Chapter

Geochemistry and Tectonic Setting of Neoproterozoic Rocks from the Arabian-Nubian Shield: Emphasis on the Eastern Desert of Egypt

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Abstract

The Neoproterozoic rocks of the Eastern Desert (ED) of Egypt represent the northwestern part of the Arabian-Nubian Shield (ANS), which was formed during the Pan-African orogenic cycle (950–450). Geochemistry of the different rock units has clarified their compositional variations, tectonic settings, and origins. The ages of these rock units were reported to predict the crustal evolution of the ANS. Island arc volcanic rocks and ophiolitic sequences formed between 700 and 800 Ma, and then, they were obducted in the earlier stage of the Pan-African orogeny. The post-collision stage was characterized by the emplacement of large masses of Dokhan volcanics (610–560 Ma) and shallow level A-type granites (610–550 Ma). Neoproterozoic ophiolites fall geochemically and tectonically into two separate groups: MORB-like ophiolites and SSZ ophiolites of fore-arc tectonic setting. Intra-oceanic island arcs and related inter-arc volcaniclastic sediments are followed by the incorporations of ophiolite fragments into the volcaniclastic matrix to form "ophiolitic mélange" through tectonic and/or concurrent sedimentary and tectonic processes. The "gneissic domes" that are metamorphic core complexes were previously interpreted to represent a pre-Neoproterozoic. However, recent age data argued that the ED gneissic rocks are juvenile in origin and Neoproterozoic. Granitoid rocks in the ED include older and younger types. Most of the older granitoids are of I-type character, displaying metaluminous, calcalkaline geochemical characteristics plot in the area of volcanic arc granites (VAG), whereas most of the younger granitoids are mainly alkaline of A-type granites and of within-plate tectonic setting (WPG). Nonmetamorphosed Dokhan volcanics and Hammamat molasse sediments formed during the final post-collisional phases.

Keywords: geochemistry, Neoproterozoic, Arabian-Nubian Shield, Eastern Desert, Egypt, age dating, crustal evolution

1. Introduction

The Arabian-Nubian Shield (ANS) forms one of the largest exposures of juvenile continental crust (1000–525 Ma) on Earth [1]. It consists of mainly juvenile

Neoproterozoic crust, now widely exposed in parts of Egypt, Saudi Arabia, Sudan, Eritrea, Ethiopia, Yemen, and Somalia. The ANS was formed during the Neoproterozoic between 900 and 550 Ma through the accretion of intra-oceanic arcs during the closure of the Mozambique Ocean and the amalgamation of Gondwana [2]. These accretion processes led to the formation of well-defined arc-arc and continent-arc suture zones [3, 4]. The ANS was essentially stable continental crust by Early Cambrian time at 530 Ma [5]. The ANS and its surroundings has been the object of geologic investigations for a wide range of geological economic and scientific reasons.

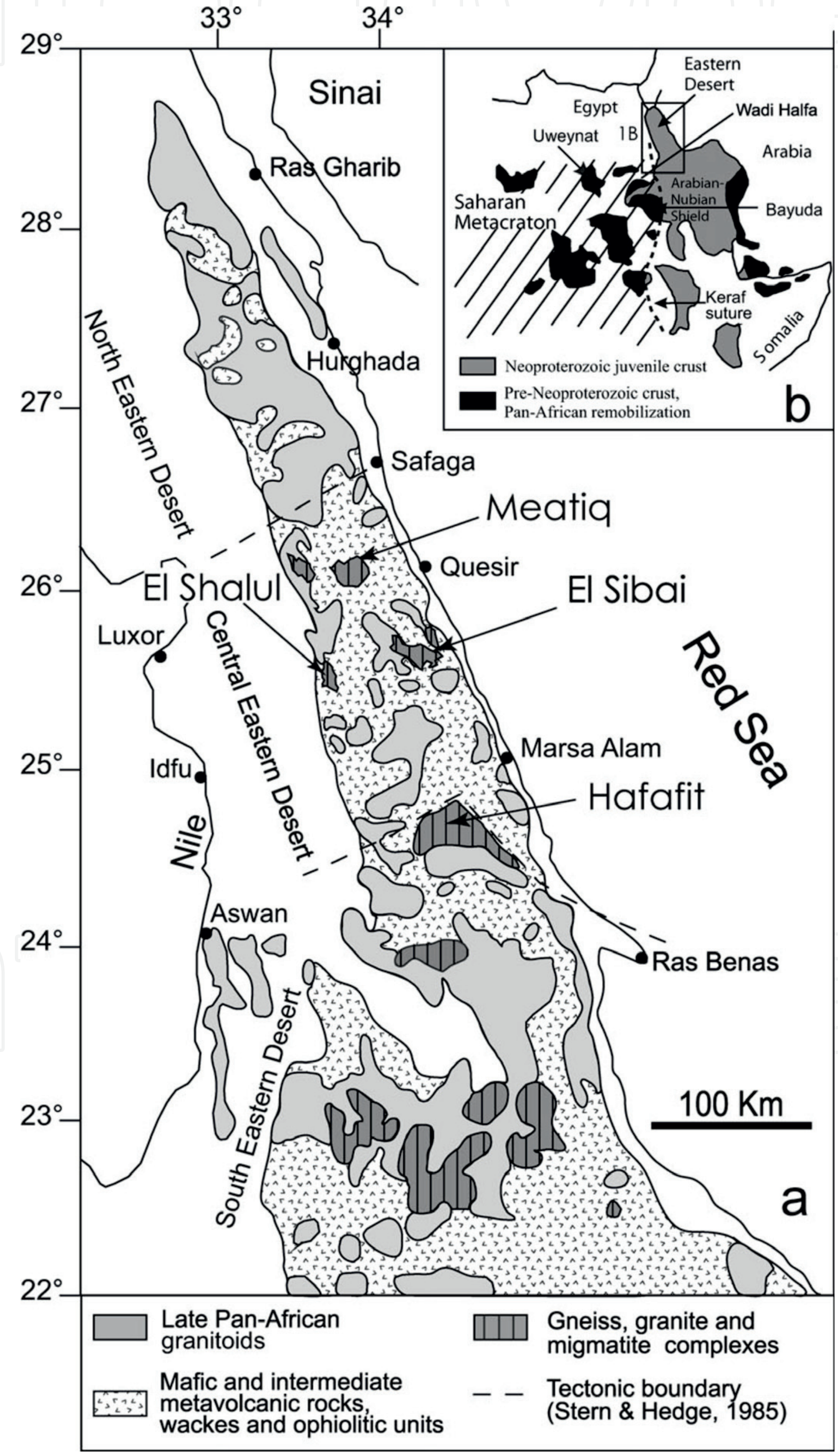


Figure 1.
(a) Inset geological sketch map of NE Africa showing the Arabian-Nubian Shield, the Saharan Metacraton, and Archaean and Palaeoproterozoic crust that was remobilized during the Neoproterozoic and (b) geological map of the Eastern Desert of Egypt showing study areas [15].

The Precambrian basement of the Eastern Desert of Egypt (ED) is a part of the Arabian-Nubian Shield (ANS) and are exposed mainly in the Eastern Desert and Sinai (**Figure 1**). The Eastern Desert of Egypt comprises variably deformed and metamorphosed volcanic, plutonic, and sedimentary rocks of Precambrian age, unconformably overlain by Cretaceous sediments. The Eastern Desert of Egypt is classified into three domains: north, central, and south [6], all revealing different aspects of the region's protracted and intense Neoproterozoic episode of deformation and igneous activity. The Central Eastern Desert (CED) preserves the oldest (Tonian-Cryogenian) history and also best preserves Ediacaran deformation as well as associated (Hammamat) basins. The Southern Eastern Desert (SED) lacks BIF, Ediacaran sedimentary or volcanic successions such as the Hammamat Group and Dokhan Volcanics, whereas the CED does not [7]. The Northern Eastern Desert (NED) is very different than either the CED or the SED. Dokhan volcanics and Hammamat molasses sediments are of widespread occurrence, whereas ophiolites are absent and gneisses are rare.

The reconstructions of this chapter are based on a compiled data of geochemistry and obtained ages on the rock units constituting the Eastern Desert of Egypt. Geochemical data are based on combination of major elements, trace elements, rare earth element (REE) distributions as well as isotope data. In this contribution, I build on previous geological and geochemical studies on the different rock units forming the ED for many years of research to summarize the most important geochemical characteristics of the different rock units and to provide some important information regarding the geochemical dynamic and evolution of Neoproterozoic crust of the ED. This chapter reviews the scope of current geochemical and isotopic datasets for the ANS, with particular emphasis on the Eastern Desert of Egypt.

2. Geologic overview of the Eastern Desert of Egypt

The Precambrian basement rocks of Egypt constitute the northern part of the so-called the Arabian Nubian Shield (ANS), which are exposed mainly in the Eastern Desert (ED) and the Sinai Peninsula (**Figure 1**). The general geological settings of the rock assemblages of the CED were grouped into two major lithotectonic units [8]. The structurally lower one, the "infrastructure," is composed of gneisses and migmatites that crop out in dome structures, such as the Meatiq, Sibai, and Hafafit domes. The overlying unit, the "suprastructure," includes the Neoproterozoic ophiolite complexes and island arc-related metavolcanic and metasedimentary rocks. The suprastructure is also known as the Pan-African Nappe Complex [9]. The juvenile crust in the ED of Egypt is characterized by four main rock units: (i) a gneiss assemblage that comprises the core complexes, (ii) an ophiolite-island arc assemblage, (iii) granitoid intrusions, and (iv) nonmetamorphosed to weakly metamorphosed Dokhan volcanics and Hammamat molasses sediments that unconformably overlie the suprastructure in places [10]. Most of the rock sequences are generally deformed and metamorphosed due to the Neoproterozoic East African orogeny. Below, the most important geological aspects of the main rock units are briefly summarized:

2.1 Granite gneisses and migmatites

A number of medium- to high-grade core complexes or "gneissic domes" have been described in the ED. These infrastructures consist of upper amphibolite facies gneisses, amphibolites, migmatites as well as granitic gneisses. They exposed in several places in the ED, including the Meatiq, El Shalul, the Migif-Hafafit, and

Beitan domes [11–15]. They are generally surrounded by low-grade supracrustal assemblages, and the contact between superstructure and infrastructure is sometimes an intrusive contact and sometimes a high-strain mylonitic zone [16]. The Meatiq Dome consists of Um Baanib deformed granite (cataclastic gneissose granite) forming the core of the dome, followed outward by schists with variable degrees of intercalated amphibolites, together with local mylonites along thrust faults [13]. The Neoproterozoic migmatitic rock association at Wadi Abu Higlig in the Hafafit region is composed of diatexites and schlieric granites (foliated or gneissic granite) in the core of a domal structure flanked by metatexites and preserved amphibolites and metagabbros [14].

2.2 Ophiolite-island arc assemblages

The CED and SED of Egypt are characterized by the widespread distribution of Neoproterozoic ophiolite, ophiolitic mélanges, and intra-oceanic island arc metavolcanic assemblages, along with volcaniclastic metasediments and banded iron formations (e.g., [17–20]). Locally, nearly complete ophiolitic sequences can be observed including serpentinized peridotites, gabbros, sheeted dykes, pillow lavas, and deep-sea sedimentary rocks such as in Ghadir, Muweilih, Esel, El Sid areas [21]. Sheeted dikes are only locally preserved in some localities, whereas pillowed metabasalts are widespread. The ophiolitic peridotites are almost completely serpentinized and are typically altered to talc-carbonate and quartz-carbonates (listwanite) bodies along shear zones. El Bahariya [20] classified the Neoproterozoic ophiolites of the Central Eastern Desert of Egypt based on field geology and mode of occurrences, together with compiled geochemical data into three types: (i) intact MORB ophiolites, (ii) dismembered ophiolites (dismembered blocks and fragments within the mélanges and ophiolites along structural contacts), and (iii) arc-associated ophiolites. The best preserved and nearly intact MORB ophiolites are represented by Wadi Ghadir and Muweilih ophiolites. The arc-associated ophiolite sequences are exposed in Abu Dahr ophiolite, Esel, and El Sid occurrences. Dismembered ophiolites occur either as individual blocks and sheets tectonically emplaced along tectonic contacts or as blocks and fragments within a sheared matrix of volcaniclastic metasediments or metapyroclastics forming “ophiolitic mélange” [19].

The island arc assemblages are concentrated mainly in the CED and SED. They include:

i. metamorphosed volcanic island-arc assemblage and

ii. metamorphosed bimodal volcanic island arc assemblage.

The metamorphosed volcanic island arc assemblages are widespread in the CED and SED [22–24]. They are composed of metavolcanics and related volcaniclastic metasediments. The metavolcanics include metabasalts, metandesites, metadacites, metarhyodacites, and metarhyolites, together with their metapyroclastic counterparts. The volcaniclastic metasediments comprise meta-mudstones, metasiltstones, metagreywackes, metaconglomerates, and schists. The volcaniclastic metasediments together with the metapyroclastics constitute the matrix of the “ophiolitic mélange” [19]. The exotic fragments within melanges are mainly ophiolites of variable sizes and shapes, which include serpentinite and metamorphosed ultramafic rocks, metagabbros, pillowed and massive metabasalts, and minor sheeted dykes and pelagic sedimentary rocks. El Bahariya [19] documents different occurrences of Neoproterozoic ophiolitic melanges in the CED of Egypt and classified the ophiolitic mélanges into:

(i) tectonic mélange, (ii) olistostrome, and (iii) olistostromal mélange. Ophiolitic melanges are also recorded in different occurrences in the SED such as Atshan Ophiolite, Gerf, and Abu Dahr [25].

The bimodal metamorphosed island arc assemblage comprises mafic and felsic volcanic intercalations and arc-related volcanoclastics sediments. They are regionally metamorphosed up to the greenschist facies, locally transformed into schists and amphibolites and commonly associated with banded iron formations and massive sulfides [13, 26, 27]. The metavolcanics together with intra-arc volcaniclastic metasediments occur in different localities in the CED and northern part of SD such as Um Khariga and metapyroclastics, Sodamine, Um Samuky, and El Shadly metavolcanics. The Shadli metavolcanics host some polymetallic massive sulfide mineralizations, e.g., Um Samiuki and Abu Gurdi [28].

2.3 Granitoid rocks

The granitoid rocks constitute about 50% of the basement complex of Egypt. They can, in general, be classified into older and younger granitoids based on their composition, color, and relative age [29]. The older granitoids (∼850–635 Ma) comprise trondhjemites, tonalites, granodiorites, and rarely granites, whereas the younger granitoids (∼630–540 Ma) are predominated by granites and alkali feldspar granites [6]. The younger granites are further classified according to their geological setting and petrography [30] into: (i) phase I granodiorites with minor monzogranites, (ii) phase II (monzogranites and syenogranites), and phase III (alkali feldspar granites). Recently, part of the Younger granites (phase III) are classified as A-type granites [31].

2.4 Nonmetamorphosed rocks

2.4.1 The Dokan volcanic rocks

The later stage of the crustal evolution of the NED and CED is characterized by the eruption of the Dokhan volcanics, which typically include basaltic andesite, andesite, dacite, and rhyolite, together with tuffs, ignimbrite, and agglomerates [32].

2.4.2 Hammamat sediments

The best exposures of the Hammamat molasses sediments found in Wadi Hammamat area of the CED of Egypt [29], where the sedimentary rocks unconformably overlie other old rock units and consist of unmetamorphosed thick sequences of unsorted conglomerates, sandstones, and siltstones. Most of the Hammamat fragments were derived from the Dokhan volcanics and their thickness varies between 4000 m in Wadi Hammamat and 7500 m thick in the Kareim basin. Locally, the Hammamat sediments are sheared and metamorphosed [33].

3. Geochemistry

The compiled available chemical data from of the ED of Egypt are used for the purpose of understanding the geochemistry of Neoproterozoic rocks, and to clarify their geochemical characteristics and tectonic settings. The overall geochemical characteristics of the different rock units are presented as follows.

3.1 Granite gneisses and migmatites

The Hafafit granitic gneisses are enriched in REE, whereas the Um Baanib orthogneiss presents alkaline granite Rear Earth Elements (REE) pattern (**Figure 2a** and **b**). Um Baanib deformed granites (granite gneisses) are enriched in High Field Strength Elements (HFSE) (Zr, Nb, Y, Th), Rb, Ga, and total REE and depleted in MgO, CaO, and V, showing alkaline and A-type characters, whereas Hafafit granitic gneisses are calcalkaline and of I-type granites [34, 35]. In terms of the Nb, Y, and Rb contents, the Hafafit granite gneisses plot in the field of volcanic arc granites [36], whereas the Um Baanib granite gneisses plot within the field of anorogenic or within-plate A-type granites. Aswan orthogneisses are clacalkaline I-type granitoids [37] that are generally described as subduction-related granitoids [38].

Thermobarometry based on composition of coexisting mineral pairs for granite gneisses indicates that peak metamorphism and partial melting occurred at ~750°C and ~5 kb at high H_2O activity for the metatexite. The granite gneiss in the core of Hafafit dome is suggested to have been formed by syntectonic partial melting of lower to middle crustal protoliths [14]. Plagioclase, clinopyroxene, hornblende, garnet, and biotite show compositional variability as a consequence of the composition of protoliths and prevailing P-T conditions of metamorphism (**Figure 2c–e**). Migmatitic rocks provide an example of the close relation among metamorphism, deformation, and melt generation and emplacement. This migmatitic rock association is interpreted as syntectonic anatectic migmatites formed during compressional phase in an Andean-type continental margin tectonic setting.

3.2 Ophiolite-island arc assemblages

3.2.1 Ophiolite geochemistry

The HFSE and (REE) of Neoproterozoic ophiolites of ED of Egypt suggest either similarities with normal-type mid-ocean ridge basalts (N-MORB) or back-arc basin

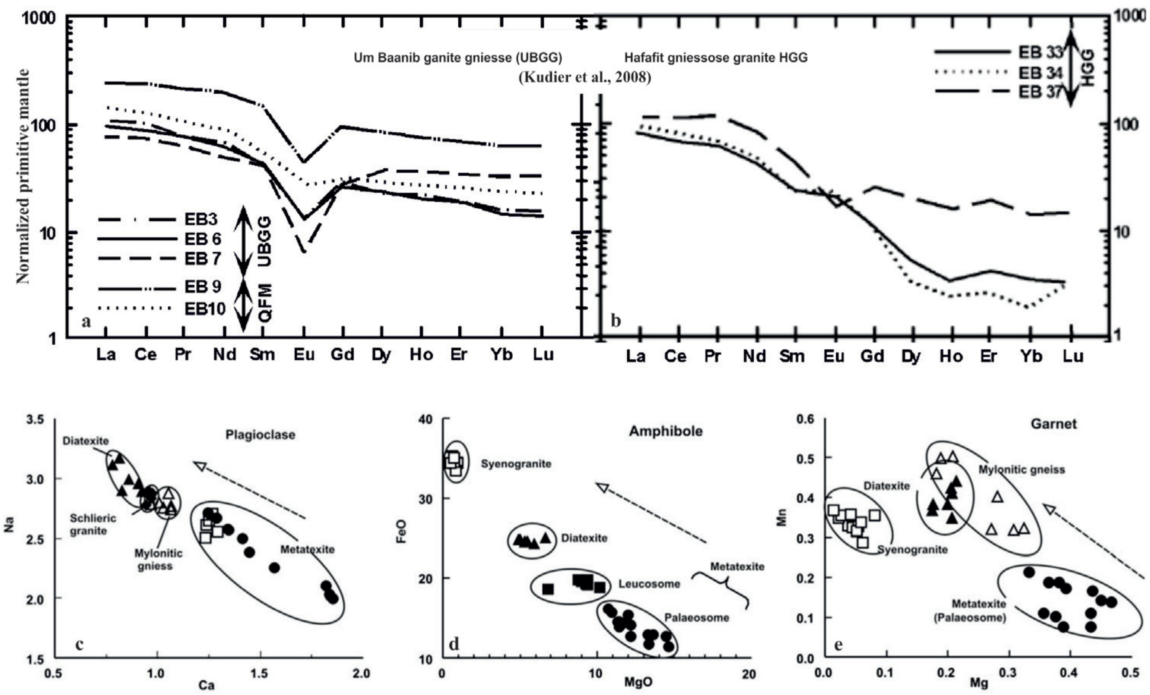


Figure 2.
Rare earth element abundances in the infrastructural rocks from Meatiq (a) and Hafafit core complexes (b) normalized to primitive mantle from [35] and (c–e) compositional variations of plagioclase, amphibole, and garnet in Hafafit migmatitic rocks from [14].

(BAB) magmas or similar to fore arc, boninites and SSZ basalts. Immobile trace-element abundances, together with significant Light Rear Earth Elements (LREE) depletion to almost flat REE patterns for pillow lavas and sheeted dykes of Gerf ophiolite, are compatible with the N-MORB distribution patterns [39]. Volcanic rocks of Fawakhir (El Sid) SSZ ophiolites display moderately depleted to slightly enriched LREE patterns (**Figure 3a**), whereas pillow lavas of Ghadir MORB ophiolites have similar chondrite-normalized REE patterns (**Figure 3b**) [40, 41]. They are enriched in LREE. Most Gerf gabbros have REE patterns with a slight LREE enrichment and a small positive Eu anomaly, whereas the Gerf serpentinized peridotites have Large Ion Lithophile Elements (LILE)-depleted patterns. The Abu Dahr metagabbro and metabasalt have enrichment LILE and LREE enrichment, whereas serpentinized harzburgite and dunite are characterized by enrichment of LILE and nearly flat and unfractionated chondrite-normalized pattern indicating they originated by up to ~30% partial melting of a spinel lherzolite mantle in a subarc setting [25].

Generally, most samples of ophiolitic lavas are subalkaline and reveal tholeiitic affinities, together with minor calcalkaline characters, although subordinate, amount of boninites have been identified as in El Sid ophiolite. On the Ti-V tectonic setting discrimination diagram (**Figure 3c**), generally, ophiolitic metavolcanics and metagabbros of the ED of Egypt fall into two groups: (i) MORB ophiolites and (ii) fore arc or suprasubduction zone (SSZ) ophiolites (e.g., [20, 25, 39, 40–46]). The MORB affinity of metagabbros from Muweilih is documented for the first time by El Bahariya [43], and the whole Muweilih ophiolite sequence is mapped and recorded for the first time as MORB intact ophiolite by El Bahariya [20].

The serpentinites and serpentinized peridotite ophiolites display a diverse suite of geochemical signatures, which make their origin or tectonic setting controversial.

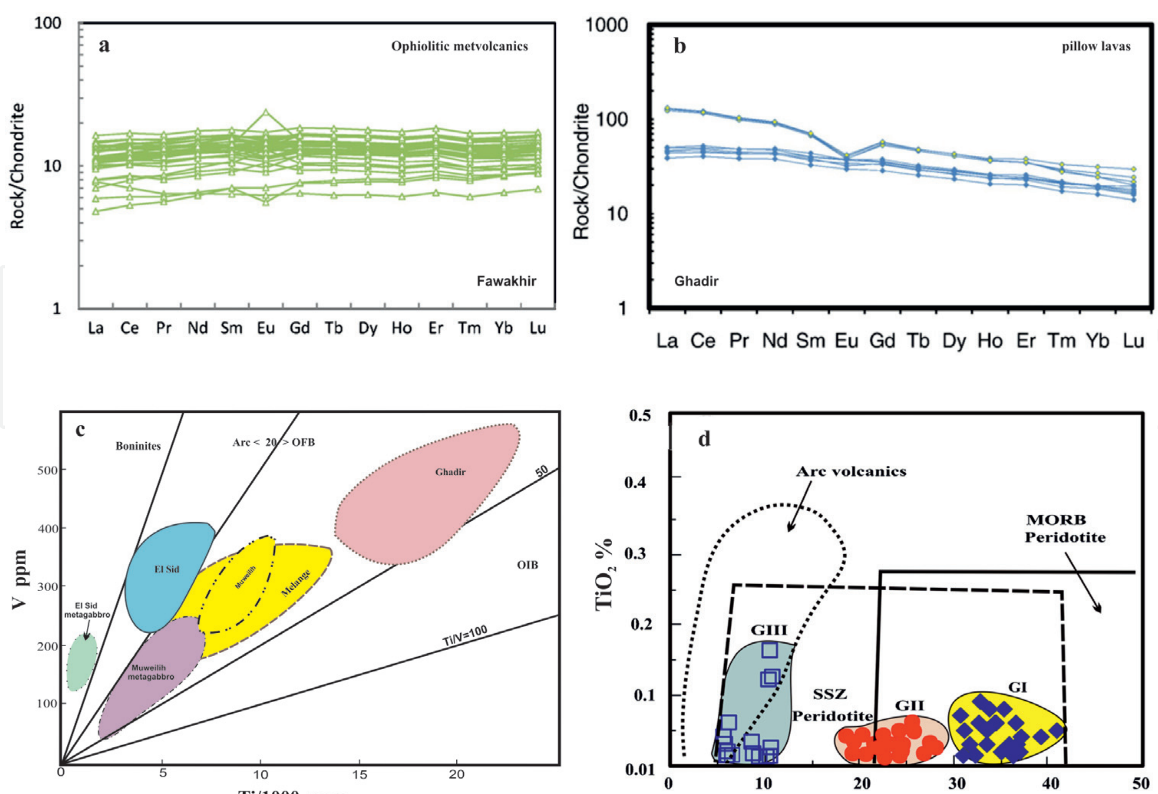


Figure 3.
Geochemical characteristics of ophiolites. (a) Chondrite-normalized REE patterns for Fawakhir (El Sid) ophiolitic pillow lavas, (b) Ghadir pillow lavas [40, 41], (c) Ti/1000 vs. V diagram [20], and (d) chrome spinels from ophiolitic blocks of metamorphosed ultramafics in mélanges [20].

Generally, the chrome spinels from the serpentinites and metamorphosed ultramafic ophiolites have a wide range of Cr#, where the Cr# ranges from ~0.3 to 0.85 and display both MORB and SSZ affinities [45]. They are classified into three groups (G1, G2, and G3) according to their Cr# (**Figure 3d**). Most serpentinized peridotites of the ED show significantly more Mg-rich olivine and chrome spinel with high Cr# (G1 and G2), suggesting a forearc or SSZ environment [42, 45, 47, 48]. Only, data of Cr-spinel from the serpentinized peridotite blocks of Esel olistostrome commonly show low Cr# (G1), and accordingly, they show MORB affinity similar to abyssal peridotites [45]. Moreover, the previous studies dealt collectively with the ophiolitic serpentinites of the ED to be of fore arc or SSZ geochemical signature. However, El Bahariya [20, 47] reported the presence of both SSZ and MORB ophiolitic serpentinized peridotites.

3.2.2 Geochemistry of island arc assemblages

Geochemistry of intermediate and acidic island arc metavolcanics, together with the native intermediate and acidic metavolcanic clasts of the ophiolitic mélanges, is presented. The metavolcanic rocks at Wadi E Dabbah show slightly fractionated REE patterns (**Figure 4a**) and negative Eu and Ce anomalies [49]. The island arc metavolcanics are of oceanic island arc affinity (**Figure 4d**) [23, 24]. The intermediate and acidic island-arc rocks at Gebel Zabara area are calcalkaline and of continental island-arc setting, representing an intermediate maturity stage between the primitive arc and the mature active continental margin [50]. Um Anab meta-andesites, metafelsites, and metarhyolites varieties are predominantly of calcalkaline nature, enriched in LILE and depleted in HFSE, with a pronounced negative Nb anomaly [51]. These rocks are most probably derived from a mantle source produced in an island arc environment where fall in the plate margin field confirming the orogenic nature of these rocks.

The REE patterns of bimodal Um Samiuki metavolcanics rhyodacites are very nearly flat (**Figure 4b**) [28]. Also, the REE patterns of the felsic lavas are slightly LREE-depleted, whereas basalt is slightly LREE-enriched and characterized by negative Eu anomalies. The trace element characteristics of both mafic and felsic members of the Shadli Metavolcanics indicate that these rocks were originated in a magmatic rift. The bimodal metavolcanics at Wadi Sodmien show mafic tholeiitic character and felsic rocks calcalkaline affinity (**Figure 4c**) [52]. They have transitional tectonic setting between island arc/active continental margin and within plate (extensional environment) tectonic setting (**Figure 4d**). Their petrogenesis can be attributed to partial melting of continental crust, and they suggested to be formed in ensialic back arc basin due to extensional rifting. Major trace elements and REE indicate that Igla Eliswid-Um Khariga bimodal mafic and felsic metavolcanic assemblages [53] are clearly tholeiitic in character and share a large number of geochemical features of island-arc tholeiites. The geochemical data are most consistent with the hypothesis that these rocks originated in a magmatic rift. The REE concentrations of Gebel El Hadid banded iron formation (BIF) have LREE depleted and HREE enriched patterns [54] and are characterized by low ΣREE contents (13.7–77.5 ppm) with an average of 45.2 ppm.

On the other hand, the geochemistry of arc-related volcaniclastic metagreywackes constituting the matrix of the mélange indicates that they are chemically similar to quartz-poor oceanic island arc sandstones and were derived mainly from intermediate and felsic volcanic igneous provenances [19, 23, 24]. They are of oceanic island arc tectonic setting (**Figure 4e** and **f**) and appear to be deposited in back-arc basins or interarc basins.

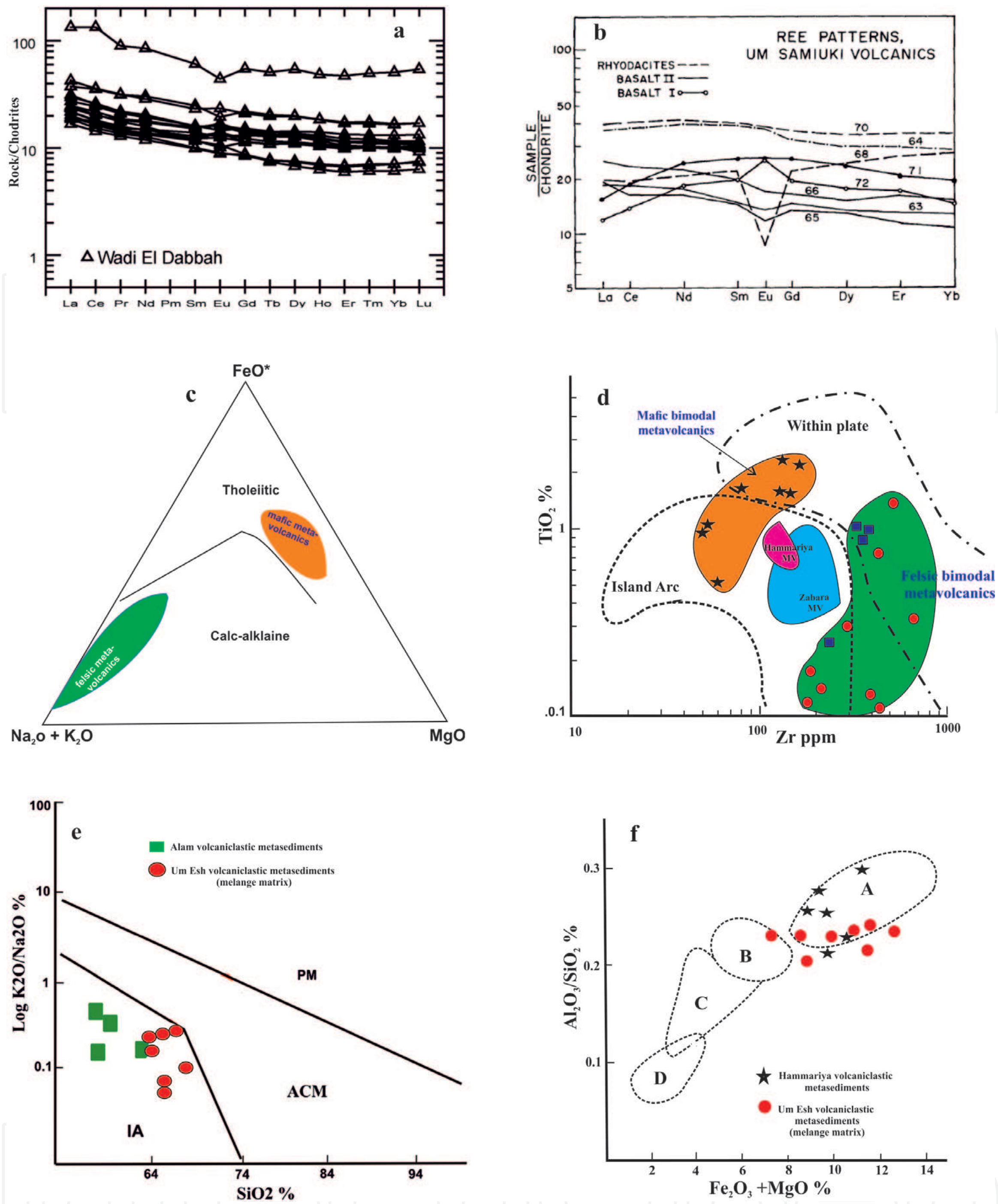


Figure 4.
(a) Rare earth element (REE) and trace element diagrams for the analyzed metavolcanic samples from Wadi El Dabbah from [49]; (b) REE patterns for Um Samiuki Volcanics, normalized to chondritic meteorites from [28]; (c) AFM diagram of Sodmien bimodal metavolcanics, fields based on data from [52]; (d) Sodmien bimodal metavolcanics, data for field of Zabara metavolcanics from [50] and field of Hammariya metavolcanics from [24]; and (e and f) tectonic setting of metagreywackes from matrix of mélanges and from bimodal intra-arc volcaniclastic metasediments, data from [23, 24, 26].

The intra-arc metagreywackes of Alam volcaniclastic metasediments show variable abundances of Zr, Cr, Ni, and V. Their provenance components are mainly of evolved felsic and mafic (bimodal) island arcs and show oceanic arc tectonic setting (**Figure 4e**). They are comparable with Archaean Ranebennur metagreywackes derived from a mixed provenance consisting of mafic and felsic source rocks (e.g., [26, 55]). The rocks are suggested to be deposited in a localized intra-arc basin. The clasts and grains constituting the sediments simulate the principal bimodal volcanic rocks of both the Sukkari metavolcanics and Um Khariga metapyroclastics in the near area [26].

3.3 Geochemistry of granitoid rocks

The geochemistry of both older and younger granites is briefly presented.

The REE patterns of the *older granodiorites* (**Figure 5a**) show enrichment in the LREE relative to HREE, Lan/Ybn values vary from 7.08 to 35.21 (mostly between 7.08 and 19.37) and with Eu anomalies ranging from (Eu/Eu* = 0.70–1.13) [56]. The slightly concave HREE pattern of some biotite suggests hornblende fractionation. *The younger alkali feldspar granites* are characterized by LREE-enrichment (Lan/Ybn = 5.28 – 13.46), moderately fractionated LREE, flat heavy REE patterns (**Figure 5a** and **b**), and moderately to strongly negative Eu anomalies (Eu/Eu* = 0.14–0.63).

Geochemistry of *older granites* reveals that they are metaluminous to slightly peraluminous and have calcalkaline affinity. The older granite can be classified as I-type granites and of volcanic-arc-granite tectonic setting (**Figure 5c**) (e.g., [57]). In the ANS, the I-type granitoids were generally interpreted to result from melting of an amphibolitic crust (e.g., [58]). Moreover, older I-type granites can form through fractionation from mantle-derived, LILE-enriched basaltic melts in subduction settings (e.g., [59]), or from remelting of mafic to intermediate igneous lower crust [60].

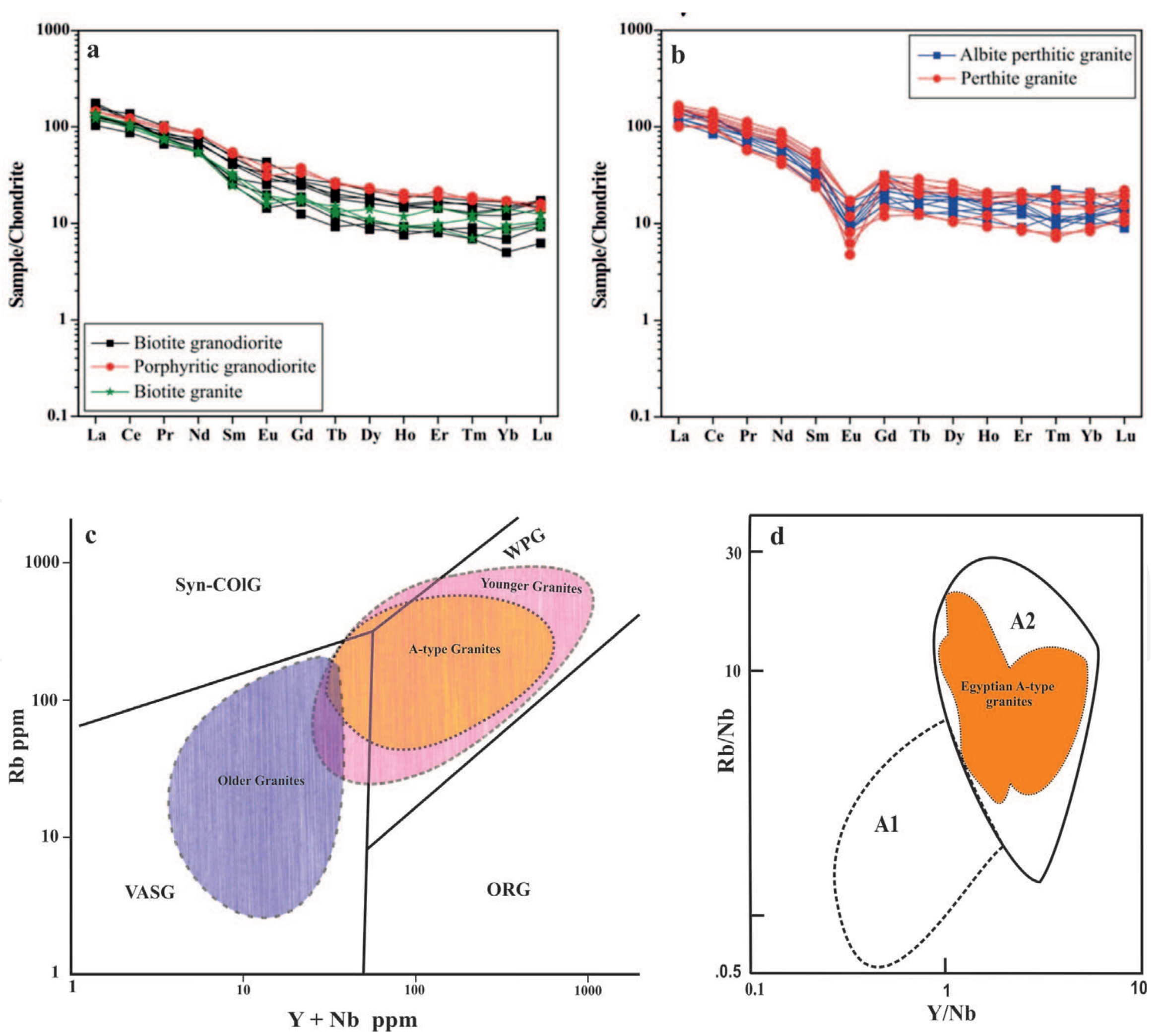


Figure 5.
(a) REE of older granites and (b) REE of younger and A-type granites (from [56]); (c) tectonic setting of granitoid rocks using diagram of Pearce et al. [61], data of older and younger granitoids from [38]; (d) division of A-type granites [62], field of Egyptian A-type granites from combined data from [37, 60] and references therein.

Most of the *younger granites* are LILE-enriched calcalkaline to mildly alkaline rocks commonly of A-type signatures. The younger granites, except phase I exhibit within plate tectonic setting [61], due to their high contents of HFS elements (**Figure 5c**). The phase-III younger granitoids (A-type) are characterized by higher SiO_2, Rb, Y, and Nb and lower MgO, Sr, and Ba contents than other phases of younger granites [38]. The A-type granites are enriched in SiO_2, Na_2O^+ K_2O, FeO*/MgO, Ga/Al, Zr, Nb, Ga, Y, Ce, Rb, and REE and low in CaO, MgO, Ba, and Sr. They are classified as alkaline, and peralkaline to mildly peraluminous A-type granites (e.g., [37]). They are generally enriched in Rb (104–198 ppm), Nb (27–53 ppm), Y (35–79 ppm), Zr (348–750 ppm), and Ga (21–29 ppm), compared to average continental crustal rocks. The overall geochemical characteristics of the A-type granitic rocks of the ED and Sinai are consistent with a within-plate tectonic settings (**Figure 5c**). The A-type granites are eligible for A1-A2 discrimination diagrams after [62] and classified mainly as A2 types (**Figure 5d**), implying that the A-type granites formed mainly in a post-collisional setting. The alkaline A-type granites are generally regarded as the product of either extensive fractional crystallization of mantle-derived mafic magmas (e.g., [63]) or partial melting of various crustal sources (e.g., [37, 49]).

3.4 Geochemistry of nonmetamorphosed rocks

3.4.1 Geochemistry of Dokan volcanic rocks

The Dokan volcanic rocks display well-defined major and trace element trends and a continuum in composition with wide ranges in SiO_2 (54–76%), CaO (8.19–0.14%), MgO (6.96–0.04%), Sr. (983–7 ppm), Zr (328–95 ppm), Cr (297–1 ppm), and Ni (72–1 ppm). The rocks are enriched in LILEs (Rb, Ba, K, Th, Ce) relative to HFSE (Nb, Zr, P, Ti) and have high total REEs with LREE enriched and display variable degrees of enrichment according to rock type (**Figure 6a**) [64]. The intermediate volcanics are characterized by moderate total REE and moderately fractionated patterns with slightly negative Eu-anomalies. Similarly, the REE pattern for the rhyolites is almost identical but with relatively lower content of REE. Generally, the Dokhan volcanics have steep LREE and nearly flat HREE and the large negative Eu anomalies in the rhyolite rocks than those of other varieties indicating formation under condition of relatively low temperature and pressure and/or low water content in the melt.

The geochemistry of the Dokhan volcanic rocks indicates medium-K to high-K calcalkaline affinity, and their tectonic setting is suggested to be: (i) subduction related [65], (ii) extensional setting/rift system (e.g., [66]), and (iii) transitional stage between subduction and extension (e.g., [67, 68]). However, the Dokan lavas mostly plot in an overlap zone between the volcanic arc and within-plate settings on the binary SiO_2—Nb diagram of Pearce and Gale [69] (**Figure 6b**), suggesting a transitional tectonic setting.

3.4.2 Geochemistry of Hammamat molasse sediments

It is of great importance to assess the composition and nature of the source rocks of the Hammamat molasses sediments geochemically, and to determine their tectonic settings. The HFSE are incompatible during most igneous processes; therefore, they tend to be enriched in felsic relative to mafic rocks. Also, they are generally resistant to changes during weathering and alteration processes [70]. The greywackes of the Hammamat molasses sediments have relatively high Zr, Nb, Y, and TH and relatively low Cr, Ni and V, and Sc. **Figure 7a** shows that Um Hassa

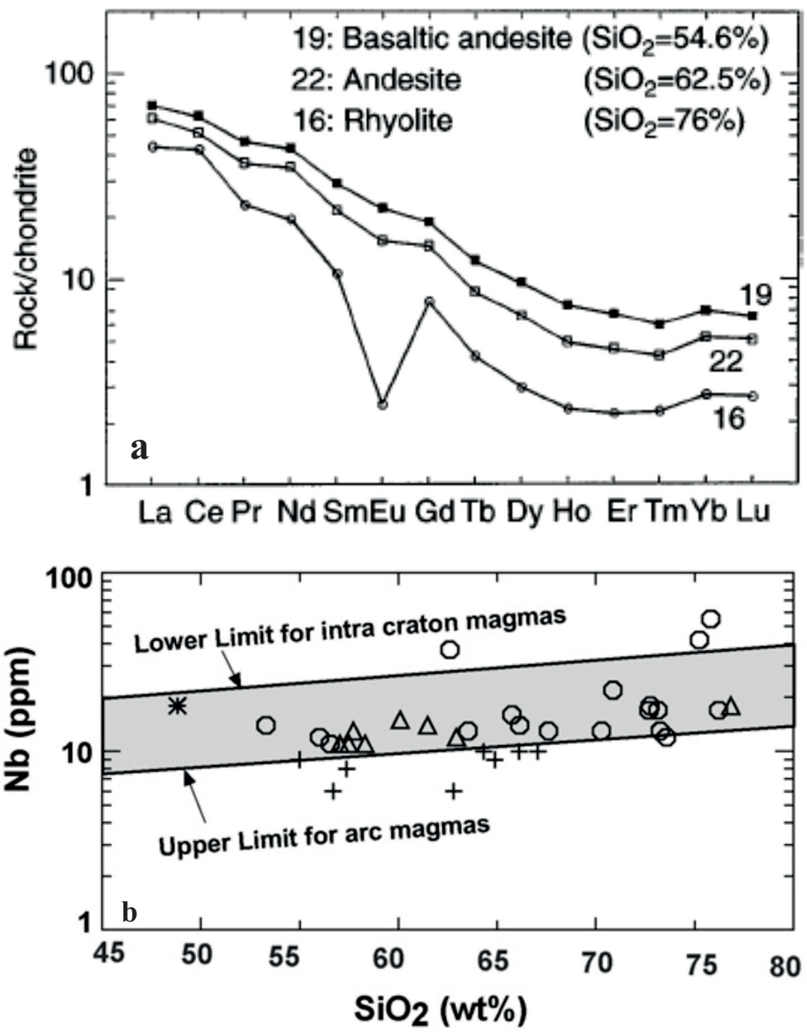


Figure 6.
(a) Chondrite-normalized REE patterns for the Wadi Fatira Dokan volcanics from [64]; (b) SiO_2 vs. Nb diagram after [69] for Wadi Um Sidra and Um Asmer Dokan volcanics from [68].

greywackes of Hammamat molasses sediments have LREE-enriched chondrite-normalized patterns similar to post-Archean Australian shale (PAAS) and UCC patterns [71]. Upper continental crust-normalized patterns for the Um Hassa greywackes reveal significant enrichment of Cr (234–434 ppm) and Ni (49–72 ppm) but depletions in Nb (4.1–7.7 ppm), Rb (33–63 ppm), and Th (3.64–8.92 ppm) relative to UCC values (35, 20, 25, 112, and 10.7 ppm, respectively).

The shale is enriched in REE relative to the coarser sediments (**Figure 7b**), but has a markedly greater Eu anomaly. Chondrite-normalized Ce/Yb ratios are very similar for the shale, the siltstone, and the sandstone ((Ce/Yb)n = 9.8−11.0) [72]. The relatively high K_2O (3.0%), Rb (79 ppm), Ba (1014 ppm), and LREE-enriched pattern ((Ce/Yb)n = 10.3) indicate that the rocks were derived from an LIL and LREE-enriched source. Plausible candidates for this enriched source include the Dokhan volcanics and the Pink younger granite, both of which occur as clasts in the conglomerates and breccias.

There is a close relationship between the tectonic setting of depositional basins and the geochemical characteristics of their sandstones [73–75]. The greywackes from Hammamat molasses sediments plot within the field of active continental margin or continental island arcs (**Figure 7c** and **d**) and appear to be formed in pull-apart intermontane basins of continental margin [33, 71]. The source rocks of the Hammamat molasses sediments are represented mainly by calcalkaline to alkaline felsic source of evolved magmatic island arcs and active continental margin together with minor inputs from calcalkaline island arcs or mafic rocks [33].

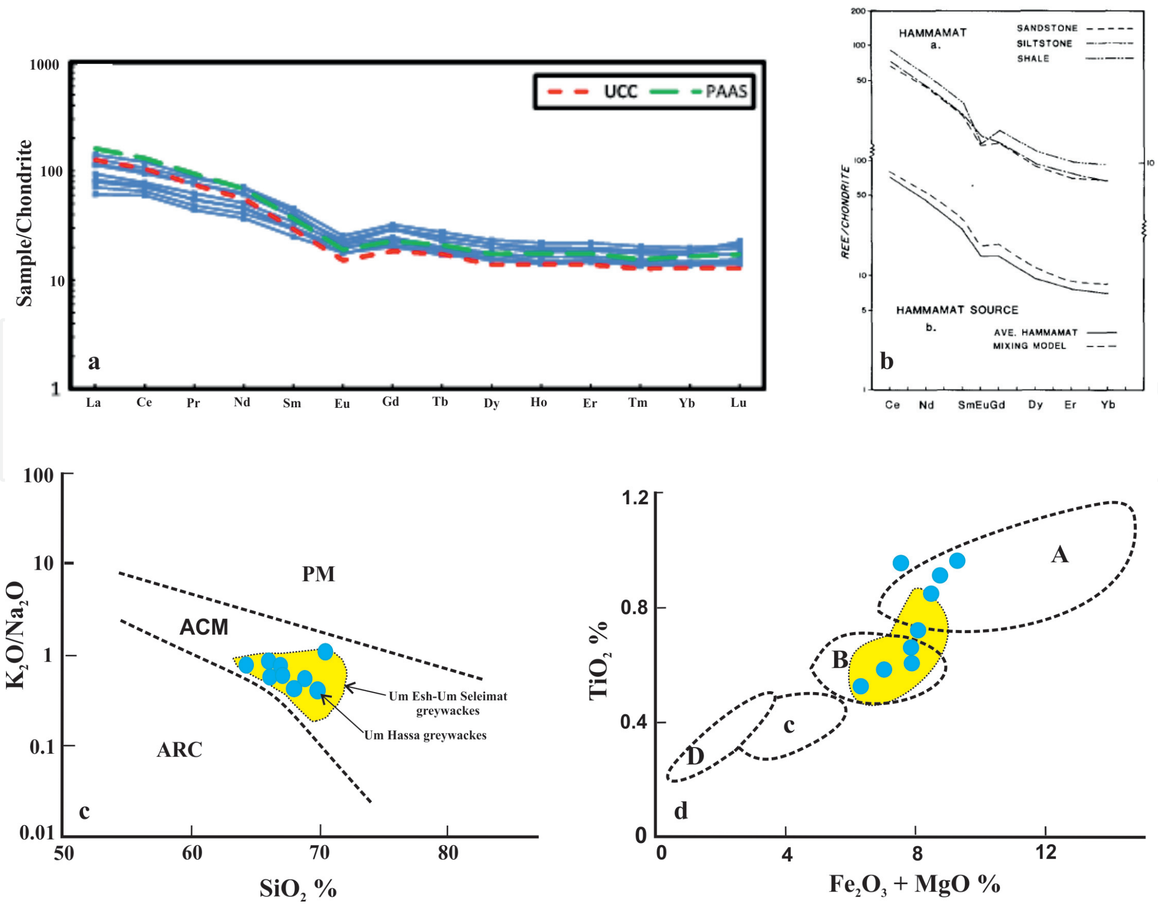


Figure 7.
(a) Chondrite-normalized REE patterns for Um Hassa greywackes from [71]; (b) REE patterns of the Hammamat lithologies from [72]; (c) K_2O/Na_2O vs. SiO_2 after [75] and (d) TiO_2 vs. Fe_2O_3 + MgO after [73] (field of Um Esh-Um Seleimat Hammamat sediments based on data from [33], plots of Um Hassa greywackes from [71].

However, there are minor inputs from island arcs and mafic rocks or ophiolites as reworked clasts from the oldest rocks or from the mélange. The Hammamat molasse area appears to have been deposited in a retroarc foreland basin [71] or appear to be accumulated in intermountain basins or foreland molasse basins [76, 77].

4. Age dating and crustal evolution

Um Ba'anib gneissose granites in the core of Meatiq dome dated 626 [78] and 631 Ma [10]. Ali et al. [15] obtained a zircon age of 631 ± 6 Ma for El-Shalul granitic gneiss. Kröner et al. [36] reported single zircon evaporation ages of 677 ± 9 and 700 ± 12 Ma for granitoid gneisses from the Hafafit gneiss complex and 704 + 8 Ma for migmatitic granitic gneiss from Wadi Bitan. Magmatic emplacement ages for samples from Wadi Beitan yielded 719 ± 10, 725 ± 9 and 744 ± 10 Ma, indicating that the gneiss protoliths are Neoproterozoic [2].

The ophiolitic rocks of the ED have isotopic ages range from 890 to 690 Ma, documenting a 200 Ma year period of oceanic magmatism [79]. The Gerf ophiolites seem to be formed at 741 ± 21 [80], 750 [41], and 730–750 [79]. The ages of the well-preserved ophiolitic rocks in Wadi Ghadir (746 ± 19 Ma, [80]) and in Fawakhir (736.5 ± 1.2 Ma [10]) in the CED are compatible with the ~750 Ma crust forming event proposed by [49].

Stern and Hedge [6] date ED island-arc volcanics to 720–770 Ma. The mafic and felsic lavas of Shadli island arc metavolcanics yield Rb-Sr isochron age of 712 Ma that probably represents the time of volcanic eruption [28]. Ali et al. [49] reported a protolith age of *c*. 750 Ma for the volcanic and volcanosedimentary rocks, and they considered that both the ophiolitic and island arc assemblages in the CED constitute an artifact of one (~750 Ma) crust-forming event.

The emplacement of the Egyptian late- to post-tectonic younger granites covers a time span between 600 and 550 Ma, [6] and 600 and 475 Ma [15]. The underformed Um Had granite has a U-Pb zircon age of 590 ± 3.1 Ma [10]. Some alkaline A-type granites in the NED of Egypt (Al-Missikat, Abu Harba, and Gattar) dated ca. ~600 Ma [81]. Available isochron Rb—Sr ages of alkaline granites are from Sinai fall in the range 550–600 Ma [82].

The transition in the tectonic style from compressional to strong crustal extension is at approximately 600 Ma [66]. Breitkreuz et al. [83] reported age range between 592 and 630 Ma (early Ediacaran) for acidic Dokan volcanics indicating that Dokan volcanism occurred over a 40 Ma time span.

Most of the Eastern Desert molasse basins were evolved between 650 and 580 Ma in individual basins with different individual tectonic settings (e.g., [84]). Rb-Sr whole-rock analyses give an age of 585 ± 15 Ma that approximates the time of sedimentation [75]. U—Pb dating of clastic zircons from the Hammamat group at

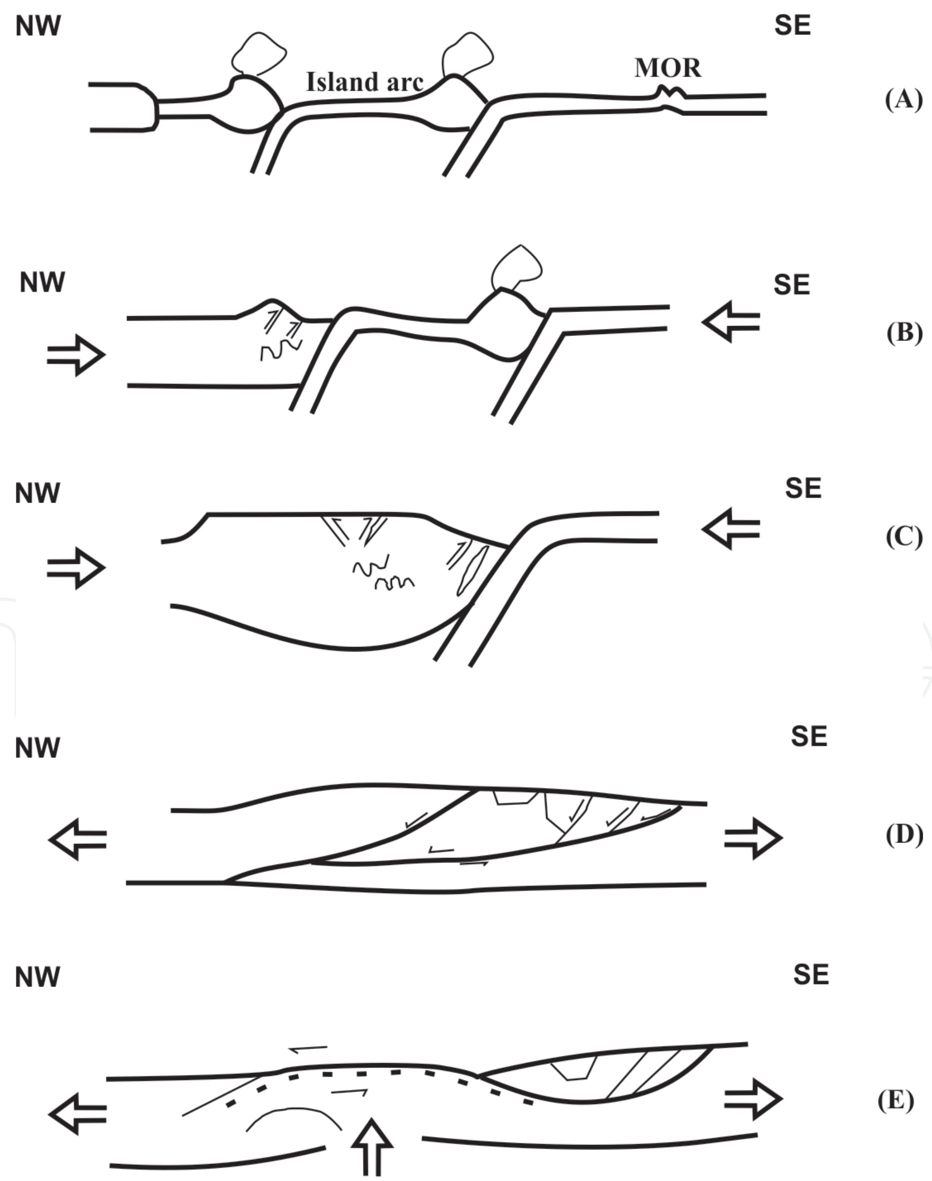


Figure 8.
A cartoon displaying the different stages of the evolution of the Arabian-Nubian Shield after [88].

Gebel Umm Tawat, North Eastern Desert indicates its depositional age as 585 ± 13 Ma [85].

The tectonic evolution of the ANS is commonly divided into three major stages, namely: (1) subduction stage (_870–635 Ma) during which oceanic crust, island arc volcano-sedimentary sequences, and plutonic rocks formed; (2) continental collision (640–650 Ma) resulting from continuing convergence between East and West Gondwana to form the East African orogen [3]; and (3) post-collision stage (580–540 Ma), evidenced by stabilization of ANS crust accompanied by the cutting of a vast peneplain [86]. Development of sedimentary basins and emplacement of increasingly alkaline igneous rocks took place during the last two stages (e.g., [87]). Finally, the ANS stabilized as continental crust by Early Cambrian time (~525 Ma) [1]. The tectonic scenario for ED of Egypt can be summarized as follows [88]:

1. intra-oceanic island arcs were formed in the Mozambique Ocean (**Figure 8A**)

2. suture possibly by a continental block in the western Egypt (**Figure 8B**)

3. arc accretion led to substantial lithospheric thickening (**Figure 8C**). At this stage, conductive heating of the lithospheric root decreased the strength of the crust. The thickened crust became gravitationally unstable and collapsed, which, in turn, led to extension (**Figure 8D**).

4. Crustal thinning, through large low-angle normal shear zones, allowed the intrusion of A-type granites. The isostatic rebound and the intrusion of these granites contributed to the doming of the lower crust and the development of metamorphic core complexes such as the Meatiq domes (**Figure 8E**). Sedimentary basins, bordered by normal faults, were formed at the upper crustal levels as a response to the extension and allowed the deposition of

5. post-orogenic molasse sequences as the Hammamat molasses group.

5. Concluding remarks

1. The Precambrian rocks of Egypt represent the northwestern part of the Arabian-Nubian Shield, which was formed during the Pan-African orogenic cycle (950–450 Ma) [89]. Island arc volcanic rocks and ophiolitic sequences formed between 700 and 800 Ma [6], and then, they were obducted in the earlier stage of the Pan-African orogeny. The Pan-African orogenic event in Egypt ended at about 615 Ma, and subsequent crustal uplifting and extensional collapse occurred within the 610–550 Ma time span [89]. This post-collision stage was characterized by the emplacement of large masses of Dokan volcanics (610–560 Ma) and shallow-level A-type granites (610–550 Ma) [6]. The most common rock units of the ED of Egypt are grouped into an ophiolitic suite/island arc assemblage and post-orogenic intrusions (**Figure 9**) [54]. **Table 1** summarizes the geochemical characteristics, tectonic setting, and age dating of the different rock assemblages.

2. Collectively, the different types of the ED ophiolites fall geochemically and tectonically into two separate groups: MORB-like ophiolites formed in a back-arc tectonic setting and SSZ ophiolites of fore-arc tectonic setting. The tectonic setting of the ophiolites changed from MORB to SSZ with time. Formation of an intra-oceanic island arcs and related volcaniclastic sediments is followed by

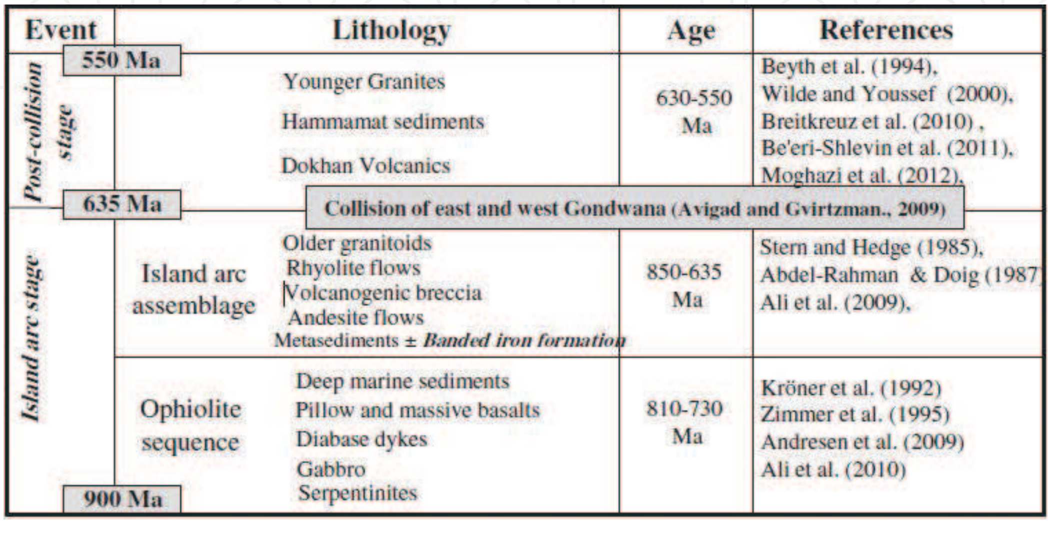
the incorporations of ophiolite fragments into the volcaniclastic matrix to form "ophiolitic mélange" through tectonic and/or concurrent sedimentary and tectonic processes to be formed in an interarc or back-arc basin [19]. Subsequent to this stage, the volcanic eruptions of bimodal-evolved island arcs are contemporaneously or shortly followed by deposition of volcaniclastic sediments in an arc-rift basin known as "intra-arc basin" [26].

3. The "gneissic domes" are metamorphic core complexes that were formerly interpreted to have been formed either in a compressional setting or in an extensional regime. However, the obtained age data indicated that the ED granite gneissic and migmatitic rocks are juvenile in origin and Neoproterozoic.

4. Granitoid rocks in the ED include (1) old calcalkaline, I-type, syn- to late-orogenic granitoid assemblages (880–610 Ma) and (2) younger commonly alkaline, post-orogenic to anorogenic granitoid assemblages emplaced between 600 and 475 Ma. Most of the older granitoids and phase I younger granitoids are of I-type character, displaying metaluminous, calcalkaline geochemical characteristic plot in the area of volcanic arc granites (VAG), whereas younger phase granitoids are mainly alkaline, of A-type granites, and of within-plate tectonic setting (WPG). Generally, I-type granitoids were interpreted to result from melting of an amphibolitic crust and dated at approximately 760–650 Ma. The origin of A-type granites is consistent with the melting of a juvenile Neoproterozoic mantle source that assimilated some older crustal materials or as anatectic melts of various crustal sources.

5. Dokan volcanics, sedimentary basins, and post-orogenic A-type granites were interpreted to have been formed in an extensional or rifting regime. This rifting event may have created accommodation space for the Hammamat molasse sediments that accumulated in a structurally controlled intermontane basin.

6. More geochemical and age dating studies are required to characterize the different rock units and to determine their ages, compositional variations, and consequently, to construct the tectonic evolution of the Neoproterozoic crust through time.



Event		Lithology	Age	References
Post-collision stage (550 Ma – 635 Ma)		Younger Granites Hammamat sediments Dokhan Volcanics	630-550 Ma	Beyth et al. (1994), Wilde and Youssef (2000), Breitkreuz et al. (2010), Be'eri-Shlevin et al. (2011), Moghazi et al. (2012),
Collision of east and west Gondwana (Avigad and Gvirtzman., 2009)				
Island arc stage (635 Ma – 900 Ma)	Island arc assemblage	Older granitoids Rhyolite flows Volcanogenic breccia Andesite flows Metasediments ± *Banded iron formation*	850-635 Ma	Stern and Hedge (1985), Abdel-Rahman & Doig (1987) Ali et al. (2009),
	Ophiolite sequence	Deep marine sediments Pillow and massive basalts Diabase dykes Gabbro Serpentinites	810-730 Ma	Kröner et al. (1992) Zimmer et al. (1995) Andresen et al. (2009) Ali et al. (2010)

Figure 9.
Lithostratigraphy, major tectonic events, and ages of the basement complex in the Eastern Desert of Egypt from [54].

Rock units	Geochemical characters and tectonic settings	Age dating
Granite gneisses, amphibolites and migmatites	Granite gneiss core varies from enriched REE, to alkaline granite REE pattern; from enriched in HFSE, Rb, Ga, and total REE showing A-type characters and within plate tectonic setting, to granitic gneisses of calcalkaline and of I-type granites and of volcanic arc tectonic setting	631 Ma for Meatiq granite gneisses [10]; 700 Ma for Hafafit granite gneisses [38]; Wadi Beitan migmatitic granitic gneisses yielded 719 ± 10, and 744 ± 10 Ma [2]
Ophiolite assemblage	MORB-like ophiolites formed in a back-arc tectonic setting and SSZ ophiolites of fore-arc tectonic setting; flat REE MORB volcanic ophiolites, and depleted to slightly enriched LREE pattern for volcanic SSZ ophiolites	Wadi Gerf 741 ± 21 Ma [80]; 730–750 Ma [79]; Wadi Ghadir 746 ± 19 Ma, [80]; Fawakhir 736.5 ± 1.2 Ma [10]
Island arc assemblage	Arc metavolcanics with slightly fractionated REE patterns of island arc affinity; bimodal metavolcanics with felsic lavas are slightly LREE-depleted, whereas basalt is slightly LREE-enriched; arc-related volcaniclastic sediments (interarc to intra-arc basin)	Island-arc volcanics to 720–770 Ma [6]; Shadli island arc metavolcanics 712 Ma [28]; 750 Ma for the volcanic and volcano-sedimentary rocks [49]
Granitoid rocks	Old tonalite-granodiorite, calcalkaline, I-type, volcanic arc granites, syn- to late-orogenic granitoids; most of younger granitoids are mainly alkaline, A-type granites, and of within-WPG tectonic setting	The Aswan Tonalite and the monumental granite intruded at 606 Ma, respectively [38]; younger granites covers a time span between 600 and 550 Ma, [6]; A-type granites dated ca. ∼600 Ma [81]; 590 ± 3.1 Ma [10] for Um Had younger granite
Dokhan volcanics	Generally, have steep LREE and nearly flat HREE; medium-K to high-K calcalkaline affinity and continental arc to within plate tectonic setting (transitional setting)	592 and 630 Ma for acidic Dokan volcanics [83]
Hammamat molasse sediments	Greywackes with relatively high Zr, Nb, Y, and TH and relatively low Cr, Ni and V, and Sc; have enriched LREE pattern; of active continental margin or continental island arcs tectonic setting and appear to be formed in pull-apart intermontane basins; their sources are felsic source of evolved magmatic island arcs and active continental margin together with minor inputs from calcalkaline island arcs or ophiolitic mafic rocks	Depositional age 585 ± 13 Ma [75, 85]

Table 1.
Summary of geochemical characteristics, tectonic settings, and age dating of the different Neoproterozoic rock assemblages of the ED of Egypt.

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