Graduate College Journal – NU
Vol.17 -2022, No. (11)
ISSN: 1858-6228, http://www.neelain .edu.sd

مجلة الدراسات العليا - جامعة النيلين
المجلد (17) –2022، العدد (11)
الرقم الدولي الموحد للدوريات: 1858-6228

Geological Setting, Petrography and Geochemistry of Mafic-Ultramafic Ophiolitic rocks in western Darfur State, West Sudan

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Abstract

A remarkable mafic-ultramafic dismembered ophiolitic units have been discovered for the first time in West Darfur State, West Sudan. Field survey coupled with petrographical studies and whole-rock chemical analysis to identify the origin of these new rock units. Scattered serpentinized mafic- ultramafic ophiolite components consist of dunite, layered gabbro and basaltic pillow lavas, are exposed withinlow-grade metavolcanics and metasediments, which consists of meta-andesite, chlorite schist, marble, graphitic schists and quartzites. The region has been affected by NE- SW shear zone with dextral strike slip movement. The tectonic discrimination diagrams revealed that the serpentinized mafic- ultramafic ophiolite rocks related to the volcanic arc field from the binary Nb/Th versus Y, while the ternary TiO2-K2O-P2O5 diagram, classifies them as both island arc tholeiite (IAT) and depleted Mantle Oceanic Floor Basalt (N-MORB). Whereas the geochemical signatures of the pillow lava basalt and layered gabbro samples have a typical mid-oceanic ridge basalt compared to the mafic- ultramafic samples, which assigned as oceanic island. The presence of serpentinized mafic- ultramafic ophiolitic units, metavolcanic rocks with associated flysch metasediments might suggest a juvenile oceanic environment.

Keywords: Ophiolite; El Geneina; Sudan; N-MORB; IAT; Arabian-Nubian Shield.

Introduction

The geology of the Darfur region has infrequently previously described due to the remoteness and inaccessibility of the region. The general geology consists of metamorphosed, folded and peneplain granitic gneisses, quartzites and pelites, intruded by small granitic batholiths (Vail, 1972). Tectonically two NNE striking linear belts of tightly isoclinals folds are separated by a central zone in which folding about granitic domes is a dominant feature (Vail, 1972; Lotfi 1963).

The study area lies in the far southwest part of West Darfur region, Sudan. The area extends from Beida – Arara villages in the southwest to Sisi village of the east of El Geneina town in the West Darfur State in West Sudan. Geographically, the area bounded by longitudes 21° 49' 28.4" E - 22° 09' 57.5"E and latitudes 12° 41' 30. 5"N - 13°06' 33.6"N (Fig. 1).

The regional survey covered areas that were not visited before and discovered new lithological units such as mafic and ultramafic rocks in Beida and Gobie area, which are classified in the field as a dismembered ophiolitic suite. Metavolcanic rocks have been recorded in Deleiba area and in south-west the study area and also marbles have been discovered in Habilah and Arara areas.

The Arabian-Nubian Shield (ANS) comprises Neoproterozoic (0.6 - 0.8 Gagreenstone belts of which ophiolites are abundant, occurring as nape complexes marking suture zones between terrains (Furnes, *et al.* 2015; Johnson, *et al.* 2011; Stern and Johnson, 2010; Kröner and Stern, 2004; Stern, *et al.* 2004). Structural and geochemical studies of arc- like complexes within these greenstone belts have shown that they rather represent supra-subduction zone oceanic lithosphere (Dilek and Ahmed, 2003), and thus can be classified as subduction-related ophiolites (Furnes, *et al.* 2015; Dilek and Furnes, 2014 and 2011).

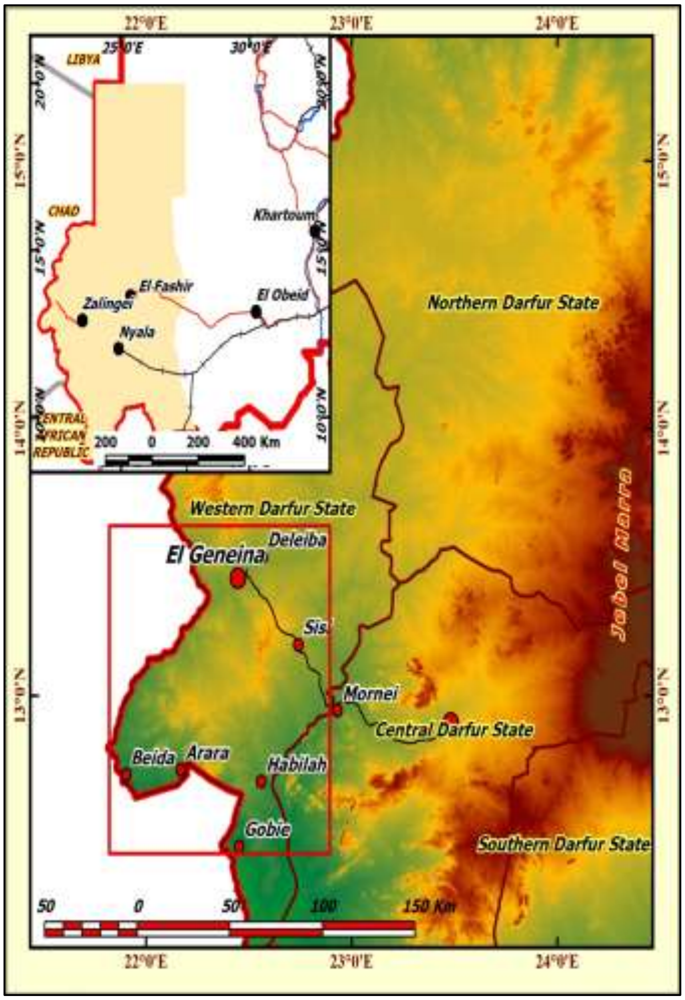

Fig. 1: Location Map of the Study area (red box).

Ophiolites are layered rock bodies which include (from Bottom to top), an ultramafic tectonite (commonly serpentinized harzburgite), cumulate mafic –ultramafic rocks, non-cumulate (isotropic) gabbros, sheeted dolerite dykes, and mafic volcanic rocks (basaltic pillow lavas and plagiogranite). This complex is commonly overlain by pelagic sediments, chert and /or other deep marine sedimentary rocks (Anon, 1972 and Coleman, 1977)

A diverse tectonic settings have been suggested for these mafic-ultramafic ophiolitic rocks, including back-arc basins and the roots of volcanic arcs (Nicolas, 1989; Shervais, 1982).

The Precambrian ophiolite complexes cover huge region of Sudan, in particular in the Sudanese Nubian Shield “SNS” (the Sudanese Red Sea Hills) and described by several authors that they are represent old geo-sutures in the SNS (Abdel Rahman, 1993; Abdelsalam and Stern, 1990; Almond and Ahmed, 1987; Kröner, *et al.* 1987; Hussein, *et al.* 1984; Embleton, *et al.* 1983; Vail, 1983). Moreover, Ophiolites described in areas away from the SNS, as the Ingessana ophiolite complex at southeast of Sudan (Abdel Rahman, 1983 and Babiker, 1977) and Kabus ophiolite mélange in northeastern Nuba Mountains (Abdelsalam, *et al.* 1991). In the western part of Sudan, the first late Precambrian ophiolite complex rocks have been reported in Jebal Rahibin north Darfur Sudan (Abdel Rahman, *et al.* 1990; Fig. 2).

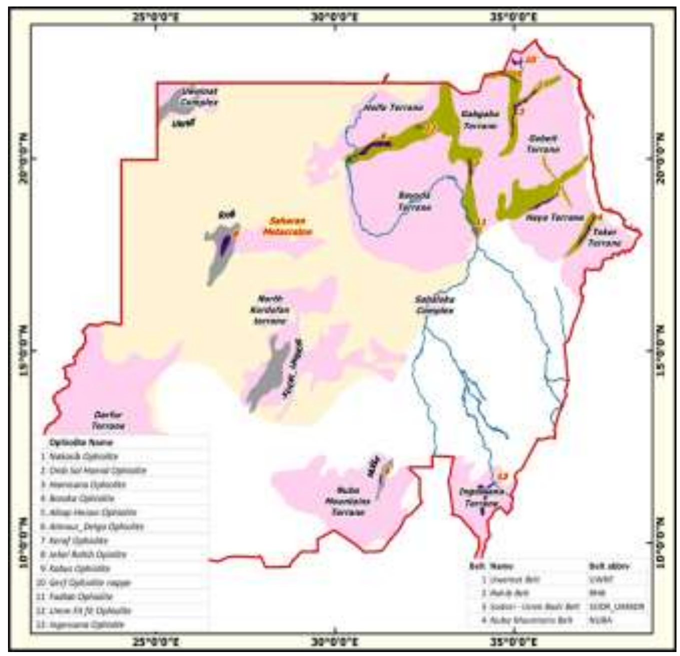

Fig. 2: Basement terranes, ophiolite sutures and metasediments belts in Sudan (*modified after* Johnson, *et al.* 2011; Küster, *et al.* 2008).

Geological Setting

The basement complex in west Darfur comprises medium-grade para- and ortho- gneiss rocks and amphibolite bands, unconformably thrust by ophiolitic rocks, and overlying by low-grade metavolcanic and metasediments sequences, and intruded by granitoid intrusions. Phanerozoic sequences consist of unconformably overlying Paleozoic sedimentary rocks of Dissa

Sandstone Formation and post- orogenic intrusions. The Quaternary and Recent alluvial deposits of the Wadies deposited in the structurally controlled drainage system, while the aeolian sand sheets and dunes cover most of the basement units (Fig. 3).

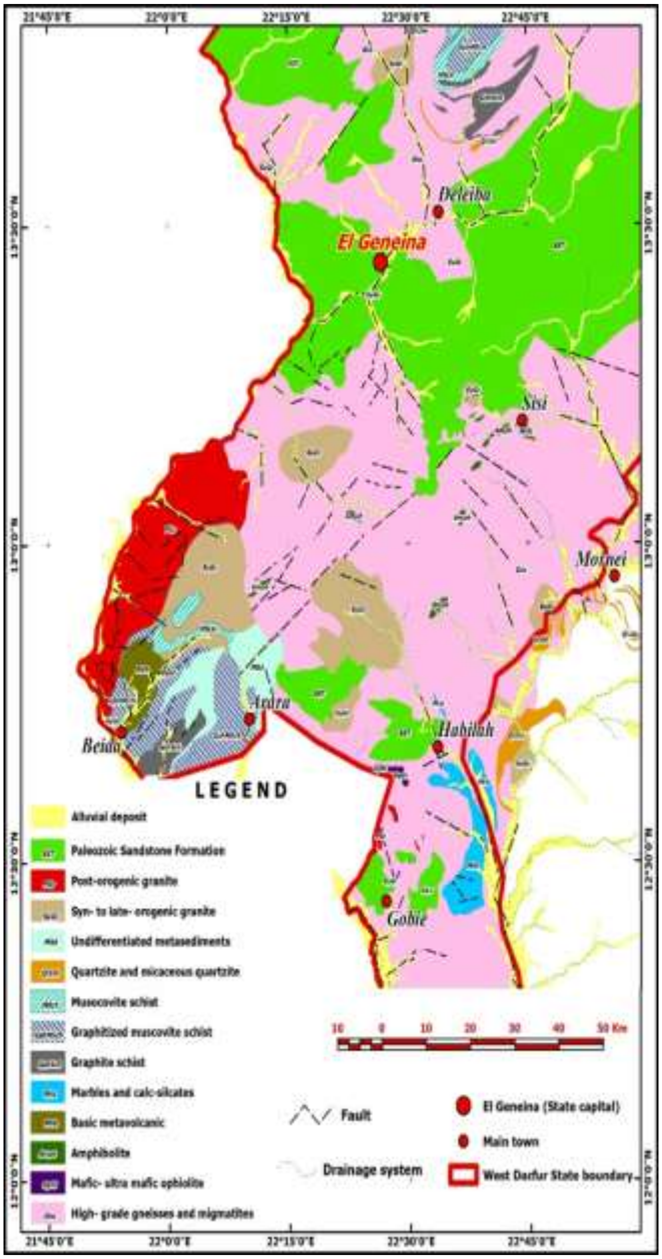

Fig. 3: Geological map of the study area

The medium-grade gneisses

The medium- grade gneisses comprised the migmatitic para- gneisses and ortho- augen gneisses rocks, they scattered all over the central part of western Darfur region. They cropped out mostly as surface laying outcrops or low- elevated ridges as Anchata mountain series. The gneisses have two texture types, the pinkish augen gneisses are strongly foliated, medium- grained size with coarse grained and large porphyroblast K- feldspars in augen texture; and the dark grey to brown well foliated, medium- grained migmatitic gneiss with peculiar gneissic banding. Gneissic rocks also appear in Habilah and Sisi areas as low-elevated hills, medium- grained, with lenticular eye- shaped mineral grains or mineral aggregates. The mineral composition of predominantly of quartz, K-feldspar, plagioclase, biotite, hornblende, garnet with opaque minerals. The type politic minerals, sillimanite - kyanite and cordierite are not uncommon in the metasedimentary rocks. These gneisses and amphibolite bands affected by poly deformational phases as they subjected interference folding and shearing (Fig. 4 a& b). In other hand,the basic to intermediate metavolcanics mainly consist of meta- andesite, located in Beida Area. The metavolcanic rocks are highly sheared and intensively injected by variable sizes and generations of quartz veins swam. Metavolcanic intruded by syn- orogenic intrusions and in some area observed intercalated with metasediments rocks.

The low-grade basic – intermediate metavolcanic

The low-grade metasedimentary rocks consist of graphite schists, marbles, quartzites, and sericitic- muscovite schist, which covered the south western part of the study area, extending from Arara south through the Beida area in the northwest closed to Chad international borders.

The graphitic schists are widely exposed and forms very dark grey to black ridges. They are easily recognized in the satellite imageries, in contrast to mica schist, is commonly hill forming. They are medium-grained, compositionally layered and contain graphite and quartz. The graphitic schists are commonly interbedded with other metasediments as quartzite and mica schist. The sericitic muscovite schists are generally sub-crop (i.e. are easily eroded) and are medium-grained, and compositionally layered (Fig. 4 c, d).

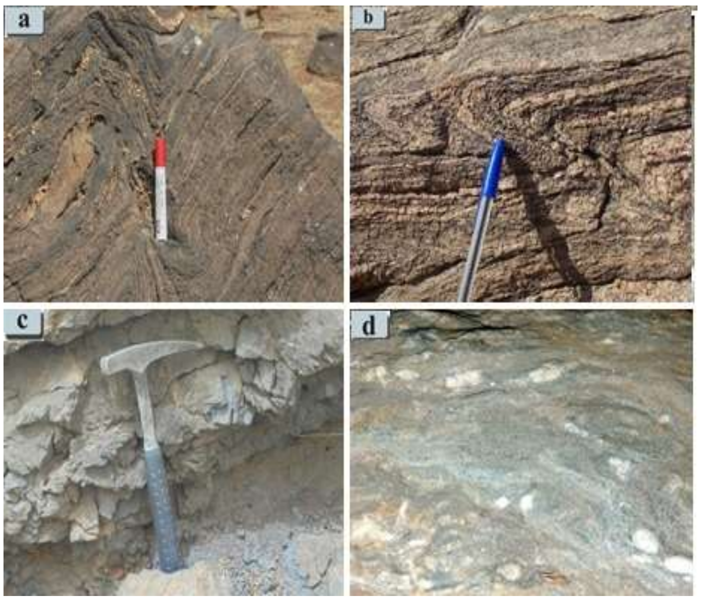

Fig. 4: **a)** Upright folded Amphibolite with syn- kinematic quartzites, Gobie area. **b)** Recumbent fold in augen granitic gneissic, Sesi area **c)** Graphite schist, Jebal Mermta. **d)** Kinematic of shearing (boudinage) in mica schist in study area.

Mineralogically, the mica schists are dominated by muscovite, plagioclase and quartz. Biotite may also be present, as can tourmaline and more rarely garnet. The quartzitic belts cropped out around Mournei village as high-standing topography ridges and discontinuous layers that generally do not exceed more than 1-2 kilometers inthickness. It consists predominantly of quartz, while the muscovite is commonly present. Quartzite is commonly exposed near the base of the siliclastic sedimentary rocks, and is bedded at various scales.

Numerous intermittent NW- trending marble belts cropped out south of Habilah and Arara areas. These metasedimentary rocks are highly deformed displaying different phases of folding and shearing. Scattered outcrops and poorly exposed calc-silicates rocks are found intercalated with the medium-grade gneisses in the area between El Geneina- Mourani and Zalingei.

Mafic-Ultramafic rocks

In the study area the mafic- ultramafic rocks have been exposed as low lain outcrops within metasedimentary rocks of graphitic schist and quartzite in Beida area, Arara area and within low grade volcano-sedimentary in Gobei area, these rocks defined as ultramafic serpentinite dunite, layered gabbro and basaltic pillow lavas.

The ultra- mafic unit

The ultramafic dismembered ophiolite rocks found in Mirmataa ridge in Beida area and appear as minor elongated highly deformed ultra-mafic bodies, sandwiched between underlying sheared granitic gneiss rocks and folded quartzite and graphitic schist that acted during thrusting as lubricant in an imbricate stack. They are serpentinized rock and under microscope are composed of dominantly antigorite, less bastite (serpentine) and minor relicts of olivine and pyroxene also there are presence of chlorite, chromite and carbonate which represent dunite and harzburgite origin (Fig. 5). Similarly, this mineral composition is compatible with the ultra-mafic rocks described from western Jebel Rahib ophiolitic belt (Abdel Rahman 1993; Abdel Rahman, *et al.* 1990).

Layered gabbroic rocks

Gabbroic rocks exposed out in Gobie area south of El Geneina town as low laying out crops, interbedded with chlorite schist and metasedimentary rocks. The gabbroic rocks are dark greenish in color, medium to coarse-grained with wavy layered texture (Fig. 6a). The layered gabbro under microscope display ophitic texture mainly composed of phenocrysts of pyroxene (diopside, augite) and Ca- plagioclase arrange in layers, minor olivine. Such remaining cumulate cycles of the basic magma during the relatively quiet crystallization condition, allowed accumulation, thus cause the layering texture. Therefore, primary rhythmic layering is well developed (El Tokhi, *et al.* 2016), where plagioclase-rich bands alternate with the pyroxene-rich bands (Fig. 6b).

Fig.5: The ultra-mafic rocks in the study area **a).** An outcrop of ultra-mafic rock sandwiched between metasedimentary rocks. **b).** photomicrograph of ultra-mafic rocks consists mainly bastite (serpentine) and talc (Talc) upper right corner show diopside (Di). **c).** photomicrograph of ultra-mafic rocks shows sliding antigorite (Atg), left corner show hypersthene (Hyp) and augite (Aug). (Minerals abbreviation symbols after Whitney and Evans, 2010).

Basaltic pillow lava

Basaltic lavas have been recognized in Gobie area intercalated with metasediments rocks, including carbonates and associated with doleritic dykes. The rocks are dark green color, with elliptical shapes displaying pillow lava forms in various diameter ranges >10 cm to more than 30 cm, show some cracks and have no regular shapes (Fig. 7a). Under the microscope the rock consists of Ca-plagioclase, epidote, and relict of clinopyroxene, minor carbonate, and chlorite, zoisite are accessory minerals. Existent of epidote and carbonate minerals indicates alteration resulting from interaction with seawater(Fig. 7b).

The pillow lava form in a subaqueous environment of spreading oceanic ridges, along transform faults and island arc, associated with deep-sea chert and carbonates(Coleman, 1977; Gansser, 1974; Miyashiro, 1973*)*.

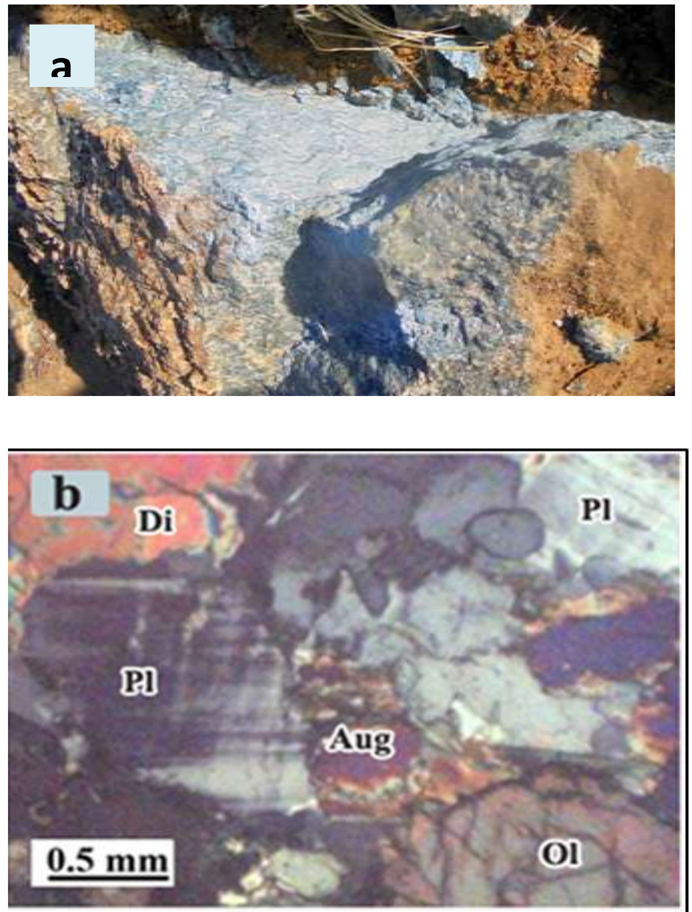

Fig.6: **a).** Meso-scale of layered gabbro, Gobei area. **b)** photomicrograph of layered gabbro consists of olivine (Ol) and augite (Aug), diopside (Di) and plagioclase (Pl).

Geochemistry

A few mafic-ultramafic cumulate samples collected and analyzed, they show a wide range have low silica content (SiO_2 = 42- 54.3%), high content of ferromagnesium (Fe_2O_3 = 9.9 - 18.5%; MgO = 9.6 - 20.2%), low alkali content (Na_2O+K_2O =1.4%), variable calcium content (CaO = 6.0 -8.4%) and moderate alumina (Al_2O_3 = 10.2 - 13.9%), while TiO_2 range between 0.42-1.0%, while P_2O_5 is low 0.03- 0.06.

Fig.7**:** **a)** basaltic pillow lava. **b).** photomicrograph of pillow lave dominantly plagioclase (Pl), epidote (Ep), minor of calcite (Cal) and zoisite (Zo).

The pillow basalt samples are characterized by moderate SiO_2 contents of (49.9 - 52.7wt %) attribute to recrystallization and metasomatic processes, low MgO (7.8 - 9.5%), high Fe_2O_3 (9.3 - 12%), low Cr (671 - 753 ppm), Ni (228 - 299 ppm) and enrichment in V (157 - 298 ppm) compared to the dunite-harzburgite ultrabasic samples (Table 1).

The Zr versus P_2O_5 tectonic discrimination binary diagrams display the ultra-mafic ophiolite samples within the tholeiite series (*Fig.8a*), while the binary diagram of Nb/Th versus Y (Jenner, et al. 1991),place these rock samples in the arc- related mafic, ultra-mafic cumulate field (Fig.8 b). This implies that both the cumulate and non- cumulate rocks have formed in subduction zone tectonic setting.

The triangle diagrams of 10 MnO-TiO_2-10 P_2O_5 (Fig.8 c) classify the ophiolitic rocks as both island arc tholeiite (IAT) and depleted mantle oceanic floor basalt (N-MORB) (the mantle from which MORB is produced must be already depleted in incompatible elements). In other handspillow lava basalt and layered gabbro samples have typical mid-oceanic ridge basalt geochemical signature compared to ultramafic samples which assigned as oceanic island (Fig.8d) as indicated by discriminate diagrams of Pearce et al., 1977. As well as diagrams of TiO_2-K_2O-P_2O_5 (Fig.8 e) and N_2O+K_2O-FeOt-MgO (Fig.8 f) show respectively the oceanic and tholeiitic trends of the ophiolitic rocks.

Table.1: XRF chemical analysis results

	Layered Gabbro		Dunite-harzburgite		basaltic pillow lava	
	H8	H9	41B	41U	Bz1	Bz2
SiO_2 %	51.9	54.357	45.473	42.012	52.767	49.945
TiO_2 %	0.5	0.426	1.016	0.946	1.031	0.85
Al_2O_3 %	15.1	13.886	12.504	10.256	14.928	13.773
Fe_2O_3 %	9.1	9.93	17.238	18.524	9.312	12.06
MnO %	0.14	0.158	0.069	0.185	0.134	0.172
MgO %	9.7	9.612	16.616	20.252	7.854	9.507
CaO %	10.3	8.441	6.064	6.645	10.738	9.864
Na_2O %	2	1.452	0.207	0.223	2.598	2.852
K_2O %	0.04	0.064	0.3107	0.295	0.0938	0.194
P_2O_5 %	0.07	0.062	0.0347	0.0555	0.0623	0.0478

Total %	**98.78**	**98.39**	**99.53**	**99.40**	**99.52**	**99.27**
Ba (ppm)	nd	441	nd	nd	137	513
Rb (ppm)	6	34	32	22	14	13
Sr (ppm	145	778	144	144	685	863
Y (ppm	22	14	17	15	13	23
Zr (ppm	98	296	170	185	nd	nd
Th (ppm	nd	4	0.3	1	9	7
U (ppm	1	<0.5	<0.5	<0.5	<0.5	<0.5
Nb (ppm	7	5	2	1	2	1
Pb (ppm	15	29	nd	nd	nd	29
Ga (ppm	13	22	15	1153	15	30
Zn (ppm	51	80	137	161	72	112
Cu (ppm	50	80	nd	nd	96	72
Ni (ppm	47	109	864	896	228	299
V (ppm	173	103	104	77	157	298
Cr (ppm	142	568	978	872	671	753
La (ppm	20	16	11	17	nd	nd
Ce (ppm	33	23	21	33	27	23
Pr (ppm	nd	1	1	2	12	1
Nd (ppm	5	nd	12	7	21	19
Sm (ppm	3	9	nd	nd	9	13
Nb/Th	nd	1	7	1	nd	nd

*nd: not detected

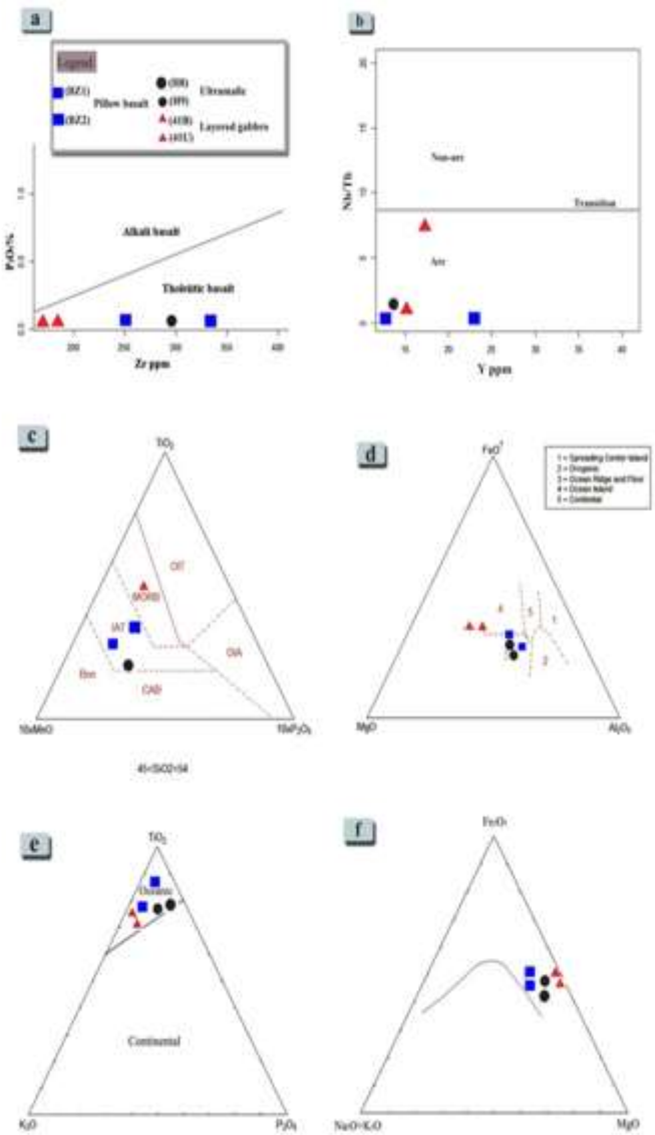

Fig.8: ophiolite samples of study area (a). Assigned as tholeiite series in Zr versus P_2O_5 binary diagram. (b). in Nb/Th versus Y diagram place these rock samples in the arc-related mafic, ultra-mafic rocks. (c). In (Mullen, 1983) 10 MnO-TiO_2-10 P_2O_5 triangle diagram classify the ophiolitic rocks as both island arc tholeiite (IAT) and depleted mantle oceanic floor basalt (N-MORB). (d). in MgO-FeO_t- Al_2O_3diagram ofPearce et al., 1977 pillow lava basalt and layered gabbro samples have typical mid-oceanic ridge basalt geochemical signature compared to ultramafic samples which assigned as oceanic island. (e). diagrams of TiO_2-K_2O-P_2O_5 whole ophiolite samples assigned as oceanic series. (f). N_2O+K_2O-FeOt-MgO diagram whole ophiolite samples show tholeiitic trend.

Conclusion:

The area of West Darfur State particularly the south western part of Beida area, and southern part of Habilah, Gobei areas have been visited and studied for the first time since nineteenth era. The old geological map illustrated the area is dominated by para-schist included graphite schist and quartzite, mica schist as well gneiss rocks and granitoids. However, in this study, new lithological unit have been reported, as the low-grade metavolcanic, marbles and the calc-silicates, beside the mafic-ultramafic ophiolitic rocks.

Tectonically, the region affected poly deformational phases of folding and refolding phases, terminated by a regional dextral strike-slip shear trend to the northeast. The shearing covered Beida – Arara area in the southwest Darfur state. In addition, this shear zone is extended to the Sisi area on the eastern part of El Geneina town.

The geochemical characteristics of the representative rock samples have been studied using X-Ray Fluorescence Spectrometry (XRF), atomic absorption (AAS) for the whole-rock chemical analysis; include the major oxides, trace elements, and rare elements.

The ophiolite remnants exposed as low lying outcrops within metasedimentary rocks of graphitic schist and quartzite in Beida area, Arara area and within low grade volcanosedimentary in Gobei area, these rocks defined as dunite, layered gabbro and basaltic pillow lavas. The tectonic discrimination diagrams e.g. Nb/Th versus Y place these ophiolite rocks in the arc field, and the triangle TiO_2-K_2O-P_2O_5 diagram, classify the ophiolitic rocks as both island arc tholeiite (IAT) and depleted mantle oceanic floor basalt (N-MORB). Whereas thepillow lava basalt and layered gabbro samples have typical mid-oceanic ridge basalt geochemical signature compared to ultramafic samples which assigned as oceanic island. The presence of serpentinized mafic-ultramafic rocks, metavolcanic rocks and extending of large marbles and quartzite bands might suggest a juvenile oceanic environment.

From the field relationships, petrography and geochemistry studies we concluded that the new basic-ultrabasic rocks of western Darfur are member of ophiolitic belt. This mafic – ultramafic ophiolitic rocks have NE- trendingin the western Sudan near to the Sudanese- Chadian international borders. The present of this ophiolite suite in Darfur region to the southwest of the Jebel Rahib ophiolitic Belt, which described as the most western ophiolitic belt in Sudan. Both belts lie away from the Nubian Shield and within the continental crustal material of the Saharan Metacraton.

This new ophiolitic dismembered units insight new tectonomorphic history and would change the geotectonic, metallogenic perspective of the region of the western Sudan. Based on the new evidences detailed petrological, structural, geochemical and geochronological studiesare highly needed for Darfur region.

Acknowledgement

This work has been sponsored by the Geological Research Authority of Sudan (GRAS). Much gratitude goes to the Mineral Resources Administration staff in Khartoum and the West Darfur GRAS regional office staff for their help during the field trip.

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