Petrography and geochemistry of the Middle Miocene Gebel El Rusas sandstones, Eastern Desert, Egypt: Implications for provenance and tectonic setting

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Petrography and bulk rock geochemistry of the Middle Miocene sandstones of the lower and upper members of Gebel El Rusas Formation along the Egyptian Red Sea Coastal plain, have been investigated to determine the provenance, tectonic setting, and weathering condition of this formation. The Lower Member is formed mainly of sandstones and conglomerates with clay interbeds. The Upper Member is more calcareous and formed mainly of sandstones and limestones with marls and clays intercalations. Petrographically, the Lower Member sandstones are mostly immature and classified as arkoses with an average framework composition of $Q_{66}F_{29}R_5$, and the Upper Member sandstones are partly submature (more quartzose, less feldspathic) and classified as subarkoses with an average framework composition of $Q_{80}F_{17}R_3$. The Gebel El Rusas sandstones are enriched in Sr, Ba, Zr and Rb and depleted in Co and U, as compared to UCC. The chemical index of alteration (CIA) values suggest moderate weathering conditions. The geochemistry results revealed that the Gebel El Rusas sandstones were derived from felsic-granitic source rocks and deposited in a passive margin of a synrift basin. The inferred tectonic setting for Middle Miocene Gebel El Rusas sandstones in the study area is consistent with the regional geology of the Eastern Desert of Egypt during Middle Miocene.

Keywords. Provenance; Gebel El Rusas sandstones; Eastern Desert.

1. Introduction

The geochemical composition of clastic sediments has been widely used to infer provenance (Armstrong-Altrin *et al.* 2015b; Migani *et al.* 2015; Odoma *et al.* 2015; Zaid 2016), to evaluate the weathering history of the source area (Rahman *et al.* 2014; Tawfik *et al.* 2015), and to infer the tectonic environment (Armstrong-Altrin *et al.* 2015b; Etemad-Saeed *et al.* 2015a,b; Verma *et al.* 2015). The composition of clastic sediments is controlled by several factors, which include the

nature of source rock, the extent of weathering, transportation and diagenesis (McLennan *et al.* 1993). However, the tectonic setting of the sedimentary basin may play a predominant part over other factors, because different tectonic settings can provide different kinds of source materials with variable chemical signatures (Bhatia 1983; Bhatia and Crook 1986).

The investigated area extends along the Egyptian Red Sea coastal plain in Central Eastern Desert (figure 1). The plain is covered mainly with Miocene deposits. Two stratigraphic successions

Figure 1. Geologic map of the study area, showing the locations of studied sections (modified after [Conoco 1987](#)).

are measured and studied in detail at the Wadi Asalay–Marsa Seifein area and Wadi Shuni–Marsa Shuni area (figure 2).

The sediments of the Middle Miocene Gebel El Rusas Formation were deposited during the initiation of rifting of the Red Sea and can provide important information of the basin opening. However, these sediments have not been fully studied by geologists, except for a few ones, which included regional geology, stratigraphy and/or sedimentology (e.g., [El-Akkad and Dardir 1966](#); [Said 1990](#); [Kora and Abdel-Fattah 2000](#); [Zaid 2002](#); [Issawi et al. 2009](#)). Moreover, there are no studies available on the petrography and geochemistry. Similarly, there are no studies that focused on provenance, tectonic setting and paleoweathering of the Gebel El Rusas Formation. The main purpose of this study is to evaluate the major and trace element geochemistry of the Middle Miocene sandstones of the Gebel El Rusas Formation from two exposed sections (Wadi Asalay and Wadi Shuni, figure 1) in north Marsa Alam, Red Sea, Egypt, in order to infer their provenance, tectonic setting and weathering signatures.

2. Geological setting

The coastal plain strip of the Red Sea consists of two main groups: Precambrian basement Complex and the sedimentary cover (figure 1). The precambrian basement complex consists mainly of older granites, younger granites, gabbros, Hammamat clastics, metasediments, metavolcanics, metagabbro and ophiolites. On the other hand, the sedimentary cover embraces sedimentary rocks of Miocene–Quaternary age. It lies unconformably on the basement complex ([El-Akkad and Dardir 1966](#)).

The Miocene sediments are divided from older to younger into Gebel El Rusas, Abu Dabbab and Samh formations. The Gebel El Rusas Formation rests unconformably on the peneplained surface of the igneous and metamorphic rocks of the basement. The Formation underlies conformably the Miocene evaporite deposits of the Abu Dabbab Formation. The Gebel El Rusas Formation has a restricted distribution in the studied area. It is exposed in the south at the plain west of Marsa Seifein, where it caps isolated hills belonging to the basement rocks. It extends northward to Wadi Shuni, where it pinches out and the Abu Dabbab Formation is found overlying directly on the

crystalline rocks as amended later by [El-Akkad and Dardir \(1966\)](#) and [Said \(1990\)](#), and accepted by [Issawi et al. \(2009\)](#).

The Middle Miocene Gebel El Rusas Formation consists of two members. The Lower Member is typically irregularly bedded, poorly sorted and heterogeneous. Conglomerates are common with fresh and partly weathered feldspars. A conglomerate bed of large granitic boulders, attaining 50 cm in diameter, separates this member from the underlying basement rocks. The Lower Member consists mainly of sandstones and conglomerates with clay interbeds. The sandstones are varicoloured and enriched with feldspar grains. The Upper Member is more calcareous than the lower member. It is formed mainly of sandstones and limestones with marls and clays intercalations. Its base is marked by a thin bed of coarse grained sandstones with poorly preserved casts. This bed is sometimes mineralised ([Kora and Abdel-Fattah 2000](#)). Gebel El Rusas Formation is generally poor in macrofauna. The only macrofauna found is poorly preserved casts of bivalves and gastropods ([El-Akkad and Dardir 1966](#)). Gebel El Rusas Formation is thinning upward, its thickness decreases from 36 m, at Wadi Asalay, to 24 m, at Wadi Shuni. In Wadi Asalay, it is made up mainly of sandstones alternating with limestone, conglomerates and marl beds. At Wadi Shuni, this rock unit is composed of sandstone and conglomerate with a few marl and limestone beds near the top of the formation. The composition of this formation refers to shallow marine conditions ([Kora and Abdel-Fattah 2000](#)).

The Red Sea lies between the African and Arabian plates and is essentially a product of their divergence. The distribution and disposition of the sediments along the coastal strip of the Red Sea seem to indicate that the rifting of the north Red Sea started immediately after the deposition of the Lower Eocene strata and has continued with episodic intensity since that time ([Said 1990](#)). The structural pattern of the Neogene rift is clearly inherited from the basement tectonics. The synrift sedimentation more or less begins with the Middle Miocene ([Purser and Philobos 1993](#)). The pre-rift and proto-rift sedimentary cover is not recorded along the measured sections of the study area. The synrift rock units include the Miocene Gebel El Rusas, Abu Dabbab and Samh formations, in addition to the post-Miocene sediments.

By Middle Miocene time, the Tethys arm, which had covered the Gulf of Suez since Early Miocene time, overflowed into the Red Sea basin ([Said 1990](#))

Figure 2. Lithologic logs and clay content (%) of the Middle Miocene Gebel El Rusas sandstones at studied sections.

due to rift subsidence and/or global sea level rise. This marine transgression is represented by the fossiliferous carbonates of Gebel El Rusas Formation. By the Late Miocene time, a salinity crisis had occurred where a great evaporitic sedimentation took place, resulting in deposition of the Abu Dabbab Formation.

The lithological characteristics of the rocks of the Gebel El Rusas Formation and their areal distribution show that they began accumulation as piedmont boulders bed along the border of actively sinking faulted trough, as indicated by the presence of a granitic boulders bed at its base and by the lithological characteristics of the lower beds of the Formation (El-Akkad and Dardir 1966). These conditions gradually changed to shallow marine conditions, the upper member have been deposited in a subsiding fault trough under conditions of rapid burial and rapid erosion.

3. Samples and methodology

In this study, two stratigraphic sections were measured and described representing the Middle Miocene Gebel El Rusas Formation (figure 2). Twenty-six thin-sections of the Middle Miocene Gebel El Rusas sandstone samples were prepared for detailed petrographic study. Framework grains were counted for each thin section. The point counts (300 grains) were done using both Gazzi–Dickinson (Gazzi 1966; Dickinson 1970) and Ingersoll *et al.* (1984) methods.

The morphology and the textural relationships among minerals were examined in 8 gold-coated samples with scanning electron microscope (SEM) equipped with EDAX spectrometer (EDS) system, using an accelerating voltage of 10 kV. In order to identify the mineralogical composition of sandstones, X-ray diffraction (XRD) analyses of the $<2\mu\text{m}$ fraction were performed in a Philips PW 1729 diffractometer in eight oriented samples. The samples were air-dried, ethylene glycol-saturated and heated at 550°C for 2 hrs. SEM-EDS, XRF spectrometry technique and XRD analyses were performed at the laboratory of the National Research Center, Cairo, Dokki, Egypt and the laboratory of Nuclear Materials Authority, Cairo, El Katameya, Egypt. The major oxides and 14 trace elements were determined in 26 bulk samples by X-ray fluorescence (XRF) spectrometry, as per the procedure given by Ahmedali (1989). Final

analysis was carried out using a Rigaku model RIX-3000 equipped with a Rh tube. Calibration curves were prepared using international reference materials (Lozano and Bernal 2005). The US Geological Survey standards AGV-1, MAG-1 and SCo-1 were used for calibration, and the analytical precision for major and trace elements are generally better than 5%.

The correlation coefficient was carried out for the chemical data by using the method of Davis (1986). Loss of ignition (LOI) was estimated by heating the dried sample at 1000°C for 2 hrs. Major-element data were recalculated to an anhydrous (LOI-free) basis and adjusted to 100% before using them in various diagrams. Total iron is reported as Fe_2O_3 (Cullers 2000).

4. Results

4.1 Petrography

The sandstones of the Lower and Upper Gebel El Rusas Formation are loosely indurated to hard. The mean grain size ranges from fine to very coarse-grained. A major portion of the framework grains is subangular to subrounded and moderate to poorly sorted (table 1). The framework grains are monocrystalline quartz (Qm), polycrystalline quartz (Qp), K-feldspar (KF), plagioclase (PF), and lithic fragments (L_F). Quartz is the most abundant framework grain in the sandstones, constituting an average 73.2% of rock volume (table 1). Sandstone classification was made using Dott-McBride scheme (figure 3a). The sandstones of the Gebel El Rusas Formation are arkoses and subarkoses. Arkoses present in the Lower Member whereas the subarkoses recorded only in the Upper Member.

The average quartz–feldspar–lithic fragment (QFR) ratio is $\text{Q}_{66}\text{F}_{29}\text{R}_5$ for the Lower Member. The matrix and cement constitutes about 17% of the rock. Matrix partly consists of clay minerals and detrital constituents. The observed type of cement includes dolomite, silica and iron oxides (figure 4). Among quartz grains, non-undulatory monocrystalline quartz is dominant over undulatory monocrystalline quartz (figure 4a). Polycrystalline quartz is a minor constituent and exhibits straight to slightly curved intercrystal boundaries (figure 4b, c). Some of the non-undulatory monocrystalline quartz grains contain inclusions (figure 4c). Orthoclase feldspar is the most common

Table 1. Textural data and detrital grains modes and the derived *QFL* indices of the Middle Miocene Gebel El Rusas sandstones.

Location	size	Avg. grain roundness	Sorting	Qm	Qp	KF	PF	Lp	Ls	M	Hm			Cement and/or matrix	QFL%			QmFLt%					
											Op	NOp	Clays		Qt	F	L	Qm	F	Lt			
Lower Member																							
Wadi Asalay																							
A1	F-VC	SA-SR	Ps	60	0.2	19.5	2.3	0.4	1.5	0	0.1	Tr	Tr	16	71.75	25.98	2.26	71.51	25.98	2.50			
A2	F-VC	SA-SR	Ps	59.8	0.2	19.8	2.4	0.7	2.3	0.1	Tr	Tr	Tr	14.7	70.42	26.06	3.52	70.19	26.06	3.76			
A3	M-VC	SA-SR	Ps	58	0.1	20.1	1.8	0.6	1.6	0	0.4	0.1	Tr	17.3	70.68	26.64	2.68	70.56	26.64	2.80			
A4	M-VC	SA-SR	M-Ps	55	0.2	20.3	1.3	1.4	2.5	Tr	0.3	0.1	Tr	18.9	68.40	26.77	4.83	68.15	26.77	5.08			
A5	M-C	SA-R	M-Ps	59	0.1	21.1	1.5	0.7	2.4	0.1	0.3	Tr	0.1	14.7	69.69	26.65	3.66	69.58	26.65	3.77			
A6	F-C	SA-R	M-Ps	58.5	0	20.9	1.6	0.7	1.8	0	0.3	Tr	Tr	16.2	70.06	26.95	2.99	70.06	26.95	2.99			
A7	F-C	SA-SR	Ps	57	0	19.9	1.8	0	1.6	0	Tr	Tr	Tr	19.7	70.98	27.02	1.99	70.98	27.02	1.99			
Wadi Shuni																							
S1	F-C	SA-SR	Ps	51.4	0.3	24.5	1.7	0.6	1.9	Tr	Tr	0.1	Tr	19.5	64.30	32.59	3.11	63.93	32.59	3.48			
S2	M-C	SA-SR	Ps	53.9	0.2	22.6	1.8	0	2.3	0.2	0.2	0.1	Tr	18.7	66.96	30.20	2.85	66.71	30.20	3.09			
S3	M-C	SA-SR	Ps	50.6	0.3	23.1	1.8	3.4	2.8	0.1	0.2	Tr	Tr	17.7	62.07	30.37	7.56	61.71	30.37	7.93			
S4	M-C	SR-R	M-Ps	48.8	0.2	22.6	1.9	4.8	2.7	Tr	0.3	0.1	Tr	18.6	60.49	30.25	9.26	60.25	30.25	9.51			
S5	M-C	SA-SR	Ps	49.3	0.3	23.4	1.8	5.5	1.6	0.2	0.3	0.1	Tr	17.5	60.56	30.77	8.67	60.20	30.77	9.04			
S6	M-C	SA-SR	Ps	49.6	0.3	24.8	2.2	6	1.7	0.3	0.4	0.1	0.3	14.3	58.98	31.91	9.10	58.63	31.91	9.46			
S7	M-C	SR-R	M-Ps	50.3	0.2	23.6	2.3	6.1	1.8	Tr	Tr	Tr	0.3	15.4	59.91	30.72	9.37	59.67	30.72	9.61			
Upper Member																							
Wadi Asalay																							
A8	F-C	SA-SR	Ps	68.9	0.2	9.3	0.3	0.4	0	0	Tr	Tr	0	20.9	87.36	12.14	0.51	87.10	12.14	0.76			
A9	M-C	SA-SR	Ps	74.4	0.2	11.1	0.3	1.9	4.2	Tr	Tr	Tr	0	7.9	81.00	12.38	6.62	80.78	12.38	6.84			
A10	F-C	SA-SR	Ps	71.1	0.3	16.1	0.3	0	2.7	0.1	0.1	Tr	Tr	9.3	78.90	18.12	2.98	78.56	18.12	3.31			
A11	F-C	SR-R	M-Ps	66.2	0.3	13	0.6	0	2.6	0	0.2	Tr	Tr	17.1	80.41	16.44	3.14	80.05	16.44	3.51			
A12	F-C	SR-R	Ms	70	0.1	12.4	0.5	0.4	0.6	Tr	0.4	Tr	Tr	15.6	83.45	15.36	1.19	83.33	15.36	1.31			
A13	M-C	SA-SR	Ps	72.8	0.3	15.5	1.5	0	4.1	Tr	0.2	Tr	0.7	4.9	77.60	18.05	4.35	77.28	18.05	4.67			
Wadi Shuni																							
S8	F-C	SA-SR	Ps	72.3	0.3	13.2	0.4	0.5	0	0	Tr	0	0	13.3	83.74	15.69	0.58	83.39	15.69	0.92			
S9	M-C	SR-R	M-Ps	72.1	0.2	13.3	0.4	5.1	0	Tr	Tr	Tr	Tr	8.9	79.36	15.04	5.60	79.14	15.04	5.82			
S10	M-C	SA-SR	Ps	66.3	0.1	17.7	1.1	0.6	2.2	0.1	0.1	Tr	Tr	11.8	75.45	21.36	3.18	75.34	21.36	3.30			
S11	F-C	SA-SR	Ps	72.5	0.4	16.3	0.3	2.7	0	0.2	0	0	0	7.6	79.07	18.00	2.93	78.63	18.00	3.36			
S12	F-C	SA-SR	Ps	69.2	0.2	17.8	0.3	0	0	0.2	Tr	Tr	Tr	12.3	79.31	20.69	0.00	79.09	20.69	0.23			
S13	F-C	SA-SR	Ps	64.2	3	18.1	0.5	0.7	0	0	1.7	Tr	Tr	11.8	77.69	21.50	0.81	74.22	21.50	4.28			
Range				48.8–74.4	0–3.0	9.3–24.8	0.3–2.4	0–6.1	0–4.2	0–0.3	0–1.7	0–0.1	0–0.7	4.9–23.9	67.3–76.9	3.76–30.6	0.5–26.38	64.2–74.7	3.76–30.6	0.5–28.14			
Average				61.58	0.32	18.46	1.26	1.66	1.73	0.09	0.32	0.08	0.18	14.64	72.64	23.37	3.99	72.27	23.37	4.36			

F-VC = fine to very coarse; F-C = fine to coarse; M-VC = medium to very coarse; M-C = medium to coarse; SA-SR = subangular to subrounded; SA-R = subangular to rounded; SR-R = subrounded to rounded; Ps = poorly sorted; M-Ps = moderate to poorly sorted; Ms = moderately sorted; Monocrystalline quartz (Qm); Polycrystalline quartz (Qp); K-feldspar (KF); Plagioclase-feldspar (PF); Plutonic lithic fragment (Lp); Sedimentary lithic fragment (Ls); Heavy minerals (Hm); Opaque (Op); Non-Opaque (NOp); Qt = total Quartz; F = Feldspar; Lt = Total lithic fragment. Qt = Qm + Qp, F = Pl + KF, L = Lp + Ls, Lt = L + Qp.

Figure 3. (a) QFL triangular diagram shows the classification of the Gebel El Rusas sandstones, modified after [Dott \(1964\)](#) and [McBride \(1963\)](#); (b) QtFL, and (c) QmFLt ternary diagrams for the Gebel El Rusas sandstones, after [Dickinson et al. \(1983\)](#).

type with subordinate amount of microcline (figure 4d) and perthite (figure 4e). Small amounts of plagioclase feldspar are also present (figure 4a–c). Minor fresh feldspar grains may locally coexist with altered ones (figure 4b, c). Clay minerals (especially kaolinite) (figure 4f) have developed with altered feldspar grains. Rock fragments are mainly of plutonic (granite) and sedimentary (carbonate shell, quartzose siltstone and chert) fragments and may range up to 5% (table 1). Heavy minerals (zircon, rutile and tourmaline) and mica flakes also exist (table 1).

The average quartz–feldspar–lithic fragment (QFR) ratio is $Q_{80}F_{17}R_3$ in the Upper Member. Matrix and cement constitute about 12%

of the rock. Two types of cement are observed: calcite and silica (figure 5). The quartz grains are dominantly non-undulatory monocrystalline (figure 5a) and rarely polycrystalline (figure 5b). Some of the monocrystalline (non-undulatory) quartz grains contain inclusions (figure 5b). Polycrystalline quartz exhibits straight to slightly curved intercrystal boundaries (figure 5b–d). Feldspar grains are fresh (figure 5b), and altered with pore filling kaolinite booklets (figure 5c). Rock fragments are mainly of plutonic (granitic, figure 5e, f) and carbonate rock fragments. Most of the samples are free of matrix, and intergranular spaces are entirely filled up by calcite cement. Some quartz and altered feldspar grains are smeared

Figure 4. Photomicrograph and SEM of arkoses of the Lower Gebel El Rusas Formation: (a) Quartz (Q) and feldspar (F) grains are fine- to very-coarse grained, subangular to subrounded and poorly sorted (Note: quartz is mainly monocrystalline with undulatory extinction); (b) Fresh and altered feldspars with abundant iron oxide cement; (c) Monocrystalline and polycrystalline quartz (Qp) grain compacted with fresh and weathered feldspars (Note: quartz inclusions (Qin)); (d) Fractured and weathered feldspars (microcline and plagioclase) grains embedded in dolomite and iron oxide cements; (e) Quartz (Q) and feldspars (perthite) grains are angular, poorly sorted and poorly cemented. (f) Quartz (Q) and highly altered feldspars grains (Note: pore filling kaolinite (K)).

with iron oxide and some others are corroded and partially replaced by calcite cement in part (figure 5d–f). Heavy minerals such as hematite, rutile, tourmaline, zircon, and muscovite also exist (table 1).

4.2 Clay mineralogy

The clay minerals identified in both Lower and Upper Gebel El Rusas sandstones are illite and kaolinite. The proportions of illite to kaolinite vary antipathetically (figure 2) from an illite dominated Lower Member to a kaolinite dominated Upper Member. These variations may be related to relative changes in the climatic conditions in the source area. The moderate crystallinity exhibited by the clay minerals indicates their detrital origin from weathering horizons and soils developed on silicic rocks, and transportation in a fluvial environment (Keller 1956; Abu-Zeid *et al.* 1989, 1991). Source area weathering is confirmed by the absence of smectite and chlorite. The absence of smectite and chlorite and predominance of kaolinite, especially at the Upper Member indicate a granitic source rock (Lonnie 1982; Tsuzuki and Kawabe 1983; Amer *et al.* 1989; Abu-Zeid *et al.* 1991).

4.3 Major element geochemistry

The major element data of the Lower and Upper members of the Gebel El Rusas sandstones of Wadi Asalay and Wadi Shuni are listed in table 2. The $\text{SiO}_{2\text{adj}}$ content is comparatively higher in subarkoses of the Upper Member (78.32 ± 0.45 , $n = 12$), than in arkoses of the Lower Member (66.44 ± 1.357 , $n = 14$), which indicate the quartz rich nature of the Upper Member. The Al_2O_3 content is high in arkoses (11.2 ± 0.43 , $n = 14$), but low in subarkoses (5.84 ± 0.35 , $n = 12$). The high CaO content (arkose 11.66 ± 1.43 , $n = 14$; subarkoses 10.3 ± 0.51 , $n = 12$) is because of the presence of secondary CaCO_3 . The lower arkoses is slightly higher in Na_2O content (0.48 ± 0.02 , $n = 14$) than in upper subarkoses (0.2 ± 0.01 , $n = 12$). The Na_2O content ($<0.5\%$) may indicate a smaller amount of plagioclase content in the two members.

The high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios (3.9 ± 0.12 , $n = 14$ and 5.33 ± 0.4 , $n = 12$) are attributed to the relatively common presence of K-bearing minerals such as K-feldspar and some micas (McLennan *et al.* 1983; Osae *et al.* 2006).

The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio is larger for Lower Member arkoses (38.5 ± 3.07 , $n = 14$) than for Upper Member subarkoses (14.77 ± 0.31 , $n = 12$).

Table 2. Major element concentrations (wt%) of the Middle Miocene Gebel El Rusas sandstones.

Location	Lower Member										Statistical parameters						
	Wadi Asalay							Wadi Shuni			Statistical parameters						
	A1	A2	A3	A4	A5	A6	A7	S1	S2	S3	S4	S5	S6	S7	n	Mean	Std
(SiO ₂) _{adj}	68.75	66.07	66.46	68.75	64.09	66.74	64.98	67.25	67.47	67.07	66.74	64.98	63.55	67.20	14	66.44	1.57
SiO ₂	57.96	55.13	55.93	54.42	53.66	56.21	53.78	57.28	58.07	57.00	55.13	56.96	53.50	56.82	14	55.85	1.59
TiO ₂	0.33	0.30	0.32	0.27	0.29	0.28	0.27	0.30	0.29	0.30	0.27	0.30	0.24	0.30	14	0.29	0.02
Al ₂ O ₃	11.07	10.82	11.68	10.51	10.85	10.87	10.95	11.63	11.80	11.64	11.33	11.64	10.77	11.45	14	11.22	0.43
Fe ₂ O ₃ *	0.76	0.72	0.78	0.70	0.68	0.73	0.71	0.74	0.71	0.75	0.78	0.75	0.66	0.76	14	0.73	0.04
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14	0.00	0.00
MgO	2.45	2.17	2.84	2.15	2.08	1.97	1.98	1.83	1.29	2.03	1.84	2.08	2.30	2.11	14	2.08	0.34
CaO	9.24	11.91	10.05	12.99	13.85	11.73	12.65	10.99	11.59	10.81	11.60	10.75	14.40	10.62	14	11.66	1.43
Na ₂ O	0.52	0.46	0.51	0.46	0.45	0.48	0.47	0.48	0.46	0.49	0.51	0.49	0.46	0.49	14	0.48	0.02
K ₂ O	1.88	1.85	1.96	1.84	1.78	1.88	1.88	1.87	1.82	1.90	2.01	1.90	1.79	1.92	14	1.88	0.06
P ₂ O ₅	0.09	0.08	0.09	0.08	0.08	0.07	0.08	0.06	0.04	0.07	0.09	0.07	0.07	0.08	14	0.08	0.01
LOI	15.70	16.56	15.84	16.58	16.28	15.78	17.23	14.82	13.93	15.01	16.44	15.06	15.81	15.45	14	15.75	0.86
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	14	100	100
CaO*	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	14	0.0	0.00
CIA	74.47	75.22	75.20	74.73	75.85	74.79	75.10	76.10	76.97	75.79	74.36	75.79	75.48	75.37	14	75.4	0.70
ICV	1.37	1.61	1.41	1.37	1.76	1.57	1.64	1.39	1.37	1.40	1.50	1.40	1.84	1.41	14	1.5	0.16
Al ₂ O ₃ /TiO ₂	33.55	36.07	36.50	33.55	37.41	38.82	40.56	38.77	40.69	38.80	41.96	38.80	44.88	38.17	14	38.5	3.07
K ₂ O/Na ₂ O	3.62	4.02	3.84	3.62	3.96	3.92	4.00	3.90	3.96	3.88	3.94	3.88	3.89	3.92	14	3.9	0.12
SiO ₂ /Al ₂ O ₃	5.24	5.10	4.79	5.24	4.95	5.17	4.91	4.93	4.92	4.90	4.87	4.89	4.97	4.96	14	5.0	0.14

Table 2. (Continued.)

Location	Upper Member													Statistical parameters	
	Wadi Asalay						Wadi Shuni								
	A8	A9	A10	A11	A12	A13	S8	S9	S10	S11	S12	S13	n	Mean	Std
(SiO ₂) _{adj}	78.08	78.58	78.49	78.72	78.43	77.0	78.48	78.53	78.44	78.34	78.59	78.14	12	78.3	0.45
SiO ₂	73.70	74.27	74.00	74.20	73.94	73.30	74.10	73.87	73.94	73.85	74.16	73.80	12	73.9	0.26
TiO ₂	0.42	0.34	0.39	0.40	0.40	0.41	0.39	0.43	0.39	0.39	0.38	0.41	12	0.40	0.02
Al ₂ O ₃	6.03	5.14	5.80	5.70	5.93	6.16	5.69	6.56	5.75	5.71	5.55	6.00	12	5.84	0.35
Fe ₂ O ₃ *	0.96	0.86	0.93	0.89	0.94	1.01	0.92	0.99	0.93	0.93	0.89	0.97	12	0.94	0.04
MnO	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.02	0.01	0.01	12	0.01	0.00
MgO	1.76	1.58	1.65	1.76	1.67	1.89	1.62	1.81	1.66	1.56	1.66	1.76	12	1.70	0.10
CaO	10.20	10.95	10.18	10.07	10.10	11.06	10.40	9.03	10.30	10.57	10.40	10.20	12	10.3	0.51
Na ₂ O	0.20	0.21	0.20	0.21	0.20	0.19	0.20	0.19	0.19	0.20	0.21	0.20	12	0.20	0.01
K ₂ O	1.06	1.10	1.07	0.98	1.05	1.12	1.04	1.13	1.04	0.99	1.05	1.06	12	1.06	0.05
P ₂ O ₅	0.05	0.05	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.05	0.05	0.04	12	0.05	0.00
LOI	5.56	5.49	5.72	5.74	5.76	4.81	5.60	5.94	5.75	5.73	5.65	5.56	12	5.61	0.28
Total	100	100	100	100	100	100	100	100	100	100	100	100	12	100	0.02
CaO*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12	0.00	0.00
CIA	76.69	72.90	75.87	76.23	76.49	76.74	75.86	77.74	76.38	76.48	74.95	76.60	12	76.1	1.20
ICV	2.42	2.93	2.49	2.51	2.42	2.55	2.56	2.07	2.55	2.57	2.63	2.44	12	2.51	0.19
Al ₂ O ₃ /TiO ₂	14.36	15.12	14.87	14.25	14.83	15.02	14.59	15.26	15.02	14.64	14.61	14.63	12	14.8	0.31
K ₂ O/Na ₂ O	5.30	5.24	5.35	4.67	5.25	5.89	5.20	5.95	5.89	4.95	5.00	5.30	12	5.33	0.40
SiO ₂ /Al ₂ O ₃	12.22	14.45	12.76	13.02	12.47	11.90	13.02	11.26	11.90	12.93	13.36	12.30	12	12.6	0.83

n = number of samples; std = standard deviation; (SiO₂) adj = major-element data were recalculated to anhydrous (LOI-free) basis and adjusted to 100%; Fe₂O₃* = Total Fe expressed as Fe₂O₃. The chemical index of alteration (CIA) = [Al₂O₃/(Al₂O₃ + CaO* + Na₂O + K₂O)] × 100 (Nesbitt and Young 1982). CaO* = CaO in silicate phase. To calculate CaO* the assumption proposed by McLennan et al. (1993) was followed. The index of compositional variability (ICV) = (Fe₂O₃ + K₂O + Na₂O + CaO + MgO + MnO + TiO₂)/Al₂O₃ (Cox et al. 1995).

Figure 5. Photomicrograph and SEM of subarkoses of the Upper Gebel El Rusas Formation: (a) Quartz (Q) grains are medium – to very coarse grained, subangular to subrounded and poor to moderately sorted (Note: quartz is mainly monocrystalline with undulatory extinction); (b) Monocrystalline and polycrystalline quartz (Qp) grain compacted with fresh and altered feldspars (Note: feldspar altered to sericite (Sc) and quartz inclusions (Qin)); (c) Fresh and highly weathered feldspars (F) with pore filling kaolinite booklets; (d) Quartz grains embedded in calcite (Ca) and iron oxide (I) cements; (e) Quartz (Q) and lithic (plutonic) fragment (Lf) grains are well cemented and highly corroded by sparry calcite cement; (f) well round, coarse-grained monocrystalline quartz (Q) and plutonic rock fragment (Lf) with thin rim of iron oxide (I) and abundant interstitial calcite cement (Ca).

The statistically significant positive correlation between Fe_2O_3 and TiO_2 , for both Lower and Upper Members sandstones ($r = 0.964, n = 26$), reveals the abundance of Fe and Ti-rich minerals (hematite and rutile).

4.4 Trace element geochemistry

The trace element data and elemental ratios of the Middle Miocene Gebel El Rusas sandstones are reported in table 3. The Lower Member arkoses are higher in Sr, V, Ni, Co, Cr, Zn, Cu, Zr, U, Th, Pb and Rb than the Upper Member subarkoses. Both the Lower and the Upper Member sandstones are depleted in Co and U compared to average upper continental crust (UCC, figure 6). The sandstones and UCC have similar V, Ni, Cr, Th, Pb, and Sc concentrations. However, the Sr, Ba, Zr and Rb content in both arkoses and subarkoses is higher than the UCC.

The correlation between SiO_2 and trace elements is statistically not significant for both Lower and Upper members. However, the correlation between Al_2O_3 and some trace elements is statistically significant for both lower and upper members (e.g.,

Sr, $r = 0.718$; Zn, $r = 0.704$; Cu, $r = 0.759$) signifying that these elements are associated with clay minerals rather than in source rocks (Armstrong-Altrin *et al.* 2015a).

5. Discussion

5.1 Provenance

The textural features such as fine-medium to coarse grains, moderate to poorly sorting and the sub-angular to subrounded shape and high-percentage of unstable grain: feldspar (9.6–27.2%) and other rock fragments (0.0–10.3%); (table 1), indicate that the Gebel El Rusas sandstones show short transport distance and quick burial. The Gebel El Rusas sandstones deposited in the craton interior to transitional continental (figure 3b, c), derived from the exposed basement shield area, probably from platform or uplifted basement rocks. They might be derived mainly from weathered and low-lying crystalline basement rocks. The presence of mixed altered and fresh feldspars may reflect immature sediments interfingering with sub-mature phases. This would favour a weathered

Table 3. Trace element concentrations (ppm) of the Middle Miocene Gebel El Rusas sandstones.

Location	Lower Member							Wadi Shuni							Statistical parameters		
	Wadi Asalay														n	Mean	Std
	A1	A2	A3	A4	A5	A6	A7	S1	S2	S3	S4	S5	S6	S7			
Sr	123.0	148.0	178.0	109.0	184.0	78.0	159.0	109.0	100.0	140.0	108.0	140.0	57.0	129.0	14	125.86	35.83
Ba	877.0	931.0	662.0	803.0	677.0	506.0	821.0	723.0	1008	846.0	642.0	666.0	643.0	718.0	14	751.64	135.03
V	16.0	22.0	33.0	61.0	21.0	23.0	37.0	32.0	13.0	43.0	17.0	17.0	32.0	25.0	14	28.00	12.96
Ni	19.0	15.0	33.0	24.0	18.0	1.0	47.0	19.0	19.0	23.5	17.0	21.0	17.0	21.0	14	21.04	10.09
Co	4.6	5.0	5.3	7.0	4.8	5.0	5.1	5.0	4.0	4.8	5.1	4.0	5.0	5.5	14	5.01	0.71
Cr	14.0	11.0	19.0	45.0	14.0	9.0	18.0	22.0	13.0	22.0	13.0	13.0	24.0	16.0	14	18.07	8.94
Zn	53.0	21.0	70.0	87.0	23.0	5.0	50.0	36.5	4.0	57.8	27.0	23.0	51.0	36.0	14	38.88	23.95
Cu	127.0	26.0	78.0	36.0	59.0	39.0	70.0	23.1	45.0	67.0	33.0	46.0	77.0	49.0	14	55.36	27.40
Zr	143.0	185.0	90.0	202.0	135.0	276.0	156.0	244.0	121.0	231.0	284.0	188.0	156.0	233.0	14	188.86	58.93
U	3.0	3.2	3.3	3.4	2.0	2.2	1.1	2.5	1.7	2.0	1.5	2.0	1.8	1.8	14	2.25	0.72
Th	14.0	9.0	9.7	15.0	9.8	11.0	5.6	12.4	8.4	10.0	7.5	10.0	9.2	9.0	14	10.04	2.46
Pb	15.0	11.0	1.0	26.0	8.0	13.0	19.0	16.2	15.0	13.5	9.0	13.0	6.0	12.0	14	12.69	5.96
Sc	11.0	9.0	11.0	10.2	7.0	13.0	21.0	10.5	9.2	10.5	16.0	13.0	7.0	13.0	14	11.53	3.65
Rb	41.0	89.0	83.0	69.0	119.0	47.0	55.0	67.0	24.0	89.0	43.0	64.0	31.0	72.0	14	63.79	25.96
Th/U	4.7	2.8	2.9	4.4	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	14	4.63	0.76
Rb/Sr	0.3	0.6	0.5	0.6	0.6	0.6	0.3	0.6	0.2	0.6	0.4	0.5	0.5	0.6	14	0.51	0.13
Th/Sc	1.3	1.0	0.9	1.5	1.4	0.8	0.3	1.2	0.9	1.0	0.5	0.8	1.3	0.7	14	0.96	0.35
Zr/Sc	13.0	20.6	8.2	19.8	19.3	21.2	7.4	23.2	13.2	22.0	17.8	14.5	22.3	17.9	14	17.16	5.14
Th/Co	3.0	1.8	1.8	2.1	2.0	2.2	1.1	2.5	2.1	2.1	1.5	2.5	1.9	1.6	14	2.02	0.48
Th/Cr	1.0	0.8	0.5	0.3	0.7	1.2	0.3	0.6	0.6	0.5	0.6	0.8	0.4	0.6	14	0.63	0.26

Table 3. (Continued.)

Location	Upper Member										Statistical parameters			
	Wadi Asalay					Wadi Shuni					n	Mean	Std	
Sr	126.0	70.0	40.0	44.0	44.0	70.0	50.0	30.0	97.0	75.0	42.0	50.0	59.25	30.39
Ba	666.0	4100.0	260.0	290.0	310.0	520.0	366.0	251.0	1024	566.0	323.0	364.0	845.38	1322.95
V	12.0	26.0	14.0	11.0	12.0	11.0	24.0	12.0	13.0	24.0	13.0	14.0	15.25	6.11
Ni	13.0	14.0	13.0	14.0	13.0	13.5	11.0	11.0	13.0	14.0	11.0	11.0	12.81	1.19
Co	4.0	3.0	2.0	4.0	2.0	6.0	2.0	6.0	5.0	4.0	2.0	3.0	3.63	0.71
Cr	15.0	14.0	8.0	14.0	9.0	9.0	22.0	21.0	12.0	14.0	6.0	7.0	14.00	5.35
Zn	4.0	4.0	4.0	0.0	1.0	0.0	4.0	7.0	4.0	3.0	3.0	1.0	3.00	2.45
Cu	9.0	8.0	9.0	10.0	6.0	10.0	8.0	8.0	7.0	10.0	7.0	11.0	8.50	1.31
Zr	217.0	210.0	266.0	75.0	66.0	69.0	141.0	271.0	78.0	116.0	155.0	66.0	164.38	87.71
U	1.9	1.8	1.7	1.7	1.6	1.4	2.7	2.7	1.3	2.5	1.7	1.7	1.94	0.49
Th	10.0	10.0	8.0	9.0	8.0	7.0	14.0	14.0	7.0	13.0	9.0	9.0	10.00	2.67
Pb	9.0	6.0	8.0	7.0	8.0	10.0	9.0	11.0	15.0	13.0	9.0	13.0	8.50	1.60
Sc	12.0	9.4	12.0	11.1	12.0	15.0	12.0	16.0	23.0	21.0	12.5	37.0	12.44	2.11
Rb	65.0	42.0	26.0	28.0	22.0	45.0	31.0	11.0	57.0	43.0	26.0	27.0	33.75	16.59
Th/U	5.3	5.6	4.7	5.3	5.0	5.0	5.2	5.2	5.4	5.2	5.3	5.3	5.15	0.25
Rb/Sr	0.5	0.6	0.7	0.6	0.5	0.6	0.6	0.4	0.6	0.6	0.6	0.5	0.57	0.10
Th/Sc	0.8	1.1	0.7	0.8	0.7	0.5	1.2	0.9	0.3	0.6	0.7	0.2	0.82	0.23
Zr/Sc	18.1	22.3	22.2	6.8	5.5	4.6	11.8	16.9	3.4	5.5	12.4	1.8	13.52	7.35
Th/Co	2.5	3.3	4.0	2.3	4.0	1.2	7.0	2.3	1.4	3.3	4.5	3.0	3.32	1.77
Th/Cr	0.7	0.7	1.0	0.6	0.9	0.8	0.6	0.7	0.6	0.9	1.5	1.3	0.75	0.13

Figure 6. Multi-element normalised diagram for the Middle Miocene Gebel El Rusas sandstone samples, normalised against average upper continental crust (Taylor and McLennan 1985). A horizontal line for sand/upper continental crust value of 1 is included for reference. (a) Lower Member arkoses and (b) Upper Member subarkoses.

crystalline granitic source terrain (Akarish and El-Gohary 2008). The presence of plutonic (granite) and sedimentary (carbonate shell, quartzose siltstone and chert) rock fragments, suggesting that the Gebel El Rusas sandstones were derived mainly from relatively low lying granitoid and supplemented by recycled sands from associated platform or passive margin basins (Akarish and El-Gohary 2008).

The dominance of unstrained monocrystalline quartz grains that contain common inclusions are present in most samples, suggesting a plutonic origin (Basu *et al.* 1975). The polycrystalline quartz grains are composed of 2–5 subcrystals with straight to slightly curved intercrystalline boundaries, suggesting a plutonic source (Blatt *et al.* 1980). The predominance of K-feldspar over plagioclase together with muscovite suggests a plutonic source (Osae *et al.* 2006). The abundance of kaolinite and illite and absence of smectite and

chlorite clay mineral indicate a granitic source rock (Abu-Zeid *et al.* 1991).

In addition, major element concentrations and its elemental ratios were also used widely to interpret the nature of provenance (Armstrong-Altrin *et al.* 2015a, b). The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio can be used as a good indicator to identify the source rock. This ratio increases from 3–8 (in mafic) to 8–21 (in intermediate) and 21–70 (in felsic) igneous rocks (Nagarajan *et al.* 2015). The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio is (38.5 ± 3.07) for Lower Member and (14.77 ± 0.31) for the Upper Member subarkoses, indicating an intermediate to felsic source rock. Also, the high values of $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio (table 2) may indicate a K-rich granitic source rocks rather than basic rocks (Potter 1978).

The relative contribution of mafic materials by the source rocks to the study areas can be identified by the enrichment or depletion of ferromagnesian trace elements like Cr, Ni, Sc, and V in sediments

Table 4. Range of elemental ratios of the Lower and Upper Gebel El Rusas sandstones in this study compared to the ratios in similar fractions derived from felsic, mafic rocks, and upper continental crust.

Elemental ratio	Lower sandstones	Upper sandstones	Range of sediment from felsic sources (Cullers 2000)	Range of sediment from mafic sources (Cullers 1994, 2000; Cullers and Podkovyrov 2000)	UCC (Taylor and McLennan 1985)
Th/Sc	0.3–1.5	0.2–1.2	0.84–20.5	0.05–0.22	0.79
Th/Co	1.1–3.0	1.2–7.0	0.67–19.4	0.04–1.40	0.63
Th/Cr	0.3–1.2	0.6–1.5	0.13–2.70	0.02–0.05	0.13

Figure 7. Discriminant function diagram using major elements for the Upper and Lower Gebel El Rusas sandstones (Provenance fields are after Roser and Korsch 1988).

(Armstrong-Altrin *et al.* 2004). Anomalous, high values of Cr (>150 ppm) and Ni (>100 ppm) are indicative of ultramafic sources (Garver *et al.* 1996). The Lower and Upper Gebel El Rusas sandstones are largely depleted on Cr (15.54 ± 7.81 , $n = 26$) and Ni (17.15 ± 8.48 , $n = 26$) contents, indicating limited contribution of intermediate rocks in the source area (Armstrong-Altrin *et al.* 2013). The ratios such as Th/Sc, Th/Co, and Th/Cr are sensitive to the nature of provenance and are highly useful to differentiate mafic from felsic source rocks (Cullers 2000). These ratios of Lower and Upper Gebel El Rusas sandstone were compared with sediments derived from the mafic and felsic source rocks (table 4). This comparison reveals that the lower and upper Gebel El Rusas sandstones in both the studied sections received a major contribution from felsic rocks.

In sedimentary provenance studies, the discriminant function diagram proposed by Roser and Korsch (1988) is frequently used (Vdačný *et al.*

2013; Armstrong-Altrin *et al.* 2015b). This diagram helps to discriminate four major provenance categories, i.e., mafic (P1), intermediate (P2), felsic (P3) and quartzose recycled (P4). On this discriminate function diagram (figure 7) the Lower Gebel El Rusas arkoses plot in the felsic igneous provenance and the Upper Gebel El Rusas subarkoses in the quartzose sedimentary provenance fields, suggesting their derivation from a cratonic interior or recycled origin (figure 7).

The K_2O/Al_2O_3 vs. Rb/Al_2O_3 bivariate plot has been widely used as indicators for source composition (Armstrong-Altrin *et al.* 2012), since the K_2O and Rb contents in sediments are sensitive during source composition and processes (Armstrong-Altrin *et al.* 2015b). This plot (figure 8) is nearly uniform for both Lower and Upper Gebel El Rusas sandstones, which indicate the same source composition (felsic).

The coexistence of lower arkosic and upper subarkosic sandstones in studied sections indicate

Figure 8. K_2O/Al_2O_3 vs. Rb/Al_2O_3 bivariate diagram for the Lower and Upper Gebel El Rusas sandstones.

rapid uplift of the source area and quick subsidence of the basin, followed by a period of quiescence within an overall transgressive–regressive cycle in a rift tectonic regime (Zaid 2015a). Finally, the petrographical and geochemical data suggests that the sandstones of the Gebel El Rusas were derived from Proterozoic granite, which have been uplifted and exposed by the Rifting Orogeny, initiated during Oligocene and continued till post Miocene.

5.2 Source area weathering and sediment recycling

The chemical composition of clastic sediments can provide useful information about weathering condition in the source area (Liu *et al.* 2015). The chemical index of alteration (CIA) proposed by Nesbitt and Young (1982) is the most widely used chemical index to assess the degree of chemical weathering in the source area. This index was calculated using the molecular proportions as shown in the equation below

$$CIA = \frac{[Al_2O_3]}{(Al_2O_3 + CaO * + Na_2O + K_2O)} \times 100$$

where CaO^* is the amount of CaO incorporated in the silicate fraction of the rock. CaO values were accepted only if $CaO < Na_2O$; consequently, when $CaO > Na_2O$, it was assumed that the concentration of CaO equals to that of Na_2O (McLennan *et al.* 1993). CIA values of the Lower and Upper Gebel El Rusas sandstones are 75.4% and 76.08% respectively, suggesting that the source rocks of

these sandstones could be uplifted basement rocks. The differences in CIA between the two members are not statistically significant, indicating a similar degree of weathering.

The ternary plot $Al_2O_3 - CaO * + Na_2O - K_2O$ (figure 9) is a graphic representation, in order to evaluate the extents of chemical weathering, where unweathered rocks plot along the left side of the plagioclase–K-feldspar line (Nesbitt and Young 1984). In this plot, the data clusters are found near the A–K edge, along illite composition, indicating a moderate degree of weathering of the source rocks. Samples of the Lower and Upper Members cluster at one point, parallel to the A–CN line (figure 9) indicating their similar extents of chemical weathering. The extrapolation of the line from the weathered sample points indicate the provenance of the Gebel El Rusas sandstones to be from average granite (Nesbitt and Young 1984).

‘Sedimentary recycling’ can be identified using Rb/Sr ratios, where Sr easily leaches compared to Rb and this leads to a significant increase in the Rb/Sr ratio, and high ratios have been interpreted to be indicators of strong weathering and sediment recycling (McLennan *et al.* 1993). The Rb/Sr ratios of the Lower and Upper Members (0.51 ± 0.13 , $n = 14$, and 0.57 ± 0.1 , $n = 12$, respectively) are slightly lower than the average PAAS value (0.80; Taylor and McLennan 1985), suggest moderate weathering intensity in the source region.

The index of compositional variability (ICV; Cox *et al.* 1995) is considered as an important parameter to evaluate the maturity of sediments (Cullers

Figure 9. A–CN–K ternary diagram of molecular proportions of $\text{Al}_2\text{O}_3 - (\text{CaO} + \text{Na}_2\text{O}) - \text{K}_2\text{O}$ for the Lower and Upper Gebel El Rusas sandstones (after Nesbitt and Young 1984). Also plotted is the average upper continental crust (Taylor and McLennan 1985), as well as some rock forming minerals important in silicate rock weathering; shown at the side is the CIA scale. Arrows 1–3 represent the weathering trends of granodiorite, adamellite and granite, respectively (Nesbitt and Young 1984).

2000). ICV values are high (>1) for detrital ferromagnesian minerals and feldspars and low (<1) for the clay minerals subjected to intensive weathering processes (Cox *et al.* 1995; Cullers 2000). The average ICV values of lower Gebel El Rusas arkoses (1.5 ± 0.16 , $n = 14$) and upper Gebel El Rusas subarkoses (2.51 ± 0.19 , $n = 12$) are >1 (table 2), indicating the abundance of less weathered detrital minerals and were probably derived from the source area with high relief. Compositionally immature sediments with high ICV values are first-cycle deposits derived by low to moderate weathering of source rocks (Armstrong-Altrin *et al.* 2015b).

The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is a widely used measure to understand the maturity of sediments, where a high value represents compositionally matured sediments (e.g., Etemad-Saeed *et al.* 2011; Madhavaraju 2015). The average $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in basic igneous rocks is 3, whereas it is about 5 in acid igneous rocks, hence the values >5 in clastic sediments indicate sediment maturity (Roser *et al.* 1996; Armstrong-Altrin *et al.* 2015b). The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio values (5.0 ± 0.14 , $n = 14$ and 12.63 ± 0.83 , $n = 12$) in the Lower and Upper Gebel El Rusas sandstones, respectively (table 2), which is slightly higher than the average UCC value (~ 4), indicating low to moderate mineralogical maturity.

The variation in the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio between the two members also reveals the difference in SiO_2 content. The Upper Member subarkoses are enriched in SiO_2 content with elevated $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio. This indicates that the Upper Member subarkoses is slightly recycled compared to Lower Member arkoses.

Similarly, the Th/Sc *vs.* Zr/Sc plot of Sharma *et al.* (2013) show that the samples of the lower arkoses and the upper subarkoses follow the trend 1 (figure 10), suggesting first-cycle deposits, low to moderate weathering and low maturity.

5.3 Tectonic setting

The modal data of the Lower Gebel El Rusas sandstones mostly plot in the transitional continental fields, whereas the Upper Gebel El Rusas sandstones fall mainly in the craton interior fields (figure 3b, c; Dickinson *et al.* 1983). These sandstones are immature (Lower Member) to submature (Upper Member). The high percentage of unstable grain (feldspars and rock fragments) in both lower (av. 34%) and upper (av. 20%) members, indicate that these sandstones show short transport distance, quick burial and are typically rift sandstone (Zaid 2015a).

Figure 10. Th/Sc vs. Zr/Sc bivariate plot (McLennan *et al.* 1993). The accumulation of zircon due to sediment sorting and recycling is observed in trend 2.

Figure 11. New discriminant-function multi-dimensional diagram proposed by Verma and Armstrong-Altrin (2013) for high-silica clastic sediments from three tectonic settings (arc, continental rift, and collision). The subscript m1 in DF1 and DF2 represents the high-silica diagram based on $\log_e$ -ratios of major-elements. The discriminant function equations are:

$$DF1_{(Arc-Rift-Col)m1} = (-0.263 \times \ln(TiO_2/SiO_2)_{adj}) + (0.604 \times \ln(Al_2O_3/SiO_2)_{adj}) + (-1.725 \times \ln(Fe_2O_3^t/SiO_2)_{adj}) + (0.660 \times \ln(MnO/SiO_2)_{adj}) + (2.191 \times \ln(MgO/SiO_2)_{adj}) + (0.144 \times \ln(CaO/SiO_2)_{adj}) + (-1.304 \times \ln(Na_2O/SiO_2)_{adj}) + (0.054 \times \ln(K_2O/SiO_2)_{adj}) + (-0.330 \times \ln(P_2O_5/SiO_2)_{adj}) + 1.588.$$

$$DF2_{(Arc-Rift-Col)m1} = (-1.196 \times \ln(TiO_2/SiO_2)_{adj}) + (1.604 \times \ln(Al_2O_3/SiO_2)_{adj}) + (0.303 \times \ln(Fe_2O_3^t/SiO_2)_{adj}) + (0.436 \times \ln(MnO/SiO_2)_{adj}) + (0.838 \times \ln(MgO/SiO_2)_{adj}) + (-0.407 \times \ln(CaO/SiO_2)_{adj}) + (1.021 \times \ln(Na_2O/SiO_2)_{adj}) + (-1.706 \times \ln(K_2O/SiO_2)_{adj}) + (-0.126 \times \ln(P_2O_5/SiO_2)_{adj}) - 1.068.$$

The tectonic setting discrimination diagrams proposed by Bhatia (1983) and Roser and Korsch (1986) for clastic sediments were used in many studies to identify the tectonic setting of unknown basins (Tobia and Aswad 2015; Zaid 2016). Many researchers cautioned against the use of these previously proposed discrimination diagrams (e.g., Armstrong-Altrin and Verma 2005; Ryan and Williams 2007). Recently, Verma and Armstrong-Altrin (2013) proposed two discriminant-function-based major-element diagrams for the tectonic

discrimination of siliciclastic sediments from three main tectonic settings; island or continental arc, continental rift and collision, that have been created for the tectonic discrimination of high-silica ($(SiO_2)_{adj} = 63-95\%$) and low-silica rocks ($(SiO_2)_{adj} = 35-63\%$). These diagrams were used in recent studies to discriminate the tectonic setting of a source region, based on sediment geochemistry (Armstrong-Altrin 2015, Armstrong-Altrin *et al.* 2016). According to the high-silica diagram (figure 11), all samples of the Lower and Upper

Figure 12. The new multi-dimensional discriminant function diagrams proposed by Verma Armstrong-Altrin (2016) for the discrimination of active (A) and passive (P) margin settings. (a) Major element (M) based diagram; (b) Combined major and trace element (MT) based diagram. The discriminant function equations are:

$$(i) DF_{(A-P)M} = (3.0005 \times \text{ilr1}_{TiM}) + (-2.8243 \times \text{ilr2}_{AlM}) + (-1.0596 \times \text{ilr3}_{FeM}) + (-0.7056 \times \text{ilr4}_{MnM}) + (-0.3044 \times \text{ilr5}_{MgM}) + (-0.6277 \times \text{ilr6}_{CaM}) + (-1.1838 \times \text{ilr7}_{NaM}) + (1.5915 \times \text{ilr8}_{KM}) + (0.1526 \times \text{ilr9}_{PM}) - 5.9948.$$

$$(ii) DF_{(A-P)MT} = (3.2683 \times \text{ilr1}_{TiMT}) + (5.3873 \times \text{ilr2}_{AlMT}) + (1.5546 \times \text{ilr3}_{FeMT}) + (3.2166 \times \text{ilr4}_{MnMT}) + (4.7542 \times \text{ilr5}_{MgMT}) + (2.0390 \times \text{ilr6}_{CaMT}) + (4.0490 \times \text{ilr7}_{NaMT}) + (3.1505 \times \text{ilr8}_{KMT}) + (2.3688 \times \text{ilr9}_{PMT}) + (2.8354 \times \text{ilr10}_{CrMT}) + (0.9011 \times \text{ilr11}_{NbMT}) + (1.9128 \times \text{ilr12}_{NiMT}) + (2.9094 \times \text{ilr13}_{VMT}) + (4.1507 \times \text{ilr14}_{YMT}) + (3.4871 \times \text{ilr15}_{ZrMT}) - 3.2088.$$

members of Gebel El Rusas sandstones are plotted exclusively within the rift field. The result obtained from this discriminant-function-based multi-dimensional diagram provides a good evidence for the Red Sea- Eastern Desert tectonic system, which is consistent with the general geology of Egypt (Said 1990).

In addition, recently, Verma Armstrong-Altrin (2016) also proposed two new discriminant-function-based multidimensional diagrams for the discrimination of active and passive margin settings. On these plots (figure 12a, b), the samples exclusively plot in the passive margin field. The results obtained from these discriminant function diagrams are consistent with the regional geology of the Red Sea Coastal plain and Eastern Desert of Egypt during the Middle Miocene (Purser and Philobos 1993).

6. Conclusions

The Middle Miocene Gebel El Rusas Formation consists of two members. The Lower Member is typically irregularly bedded, poorly sorted and heterogeneous. A conglomerate bed of large granitic boulders separates this member from the underlying basement rocks. The Lower Member is formed mainly of sandstones, conglomerates with clay interbeds. The sandstones are varicoloured and

enriched in feldspar gains. The Upper Member is more calcareous and formed mainly of sandstones and limestones with marls and clays intercalations. The provenance of the Middle Miocene Gebel El Rusas sandstones has been assessed using integrated geochemical and petrographical data. The Lower Member sandstones are arkoses and derived from transitional continental provenance, while the Upper Member sandstones are subarkoses and derived from cratonic interior.

The CIA and Rb/Sr ratio values and A-CN-K diagram suggest that the source rocks of Gebel El Rusas sandstones could be weathered crystalline granitic source terrain. Also, the ICV and $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio values and Th/Sc vs. Zr/Sc diagram of Gebel El Rusas sandstones suggest first-cycle deposits, moderate weathering and low maturity.

Th/Sc, Th/Co, Th/Cr, Rb/Sr, $\text{Al}_2\text{O}_3/\text{TiO}_2$ and $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios for the Gebel El Rusas sandstones in both studied sections received a major contribution from felsic rocks. In addition, these sandstones are largely depleted on Cr and Ni contents, indicating limited contribution of intermediate rocks in the source area. The chemical characteristics and tectonic discriminant-function diagrams suggest that the Gebel El Rusas sandstones were deposited on a passive continental margin of a synrift basin that received large amounts of mature detritus from the hinterland

areas. The Proterozoic granites situated on the western side of study area are the potential source rocks for the Gebel El Rusas sandstones, which have been uplifted and exposed by the Rifting Orogeny (Oligocene–post Miocene).

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