eU versus eU-eTh/3.5 for the studied granitic pegmatites, W. Ghadir, SED, Egypt

Fig. 11 SEM image and EDX analysis data of uranothorite mineral for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 12 SEM image and EDX analysis data of columbite mineral for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 13 SEM image and EDX analysis data of zircon for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 14 SEM image and EDX analysis data of monazite for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 15 SEM image and EDX analysis data of xenotime for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 16 SEM image and EDX analysis data of sphalerite for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

Fig. 17 SEM image and EDX analysis data of pyrite for the granitic pegmatites, W. Ghadir, south Eastern Desert, Egypt

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