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New ophiolite occurrences in Sudan and constraint on the western boundary of the Nubian Shield: Petrographical and geochemical evidence

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ABSTRACT

Important mafic–ultramafic masses have been located for the first time in the intersection area between the Keraf Shear Zone and the Nakasib Suture Zone of the Nubian Shield. The masses, comprising most of the members of the ophiolite suite, are Sotrebab and Qurun complexes east of the Nile, and Fadllab complex west of the Nile. The new mafic–ultramafic masses are located on the same trend of the ophiolitic masses decorating the Nakasib Suture. A typical complete ophiolite sequence has not been observed in these complexes, nevertheless, the mafic–ultramafic rocks comprise basal unit of serpentinite and talc chlorite schists overlain by a thick cumulate facies of peridotites, pyroxenites and layered gabbros overlain by basaltic pillow lavas with dolerite dykes and screens of massive gabbros. Associated with pillow lavas are thin layers of carbonates and chert. The best section of cumulate mafic–ultramafic units has been observed in Jebel Qurun and El Fadlab complexes, comprising peridotites, pyroxenites and layered gabbros. Dolerite dykes and screens of massive gabbros have been observed with basaltic pillow lava sections in Wadi Dar Tawaiy. The basal ultramafic units of the complexes have been fully or partly retrograded to chlorite magnetite schist and talc to talc-carbonate rocks (listowenites), especially in the Jebel Qurun and Sotrebab complexes. Petrographically, the gabbros (layered and massive) and the basaltic pillow lavas show mineral assemblages of epidote amphibolite facies. The mafic members from the three complexes show a clear tholeiitic trend and oceanic floor affinity. The pillow lavas plot in the field of oceanic floor basalt, namely in the back arc field. Primitive mantle normalized spider diagram of the pillow lavas reveals a closer correspondence to Enrich-Mid-Oceanic Ridge Basalt (E-MORB) type, which is confirmed by the flat chondrite normalized Rare Earth Elements (REE) pattern. Field, petrographical and geochemical evidence supports ophiolitic origin of the three complexes. The newly discovered ophiolitic complexes mark the western continuation of the Nakasib Suture Zone.

1. Introduction

An ophiolite is a rock association that resembles the oceanic lithosphere and is associated with deep-water sedimentary rocks that has been tectonically emplaced on continental crust (Moores, 1982; Nicolas, 1989). As defined by the Penrose conference (Anon, 1972) and (Coleman, 1977) ophiolites are distinctive, layered rock bodies which include (from bottom to top), an ultramafic tectonite (commonly serpentinitized harzburgite), cumulate mafic–ultramafic rocks, non-cumulate gabbros, sheeted dolerite dykes, and mafic volcanic rocks (basaltic pillow lavas). This complex is commonly overlain by plagic sediments, chert and/or other deep marine sedimentary rocks. Previously, ophiolites were considered representing oceanic crust formed at mid-ocean ridges (Coleman, 1977). However, several workers (e.g. Nicolas, 1989; Shervais, 1982) suggested a diverse tectonic setting to these mafic–ultramafic rocks, including back-arc basins and the roots of volcanic arcs.

Although the best examples of ophiolites were firstly reported from the younger orogenic belts in Cyprus (Troodos ophiolite, Moores and Vine, 1971) and Oman (Semail ophiolites, Pallister and Hopson, 1981), late Precambrian ophiolites have widely been reported from the Pan-African Nubian–Arabian Shield decorating old geosutures (Abdel Rahman, 1993; Almond and Ahmed, 1987; Camp, 1984; Hussein et al., 1984; Kröner et al., 1987; Vail, 1983). The Nakasib Zone (Embleton et al., 1983) the central suture in the Sudanese segments of the Nubian Shield received much attention by previous workers (Abdel Rahman, 1993; Abdelsalam and Stern, 1994). However, previous workers fully described the ophiolite masses in the eastern and the central part of the Nakasib Suture (Nakasib complex Abdelsalam and Stern, 1990 and Oshib complex, Abdel Rahman, 1993 respectively) even though no an

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equivalent pillow lava sections have been reported. This work describes for the first time complete, but dismembered ophiolite masses in the western geographical continuation of the Nakasib Suture (Fig. 1).

2. Geological and structural settings

Three ophiolite complexes have been newly located and investigated in detail namely Sotrebab and Qurun complexes east of the River Nile, and El Fadllab complex west of the Nile marking the western geographical continuation of the Nakasib Suture Zone (Fig. 2).

The most extensive and best exposures of the ophiolitic mafic–ultramafic rocks are mainly in the NE of Jebel Sotrebab, south of wadi Dar Tawaiy and Jebel Qurun east of the River Nile while others have been found between wadi Kurmut and wadi Abu Haraz west of the River Nile, all having tectonic contacts with the adjacent rocks (Fig. 3). The El Fadllab complex is characterized by intense vertical to sub vertical shearing and sub-horizontal thrust planes forming a linear belt trending North-South. It consists of highly serpentinized basal ultramafic rocks and sheared mafic–ultramafic cumulates (pyroxenites and layered gabbros). Left lateral movement of the Keraf Shear Zone controls the present orientation of the thrusted greenschist assemblage of the El Fadllab complex (Fig. 3). Lithologies continue and intercalate with volcano-sedimentary sequences east of the River Nile and turn to extend NE passing through Jebel Sotrebab to produce a big Z-shape with the Nakasib structure (Fig. 2).

The Sotrebab and the Qurun complexes consist of a basal unit of serpentinite and talc chlorite schists, overlain by a thick cumulate facies of peridotites, pyroxenites and layered gabbros and covered by basaltic pillow lavas associated with thin layers of carbonates and chert. Locally in Wadi Dar-Tawaiy dolerite dykes with screen of massive gabbros have been recognized associated with basaltic pillow lavas and minor ferruginous chemical chert. The above sequence is not fully developed everywhere in the area of the study. The rocks are highly sheared forming a large synformal structure plunging to the south, with highly deformed metavolcanics and associated metasediments dominating the core of the synformal structure. The mafic–ultramafic assemblage and the metavolcanosedimentary sequences are intruded by syn-tectonic granites. The geology of these mafic–ultramafic rocks and their petrographic and geochemical characteristics will be described below.

2.1. The basal ultramafic tectonite sequence

Ultramafic tectonites are regarded as the lower or mantle part of the ophiolite suite (Coleman, 1977). They are usually occurred as deformed, intensely sheared, highly serpentinized chromotiferous-dunite-harzbergite facies. The best exposures of these units in the study area occur around Jebel Sotrebab and extend in a NE direction discontinuously to merge with J. Derbekan in the Oshib complex (Abdel Rahman, 1993). These units are in tectonic contact with the adjacent volanosedimentary rocks and syn-tectonic granite. The lack of chilled margin and the complete absence of contact metamorphism around the ultramafic rocks on all complexes characterize these basal tectonites. Lithologically, the most common facies are serpentinites, talc carbonate schist (Listowenite) and talc chlorite schists. The basal ultramafic massifs were subjected to intense shearing giving rise to boudinage structures of parental rocks in a tectonite mélange with talc and serpentine as matrixes (e.g. NE of Jebel Sotrebab, (Plate 1A)).

Microscopically the basal units are composed of antigorite as the main serpentine minerals plus talc and magnesite and minor relicts of primary minerals such as olivine and orthopyroxene. Serpentinites rocks formed at the expense of harzburgites, often intergrown by carbonates. Relicts of the porphyroblast orthopyroxene were observed along the foliation planes in some thin sections. Ore minerals are represented by oxides (i.e. chromite and magnetite) in octahedron form. This mineral assemblage suggests

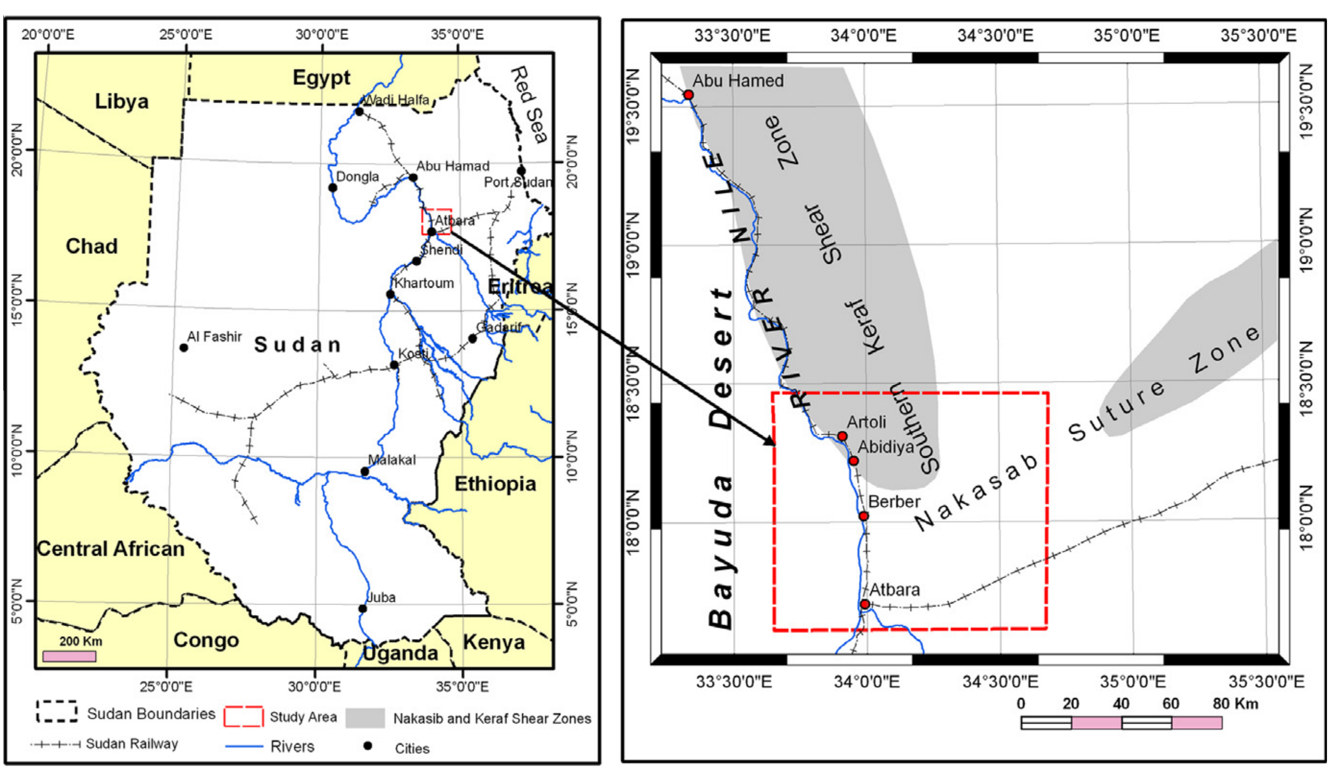

Fig. 1. Landsat ETM+7 Image of band 7, 4, 1 showing the location of the study area.

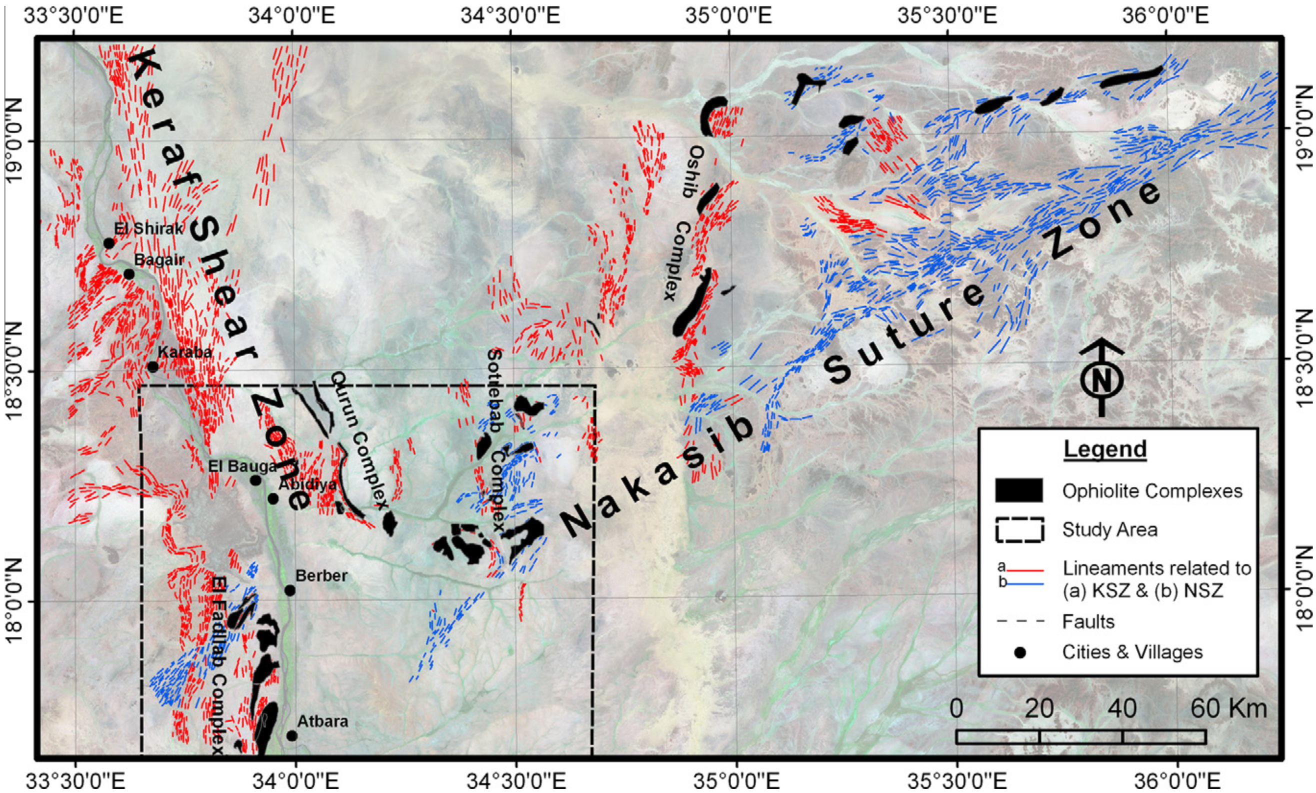

Fig. 2. Tectonic lineament map and the ophiolite occurrence in the Study Area and adjacent Oshib ophiolite.

harzburgite and dunite protolith. Field observation and petrographical investigation suggest tectonic emplacement in their present position.

2.2. Cumulate Mafic–Ultramafic rocks

The serpentinite tectonite facies is overlain structurally by highly altered cumulates. Cumulates comprise a variety of peridotites, pyroxenites and layered gabbros. The best examples of cumulates have been observed in the Jebel Qurun and the El Fadlab complexes (Figs. 2 and 3).

The dominant rocks are coarse- to medium-grained pyroxenites and layered gabbros. In Jebel Qurun complex peridotite occur at the base followed by pyroxenites and layered gabbros, forming two limbs of a major synformal structure trending North-South. Planar structures are shown by compositional layering in the ultramafic and gabbroic rocks. Rhythmic layering (Wager and Brawn, 1968) and phase layering (Irvine, 1982) characterize the layered gabbros. The cumulate gabbros and pyroxenites of the El Fadlab Complex form a N–S trending belt extending between the road to Atbara quarry in the south and to the village of Kadabas in the north (Fig. 2). Layering is well developed in the cumulate section in the El Fadlab complex, with alternating layers of different ratios of plagioclase and ferromagnesian minerals (Plate 1B). The layer may range in thickness from 2 to 10 cm. The general trend of the primary magmatic layering is N–S to NNE–SSW with vertical to sub vertical dip.

Mineralogically, Olivine and orthpyroxene as the main minerals constituents in ultramafic cumulates. Orthopyroxene rich peridotites consist of highly serpentinized olivine, abundant clinopyroxene, and subordinate orthopyroxene (Plate 1C). Some Ca-plagioclase crystallized later, no inter-cumulate spaces between mafic minerals. Crystallization order of olivine, orthopyroxene and clinopyroxene respectively suggest fractional crystallization and accumulation of basic magma that was derived from partial melting of the underlying basal unit.

Pyroxenites consist of coarse clinopyroxene altered to actinolite indicating retrograde metamorphism to green schist facies (Plate 1D). Rare Plagioclase (mainly oligoclase) and hornblende occur in lesser abundances. The presence plagioclase crystals among the clinopyroxenes crystals indicates that these rocks are cumulate, in addition to the early cumulate phase of serpentinized olivine and orthopyroxene in large piokilitic clinopyroxenes. Epidote, carbonates and opaques are secondary minerals.

Layered Gabbros consist of calcic-plagioclase (andesine to labrodorite), augite, hypersthene, and relicts of hornblende and olivine. There is partial to complete replacement of pyroxenes by hornblende (Plate 1E). Secondary minerals include actinolite and chlorite after mafic minerals. Iron oxides, epidote and apatite occur as accessory minerals. The deformation is recognized by blastopoikilitic texture in pyroxene and amphibole crystals and deformed lamellae of plagioclase. The rock is characterized by the growth of clinopyroxene phenocrysts (inter-cumulate phase) surrounding disjointed plagioclase crystals of two sizes (cumulate phase) (Plate 1F). This ophitic texture partly corresponds to the precipitation of the relatively simple plagioclase-clinopyroxene system. The layering is the result of the remaining cumulate cycles of the basic magma during the relatively quite crystallization condition, which allowed accumulation.

2.3. Massive gabbros and dolerite dykes

Massive gabbros represent layer three of the ophiolite suite (Coleman, 1977). In the area investigated cumulate mafic–ultramafic rocks are overlain structurally by non-cumulate massive gabbros e.g. east and west of Jebel Qurun. In Dar-Tawaiy area, screens of massive gabbros have been identified associated pillow lava sections. The rocks are medium to coarse-grained in texture

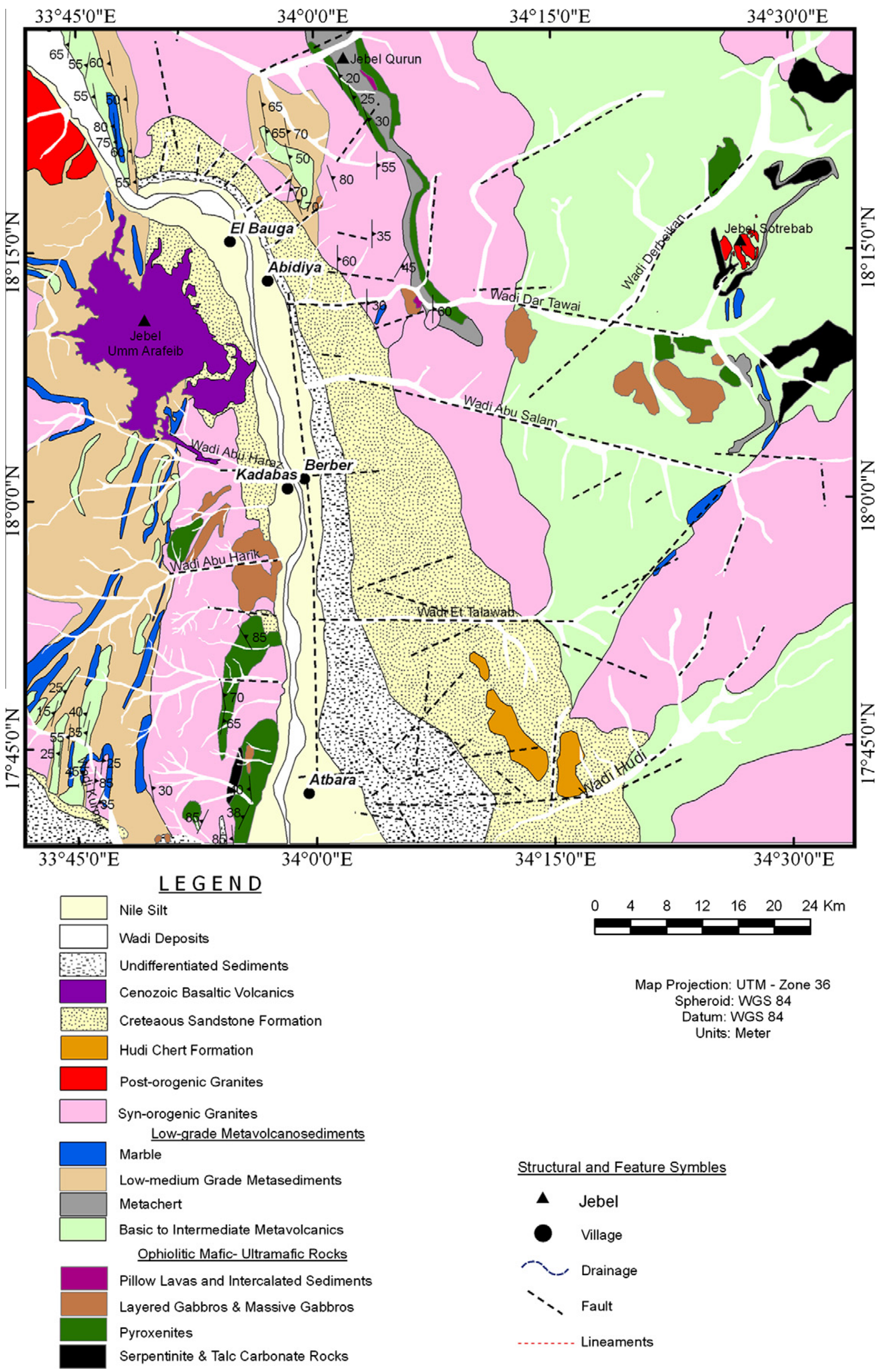

Fig. 3. Detailed structural geological map of the study area.

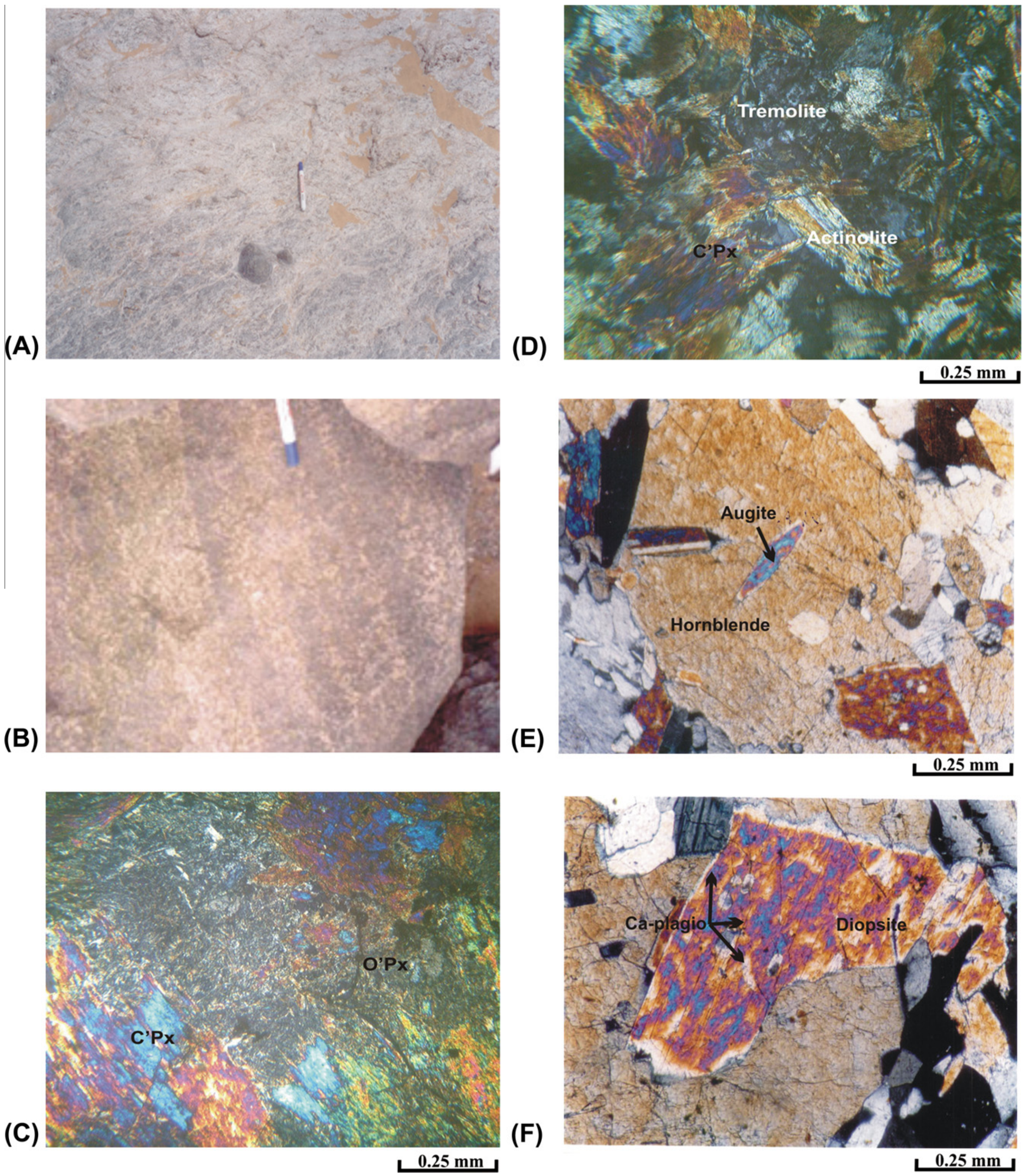

Plate 1. (A) Boudinage structure in a tectonic melange matrix, NE of Jebel Sotrebab. (B) Primary magmatic layering in cumulate gabbros, El Fadllab complex. (C) Clinopyroxene rich predotites and subordinate orthopyroxene. (D) Retrograde metamorphism of pyroxenites and formation of actinolite after clinopyroxene. (E) Layered gabbros showing piokilitic texture of augite (inner) surrounded by hornblende. (F) Layered gabbros showing cumulate phase (augite phenocryst) and inter-cumulate phase (Ca-plagioclase).

and predominantly massive showing no indication of layering. The rocks are highly sheared and are in some places transformed to amphibolites and mylonites.

Sheeted dolerite dykes of ophiolitic mafic–ultramafic rocks are considered to have formed by continuous injection of basaltic magma along the axes of spreading system (Coleman, 1977). The original orientation of sheeted dykes may correspond to the mid-oceanic spreading ridge, back-arc spreading centers or minor oceanic basins. A full sheeted dykes complex has been reported from the Late Precambrian Al Hamry ophiolite in Delgo Suture Zone (Denkler et al., 1994) and a 50% dyke complex has been recognized in Wadi Tabon area in the Onib ophiolite (Abdel Rahman, 1993). In this work dolerite dykes have been recognized in Wadi Dartawaiy and can only be distinguished from massive gabbros

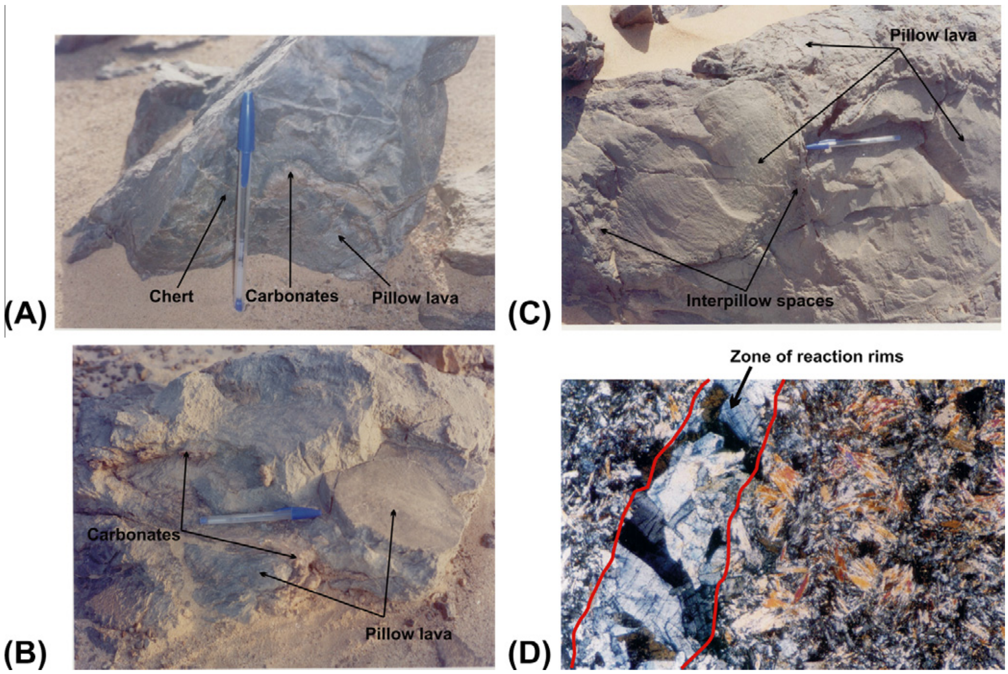

Plate 2. (A and B) Photomicrograph of intercalation of basaltic pillow lavas with chert and carbonates. (C) Reaction rims of basaltic pillow lavas with hayloclastic materials filling inter-pillow spaces. (D) Microscopic view of basaltic pillow lavas showing formation of carbonates and epidote minerals as a result of cooling under seawater.

by contrast in textures. Structurally, they overlie the cumulate gabbros and associated with massive gabbros and pillow lavas which are associated with thin lenses of chemical metachert. The dolerite dykes are deformed and they appear as irregular lense-like bodies of fine-grained texture discordant to layering of the rocks they intrude. The dykes are non-schistose amphibolites, and the minor deformation has slightly developed metamorphic overprint. They are generally oriented NE–SW, parallel and sub-parallel to the general trend of the main mafic–ultramafic massifs, and are comparable with the mafic dykes of the Oshib complex (Abdel Rahman, 1993). The dolerite dykes have the same composition of the basaltic pillow lavas with difference in texture and they contain more actinolite than the basaltic pillow lavas.

2.4. Basaltic pillow lavas and associated sediments

The submarine basaltic pillow lavas generally represents layer four in the ophiolite association as defined by the Penrose conference (Anon, 1972). Most of the Precambrian geologists (Coleman, 1977; Gansser, 1974; Miyashiro, 1973) considered that the basaltic pillow lava have been formed in subaqueous environment at spreading oceanic ridges, along transform faults and island arc, associated with deep-sea chert and carbonates. So far, typical sections of basaltic pillow lavas have only been reported from the upper part of the late-Precambrian Jebel Rahib ophiolite complex in NW Sudan (Abdel Rahman et al., 1990).

Well preserved typical basaltic pillow lava sections have been identified for the first time in the western extension of the Nakasib Suture Zone (Ali, 2005) in Wadi Dar Tawai J. Qurun complexes and SW of Jebel Sotrebab (Fig. 3). The lavas are intercalated with bands of chert and carbonates (black limestone) (Plate 2A and B) and are associated with dolerite dykes and screens of massive gabbros all of which in some places are structurally overlain by cumulate mafic–ultramafic units, for example, on the eastern side of Jebel Qurun. The rocks are dark green in color with well developed circular to elliptical shape. Locally deformed pillow structures are still obvious and inter-pillow spaces and vesicles have escaped deformation (Plate 2C). Coarse hayloclastic materials such as silica, rock fragments and recrystallized carbonates fill the inter-pillow spaces.

Under the microscope the rocks are none foliated showing extensive hydrothermal alteration especially in reaction rims (Plate 2D). Albite, epidote, actinolite and chlorite are the main mineral assemblages. Relicts of magmatic minerals (orthopyroxene) are occasionally preserved in some thin sections which enable an approximation of the original mineralogical composition. Pseudomorphs of actinolite are possibly formed after clinopyroxene. The ca-plagioclase has been completely altered to albite, epidote (ziosite and clinziosite). kaolinitization, epidotization (saussoritization) and carbonitization are the main alteration processes resulting from reactions with seawater. The above mineral assemblage indicates epidote amphibolite facies of seafloor metamorphism. This is the typical spilitic alteration assemblage. The broad range of mineral assemblage and textures indicate disequilibrium condition for all rocks.

3. Litho-geochemistry

3.1. Analytical techniques

The geochemical study of the three ophiolitic complexes has been based on a selection of Eighteen representative rock samples (9 of basaltic pillow lava and 9 of cumulate mafic–ultramafic rocks) (Tables 1) for major, trace and rare earth elements (REE). The basal ultramafic sequence have been excluded because of highly metamorphism and alteration. Rock samples were analyzed using X-ray Fluorescence (XRF) in the TU Berlin geochemical Lab and Inductively Coupled Plasam Mass Spectrometry (ICP/MS) at Omac laboratory.

3.2. Classification and geochemical variations

Field observations as well as the petrographic and geochemical investigations indicate that the analyzed rocks are affected either by low-grade metamorphism or late hydrothermal alterations. Therefore major oxides were excluded to avoid any

Table 1
Geochemical analysis (major, trace and REE) of basaltic pillow lavas and cumulate mafic–ultramafic rocks.

Oxides%	Basaltic Pillow Lavas								Cumulate Mafic–Ultramafic Rocks									
	Qurun complex					Sotrebab complex			El Fadllab complex			Qurun complex					Sotrebab complex	
	D 1	D 2	D 3	D 4	D 5	S-20a	S-20b	S-14c	A 4	A 38	A 43b	Cb-1	OP 1	OP 2	OP 3	S-19	S-22	S-25
SiO_2	49.04	48.4	48.57	49.78	47.69	49.25	47.58	48.96	47.56	46.03	48.57	51.23	40.07	44.54	45.73	48.38	50.11	51.23
Al_2O_3	14.42	14.52	14.55	13.37	14.29	12.56	14.62	14.15	18.96	10.41	20.19	14.09	10.61	13.33	13.44	14.63	13.43	14.96
Fe_2O_3	11.13	11.28	11.2	10.79	11.34	12.17	12.19	11.88	5.94	9.52	6.12	11.02	10.88	8.97	9.16	10.6	10.61	12.37
MnO	0.169	0.168	0.165	0.185	0.175	0.18	0.17	0.17	0.104	0.199	0.102	0.194	0.163	0.141	0.152	0.16	0.16	0.28
MgO	7.62	7.46	7.69	7.52	7.9	8.2	7.46	7.86	9.66	6.93	7.82	7.63	20.34	16.88	15.21	11.44	8.02	7.04
CaO	10.87	11.07	10.68	12	11.77	12.12	12.26	10.37	13.11	21.97	12.4	10.43	6.88	8.85	8.8	8.03	11.8	11.54
Na_2O	2.63	2.47	2.65	2.3	1.96	1.95	2.17	2.54	1.54	0.4	1.97	1.89	0.22	1.3	1.6	2.37	2.63	1.29
K_2O	<.02	<.02	<.02	0.04	<.02	0.12	0.09	0.7	<.02	<0.02	0.05	<.02	<.02	0.06	0.04	0.07	0.12	0.02
TiO_2	1.09	1.1	1.08	1.03	1.1	1.2	1.18	1.12	0.28	1.49	0.24	1.2	0.68	0.57	0.64	1.01	0.92	0.54
P_2O_5	0.052	0.047	0.057	0.053	0.055	0.11	0.1	0.09	<.01	0.216	0.027	0.118	0.078	0.045	0.057	0.15	0.07	0.05
L.O.I	2.04	2.2	2.35	1.99	2.2	1.9	2	1.9	0.66	1	0.78	0.43	6.91	3.69	3.45	2.4	2	0.5
Sum	99.11	98.8	99.07	99.07	98.53	99.85	99.88	99.54	97.89	98.15	98.3	98.36	97.22	98.55	98.42	99.77	99.86	99.86
Ba	62	108	37	75	80	199	67	43	58	43	56	34	39	47	103	161	79	16
Co	51	49	51	47	55	47.9	49.6	46.5	49	55	47	65	109	75	70	65.2	46.2	55.9
Cr	187	199	167	162	186	370	370	340	520	521	510	970	3028	1404	1033	1560	480	250
Cu	83	93	94	40	37				62	<10	37	<10	116	22	171			
Ga	11	16	15	14	15	14.9	17.3	14.2	13	12	13	17	8	11	12	15.2	13.2	14.8
Hf	4	4	4	4	5	1.8	2	1.7	4	5	4	5	4	4	4	1.6	1.2	0.9
Nb	<3	<3	<3	<3	3	4.2	4.3	3.7	<3	<3	<3	<3	<3	<3	<3	7.9	3	1.2
Ni	131	127	134	121	131	143	140	147	229	104	181	311	998	576	455	415	163	116
Pb	<10	<10	<10	<10	<10				<10	<10	<10	<10	<10	<10	<10			
Rb	<10	<10	<10	13	<10	2.2	2.4	0.7	11	<10	<10	<10	<10	<10	<10	1.9	2.2	<0.5
Sc	33	41	41	27	37	46	47	43	29	61	14	35	25	20	27	42	43	56
Sr	199	228	238	163	214	173.1	219.1	132.2	245	286	363	209	35	293	137	195	220	256.1
Th	<5	9	6	10	8	0.6	0.5	0.7	<5	8	<5	5	9	<5	<5	0.4	0.1	<0.1
U	<5	<5	<5	<5	<5	0.1	<1	0.1	<5	<5	<5	<5	<5	<5	<5	0.3	0.2	<0.1
V	300	300	298	304	321	300	324	293	95	185	90	209	160	122	161	227	296	317
Y	21	22	22	20	19	23	23	21	<10	19	<10	20	<10	10	11	22	18.9	23.5
Zn	62	60	66	60	61				28	55	38	68	54	51	47			
Zr	58	57	57	56	58	57.2	59.4	53.6	<25	103	<25	59	45	38	42	64.2	45.3	22
Ce	27	29	<20	<20	<20	11.4	10.6	10.7	24	<20	<20	37	<20	24	<20	12.7	7.7	2.3
La	<20	<20	<20	<20	<20	4.4	4.2	4	<20	<20	<20	<20	<20	<20	<20	5.5	2.9	0.7
Nd	<10	<10	<10	<10	<10	9.1	9.4	8.2	11	<10	<10	17	<10	<10	<10	9.1	6.8	2.4
Pr	18	14	15	12	<10	1.65	1.6	1.61	<10	<10	<10	<10	<10	<10	<10	1.75	1.16	0.38
Sm	4	<4	<4	<4	<4	2.6	2.7	2.5	<4	<4	<4	<4	<4	<4	<4	2.6	2.1	1.3
Eu						0.92	1.19	1								0.82	0.21	0.58
Gd						5.94	3.31	3.37								3.06	1.41	2.06
Tp						1.09	0.58	0.58								0.57	0.24	0.49
Dy						6.02	3.88	3.46								3.68	1.36	3.4
Ho						1.34	0.77	0.76								0.76	0.19	0.81
Er						3.45	2.17	1.98								2.24	0.52	2.53
Tm						0.6	0.35	0.34								0.35	0.06	0.44
Yb						3.99	2.07	1.96								2.2	0.37	2.71
Lu						0.59	0.28	0.29								0.29	0.04	0.39

misinterpretation resulting from secondary processes. According to Pearce (1983), trace elements in metamorphic rocks can be generalized into two groups: generally mobilized Low Field Strength Elements (LFS) namely (Cs, Sr, K, Rb, and Ba) and relatively immobile High Field Strength Elements (HFS) that include REE, Sc, Y, Th, Zr, Hf, Ti, Nb, Ta, Th, and P. Further, Co, Ni, V, and Cr are also considered immobile (Rollinson, 1993).

The mafic–ultramafic cumulate rocks show a wide range in concentrations, particularly of major elements and some trace elements (Table 1). Their SiO_2 contents range between 40% and 51%. They are characterized by high value of Al_2O_3 (13.33–18.96 wt%), CaO (6–12.97 wt%), FeO (total) (5.94–12.37 wt%) and higher values of MgO (6.93–20.34 wt%). The MgO/FeO (total) >1 indicating formation in an upper mantle source area and they are chemically regarded as Mg-gabbros (Hallberg, 1985). Diopside and hypersthene are predominant normative components with subordinate plagioclase. High values of trace elements are represented by Cr (250–3028 ppm) and Ni (116–998 ppm). On the AFM diagram (Fig. 4) all the analyzed samples follow the sub-alkaline tholeiitic trend.

The basaltic pillow lava is characterized by SiO_2 contents of 47.58–51.23 wt%, low MgO (7.4–8.2 wt%), high Fe_2O_3 (10.79–12.19 wt%), low Cr (162–370 ppm) and Ni (121–143 ppm) and enrichment in V compared to those of ultrabasic rocks indicating an advanced stage of magmatic differentiation. A clear tholeiitic trend is illustrated in the AFM diagram (Fig. 4).

In the Zr/TiO∗0.0001 versus Nb/Y classification diagram all samples plot in the field of sub-alkaline basalt (Fig. 5). The analyzed basaltic pillow lavas are characterized by relatively similar Zr/Y (2.55–2.61), lower Zr/Nb (13.6–14.48) and La/Nb (0.98–1.04) and higher Th/Yb (0.15–0.35) ratios than the normal mid-oceanic ridge basalts (N-MORB) (2.64, 31.75, 1.07 and 0.04 respectively: Sun and Mc Donough, 1989). These features are similar to some subduction-related basalts, back-arc basin basalts (BABB) and the more enriched type of mid-oceanic ridge basalts (E-MORB) (Saunders and Tarney, 1984; Sun and Mc Dounogh, 1989).

N-MORB and mantle normalized spider diagrams of the basaltic pillow lava reveal a closer correspondence to E-MORB rather than N-MORB and OIB (Fig. 6), where the patterns are similar, crossing the typical N-MORB line at a small angle and paralleling the E-MORB reference line at slightly lower abundances. The rare earth elements (REE) are regarded to be the least mobile elements during seafloor alteration processes (Ridley et al., 1994). They are particularly useful for making inferences about the nature of the magma source, as well as fractionation processes. The REE patterns for all basaltic pillow lava are similar with chondrite normalized abundance between 15 and 20 times chondrite for the light rare earth elements (LREEs) and near 15 times chondrite for heavy rare earth elements (HREEs) (Fig. 7). The similarity, the small or no positive Eu anomalies and the smoothness of REE patterns suggest that they have not been significantly affected by seafloor weathering and have a transitional to enriched MORB origin.

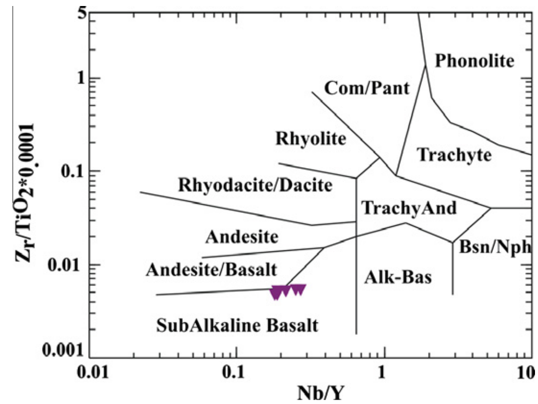

Fig. 5. Nb/Y versus Zr/TiO∗100 binary rock classification diagram for the basaltic pillow lava (after Winchester and Floyd, 1977).

3.3. Tectonic setting discrimination

The most powerful interpretation for tectonic setting discrimination is primarily based on a set of trace elements. In Ti and Cr empirical tectonic discrimination diagrams (Pearce, 1975), all basaltic rocks plotted in the field of oceanic floor basalt (Fig. 8). Zr/Y plotted against the fractionation index Zr (Pearce and Norry, 1979) provided an effective discrimination between the basalts from oceanic-island arcs, mid-ocean basalts, within-plate basalts and back-arc basin basalts (Rollinson, 1993). Most samples plot within the field of BABB (Fig. 9). In this case, Zr serves as an index of fractionation, while the concentration of Y in relation to Zr (the Zr/Y ratio) is controlled by the chemistry of the mantle source. A mix of island arc and MORB characteristics can be a sign of formation in a back-arc basin environment (Saunders and Tarney, 1993). Basalts in a back-arc setting are generated by adiabatic upwelling and partial melting of the mantle, the same process by which MORB is created. Therefore, this is either extension due to trench rollback, or convection induced by motion of the subducting slab (Sauders and Tarney, 1991).

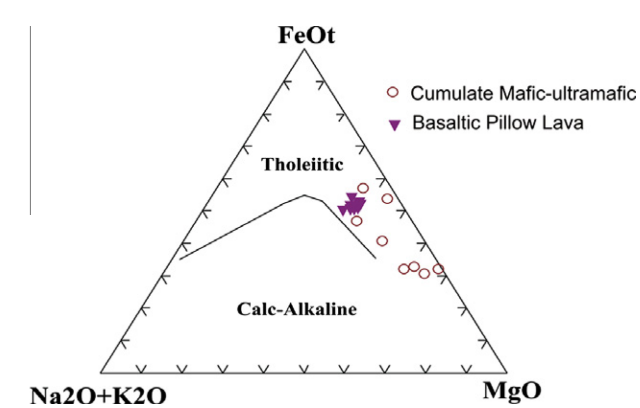

Fig. 4. AFM diagram shows the tholeiitic trend of cumulate units and basaltic pillow lavas of ophiolite complexes. (After Irvine and Baragar, 1971.)

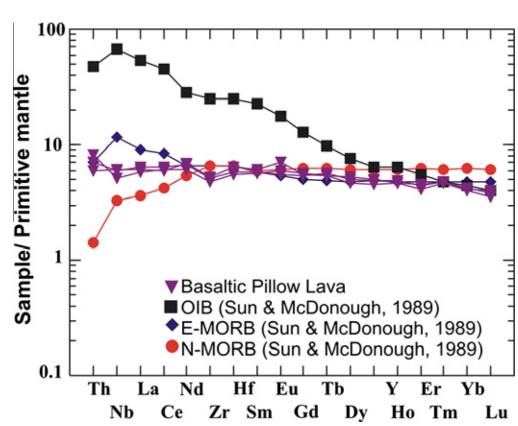

Fig. 6. Primative mantle normalized multivariation spider diagram for the basaltic pillow lavas. (Normalized values from Sun and Mcdonough (1989).)

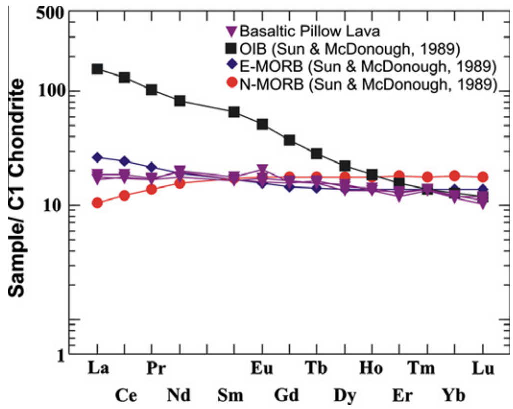

Fig. 7. Chondrite-normalized REE diagram for the pillow lava. (Normalizing values from Sun and Mcdonough (1989).)

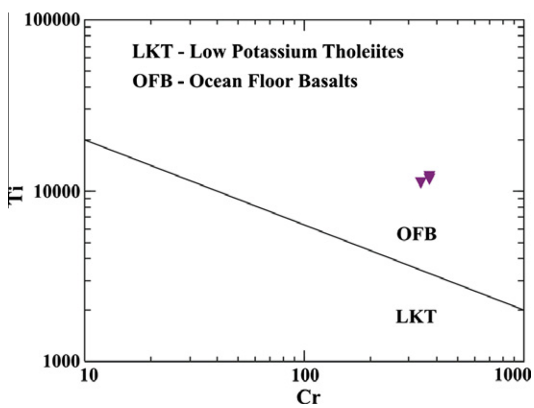

Fig. 8. Tectonic discrimination diagram for basalts based on Ti, Cr variations (after Pearce, 1975).

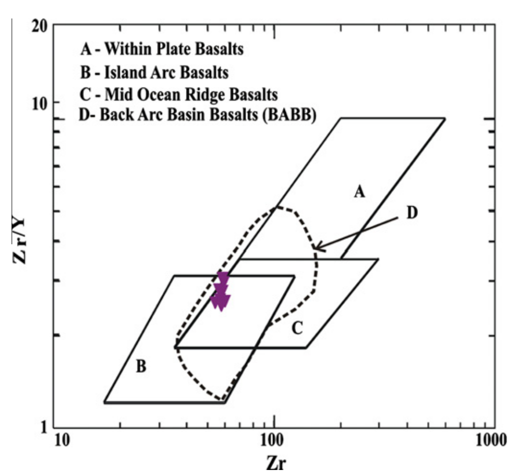

Fig. 9. Tectonic discrimination diagram for Dartawai basaltic pillow lava based upon Zr/Y–Zr (Pearce and Norry, 1979; back-arc basin basalts discrimination from Floyed et al. (1991)).

4. Conclusions

Geological investigation of the intersection area between the Keraf Shear Zone and the Nakasib Suture Zone revealed the existence of large mafic–ultramafic masses: namely the Sotrebab and the Qurun complexes east of the River Nile, and the El Fadllab complex west of the R. Nile. Although, they are highly sheared and dismembered, the masses comprise all the characteristic features and distinctive members of the ophiolite suite. The complexes are associated with folded volcanosedimentary units and there is no evidence of contact metamorphism or chilled margins with the adjacent rocks. The basal sections of the complexes comprise highly serpentinized ultramafic facies which have locally been transformed to talc chlorite schist and talc-carbonate rocks along the margins of the outcrops. Cumulate predotite, pyroxenite and layered gabbros are well developed and are followed upwards by sections of pillow lavas. A typical sheeted dolerite dyke complex has not so far been observed in these masses probably due to intense deformation. Nevertheless, numerous dolerite dykes with screens of massive gabbros have been observed within the pillow lava sections. Petrographical investigation of mafic units discloses mineral assemblages of low-grade metamorphism (epidote amphibolite facies).

Geochemical data shows that the mafic units from the three masses are sub-alkaline of tholeiitic affinity. On tectonic discrimination diagrams, the pillow lavas plot as ocean floor basalt (OFB) and are clearly discriminated as back-arc basin basalt (BABB). In primitive mantle multivariate spider diagram the pillow lavas have a typical pattern of Enrich-Mid-Oceanic Ridge Basalt (E-MORB), and have chondrite normalized pattern similar to E-MORB type, with slightly enriched light rare earth elements (LREE).

On a regional scale, these complexes line up to form a NE–SW continuous linear structure with NE-trending lineaments, that links with the other ophiolitic fragments along the Nakasib Suture Zone in the central part of the Nubian Shield suggesting the continuation of the Nakasib Suture Zone west of the Nile. Later North-South strike-slip movements brought some sections to the parallelism e.g. along the Keraf Shear Zone.

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