

Article



Petrogenesis and Tectonic Evolution of Kab Amiri Ophiolites and Island-Arc Assemblages, Central Eastern Desert, Egypt: Petrological and Geochemical Constraints

Sherif A. Taalab ¹, Ahmed M. Abdel-Rahman ¹, Hamada El-Awny ¹, Hamdy A. Awad ^{2,*}, Hesham M. H. Zakaly ³, Wael Fahmy ¹ and Antoaneta Ene ^{4,*}

- ¹ Geology Department, Faculty of Science, Al-Azhar University, Cairo 11884, Egypt
- ² Geology Department, Faculty of Science, Al-Azhar University, Assiut Branch, Assiutt 71524, Egypt
- ³ Institute of Physics and Technology, Ural Federal University, 620002 Yekaterinburg, Russia
- ⁴ INPOLDE Research Center, Department of Chemistry, Physics and Environment, Faculty of Sciences and
- Environment, Dunarea de Jos University of Galati, 47 Domneasca Street, 800008 Galati, Romania
- * Correspondence: hamdiawaad@gmail.com (H.A.A.); antoaneta.ene@ugal.ro (A.E.)

Abstract: The Kab Amiri area in the Central Eastern Desert (CED) of Egypt comprises ophiolitic rocks, island arc metasediments, and granitic rocks. This study deals with the petrography and geochemistry of the ophiolitic and island arc rocks to understand their petrogenesis and geodynamic evolution of the CED ophiolitic belt. The Kab Amiri ophiolite is dismembered, comprising serpentinites and metabasalt (spilite). Serpentinites have low contents of Al₂O₃ (1.14 wt%) and CaO (0.65 wt%), suggesting they are depleted peridotite protoliths (e.g., depleted harzburgites to dunites). The high L.O.I. value (13.7 wt%) of serpentinite rocks indicates intense hydration and serpentinization during alteration processes. Petrographic and geochemical studies suggest that serpentinites were likely formed after depleted peridotites in a supra-subduction zone (SSZ) setting (e.g., a fore-arc setting). Spilitic basalt shows a tholeiitic affinity of the depleted mantle source. The arc-related metasediments are represented mainly by schists and slate. Many samples of metasediments are relatively low in alumina (Al₂O₃ < 15%), suggesting a low clay content and formation in an island arc setting. In contrast, protoliths of island-arc metabasalts and meta-andesites crystallized from calc-alkaline magmas in the immature oceanic arcs.

Keywords: ophiolite; serpentinites; fore-arc; spilite; metasediments; Central Eastern Desert; tectonic implication

1. Introduction

The Eastern Desert of Egypt is divided into the northern (NED), central (CED), and southern (SED) sectors by two arbitrary lines that were drawn from Qena to Safaga and from Idfu to Marsa Alam (Figure 1a). The CED supracrustal sequences are an oceanic assemblage consisting of various Neoproterozoic ophiolitic rocks, primarily with greenschist facies, arc volcanic, as well as volcaniclastic rocks, banded iron formations (BIF), and diamictite. Ophiolitic ultramafic and island arc of the Neoproterozoic age are widespread in the CED and SED sectors of the Eastern Desert of Egypt [1–3]. Throughout the CED, there are many Neoproterozoic ophiolites. Figure 1a shows the distribution of various lithologies [3–5]. Ophiolite rocks of the Neoproterozoic age 800 and 730 Ma [6,7] are considered the most significant and widespread units with granitoid rocks in the Egyptian basement rocks of the Eastern Desert (ED) of Egypt. They are vestiges of oceanic lithosphere with intraoceanic island arcs that are connected to the opening and closing of the Neoproterozoic Mozambique oceanic basin, and they constitute the northern extent of the East African Orogen 550–850 Ma [8,9]. Neoproterozoic ophiolites of the CED of Egypt are divided into



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the following categories: (i) complete MORB ophiolites; (ii) dismembered ophiolites; and (iii) arc-associated ophiolites [5].

Metasediments are abundant and extensively distributed in the Egyptian Eastern Desert south of the 26° N latitude line, both in the Central and Southern Eastern Desert and in southeastern Sinai. These metasediments exhibit substantial thicknesses, with values surpassing several kilometres and occupying substantial land areas. The basement complex in the Eastern Desert features distinctive ensimatic signatures, primarily composed of an island arc complex encompassing multiple banded iron formations, which are overlain by fragmented ophiolitic sequences and syn-tectonic gray granitoid [10–12]. The study area is primarily underlain by ophiolitic rocks (serpentinite and metabasalt), arc-related metasedimentary rocks, metavolcanic rocks (i.e., metabasalt and andesite), and different granitoid. The ophiolitic assemblages in the region are comprised of fragmented components such as serpentinite, metabasalt (spilite), and heterogeneous mélange rocks. Serpentinites, which are believed to have originated from fore-arc seafloor spreading, are the most widely occurring ophiolitic rock type in the area [2,13].

Additionally, younger alkali granites and older calc-alkaline granitoid have intruded into the island arc and ophiolitic sequences. Numerous faults trend in several directions, including NE–SW, NNW–SSE, NW–SE, WNW–ESE, and ENE–WSW in the region. While the NNW–SSW and NW–SE faults are frequently connected to significant left lateral displacement, the ENE–WSW and WNW–ESE faults allow minor right-lateral displacement [14]. In the investigated region, there are two primary generations of mineral foliation: older E–W foliation and younger, less prevalent N–S crenulation foliation, which is best developed in the metasediments and mélange matrix rocks. Several workers have studied the Kab Amiri area, such as [15–21]. Their research focused on the field and geophysical studies of stream sediments to ascertain the mineralization of radioactive elements. However, this research paper focuses on the basement rocks rather than stream sediments.

This study endeavours to clarify the geological and geochemical aspects of the study area by conducting a comprehensive examination of the petrology, alteration imprints and geochemistry of ophiolitic and island arc rock assemblages in the Kab Amiri area. The study aims to comprehend the tectonic environments and gain insight into these rocks' petrogenesis.



Figure 1. (a) Simplified geologic map showing the classification of the eastern desert, Egypt, and location map of the Kab Amiri area (after compilation by Fowler cited in [22]. Abbreviation; Ad-Atmur-Delgo, CED-Central Eastern Desert, ED-eastern desert, Ga-Gabgaba, Gb-Gebeit, HHijaz, M-Midyan, NED-north eastern desert, S-Sinai, SED-south eastern desert, AH-Allaqi-Heiani, Ha-Hamisana, K-Keraf, OS-Onib-Sol Hamed, Y-Yanbu. (b) Geologic map of Kab Amiri area, Central Eastern Desert, Egypt (modified after [15].)

2. Geologic Setting

Kab Amiri area is situated in the Central Eastern Desert of Egypt, south of the Qena-Safaga Road and mainly comprises Precambrian exposures. The main wadies draining in the Kab Amiri area include Wadis Kab Amiri, Abu Grahishi, El Bohlog, and Kab Um El Abas (Figure 1b). It is encircled by Latitudes 26°15′ and 26°25′ N and Longitudes 33°30′ and 33°40′ E. The lowest relief is south of Gabal Kab Amiri, while the highest relief (911 m above sea level) is at Gabal Kab Um El Abas, east of Gabal Kab Amiri. The volcano-sedimentary associations have been deformed and metamorphosed under

greenschist to lower amphibolite facies conditions [23]. The ophiolitic rocks in the study area are represented by serpentinites and metabasalts (spilite). While island arc assemblages are comprised of metasediments and metavolcanic and followed by granitoid rocks and different post-orogenic dykes (pegmatite, basaltic) (Figure 2b). Several significant faults that cut across the Kab Amiri stretch mostly in the NW direction (Figure 1b) consist of the Najid fault trend, with a smaller number of faults trending in the NE and E–W directions [17,23].



Figure 2. Field observations of the Kab Amiri area show (**a**) serpentinite masses ridge with sharp, irregular talc carbonate alteration (westward view). (**b**) serpentinites tectonically emplaced over trusted over the metasediments (eastward view) (**c**) pillow structure (yellow dash outline)-rind, vesicle zone and core seen on pillow lava cliff section. (**d**) elongated (elliptical) shapes of pillow lavas. (**e**) quartz veinlets in the folded metasediments. (**f**) highly jointed island metavolcanic (eastward view).

Dismembered ophiolitic rocks are concentrated in the northern and central parts of the study area. It is noticeable in this region that the serpentinites turned into talc carbonate rocks (Figure 2a). Serpentinites are grey to greyish on the weathered surface, while the fresh surfaces have dark green. They have moderate to high relief. They vary in size and shape and always have tectonic contact with country rocks without thermal effects. The exposed serpentinites shape elongated bodies generally extending in the E–W direction southwest and southeast of Gabal Kab Amiri granites. Figure 2b shows a structural contact between serpentinites and metasediments. They are embedded in the metasediments mainly along axial planes of large anticlinal folds. The talc–carbonate rocks are found along faults and shear zones within the mountain range. Asbestos and calcite occur as veins about 5 cm thick along the fractures and shear zones, suggesting mixed H_2O-CO_2 introduction during deformation.

The Kab Amiri ophiolitic metabasalts are related to the older metavolcanic, which occupy substantial exposures in the northwestern sector of the study area, as depicted in Figure 1b. These metabasalts are elliptical (elongated) and irregularly curved pillow lobes, ranging in size from 40 to 70 cm in length, with a chilled margin visible along the peripheral boundary, as shown in (Figure 2c,d). The metabasalts are surrounded by a rim rich in epidote, chlorite, and other minerals, indicative of alteration processes on the seafloor and through subsequent hydrothermal activity, as depicted in Figure 2c. The metabasalts exhibit moderate topographic relief and are characterized by a dark grey to greenish-grey colouration, as depicted in (Figure 2d).

The metasediments and metavolcanic comprising the island arc assemblage constitute the majority of the rocks in the study area. The metasediments are primarily located in the southern portion of the mapped site, forming a curvilinear belt that encircles the Kab Amiri granite from the south, as depicted in Figure 1b. These rocks are characterized by medium-grained immature sediments, sometimes containing banded iron formations, and are primarily foliated, folded, and exhibit a greyish-green colouration with moderate to high relief. The lowest relief is observed in the southern region of Gabal Kab Amiri, while the highest relief, reaching 911 m above sea level, is present at Gabal Kab Um El Abas, located to the east of Gabal Kab Amiri. The metasediments are related to the Abu Fannani schist around the Meatiq dome [24]. The contacts between the metasediments and metavolcanic are tectonic in nature, particularly along Wadi El Saqia. The interaction between the dismembering ophiolite and Abu Fannani schist is tectonic, with the ophiolite rocks thrust over the Abu Fannani schist, which has been described as a tectonic mélange by [25]. These rocks exhibit an advanced schistosity and are bisected by quartz veins and veinlets, as depicted in Figure 2e.

The metavolcanic rocks are represented by substantial exposures located in the southern and northeastern parts of the mapped area and are characterized by tectonic contact with the metasediments. These rocks are related to the young metavolcanic (YMV), visible along Wadi El Saqia and extending east, as depicted in Figure 1b. These rocks form moderate to high relief ridges with dark grey to greenish-grey and pink colour. They are highly fractured, altered, sheared, and traversed by some mafic and felsic dykes (Figure 2f). The metavolcanic and metasediments are structural, while their contacts with Kab Amiri granites are intrusive.

3. Analytical Methods

In the study area, 12 samples were procured from ophiolitic rocks, 4 samples of serpentinites, 4 samples of talc-carbonates and 4 samples of metabasalts, and 11 samples from the island arc assemblage, including 7 samples of metasediments and 4 samples of metavolcanic. These samples were subjected to microscopic analysis using 15 thin sections prepared at the Laboratories of the Nuclear Materials Authority (NMA). A Nikon polarizing microscope (Nikon, Tokyo, Japan) equipped with an automatic photomicrographic and mechanical stage attachment was used to identify the minerals and textures.

Chemical analyses of whole rock samples were carried out at ACME Analytical Laboratories of Vancouver, Canada, for major oxides, trace, and rare earth elements. Total abundances of the major oxides and several minor elements are based on a 0.2 g sample analyzed by ICP-Optical emission spectrometry ICP-OES following a lithium metaborate/tetraborate fusion and dilute nitric digestion. Elements are expressed as common oxides for each element (i.e., Al₂O₃, CaO, Fe₂O₃, K₂O, MgO, MnO, Na₂O, P₂O₅, TiO₂). For determination of the loss on ignition (L.O.I.), 1 g of each sample was heated at 950 °C for 90 min, and then the weight loss during this process was calculated as L.O.I. The trace elements (Cr, Co, Sr, Zr, Nb, Mo, Cu, Pb, Zn, Ni, Bi and Sc) were determined by ICP-OES. In comparison, large ion lithophile elements (LILE) (Sr, Ba, Rb and Cs), high field strength elements (HFSE) (Zr, Nb, Y, Hf, Th, U, Ta) and rare earth elements (REE) (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) method at the same Laboratory (ACME). The concentration of major oxides and trace/rare earth elements are given in wt% (weight per cent) and parts per million (ppm), respectively. Detection limits for major oxides and trace elements vary from 0.001 wt% to 0.04 wt% and 0.01 to 0.5 ppm, respectively. Analytical precision calculated from replicate analyses was 0.5% for major oxides and varied from 2% to 20% for trace elements. The geochemistry (Minpet) program was used to calculate the current data in order to determine the classification, nomenclature, magma type, and tectonic setting of the granitic rocks in the study area. Furthermore, utilizing the major oxides and trace elements, some binary and ternary diagrams have been created for the same purpose.

4. Results

4.1. Petrography

Serpentinites are composed primarily of serpentine minerals (over 90% by volume), with minor amounts of other minerals such as olivine, chromite spinel, carbonates, and opaque minerals. The serpentine minerals antigorite, chrysotile, and lizardite are characterized by colourless, weakly birefringent, and parallel extinct crystals. Antigorite often occurs as elongated blade-like crystals, sometimes arranged in a parallel fashion, creating a pseudomorph after orthopyroxene minerals, known as the bastite texture. When the geometric configuration of the original mafic minerals is preserved, a pseudomorphic texture is created. In contrast, lizardite is a fine-grained matrix filling the pseudomorphs of olivine and is characterized by a mesh texture after olivine. Olivine is partially serpentinized and eventually altered to talc and carbonates. Chrysotile is a serpentine mineral present as randomly oriented fibrous crystals and associated with antigorite. Chromite is the primary opaque Mineral, forming subhedral fractured crystals filled with carbonates (Figure 3c).

Talc–carbonate rocks are massive and schistose a fine-grained texture. Their hues range from pale green to greenish-grey-coloured rocks and are often spotted with a brownish colour. These rocks comprise talc and carbonate with small quantities of opaque. Talc presents as fine-grained fibrous aggregates of parallel arrangement characterized by asbestos structure replacing the tremolite and actinolite (Figure 3d). It is colourless and displays strong birefringence with low relief, parallel extinction, and high interference colours. Talc also presents as a few crystals associated with the serpentine, while antigorite occasionally presents as blade-like crystals in the talc rocks (Figure 3e). The opaque are present as fine anhedral crystals of iron oxides disseminated throughout the rock (Figure 3f).

The ophiolitic metabasalts (spilite) are dark green consisting of plagioclase, chlorite, carbonate, and epidote. They are cryptocrystalline with an amygdaloidal texture that is oriented parallel to the schistosity planes. Plagioclase microphenocrysts are predominant in the rocks and occupy about 50%–70% of the studied rock volume. The crystals are intensively altered and albuminized, where sodium ions replace the calcium ions to form albite and liberate Ca form epidote and carbonate as secondary minerals (Figure 3g). Carbonates are common in this rock and constitute about 20 modal vol.% of the rock; they occur in two forms: as an aggregate of calcite associating the main constituents resulting from the process of albitization of the plagioclase (Figure 3h) and as amygdale fillings



during seawater infiltration usually associated with the secondary quartz (Figure 3i). The rock primarily comprises chlorite, which makes up about 10% of the rock and is associated with plagioclase and mafic minerals.

Figure 3. Microphotographs showing serpentinites and metabasalt (spilite): (**a**) pseudomorph of pyroxene replaced by antigorite (Atg) in serpentinites (*XPL*). (**b**) relics of olivine (Ol) surrounded by carbonate in serpentinites (*XPL*). (**c**) fractured oval crystal of opaque, usually chromite (Chr) surrounded by fibrous chrysotile (Ctl) in serpentinites (*PPL*). (**d**) fibrous tremolite surrounded by carbonate (Carb) and talc (Tlc) matrix in talc–carbonate rocks (*XPL*). (**e**) blade-like crystal of antigorite surrounded by fibrous talc in talc–carbonate rocks (*XPL*). (**f**) iron oxides (Fe-Ox) staining talc crystals in talc–carbonate rocks (*XPL*). (**f**) aggregates of carbonate (Carb) surrounded by cryptocrystalline plagioclase (Pl) in spilitic rocks (*XPL*). (**i**) secondary epidote (Ep.) surrounded by cryptocrystalline plagioclase (Pl) in spilitic rocks (*XPL*). PPL = plane polarized light; XPL = cross polarized light.

The metasediments of Kab Amiri can be categorized according to the grain size into two types, schist and slate. These types are characterized by schistose texture, where the constituting minerals are elongated and foliated by stress.

Quartz–actinolite–chlorite schists are composed of amphibole, biotite, plagioclase, and quartz. Amphibole minerals are represented by hornblende, tremolite and actinolite (Figure 4a). Hornblende is found as hypidioblastic prisms commonly foliated and dark brown intensively altered to the tremolite-actinolite association and finally to chlorite. Actinolite is characterized by a brownish-green colour with pleochroism from pale green

to greenish black. It is mostly associated with tremolite and is considered an alteration product of amphibole minerals. Tremolite, the most common amphibole, exists as fibrous crystals characterized by asbestos structure and exhibits third-order interference colours (Figure 4b). Biotite is less common and occurs as hypidioblastic pale brown flakes up to 0.4 mm long (Figure 4c). Sometimes, biotite occurs as porphyritic flakes surrounded by finer crystals of quartz, epidote, and carbonate (Figure 4c). Chlorite is more dominant and associated with mica minerals. It occurs as greenish folia with polysynthetic structure (Figure 4d) and as pseudomorphs after the earlier mafic minerals. Plagioclase is moderately saussuritized and altered to epidote and saussurite minerals, where its longer dimension is parallel to the schistosity (Figure 4c). Epidote is the most common secondary Mineral; it is found as oval crystals associating zoisite and chlorite as alteration products (Figure 4c). Quartz is found as elongated crystals with rounded to sub-rounded shapes. It also occurs as porphyritic elongate crystals with chlorite following the schistose texture (Figure 4d). The rock encloses a few crystals of primary calcite that are characterized by twinkling.

Slate is a fine-grained metamorphic rock produced by low-grade regional metamorphism for shale or mudstone, varying in colour from buff to brown and black. The main foliation is defined by aligned mafic minerals, such as chlorite showing well-developed schistosity. The slate is composed mainly of quartz, sericite, and chlorite. It appears banded due to the elongation and orientation of its constituents (Figure 4e). Quartz is the main constituent, comprising about 60 vol% of rocks and occurs as rounded to sub-rounded porphyroblastic crystals with diameters of about 0.6 mm (Figure 4e) or as minute crystals prevailing the groundmass. Chlorite exists as xenomorphic secondary flakes, associated with quartz, epidote and carbonates showing schistosity (Figure 4e). Chloritization is dominant, so the rock's texture yields bands of green colour. Carbonates occur as cross-cutting micro veinlets of calcite (Figure 4f). Opaque minerals are represented by fine deep black grains disseminated through the rock. Sericite occurs as minute shreds and acicular crystals scattered throughout the groundmass (Figure 4e).

Petrographic investigation revealed that the metavolcanics are basic (metabasalts) and intermediate (metapyroclastic).

Metabasalts are fine-grained rocks with dark grey colour characterized by porphyritic texture. They are composed mainly of plagioclase and mafic minerals. Plagioclase occurs as hypidioblastic to xenoblastic crystals up to 0.6 mm in length and 0.3 mm in width (Figure 5a); it is partially altered to saussurite (Figure 5a) and epidote. Plagioclase also occurs as porphyritic crystals embedded in a fine-grained groundmass composed of plagioclase microlites and chlorite, exhibiting phenocryst texture. Mafic minerals are represented by actinolite, chlorite, and tremolite. The alteration minerals are also present as kinked xenoblastic crystals (up to 0.4 mm long) of chlorite tremolite (Figure 5b) and (Figure 5c) associated with epidote, iron oxides and relict biotite and hornblende. The mafic minerals are foliated and associated with carbonates as alteration products that are partially dissolved, replaced by secondary polycrystalline quartz (Figure 5a), and associated with epidote (Figure 5c).

The metapyroclastic rock is an andesitic and composed primarily of porphyritic clasts of plagioclase, quartz, carbonate, and perthite. The clasts are embedded in a fine-grained groundmass of chlorite and epidote. Plagioclase is the dominant Mineral, making up about 55% of the rock's volume, and is present as porphyroblastic clasts and fine lathes in the groundmass. The plagioclase crystals have zoning and lamellar twinning and have been partially saussuritized (Figure 5d). The potash feldspar is present in the metapyroclastic rock as porphyritic clastic perthite with a string-like shape and measures 1.3 mm in length and 1.1 mm in width (Figure 5d), constituting about 20% of the rock. Few crystals of quartz mantled by plagioclase are recorded as porphyritic (Figure 5e). Quartz is also present as rounded to subrounded porphyroblastic crystals and fine crystals in the groundmass, accounting for about 15% modal vol.%. The porphyroblastic crystals are characterized by boundaries assimilated by the thermal effect of the groundmass (Figure 5e). Biotite and muscovite are found as minute flakes in the groundmass and altered to chlorite (Figure 5f),



while epidote accounts for about 10% of the rock. The plagioclase crystals are present as porphyroblastic clasts and fine lathes in the groundmass, making up 55% of the rock and are characterized by zoning and lamellar twinning with partial saussuritization.

Figure 4. Microphotographs showing metasediments rocks (quartz–actinolite–chlorite schist and slate); (**a**) quartz (Qtz) bedding with hornblende (Hb) and actinolite (Act) in quartz–actinolite–chlorite schist (*XPL*). (**b**) porphyroblast of tremolite (Tr) surrounded by actinolite (Act) in quartz–actinolite-chlorite schist (*XPL*). (**c**) porphyroblast of biotite (Bt) surrounded by epidote (Ep) and plagioclase (Pl) in quartz–actinolite–chlorite schist (*XPL*). (**c**) porphyroblast of biotite (D foliated chlorite (Chl) surrounded by quartz (Qtz) in quartz–actinolite–chlorite schist (*XPL*). (**d**) foliated chlorite (Chl) surrounded by quartz (Qtz), chlorite (Chl) and sericite (Ser) in slate rocks (*XPL*). (**f**) micro veinlet of calcite (Cal) with green chlorite (Chl) crystals in slate rocks (*XPL*).



Figure 5. Microphotographs showing island arc metavolcanics: (**a**) porphyritic saussuritized plagioclase (Pl) with carbonate (Carb) in metabasalts (*XPL*). (**b**) kinked crystal of tremolite (Tr) associated with epidote (Ep) in metabasalts (*XPL*). (**c**) a pocket of carbonate(Carb) minerals associated with epidote (Ep) in metabasalts (*XPL*). (**d**) porphyritic perthite mantled by plagioclase (Pl) in metapyroclastic rocks (*XPL*). (**e**) porphyritic quartz (Qtz) crystal with recrystallized boundaries in cryptocrystalline groundmass in metapyroclastic rocks (*XPL*). (**f**) flakes of chlorite (Chl) crystals associated with carbonate (Carb) and groundmass of Quartz (Qtz) in metapyroclastic rocks (*XPL*).

4.2. Geochemical Characteristics of the Ophiolitic Rocks

4.2.1. Chemical Compositions and Behaviour of Elements in the Ophiolitic Rocks

The dismembered ophiolitic rocks comprise serpentinites, talc–carbonate and metabasalts (spilite). The major oxides, trace and REEs elements of dismembered ophiolitic samples are recorded in Table 1. Serpentinite samples exhibit high enrichment in MgO, L.O.I., Ni, Co, and Cr contents relative to metabasalt (spilite). On the other hand, metabasalt (spilite) samples are enriched in SiO₂, Al₂O₃, FeOt, CaO, Na₂O, K₂O, Zn, V, Ba, Zr, Y, HREE, and LREE compared with serpentinities and talc-carbonates (Table 1). The average SiO_2 content varies in the range from 35.54 to 46.31 wt% due to different serpentine phases from antigorite (high SiO₂ up to 46.31 wt%) to lizardite with low SiO₂ (around 35.54 to 37 wt%) and has a low amount of Al_2O_3 0.45–3.0 wt%, and CaO 0.20 to 1.98 wt% and high total FeOt 9.34–12.36 wt%, suggesting depleted harzburgite protoliths [1,26,27]. Furthermore, the majority of MnO, Na₂O, K₂O, TiO₂ and P₂O₅ contents in the serpentinites are lower than 1 wt% and show the depletion degree of the mantle of investigated samples [28]. Volatile components are reported as a loss on ignition (L.O.I.) and can be used to measure the degree of serpentinization. The average L.O.I. content varies from 10.43 to 20.76 wt%, with an average of 13.7 wt%. The high value of L.O.I. in serpentinite rocks reflects intense hydration and serpentinization during alteration processes and abundance in talc and carbonates. According to [29], L.O.I. values of more than six wt% are regarded as changed because either (1) these samples are partially dehydrated during their subduction and prograde metamorphism or (2) a higher amount of antigorite.

Trace element analyses show that the samples tend to be richer in Cr (1989 ppm), Ni (2130 ppm) and Co (33.7–101.4 ppm) than the other analyzed trace elements. According to [30], serpentinites have a higher concentration of lithium than saltwater, which is consistent with this property [31]. Bulk serpentinites have lithium contents ranging from 1.3 to 18.9 ppm. According to [32,33], the processes that took place before serpentinization may have contributed to the Li enrichment, and serpentinization itself ought to lower the bulk sample's Li concentration. The high mobile arsenic, antimony, and lead in fluids made these elements represent potential tracers of the nature of fluids during serpentinization. The serpentinites show (0.4 < As < 10.2 ppm; 0.08 < Sb < 1 ppm)that they are moderate to highly enriched in these elements compared to the primitive and depleted mantle (0.1 < As < 10 ppm; 0.001 < Sb < 1 ppm) [34,35]. They showed that they are transferred by aqueous fluids from the slab to the mantle wedge and are incorporated into serpentinites under oxidized conditions at shallow depths (~25 km) [36]. The serpentinites show Pb concentrations from 0.49 to 10.89 ppm. Nb/La and Nb/Ce value ranges of the serpentines are (0.23–0.80) (0.13–0.32), with averages (of 0.44, 0.21), respectively. These values are lower than that of the primitive mantle (PM 1.02 and 0.40, respectively [33,37], 1.04 and 0.40, respectively, [38] and the average bulk crust (0.69 and 0.33, respectively), which could be evidence of possible crustal contamination. Mantle-derived magmas are characterized by high Ce/Pb (25 \pm 5) and Nb/U (47 \pm 10), low Lu/Yb (0.14–0.15), and relatively lower La/Sm (<4.5), [39]. Continental crust has relatively low Ce/Pb (<15) and Nb/U (~9.7), along with higher Lu/Yb (0.16-0.18) and La/Sm (>4.5). Thus, these ratios can be used to reveal crustal contamination. All samples of serpentinites samples have a La/Sm ratio of <4.5, indicating a mantle derived source [39]. In addition, the Nb/U ratio is lesser than 9.7, in addition, all serpentinite samples have Ce/Pb ratio of <15, which also indicates some crustal contamination.

Rock Type		Serpentinites			Talcite					Metabasalts						
S. No.	9 C	20 D	10 C	16 E	Av.	19 D	17 E	9 E	23 D	Av.	6 B	11 B	17 B	6 E	Av.	
							N	lajor oxides (wt	%)							
SiO ₂	37.83	35.54	39.9	46.31	39.89	41.76	43.6	44.17	45.50	43.78	49.54	50.92	45.47	47.35	48.3	
TiO ₂	0.01	0.01	0.02	0.07	0.03	0.16	0.09	0.35	0.32	0.23	1.15	1.47	0.98	1.18	1.2	
Al_2O_3	0.62	0.45	0.50	3.00	1.14	3.98	5.69	4.32	4.50	4.62	14.70	15.25	13.19	13.49	14.16	
FeOt	12.14	9.34	10.15	12.36	10.99	16.89	14.7	18.66	15.49	16.44	18.01	17.29	19.46	17.89	18.16	
MnO	0.09	0.07	0.06	0.11	0.08	0.19	0.13	0.13	0.29	0.19	0.49	0.14	0.21	0.18	0.26	
MgO	37.33	33.11	36.47	25.20	33.03	30.90	26.2	27.51	26.55	27.79	3.70	2.77	4.81	6.88	4.54	
CaO	0.24	0.20	0.19	1.98	0.65	3.52	2.70	2.50	2.32	2.76	5.86	6.71	11.08	8.04	7.92	
Na ₂ O	0.02	0.01	0.01	0.02	0.02	0.41	0.09	0.18	0.05	0.18	2.70	3.98	2.12	2.70	2.88	
K ₂ O	0.01	0.01	0.01	0.01	0.01	0.24	0.10	0.22	0.16	0.18	0.04	0.40	0.12	0.18	0.19	
P_2O_5	0.00	0.00	0.01	0.01	0.01	0.09	0.01	0.08	0.15	0.08	0.11	0.05	0.07	0.11	0.09	
L.O.I.	11.11	20.76	12.34	10.43	13.66	1.53	6.19	1.48	4.57	3.44	3.45	1.00	2.39	1.57	2.10	
Total	99.4%	99.5%	99.6%	99.5%	99.5%	99.7%	99.5%	99.6%	99.9%	99.7%	99.75%	99.98%	99.9%	99.57%	99.8%	
Mg	0.75	0.80	0.78	0.67	0.75	0.65	0.64	0.60	0.63	0.63	-	-	-	-		
OĬ	71.7	69.2	70.6	69.1	-	65.6	70.1	72.5	69.7	-						
Opx	24.8	28.4	27.8	26.9	-	28.9	25.9	21.3	25.5	-						
Cpx	1.6	2.1	1.4	3.4	-	4.9	2.9	5.2	4.2	-						
-1							Tr	ace elements (pp	om)							
Мо	0.18	0.05	0.12	0.05	0.1	0.05	0.08	0.34	0.07	0.14	0.12	1.12	0.19	0.09	0.38	
Cu	0.4	4.9	16.8	25.2	11.83	51.6	20.5	83.6	95.2	62.73	1.8	20.4	93.2	112.0	56.85	
Pb	10.89	0.49	6.54	0.57	4.62	1.14	1.20	3.57	0.75	1.67	4.14	2.51	0.98	1.13	2.19	
Zn	62.0	31.1	70.3	58.4	55.45	89.4	63.4	51.6	106.5	77.7	137.2	60.8	83.9	80.5	90.6	
Ag	183	160	198	178	179	47	170	67.0	91	93.8	29.0	32.0	23.0	56.0	35	
Ni	2130	2072	1948	1204	1838	240	1350	279.7	345	553	7.3	6.8	18.5	72.1	26.18	
Co	101.4	93.2	110.2	84.4	97.3	39.8	90.5	33.7	62.5	56.6	29.7	20.7	40.6	46.9	34.48	
As	0.4	1.9	2.3	3.7	2.1	2.4	2.9	10.2	2.4	4.5	1.4	1.1	1.5	1.5	1.38	
U	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.13	
Th	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.7	0.2	0.3	0.3	0.3	0.1	0.4	0.28	
Sr	5.0	2.0	15.3	53.0	18.8	97	77.3	22	6.0	50.6	125.0	123.0	138	174	140	
Cd	0.06	0.10	0.09	0.10	0.09	0.10	0.10	0.10	0.02	0.08	0.12	0.08	0.10	0.04	0.09	
Sb	0.08	0.58	0.40	0.11	0.29	0.61	0.10	0.40	0.47	0.39	0.20	0.04	0.19	0.15	0.15	
Bi	0.04	0.06	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.07	0.04	0.04	0.04	0.05	
V	32.0	24.0	50.4	62.0	42.1	325	102	133	541	275	312	164	379	288	285.8	
Cr	1459	1487	1873	1989	1702	485	1830	428	542	821	10.0	8.0	20.0	97.0	33.75	
Ва	1.0	1.0	2.5	3.0	1.9	25.0	2.0	4.3	32.5	15.9	26.0	21.0	20.0	22.0	22.25	
W	1.7	0.1	0.9	0.1	0.7	0.1	0.1	0.1	0.4	0.2	0.3	0.1	0.1	0.1	0.15	
Zr	1.0	0.4	1.6	5.0	2	26.9	4.2	16.5	5.2	13.2	26.4	15.3	24.3	27.7	23.42	
Sn	0.4	0.1	0.6	1.0	0.5	0.8	0.8	0.4	0.7	0.7	0.7	3.0	0.5	0.7	1.23	
Be	1.0	1.0	1.2	1.0	1.05	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Sc	3.4	4.3	4.6	12.5	6.2	36.5	17.5	26.3	57.4	34.4	32.5	23.2	42.0	43.2	35.23	
S	0.10	0.10	0.09	0.04	0.08	0.10	0.10	0.04	0.04	0.07	0.10	0.10	0.10	0.10	0.1	
Y	0.3	0.4	0.9	2.2	0.9	23.5	1.6	9.0	4.0	9.5	31.1	20.0	22.5	21.9	23.88	
Hf	0.05	0.02	0.02	0.16	0.06	1.12	0.18	0.65	0.14	0.52	0.5	0.58	0.99	1.04	0.78	
Li	1.4	1.3	1.9	4.7	2.3	10.4	1.5	6.1	18.9	9.2	25.1	13.3	7.8	20.8	16.75	
Rb	0.5	0.1	0.2	0.1	0.2	1.8	0.1	3.9	4.3	2.5	0.5	3.8	1.6	2.7	2.15	

 Table 1. The chemical composition of Kab Amiri investigated serpentinites, talc-carbonates and metabasalts.

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Tab	le	Ι.	Cont.

Rock Type		Serpentinites				Talcite							Metabasalts		
S. No.	9 C	20 D	10 C	16 E	Av.	19 D	17 E	9 E	23 D	Av.	6 B	11 B	17 B	6 E	Av.
							М	ajor oxides (wt	%)						
Ta	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.13
Nb	0.08	0.04	0.10	0.21	0.11	0.79	0.17	1.87	1.19	1.01	1.27	1.13	0.72	1.04	1.04
Cs	0.2	0.1	0.2	0.1	0.15	0.1	0.1	0.1	0.3	0.2	0.1	0.2	0.1	0.1	0.13
Ga	1.80	0.85	2.47	3.06	2.05	13.60	2.80	12.87	20.22	12.37	20.15	13.39	16.92	13.57	16.1
In	0.02	0.01	0.02	0.02	0.02	0.07	0.02	0.04	0.13	0.07	0.10	0.10	0.08	0.07	0.09
Re	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.006	0.003
Se	0.4	0.4	0.05	0.7	0.39	0.3	0.5	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3
Te	6.50	5.75	7.11	4.71	6.02	0.65	4.0	1.81	0.74	1.80	0.34	0.30	0.81	1.59	0.76
T1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.5	0.22	0.21	0.05	0.06	0.05	0.05	0.05
							Rare eat	th elements RE	Es (ppm)						
La	0.1	0.1	0.3	0.9	0.35	2.4	0.8	5.2	4.1	3.1	3.1	2.6	1.6	4.6	2.98
Ce	0.25	0.25	0.40	1.57	0.62	6.88	1.25	10.8	12.1	7.8	8.55	7.23	4.76	11.70	8.06
Pr	0.1	0.1	0.2	0.2	0.2	1.3	0.3	1.7	2.0	1.3	1.5	1.1	1.0	1.8	1.35
Nd	0.2	0.2	0.6	0.8	0.5	6.5	1.0	5.5	9.9	5.7	7.8	5.3	5.1	8.6	6.7
Sm	0.1	0.1	0.1	0.3	0.2	2.5	0.3	1.4	2.8	1.8	2.9	1.6	2.0	2.9	2.35
Eu	0.1	0.1	0.2	0.1	0.1	0.7	0.1	0.4	0.6	0.5	1.3	0.6	0.9	1.1	0.98
Gd	0.1	0.1	0.1	0.1	0.1	3.0	0.2	1.7	2.1	1.8	4.0	2.4	3.0	3.6	3.25
Tb	0.1	0.2	0.2	0.1	0.2	0.6	0.1	0.4	0.2	0.3	0.8	0.5	0.5	0.6	0.6
Dy	0.1	0.1	0.2	0.3	0.2	4.0	0.2	1.7	1.0	1.7	4.8	2.9	4.0	4.3	4.0
Ho	0.1	0.1	0.1	0.1	0.1	1.0	0.1	0.4	0.1	0.4	1.2	0.8	1.0	0.9	0.98
Er	0.1	0.1	0.1	0.3	0.2	2.5	0.4	1.0	0.4	1.1	3.3	2.2	2.4	2.3	2.55
Tm	0.1	0.1	0.2	0.1	0.1	0.4	0.1	0.1	0.1	0.2	0.5	0.4	0.4	0.4	0.43
Yb	0.1	0.2	0.1	0.2	0.2	2.4	0.1	0.9	0.4	0.9	3.0	2.3	2.1	2.1	2.38
Lu	0.1	0.1	0.2	0.1	0.1	0.4	0.1	0.1	0.1	0.2	0.5	0.4	0.4	0.3	0.4
Nb/La	0.80	0.4	0.33	0.23	0.44	0.32	0.21	0.36	0.29	0.29	0.41	0.43	0.45	0.23	0.38
Nb/Ce	0.32	0.16	0.25	0.13	0.21	0.11	0.14	0.17	0.10	0.13	0.15	0.16	0.15	0.09	0.14
Ce/Pb	0.02	0.51	0.02	2.75	0.83	6.04	1.04	3.03	16.12	6.56	2.07	2.88	4.86	10.35	5.04
Nb/U	0.8	0.4	0.5	2.1	0.9	7.9	1.7	9.35	11.9	7.7	12.7	11.3	7.2	5.2	9.1
La/Sm	1	1	3	3	2	0.96	2.67	3.71	1.46	2.2	1.07	1.63	0.8	1.59	1.27
Lu/Yb	1	0.5	2	0.5	1	0.17	1	0.11	0.25	0.38	0.17	0.17	0.19	0.14	0.17
ΣREE	1.65	1.65	3.0	5.17	2.87	34.58	5.05	31.32	35.89	26.71	43.25	30.33	19.16	45.2	34.49
LREE	0.85	0.85	1.80	3.87	1.84	20.3	3.75	25.02	31.49	20.14	25.15	18.43	15.36	30.7	22.41
HREE	0.80	1.0	1.20	1.3	1.1	14.3	1.3	6.3	4.4	6.6	18.1	11.9	13.8	14.5	14.58
LREE/HREE	1.1	0.85	1.5	3.0	1.6	1.4	2.9	4.0	7.2	3.9	1.4	1.5	1.1	2.1	1.53
Eu/Eu*	3.0	3.0	2.5	1.2	2.4	0.8	0.8	3.0	0.8	1.4	1.2	0.9	1.1	1.0	1.05
La/Yb _N	0.7	0.3	0.6	1.4	0.8	0.7	1.2	0.8	0.7	0.9	0.7	0.8	0.5	1.5	0.88
Tb/Yb _N	4.3	4.3	4.1	3.0	3.9	1.1	5.4	3.9	6.9	4.3	1.1	0.9	1.0	1.2	1.05
Gd/Yb _N	0.8	0.4	0.9	2.1	1.1	1.0	4.3	1.9	2.1	2.3	1.1	0.8	1.2	1.4	1.13
La/Sm _N	0.6	1.2	1.1	1.1	1	0.6	1.1	3.5	4.2	2.3	0.7	1.0	0.5	1.0	0.8
Ce/Ce*	0.949	0.949	0.915	0.867	0.920	0.983	0.693	0.976	1.051	0.926	0.969	1.048	0.966	0.987	0.99

 FeO^t is total iron oxides ($Fe_2O_3 + FeO$).

4.2.2. Protolith of Serpentinites

According to the Ol-Opx-Cpx ternary diagram [40], the serpentinites and talc-carbonates are mainly formed after harzburgites, with minor dunites (Figure 6a) because of the serpentinites alteration and lack of primary mineral phases, low content of Al_2O_3 and CaO and higher MgO. The (AFM) (Na₂O + K₂O)-FeO^t-MgO diagram [41] can discriminate tholeiitic and calc-alkaline affinity. Plotting the investigated serpentinites and talc-carbonates on this diagram revealed that the samples plot within the calc-alkaline field (Figure 6b). The most significant variations among the major oxides are usually in the abundances of K₂O and SiO₂. According to the binary diagram of SiO₂ and K₂O of [42], the serpentinites and talc-carbonates plot in the low-K tholeiitic field (Figure 6c).



Figure 6. (a) olivine (Ol)-orthopyroxene (Opx)-clinopyroxene (Cpx) classification diagram for samples of the serpentinites and talc-carbonates [40]. (b) AFM ternary diagram (Na₂O + K₂O-FeO^t-MgO) for serpentinites and talc-carbonates [41]. (c) K₂O versus SiO₂ binary diagram for serpentinites and talc-carbonates rocks [42].

5. Discussion

5.1. Tectonic Implication of Serpentinites and Talc-Carbonates

The studied serpentinites and talc-carbonates are low in Ti and high in Cr# [19] (Figure 7a,b). The Cr-spinel in serpentinites lies in fore-arc peridotites [2,27], but Cr-spinel in dunites and some highly depleted harzburgites plots in the boninite field. In the Cr# [19] and Mg# diagram (Figure 7c), the serpentinites and talc-carbonates lie in fore-arc

peridotites, showing a good negative Cr# - Mg# trend reflecting the partial melting trend from harzburgites to dunites. Based on the variation diagram of [43] of SiO₂/MgO versus Al₂O₃, the serpentinites plot in the peridotite field (Figure 7d).

In the MgO/SiO₂ and Al₂O₃/SiO₂ diagrams (Figure 8a), each sample examined plotted below the "terrestrial mantle array" trend and showed a trend of magmatic depletion or enrichment from a primitive mantle to a highly depleted harzburgitic composition [44–47]. This shift could be attributed to Mg loss due to seafloor weathering during serpentinization [45,48]. The Al₂O₃/SiO₂ and MgO/SiO₂ ratios are comparable to those of Arabian shield and fore-arc peridotites (Figure 8a; [22,27,49]). When plotting compiled serpentinites and talc-carbonates in an Al₂O₃ versus CaO (wt%) diagram (Figure 8b) of [27,49] all samples plotted in the fore-arc peridotite field. The serpentinites have low Al_2O_3 and CaO contents, like depleted fore-arc peridotite [2,27]. On the SiO₂/MgO versus Al₂O₃ diagram (Figure 8c), they are affiliated with ophiolitic peridotites, as are the other Eastern Desert ophiolitic ultramafics [43]. The investigated serpentinites differ significantly from those found elsewhere in Egypt, as seen in Figure 8c. The Al_2O_3 content seems to be relatively uninfluenced by serpentinization, demonstrating that the bulk-rock Al content typically reflects its original primary concentration [28,45]. Low Al₂O₃ abundances (average 1.14 wt%) define the investigated serpentinites, like peridotites from the fore-arc setting and Neoproterozoic serpentinized peridotites from the Eastern Desert, Egypt (Figure 8d). The chemistry of serpentinites (low in Al₂O₃, CaO and TiO₂, but high in MgO, Ni, Cr and Co) suggests that they were formed after depleting harzburgite protoliths in fore-arc settings.



Figure 7. (a) Cr# after [19] versus TiO₂ binary diagram [50] of the serpentinites and talc-carbonates. (b) TiO₂ versus Cr# diagram [50,51]. (c) Mg# versus Cr# binary diagram [52]. CED field for chromites in the Central Eastern Desert serpentinites is from [53]. (d) SiO₂/MgO versus Al₂O₃ binary diagram [43]. Symbols as in Figure 6.



Figure 8. (a) MgO/SiO₂ versus Al₂O₃/SiO₂ of the serpentinites and talc-carbonates. Depleted mantle, primitive mantle, and abyssal peridotite are from [43,54,55], respectively. The black line is the terrestrial array after [46]. The blue area highlights a global compositional range of abyssal peridotites [43]. (b) Al₂O₃ versus CaO binary diagram of [49]. (c) SiO₂/MgO ratios versus Al₂O₃ diagram. Fields of ophiolitic gabbros and peridotites as well as MORB are from [43]. Data from the Eastern Desert are shown for comparison [56,57]. (d) The contents of the bulk-rock Al₂O₃ (wt%) of Kab Amiri serpentinites were compared with those from different tectonic settings and the Pan-African serpentinites [58]. Symbols as in Figure 6.

5.2. Classifications and Magma Type of Basalts

The present samples show sub-alkali basalt affinity on the $Zr/TiO_2 \times 0.0001$ vs. Nb/Y diagram [59] (Figure 9a). While on the variation diagram of $(Na_2O + K_2O)$ vs. SiO₂ [60], all samples plot in the subalkaline field (Figure 9b). The Ti/Y versus Nb/Y ratio diagram discriminates between the tholeiitic and alkaline magmas [61]. The metabasalts samples lie in the tholeiitic field (Figure 9c). These features indicate that the parental magma of basalt was tholeiitic in composition.



Figure 9. (a) Zr/TiO_2 vs. Nb/Y Classification diagram for the metabasalts [59]. (b) Na₂O + K₂O vs. SiO₂ binary diagram of [60]. (c) Ti/Y vs. Nb/Y binary diagram for the metabasalts. (d) Th/Yb vs. Nb/Yb plot [61].

5.3. Tectonic Significance and Petrogenesis of Basalts

The geochemical characteristics of the ophiolite suite of rocks, in general, show variations in their major and trace elemental concentration, which could be due to mantle heterogeneity without any influence of crustal contamination [45,62]. In the Th/Yb vs. Nb/Yb discrimination diagrams of [63], all the metabasalts rocks fall above the N-MORB array suggesting arc-related magmatism (Figure 9d). Figure 10a shows that there is considerable overlapping between N-MORBs and E-MORBs, and between E-MORBs, P-MORBs, and ABs. Th and Nb behave similarly during both partial melting and fractional crystallization processes (see trends in Figure 10b). In the Th-Nb diagram, basalts generated in oceanic subduction-unrelated settings, rifted margins, and OCTZ can be distinguished from subduction-related basalts with a misclassification rate of <1% (Figure 10b). Three different types of convergent plate settings can be discriminated on the Th_N vs. Nb_N diagram in Figure 10b. Island arcs with complex polygenetic crustal nature are primarily characterized by the occurrence of CABs, which are displaced to the highest Th-Nb values. Intra-oceanic arcs display a large variability in Th-Nb contents, which can be used for recognizing two sub-types of intra-oceanic arc basalts. The Th/Nb enrichment indicates subduction-mantle source interaction, whereas decreasing Th-Nb compositions concerning PM define an array of mantle depletion without contribution from subduction-derived components Figure 10a,b.



Figure 10. (a) Summary of the compositional variations of different post-Archean ophiolitic basaltic rock types on the Th_N vs. Nb_N diagram. Vectors indicate the trends of compositional variations due to the main petrogenetic processes. Abbreviations: SSZ-E: supra-subduction zone enrichment; AFC: assimilation-fractional crystallization; OIB-CE: ocean island-type (plume-type) component enrichment; FC: fractional crystallization. Crosses indicate the composition of typical N-MORB, E-MORB and OIB [38]. (b) Tectonic interpretation of ophiolitic basaltic types based on Th_N-Nb_N systematics. Backarc A indicates backarc basin basalts (BABB) characterized by the input of subduction or crustal components (e.g., immature intra-oceanic or ensialic backarcs). In contrast, Backarc B indicates BABBs showing no input of subduction or crustal components (e.g., mature intra-oceanic backarcs). OCTZ: ocean-continent transition zone. In both panels, Nb and Th are normalized to the N-MORB composition [38].

Chondrite-normalized rare Earth elemental (REE) patterns of the metabasalts are shown in (Figure 11). The studied rocks have rare earth element (REE) contents ($\Sigma REE = 19.16-45.2 \text{ ppm}$). These metabasalts show moderate LREE/HREE fractionation (La/Yb)_N = 0.5 to 1.5 and (Gd/Yb)_N = 0.8 to 1.4 with Eu/Eu* = 0.9–1.2 and display flat pattern without an Eu anomaly, similar to typical N-MORB.



Figure 11. Chondrite-normalized REEs diagram of [64] for the studied metabasalts.

5.4. Geochemical Behavior of Elements in Metasediments

5.4.1. Elemental Distribution in Schists

The chemical analyses of seven representative samples of the island arc metasediments and four representative samples of the island arc metavolcanic of the Kab Amiri area are listed in Table 2. The metasediments are characterized by high silica contents from 49.20 to 64.52 wt% and $A1_2O_3$ 12.57 to 16.36%, which reflects the dominance of aluminous clay minerals. The percentages of MgO, CaO, and Na2O in metasediments range from 1.03 to 7.30, 1.32 to 9.6, and 1.93 to 6.38, respectively. The Ni, Cr, Sc, and V elements, regarded as compatible ferromagnesian trace elements, exhibit quite variable abundances in the metasediments. Ni is in the range from 18 to 94 ppm, while Cr content varies from 17 to 145 ppm. Alternatively, Sc and V abundance ranges are from 19.8 to 30.2 ppm and 112 to 342 ppm, respectively. The Large ion lithophile elements (LILEs) Cs, Rb, Ba, K and Sr concentrations are variable. Cs have lower content and vary from 0.1 to 0.9 ppm, Rb ranges from 3.6 to 30.8 ppm, and Ba from 3.98 to 2.83 ppm. Sr is depleted and ranges from 87 to 258 ppm. Depletion of Sr is connected to the low abundance of CaO, implying that these metasediments' source material is plagioclase poor. Th, U, Zr and Y show concentrations ranging from 0.2 to 0.6 ppm, 0.1 to 0.4 ppm, 15.2 to 100.3 ppm, and 6.2 to 21.8 ppm, respectively. In addition, normal to low concentration of Zr, which is concentrated in zircon and increases with maturity, infers immaturity to semi-maturity for these metasediments (Table 2). The related pairs Nb and Ta show exceptional coherence and are depleted in all samples, and they range from 0.67 to 7.0 ppm, and 0.1 to 3 ppm, respectively. These metasediments have Σ REE contents varying from 15.5 to 30.1 ppm, LREE contents from 11 to 17.9 ppm, HREE from 4.4 to 11.8 ppm, and slightly negative to positive Eu/Eu* anomalies ranging from 0.3 to 1.3, suggesting vigorous changes in the physic-chemical conditions.

Rock Type

				Metavolcanic		
3 F	Av.	6 D	17 D	3 D	11 D	Av.
des (wt%)						
64.52	55.3	56.63	54.10	55.10	51.95	54.45
0.62	0.75	0.88	0.73	1.31	0.92	0.96
16.36	14.76	12.50	12.61	13.0	13.81	12.98
4.00		0.10	10 (0	0.05	0.01	0.41

Table 2. Whole-rock major oxides,	trace and REEs ele	ement compositions of	f metasediments and	ł metavolcanic rock	s from Kab Amiri.
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Metasediments

S. No.	5 D	14 D	7 E	18 E	4 D	2 E	3 F	Av.	6 D	17 D	3 D	11 D	Av.
						Major oxi	des (wt%)						
SiO ₂	51.10	57.78	51.77	49.20	53.10	59.69	64.52	55.3	56.63	54.10	55.10	51.95	54.45
TiO ₂	0.39	0.34	0.30	1.42	0.99	1.23	0.62	0.75	0.88	0.73	1.31	0.92	0.96
Al_2O_3	12.57	13.42	15.44	14.99	15.68	14.85	16.36	14.76	12.50	12.61	13.0	13.81	12.98
FeOt	11.74	12.14	16.38	12.36	9.5	7.62	4.32	10.56	9.12	10.69	8.95	9.01	9.41
MnO	0.14	0.11	0.13	0.17	0.19	0.14	0.13	0.14	0.31	0.33	0.21	0.14	0.24
MgO	6.09	6.58	5.60	7.30	6.69	3.21	1.03	5.2	9.10	8.50	8.99	10.0	9.14
CaO	7.08	4.87	6.91	9.6	8.7	5.43	1.32	6.26	8.0	8.72	7.90	9.0	8.4
Na ₂ O	2.83	2.43	1.93	2.1	3.2	4.89	6.38	3.38	2.20	2.90	2.85	3.4	2.83
K ₂ O	0.28	0.18	0.76	0.19	0.14	1.14	3.89	0.9	0.92	1.0	1.15	0.91	0.98
P_2O_5	0.05	0.07	0.05	0.10	0.11	0.09	0.09	0.08	0.10	0.08	0.12	0.09	0.09
L.O.I.	7.53	2.02	0.54	2.45	1.46	1.31	1.14	2.32	0.14	0.15	0.27	0.48	0.39
Total	99.8	99.94	99.81	99.88	99.76	99.6	99.8	99.65	99.9	99.81	99.85	99.71	99.87
					Tre	ice elements (pp	m)						
Mo	0.16	0.8	0.17	0.52	0.47	0.36	0.27	0.39	0.16	0.19	0.12	0.17	0.16
Cu	54.9	18.0	77.9	89	97	18.5	23.5	54.11	98.5	80.9	37.5	30.2	61.78
Pb	1.51	1.83	2.16	2.9	3.1	4.1	2.8	2.63	3.90	4.50	4.17	3.12	3.92
Zn	57.1	56.4	122.5	83	96.3	98.7	78.9	84.7	77.1	100.7	99.3	80.6	89.43
Ag	45.0	45.0	30.0	30.0	50.3	35.6	40.5	39.48	29.0	50.7	41.2	33.5	38.6
Ni	19.9	12.4	60.2	94	65	18	23	41.79	80.2	47.5	12.6	50.3	47.65
Co	21.1	17.6	30.0	41	38	21	17.5	26.6	39.8	59.3	51.5	49.2	49.95
As	1.0	0.7	0.8	0.8	0.7	0.9	1.1	0.76	3.0	2.9	3.2	2.1	2.8
U	0.2	0.1	0.1	0.3	0.4	0.2	0.4	0.24	0.2	0.1	0.2	0.1	0.15
Th	0.3	0.4	0.3	0.4	0.6	0.2	0.5	0.39	0.4	0.3	0.4	0.5	0.4
Sr	102.0	87.0	258	160.3	139	140	186	153.19	340.0	195.5	244.1	207.9	246.9
Cd	0.13	0.07	0.09	0.10	0.9	0.7	0.19	0.31	12.3	9.3	6.9	7.5	9.0
Sb	0.24	0.06	0.51	0.27	0.09	0.9	0.21	0.33	0.17	0.09	0.03	0.10	0.09
Bi	0.05	0.04	0.05	0.03	0.04	0.08	0.07	0.05	0.04	0.03	0.06	0.07	0.05
V	112	144	245	241	342	226.9	175.6	212.36	176	290	312	210	247
Cr	120	58.0	17.0	145	75.7	19.6	21.9	65.31	33.0	22.0	17.5	10.0	20.62
Ba	72.0	27.0	283	36.2	48.7	3.98	4.12	67.86	105.0	85.0	96.5	100.7	96.8
W	0.1	0.1	0.2	0.1	0.2	0.4	0.3	0.2	0.2	0.3	0.6	0.4	0.375
Zr	40.2	28.3	15.2	51.8	98.3	75.9	100.3	58.57	98.6	82.6	70.2	56.3	76.92
Sn	0.5	0.5	0.3	0.6	0.9	0.5	0.7	0.57	0.4	0.6	1.8	0.8	0.9
Be	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	0.98
Sc	22.3	21.8	29.3	25.1	30.2	28.7	19.8	25.31	36.5	29.5	41.2	30.3	34.38
S	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.1	0.10	0.10	0.10	0.10	0.1
Y	14.6	13.6	6.2	21.8	19.3	18.9	8.6	14.71	29.3	27.5	29.3	32.0	29.53

Rock Type	Metasediments								Metavolcanic						
S. No.	5 D	14 D	7 E	18 E	4 D	2 E	3 F	Av.	6 D	17 D	3 D	11 D	Av.		
Maior oxides (wt%)															
Hf	0.94	0.64	0.74	3.2	5.9	6.3	5.7	3.35	0.83	1.2	0.92	0.61	0.89		
Li	10.7	27.6	27.6	12.0	18.9	32.5	19.8	21.3	9.7	18.2	15.3	7.5	12.67		
Rb	6.0	13.8	13.6	3.6	4.2	30.8	15.7	12.53	17.8	20.3	18.6	20.2	19.22		
Ta	0.1	0.1	0.1	2.0	1.8	3	1.7	1.26	0.2	0.1	0.4	0.2	0.23		
Nb	0.77	0.67	0.69	2.9	2.1	7	4.3	2.63	3.7	2.9	3.1	2.5	3.05		
Cs	0.1	0.8	10.9	0.7	0.7	0.9	0.8	0.7	0.2	0.1	0.3	0.1	0.18		
Ga	10.38	11.69	12.69	16.3	12.9	30.4	27.3	17.38	22.7	18.9	19.2	15.5	19.08		
In	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.06	0.09	0.10	0.07		
Re	0.002	0.003	0.003	0.003	0.003	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.002		
Se	0.3	0.3	0.3	0.4	0.3	0.5	0.3	0.34	0.33	0.29	0.30	0.21	0.28		
						Rare earth elem	ents REEs (ppm)							
La	2.6	2.4	2.0	4.3	4.9	5.1	4.9	3.74	2.9	3.8	7.2	4.5	4.6		
Ce	6.83	5.95	4.38	5.2	6.1	5.6	4.3	5.48	8.5	12.1	14.7	10.3	11.4		
Pr	1.1	3.8	1.2	2.1	1.1	2.0	1.7	1.86	1.7	1.5	1.3	1.0	1.38		
Nd	5.2	4.9	2.6	3.7	4.2	2.9	3.2	3.81	9.7	8.2	8.1	7.5	8.38		
Sm	1.7	1.5	0.7	1.3	1.2	0.9	1.5	1.26	5.8	4.7	1.9	3.5	3.98		
Eu	0.5	0.5	0.2	0.4	0.3	0.2	0.7	0.4	1.2	1.1	0.8	0.9	1.0		
Gd	2.2	2.2	0.9	1.9	2.6	3.0	1.9	2.1	6.3	8.9	5.2	7.0	6.85		
Tb	0.4	2.9	0.6	0.4	3.5	0.9	1.0	1.39	0.5	0.7	0.9	0.8	0.73		
Dy	2.5	2.1	1.0	1.3	2.5	2.2	2.5	2.01	4.0	4.1	3.9	4.7	4.18		
Ho	0.6	0.5	0.2	0.3	0.7	0.2	0.3	0.4	0.8	0.9	1.2	1.3	1.05		
Er	1.7	1.6	0.7	1.9	1.6	1.5	1.8	1.54	6.0	4.1	5.2	3.9	4.8		
Tm	0.3	0.2	0.1	0.4	0.3	0.4	0.3	0.29	0.4	0.5	0.8	0.2	0.48		
Yb	1.5	1.4	0.8	1.6	0.4	1.9	0.8	1.2	3.6	4.3	5.2	6.0	4.78		
Lu	0.2	0.3	0.1	0.2	0.2	0.3	0.5	0.26	0.5	0.6	0.3	0.2	0.4		
ΣREE	27.3	30.1	15.5	25	29.6	27.1	25.4	25.71	51.9	55.5	56.7	51.8	53.98		
LREE	17.9	19	11	17	17.8	16.7	16.3	16.53	28.9	31.4	34.0	27.7	30.5		
HREE	9.4	11.2	4.4	8	11.8	10.4	9.1	9.19	21.1	24.1	22.7	24.1	23		
LREE/HREE	1.9	1.7	2.5	2.1	1.5	1.6	1.8	1.87	1.4	1.3	1.5	1.4	1.4		
Eu/Eu*	0.8	0.8	0.8	0.8	0.5	0.3	1.3	0.76	0.6	0.5	0.7	0.5	0.58		
La/Yb_N	1.2	1.2	1.7	1.8	8.3	1.8	4.1	2.87	0.5	0.6	0.9	0.5	0.63		
Tb/Yb _N	1.1	8.9	3.2	1.1	37.4	2.0	5.3	8.43	0.6	0.6	0.7	0.6	0.63		
Gd/Yb _N	1.2	1.3	0.9	1.0	5.3	1.3	1.9	1.84	1.4	1.7	0.8	0.9	1.2		
La/Sm _N	1.0	1.0	1.8	2.1	2.6	3.6	2.1	2.03	0.3	0.5	2.4	0.8	1.0		
Ce/Ce*	0.997	0.934	0.959	0.608	0.627	0.634	0.484	0.75	0.937	1.178	0.938	0.923	0.99		

5.4.2. Classifications and Origin of Schists

 Na_2O -FeO + MgO-K₂O ternary diagram [64] was used to determine the origin of metasedimentary samples. Plotting of the investigated metasediments on this diagram revealed that they fall in the greywacke field, which suggests a sedimentary origin (Figure 12a). The FeO^t-MgO-Al₂O₃ ternary diagram of [65] supports the metamorphic origin of these rocks (Figure 12b). According to the (SiO_2/Al_2O_3) – (K_2O/Na_2O) binary diagram of [66], the metasediments plot in the pelitic greywackes field (Figure 12c). Based on the log (FeO/K₂O) versus log (SiO₂/Al₂O₃) of [67], the samples fall within the Fe-shale field, indicating high content of iron oxides (Figure 12d). K₂O versus Na₂O of [68] divided the greywacke into quartz rich, quartz intermediate, and poor quartz varieties; the studied samples are fitted with quartz intermediate and poor fields. (Figure 12e). Chondrite normalized rare Earth elemental (REE) patterns of the metasediments are shown in Figure 13. The metasedimentary samples are characterized by a moderate degree of REE fractionation, as revealed by their contents (La/Yb)_N ratios (1.2 to 8.3 ppm). The degree of LREE fractionation is quite low, and (La/Sm)_N content ranges from 1.0 to 3.6 ppm, while the heavy REEs are weakly fractionated and (Gd/Yb)_N content range from 0.9 to 5.3 ppm.



Figure 12. (a) Geochemical classification diagram of the Na₂O-FeO + MgO-K₂O for samples of the metasediments [64]. (b) FeO^t-MgO-Al₂O₃ ternary diagram of [65] for the study metasediments. (c) Classification diagram of the SiO₂/Al₂O₃ vs. K₂O/Na₂O for samples of the metasediments [66]. (d) log (FeO/K₂O) vs. log (SiO₂/Al₂O₃) for samples of the metasediments [67]. (e) K₂O versus Na₂O classification diagram of [68]. Blue box means plotting samples.



Figure 13. Chondrite-normalized REEs patterns for the metasediments [63].

5.5. Classifications and Magma Type of Island-Arc Metavolcanic

According to Middlemost's Na₂O + K₂O vs. SiO₂ diagram [69], metavolcanic samples fall in the basaltic–andesite field (Figure 14a). On the variation diagram of Na₂O + K₂O vs. SiO₂ [60], all samples plot in the subalkaline magma field (Figure 14b). The (AFM) Alkalis-FeO^t-MgO diagram proposed by [60] can discriminate tholeiitic and calc–alkaline affinity. In this diagram, the samples plot within the calc–alkaline field (Figure 14c). On the SiO₂ versus FeO^t/MgO variation diagram of [70], the metavolcanic samples plot in the calc–alkaline field (Figure 14d). The investigated metavolcanic in chemistry resembles Shadli island-arc metavolcanic [71].



Figure 14. (a) $K_2O + Na_2O vs. SiO_2$ Classification diagram for the metavolcanic [69]. (b) $Na_2O + K_2O vs. SiO_2$ binary diagram of [58] for the, studied the metavolcanic. (c) AFM ternary diagram of [60] for

the study metavolcanic. (d) SiO_2 versus FeO^t/MgO variation diagram of [70] for the study metavolcanic. (e) Nb versus SiO_2 variation diagram for samples of the metavolcanic of [72]. (f) Th/Yb versus Nb/Yb diagram of [73], for the metavolcanic rocks. The red symbol means plotting samples.

5.6. Tectonic Setting and Petrogenesis of the Island-Arc Metavolcanic Rocks

According to Nb versus SiO₂ variation diagram of [72] to discriminate between the active continental margin, orogenic volcanic terrains and immature island arcs. All metavolcanic samples plot in the immature island arcs (Figure 14e). Based on the Th/Yb versus Nb/Yb variation diagram of [73], all samples plot in the oceanic arc field (Figure 14f), suggesting an arc-related (island-arc) setting [72].

5.7. Tectonic Model and Emplacement Mechanism

Egypt's Central Eastern Desert (CED) is divided into two ophiolite belts with controversial genetic systems. The first belt is called Ghadir–Mubarak–Barramiya and is located in the south [26], while the second belt is the Wadi Semna–Fawakhir–Um Gheig belt in the north of CED [21]. The study area is located in the northern belt of CED (Figures 15 and 16), which is affected by NW obduction-related thrust faults resulting from the structure evolution of the Najd fault system (NFS).

The two Cryogenian ophiolitic belts in the CED and the accretionary history of the Eastern Desert of Egypt were overprinted by the Najd fault system (NFS) with fore-arc and back-arc geochemical characteristics (Figure 15a); Abd El-Rahman et al. propose that an intra-oceanic island connected to a NE-dipping subduction zone formed during the tectonic history of the CED [4]. A fore-arc ophiolite belt, however, stretches from El Barramiya [26] in the southern portion of the CED (SCED) to Fawakhir in the northern section of the CED (NCED). In addition, a back-arc basin parallel to the fore-arc belt formed to the east (in modern coordinates), and the back-arc basin was closed by a WSW-dipping subduction zone [21] (Figure 15b).



Figure 15. The controversial models for the evolution of the CED ophiolite belts according to [21]; (a) Model I after [74]; (b) Model II after [4] showing the distribution of serpentinite in the Eastern Desert of Egypt. Zones with blue colour in both models are the fore-arc association, while the zones with red colour are the back-arc association.

Alternatively, some studies argue that the Eastern belt (toward the Southern Eastern Desert) is a fore-arc, and the Western belt (toward the Northern Eastern Desert) is a back-arc, both of which have opposing directions. This theory is more consistent with the overall structural patterns (Figure 16a). The metasomatized serpentinites of Kab Amiri match the majority of Egyptian ophiolites' proposed tectonic settings, which featured oceanic lithosphere fragments deposited over a subduction zone in a fore-arc setting, according to the aforementioned data (Figure 16b) [75–77].

In the suggested models for the CED's development, the presence of the paired belts is indicated by ophiolite belts. Having geochemical affinities in the fore-arc and back-arc [4]. The first piece of evidence for this concept is the age of the fore-arc belt, which should be older than the back-arc belt. However, the beginning of a back-arc basin happens later to the spreading at the front of the subduction zone at the fore-arc setting [21].



Figure 16. (a) The proposed model of Neoproterozoic fore-arc ophiolite belts in the northern Arabian-Nubian Shield at Central Eastern Desert (CED), Egypt [21,74]. (b) Tectonic model for the evolution of the studied ultramafic rocks and the Arabian–Nubian [76–78].

6. Conclusions

- 1. Most previous studies mainly concern granitic rocks' geology, petrography, and chemistry. We carried out detailed field, petrographical and geochemical studies on the serpentinites, spilite, metasediments and metavolcanic (metabasalt) at Wadi Kab Amiri.
- 2. Dismembered ophiolitic rocks are distributed in the northern and eastern parts of the study area and comprise serpentinites, talc carbonates and metabasalt rocks. Serpentinites in the present area are the oldest rock unit. Petrographically, the serpentinites are composed of serpentine minerals (90%), and olivine with minor amounts of carbonates and opaques. Geochemically, the serpentinites resemble those of depleted mantle peridotites (harzburgite-dunite) and tend to have abyssal geochemical characteristics.
- 3. Kab Amiri metabasalt is related to the older metavolcanic (OMV), characterized by large exposure of pillow structures. They consist of plagioclase, chlorite, carbonate and epidote; they are also characterized by cryptocrystalline grain size and amygdaloidal texture. The ophiolitic metabasalt are sub-alkali basalt affinities, tholeiitic and formed in the fore-arc basin. The chondrite normalized rare Earth elemental (REEs) patterns of the metabasalts show low fractionated patterns.
- 4. Island arc assemblages are represented by metasediment and metavolcanic rocks. Metasediments rocks comprise quartz–actinolite–chlorite schist and slate. They are mostly foliated and highly folded. Microscopically, the schists are essentially composed of amphibole and mica minerals, plagioclase, and quartz. In contrast, slate samples are composed mainly of quartz, sericite, and chlorite and are related to oceanic island arc tectonic setting.
- 5. Large exposures of andesitic basalt in the southern and northeast parts of the mapped area represent metavolcanic rocks. Microscopically, the island arc metavolcanic is classified as metabasalt (plagioclase and mafic minerals) and metapyroclastic (porphyroblasts of clastic plagioclase, quartz, carbonate and perthite embedded in a fine-grained groundmass of chlorite and epidote). Geochemically, the metavolcanic are basaltic-andesite andesite in composition, and calc-alkaline affinity is related to the island arc tectonic setting. Chondrite-normalized rare earth element (REE) patterns show slightly fractionated patterns.
- 6. The large serpentinite bodies are concentrated on the CED's western side, extending in an NNW-SSE direction. To the west of the arc-back-arc assemblages, arc-forearc assemblages are still visible, proving that the intra-oceanic island arc system was formed over an E-dipping subduction zone (present coordinates). Both assemblages define a suture zone in the CED by extending as NW-SE belts.
- 7. The geochemical signature of subduction increases in the direction of the south in arc-back-arc assemblages. Bimodal volcanism's prevalence in the south suggests that a back-arc basin has been gradually expanding from the north to the south, but the rift island arc assemblages farther south have been preserved.

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References

- 1. Khedr, M.Z.; Arai, S. Origin of Neoproterozoic ophiolitic peridotites in south Eastern Desert, Egypt, constrained from primary mantle mineral chemistry. *Miner. Pet.* 2013, 107, 807–828. [CrossRef]
- 2. Azer, M.K.; Stern, R.J. Neoproterozoic (835–720 Ma) serpentinites in the Eastern Desert, Egypt: Fragments of forearc mantle. *J. Geol.* 2007, 115, 457–472. [CrossRef]
- 3. Stern, R.J. Neoproterozoic formation and evolution of Eastern Desert continental crust—The importance of the infrastructuresuperstructure transition. *J. Afr. Earth Sci.* 2018, 146, 15–27. [CrossRef]
- 4. El-Rahman, Y.A.; Polat, A.; Dilek, Y.; Kusky, T.; El-Sharkawi, M.; Said, A. Cryogenian ophiolite tectonics and metallogeny of the Central Eastern Desert of Egypt. *Int. Geol. Rev.* 2012, *54*, 1870–1884. [CrossRef]
- 5. A El Bahariya, G. Classification of the Neoproterozoic ophiolites of the Central Eastern Desert, Egypt based on field geological characteristics and mode of occurrence. *Arab. J. Geosci.* **2018**, *11*, 1–23. [CrossRef]
- 6. Kroner, A.; Todt, W.; Hussein, I.; Mansour, M.; Rashwan, A. Dating of late Proterozoic ophiolites in Egypt and the Sudan using the single grain zircon evaporation technique. *Precambrian Res.* **1992**, *59*, 15–32. [CrossRef]
- Ali, K.A.; Azer, M.K.; Gahlan, H.A.; Wilde, S.A.; Samuel, M.D.; Stern, R.J. Age constraints on the formation and emplacement of Neoproterozoic ophiolites along the Allaqi–Heiani Suture, South Eastern Desert of Egypt. *Gondwana Res.* 2010, 18, 583–595. [CrossRef]
- Fritz, H.; Abdelsalam, M.; Ali, K.; Bingen, B.; Collins, A.; Fowler, A.; Ghebreab, W.; Hauzenberger, C.; Johnson, P.; Kusky, T.; et al. Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. *J. Afr. Earth Sci.* 2013, 86, 65–106. [CrossRef] [PubMed]
- 9. El Dien, H.G.; Li, Z.-X.; Abu Anbar, M.; Doucet, L.S.; Murphy, J.B.; Evans, N.J.; Xia, X.-P.; Li, J. The largest plagiogranite on Earth formed by re-melting of juvenile proto-continental crust. *Commun. Earth Environ.* **2021**, *2*, 138. [CrossRef]
- 10. Khalil, A.E.; El-Desoky, H.M.; Shahin, T.M.; Abdelwahab, W. Late Cryogenian arc-related volcaniclastic metasediment successions at Wadi Hammuda, Central Eastern Desert, Egypt: Geology and geochemistry. *Arab. J. Geosci.* 2018, *11*, 74. [CrossRef]
- 11. Habib, M.E. Microplate accretion model for the Pan-African basement between Qena-Safaga and Qift-Quseir roads, Egypt. *Bull. Fac. Sci. Assiut Univ. C Biol. Geol.* **1987**, *16*, 199–239.
- 12. AbdulKarim, A.M.; Abdel-Karim, A.M. Metavolcanics and older granites of the central Eastern Desert of Egypt: A geochemical approach. *Bull. Fac. Sci. Zagazig Univ.* **1994**, *16*, 338–361.
- Abdel-Rahman, A.M.; El-Desoky, H.M.; Shalaby, B.N.A.; Awad, H.A.; Ene, A.; Heikal, M.A.; El-Awny, H.; Fahmy, W.; Taalab, S.A.; Zakaly, H.M.H. Ultramafic Rocks and Their Alteration Products From Northwestern Allaqi Province, Southeastern Desert, Egypt: Petrology, Mineralogy, and Geochemistry. *Front. Earth Sci.* 2022, 10. [CrossRef]
- Zoheir, B.; Akawy, A.; Hassan, I. Role of fluid mixing and wallrock sulfidation in gold mineralization at the Semna mine area, central Eastern Desert of Egypt: Evidence from hydrothermal alteration, fluid inclusions and stable isotope data. *Ore Geol. Rev.* 2008, 34, 580–596. [CrossRef]
- 15. Gaafar, I.; Aboelkhair, H. Analysis of Geological and Geophysical Datasets for Radioelement Exploration in Kab Amiri Area, Central Eastern Desert, Egypt. *Open Geol. J.* **2014**, *8*, 34–53. [CrossRef]
- El-Mezayen, M.M.; Rueda-Roa, D.T.; Essa, M.A.; Muller-Karger, F.E.; Elghobashy, A.E. Water quality observations in the marine aquaculture complex of the Deeba Triangle, Lake Manzala, Egyptian Mediterranean coast. *Environ. Monit. Assess.* 2018, 190, 436. [CrossRef] [PubMed]
- El Mezayen, A.M.; Ibrahim, E.M.; El-Feky, M.G.; Omar, S.M.; El-Shabasy, A.M.; Taalab, S.A. Physico-chemical conditions controlling the radionuclides mobilisation in various granitic environments. *Int. J. Environ. Anal. Chem.* 2022, 102, 970–986. [CrossRef]
- 18. El Dabe, M.M.; Ismail, A.M.; Metwaly, M.; Taalab, S.A.; Hanfi, M.Y.; Ene, A. Hazards of Radioactive Mineralization Associated with Pegmatites Used as Decorative and Building Material. *Materials* **2022**, *15*, 1224. [CrossRef]
- 19. Kharbish, S.; Amer, O.; El-Awady, A. Mineral chemistry, geochemistry, Raman spectroscopy and geotectonic significance of Neoproterozoic ophiolitic peridotites and pyroxenites from Kab Amiri district, central Eastern Desert, Egypt. *Front. Sci. Res. Technol.* **2020**, *1*, 30–45. [CrossRef]
- 20. El Mezayen, A.M.; Abu Zeid, E.K.; Hosny, W.S.; El-Feky, M.G.; Omar, S.M.; Taalab, S.A. Geochemistry, mineralogy, and radioactivity of the Abu Furad Area, Central Eastern Desert, Egypt. *Acta Geochim.* **2018**, *38*, 307–326. [CrossRef]
- Sehsah, H.; Eldosouky, A.M. Neoproterozoic hybrid forearc—MOR ophiolite belts in the northern Arabian-Nubian Shield: No evidence for back-arc tectonic setting. *Int. Geol. Rev.* 2022, 64, 151–163. [CrossRef]
- 22. Moghazi, A.M. Petrology and geochemistry of Pan-African granitoids, Kab Amiri area, Egypt–implications for tectonomagmatic stages in the Nubian Shield evolution. *Mineral. Petrol.* **2002**, *75*, 41–67. [CrossRef]

- Johnson, P.R.; Andresen, A.; Collins, A.S.; Fowler, A.R.; Fritz, H.; Ghebreab, W.; Kusky, T.; Stern, R.J. Late Cryogenian–Ediacaran history of the Arabian–Nubian Shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. J. Afr. Earth Sci. 2011, 61, 167–232. [CrossRef]
- 24. Akaad, A.K. Geology and lithostratigraphy of the Arabian Desert orogenic belt of Egypt between 25°35′ and 26°30′N. In *Evolution and mineralization of the Arabian-Nubian Shield;* Elsevier: Amsterdam, The Netherlands, 1980; pp. 4–127.
- 25. Hassan, M.A.; Hashad, A.H. Precambrian of Egypt. In The Geology of Egypt; Routledge: Oxfordshire, UK, 1990; pp. 201–248.
- 26. Khedr, M.Z.; Arai, S. Peridotite-chromitite complexes in the Eastern Desert of Egypt: Insight into Neoproterozoic sub-arc mantle processes. *Gondwana Res.* 2017, 52, 59–79. [CrossRef]
- Khedr, M.Z.; Takazawa, E.; Arai, S.; Stern, R.J.; Morishita, T.; El-Awady, A. Styles of Fe–Ti–V ore deposits in the Neoproterozoic layered mafic-ultramafic intrusions, south Eastern Desert of Egypt: Evidence for fractional crystallization of V-rich melts. *J. Afr. Earth Sci.* 2022, 194, 104620. [CrossRef]
- 28. Bonatti, E.; Michael, P.J. Mantle peridotites from continental rifts to ocean basins to subduction zones. *Earth Planet Sci. Lett.* **1989**, 91, 297–311. [CrossRef]
- 29. Polat, A.; Hofmann, A. Alteration and geochemical patterns in the 3.7–3.8 Ga Isua greenstone belt, West Greenland. *Precambrian Res.* **2003**, *126*, 197–218. [CrossRef]
- Agranier, A.; Lee, C.-T.A.; Li, Z.-X.A.; Leeman, W.P. Fluid-mobile element budgets in serpentinized oceanic lithospheric mantle: Insights from B, As, Li, Pb, PGEs and Os isotopes in the Feather River Ophiolite, California. *Chem. Geol.* 2007, 245, 230–241. [CrossRef]
- Li, Z.-X.A.; Lee, C.-T.A. Geochemical investigation of serpentinized oceanic lithospheric mantle in the Feather River Ophiolite, California: Implications for the recycling rate of water by subduction. *Chem. Geol.* 2006, 235, 161–185. [CrossRef]
- 32. Kodolányi, J.; Pettke, T.; Spandler, C.; Kamber, B.; Gméling, K. Geochemistry of Ocean Floor and Fore-arc Serpentinites: Constraints on the Ultramafic Input to Subduction Zones. *J. Petrol.* **2012**, *53*, 235–270. [CrossRef]
- Pelletier, L.; Müntener, O.; Kalt, A.; Vennemann, T.W.; Belgya, T. Emplacement of ultramafic rocks into the continental crust monitored by light and other trace elements: An example from the Geisspfad body (Swiss-Italian Alps). *Chem. Geol.* 2008, 255, 143–159. [CrossRef]
- Deschamps, F.; Godard, M.; Guillot, S.; Chauvel, C.; Andreani, M.; Hattori, K.; Wunder, B.; France, L. Behavior of fluid-mobile elements in serpentines from abyssal to subduction environments: Examples from Cuba and Dominican Republic. *Chem. Geol.* 2012, 312–313, 93–117. [CrossRef]
- 35. Hattori, K.H.; Guillot, S. Geochemical character of serpentinites associated with high-to ultrahigh-pressure metamorphic rocks in the Alps, Cuba, and the Himalayas: Recycling of elements in subduction zones. *Geochem. Geophys. Geosyst.* 2007, 8. [CrossRef]
- Hattori, K.; Takahashi, Y.; Guillot, S.; Johanson, B. Occurrence of arsenic (V) in forearc mantle serpentinites based on X-ray absorption spectroscopy study. *Geochim. Cosmochim. Acta* 2005, 69, 5585–5596. [CrossRef]
- 37. Taylor, S.R.; McLennan, S.M. The geochemical evolution of the continental crust. *Rev. Geophys.* 1995, 33, 241–265.
- 38. Sun, S.S.; McDonough, W.F. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In *Magmatism in the Ocean Basin*; Geological Society Special Publication: London, UK, 1989; Volume 42, pp. 313–345.
- 39. Ramsay, W.R.H.; Crawford, A.J.; Foden, J.D. Field setting, mineralogy, chemistry, and genesis of arc picrites, New Georgia, Solomon Islands. *Contrib. Mineral. Petrol.* **1984**, *88*, 386–402. [CrossRef]
- 40. Streckeisen, A. To each plutonic rock its proper name. Earth-Sci. Rev. 1976, 12, 1–33. [CrossRef]
- 41. Irvine, T.N.; Baragar, W.R.A. A Guide to the Chemical Classification of the Common Volcanic Rocks. *Can. J. Earth Sci.* **1971**, *8*, 523–548. [CrossRef]
- 42. Le Maitre, R.W. A classification of igneous rocks and glossary of term's recommendation of international union of geological sciences subcommision on the systematic of the igneous rock. *Blackwell Oxf.* **1989**, *193*.
- 43. Niu, Y. Bulk-rock Major and Trace Element Compositions of Abyssal Peridotites: Implications for Mantle Melting, Melt Extraction and Post-melting Processes Beneath Mid-Ocean Ridges. J. Petrol. 2004, 45, 2423–2458. [CrossRef]
- 44. Bodinier, J.L.; Godard, M. Orogenic, ophiolitic, and abyssal peridotites, Treatise on Geochemistry. Treatise Geochem. 2003, 2, 568.
- 45. Deschamps, F.; Godard, M.; Guillot, S.; Hattori, K. Geochemistry of subduction zone serpentinites: A review. *Lithos* **2013**, 178, 96–127. [CrossRef]
- 46. Khedr, M.Z.; Arai, S.; Python, M.; Tamura, A. Chemical variations of abyssal peridotites in the central Oman ophiolite: Evidence of oceanic mantle heterogeneity. *Gondwana Res.* **2014**, *25*, 1242–1262. [CrossRef]
- 47. Jagoutz, E.; Palme, H.; Baddenhausen, H.; Blum, K.; Cendales, M.; Dreibus, G.; Spettel, B.; Lorenz, V.; Wänke, H. The abundances of major, minor and trace elements in the E' 'Earth's mantle as derived from primitive ultramafic nodules. In *Lunar and Planetary Science Conference, 10th, Houston, Tex., 19–23 March 1979*; A80-23617 08-91; Pergamon Press, Inc.: New York, NY, USA, 1979; Volume 2, pp. 2031–2050, Research supported by the Deutsche Forschungsgemeinschaft; **1979**, *10*, 2031–2050.
- 48. Hart, S.R.; Zindler, A. In search of a bulk-Earth composition. Chem. Geol. 1986, 57, 247–267. [CrossRef]
- 49. Snow, J.E.; Dick, H.J. Pervasive magnesium loss by marine weathering of peridotite. *Geochim. et Cosmochim. Acta* 1995, 59, 4219–4235. [CrossRef]
- 50. Pearce, J.A.; Barker, P.F.; Edwards, S.J.; Parkinson, I.J.; Leat, P.T. Geochemistry and tectonic significance of peridotites from the South Sandwich arc-basin system, South Atlantic. *Contrib. Mineral. Petrol.* **2000**, *139*, 36–53. [CrossRef]

- 51. Dick, H.J.B.; Bullen, T. Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. *Contrib. Mineral. Petrol.* **1984**, *86*, 54–76. [CrossRef]
- 52. Jan, M.Q.; Windley, B.F. Chromian spinel-silicate chemistry in ultramfic rocks of the Jijal Complex, northwest Pakistan. *J. Petrol.* **1990**, *31*, 67–71. [CrossRef]
- Stern, R.J.; Johnson, P.R.; Kröner, A.; Yibas, B. Neoproterozoic Ophiolites of the Arabian-Nubian Shield. Precambrian ophio-lites and related rocks. In *Developments in Precambrian Geology*; Kusky, T.M., Ed.; Elsevier: Amsterdam, The Netherlands, 2004; pp. 95–128. [CrossRef]
- 54. Farahat, E.S.; Hoinkes, G.; Mogessie, A. Petrogenetic and geotectonic significance of Neoproterozoic suprasubduction mantle as revealed by the Wizer ophiolite complex, Central Eastern Desert, Egypt. *Int. J. Earth Sci.* **2011**, *100*, 1433. [CrossRef]
- 55. Salters, V.J.M.; Stracke, A. Composition of the depleted mantle. Geochem. Geophys. Geosyst. 2004, 5. [CrossRef]
- 56. McDonough, W.F.; Sun, S.S. The composition of the Earth. Chem. Geol. 1995, 120, 223–253.
- 57. Azer, M.K.; Samuel, M.; Ali, K.; Gahlan, H.A.; Stern, R.J.; Ren, M.; Moussa, H. Neoproterozoic ophiolitic peridotites along the Allaqi-Heiani suture, South Eastern Desert, Egypt. *Mineral. Petrol.* **2013**, *107*, 829–848. [CrossRef]
- 58. Abdel-Karim, A.-A.M.; Ali, S.; El-Shafei, S.A. Mineral chemistry and geochemistry of ophiolitic metaultramafics from Um Halham and Fawakhir, Central Eastern Desert, Egypt. *Int. J. Earth Sci.* 2018, 107, 2337–2355. [CrossRef]
- 59. Abdel-Karim, A.-A.M.; Ahmed, Z. Possible origin of the ophiolites of Eastern Desert, Egypt, from geochemical perspectives. *Arab. J. Sci. Eng.* **2010**, *35*, 115.
- 60. Winchester, J.; Floyd, P. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chem. Geol.* **1977**, *20*, 325–343. [CrossRef]
- 61. Pearce, J.A. Trace element characteristics of lavas from destructive plate boundaries. Orog. Andesites Relat. Rocks. 1982, 528–548.
- 62. Pearce, J.A.; Norry, M.J. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contrib. Mineral. Petrol.* **1979**, 69, 33–47. [CrossRef]
- 63. Pearce, J.A. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos* **2008**, *100*, 14–48. [CrossRef]
- 64. Boynton, W.V. Cosmochemistry of the Rare Earth Elements: Meteorite Studies. In *Developments in geochemistry*; Elsevier: Amsterdam, The Netherlands, 1984; Volume 2, pp. 63–114. [CrossRef]
- 65. Pettijohn, F.J.; Potter, P.E.; Siever, R. Sand and Sandstone; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012.
- 66. Nockolds, S.R. The relation between chemical composition and paragenesis in the biotite micas of igneous rocks. *Am. J. Sci.* **1947**, 245, 401–420. [CrossRef]
- 67. Wimmenauer, W. Das prävariskische Kristallin im Schwarzwald. Fortschr. Der Mineral. Beih. 1984, 62, 69–86.
- Herron, M.M. Geochemical Classification of Terrigenous Sands and Shales from Core or Log Data. J. Sediment. Res. 1988, 58, 820–829. [CrossRef]
- Crook, K.A.W. Lithogenesis and Geotectonics: The Significance of Compositional Variation in Flysch Arenites (Graywackes); Sepm Society for Sedimentary Geology: Tulsa, OK, USA, 1974; pp. 304–310. [CrossRef]
- 70. Middlemost, E.A.K. Naming materials in the magma/igneous rock system. Earth-Sci. Rev. 1994, 37, 215–224. [CrossRef]
- 71. Miyashiro, A. Volcanic rock series in island arcs and active continental margins. Am. J. Sci. 1974, 274, 321–355. [CrossRef]
- 72. McGonigle, A.J.S.; Oppenheimer, C. Optical sensing of volcanic gas and aerosol emissions. *Geol. Soc. London Spéc. Publ.* 2003, 213, 149–168. [CrossRef]
- 73. Abdel-Karim, A.-A.M.; Ali, S.; El-Awady, A.; Elwan, W.; Khedr, M.Z.; Tamura, A. Mineral and bulk–rock chemistry of Shadli bimodal metavolcanics from Eastern Desert of Egypt: Implication for tectonomagmatic setting and Neoproterozoic continental growth in the Arabian–Nubian Shield. *Lithos* **2019**, *338–339*, 204–217. [CrossRef]
- Ewart, A. The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks; With special reference to the andesitic-basaltic compositional range. *Andesites Orog. Andesites Relat. Rocks* 1982, 26–87.
- 75. Pearce, J.A. Immobile Element Fingerprinting of Ophiolites. Elements 2014, 10, 101–108. [CrossRef]
- Farahat, E. Neoproterozoic arc–back-arc system in the Central Eastern Desert of Egypt: Evidence from supra-subduction zone ophiolites. *Lithos* 2010, 120, 293–308. [CrossRef]
- 77. Azer, M.K. Evolution and Economic Significance of Listwaenites Associated with Neoproterozoic Ophiolites in South Eastern Desert. *Egypt. Geol. Acta* **2013**, *11*, 113–128.
- Abdel-Karim, A.A.M.; Elwan, W.I.; Helmy, H.; El-Shafey, S.A. Spinels, Fe-Ti Oxide Minerals, Apatites and Carbonates Hosted in the Ophiolites of Eastern Desert of Egypt: Mineralogy and Chemical Aspects. *Arab. J. Geosci.* 2014, 7, 693–709. [CrossRef]

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