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The Neoproterozoic Kolet Um Kharit bimodal metavolcanic rocks, south Eastern Desert, Egypt: a case of enrichment from plume interaction?

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Abstract Neoproterozoic metavolcanic rocks of Kolet Um Kharit (KUKh) in the southern Eastern Desert of Egypt have been traditionally regarded as a bimodal island-arc sequence. However, geological and geochemical arguments presented here make this interpretation doubtful. Geochemically, these rocks are classified into mafic (tholeiitic basalts) and felsic (high-K rhyodacites to rhyolites) groups. Both the KUKh mafic and felsic metavolcanic rocks show similar geochemical characteristics, implying a genetic link. They have comparable trace element ratios, such as Zr/Nb (27–30 vs. 20–36), Y/Nb (5.44–6.25 vs. 5.05–5.9), K/Rb (577–1164 vs. 573–937), Ba/La (4.29–25–9 vs. 11.4–16.2), Nb/Yb (1.82–2.03 vs. 1.76–1.99). Similarly both groups have parallel LREE-enriched patterns (La/Yb_{CN} = 2.37–2.81 vs. 2.55–3.17); and negative Nb and Ta anomalies (Nb/La_{pm} = 0.51–0.58 vs. 0.45–0.52 and Ta/La_{pm} = 0.51–0.62 vs. 0.49–0.55). The observed negative Nb and Ta anomalies in the KUKh metavolcanic rocks cannot be attributed to crustal contamination or fractional crystallization. These rocks could represent either a remnant of break-up LIP or were derived from an enriched mantle source containing subduction components beneath an intraoceanic back-arc basin. The recognition of the KUKh rocks as derived from an enriched mantle source revives interest in models that involve enrichment from "plume" interaction during the evolution of the Arabian-Nubian Shield.

Keywords Arabian-Nubian Shield · Egypt · Neoproterozoic · Pan-African · Volcanic geochemistry

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Introduction

The Neoproterozoic Kolet Um Kharit (KUKh) metavolcanic rocks are part of the Arabian-Nubian Shield (ANS). This shield constitutes the northern sector of the East African Orogen (Stern 1994) and is exposed in Arabia, Sinai, Eastern Desert of Egypt, the Red Sea Hills of Sudan, Eritrea and Ethiopia (El Gaby 1994; Abdelsalam and Stern 1996; Stern 2002). Neodymium isotopic evidence indicates that the core region of the ANS comprises juvenile Neoproterozoic crust produced from 870 to at least 690 Ma (Stern 1994; 2002). Lateral crustal growth through arc accretion has been proposed as the main mechanism for the evolution of the ANS (El Gaby et al. 1988; Kröner et al. 1987 1991; Stern 1994). Raymer and Schubert (1986) pointed out, however, that the rate of growth of the ANS exceeds significantly the present rate of addition of juvenile mantle material along subduction margins. They proposed that hot spot (or mantle plume) magmatism may have played an important role in the evolution of the ANS. This idea was further developed by Stein and Hofmann (1994), relating the formation of the juvenile crust in the ANS to major upwelling events in the mantle. According to this model, the plume and subduction models of continental crust growth are reconciled. Neodymium isotopic characteristics of post-orogenic late Neoproterozoic dykes, alkali granite and Phanerozoic alkali basalts from northern ANS was interpreted to result from melting of this previously enriched metasomatized lithospheric mantle (Kessel et al. 1998; Stein 2003). The 854 Ma Nakfa metavolcanic rocks from the southern part of the ANS in Eritrea show trace element characteristics similar to modern arcs coupled with juvenile Neoproterozoic epsilon-Nd values. Teklay et al. (2002) suggested that a mantle plume had enriched the mantle source of these metavolcanics prior the onset of subduction.

Two major volcanic episodes have been recognized in the Neoproterozoic crust of the Nubian shield. Volcanism associated with the first episode produced the 'metavolcanic' sequences including older (800–614 Ma), metamorphosed, and largely mafic rocks (Stern and Hedge 1985; Kröner et al. 1992; Stern 1994). This was succeeded by a younger Neoproterozoic volcanic cycle (614–550 Ma) that produced voluminous volcanic assemblages, referred to as the 'Dokhan volcanic rocks' (e.g. El Ramly 1972)

In Egypt, metavolcanic rocks are widely distributed in the central and southern parts of the Eastern Desert and are rare in the north Eastern Desert (El Gaby 1994). Stern (1979) subdivided these rocks into older and younger metavolcanic rocks. Old metavolcanic rocks (OMV) are considered as part of dismembered ophiolites or form individual ophiolitic fragments in the widespread Eastern Desert mélange. The young metavolcanic rocks (YMV) are part of the island-arc mafic to felsic metavolcanic rocks (Stern 1979). In the field, it is generally difficult to resolve the original tectonic setting of these metavolcanic rocks or to establish their time-space relationships due to rapid lithofacies changes, the complexity of tectono-metamorphic relationships and the nearby emplacement of younger plutons (El Ramly et al. 1982).

Kolet Um kharit metavolcanic rocks (Fig. 1) lie in the northwestern part of the Shadli Metavolcanic Belt (SMB)(El Ramly 1972) in the south Eastern Desert. Among all metavolcanic occurrences in the Egyptian Shield, Shadli metavolcanic rocks are in some ways unique. They constitute the largest metavolcanic exposure (80×25 km and attain a maximum thickness of 10 km (Shukri and Mansour 1980; Stern et al. 1991). The SMB has been traditionally regarded as a bimodal island-arc metavolcanic rocks (e.g. Shukri and Mansour 1980; Hafez and Shalaby 1983; Khudeir et al. 1988). El Ramly et al. (1982) studied the KUKh metavolcanic rocks and found it difficult to evaluate their tectonic setting but accepted an island-arc setting, in spite of the recognition of relatively high TiO_2 contents. Based on a series of geological and geochemical arguments Stern et al. (1991) rejected this hypothesis for metavolcanic rocks from Um Samiuki area (Fig. 1) and suggested a continental rift origin for these rocks.

From the above it is clear that there exist a controversy about whether or not the SMB formed in subduction environment. In this study, new high precision geochemical data have been obtained for 14 samples of both mafic and felsic varieties of KUKh metavolcanics. These data are compared with the correlative metavolcanic rocks from the well-studied Um Samiuki metavolcanic rocks (Stern et al. 1991). The goal is to: (a) interpret the geochemistry of the KUKh metavolcanic rocks using key trace elements (e.g. Nb, Zr, Y, Ta, Th,

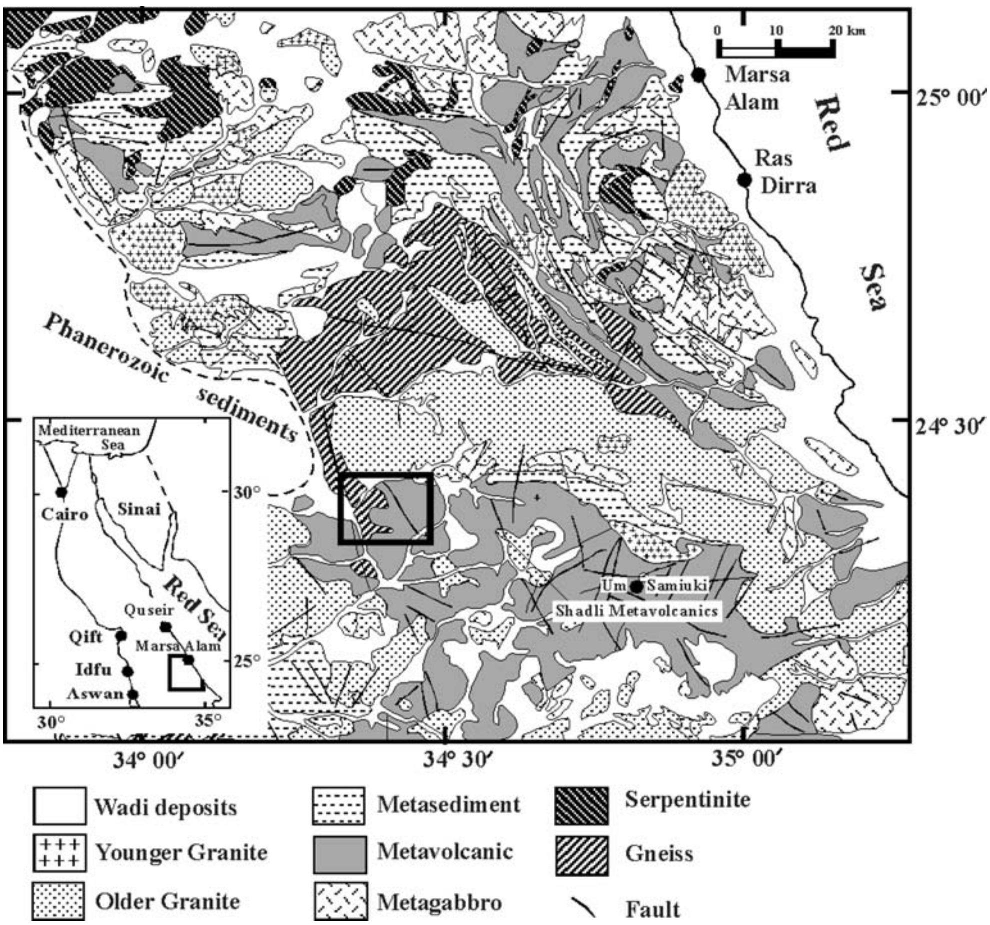

Fig. 1 Generalized geology of part of the South Eastern Desert, Egypt (Anonymous 1981). The *rectangle* shows the location of Fig. 2. The location of the correlative (~710 Ma) metavolcanic rocks from the Um Samiuki area is also shown

Hf and REE); (b) discuss the tectonic environment of origin of these rocks, and (c) investigate possible connection between Neoproterozoic subduction zone volcanism and enriched mantle plume.

Geologic settings

Kolet Um Kharit area is located in the South Eastern Desert (SED), which is one of the three basement provinces defined by Stern and Hedge (1985). The SED contains diverse lithologicies, including gneisses, granitoids, metasedimentary rocks, serpentinites and metavolcanic rocks. U/Pb zircon and Rb/Sr ages range from 800 to 580 Ma (Hashad et al. 1972; Stern and Hedge 1985). Stern and Hedge (1985) concluded that the principal episodes of crustal growth in the SED occurred at 715–700 and 685–665 Ma.

El Ramly et al. (1982) described the metavolcanic rocks of KUKh (see Fig. 2) in detail and showed that they form a bimodal volcanic sequence. The metavolcanic rocks are composed of massive mafic lavas, overlain by a complex suite of cherts, rhyolites and associated pyroclastics (thinly banded tuffs). The contact between metavolcanic rocks and surrounding quartzofeldspathic gneisses in the KUKh area is hidden by wadi sediments. The massive mafic lava units extend further southeast outside the area of Fig. 2 and are associated with metagabbros and together form a dismembered ophiolite sequence (El Ramly et al. 2001). The contact between the felsic metavolcanic rocks and the granite in the southern part of KUKh and Gabal Nasb Um Usheira is sharp (Fig. 2). El Ramly et al. (2001) studied the eastern extension of this granite, outside the mapped area of Fig. 2, and classified it as calc-alkaline (synorogenic) granite. They stated that these granites become mylonitic along the contact with the felsic metavolcanic rocks, marking a shear zone.

The mafic metavolcanics are well exposed in the southern part of the area. Therein, they form low lands and have remarkably sharp contacts with the felsic varieties. The mafic metavolcanic rocks are often cut by quartz veins.

The felsic metavolcanic rocks cover an extensive area constituting KUKh and Gebel Nasb Um Usheira regions. They stand as modest mountain ranges (constituting the highest peak in the area, Gabal Um Kharit 664 m above sea level). In hand specimen, the rocks are compact and gray to red. The associated felsic pyroclastics are found in the northern side of KUKh. Stern et al. (1991) reported Rb/Sr whole rock age of 712 ± 24 Ma for correlative rocks at Um Samiuki. KUKh metavolcanic rocks have identical paleomagnetic pole position to those of El Shadli, implying similar ages (H. Lofty, personal communication, 2004).

Petrography

Mafic rocks The mafic rocks are metamorphosed in greenschist-amphibolite transitional facies (Farahat 2003). They contain hornblende + actinolite + albite + epidote ± chlorite ± biotite ± titanite + ilmenite + magnetite ± calcite ± quartz ± K-feldspar mineral assemblage.

Amphiboles are subhedral to anhedral pale green actinolite to dark green hornblende. The two amphiboles form porphyroblasts that are patchwork of the two phases, in a fine-grained groundmass of plagioclase, commonly albite, epidote and Fe-Ti oxides. Microprobe analyses reveal an abrupt compositional break between the two amphiboles (Farahat 2003). Amphiboles also occur in the groundmass. Plagioclase commonly forms euhedral porphyroblasts and albite twinning is often destroyed by alteration. The porphyroblasts are sometimes corroded and engulf groundmass. Plagioclase is enclosed in large amphiboles, possibly the metamorphic product of an original ophitic texture. Plagioclase porphyroblasts are often highly to moderately transformed

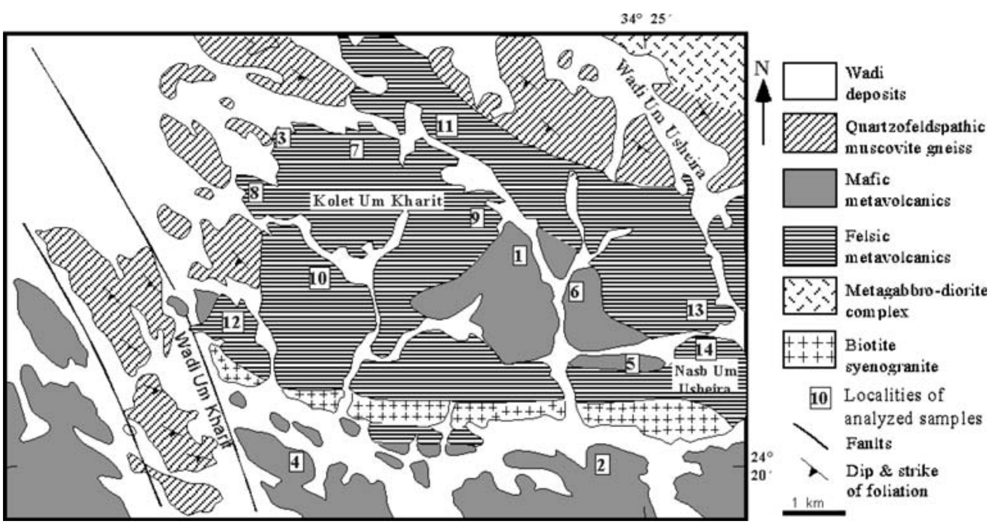

Fig. 2 Geological map of the Kolet Um Kharit area showing sample localities. Simplified from El Ramly et al. (1982)

to epidote. The porphyroblasts are frequently deformed and fractured as indicated by bent twin lamellae. Opaque minerals are Ti-magnetite commonly containing ilmenite lamellae (Farahat 2003).

Felsic rocks The felsic rocks are mostly massive, fine-grained, gray to reddish porphyritic rhyodacites to rhyolites. Plagioclase, K-feldspar, quartz, and biotite occur as phenocrysts and microphenocrysts, set in a fine-grained groundmass of feldspars, quartz, biotite and iron oxides. Plagioclase phenocrysts are euhedral to subhedral and frequently albite twinned. K-feldspars are mainly orthoclase and microperthite intergrowth is rare. Quartz forms subhedral to anhedral phenocrysts with sharp contacts frequently exhibiting wavy extinction and are sometimes embayed by the groundmass. Fine-grained quartz crystals and feldspar laths dominate the groundmass. Brownish-yellow biotites are micro-phenocrysts. Deformation features are evident by the schistose appearance of biotite. Oxide minerals are represented by fine-grained magnetite in the groundmass.

Analytical techniques

Fourteen samples were powdered in an agate mortar and analyzed for major, trace and rare earth element contents at the Activation Laboratories, Ontario (Canada) using Fusion-ICP and Fusion-ICP-MS techniques. Fusion-ICP (Thermo Jarrell-Ash ENVIRO II) has been used to measure major elements and selected trace elements (Ba, Sr, Y, Zr, Sc, Be, V). ICP-MS (Perkin Elmer SCIEX ELAN 6000) was used for the analysis of trace (including Ba, Sr, Y, Zr and V which were measured using fusion-ICP technique) and rare earth elements. Detailed analytical methodology can be found in the *ACTLABS Group* website (http://www.actlabs.com)

Detection limits for major elements are 0.01 wt%, while for trace elements and REE, in ppm, are as follows: Ni, Cr (10); Ga, Y, Nb, Ba (1); Rb, Zr (0.5); Hf (0.2); Sr, Th, U La, Ce, Nd, Sm, Gd, Tb, Dy, Ho, Er, Yb(0.1); Ta, Pr, Eu, Tm (0.05); Lu (0.04). Precision for most elements at the concentration present in the international reference material W2 is between 2% and 4%, relative standard deviations. Chondrite-normalized (e.g. La/Yb_{CN}) and primitive mantle-normalized ratios (e.g. Nb/La_{pm}) are calculated from the values of Sun and McDonough (1989).

Geochemistry

The results of major, trace and rare-earth elements analyses are listed in Table. 1 and 2. Based on SiO_2 contents the samples were divided into mafic (SiO_2 = 48.18 to 49.46 wt%), intermediate (59.94 SiO_2 wt%), and felsic (SiO_2 = 69.46–75.03 wt%) varieties. The trace element content of the intermediate sample is more akin to those of the associated felsic rocks, so it is grouped with felsic rocks. Overall, the KUKh sequence has a bimodal distribution of silica contents, as has been noted previously for the SMB.

In the SiO_2-Nb/Y diagram (Fig. 3a) the KUKh metavolcanic rocks occupy the subalkaline basalts, andesite, rhyodacite-dacite and rhyolite fields, similar to those from Um Samiuki. The silica versus alkalies diagram of Irvine and Baragar (1971; not shown) shows that KUKh rocks are subalkaline. According to Irvine and Baragar (1971) the Al_2O_3 content of the tholeiitic series should be lower than 16%, which is the case of the investigated rocks. The diagram of Peccerillo and Taylor (1976) classifies the KUKh mafic metavolcanic rocks and Basalt I of Stern et al. (1991) as a low-K tholeiitic magma series and the felsic rocks as high-K magma series (Fig. 3b). Basalt II and Um Samiuki felsics are compositionally distinct from KUKh lavas.

The mafic rocks are almost silica undersaturated (48.19–49.46 wt.% SiO_2). Their low MgO (4.35–5.93 wt.%), Mg# (36–45), Cr (66–84 ppm) and Ni (27–89 ppm), indicate extensive fractionation of olivine and pyroxene. Overall, they are characterized by high contents of TiO_2 (2.5–3.2 wt%), Fe_2O_3 (13.3–15 wt%), P_2O_5 (0.51–0.54 wt.%), Ba (55–409 ppm), Sr (282–333 ppm), Y (45–63), Zr (208–331) and Nb (7.92–11 ppm). The felsic rocks (69.46–75.03 wt% SiO_2) have high K_2O (2.9–4.97 wt%), Ba (530–890 ppm), Zr (397–1340 ppm), Y (100–195 ppm) and Nb (19.79–37.14 ppm) and low TiO_2 (O.27–0.54), Al_2O_3 (10.31–12.67), MgO (0.2–0.81 wt%), CaO (0.46–1.85 wt%) and Sr (31–114 ppm). It is noteworthy that both the KUKh mafic and felsic metavolcanic rocks have comparable trace element ratios (Table. 1 and 2), for example, Zr/Nb (27–30 vs. 20–36), Y/Nb (5.44–6.25 vs. 5.05–5.9), K/Rb (577–1,164 vs. 573–937), Ba/La (4.29–25–9 vs. 11.4–16.2), Nb/Yb (1.82–2.03 vs. 1.76–1.99) and negative Nb and Ta anomalies (Nb/La_{pm} = 0.51–0.58 vs. 0.45–0.52 and Ta/La_{pm} = 0.51–0.62 vs. 0.49–0.55). The mafic suite of KUKh metavolcanic rocks is remarkably similar to "basalt I" of Stern et al. (1991) from Um Samiuki. Both have high TiO_2 (2.53–3.16 vs. 2.28 wt%), K/Rb (577–1,164 vs. 1,660–3,250) and low Al_2O_3 (13.26–14.36 vs. 13.59–14.3 wt.%), K_2O (0.26–0.68 vs. 0.25–0.29 wt.%) and Ba/La (4.29–25.9 vs. 7). Stern et al. (1991) distinguished "Basalt I" from more primitive lower TiO_2 "Upper basalt" or "Basalt II", which is not recognized in KUKh area. Also, the KUKh felsics are significantly more enriched in potassium than are the Um Samiuki felsics (Stern et al. 1991).

Absolute REE concentrations of KUKh metavolcanic rocks increase with increasing silica content (Fig. 4 and Table 2), with a compositional gap between the mafic and felsic rocks. The REE patterns are generally parallel to subparallel. All samples are LREE-enriched (La/Yb_{CN} = 2.37–2.81 vs. 2.55–3.17). The felsic lithologies exhibit significant negative Eu-anomalies (Eu/Eu^* = 0.39–0.61). Early fractionation of feldspars may be responsible for the negative Eu-anomalies.

Table 1 Major and trace element geochemical analyses data of KUKh rocks (*ND* not detected)

Rock Type	Basic							Inter.	Acidic					
Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Major elements (wt.%)														
SiO_2	49.18	48.78	48.19	49.18	49.46	48.93	48.89	59.94	70.98	71.45	71.23	69.46	74.82	75.03
TiO_2	2.53	2.72	2.56	2.87	3.16	2.55	2.58	1.67	0.44	0.48	0.43	0.54	0.28	0.27
Al_2O_3	13.60	14.06	14.36	13.76	13.26	13.98	14.22	12.95	12.24	12.34	12.11	12.67	10.60	10.31
Fe_2O_3	13.26	14.24	13.75	14.72	15.14	13.51	14.30	9.31	4.38	4.19	4.39	4.03	3.70	3.35
MnO	0.20	0.19	0.19	0.20	0.22	0.20	0.17	0.12	0.10	0.09	0.09	0.08	0.06	0.05
MgO	4.72	5.48	5.82	5.14	4.35	5.27	5.93	2.62	0.35	0.60	0.34	0.81	0.20	0.23
CaO	8.61	7.10	6.99	7.21	7.93	7.80	6.48	4.51	1.64	1.45	1.19	1.85	0.49	0.46
Na_2O	2.87	3.70	3.91	3.48	3.97	3.36	2.99	2.95	4.56	4.57	4.58	4.52	2.31	2.00
K_2O	0.58	0.38	0.26	0.50	0.68	0.41	0.31	1.99	2.90	2.93	3.04	2.91	4.39	4.97
P_2O_5	0.51	0.54	0.54	0.54	0.54	0.51	0.53	0.40	0.12	0.14	0.11	0.17	0.05	0.06
LOI	2.45	2.55	2.76	2.54	1.67	2.60	3.82	2.36	1.64	1.54	1.11	1.88	1.87	1.91
TOTAL	98.51	99.73	99.33	100.12	100.39	99.12	100.22	98.83	99.35	99.78	98.61	98.90	98.75	98.64
Mg#	41.4	43.3	45.6	40.9	36.3	43.6	45.1	35.8	13.7	22.1	13.3	28.5	9.7	12.0
Trace elements (ppm)														
Sc	36	32	30	34	42	33	29	17	6	6	6	7	2	2
Be	2	2	2	2	2	2	1	2	4	4	4	4	5	5
V	284	191	259	320	393	282	243	142	13	17	14	34	9	15
Cr	66	77	84	70	70	76	78	20	26	22	20	20	20	20
Co	31	41	40	42	36	36	46	21	2	4	2	6	2	3
Ni	29	66	75	55	27	54	89	20	50	n.d.	15	n.d.	n.d.	n.d.
Cu	54	52	35	68	78	46	61	49	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	120	134	133	132	146	125	116	147	180	162	184	111	207	207
Ga	21.32	20.11	18.64	21.51	22.79	20.35	20.20	25.70	25.40	26.21	27.77	22.71	25.64	24.64
Ge	1.61	1.10	1.51	1.03	1.93	1.54	1.01	1.51	1.39	1.15	1.37	1.66	1.18	1.42
As	n.d.	6.07	6.04	6.14	5.00	5.82	7.53	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	7.59	5.43	2.66	6.24	9.19	4.93	2.21	36.95	25.99	27.13	30.25	42.19	52.27	44.05
Sr	333	300	317	284	291	325	282	311	97	95	86	114	31	37
Y	60	50	46	54	63	53	45	133	142	125	142	100	195	175
Zr	298	241	214	268	331	256	208	809	836	702	842	397	1340	1150
Nb	11.02	8.00	7.92	9.02	11.00	8.97	7.41	23.45	24.08	22.01	27.52	19.79	37.14	31.96
Sn	2.49	2.54	1.76	3.01	2.75	2.18	1.96	5.64	6.37	6.81	7.01	6.61	9.79	9.11
Sb	0.68	0.71	1.29	0.12	0.77	0.95	1.10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.61
Ba	409	285	349	221	205	379	55	434	760	675	734	536	890	870
Hf	7.28	5.70	5.07	6.40	7.92	6.20	4.90	19.51	17.89	16.90	20.73	11.48	32.17	27.29
Ta	0.63	0.51	0.48	0.60	0.68	0.61	0.41	1.47	1.47	1.40	1.65	1.35	2.20	1.95
Tl	0.20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.19	0.15	0.11	0.15	0.20	0.34	0.30
Pb	258	1653	2790	669	608	1520	717	5120	542	512	353	532	220	1550
Bi	n.d.	0.30	0.32	0.36	0.35	0.21	0.24	0.30	0.25	0.33	n.d.	n.d.	n.d.	0.53
Th	1.22	0.61	0.50	0.79	1.20	0.90	0.46	3.40	3.85	4.11	4.19	4.89	5.73	4.50
U	0.40	0.23	0.18	0.31	0.44	0.23	0.17	1.27	1.50	1.50	1.56	1.71	2.30	1.86
Rb/Zr	0.03	0.02	0.01	0.02	0.03	0.02	0.01	0.05	0.03	0.04	0.04	0.11	0.04	0.04
K/Rb	634	577	812	656	614	690	1164	447	926	897	834	573	697	937
Zr/Nb	27.04	30.13	27.02	29.71	30.09	28.54	28.07	34.50	34.72	31.89	30.60	20.06	36.08	35.98
Y/Nb	5.44	6.25	5.81	5.99	5.73	5.91	6.07	5.67	5.90	5.68	5.16	5.05	5.25	5.48
Th/Nb	0.11	0.08	0.06	0.09	0.11	0.10	0.06	0.14	0.16	0.19	0.15	0.25	0.15	0.14

Discussion

Mobility of elements

A general consensus exists that transition metals (e.g. Cr, Ni), REE, high field strength elements (HFSE) as well as Th and Ti are relatively immobile during low-temperature alteration (Staudigel et al. 1996). N-type MORB normalized incompatible trace element concentrations for the KUKh rocks have been plotted as multi-element patterns in Fig. 5. The normalized patterns of the HFSE, Ta, Nb, Ti, Zr, Hf, Y and heavy rare earth elements (HREE), fall within a consistently narrow range and relatively smooth, parallel to subparallel patterns. These incompatible element profiles suggest that, despite metamorphism, most of the HFSE, along with REE, have remained largely intact. Indeed, KUKh mafic metavolcanics have Th/Nb ratios (0.09 ± 0.02, Table 1) close to the primitive mantle value of 0.117 (Sun and McDonough 1989). In addition, Nb/La_{pm} and Th/La_{pm} do not show any correlation with either Eu/Eu* or LOI (Table. 1 and 2), suggesting that alteration and/or metamorphism had not disturbed the primary Th-Nb-LREE concentrations in the rocks. However, the large ion lithophile elements (LILE) such as Ba, Rb and K show variable concentrations (Fig. 5), implying that their original concentrations were probably changed by alteration and/or metamorphism. Nevertheless, Ba, K, and Rb contents are used to quantify the LILE enrichment in the KUKh rocks. This is

Table 2 REE data of the KUKh rocks.

Rock Type	Basic							Inter.	Acidic					
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
La	21.3	15.3	13.5	17.1	21.1	17.4	12.8	48.2	46.9	46.3	52.1	43.9	78.0	68.5
Ce	54	40	36	44	54	45	34	122	127	124	136	105	192	168
Pr	7.7	6.0	5.4	6.5	7.9	6.6	5.2	17.1	16.2	15.9	17.8	13.7	26.4	23.5
Nd	37.3	29.8	27.2	32.4	38.4	32.2	26.4	76.8	72.1	69.1	79.0	58.8	119.4	105.0
Sm	9.5	7.8	7.2	8.3	9.7	8.4	6.9	19.1	17.4	16.8	19.4	13.5	28.7	25.6
Eu	2.54	2.42	2.34	2.50	2.68	2.45	2.32	3.64	3.42	3.11	3.66	1.67	4.19	3.75
Gd	9.1	7.6	7.1	8.1	9.4	8.1	6.9	18.1	16.8	16.1	18.4	12.6	27.4	23.8
Tb	1.7	1.5	1.4	1.6	1.8	1.5	1.3	3.6	3.4	3.1	3.8	2.5	5.5	4.7
Dy	10.3	8.7	8.0	9.3	11.0	9.1	7.7	21.4	21.0	19.9	23.2	15.9	33.7	28.5
Ho	2.1	1.8	1.6	1.9	2.2	1.9	1.6	4.5	4.5	4.3	4.9	3.3	7.1	6.1
Er	6.2	5.0	4.7	5.4	6.4	5.5	4.5	13.6	13.8	12.9	15.1	10.2	21.5	18.6
Tm	0.86	0.70	0.65	0.75	0.90	0.76	0.60	1.95	2.07	2.01	2.25	1.59	3.19	2.81
Yb	5.4	4.4	4.1	4.7	5.6	4.8	3.7	12.4	13.2	12.5	14.2	9.9	19.9	18.1
Lu	0.83	0.66	0.62	0.71	0.85	0.72	0.56	1.86	2.03	1.89	2.19	1.53	3.10	2.75
Eu/Eu*	0.83	0.96	0.99	0.93	0.86	0.91	1.03	0.60	0.61	0.58	0.59	0.39	0.46	0.46
La/Yb_{CN}	2.81	2.50	2.37	2.61	2.71	2.60	2.48	2.80	2.55	2.65	2.64	3.17	2.81	2.71
Ba/La	19.21	18.64	25.90	12.92	9.70	21.78	4.29	9.00	16.21	14.58	14.08	12.2	11.4	12.7
Nb/Yb	2.03	1.82	1.94	1.92	1.96	1.87	1.99	1.90	1.83	1.75	1.94	1.99	1.87	1.76
Nb/La_{pm}	0.51	0.52	0.58	0.52	0.52	0.51	0.57	0.48	0.51	0.47	0.52	0.45	0.47	0.46
La/Nb_{pm}	1.95	1.92	1.71	1.91	1.94	1.95	1.74	2.07	1.96	2.12	1.91	2.24	2.12	2.16
Th/La_{pm}	0.48	0.34	0.31	0.39	0.48	0.44	0.30	0.59	0.69	0.75	0.68	0.94	0.62	0.55
Ta/La_{pm}	0.51	0.58	0.62	0.61	0.55	0.61	0.55	0.53	0.54	0.52	0.55	0.53	0.49	0.49

justified by the very good linear correlation between the immobile Th and the fluid mobile Rb (R^2 = 0.97); K (R^2 = 0.95) and the fairly good linear correlation between Th and Ba (R^2 = 0.89).

Petrogenetic Interpretation

Mafic metavolcanic rocks

The bimodal nature of the KUKh magmatism is evident as the metavolcanic rocks have basalt and rhyodacite to rhyolite compositions (Fig. 3a). The enrichment in LREE recorded in KUKh rocks (Fig. 4) can be produced by melting of an enriched LREE mantle source and/or assimilation of continental crust. The basalt trace element patterns (Fig. 5) similar to those of within-plate basalts (Pearce 1982). This is in contrast to island-arc rocks, which exhibit distinctive patterns of enrichment in LILE (Sr, K, Rb, Ba and Th) and/or LREE and depletion in HFSE (Zr, Hf, Ti and Nb) relative to N-MORB (Pearce 1982). However, KUKh rocks exhibit modest negative anomalies of Nb and Ta (Fig. 5), characteristic of subduction-related rocks, excepting rare Nb-enriched basalts (Pearce and Peate 1995; Hollings and Kerrich 2004). Such depletion in Nb and Ta is, however, not exclusive to subduction related rocks. Crustal contamination and solid-melt equilibria during partial melting and/or fractional crystallization can also lead to significant negative anomalies in Nb and Ta (Wilson 1989). Nb–Ta depletions are also found in some continental flood basalt provinces (Kerr et al. 2000).

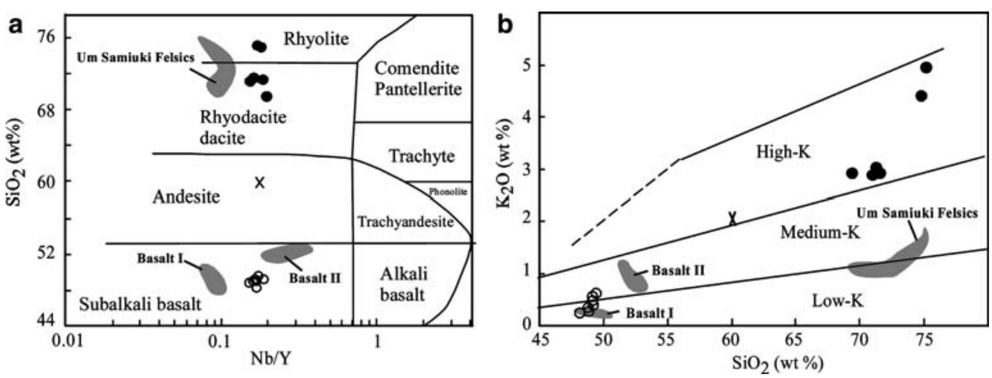

Fig. 3 **a** SiO_2 vs. Nb/Y (Winchester and Floyd 1977) and **b** SiO_2 vs. K_2O (Peccerillo and Taylor 1976) diagrams showing geochemical classification of the KUKh metavolcanic rocks. Also shown the fields of the Um Samiuki metavolcanic rocks (Stern et al. 1991). Symbols: *open circles* mafic samples; *X* intermediate sample; *closed circles* felsic samples. The intermediate sample is treated with the felsic rocks, see text for explanation

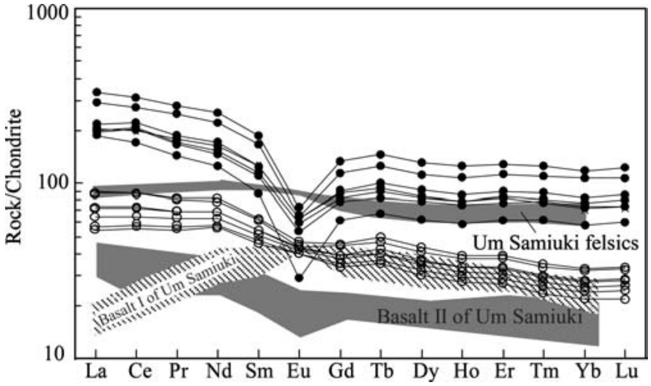

Fig. 4 Chondrite-normalized REE patterns of the KUKh metavolcanic rocks compared to those from the Um Samiuki (Shaded fields). Normalization values used are taken from Sun and McDonough (1989). Symbols as in Fig. 3

Th/Yb versus Ta/Yb diagram of Pearce (1983) (Fig. 6a) is useful in discriminating depleted from enriched mantle sources and also in separating crustal and subduction-related from mantle components in the petrogenesis of the magmas (Keskin et al. 1998; Aldanmaz et al. 2000). Yb is used as denominator in these ratios, eliminating variations due to partial melting and fractional crystallization processes, allowing attention to be focused on source variations and crustal assimilation. Basaltic magmas derived from depleted MORB mantle, plume asthenosphere or mantle lithosphere, all lie within a diagonal mantle array defined by constant Th/Ta ratios. However, source region metasomatism by subduction processes enriches Th with respect to Ta and consequently increases Th/Yb relative to Ta/Yb, as subduction components in general carry Th but not Ta or Yb. Crustal contamination may also increase Th/Yb relative to Ta/Yb because of higher abundances of Th relative to Ta in continental crust.

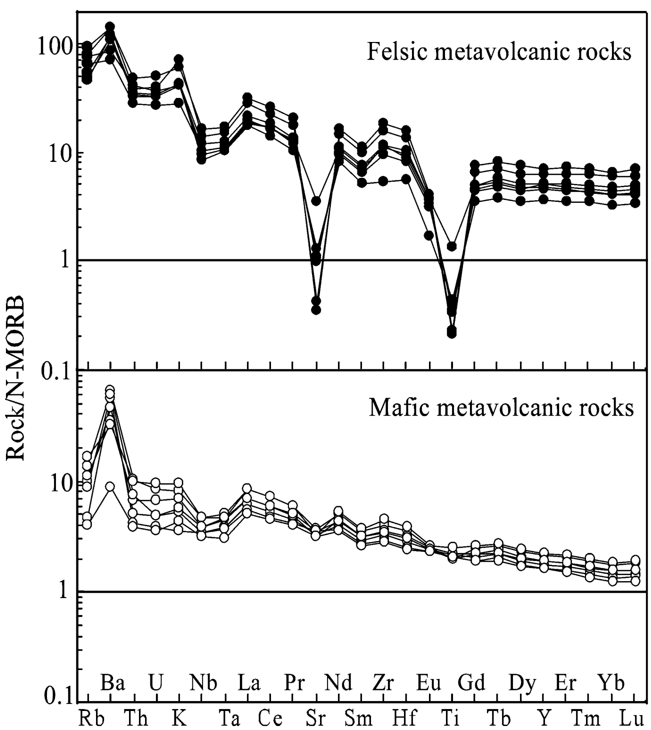

Fig. 5 N-MORB normalized patterns for the KUKh metavolcanic rocks. N-MORB normalizing values are from Sun and McDonough (1989). Symbols as in Fig. 3

Figure 6a shows that KUKh mafic samples fall into parts of the mantle array between depleted (MORB) and mildly enriched mantle sources, with some samples displaced to slightly higher Th/Yb. This may reflect a modest influence of subduction-zone fluids. Similarly, on Y/Nb versus Zr/Nb diagram (Fig. 6b) the investigated mafic rocks plot on an apparent mixing trend between enriched (OIB) source and depleted (MORB) source components, with an affinity to the latter. "Basalts I" from the Um Samiuki area show a similar correlation, while "Basalt II" plot close to the enriched source component.

Although the effects of crustal contamination on magma composition are difficult to distinguish from those of metasomatism by subduction processes, plotting the investigated rocks within and near the depleted end of the oceanic mantle array provides evidence that crustal contamination was not important, because contaminated basalts usually plot above the enriched mantle source (Wilson 1989). The presence of chert and the paucity of terrigneous sediments in KUKh area argue in favor of an intraoceanic setting. Support for lack of significant crustal contamination is also provided by the neodymium isotopic data from Um Samuiki metavolcanic rocks which indicate initial epsilon-(Nd) of +6.3 to +7.8 at ~710 Ma and $^{87}Sr/^{86}Sr$ of 0.7022 ± 1 (Stern et al. 1991). These data are similar to those found for Abu Hammamid concentrically-zoned mafic-ultramafic intrusion (epsilon Nd = +6.9 to +7.7 at ~735 Ma), which intrude the SMB (Helmy et al. 2005; E. S. Farahat and H. M. Helmy, in preparation). Moreover, U/Pb and Rb/Sr geochronological data for the Neoproterozoic basement rocks from the Eastern Desert of Egypt (Stern and Hedge 1985) indicate that crustal contamination is insignificant. They suggested, instead, that these rocks were generated via melting of metasomatically enriched mantle. Also, if large scale anatexis of continental crust was important, this should be evident in the felsic lavas, which have trace element ratios that are identical to the mafic lavas. This argues that fractionation was more important than anatexis. Consequently, contamination by continental crust is not considered to be important for the magmatic evolution of KUKh metavolcanics.

In spite of the fact that the investigated mafic rocks may have been derived from a mildly enriched source, their depletion in compatible elements (e.g. Cr and Ni) relative to incompatible ones (Table 1) indicates significant fractionation of olivine and pyroxene. The fractionation of these phases during magmatic differentiation cannot account for depletion in Nb and Ta,

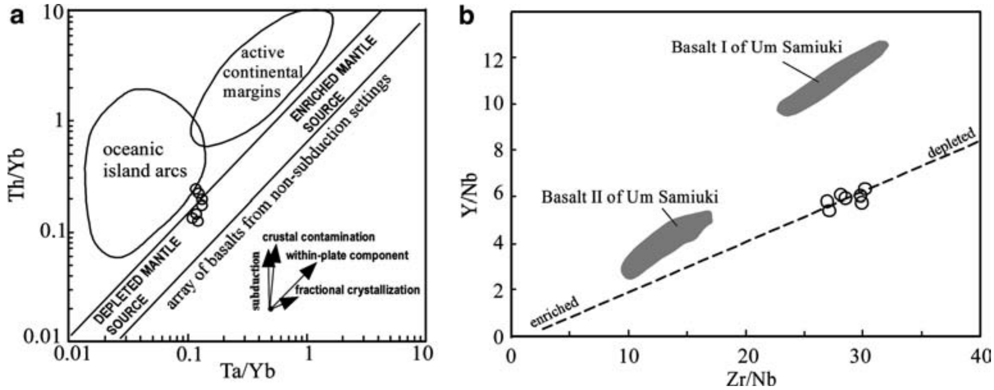

Fig. 6 **a** Th/Yb vs. Ta/Yb diagram of the KUKh mafic rocks (Pearce 1983) and **b** Variation of Y/Nb vs. Zr/Nb for the KUKh mafic metavolcanic rocks compared with those from the Um Samiuki area (*shaded fields*). The *dashed line* represents a mixing trend between enriched and depleted source components (Wilson 1989)

because these are incompatible relative to both olivine and pyroxene. On the other hand, titanate phases like Fe–Ti oxides and titanite tend to sequester Nb and Ta (Ryerson and Watson 1987). The magnitude of negative Nb and Ta anomalies does not correlate with TiO_2, Fe_2O_3 or Mg number (Table. 1 and 2), and consequently does not appear to be a function of fractional crystallization of Fe-Ti oxides. Thus, the observed negative Nb and Ta anomalies for KUKh mafic metavolcanics reflect the influence of subduction zone metasomatism. This is consistent with the recognition of a concentrically-zoned mafic-ultramafic intrusion in the SMB. The morphology and the rock assemblages of the Abu Hammamid mafic-ultramafic intrusion (Helmy et al. 2005; E. S. Farahat and H. M. Helmy, in preparation) resembles Alaskan-type intrusions which are Phanerozoic intrusive rocks formed above subduction zones. A Neoproterozoic north–west dipping subduction zone to the south of SMB was proposed by Schandelmeier et al. (1994).

Given that the KUKh mafic metavolcanic rocks may have formed in a subduction-related tectonic environment, LILE and LREE enrichment are the subduction derived components, whereas HFSE are inherited from the mantle (Hawkesworth et al. 1993; Pearce and Peate 1995). Due to their low solubility in aqueous fluids, HFSE have been used to constrain the composition, and enrichment or depletion history of the mantle source (Woodhead et al. 1993; Pearce el al. 2000). As a result, high abundances of HFSE for the KUKh mafic rocks with respect to N-MORB may be explained by the melting of an enriched mantle source containing subduction components.

Felsic metavolcanic rocks

The petrogenesis of the KUKh felsic metavolcanic rocks is enigmatic. The overall N-MORB normalized patterns (Fig. 5) of these rocks are broadly similar to those of the mafic metavolcanic rocks in terms of having moderate negative Nb and Ta anomalies and positive Ba anomalies. However, they are distinguished by far more LILE enrichment. On Nb versus Y diagram (Fig. 7a) KUKh felsic samples fall into the within plate granite field. Also, almost all samples of the felsic rocks straddle or are close to the boundary between within plate and oceanic ridge granite on Ta versus. Yb diagram (Fig. 7b). Additionally, the felsic metavolcanic rocks possess striking negative anomalies of Sr and Ti. They are strongly enriched in LREE (>100 times chondrite), with marked negative Eu anomalies (<0.7) and have generally flat HREE profiles (Fig. 4), which is similar to within-plate (A-type) granite. Their subalkaline nature and similarity to the mafic volcanic rocks does not support such a setting. In most of the KUKh samples, there is no systematic variation in K/Rb and Rb/Zr (Table 1). Variations in these ratios are usually attributed to crustal contamination by assimilation fractional crystallization processes (AFC) (Davidson 1987).

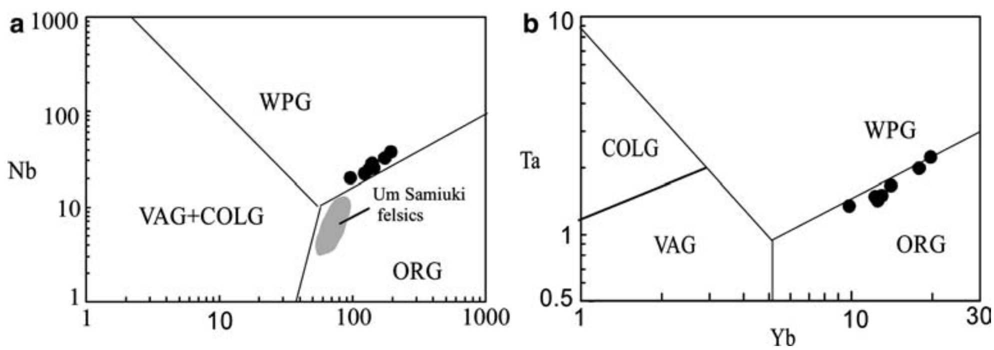

Fig. 7 Ta vs. Yb **a** and Nb vs. Y **b** diagrams for felsic rocks (Pearce et al. 1984). *WPG* within plate granite; *ORG* ocean-ridge granite; *VAG* volcanic arc granite; *COL* collision-related granite. The field of Um Samiuki felsic rocks is shown

The felsic metavolcanic rocks may represent fractionation of mafic melts. Several geochemical lines of evidence support such an interpretation, including: (1) the felsic rocks have higher concentrations of incompatible elements K_2O, Rb, Nb, Y and Th and lower concentrations of compatible elements Al_2O_3, CaO, MgO, $Fe_2O_3^t$, P_2O_5, TiO_2, Cr, and Sr compared to the associated mafic rocks; (2) The depletion in Sr and Ti, observed on MORB-normalized patterns (Fig. 5), probably was caused by plagioclase and Ti-magnetite fractionation, respectively; (3) the parallel mafic and felsic REE patterns (Fig. 4) with increasing total REE contents and Eu anomalies (decreasing Eu/Eu*) with increasing SiO_2 (Table. 1 and 2); (4) the nearly colinear variations in incompatible element pairs (Fig. 8a–c); (5) La/Sm data (Fig. 8d) plot along a horizontal line, which is a feature restricted to the process of fractional crystallization (FC) (Allegre and Minster 1978).; and (6) similar trace element ratios Zr/Nb, Y/Nb, K/Rb, Ba/La, Nb/Yb.

Geodynamic Setting

The presented MORB-normalized spidergrams and REE patterns revealed that KUKh metavolcanic rocks were not developed in a typical island-arc environment. Most of these rocks represent subduction-related to within-plate basalts. Similar tectonic settings have been inferred for the late Neoproterozoic Dokhan volcanics (614–550 Ma; Stern and Gottfried 1986; Moghazi 2003). Abdel Rahman (1996) argued, however, that the Dokhan volcanic suite is a typical calc-alkaline orogenic complex and exhibits mineralogical-geochemical traits of arc-related volcanism. MORB to within-plate basalts tectonic setting, has been recorded for the amphibolite inclusions in the older (i.e. infrastructure) gneisses (e.g. Neumayer et al. 1996). The infrastructure essentially comprises the gneisses and metasedimentary cover exposed in the basement domes and is considered as a pre-Pan-African (continental) crustal basement (El Gaby 1994), but this interpretation is controversial because of the abundance of Neoproterozoic crust in the region. Additionally, in contrast to the massive nature and monometamorphic evolution of KUKh mafic rocks, the older amphibolites are polymetamorphosed up to the amphibolite facies, commonly foliated and occasionally migmatized.

Bimodal suites from continental collision zones (e.g. Buket and Temel 1998; Aranda-Gomez et al. 2003) show geochemical characteristics similar to those of KUKh volcanics. However, such a tectonic setting of origin for the KUKh metavolcanic rocks is inconsistent with the above suggested intraoceanic setting for these rocks and the presence of Alaskan-type complex in the ~710 Ma SMB. Moreover, this hypothesis is incompatible with the geological framework which has been established for the Eastern Desert. The metamorphic event between 650–620 Ma (Finger and Helmy 1998) has been interpreted as a probable collision during

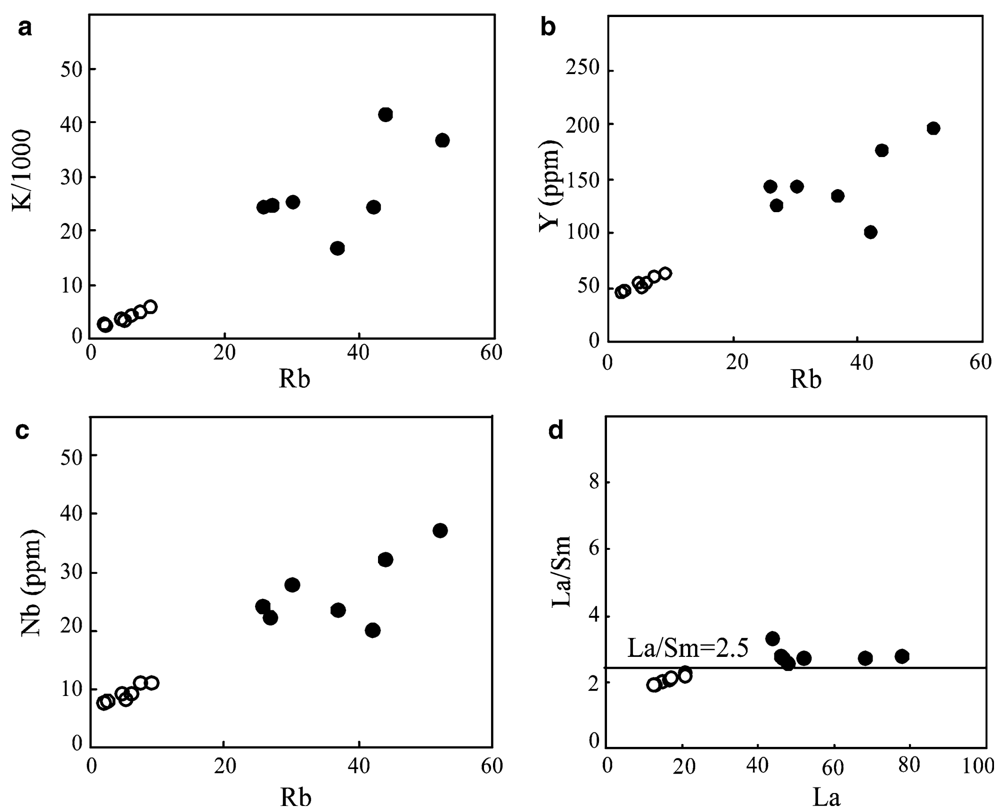

Fig. 8 Rb vs. K, Y, and Nb (**a**, **b**, and **c**) and La vs. La/Sm (**d**) for the KUKh metavolcanic rocks. Notice the linear trends in incompatible (Rb) vs. incompatible (K, Y, and Nb). However, there is no significant variation in La/Sm. Symbols as in Fig. 3

which the Neoproterozoic terranes were sutured to the East Saharan Craton.

From the existing field and geochemical data of the mafic rocks, three alternative tectonic settings can be deduced: (a) oceanic plateau, (b) continental rift or Large Igneous Province (LIP), and (c) back-arc basin.

Stein and Goldstein (1996) have suggested that oceanic plateaus may have been an important component in continent growth of the ANS. According to Kerr et al. (2000) the salient features of oceanic plateaus are as follows: thick sequence (~5 km) of basalts; the occurrence of high-MgO lavas (picrites and komatites); chemically homogeneous basalts with relatively flat chondrite-normalized REE patterns and low $La/Nb_{pm} < 1.1$; pillowed lavas; low abundance of volcanoclastic deposits; lack of sheeted dyke complex. Generally, the geological discriminantes of oceanic plateaus in the ancient terranes may be ambiguous. However, the geochemistry of KUKh mafic rocks, LREE-enriched and high La/Nb_{pm} (1.7–2, Table 2), do not meet well with those of oceanic plateaus as defined by Kerr et al. (2000). It is important to note that the chemical features of Um Samiuki rocks (Stern et al. 1991), nearly flat REE patterns ($La/Yb_{CN} =$ 0.80 and 0.81 for Basalt I and 1.29–1.65 for Basalt II, Fig. 5), and La/Nb_{pmn} ratios (0.79–1 for Basalt I and 1.12–1.48 for Basalt II) are more akin to those of oceanic plateaus. Furthermore, the thick sequence of these metavolcanic rocks (~ 10 km), low abundance of volcanoclastic deposits; lack of sheeted dyke complexes and their pillowed forms are most consistent with the suggestion that they represent an oceanic plateau.

The bimodal composition and the enrichment in HFSE and LREE all point that the KUKh rocks were formed in a continental rift or LIP environment. Stern et al. (1991) rejected the hypothesis that the bimodal (~710 Ma) Um Samiuki metavolcanic rocks, about 50 km to the east of the KUKh metavolcanics and to which they may be related, were formed at a subduction-related environment. Instead, they proposed that the field and geochemical data are most consistent with the hypothesis that these rocks were erupted in a continental rift environment not associated with a convergent margin, in a manner similar to the Rio Grand Rift or Afar Triangle. The Afar rift volcanic assemblage in Ethiopia appears to represent a modern analogue to the KUKh metavolcanic lithologies. Several lines of evidence show the striking similarities between the KUKh mafic volcanics and those of the Afar rift. These include: (1) both are enriched in incompatible elements including the REE; (2) volcanic assemblages from both regions are generally subalkaline; (3) primary magmas of the investigated mafic rocks and those of the Ethiopian sector of East African rift have been interpreted to be from a MORB, to slightly enriched mantle source. Therefore, the possibility that KUKh metavolcanics represent a remnant of a flood basalt province of break-up LIP cannot be ruled out.

On the other hand, plotting of KUKh mafic metavolcanic rocks closer to the oceanic-arc basalt field than to continental–arc basalts on the Th/Yb versus Ta/Yb diagram (Fig. 6a) suggests that they probably developed in an intraoceanic arc setting. Also, the higher Th/Yb of some of these samples, in addition to negative Nb and Ta anomalies ($Nb/La_{pm} = 0.51–0.58$ and $Ta/La_{pm} = 51–62$, Table 2) and the presence of Alaskan-type intrusion in the SMB, may reflect subduction effect. Therefore, the formation of these rocks in subduction-related settings is likely. The relative depletion of Nb relative to La observed in the KUKh mafic volcanics is not as large as the depletion found in typical island-arc basalts ($Nb/La_{pm} = 0.27$, Hawkesworth et al. 1991). The overall incompatible elements enrichment and Nb and Ta negative anomalies of the investigated rocks on MORB-normalized diagram (Fig. 5) are characteristic features of continental-side (ensialic) back-arc basins (Saunders and Tarney 1984). Farahat et al. (2004) recognized such tectonic setting for Wadi Beririq, Gabal Ghadir and Wadi Ghadir ophiolite sequences, central Eastern Desert of Egypt. However, as previously discussed, the geochemical features of KUKh metavolcanic rocks suggest an intraoceanic setting, with no direct contamination from continental crust. It is therefore proposed that these rocks were most probably derived from an enriched mantle source containing subduction components beneath an intraoceanic back-arc basin. The absence of subaqueous lava, gabbros and ultramafic rocks that might make KUKh metavolcanic rocks part of an ophiolite sequence and the presence of volumetrically important felsic lavas, although bimodal volcanism is recognized in some back-arc basins (Condie 1986), argue against such a model. Nevertheless, the possibility that KUKh rocks were formed in back-arc basin cannot also be ruled out.

Implications and conclusions

The recognition of KUKh rocks as derived from an enriched mantle source, whatever in LIPs or marginal basin settings, revives interest in models that involve enrichment from ‘‘plume’’ interaction during the evolution of ANS. The interpretation that KUKh rocks may represent an oceanic plateau or LIP is consistent with the model suggested by Stein and Goldstein (1996) and Stein (2003) for the evolution of the ANS. They have ascribed the high growth rate of the ANS to the rise of a plume head to the shallow mantle in the early Neoproterozoic history of the ANS (~900–870 Ma), leading to the production of an enriched ‘‘plume mantle’’ and oceanic plateaus. The enriched ‘‘plume mantle’’ was later transformed by the subduction mechanism into continental crust and lithospheric mantle during the island-arc activity stage between ~870–650 Ma. It is clear that the age of the SMB is consistent with the time of active subduction and crust formation in the ANS.

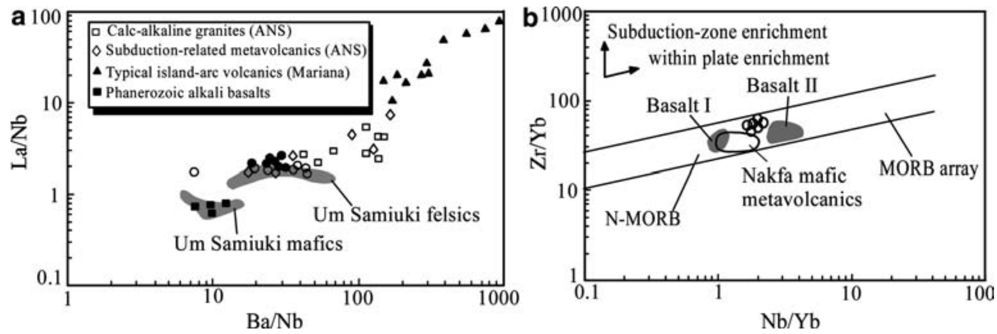

Fig. 9 **a** KUKh and Um Samiuki metavolcanics and other ANS igneous rocks in the Nb/La vs. Ba/Nb variation diagram. Note that the KUKh metavolcanics, similar to the subduction-related magmas from the ANS, lie between the plume material (manifested by the Phanerozoic alkali basalt) and typical island-arc volcanics from Mariana island-arc. The mafic metavolcanic rocks of the Um Samiuki overlap with the plume material. Symbols for KUKh rocks as in Fig. 3. (Data from: Kessel et al. 1998; Stein and Hofmann 1992, Woodhead 1988) **b** Nb/Yb vs. Zr/Yb variation diagram for the KUKh mafic rocks compared with those of (~710 Ma) Um Samiuki metavolcanic rocks and (850 Ma) Nakfa arc rocks from north Eritrea (Teklay et al. 2002). MORB-array and N-MORB are from Pearce and Peate (1995) and Hofmann (1988), respectively

Derivation from ''enriched'' mantle is suggested for Neoproterozoic subduction-related magmas from the north ANS (Stein and Goldstein 1996) and the south ANS (Teklay et al. 2002). Ba/Nb vs. La/Nb variation diagram has been used by Stein (2003) to illustrate the transition from the enriched ''plume'' mantle to the subduction environment for the ANS calc-alkaline magma sources. The subduction-related metavolcanic rocks and calc-alkaline granites from the ANS (Stein 2003), together with the KUKh metavolcanic rocks, occupy the field between the plume material (manifested by the Phanerozoic alkali basalts, which are close to the ANS ''plume mantle'' composition) and typical Cenozoic island-arc volcanics from Mariana island-arc (Fig. 9a). The KUKh metavolcanic rocks overlap in the diagram with subduction-related metavolcanics and calc-alkaline granites from the ANS, implying genetic linkage. It is noteworthy that the extreme depletion in Nb in the typical island-arc volcanics finds no counterparts in the ANS inventory, suggesting the importance of plume materials (Stein 2003). This may also account for the moderate negative Nb anomalies observed on the N-MORB-normalized spidergram (Fig. 5).

Teklay et al. (2002) used Nb/Yb versus Zr/Nb diagram to resolve the question of whether the enrichment of the mantle source from which the 854 Ma Nakfa metavolcanic rocks from the southern ANS in Eritrea took place before or after the subduction component was added (i.e. was it the slab-derived fluid or OIB-like silicate melts that were responsible for the enrichment of the mantle source?). In this diagram (Fig. 9b), the KUKh mafic metavolcanic rocks, like those of Nakfa, are aligned along the MORB-OIB array. Figure 9b indicates that for the KUKh mafic rocks Zr and Nb are not present in significant contributions in the subduction component. Moreover, the shifts towards high Nb/Yb and Zr/Yb ratios than average N-MORB indicate a contribution from melt enriched in incompatible element as observed in OIB-type mantle source. This further confirms the conclusion that the KUKh rocks, are derived from an enriched mantle source with an additional enrichment of LILE induced by slab-derived fluids. According to Teklay et al. (2002) there may be areas beneath the oceanic crust where trace element enriched mantle persists at sufficiently shallow levels to be present in the mantle beneath some oceanic arc systems. This would be possible only if subduction took place beneath the source of trace element enriched OIB. Enrichment of the mantle wedge prior subduction is postulated for the KUKh metavolcanic rocks as is also suggested for Neoproterozoic subduction-related magmas from the north (Stein and Goldstein 1996) and the south (Teklay et al. 2002) ANS. Several mechanisms may produce incompatible element enrichment in the oceanic environment, including freezing of mantle plume-derived melts (White 1995) and fossil plume model (Stein and Hofmann 1992). Hence, the presence of plume-related magmatism may be responsible for the enrichment of the mantle source probably before subduction took place.

From the trace element systematics of the KUKh metavolcanic rocks it appears that they are unique among the Neoproterozoic metavolcanic rocks in Egypt. Further radiogenic isotope data will be necessary for more complete understanding of the tectonic setting of origin of the KUKh and the adjacent terranes to the south and to the north.

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