



Natural radioactivity and geochemical aspects of radioactive mineralisation in El Sela, South Eastern Desert, Egypt

Mohamed M. Ghoneim^{a,b}, Elena G. Panova^b and Ahmed E. Abdel Gawad^a

^aNuclear Materials Authority, Cairo, Egypt; ^bGeochemistry Department, Saint Petersburg State University, University Embankment, Saint Petersburg, Russia

ABSTRACT

The natural radioactivity data revealed that eU reached up to 157.4, 1625 and 178 ppm in microgranite and dolerite dikes as well as jasper vein, respectively, whereas the two-mica granite possesses the higher eTh-contents up to 53.8 ppm. Mineralogically, the two-mica granite is enriched in thorite, brockite and uranothorite, whereas uraninite and coffinite are recorded in dolerite, and the latter one is recorded in microgranite, bostonite and jasper. Primary uranium minerals as uraninite and coffinite could be a source for uranium enrichment and the formation of secondary uranium mineralisation. Uranium mobilisation was active towards the two perpendicular shear zones having NNW-SSE and ENE-WSW rejuvenated trends. Successive hydrothermal alterations play their role in the formation of uranium ore deposits to be trapped in post-granitic dikes.

ARTICLE HISTORY

Received 23 January 2021

Accepted 14 February 2021

KEYWORDS

Natural radioactivity;
uranium; thorium;
mineralogy; shear zone; El
Sela

1. Introduction

Uranium fertile granites are not depending only on their total uranium contents but also on the capacity of the granite bearing uranium they host. In high K- Calc-alkaline or peralkaline granites, uranium is hosted in refractory minerals as uranothorite, zircon and/or monazite. In this case, uranium is not easily leached by fluids. On the contrary, uranium is hosted as uranium oxides in peraluminous granites which are considered as a good source for U-ore deposits [1].

In the Eastern Desert of Egypt, fertile granites such as El-Missikat [2], El-Erediya [3], Gattar [4] and Um Ara [5] are associated with meta- and/or peraluminous granites. Uranium mineralisation in these granites belongs to the vein-type except Gattar and Um Ara granite, where U-mineralisation belongs to metasomatites. Their characteristics are corresponding to those of A-type granites (high-K Calc-alkaline granite).

Numerous, studies were carried out in El Sela shear zone which attracted the attention of several workers [6–20].

Most of these investigations concentrated on two-mica granite whereas the other intrusive rocks as well as jasper veins have not been investigated. This work aims to study the geochemical features of radioactive mineralisation of the El Sela area in the south Eastern Desert of Egypt.

2. Geological setting

El Sela area is located in the southern part of the Eastern Desert of Egypt (Figure 1). It encompasses two-mica granite, intruded by post-granitic dikes as well as quartz and jasper veins.

The two-mica granite occupies the major and important part of the present study of the area which varies in colours from red, pink to buff. It forms low- to moderate-relief ellipsoidal bodies, characterised by intensive fractures, joints, cavernous structures and highly weathered. It is medium to coarse-grained and characterised by hypidiomorphic granitic texture. It is dissected by two perpendicular mineralised shear zones having ENE-WSW and NNW-SSE directions. Field investigations showed that the post-granitic dikes could be arranged from the oldest by microgranite, dolerite and bostonite.

The first ENE-WSW rejuvenated mineralised shear zone extends for about 6 km or more, dips between 70° and 80° to the southward, and is injected by microgranite and dolerite dikes as well as quartz and jasper veins. It is intersected by N-S left-lateral strike-slip faults. This rejuvenation trend is accompanied by acidic hydrothermal alteration (clay alteration) are mostly responsible for the presence of visible secondary U-mineralisation as well as sulphide megacrysts in post-granitic dikes and jasper veins, except white quartz which is barren. On the other hand, the second NNW-SSE mineralised shear zone extends for

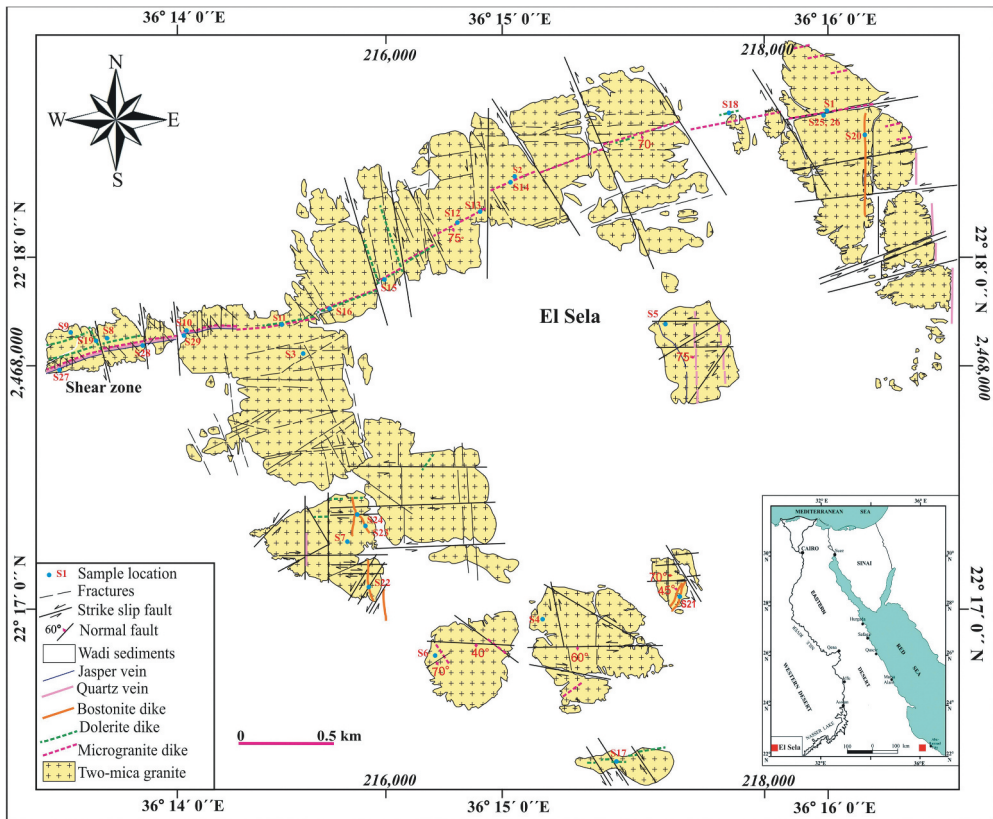


Figure 1. Compiled geologic map of El Sela, South Eastern Desert of Egypt [6,7,9,12].

a short distance extending for about 100 m. A dolerite dike invades the second shear zone, which strikes N25°W and dips 60° to the westward. It is strongly altered and enriched by visible autunite minerals.

Bostonite dikes invade the hosting two-mica granite. They strike N85°W and dip in a range that varies between 70° and 80° westward to be nearly vertical. They are fine-grained, brownish-black to reddish-brown, strongly sheeted, and range from a few cm to 2 m thick.

White and black quartz veins were dissected by grey to reddish black jasper veins. Jasper veins are mineralised and contain visible secondary uranium minerals.

3. Materials and methods

The ground gamma-ray spectrometric measurements were conducted by using a Geophysica Brno GS-256 spectrometer having a 0.35 L sodium iodide (NaI) thallium activated detector and a counting time of 120 seconds. Within the detector, an internal ^{137}Cs source allows the spectrometer to be automatically maintaining a system of stability. A total-count scintillometer survey were used to continuously monitor the changes in total radioactivity. The spectrometer measure daughters of the three radioelements and internally stores data of conversion/correction constants to allow the display of data in conventional counts/time period or directly equivalent uranium content in ppm (eU), equivalent thorium content in ppm (eTh) and K%.

Scientific research was performed at the centre for microscope and microanalysis of the research park using Scanning Electron Microscope (FEI, the Netherlands, 2006), which is mounted on the base of an analytical complex Pegasus 4000 (EDAX, USA). The analysed data were obtained using Electron Microprobe equipped with CAMECA SX 100 using the following conditions: the diameter of the analysed area on the specimen surface is under 1 μm at standard conditions (15 kV acceleration potential, 15 nA beam current, sample: iron oxide; volume: $3 \times 10^{-19} \text{ m}^3$; mass: $2 \times 10^{-12} \text{ g}$). The microprobe is equipped with five automated wavelength-dispersive spectrometers (WDS) and an energy-dispersive spectrometer (EDS), WDS includes crystal LiF, PET, TAP, PC0, PC1, PC2 and PC3 whereas spectrometer range (0.22 to 0.83) sin-theta with a resolution of 10^{-5} . Natural standards orthoclase for Si (K α), albite for Al (K α), haematite for Fe (K α), olivine for Mg (K α), wollastonite for Ca (K α), and monazite for Yb (La), whereas the synthetic compounds are UO_2 , ThO_2 , ZrO_2 , PbCrO_4 , YPO_4 , CePO_4 , NdPO_4 , SmPO_4 , GdTiGe and DyRu_2Ge_2 which used as standards for U (M β), Th (Ma), Zr (La), Pb (Ma), Y (La), Ce (La), Nd (La), Sm (La), Gd (La) and Dy (La), respectively.

4. Results

4.1. Ground gamma-ray spectrometric data of radioelements

The present part aims to investigate the behaviour of radioelements during the magmatic evolution of the studied rocks. These rocks are characterised by considerable radioactivity as mentioned in Table 1 and (Figure 2(a–d)).

As reported by Clarke et al. [21], the Th/U ratio is about 3.5 or (4:1) in granites. It is known that thorium is an immobile element, so that this ratio depends mainly on uranium content as a mobile element. In granitic rocks, uranium leach out or poor source rocks depend on a high Th/U ratio (>3.5), while uranium enrichment source rocks (uraniferous

Table 1. Summary of the statistics of the distribution of total count (TC(Ur)) and the three radioelements K%, eU(ppm), eTh(ppm) in the different rocks in El Sela area.

	TC (Ur)	K (%)	eU (ppm)	eTh (ppm)	eTh/eU
Two-mica granite					
Min.	3.20	3.84	2.40	4.50	0.23
Mean	19.11	4.62	11.02	21.31	2.30
Max.	33.90	8.55	36.70	53.80	7.17
S.D.	5.63	1.05	6.08	7.63	1.03
No.			125		
Microgranite dike					
Min.	5.90	1.10	4.30	11.30	0.01
Mean	108.2	3.49	157.4	18.05	0.19
Max.	1723	7.10	1686	25.6	2.39
S.D.	139	1.31	190	3.96	0.37
No.			170		
Dolerite dike					
Min.	5.00	1.20	2.90	3.60	0.02
Mean	81.64	3.61	117.8	12.50	0.55
Max.	890	7.9	1625	22.40	3.58
S.D.	142.44	2.13	235.39	9.41	0.71
No.			98		
Bostonite dike					
Min.	13.70	3.10	4.80	11.90	0.84
Mean	18.76	4.14	9.49	18.77	3.37
Max.	23.10	4.90	18.30	28.60	7.40
S.D.	2.17	0.40	3.84	3.58	1.53
No.			70		
Jasper vein					
Min.	10.7	1.00	4.80	1.50	0.06
Mean	30.05	2.96	34.30	9.45	0.33
Max.	148	3.90	178	18.90	1.85
S.D.	14.96	0.60	19.54	3.48	0.23
No.			111		

Statistical parameters: Min. Minimum; Max. Maximum, No. numbers of reading, S.D. Standard deviation.

or fertile sources) depend on a low Th/U ratio (<3.5). Microgranite and dolerite dikes as well as jasper vein show lower Th/U ratio reached to 0.01, 0.02, and 0.06 as mentioned in Table 1, respectively. These values are lower than Clark values indicate successive uranium enrichment that could be related to primary and/or secondary uranium mineralisation.

The two-mica granite and bostonite dikes show lower total radioactivity level reached up to 33.9 and 23.1 Ur for TC, respectively, when compared with microgranite and dolerite dikes as well as jasper vein up to 108.2, 890. And 148 Ur for TC (Table 1 and Figure 2(a)). The two-mica granite, and microgranite and dolerite dikes exhibit higher concentration than others up to 8.55%, 7.1% and 7.9% for K could be related to extreme effects of hydrothermal alteration (clay alterations) (Table 1 and Figure 2(b)). Microgranite and dolerite dikes as well as jasper vein possess higher contents in eU reached up to 157.4, 1625, 178 ppm that could be related to the presence of primary and secondary uranium mineralisation as coffinite, uraninite, meta-autunite, uranophane, meta-ankoleite and kasolite (Figure 2(c)). The two-mica granite possesses the highest value in eTh reached up to 53.8 could be related to the presence of radioactive mineralisation as thorite, brockite and uranothorite when compared with others (Figure 2(d)).

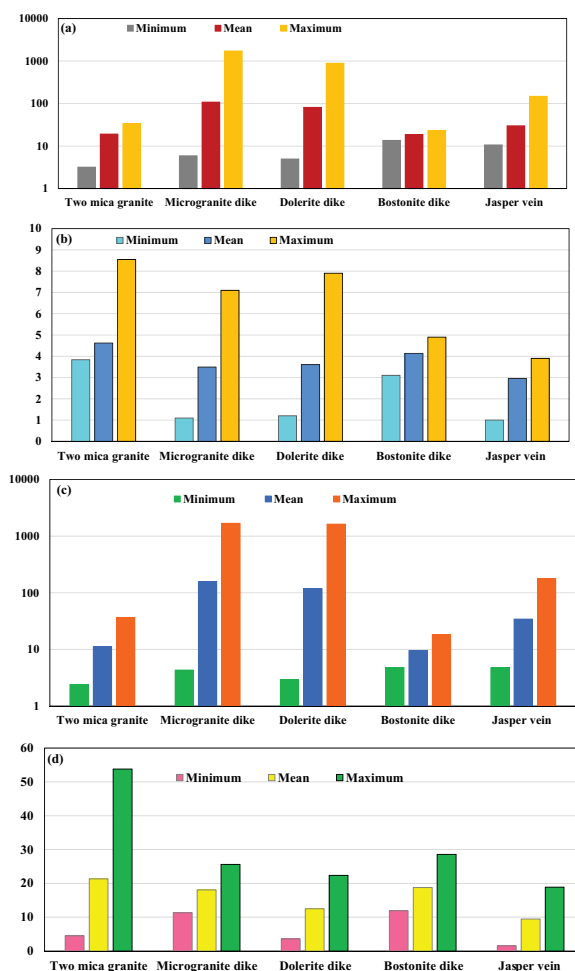


Figure 2. Histogram showing the distribution of (a) total count (TC(Ur)) and (b, c, d) the three radioelements K%, eU(ppm), eTh(ppm) in the studied rocks of El Sela area, respectively; data as mentioned in (Table 1).

4.2. Radioactive mineralisation

4.2.1. Primary radioactive mineralisation

There are three thorium minerals are investigated; thorite, brockite and uranothorite which recorded only in the two-mica granite (Table 2 and Figure 3(a–f)).

Thorite occurs as subhedral to anhedral crystals, individual grains reached up to 50 μm in size, intergrowths with zircon, and inclusions in zircon (Figure 3(a,b)). It somewhat resembles zircon, but brighter occurring as small, square prismatic crystals, with pyramidal points and was found around zircon crystals in the peripheries. Thorite also may be surrounded by iron oxides. The chemical composition of thorite shows that ThO_2 ranges from 66.69 to 73.17 wt% (mean 69.55 wt%), UO_2 from 1.03 to 5.44 wt% (mean 2.99 wt%), SiO_2 from 12.19 to 16.59 wt% (mean 14.09 wt%), Y_2O_3 (mean 2.71 wt%). Small amounts of CaO, P_2O_5 and REE, Al_2O_3 and Fe_2O_3 were reported as substitutions in thorite. The back-

scattered (BSC) image shows that thorite enclosed fine inclusion of xenotime and surrounded by zircon grains (Figure 3(c)).

Brockite is a calcium thorium phosphate mineral. The EPMA analyses indicate that it exhibits a wide range of chemical composition in which ThO₂ ranges from 44.3 to 51.17 wt %, P₂O₅ from 22.05 to 25.09 wt%, CaO from 11.12 to 12.9 wt%, SiO₂ from 3.32 to 6.05 ppm. Na₂O, Al₂O₃, PbO, ZrO₂ and Nd₂O₃ are reported in brockite.

Uranothorite occurs as euhedral to subhedral grains up to 20 µm size and others are very fine grained. It occurs in the form of individual small crystals, while other grains adjacent to the periphery of zircon crystals (Figure 3(d,e)). The EPMA chemical analysis of uranothorite reveals that ThO₂ ranges from 59.97 to 63.54 wt% with a mean of 62.12 wt%, UO₂ from 7.96 to 10.43 wt% with a mean of 9.02 wt%, in addition to appreciable amounts of silica that ranges from 14.01 to 18.59 wt%, with a mean of 15.87 wt%. CaO and PbO were reported in small amounts in uranothorite. On the other hand, magmatic zircon and uranothorite crystals having a mixed composition between both of them (grey coloured zone) in which EPMA analyses of ZrO₂ are (48.52 wt%), ThO₂ (37.46 wt%), SiO₂ (42.57 wt%) and UO₂ (8.97 wt%) with lower values of CaO and HfO₂ (2.70 wt% and 1.66 wt%), respectively.

Coffinite is recorded in microgranite, dolerite and bostonite dikes, as well as jasper vein in the study area, for the first time. The EPMA analyses show that the chemical composition of coffinite indicates that the mean of UO₂ contents is nearly similar. They are (71.4, 70.1, 72.7 and 71.6, wt%) in microgranite, dolerite, bostonite and jasper, respectively. The composition of SiO₂ varies from (22.1, 20.2 and 18.2, wt%) in microgranite, dolerite and bostonite, respectively. The highest SiO₂ content is recorded in jasper (26.8 wt%). Other impurities are recorded as Y₂O₃, P₂O₅, Al₂O₃ and CaO (Table 3).

Uraninite is an abundant mineral and forms euhedral crystals and aggregates acicular and platy crystals of uraninite in dolerite, typically up to 20 µm in size in the study area (Figure 3(f)). It is often altered to supergene minerals, especially autunite to meta-autunite. The chemical composition of uraninite shows that UO₂ ranges from 75.3 to 80.8 wt% (mean 78.43 wt%) (Table 3). ThO₂ is not detected, while CaO and P₂O₅ are high, indicating the substitution of PbO in the uraninite by CaO and P₂O₅ during hydrothermal alteration (clay alteration) affecting dolerite along the shear zone.

4.2.2. Secondary radioactive mineralisation

Secondary U-mineralisation as kasolite, uranophane and meta-autunite are recorded in microgranite and dolerite dikes as well as jasper vein.

Meta-autunite is recorded in microgranite, dolerite and jasper. It occurs mainly as disseminated grains filling cavities, vugs, fractures and joints. The dominant crystal forms are platy, acicular and fan-shaped forms. The chemical composition of meta-autunite in microgranite shows that UO₃ ranges from 65.0 to 66.69 wt% (mean 66.01 wt%), P₂O₅ from 16.4 to 16.9 wt% (mean 16.63 wt%), SiO₂ from 2.3 to 3.2 wt% (mean 3.37 wt%) and CaO from 4.30 to 5.50 wt% (mean 4.83 wt%). The content of K₂O varies from 2 to 4 wt% and at high values it already corresponds to another uranium mineral from the autunite group – meta-ankoleite [22]. The EPMA shows that meta-autunite in dolerite is composed of UO₃ which ranges from 67.3 to 68.46 wt% (mean 67.99 wt%), P₂O₅ from 17.5 to 18.8 wt.% (mean 18.33 wt%), CaO from 5.4 to 6.8 wt% (mean 6.03 wt%) and SiO₂ from 3.1 to 3.8 wt% (mean 2.8 wt%). The recorded chemical analyses of meta-autunite in jasper are characterised by

Table 2. Representative EPMA of Th-minerals in the two-mica granite.

Mineral	Thorite				Brockite				uraniothorite						
Oxides (wt%)	71	67.35	73.17	66.69	48.94	51.17	45.96	44.3	61.49	61.20	59.97	63.54	62.58	63.45	62.58
ThO ₂															
SiO ₂	14.94	12.19	16.59	12.62	4.30	3.32	6.05	5.09	17.2	14.42	14.08	14.01	14.23	18.55	18.59
UO ₂	5.44	1.03	2.72	2.76	bdl	bdl	bdl	bdl	8.29	9.03	8.33	9.63	7.96	10.43	9.49
Y ₂ O ₃	2.30	3.83	1.06	3.63	0.98	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Ce ₂ O ₃	0.35	bdl	0.45	bdl	bdl	0.63	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Nd ₂ O ₃	bdl	0.17	bdl	0.17	1.69	1.66	1.59	1.26	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Sm ₂ O ₃	bdl	0.26	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Gd ₂ O ₃	bdl	0.15	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Dy ₂ O ₃	bdl	0.27	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
P ₂ O ₅	1.94	6.41	1.03	6.45	22.05	24.02	25.09	22.82	bdl	bdl	bdl	bdl	bdl	bdl	bdl
CaO	1.80	2.99	1.06	2.32	11.49	11.90	12.90	11.12	0.71	bdl	1.37	bdl	1.23	bdl	bdl
Fe ₂ O ₃	1.59	4.10	1.53	2.41	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
PbO	bdl	bdl	1.47	0.92	bdl	bdl	3.26	2.87	2.08	0.78	0.40	bdl	bdl	3.49	2.81
Al ₂ O ₃	0.18	0.41	0.47	0.65	bdl	bdl	1.47	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
ZrO ₂	0.65	1.10	0.85	1.20	1.46	1.50	1.85	1.36	2.20	1.45	1.25	2.12	1.76	1.65	1.85
Total	100.2	100.3	100.4	99.8	90.9	94.2	98.2	88.8	92.0	86.9	85.4	89.3	87.8	97.6	95.3
Calculated formulae (apfu)															
Th	0.86	0.75	0.88	0.75	0.48	0.48	0.39	0.43	0.80	0.89	0.88	0.91	0.90	0.79	0.79
Si	0.79	0.59	0.87	0.62	0.19	0.14	0.23	0.22	0.99	0.93	0.91	0.89	0.90	1.01	1.03
U	0.06	0.01	0.03	0.03					0.11	0.13	0.12	0.14	0.11	0.13	0.12
Y	0.06	0.10	0.03	0.10	0.02										
Ce	0.01		0.01			0.01	0.02	0.02							
Nd		0			0.03	0.02		0.02							
Sm		0													
Gd		0													
Dy		0													
P	0.09	0.26	0.05	0.27	0.8	0.85	0.8	0.83							
Ca	0.1	0.16	0.06	0.12	0.53	0.53	0.52	0.51	0.04		0.09		0.08		
Fe	0.06	0.15	0.06	0.09											
Pb			0.02	0.01			0.03	0.03	0.03	0.01	0.01			0.05	0.04
Al	0.01	0.02	0.03	0.04			0.07								
Zr	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.06	0.05	0.04	0.07	0.05	0.04	0.05
Σcations	2.07	2.08	2.06	2.06	2.08	2.06	2.1	2.07	2.04	2.01	2.05	2.00	2.04	2.03	2.02
dl = below detection limit; calculated based on four (thorite, brockite and uranothorite) oxygen atom per formula unit (apfu).															

bdl = below detection limit; calculated based on four (thorite, brockite and uranothorite) oxygen atom per formula unit (apfu).

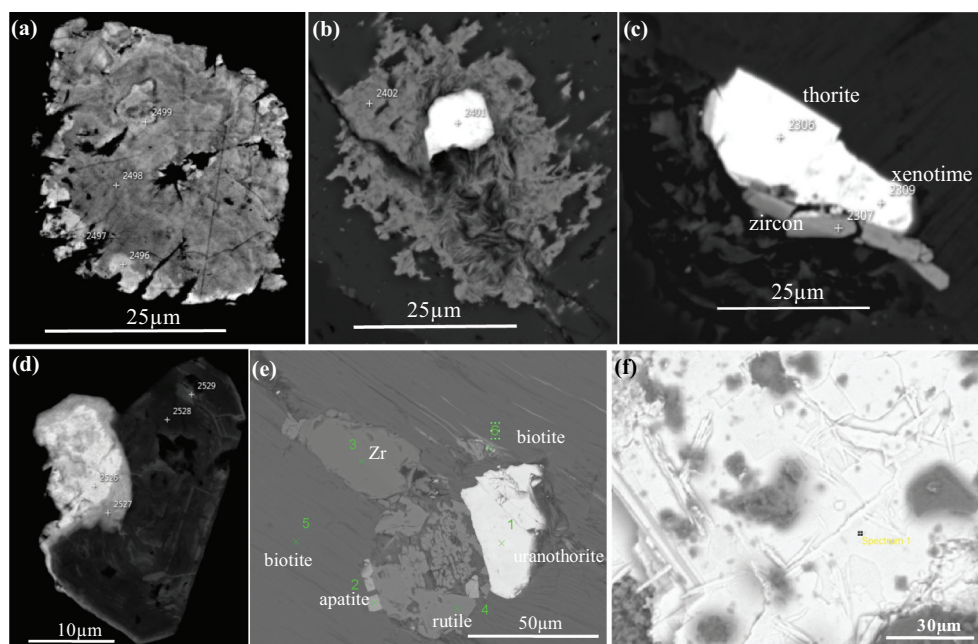


Figure 3. Back scattered images of thorium and uranium mineralisation in El Sela area. (a) Faint zoning of thorite crystal has an oval shape. (b) Thorite surrounded by haematite due to alteration of two-mica granite. (c) Association of thorite, xenotime and zircon. (d) Uranothorite along periphery of zircon crystal has a mixed composition between them (grey point 2527). (e) Uranothorite, zircon and apatite poikilitically enclosed in biotite crystals. (f) Platy crystals of uraninite.

higher values of SiO_2 (mean 4.64 wt%) and CaO (mean 7.86 wt%) than those reported in microgranite and dolerite. Na_2O and K_2O are not represented in the meta-autunite of jasper. UO_3 values are nearly similar in microgranite, dolerite and jasper (Table 4).

Uranophane is characterised by its lemon yellow shades to yellow colours in uraniferous jasper vein, but in profitable amounts and potential concentrations in the two perpendicular shear zones. The EPMA analysis data suggest that uranophane is composed of UO_3 that ranges from 72.7 to 73.72 wt% (mean 73.22 wt%), SiO_2 from 15.06 to 18.78 wt% (mean 16.99 wt%) and the consistent detection of CaO from 6.16 to 7.62 wt% (mean 6.67 wt%), whereas P_2O_5 is recorded as low values. Al_2O_3 and Na_2O were reported as impurities of small amounts.

Kasolite is only recorded in the mineralised microgranite and is usually forms clusters of yellow acicular crystals that fill micro-fractures and cavities. The chemical composition of kasolite shows that UO_3 ranges from 40.26 to 45.91 wt% (mean 42.73 wt%), PbO from 32.80 to 39.43 wt% (mean 35.90 wt%), SiO_2 from 8.10 to 16.00 wt% (mean 12.28 wt%). Small amounts of P_2O_5 , Fe_2O_3 , Al_2O_3 , K_2O and Na_2O were reported as impurities. UO_3 , PbO and P_2O_5 are higher in the centres than in the peripheries of kasolite crystal (Table 4).

Table 3. Representative EPMA of the primary U-minerals.

Mineral/ dike, vein	Coffinite				Uraninite									
	Microgranite	Dolerite	Bostonite	Jasper	Dolerite									
Oxides (wt%)														
UO ₂	71.6	71.2	70	70.2	72.8	72.78	72.4	70.8	80.8	75.3	78	78.3	79.3	78.9
SiO ₂	21.9	22.35	20.3	20.2	18.2	18.25	26.3	27.4	2.2	2.0	2.1	1.5	2.3	3.0
Al ₂ O ₃	1.1	0.4	2.4	2.35	1.3	1.25	bdl	bdl	1.4	0.8	1	0.5	0.9	1.5
CaO	0.5	0.5	0.6	0.62	0.9	1	0.4	0.4	2.3	1.3	2	2.5	2	3.5
P ₂ O ₅	1.4	bdl	3.6	3.45	2.5	2.6	0.9	0.7	2.5	5.5	4	4.1	4.3	1.7
Fe ₂ O ₃	bdl	2.1	bdl	bdl	bdl	bdl	bdl	0.7	2.3	0.4	bdl	bdl	bdl	0.5
Y ₂ O ₃	3.35	3.45	3	2.92	4.5	4.35	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
PbO	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	2.15	2.55	2.3	2.2	1.3	1.6
Total	99.9	100	99.9	99.7	100.2	100.2	100	100	93.7	87.9	89.4	89.1	90.1	90.7
Calculated formulae (apfu)														
U	0.76	0.77	0.72	0.73	0.80	0.80	0.74	0.71	0.67	0.63	0.67	0.69	0.66	0.67
Si	1.05	1.08	0.94	0.94	0.90	0.90	1.21	1.23	0.08	0.08	0.08	0.06	0.09	0.12
Al	0.06	0.02	0.13	0.13	0.08	0.07	0.08	0.02	0.06	0.04	0.05	0.02	0.04	0.07
Ca	0.03	0.03	0.03	0.03	0.05	0.05	0.02	0.02	0.09	0.05	0.08	0.11	0.08	0.07
P	0.06		0.14	0.14	0.10	0.11	0.03	0.03	0.08	0.18	0.13	0.14	0.14	0.06
Fe		0.11						0.04	0.06	0.01				0.01
Y	0.09	0.09	0.07	0.07	0.12	0.11								
Pb									0.04	0.05	0.05	0.05	0.03	0.03
Σcations	2.04	2.10	2.03	2.03	2.05	2.05	2.00	2.02	1.90	1.03	1.06	1.06	1.04	1.10

bdl = below detection limit; calculated based on four (coffinite) and two (uraninite) oxygen atom per formula unit (apfu), respectively.

Table 4. Representative EPMA of secondary U-minerals.

Mineral/ dike, vein	Meta-autunite, meta-ankoleite						Uranophane					
	Microgranite			Dolerite			Jasper	Jasper				
Oxides (wt%)												
UO ₃	66.3	65.0	66.7	68.5	67.3	68.2	66.5	65.7	66.2	72.70	73.46	73.72
SiO ₂	3.20	2.30	2.90	3.10	3.20	3.80	4.30	4.40	5.21	15.06	18.78	17.13
Al ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.74
CaO	5.50	4.30	4.70	5.40	5.90	6.80	7.50	8.30	7.78	6.16	7.62	6.23
P ₂ O ₅	16.40	16.60	16.90	17.50	18.70	18.80	15.40	17.30	16.23	0.89	0.57	bdl
PbO	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Na ₂ O	0.15	0.16	0.25	0.27	0.30	0.17	bdl	bdl	bdl	bdl	0.15	bdl
K ₂ O	3.20	4.00	2.10	1.80	3.00	2.10	bdl	bdl	bdl	bdl	bdl	bdl
Fe ₂ O ₃	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl
Total	94.8	92.4	93.5	96.5	98.4	99.9	93.7	95.7	95.4	94.80	100.60	97.80
Calculated formulae (apfu)												
U	1.84	1.86	1.86	1.84	1.75	1.73	1.84	1.73	1.76	2.54	2.32	2.44
Si	0.42	0.31	0.39	0.40	0.40	0.46	0.57	0.55	0.66	2.50	2.82	2.70
Al												0.14
Ca	0.78	0.63	0.67	0.74	0.78	0.88	1.06	1.11	1.05	1.10	1.22	1.06
P	1.83	1.92	1.90	1.90	1.96	1.93	1.72	1.84	1.74	0.12	0.08	
Pb												
Na	0.04	0.04	0.06	0.07	0.07	0.04					0.04	
K	0.54	0.70	0.36	0.29	0.47	0.32						
Fe												
Zcations	5.45	5.46	5.24	5.25	5.44	5.37	5.19	5.23	5.21	6.26	6.48	6.34

Mineral dike	Kasolite				
	Microgranite				
spot	Rim	Center	Rim	Fine grained	
Oxides (wt%)					
UO ₃	43.50	42.50	45.91	41.70	40.26
SiO ₂	16.00	9.52	8.30	8.10	9.47
Al ₂ O ₃	1.85	2.42	1.3	1.38	3.42
CaO	bdl	bdl	bdl	bdl	bdl
P ₂ O ₅	1.42	1.19	2.41	2.60	0.87
PbO	33.4	38.5	39.43	39.77	35.88
Na ₂ O	0.15	0.17	0.13	0.12	0.18
K ₂ O	bdl	1.23	0.34	0.44	1.27
Fe ₂ O ₃	2.93	4.62	1.27	3.42	3.1
Total	99.3	100.2	99.1	97.5	94.5
Calculated formulae (apfu)					
U	0.7	0.77	0.89	0.8	0.76
Si	1.23	0.83	0.76	0.74	0.86
Al	0.17	0.25	0.14	0.15	0.36
Ca					
P	0.09	0.09	0.19	0.2	0.07
Pb	0.69	0.9	0.97	0.98	0.87
Na	0.02	0.03	0.02	0.02	0.03
K		0.14	0.04	0.05	0.15
Fe	0.17	0.3	0.09	0.24	0.21
Σ cations	3.07	3.3	3.1	3.19	3.32

bdl = below detection limit; Calculated based on 12 (meta-autunite, meta-ankoleite and uranophane) and 6 (kasolite) oxygen atom per formula unit (apfu), respectively.

5. Discussion

Uranium mineralisation in the study area is formed under reduction-oxidation conditions (redox), in which primary U-minerals, such as uraninite and coffinite, may be a source for uranium enrichment, which led to the formation of profitable amounts of secondary U-ore deposits. These primary U-minerals contain uranium in the form of a tetravalent state (U^{4+}), which is immobile and stable under a reducing environment. Under oxidising conditions, it will be converted into (U^{6+}), which is stable in the oxidising medium and easily mobile with any circulating fluids. The changing physicochemical conditions of the hot fluids (acid and/or alkaline), due to their mixing with meteoric water, and continuous interaction with the hosting two-mica granite and microgranite, dolerite and bostonite dikes, as well as jasper vein, caused a complicated series of alteration processes.

Alteration processes, successive hydrothermal alterations comprising beresitisation, propylitisation, argillitisation and hematitisation suggest the remobilisation of uranium from large granitic batholith to these alterations along El Sela shear zones. Beresitisation is defined as the decomposition of feldspars, due to their sericite and quartz with simultaneous pyritisation of the rock affected microgranite. Consequently, beresites are quartz-sericite rocks, formed as a result of a hydrothermal-metasomatic alteration of granites. In beresitisation zone, pyrite is oxidised into goethite (framboidal texture) identified as desulphurisation processes which creates voids in microgranite dikes that filled with uranophane [23]. It is worthy to mention that propylitisation affected sheared dolerite dikes are enriched in visible secondary uranium and fluorite mineralisation. Argillitisation (clay alteration) affected microgranite in which the mineral composition and texture of microgranite completely disappeared and quartz is bleached.

6. Conclusions

The radiometric data revealed that eU reached up to 157.4, 1625, 178 ppm in microgranite and dolerite dikes as well as jasper vein related to primary and secondary U-mineralisation while eTh reached up to 53.8 ppm in the two-mica granite owing to Th-mineralisation.

Mineralogically, thorite, brockite and uranothorite are represented in the two-mica granite. Coffinite, meta-autunite, meta-ankoleite and kasolite are presented in microgranite dike. Uraninite and coffinite are recorded in dolerite dike, but the latter mineral is recorded in microgranite and bostonite dikes as well as jasper vein. Uranophane is also recorded in jasper vein, while meta-autunite is presented in microgranite and dolerite dikes and jasper vein.

Uranium mobilisation was active towards the two perpendicular shear zones having ENE-WSW and NNW-SSE. Hydrothermal alterations play their role in remobilisation of the profitable uranium ore deposits to be trapped in post-granitic dikes and jasper vein.

Acknowledgments

The authors would like to express their gratitude to members of Geomodel Research Center, Saint Petersburg State University, Saint Petersburg, Russia for their assistance in scanning electron

microscope and electron microprobe. The authors would like to thank Yuriy V. Erokhin at the Institute of Geology and Geochemistry (IGG) of the Ural Branch of the Russian Academy of Sciences, Chairman of the Ural Branch of the Russian Mineralogical Society for valuable discussion, constructive comments and revising this manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

- [1] M. Cuney, *Bull. Soc. Geol. Fr.* **185**, 75 (2014). doi:[10.2113/gssgfbull.185.2.75](https://doi.org/10.2113/gssgfbull.185.2.75).
- [2] H.A.M. Awad, H.M.H. Zakaly, A.V. Nastavkin and A. El-Taher, *Int. J. Environ. Analytic.* (2020). doi:[10.1080/03067319.2020.1845666](https://doi.org/10.1080/03067319.2020.1845666)
- [3] M. Elsaid, H. Aboelkhair, D. Dardier, E. Hermas and U. Minoru, *Open Geol. J.* **8**, 69 (2014).
- [4] N.M. Mahdy, B.A. El Kalioubi, C.C. Wohlgemuth-Ueberwasser, M.H. Shalaby and A.H. El-Afandy, *Ore. Geol. Rev.* **71**, 57 (2015). doi:[10.1016/j.oregeorev.2015.05.001](https://doi.org/10.1016/j.oregeorev.2015.05.001).
- [5] Y.H. Dawood and H.H. Abd El-Naby, *J. Afr. Earth Sci.* **32**, 317 (2001). doi:[10.1016/S0899-5362\(01\)90009-0](https://doi.org/10.1016/S0899-5362(01)90009-0).
- [6] A.A. Abdel-Meguid, M. Cuney, S.E. Ammar, T.M. Ibrahim, K.G. Ali, H.A. Shahin, S.A. Omer, I. M. Gaafar, S.M. Masoud, A.A. Khamis, M.H. Haridy, A.I. Kamel, B.M. Mostafa, A.M. Abo Donia, A. E. Abdel Gawad and E.M. Aly, Internal Report for the international Project (EGY/03/014), Technical Assistance of (IAEA); (2003).
- [7] T.M. Ibrahim, T.E. Amer, K.G. Ali and S.A. Omar, *J. Faculty Sci. Menoufia Univ.* **XXI**,1 (2007).
- [8] M.A. Ali and D.R. Lentz, *Chin. J. Geochem.* **30**, 453 (2011). doi:[10.1007/s11631-011-0531-5](https://doi.org/10.1007/s11631-011-0531-5).
- [9] K.G. Ali, *Arab. J. Geosci.* **6** (6), 1753 (2013). doi:[10.1007/s11631-011-0531-5](https://doi.org/10.1007/s11631-011-0531-5).
- [10] H.A. Shahin, *Arab. J. Geosci.* **6** (7), 2245 (2013).
- [11] I. Gaafar, M. Cuney and A.E. Abdel Gawad, *Open J. Geol.* **4**, 137 (2014). doi:[10.4236/ojg.2014.44011](https://doi.org/10.4236/ojg.2014.44011).
- [12] A.E. Abdel Gawad, A.H. Orabi and M.B. Bayoumi, *Arab. J. Geosci.* **8**, 4565 (2015). doi:[10.1007/s12517-014-1499-3](https://doi.org/10.1007/s12517-014-1499-3).
- [13] A.E. Abdel Gawad and E.M. Ibrahim, *J. Radioanal. Nucl. Chem.* **308**, 129 (2016). doi:[10.1007/s10967-015-4374-0](https://doi.org/10.1007/s10967-015-4374-0).
- [14] A.H. El-Afandy, A.A. El-Kammar, A.A. Abdel Gawad and T.N. Rizk, *Nuc. Sci. Sci. J.* **7** (1), 135 (2018). doi:[10.21608/nssj.2018.30735](https://doi.org/10.21608/nssj.2018.30735).
- [15] M.M. Ghoneim and A.E. Abdel Gawad, *News Ural State Min. Uni.* **1**, 49 (2018).
- [16] M.M. Ghoneim and A.E. Abdel Gawad, In Russian. (2018).
- [17] A.E. Abdel Gawad, VIII young geoscientists school, New knowledge about ore-forming processes, 26–30 Nov. 2018, IGEM RAS. Moscow, (2018).
- [18] M.M. Ghoneim, E.G. Panova and A.E. Abdel Gawad, Proceedings of the 22th International Scientific Symposium of students, postgraduates and young scientists devoted to the 120th anniversary of Academician K.I. Satpaev and 120 th anniversary of Professor K.V. Radugin, 2019. (Russian).
- [19] M.M. Ghoneim, E.G. Panova, A.E. Abdel Gawad and S.Y. Yanson, *News Ural State Min. Uni.* (2020). doi:[10.21440/2307-2091-2020-3-7-18](https://doi.org/10.21440/2307-2091-2020-3-7-18)
- [20] E.A. Abu Zeid, *Open J. Geol.* **10**, 703 (2020).
- [21] S.P.J. Clarke, Z.E. Peterman and K.S. Heier, *Geol. Soc. Am. Mem.* **97**, 521 (1966).
- [22] M.J. Gallagher and D. Atkin, *Bull. Geol. Survey Great Brit.* **25**, 49 (1966).
- [23] H.A. Abd Elaal, MSc Thesis, Cairo University, Geizah, Egypt, (2006).