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Petrographical and Geochemical Studies of Amphibolites Rocks (Metamorphic Sole) At Masafi Area, UAE

Mohamed El Tokhi[1], Bahaa Eldin Mahmoud Amin[2], Ahmed B. O. Abdelwahed[3], Amr A. Abdelsamad[4], Ali A. M. Bustanji[5] and Muhammad R. Khairunnas[6]

[1,2,3,4,5,6]UAE University, College of Science, Geology Department, Al Ain, United Arab Emirates.

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ABSTRACT

Metamorphic rocks occur in several locations in the UAE, including the Masafi-Asimah area and the area around bordering Bulaydeh. Both have previously been interpreted as forming part of the metamorphic sole of the Oman-UAE ophiolite. The age of these metamorphosed by hornbland dating is around 90-95 Ma Late Cretaceous (Cenomanian to Turonian). In the Masafi area, ortho- and para-amphibolites exist within sheared rocks as bands, lenses, and linear bodies up to 100m thick. The amphibolites are composed of amphibole and plagioclase commonly secondary epidote and garnet. In some outcrops, parallel-sided plagioclase-rich veins cut across the amphibolites and in other areas, migmatitic segregations within the amphibolite were observed. Whole-rock analyses confirm that the amphibolites were originally tholeiitic basalts. A comparison of trace element suggests that the protoliths were not equivalent to the Haybi alkaline and transitional tholeiites found in the underlying structural slice, or to the Semail ophiolite volcanic rocks, which lie structurally higher in the sequence. Structurally, the amphibolites lie within the metamorphic sheet: greenschist facies metasedimentary rocks, including quartzites and marbles and interbanded with metamafic rocks. It is suggested that the sedimentary and volcanic protoliths were metamorphosed in a subduction zone environment during underthrusting initial ophiolite displacement. The amphibolites were incorporated into the ophiolitic rocks after they were metamorphosed as part of a metamorphic sole at the base of peridotites during the northward subduction of a branch of Neotethys.

Keywords: Masafi, Asimah, Amphibolites, UAE.

1. INTRODUCTION

In the Asimah tectonic window of the northeast UAE the amphibolites form a <100 m thick sheet of highly metamorphosed rocks in the upper most part of a much thicker metamorphic sole (~2000 m thick) dominated by greenschist facies quartz rich gneisses and meta carbonate rocks. The sole was attached to the base of the Semail Ophiolite, a 10 - 20 km thick piece of oceanic crust and upper mantle lithosphere of Cretaceous age that was thrusted over the ancient Arabian continental margin during the closure of the Tethys Ocean with obduction completed as 75 million years ago. The amphibolites and other metamorphic rocks at the base of the Semail are exposed in a complexly arched section of the ophiolite that was cut by erosion to expose the underlying metamorphic rocks in its core. This exposure is a long southward tapering area called the Asimah Window (Fig. 1). Ophiolite represented slices of the upper mantle and oceanic crust lithosphere that have been thrusted onto the continent during tectonic convergence. The ophiolite usually, but not necessarily, indicates supra subduction zone rifting and spreading [19] and represents the formation of a fresh oceanic crust. The ophiolite lithology is complicated and is divided by some geologists into: a mantle sequence and a crustal sequence. The Semail mantle sequence in the UAE- Oman (at the bottom) includes peridotites (tectonized, foliated and serpentinized) with dunitic layers and lenses increasing upward, as well as chromititic pods. Overlying this is the crustal sequence, which consists of gabbros (cumulus, layered and massive), diabase (dolerite) sheeted dikes enclosing small intrusions of plagiogranites that may sit between the gabbro and sheeted dikes, and extrusive pillow lavas covered by deep seated pelagic sediments. The transition or boundary between the mantle and crustal sequences in the ophiolite complex is termed the Petrological Moho.

The mantle sequence also contains various types of intrusions that vary from ultramafic, mafic, to felsic compositions, and range from a few millimeters to several meters thick. Dunites, pyroxenites, chromitites, wehrlites, gabbros, amphibolites, diorites, granites and others are all observed. They occur as dikes, sills, veins, pods, or lenses, and concordant or discordant with the wall-rock structures [6]; [9].

In the Masafi metamorphic sole, masses of amphibolites form bands, irregular lenses and elongated bodies interlayered with variegated metavolcanics and metasediments. These bodies vary in thickness from less than 10cm to more than 5m (Figure 2). The aim of the present paper is to determine the field relationship, petrology and bulk-rock chemistry of the amphibolites rocks and thereby more closely define their protoliths.

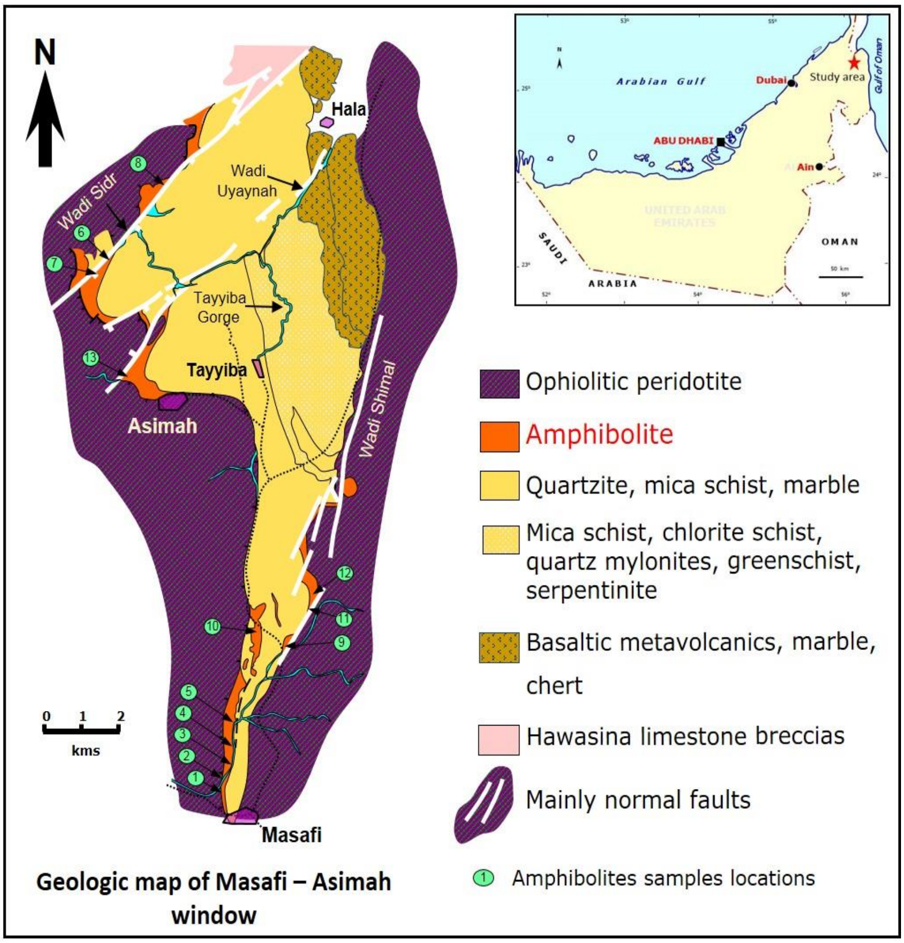

Fig.1: Geological map of Massafi-Asimah window area

2. FIELD RELATIONS

The metamorphic rocks underlie a 10 km thick ophiolite sequence, the Semail ophiolite, and are exposed discontinuously along a strike length of over 450 km (Glennie et al. 1973, 1974). The Metamorphic sole has exhumed to higher structural levels and accreted onto the base of the Semail Ophiolite (Cenomanian/Turonian boundary (94–93 Ma)). The ophiolite has obducted onto the margin together with underlying thrust sheets of Haybi

Complex and Hawasina Complex rocks. Thrusting has progressed by deep subduction-related ductile shearing to more brittle fold-thrust structures as seen in the Dibba-Masafi Zone [10] (Figure 3).

Fig.2: Photograph showing different amphibolites pockets

The best exposures occur in the Dibba-Masafi area. The Haybi Complex [16] generally underlies them tectonically. The Haybi Complex itself always overlies the Hawasina Complex (deep marine sedmintes), which comprises a sequence of Mid-Permian to Upper Cretaceous deep-sea sediments [4], [5]; [7]. In the Dibba-Masafi area, the most extensive sequence of amphibolites and greenschists is present, although the rocks have been imbricated and structurally repeated, while in Wadi Ham South of Masafi a 500m thick sequence of amphibolites has been thrust over harzburgites (ophiolite rocks).

The structure of the amphibolites so far discovered in this study involves at least three stages of deformation represented by folds, foliations, stretching lineations and shear zones. The three stages are referred to as D1, D2 and D3 (where "D" denotes deformation event).

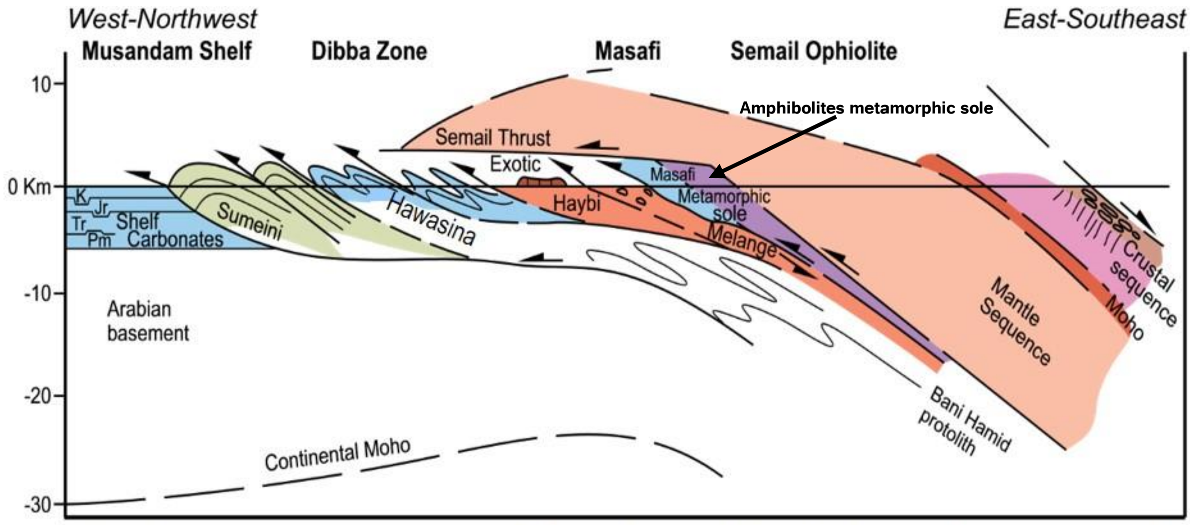

Fig. 3: Tectonic cartoon showing the evolution of the ophiolites and replacement of metamorphic sole (after Searle, et al. 2014).

The earliest event, D1, is most interesting and difficult to evaluate because all of its structures have been deformed again by D2 and D3. The most obvious D1 structure is a high temperature foliation (a plane of flattening defined by parallel metamorphic minerals). These foliations have of course been later folded but after unfolding they appear to have N-S to NNW-SSE stretching lineations on them which are parallel to hook-like dismembered fold hinges (intrafolial folds). Stretching lineations are commonly parallel to thrusting directions, but the parallelism of folds to these lineations is a problem that requires more work to establish if the concept is valid in this case. If this is the thrusting direction then D1 may indicate a different direction of detachment of the ophiolite than previously thought. The intrafolial folds and high temperature foliations are refolded about tight but continuous folds with NNW-SSE hinges. These are commonly associated with intense planes of ductile shearing called mylonites. The folds and the mylonites suggest a transport of the ophiolite towards the WSW – in line with the conventional model for Semail obduction. These tight folds are still considered to be part of the D1 event because they are also associated with high temperature foliation, and have the same trends as the intrafolial folds. However, further work may justify separating these two fold styles.

Later folding in events D2 (NNW-SSE trending open to closed folds with variable axial plane orientations) and D3 (NE-SW trending steeply plunging open folds) are later events than the obduction but still give information on how the Asimah Window actually formed, and in any case must be assessed in order to remove their effects on the D1 structural data. The D2 event was probably associated with the thrust slicing of the metamorphic rocks in the last stages of obduction. This thrusting was intense enough to stack the rocks as buckled steep slices causing a bulge underneath the Semail Ophiolite. The bulge is the likely origin of the Asimahh Window arch. The D3 folds are probably associated with a later tectonic event in the Tertiary that involved the collision of the Arabian continent with Asia and involved NW-SE compressive stresses.

3. PETROGRAPHY

The amphibolites include schistose mafic rocks composed of hornblende, plagioclase and minor clinopyroxene, garnet, quartz, epidote and biotite. Lenses of serpentinized biotite-bearing alkali pyroxenites occur within amphibolites. Other lithologies present within the amphibolite facies include banded quartzites and calc-silicate marbles with hornblende, augite and garnet. Amphibolites are in places altered by metasomatism and exhibit the secondary assemblage: prehnite, calcite, clinozoisite, wollastonite, white mica and garnet. The rocks are typically medium to coarse grained and granoblastic in texture. Hornblende prisms may exhibit random or preferred orientations. Grain boundaries are straight to slightly curved. Hornblende is pleochroic with (x) yellowish green (y) olive green and (z) dark green, and incorporates inclusions. Plagioclase grains are generally equant unzoned or slightly zoned and often show strain-induced twins. Plagioclase is oligoclase to andesine in composition. Quartz occurs as an accessory and is commonly xenoblastic. Chlorite is an alteration product of hornblende. Sphene, epidote also occurs as discrete grains in some samples. Zircon and rutile are very scarce and commonly occur along cleavage of hornblende. Opaque minerals include minor ilmenite and magnetite (Fig. 4). Basalt-gabbro (Ortho-amphibolite) including: hornblende/actinolite +/- albite +/- biotite +/- quartz +/- accessories; often remnant greenschist facies assemblages including, notably, chlorite, in addation to sedimentary (para-amphibolite) including: hornblende/actinolite +/- albite +/- biotite +/- quartz +/- garnet (calcite +/- wollastonite). Para-amphibolites will generally have the same equilibrium mineral assemblage as orthoamphibolites, with more biotite, and may include more quartz, albite, and depending on the volcano-sediments (Haybi complox) protolith.

4. ANALYTICAL TECHNIQUES

From forty different rock samples, we were selected twenty-two samples for major and trace elements for chemical analysis. Major and minor element concentrations were determined using a Philips PW 2400 X-ray fluorescent spectrometer housed at the Acme lab in Turkey. Concentrations of the major oxides were obtained on fused lithium-tetraborate discs, while the trace elements were determined on press pellets. Losses on ignition (LOI) were determined by heating powdered samples for 50 min at 1000 oC (Table 1). Some rare earth elements and the trace elements were determined by isotopic dilution technique at Uppsala University, Sweden.

5. DISCUSSION THE RESULTS

The chemical analysis of whole-rock samples from amphibolites (metamorphosed rocks) presents considerable problems, especially when shearing and deformation has accompanied the metamorphism. In the study area, the amphibolites are fairly thick-bedded and semi-uniformity of their bulk-rock chemistry. Their signatures show high trace elements such as Cr (average 196.83 ppm) and Ni (average 53.1 ppm) suggest that they have been derived from basic igneous rocks. While the sedimentary origin of the amphibolites reflect high percentage of calc-silicate minerals with lower values of Cr (average 110.44 ppm) and Ni (average 31.6 ppm) and higher values of CaO (27.27 wt %) rather than lower values of CaO in igneous origin (12.71 wt %). The twenty-two amphibolite samples analysed from the Asimah area are all of a composition that generally resembles ocean floor basalts shown in Table

If a basic igneous origin for Masafi amphibolites is accepted, it is pertinent to study the chemical affinities of the original magmas. Before that, it is necessary to determine to what extent the chemical composition of the present rocks approximate the pristine compositions of their presumed volcanic precursors. Amphibolites are petrographically and chemically heterogeneous. This difference in the character may reflect different degrees of partial melting and mantle source heterogeneity. The variation of SiO2, Na2O, CaO and particularly K2O in the present amphibolites support the possibility that contamination to different degrees. The contacts between the amphibolites and the surrounding metasediments in the field are rather sharp and there is no evidence, for gradational contacts, that would alter to suggest introduction of material from these metasediments. This may stand as evidence against secondary. Fig. 4: Photomicrograph showing: The fine-grained amphibolites. The garnet (G) phenocrystals in fine grained amphibolites.

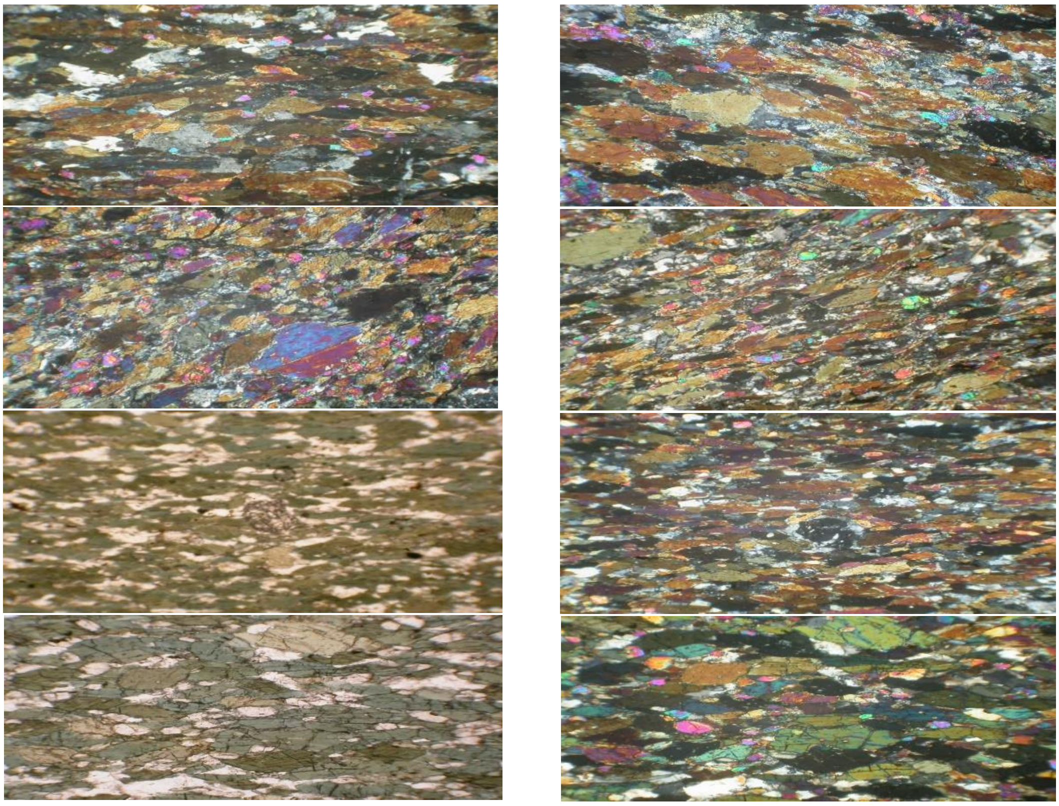

Fig. 4: Photomicrograph showing: The fine-grained amphibolites. The garnet (G) phenocrystals in fine grained amphibolites

metasomatism, but it is insufficient to conclude that chemical modification did not take place during metamorphism. However, the high variation of K2O content (which is one of the most mobile elements in the amphibolites) is not related to inherited variations but it is probably the result of chemical modification during metamorphism.

The main difference between the present amphibolites and those described by [15]; [2]; [13]; [8] and [11] are the relatively highly variations in Si and Ca and slightly variations in Na and K (Table 2). This suggests a redistribution of these elements different from typical reconstituted basalts. This may indicate that the present chemical heterogeneity was developed during regional metamorphism.

Table (1) Chemical analysis of the studied amphibolites

Samples	1	3	4	5	8	10	11	14	15	16	18
SiO2	39.51	40.08	40.69	38.59	39.92	40.19	38.38	39.96	38.77	38.84	39.65
TiO2	1.50	1.61	1.34	1.61	1.56	1.36	1.63	1.62	1.14	1.75	1.35
Al2O3	9.58	7.37	9.11	7.89	8.61	8.55	8.03	8.89	8.56	8.53	9.40
Fe2O3	12.12	12.49	11.96	14.77	13.41	11.38	13.63	14.07	11.23	14.44	11.90
MnO	0.13	0.18	0.16	0.19	0.18	0.16	0.17	0.18	0.15	0.19	0.14
MgO	5.18	4.15	4.70	4.49	4.80	7.18	4.26	4.74	5.92	5.01	4.98
CaO	26.62	29.75	26.53	27.54	26.10	26.37	29.42	25.43	29.19	26.26	26.73
Na2O	3.13	2.13	3.10	2.75	3.03	2.01	2.57	3.36	2.35	2.99	2.51
K2O	0.90	0.61	0.86	0.40	0.86	0.58	0.47	0.48	0.84	0.49	1.34
P2O5	0.23	0.26	0.24	0.20	0.22	0.20	0.24	0.23	0.13	0.20	0.12
L.O.I	0.86	1.09	1.07	1.10	1.09	1.77	0.86	0.76	1.42	1.05	1.61
V	459.1	433.2	404.1	423.1	393.8	403.4	444.0	428.0	365.4	464.7	357.9
Cr	115.1	106.3	107.0	58.0	92.5	159.4	75.2	77.8	163.4	67.5	192.6
Co	53.6	53.0	50.6	55.5	53.4	48.7	59.1	58.7	53.7	59.7	62.7
Ni	32.6	12.0	34.2	4.5	9.0	46.2	3.8	3.5	37.3	4.1	49.7
Cu	46.0	33.3	72.5	44.9	46.2	75.0	45.7	53.9	69.3	95.5	69.8
Zn	73.8	61.8	75.1	71.2	77.1	156.2	67.2	61.8	61.9	62.6	89.9
Rb	8.2	5.3	8.9	3.1	7.7	7.8	5.8	6.6	10.9	6.1	18.7
Sr	189.3	212.9	187.0	224.3	204.4	194.1	220.1	233.0	206.5	255.3	172.5
Y	15.4	16.4	14.3	13.1	14.8	14.7	12.8	12.4	13.3	13.5	14.6
Nb	8.2	11.4	7.9	8.3	9.2	6.8	9.6	8.9	7.2	9.0	5.8
Mo	1.0	1.8	1.6	1.1	1.4	1.3	1.4	0.9	1.4	2.0	1.5
Sn	0.7	2.6	0.2	1.4	1.7	1.5	0.3	1.9	2.7	< 1	1.2
Ba	152.0	63.5	75.4	133.2	57.3	75.0	94.0	292.9	124.3	307.2	61.6
La	181.7	154.2	107.8	225.5	19.2	98.1	18.5	< 1	< 1	< 1	330.7
Yb	3.0	3.0	3.3	2.1	2.6	3.6	2.0	1.7	3.6	2.8	2.8
Hf	2.0	3.3	2.7	2.9	1.8	1.8	2.2	3.0	2.4	0.6	2.0
Ta	1.9	1.9	2.3	2.4	1.6	1.7	2.5	2.6	2.6	0.9	1.8
Pb	4.5	10.4	5.2	6.2	6.4	8.3	6.2	4.7	2.6	6.0	8.5
Th	0.5	< 1	<1.0	1.0	5.1	1.3	2.7	1.4	1.0	4.0	< 1
Samples	**19**	**20**	**21**	**23**	**26**	**28**	**29**	**31**	**32**	**33**	**34**
SiO2	48.35	46.05	40.82	45.51	46.45	48.01	48.12	45.75	47.12	47.88	47.74
TiO2	1.57	1.54	1.81	1.82	0.92	1.85	1.62	1.01	1.09	1.24	1.22
Al2O3	11.80	9.80	9.79	11.64	11.80	11.28	10.60	12.30	11.30	11.30	10.70
Fe2O3	13.90	16.30	18.20	14.80	11.60	16.30	15.70	11.40	11.20	12.10	13.66
MnO	0.15	0.20	0.23	0.18	0.15	0.28	0.20	0.15	0.16	0.15	0.25
MgO	5.76	7.02	8.14	8.30	10.30	6.10	5.54	9.62	9.90	9.83	9.80
CaO	12.22	13.40	15.80	10.50	13.30	10.60	12.20	14.30	13.90	12.90	10.70

Na2O	3.21	2.61	1.58	3.00	2.27	3.51	3.33	2.85	3.30	2.45	3.50
K2O	1.03	0.99	1.08	0.92	0.82	0.42	0.61	0.63	0.25	0.45	0.51
P2O5	0.20	0.14	0.24	0.44	0.05	0.25	0.22	0.07	0.12	0.12	0.15
L.O.I	1.38	1.57	1.83	2.41	1.89	1.03	1.38	1.50	1.31	1.12	1.27
V	371.0	408.2	473.6	384.7	273.6	444.8	363.5	287.6	289.8	330.7	358.8
Cr	187.2	124.3	123.1	158.5	278.9	89.4	154.3	292.7	302.6	276.9	172.1
Co	54.0	60.8	53.7	69.9	46.6	58.7	55.5	43.5	42.0	41.7	52.5
Ni	35.6	13.6	12.4	33.4	108.0	28.1	31.6	104.5	106.0	57.3	53.6
Cu	51.9	45.5	50.2	3.9	62.9	41.6	58.4	46.8	55.7	63.7	222.0
Zn	82.7	72.2	87.9	98.4	51.1	74.6	73.6	43.1	51.5	53.8	108.7
Rb	8.8	8.4	6.3	6.5	10.0	5.4	5.8	7.5	3.2	5.2	5.8
Sr	191.2	178.6	249.0	260.6	231.1	189.2	223.3	213.5	205.1	147.6	138.9
Y	15.8	12.9	16.7	14.1	10.8	14.4	14.0	10.8	10.8	11.6	11.6
Nb	7.4	7.2	7.7	11.5	4.8	9.3	7.5	5.6	6.2	6.1	6.2
Mo	2.0	1.4	1.8	1.3	1.7	1.7	1.6	2.0	1.7	1.9	1.8
Sn	1.1	2.5	0.8	< 1	< 1	< 1	1.6	2.8	0.6	< 1	2.0
Ba	48.2	37.3	5.7	21.2	47.4	32.8	39.5	41.7	28.3	11.5	5.0
La	29.7	49.6	< 1	248.3	< 1	< 1	< 1	220.3	< 1	193.6	127.3
Yb	2.9	2.5	3.0	2.6	5.2	3.7	3.0	4.7	4.0	3.0	3.1
Hf	2.4	2.2	3.2	4.2	2.4	3.1	2.5	1.6	2.0	1.9	< 1
Ta	1.6	2.9	2.2	2.5	1.5	1.4	1.8	2.3	0.9	2.0	0.4
Pb	3.0	5.9	7.1	6.1	5.9	6.1	5.0	4.5	7.2	8.3	9.3
Th	2.9	2.3	< 1	<1.0	2.4	1.6	1.7	< 1	1.7	5.0	2.5

Table (2) Comparison between average Masafi amphibolites and other related rocks

Oxides	1	2	3	4	5	6
SiO_2	43.02	48.38	50.73	50.83	53.29	50.32
Ti O_2	1.46	1.61	1.90	2.03	1.15	1.45
$A1_2O_3$	9.86	14.73	15.29	14.07	13.85	15.63
$FeO_{(t)}$	13.48	10.42	12.68	11.94	11.96	9.98
MnO	0.18	0.21	0.22	0.18	0.18	0.20
MgO	6.62	7.72	6.69	6.34	6.51	7.29
CaO	19.99	10.34	7.83	10.42	6.38	9.98
NaO_2	2.80	3.22	3.90	2.23	2.39	3.06
K_2O	0.71	1.01	0.61	0.82	1.13	0.59
P_2O_5	0.19	0.27	0.25	0.23	0.11	0.21
L.O.I	1.33	1.77	—	0.9	3.09	1.37
Total	**99.64**	**99.68**	**100.10**	**100.00**	**100.04**	**100.08**

1. Average of Massafi area amphibolites.
2. Average of 30 Grand Forks amphibolites (Preto, 1970).
3. Average Connemara striped amphibolites (Evans and Leake, 1960).
4. Average of basic igneous rocks (Nockolds, 1954).
5. Average of ortho-amphibolites (Kamp, 1970).
6. Average of ortho-amphibolites (Mogessie et al., 1985).

5.1 -Ortho or para -amphibolites

The MgO-CaO-FeO(t). diagram clearly shows that igneous and sedimentary precursors exist for the amphibolites, as can be seen on (Figure 5) [17], where the amphibolite plots lie within the both ortho and para amphibolite fields.

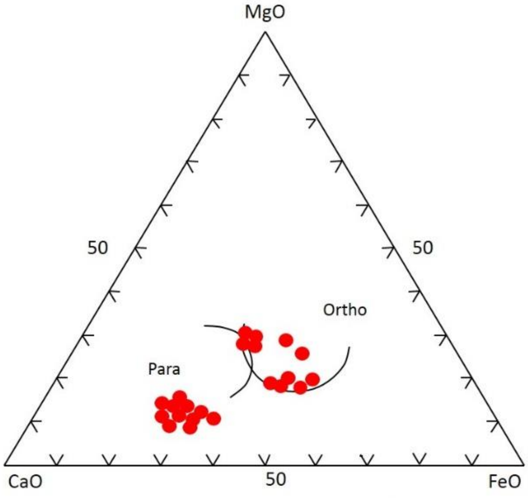

Fig. 5: MgO – CaO – FeO diagra (after Walker et al., 1960).

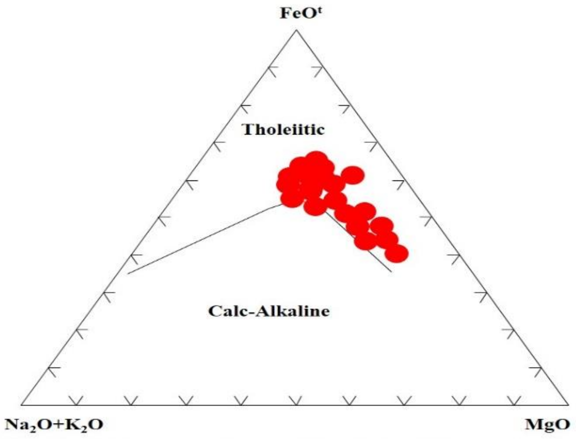

Fig. 6: : AFM ternary diagram (after Irvine & Baragar,1971).

5.2 3-Chemical Affinities of the Original Magma

Using AFM diagram after [18] (Figures 6) it is clear that the amphibolites of Masafi amphibolites describe have a tholeiitic trend more than a Calc alkaline trend. Variation of Ti against Cr after [3] (Figure 7) produces the best descrimination between low potassium tholeiites and ocean floor basalts. All the studied samples lie clearly in the low potassium tholeiites. On the triangular plot of TiO2-K2O-P2O5 (after [14]) all of the samples plot lie in the Oceanic rather than the continental field (Figure 8).

On another diagram using Ti, Mn and P [12], the majority of samples fall in the island arc tholeiite field (TAT) (Figure 9). Island arc tholeiites are simillar to oceanic tholeiites which occur nearest to the trench in modern island arcs [1].

Normalized geochemical distribution patterns of trace elements (Fig.10) illustrate the characteristic depletion of the large ion lithophile elements (LILE) (Sr, Rb, Ba) and the enrichment of the high field strength elements (HFSE (Y) in the studied amphibolites rocks, in general, as compared with chondrite. This may indicate that these rocks have the same fractionation history or they may have been formed from a common oceanic source.

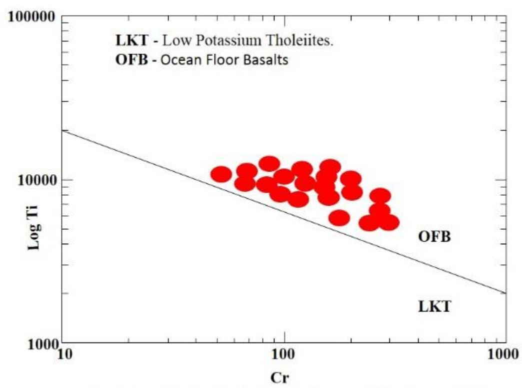

Fig. 7: Log Ti – Cr discrimination diagram (after Pearce 1975).

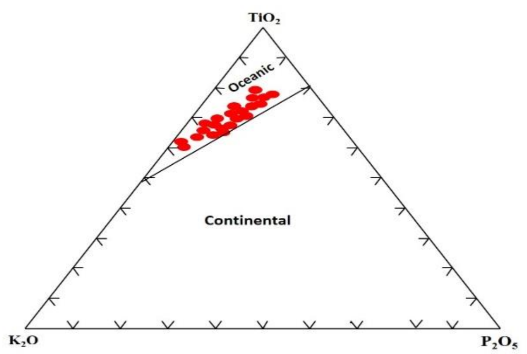

Fig. 8: TiO2 – K2O-P2O5 diagram for amphibolites (after Pearce 1975).

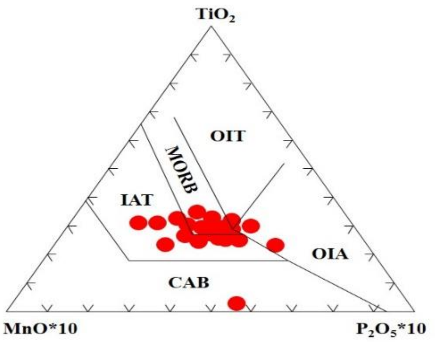

Fig. 9: TiO_2 - MnO*10 - P_2O_5*10 ternary diagram (after Mullen, 1983).
CAB: calc-alkaline basalt, IAT: island arc tholeiite, OFB: ocean floor basalt,
OIT: ocean island tholeiites, OIA: ocean island alkali basalt.

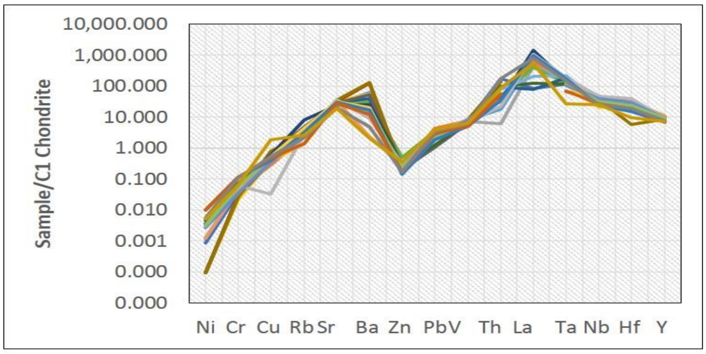

Fig. 10: Chondirite normalized spider diagram for the study area.

6. CONCLUSION

The conclusions arrived at from the present study may be summarized as follows:

1. The amphibolites were incorporated into the ophiolitic mélange after they were metamorphosed as part of a metamorphic sole at the base of peridotites during the northward subduction of a branch of Neotethys.
2. The amphibolites under consideration display an igneous /sedimentary origin, where the most amphibolites in Masafi area reveal a tendency toward an igneous origin with a other show a sedimentary origin.
3. The heterogeneity of their chemistry may reflect chemical modification which took place during metamorphism,
4. The studied amphibolites were derived from a tholeiitic rather than calc alkaline magma
5. The studied rocks showing green schist to amphibolites facies.

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