CUMULATE AND TECTONITE DUNITE FROM MAWAT OPHIOLITE, KURDISTAN REGION, NORTHEASTERN IRAQ: FIELD EVIDENCE AND MINERAL CHEMICAL CONSTRAINTS

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ABSTRACT

The Mawat ophiolite Complex, with an exposed surface area of ~235 Km^2, is one of the largest ophiolitic segments in the Zagros Imbricate Zone in Iraq of the main Zagros ophiolite belt. The ultramafic portion is studied in this paper to verify petrogenetic nature, occurrences and mineral constitutes of the dunites in the Mawat Ophiolite Complex. The dunites in Mawat ophiolite can be grouped into cumulate and tectonite based on the field observations, petrographic study and mineral chemical data of the constituents and stratigraphic succession. The lower tectonite member of the Mawat ophiolite is mainly composed of harzburgite-dunite association and the upper cumulate member is composed of dunite, cross cut by clinopyroxenite veins. The lower tectonite dunite shows typical characteristics of alpine-type II dunite which is characterized by metamorphic deformed rocks with a strong deformed fabric. These rocks have been subjected tosepentinization, spherical weathering, spinel alteration and chloritization of the dominant mineral phases. The upper cumulate dunite comprises the top summit of Mawat Ophiolite Complex. The rock is coarse crystalline massive highly fractured in the outcrop and shows granular mosaic texture in thin sections. The petrographic study shows that the cumulate dunite consists of primary mineral assemblages of olivine (black and green) + pyroxene (cpx and opx) + chromian spinel. No evidence of secondary alteration and metamorphism observed in hand samples and thin section, which may be attributed to crystallization in hydrous magmatic condition at crust-mantle boundary. As it was crystallized in equilibrium conditions with H_2O rich fluid, thus would be stable during emplacement and exposure on the earth surface and unsusceptible to water to convert it to serpentine. Chromian spinels in dunites from Mawat ophiolite retain the peculiar major element signature of boninite melt and upper mantle peridotite, which are involved in the formation of cumulate and tectonite dunites in Mawat ophiolite respectively. Olivine and spinel from cumulates dunites have compositions in the range Fo 90 − 92 and Cr#0.81 − 0.82, whereas the same minerals in tectonite duninetes have compositions Fo 91 and Cr# 0.62 − 0.63. The black colored olivine in cumulate dunite may attribute to occurrences of minute inclusions of spinel + diopside, in addition to low Fo 90 − 91, MnO and NiO as compared to green olivine generation.

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الدونيت التراكمي والتكتوني لاوفيولايت ماوات اقليم كردستان، شمال شرق العراق:
الدلائل الحقلية والمحددات الكيميا ئية المعدنية

يوسف عثمان محمد

المستخلص

يعتبر معقد ماوات الاوفيولايتي، والمتكشف بمساحة تقدر بـ ~250 كم2، واحدا من اكبر المعقدات الموجودة ضمن نطاق زاغروس العراق والذي يمثل جزء من حزام الزاغروس الاوفيولايتي الرئيسي. تبين هذه الدراسة ان الجزء فوق القاعدي للمعقد يتكون بصورة رئيسية من عضو تكتوني سفلي متكون من مجموعة صخور الهارزبركايت-دونيت، وعضو علوي تراكمي متكون من صخور الدونيت المقطوعة بعروق البايروكسينايت. يمكن تقسيم صخور الدونيت ضمن اوفيولايت ماوات أعتماد على الملاحظات الحقلية والبيانات الكيميائية المعدنية والتتابع الطباقي الى دونيت تراكمي وتكتوني. يتميز الدونيت التكتوني السفلي بخصائص نموذجية من نوع الالبين دونيت-النوع الثاني والذي يتميز بصخور متحولة مشوهة مع تشوه عالى في الانسجة الصخرية. اضافة لذلك فان هذه الصخور تعاني من عمليات السربنة الشديدة, التجوية الكروية، تواجد السبينل التحولي وتاثر الاطوار المعدنية الرئيسية بعملية التحول الى معادن الكلورايت. يحتل الدونيت التراكمي الجزء العلوي لاوفيولايت ماوات ويتكون من بلورات خشنة، كتلية، عالية التكسر، ضمن المكشف الصخري، وتمتاز مجهريا بنسيج الفسيفساء الحبيبي. بينت الدراسة المجهرية لصخورالدونيت التراكمي بانه يتكون من معادن أولية هي الاوليفين (أسود وأخضر) والبايروكسين (كلاينوبايروكسين والاورثوبايروكسين) والسبينل الكرومي. وتتميز هذه الصخور ايضا بعدم وجود اي دليل ملحوظ على التحول أو التحلل الثانوي ضمن النماذج الصخرية اليدوية اوالشرائح الصخرية المجهرية وهذا قد يعزى الى تبلور هذه الصخور ضمن بيئة صهيرية مائية على الحد الفاصل بين القشرة والجبة. بناء على ذلك، ان هذه الصخور تبلورت تحت ظروف متوازنة في بيئة غنية بالسوائل المائية، مما يجعلها اكثر استقرارا عند تموضعها وتكشفها على سطح الارض وعدم تاثرها بالمياه وبالتالي عدم تحول معادن الاوليفين الى سربنتين. بينت الدراسة الحالية بأن السبينل الكرومي ضمن صخور الدونيت لاوفيولايت ماوات يحتفظ بخصائص البونينايت وبيريدوتايت الجبة العليا من ناحية العناصر الرئيسية وهما المسؤولان عن تكون صخور الدونيت التراكمي والتكتوني على التوالي.

INTRODUCTION

Ophiolites are fragments of ancient oceanic lithosphere that have been emplaced onto continental margins, accretionary prisms, or island arcs during collision and subduction-accretion events (Moores, 1982; Dilek and Furnes, 2014). The well-preserved peridotites within these ophiolites provide important information on melt extraction, partial melting, and melt-rock interaction within the upper mantle sections of the paleo-oceanic lithosphere (Dilek and Thy, 2009; Arai *et al*., 2007).

Dunite is a member of peridotite family, which is composed exclusively of olivine with less than 5% pyroxene and spinel as accessories. Dunite bodies are significant components of the alpine-type peridotites and ultramafic sections of ophiolites (Irvine and Findlay, 1972; Coleman, 1977; Moores, 1969; Harkins *et al*., 1980; Hopson *et al*., 1981; Boudier and Coleman, 1981). They occur as irregular to tabular-shaped bodies within a harzburgite or lherzolite host and range in size from centimeters to kilometers. Dunite is rarely found within continental rocks, but where it is found, it typically occurs at the base of ophiolite suite, where section of mantle rock from a subduction zone have been thrusted onto continental crust as results of collisions between earth plates. Rarely, xenoliths of dunite have been recorded in basaltic lava of the Hawaian Island and Kimberlites (Sen and Presnall, 1986; Rehfeldt *et al*., 2007).

Dunite comprises the integral outer part of peridotite unit of the the Mawat ophiolite, and consists mainly of olivine with accessory chromian spinel and orthopyroxene (Buda and Al-Hashimi, 1977, Aqrawi, 1990; Zakaria, 1992; Mohammad, 2008; and Mirza, 2008). Geochemical and mineral chemical data suggest that the dunite represents residual rock formed by partial melting of the upper mantle peridotite of alpine type (Aqrawi, 1990; Mohammad, 2008; Mirza, 2008). Dunite typically undergoes retrograde metamorphism

(serpentinization) and alteration in near-surface conditions, as its mineral components are very unstable on the earth surface especially olivine. The polygenetic nature of dunite in ophiolites has been documented by many mantle petrologists (Su *et al*., 2016 and references there in) based on stratigraphic position, structural, mineralogical and textural divergence. Three main genetic categories are addressed including: **1)** tectonite dunite, **2)** cumulative dunite and **3)** replacive dunite. Tectonite dunite is a residual product, formed after extensive partial melting of the mantle peridotite. Cumulative dunite is formed by olivine fractionation from a mafic melt. Replacive dunite is a formed by the reaction of a harzburgite host rock and an olivine-saturated magma. In ophiolite, dunites are usually accommodating various types of magmatic mineral deposits that range from chromitite through nickel sulfide to platinum-group minerals. Since the significance of understanding the generation and evolution of this lithology in ophiolite, dunites of the Mawat ophiolite are considered in this study. It will be reasoned, based on combined field and mineral chemical overprint that for the first time two types of dunites occur in this ophiolite complex, which are products, individually or in combination, of different processes that include partial melting and crystallization. As the chromian spinels and olivines are petrogentic pathfinder phases in mantle peridotites and overlying ultramafic cumulates, hence the chemical compositions of these minerals are used for constraining the tectono-magmatic condition from which they were crystallized.

GEOLOGICAL BACKGROUD

The Zagros Orogenic Belt in northern Iraq comprises four parallel northwest – southeast trending structural domains. These are the Sanandaj – Sirjan Zone, the Imbricate Zone, the Zagros High and Low Fold and Thrust Belts, and the Mesopotamian Foreland BasinMohammad *et al*., 2014). The Mesozoic ophiolites of Iraq include four confirmed ophiolites, which, are from southeast to northwest, the Penjween, Mawat, Hasan Bag and Qalander and are an integral part of the Imbricate Zone. Available geochronological and geochemical data support congenetic nature among Iraqi ophiolites as northeast extension of the outer Zagros Ophiolite Belt (Mohammad and Cornell, 2017).

The Mawat ophiolite of the main Zagros Ophiolite Belt is considered to be an integral part of Zagros Mountain Belt that stretches between Iranian plateau of Eurasia and north and northeastern margins of the Arabian Plate (Fig.1a). The allochthonous Mawat ophiolite (Fig.1b) covers an area of about 235 square kilometers (Othman and Gloaguen, 2014). The Mawat ophiolite represents longitudinal igneous body of 25 Km long and 7 – 12 Km wide striking NE – SW (Mirza, 2008). The dominant rock units consist of peridotite, gabbro, metagabbro, metavolcanic and pillow basalts with minor leucogranite and granitic pegmatite. The Mawat ophiolite tectonically rests on Cretaceous – Tertiary igneous and sedimentary rock units represented by Walash volcanics, Shiransh Formation, Tanjero Formation and Red bed Series (Al-Mehiadi, 1974). It is considered to be the largest ophiolitic block in Iraq. As a result of rough topography and semi-arid environmental condition, vegetation and soil cover are minimal in the Mawat ophiolite area, making the rock units almost completely accessible to observation. However, remnants of anti-personnel mines spread over the Mawat ophiolite area makes it difficult to reach different rock units easily.

Recently Othman and Gloaguen (2014) updated the geological map of Mawat ophiolite using Support Vector Machine (SVM) methods based on Advanced Space-borne Thermal Emission and Reflection radiometer (ASTER) satellite. In their reversion, a new mafic unit was identified in addition to accurate geometry and area measurements of different igneous units of the Mawat ophiolite. The mantle sequence consists predominantly of massive alpine-type peridotite and comprises tectonized harzburgite and dunite with variable degrees of

deformation and serpentinization, covering an area of about 33.9 Km^2. The dominance of harzburgite among the peridotite family in association with podiform chromite in Mawat ophiolite may suggests that the ophiolite body belong to Harzburgite Ophiolite Type (HOT), similar to most ophiolites in the Zagros Orogenic Belt. The dominant outcrops in the Mawat ophiolite consist of mafic rocks, including gabbro and basaltic rocks affected by variable degrees of deformation, metamorphism and alteration, covering about 195 Km^2 of the exposed area of the Mawat ophiolite. Stratigraphic relationships show that the ophiolite is overturned with local thrust faults within the sequence, from pillow basalts at the bottom, through amphibolitized gabbro, to ultramafic at the top of the sequence (Mohammad and Cornell, 2017). A comparable sequence is observed in the Kermanshah ophiolite in Iran (Allahyari *et al.*, 2010).
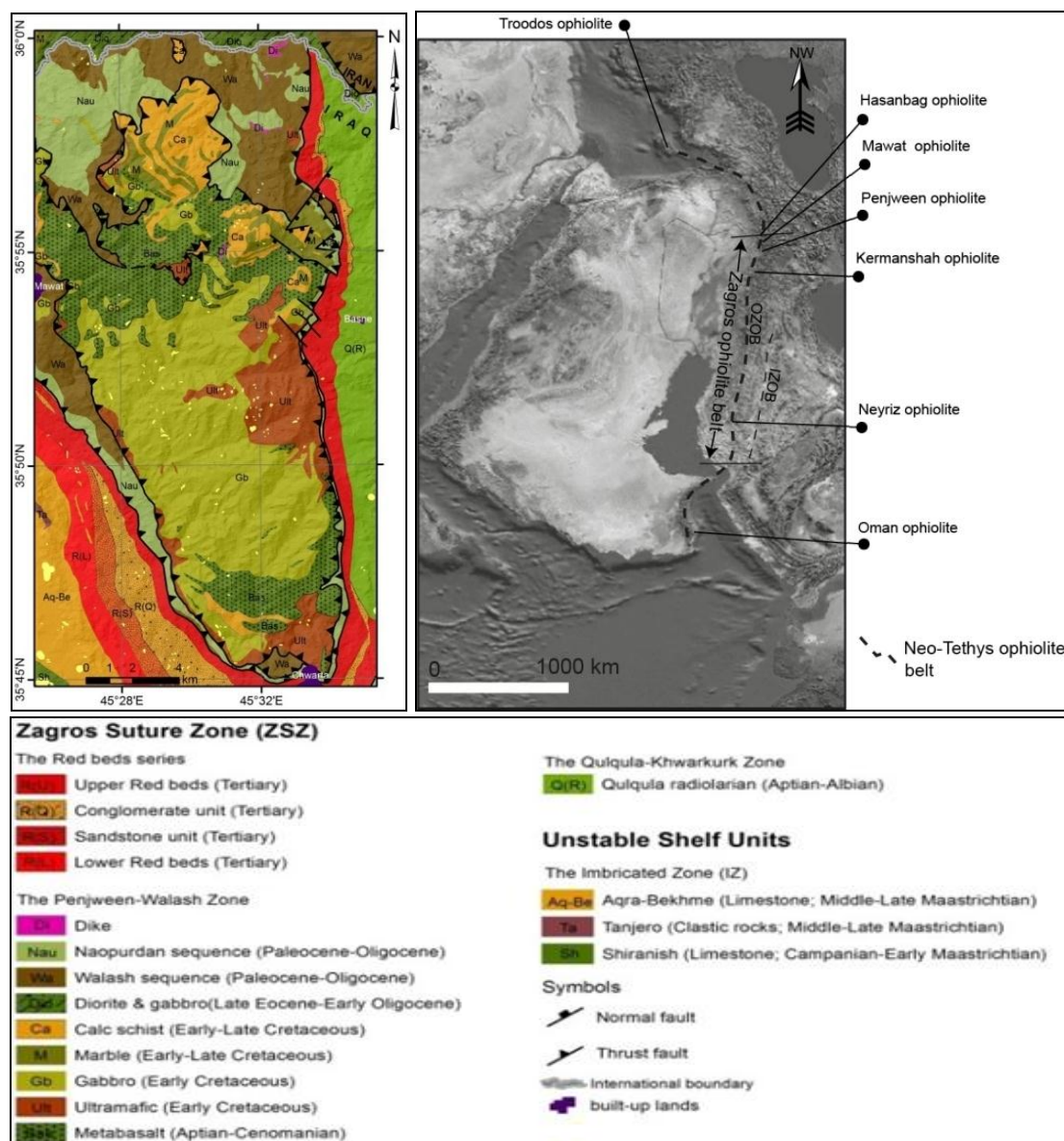

Fig.1: **a)** Location of the Mawat ophiolite within the ~3000 Km long Late Cretaceous Ophiolite Belt spanning from Cyprus to Oman (after Mohammad and Cornell, 2017), **b)** Geological map of the Mawat area (after Othman and Gloaguen, 2014 compiled from Al-Mehaidi, 1974)

METHODOLOGY

Filed work for various research projects have been done for different parts of the Mawat ophiolite by the author since 2002 (Mohammad, 2008; Mohammad *et al*., 2014; Mohammad and Qaradaghi, 2016; Mohammad and Cornell, 2017). Hundreds of samples were collected covering a nearly complete cross section of the peridotite body at the three master outcrop sections represented by Rashakani, Goranga and Sarshew Valley sections (Fig.2). Few slab sections have been prepared from the podiform and massive samples collected along three master sections. Hundreds of polished thin sections were prepared from the samples for petrographical examination. Three samples of cumulate dunite and three samples of tectonite dunite have been chosen for mineral chemical composition analysis using scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS). The results of chemical analysis of the olivine and spinel are listed in Tables 1 and 2. SEM-EDS analyses of major phases were performed at Osaka Prefecture University (JEOL-840A scanning electron microscope), Japan and Gothenburg University (Hitachi S-400N scanning electron microscope) Sweden. The analytical conditions were: 20 kV, working distance 10 mm, specimen current 6 nA. The calibration standards were manufactured by Microanalysis Consultants, St. Ives, Cambridgeshire, UK.

Fig.2: Google earth image showing the main ultramafic unit of Mawat ophiolite.
The location of the three sampling master sections is indicated

Table 1: Chemical analysis of olivine from tectonite and cumulate dunite from Mawat ophiolite

Mineral	B-OL-1	B-OL-2	B-OL-3	B-OL-3	B-OL-4	B-OL-5	B-OL-6	B-OL-7	B-OL-8	B-OL-9	B-OL-10	G-OL-1	G-OL-2	G-OL-3	G-OL-4	G-OL-5	G-OL-6	G-OL-7	G-OL-8	G-OL-9	G-OL-10	T-OL-1	T-OL-2	T-OL-3	T-OL-4	T-OL-5	T-OL-6	T-OL-7	T-OL-8	T-OL-9	T-OL-10
SiO₂	39.86	40.96	40.44	40.12	40.16	40.24	40.23	40.15	39.99	40.52	39.82	39.76	39.94	40.00	40.15	40.18	40.19	40.12	40.77	40.38	40.19	40.84	40.85	40.73	40.84	40.67	41.05	40.77	40.94	40.89	40.86
TiO₂	0.18	0.32	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.12	0.26	0.05	0.11	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.10	0.02	0.02	0.00	0.00	0.00	0.03	0.05	0.11	0.07	0.04
FeO	9.23	9.03	9.06	8.74	8.88	8.90	8.84	8.65	9.02	9.07	8.59	7.63	7.80	7.74	7.88	7.94	7.87	7.91	7.46	7.47	7.53	8.25	8.22	8.29	8.31	8.12	8.11	8.05	7.89	7.85	8.12
MnO	0.10	0.10	0.10	0.10	0.26	0.27	0.20	0.19	0.29	0.15	0.10	0.24	0.32	0.30	0.21	0.33	0.24	0.23	0.10	0.14	0.23	0.27	0.24	0.19	0.17	0.53	0.54	0.51	0.45	0.47	0.41
MgO	50.41	49.17	49.95	50.14	50.02	50.22	50.14	50.05	50.70	49.61	51.30	51.65	51.61	51.06	50.85	50.92	50.75	50.77	50.81	50.78	50.66	50.42	50.48	50.44	50.45	51.08	50.85	50.53	50.43	50.21	50.51
NiO	0.25	0.17	0.13	0.10	0.23	0.33	0.20	0.33	0.30	0.16	0.37	0.30	0.35	0.34	0.37	0.34	0.35	0.30	0.50	0.48	0.46	0.50	0.45	0.43	0.53	0.46	0.38	0.21	0.26	0.30	0.48
Total	100.03	99.75	99.68	99.20	99.56	100.02	99.61	99.37	100.30	99.63	100.44	99.63	100.13	99.44	99.46	99.71	99.40	99.33	99.69	99.35	99.17	100.30	100.26	100.08	100.30	100.86	100.96	100.12	100.08	99.79	100.42
Si	0.977	1.002	0.992	0.988	0.987	0.985	0.988	0.988	0.978	0.994	0.971	0.973	0.974	0.981	0.984	0.983	0.986	0.985	0.994	0.989	0.987	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99
Ti	0.003	0.006	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.005	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe²⁺	0.189	0.185	0.186	0.180	0.183	0.182	0.181	0.177	0.184	0.186	0.175	0.156	0.159	0.159	0.162	0.162	0.161	0.162	0.152	0.153	0.155	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.16	0.16	0.16
Mn	0.002	0.002	0.002	0.002	0.005	0.006	0.004	0.004	0.006	0.003	0.002	0.005	0.007	0.006	0.004	0.007	0.005	0.005	0.002	0.003	0.005	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Mg	1.843	1.794	1.826	1.840	1.833	1.833	1.835	1.836	1.848	1.815	1.864	1.885	1.876	1.867	1.858	1.858	1.855	1.858	1.847	1.854	1.854	1.83	1.83	1.83	1.83	1.84	1.83	1.83	1.84	1.83	1.83
Ni	0.005	0.003	0.003	0.002	0.005	0.006	0.004	0.007	0.006	0.003	0.007	0.006	0.007	0.007	0.007	0.007	0.007	0.006	0.010	0.009	0.009	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Fo	90.687	90.661	90.766	91.094	90.944	90.959	91.001	91.210	90.927	90.699	91.414	92.348	92.185	92.164	92.003	91.957	91.998	91.964	92.391	92.378	92.305	91.59	91.63	91.56	91.54	91.81	91.79	91.80	91.93	91.94	91.73
Fa	9.313	9.339	9.234	8.906	9.056	9.041	8.999	8.790	9.073	9.301	8.586	7.652	7.815	7.836	7.997	8.043	8.002	8.036	7.609	7.622	7.695	8.41	8.37	8.44	8.46	8.19	8.21	8.20	8.07	8.06	8.27

Black Olivine and Green Olivine columns belong to **Cumulate Dunite**; T-OL columns belong to **Tectonite Dunite**.

$Fo = Mg*100/(Mg + Fe)$, $Fa = Fe*100/(Mg + Fe)$, Oxides in Wt.%

Table 2: Chemical analysis of chromian spinel from tectonite and cumulate dunite from Mawat ophiolite

Mineral	Cumulate Dunite										Tectonitedunite									
	C-Spl-1	C-Spl-2	C-Spl-3	C-Spl-4	C-Spl-5	C-Spl-6	C-Spl-7	C-Spl-8	C-Spl-9	C-Spl-10	T-Spl-1	T-Spl-2	T-Spl-3	T-Spl-4	T-Spl-5	T-SPL-6	T-Spl-7	T-Spl-8	T-Spl-9	T-Spl-10
SiO_2	0.08	0.02	0.03	0.01	0.06	0.06	0.05	0.05	0.05	0.06	0.1	0.08	0.08	0.09	0.08	0.08	0.07	0.09	0.09	0.07
TiO_2	0.21	0.15	0.13	0.8	0.1	0.12	0.15	0.04	0.19	0.36	0.08	0.14	0.06	0.12	0.13	0.05	0.06	0	0.01	0.02
Al_2O_3	8.85	8.99	9.32	9.56	9.67	9.68	9.17	9.12	9.26	9.18	20.76	20.3	20.57	20.37	20.51	20.4	20.2	20.69	20.74	20.73
Cr_2O_3	62.21	60.31	60.53	60.72	61.1	61.14	61.51	61.24	60.08	60.78	51.81	51.52	51.7	52.13	51.75	51.68	51.62	51.6	51.62	50.73
V_2O_5	0	0.63	0.3	0.47	0.65	0.61	0.41	0.56	0.13	0.11	0.02	0.1	0.14	0.1	0.23	0.38	0.44	0.52	0.49	0.78
FeO	22.02	23.14	22.88	23.13	23.47	23.59	23.47	23.3	21.71	21.97	19.13	19.4	19.26	19.08	18.98	18.57	18.79	18.88	18.77	18.64
MnO	1.02	0.77	0.9	0.98	0.56	0.69	0.49	0.68	0.46	0.89	0.14	0.16	0.21	0	0	0.13	0.17	0.15	0.14	0.16
MgO	5.13	5.12	5.24	5.26	5.38	5.49	5.51	5.86	5.67	5.45	7.74	8.3	8.3	8.19	8.21	8.18	8.28	8.33	8.34	8.86
Total	99.52	99.13	99.33	100.93	101	101.38	100.8	100.9	97.55	98.8	99.78	100	100.3	100.1	99.89	99.47	99.63	100.3	100.2	99.99
Si	0.003	0.001	0.001	0	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.003	0.003	0.002
Ti	0.005	0.004	0.003	0.02	0.003	0.003	0.004	0.001	0.005	0.009	0.002	0.003	0.001	0.003	0.003	0.001	0.001	0	0	0
Al	0.357	0.365	0.377	0.38	0.384	0.383	0.366	0.363	0.379	0.372	0.776	0.758	0.765	0.759	0.765	0.764	0.756	0.769	0.77	0.77
Cr	1.684	1.643	1.642	1.618	1.627	1.623	1.645	1.636	1.65	1.652	1.299	1.291	1.29	1.303	1.295	1.298	1.297	1.286	1.285	1.265
V	0	0.017	0.008	0.013	0.018	0.016	0.011	0.015	0.004	0.003	0.001	0.003	0.004	0.003	0.006	0.01	0.011	0.013	0.012	0.02
Fe^{2+}	0.63	0.667	0.656	0.652	0.661	0.662	0.664	0.658	0.631	0.632	0.507	0.514	0.508	0.505	0.502	0.493	0.499	0.496	0.497	0.492
Mn	0.03	0.022	0.026	0.028	0.016	0.02	0.014	0.019	0.014	0.026	0.004	0.004	0.006	0	0	0.003	0.005	0.004	0.004	0.004
Mg	0.262	0.263	0.268	0.264	0.27	0.275	0.278	0.295	0.294	0.279	0.366	0.392	0.391	0.386	0.387	0.388	0.392	0.392	0.392	0.417
Cr ≠	0.83	0.82	0.81	0.81	0.81	0.81	0.82	0.82	0.81	0.82	0.626	0.63	0.628	0.632	0.629	0.63	0.632	0.626	0.625	0.621
Mg ≠	0.29	0.28	0.29	0.29	0.29	0.29	0.3	0.31	0.32	0.31	0.419	0.433	0.434	0.434	0.435	0.44	0.44	0.441	0.441	0.459

Cr ≠ = Cr/ (Cr + Al); Mg ≠ = Mg/ (Mg + Fe); Oxides in Wt.%

RESULTS

▪ **Field observations**

− **Cumulate Dunite:** The dunite body occurs as massive blocks in the upper parts of the Mawat ophiolite covering about 1 × 1.5 Km surface area with approximate 70 m thickness. Stratigraphically the rock occupies the highest portion of the Mawat ophiolite. The rocks show weak layering in outcrop with vertical and lateral thickness variation (Fig.3a). In hand samples, the rocks show green and black color (Fig.3b). The size of black olivine grains sometimes reaches up to 3 cm (Fig.3c). Green olivine shows typical fresh light olive green color. Spinel grains are disseminated within the massive dunite body ranging in size from 1 mm to 5 mm. Dunites are intercalated with clinopyroxenite veins rich in nickel sulfide and native copper minerals (Fig.3d). The distribution of spinel is heterogeneous in the dunite body with local segregation. Coarse crystals of olivine and spinel are dominant. No serpentinization and serpentine polymorphs are observed along the cracks, suggesting that the dunites are not suffering any degree of alteration and serpentinization, which could be an interesting topic for mantle petrologists. The underlying rocks consist of highly deformed and jointed massive serpentinized harzburgite. Exposure of the contact between cumulate and tectonite dunites has not been found due to extensive crushing. No evidence of spheroidal weathering observed, however, the rocks are highly jointed and fractured.
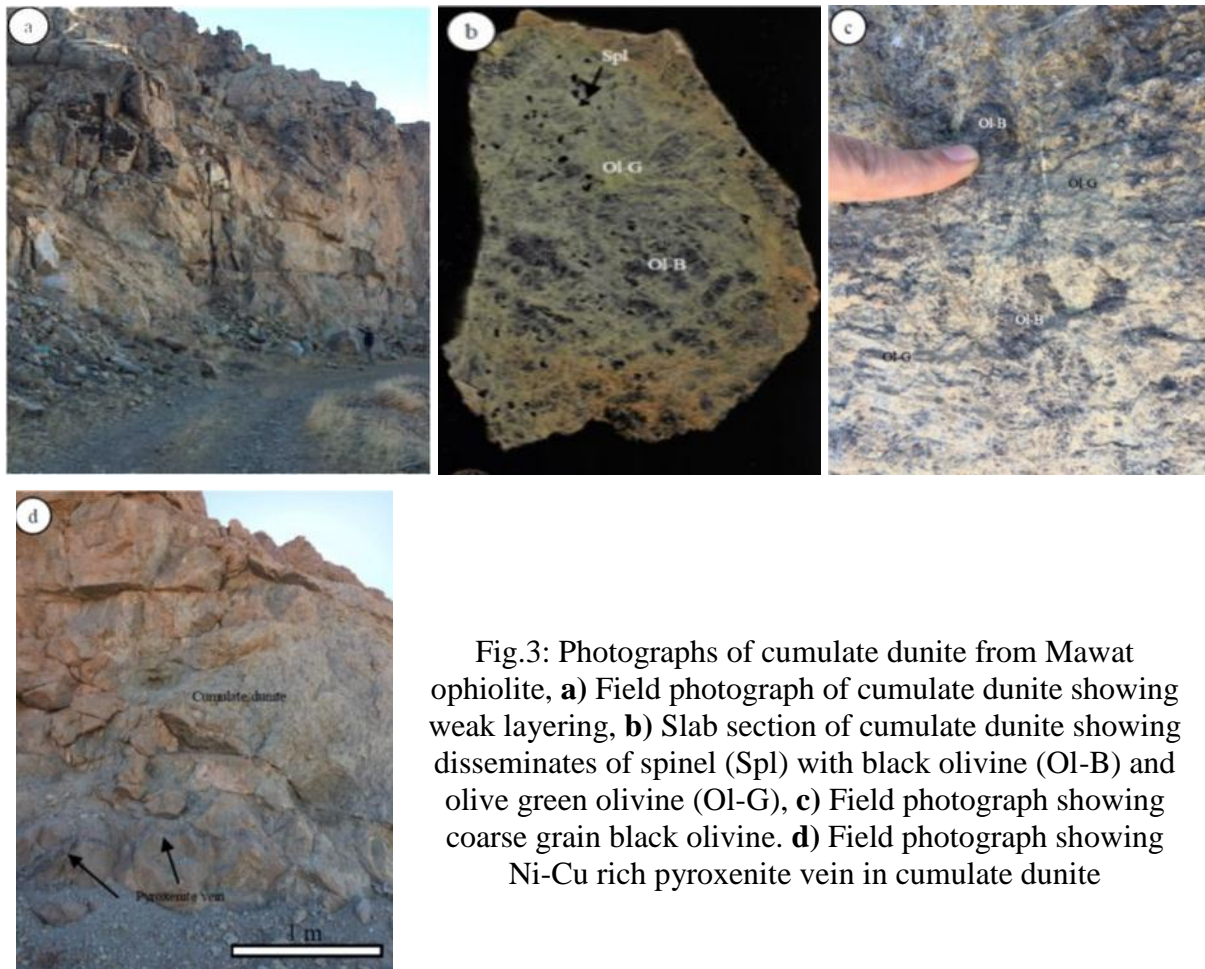
Fig.3: Photographs of cumulate dunite from Mawat ophiolite, **a)** Field photograph of cumulate dunite showing weak layering, **b)** Slab section of cumulate dunite showing disseminates of spinel (Spl) with black olivine (Ol-B) and olive green olivine (Ol-G), **c)** Field photograph showing coarse grain black olivine. **d)** Field photograph showing Ni-Cu rich pyroxenite vein in cumulate dunite

− **Tectonite Dunite:** Tectonite dunite occurs as irregular to tabular-shaped bodies within harzburgite host (Fig.4a), stratigraphically, occurs at the base of ultramafic rocks and commonly associated with massive podiform chromite especially in Ser Shiw valley (Fig.4b).

It occurs as a podiform or spheroidal shape in the outcrops with variable size, ranging from meter to centimeter scale. The olivine grains are of dark green color on fresh surfaces. Fine grains of spinel, ranging in size from 0.3 to 1 mm, are disseminated in the dunite and occur as irregular grains and aggregates. Extensive serpentinization process and serpentine mineral observed along the cracks, suggesting that the rocks have suffered extensive degree of serpentinization. Spheroidal weathering is typical in the outcrops (Fig.4c). Dunite pods are intercalated with extensive serpentine, carbonate and magnetite veins. Along the rims of the dunite pods, magnetite transformed to hematite by oxidation of Fe^{2+} to Fe^{3+} is evident by yellow brownish mantle shell (Fig.4d). On weathered surfaces they show yellow brown color very similar to the weathered harzburgite except that the later one occurs as massive blocky unit in the outcrops. Dunite can be easily separated from harzburgite as the later shows clear evidence of differential weathering among the mineral phases; such that the pyroxene stand out forming positive dominated relief as compared to olivine (Fig.4e).
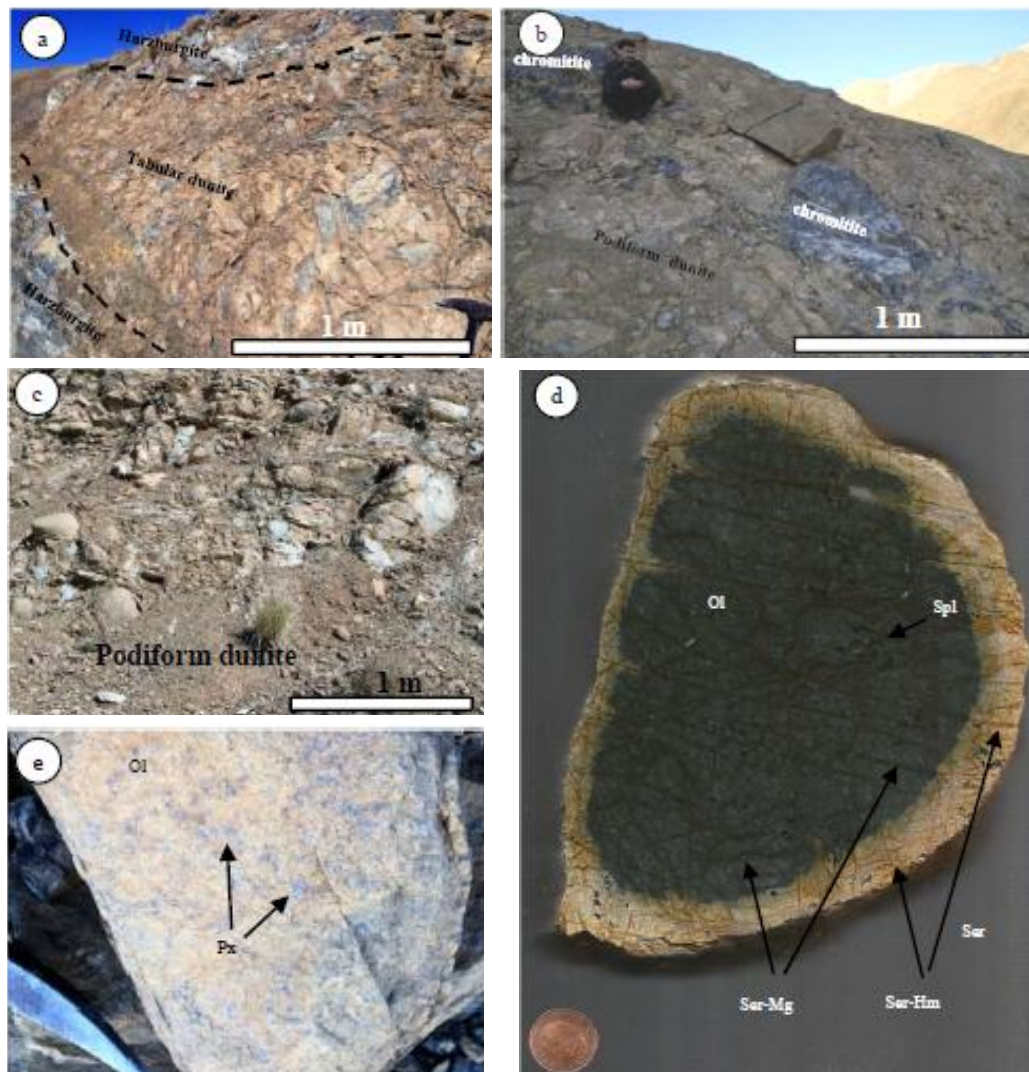
Fig.4: Photographs of tectonite dunite from Mawat ophiolite, **a)** Field photograph of tabular tectonite dunite hosted in harzburgite, **b and c)** Field photographs showing the podiform or spherical shaped bodies of dunite, **d)** Slab section of the tectonite dunite, showing spherical weathering. Mineral abbrivations: Ol, olivine; Spl, spinel; Ser, serpenitine; Mag, magnetite; Hem, Hematite, **e)** Field photograph showing pyroxene stand in harzburgite

- **Petrography**
- **Tectonite Dunite:** Dunite is extensively serpentinized. Modal mineral percentage is given in Table 3. Olivine is replaced by serpentine and magnetite along the rims forming typical mesh texture (Fig.5a). Rarely, orthopyroxene is serpentinized along the cleavage plane (Fig.5b). Reddish brown spinel of irregular amoeboid shape is present in most samples that have survived extensive alteration to ferritchromite in back scattered images (Figs.5c and d). Secondary magnetite is transformed to hematite along the outer rims of the spheroidal dunite (Fig.4d). Olivine grains, ranging in size from 0.5 to 1 mm, are replaced by serpentine along fractures and grain margins. Transformation of syn-serpntinization magnetite by post serpentinization hematite is obvious along the crust of spheroidal bulls of dunite. Cataclastic texture and pull-apart structures in chromite grains are common. Pseudomorphs after olivine and orthopyroxene are recognized by their shape because syn-serpentinization magnetites frequently form trails along grain boundaries of these pseudomorphs. On the basis of magnetite trails, the primary texture of dunite is inferred to be equigranular. The size of spinel grains is variable ranging from $1 - 2$ mm. Only a few grains occur in one thin section.

- **Cumulate Dunite:** The dunite consists of nearly monomineral fresh olivine with no effect of serpentinization developed along the fractures (Fig.5e). Olivine grains tend to have fairly straight sides (Fig.5e) and some grain boundaries intersect in triple junctions at approximately $120°$ (Fig.5f), which is typical for mosaic texture (Ragan, 1969). Undulatory extinction and strain lamellae olivine grains in dunite are typical. Based on the megascopic and microscopic observations "green" and "black" olivines, are found in the cumulate dunite (Fig.3b). Green generation of olivine is fine and lacks any mineral inclusions. Chromite, ranging in size from 0.3 to 4 mm, occurs as disseminated irregular grains and aggregates. The dunite is composed of multiple generations of olivine $(90 - 95\ \%)$, pyroxene $(< 5\%)$ and chromian spinel $(> 6\%)$. Modal mineral percentage is given in Table 3. Magnetite, chromian spinel and diopside exsolutions in black colored olivine were first observed in thin sections and then confirmed by electron microprobe analysis. These lamellae are oriented in one direction (Figs.5g and h). Chromian spinel lamellae are normally $1 - 2$ µm wide and 2µm $- 50$µm long, whereas diopside lamellae have the same width but are typically a little shorter of maximum length 20µm (Figs.6a and b). Magnetite occurs as tiny separate grains distributed heterogeneously within the olivine host (Fig.6c). The two are commonly intergrown as seen in back scattered images where a single lamella is composed of chromian spinel at one end and diopside at the other. Volumetrically, diopside exsolution lamellae are much less abundant than chromian spinel lamellae.

- **Mineral chemistry**
- **Cumulate Dunite:**
  - **Olivine:** Olivine crystals are unzoned homogeneous from core to rim and are generally bimodal in color and composition within individual thin section. Green olivines from the cumulate rocks are unzoned homogenous and display a quite restricted forsterite content ranging from Fo_{91} to Fo_{92}, and NiO and MnO contents range from 0.3 to 0.5; and from 0.1 to 0.3 wt.%, respectively (Table 1). Meanwhile, the black colored olivine grains are less MgO rich, with forsterite content ranging from Fo_{90} to Fo_{91}. NiO and MnO contents of olivine range from 0.1 to 0.3 wt.% and from 0.1 to 0.2 wt.%, respectively (Table 1). As the lamellae inclusions in the black olivines are tiny and commonly superimposed, it was difficult to get accurate compositions; however, the EDS spectral analyses show elemental spectras identical for magnetite, diopside and chromian spinel (Figs.6d, e and f).
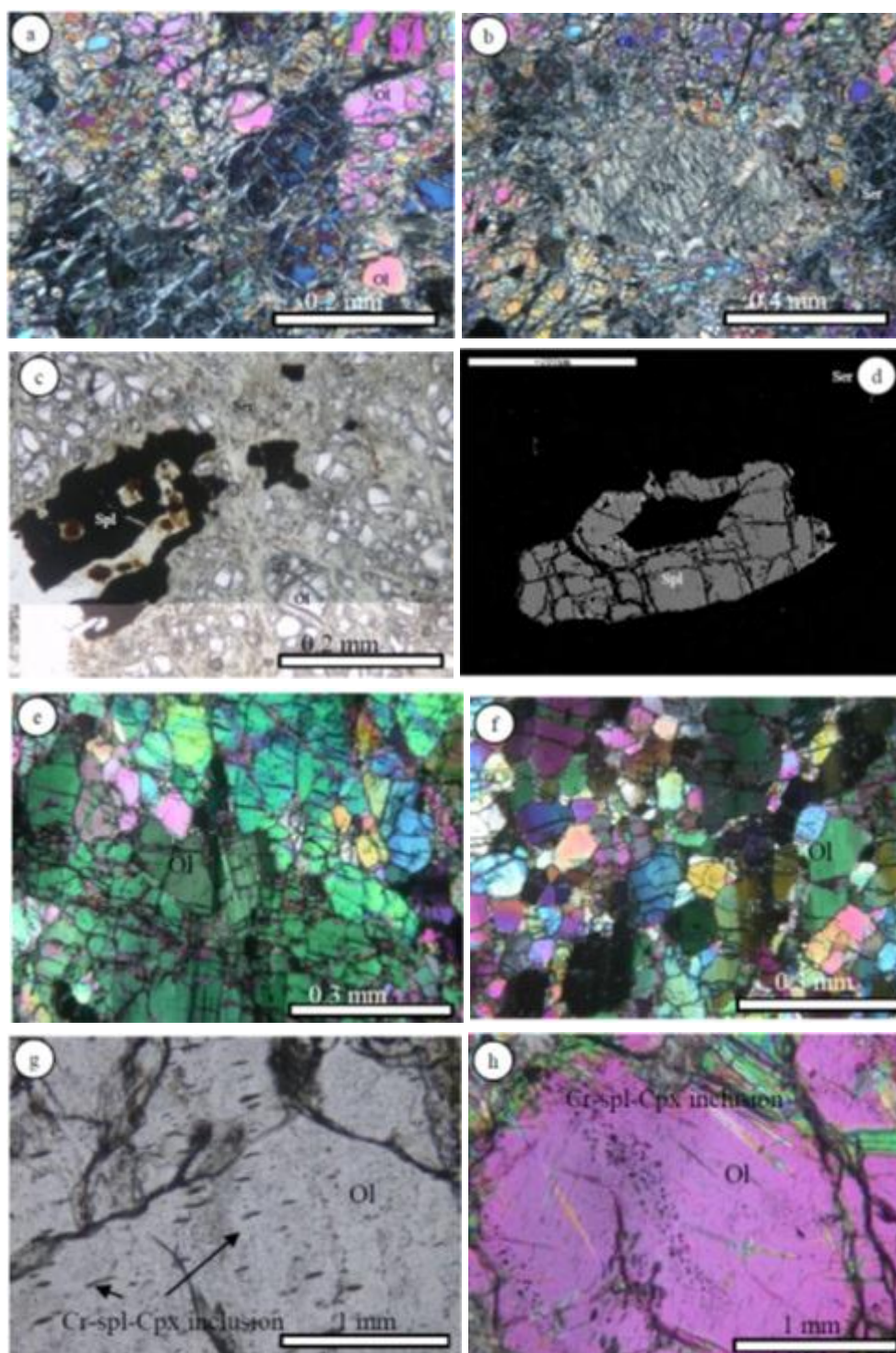
Fig.5: **a)** Photomicrograph of mesh texture in tectonite dunite, **b)** Photomicrograph of orthopyoxene serpentinized along the cleavage plane, **c)** Photomicrograph of amboied spinel in tectonite dunite with silicate inclusions, **d)** Back scatter image (BSE) of chromian spinel in tectonite dunite, **e and f)** Photomicrograph of fairly straight sides and triple junction among olivine grain in cumulate dunite, **g and h)** inclusions of spinel and cpx in black colored olivine from cumulate dunite. Abbreviations as in Figure 4. Fig.5 (**a, b, e, f** and **h**) under XN; and Figs.5 (**c** and **g**) under PPL

Table 3: Modal mineral percentages of the cumulate and tectonite dunites from Mawat ophiolite. Scanned thin section provided

Sample No.	Primary minerals %				Accessory Minerals %	Secondary Minerals %				
	Olivine		Pyroxene							
	Ol-G	Ol-B	Cpx	Opx	Cr-spl	Ser	Ch	Car	Tlc	Mag-Hem
1D-TE	60		3		8	19	2	1	1	6
2D-TE	70		4		5	15	1	1	1	5
3D-TE	69		5		7	10	3	1	2	3
1D-CU	50	33		2	15					
2D-CU	62	30		3	5					
3D-CU	65	20		3	12					

| 2D-CU | 1D-CU | 3D-CU | 1D-TE | 2D-TE | 3D-TE |

Mineral Abbrivations: Ol-G: Green Olivine, Ol-B: Black olivine, Cpx: Clinopyroxene, Opx: Orthopyroxene, Cr-spl: Chromian spine, Ser: Serpentine, Car: Carbonate, Tlc: Talc: Mag-Hem: Magnetite-Hematite
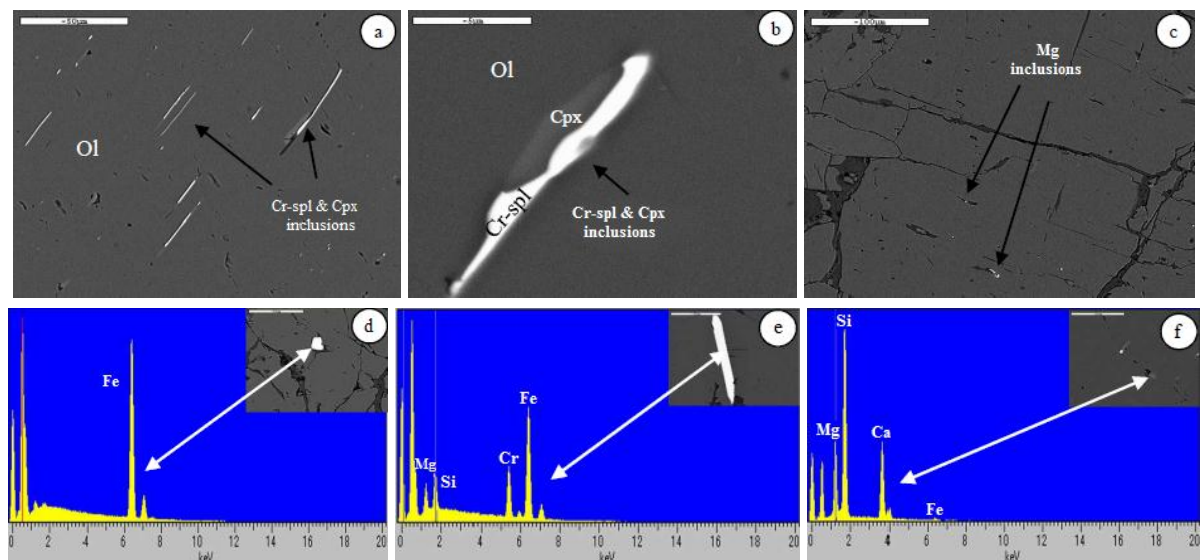
Fig.6: **a, b and c**) BSE of chromian spinel, clinopyroxene and magnetite in olivine from cumulate dunite. **d, e and f**) EDS elemental spectra of mineral inclusions in balck olivine from cumulate dunite

- **Chromian spinel:** The spinel crystals are compositionally unaltered and homogeneous from core to rim in the cumulates dunite. The Cr_2O_3 content of spinel is very uniform and high, ranging from 60 to 62.8 wt.%, and is dominantly higher than 60 wt.%, (Table 2). Spinels in dunites are characterized by very low Al_2O_3 contents (~8.8 – 9.6 wt.%) and all

are chromian spinel with high Cr# $(= 0.81 - 0.82)$ and relatively high TiO_2 content (0.1 to 0.36 wt.%), (Table2).

–   **Tectonite Dunite:**
-   **Olivine:** Relict olivines in the tectonite dunite are compositionally uniform within the range of Fo_{91}. NiO and MnO contents of the olivines range from 0.2 to 0.5; and 0.2 to 0.5 wt.%, respectively with very low TiO_2 and Al_2O_3 contents (Table 1).

-   **Chromian spinel:** The spinel composition in the basalt tectonite dunite of the Mawat ophiolite are slightly poor in Cr_2O_3 $(50.7 - 51.8$ wt.%), high in Al_2O_3 $(20.4 - 20.7$ wt.%), low $TiO_2(0.01$ to 0.1 wt.%) and the Cr#$(100 \times$ Cr/ Cr + Al) ranges from 62 to 63 (Table 2).

DISCUSSION
▪   **Black Olivine**
Fresh olivines that are black to the naked eye are found in some cumulate dunites. Tectonite dunites are easily converted to be black in color, when serpentinized, due to production of secondary fine magnetite particles. The dunites that contain fresh but black-colored olivines are usually coarse-grained. These coarse olivine grains are sometimes very heterogeneous in color; the blackish part grades to whitish part in single grains. The black color is due to homogeneous distribution of minute $(< 10$ microns) black particles in olivine. They are rod-like or plate-like in shape in thin section, sometimes being aligned under crystallographic control of the host olivine. Olivines are clear and free of these inclusions around primary chromian spinel inclusions or chromian spinel lamellae (Arai, 1978). The EDS spectroscopy indicates that the minute black particles are chromian spinel always associated with diopside.

It is interesting to note that the olivines, in basal mantle dunite underlain by the black-colored dunites, are totally free of the black inclusions, giving the ordinary colors of olive deep green of Mg-rich olivine. It is not likely that the chromian spinel inclusions are formed t by secondary oxidation of olivine by invasion of oxygen, which is possible along cracks or grain boundaries. They most probably formed due to dehydrogenation from primary OH-bearing olivines upon cooling (Arai *et al*., 2015; Khisina and Lorenz, 2015). Hydrogen was quickly diffused out from the olivines to leave magnetite and excess silica (Demouchy, 2010). The excess silica was possibly combined with a monticellite $(CaMgSiO_4)$ component of the host olivine to form diopside. The OH-bearing (hydrous) olivines can be precipitated from hydrous magmas, and the hydrous nature of the magma can promote an increase in grain size due to faster diffusion of elements. The minute inclusions of magnetite, chromian spinel + diopside are thus indicators of primary hydrous character of host olivine.

In the literatures, the black colored olivine in terrestrial rocks has only recorded intwo localities including Horoman peridotite, Japan and Zambales ophiolite, Philippines (Arai *et al*., 2015; Yumul, 2004). In Horoman peridotite the black colored olivine is attributed to minute inclusions of magnetite + Cr-spinel + pyroxene while no interpretation is given to that in Zambales ophiolite of the Philippines.

▪   **Spheroidal weathering versus fresh olivine**
Field observation suggests that the dunite in Mawat ophiolite shows different behaviors toward serpentinization process as a result of water infiltration. The tectonite dunites are extensively serpentinized, reflected by spheroidal weathering and exfoliation (Fig.7a and b). Meanwhile the cumulate dunites show fresh olivines without any effect of serpentinization.

The question which arises here is why olivine, which is usually unstable on the earth surface, shows different response to weathering processes in the Mawat ophiolite. This phenomena can be explained based on two mechanisms: First the rounded or spherical shapes of tectonite dunite are by product of two processes; water infiltration and spheroidal jointing (Ollier, 1971). As the olivine in tectonite dunite is crystallized in anhydrous mantle conditions it will be highly susceptible to weathering when it is exposed on the earth surface. Consequently the weathering attacks an exposed tectonite from all sides at once, and decomposition is most rapid along the corners and edges of the rocks. As the decomposed materials fall off, the corners become rounded, and the blocks are eventually reduced to an ellipsoid or a podiform shapes. Concurrently the pods undergo exfoliation due to volume expansion-contraction as the olivine and magnetite transform to serpentine and hematite respectively (O'Hanley, 1992; Zhao *et al.*, 2019). This is supported by the observed karnel pattern and color change from core to rim of the tectonite dunite pods. Second, the fresh olivine in cumulate dunite that survived serpentinization, however the rock unit undergoes fracturing and jointing may suggests that the olivine is crystallized in hydrous condition at the crust-mantle boundary (Zhang *et al.*, 2010).

The stratigraphic position, occurrences of the minute inclusions in olivine in addition to pegmatitic nature of some olivine grains support the hydrous low- pressure crystallization nature of cumulate dunite. Indirect depth of crystallization of cumulate dunite has been estimated from the enclosing pegmatite granite body. Currently, it is suggested that cumulative dunites formed within the lower continental crust before subduction (Zhang *et al.*, 2010; and Seo *et al.*, 2013) or at the crust-mantle boundary above the sub-arc mantle before transport to deep levels by subduction-induced corner flow (Song *et al.*, 2007; and Rajesh *et al.*, 2013).A low pressure 2.5 kbar environment is indicated by minimum melt composition, in addition, the presence of andalusite in the pegmatite granitic rocks corresponding depths for pressures of $2 - 3$ kbar are $\sim 6 - 9$ Km (Mohammad *et al.*, 2016). Hence, confirming the crystallization conditions of cumulate dunite at the crust-mantle boundary in an oceanic setting (Stern, 2002).

▪ **Origin and Tectonic setting of dunites in the Mawat ophiolite**
As the chromian spinel is an ubiquitous accessory phase in both cumulate and tectonite dunites, it is the best key petrogenetic candidate phase to explore its chemical composition to constrain the parental melt composition and petrogenetic characteristics of the dunite in Mawat ophiolite. The chromian spinel composition in the tectonite and cumulate dunites are analogous to those of alpine type II dunite and stratiform complexes respectively (Fig.8: Dick and Bullen, 1984). Dick and Bullen (1984) suggested that spinels with high Cr≠ (> 60%) are characteristic of alpine type II dunite and stratiform complexes, whereas low Cr≠ (< 60%) spinels are typical of oceanic crust.

Relatively low TiO_2 -high Al_2O_3 and highTiO_2 -low Al_2O_3 in chromian spinel from tectonite and cumulate dunite respectively, suggest a supra-subduction tectonic setting for the Mawat ophiolite, followed by late stage intrusions of boninitic arc magma (Fig.9). Furthermore, the position of the dunite within the olivine-spinel mantle array (Arai, 1994) shows that the tectonite unit section of the Mawat ophiolite preserves a supra-subduction zone signature (Fig.10). Moreover the tectonite unit represents refectory residual of extensively partial melted (33%) upper mantle peridotite. The presence of spinels with high Cr# and extremely low Mg # in cumulate dunite is sufficiently high to be indicative of a source form fractionation of boninitic melt as stratified layered intrusion overlying the tectonite unit (Figs.8 and 11).

Fig.7: **a)** Field photo of podiform unit showing exfoliation texture in the tectonite unit,
b) Field photo showing spheroidal jointing, produced in the tectonite unit
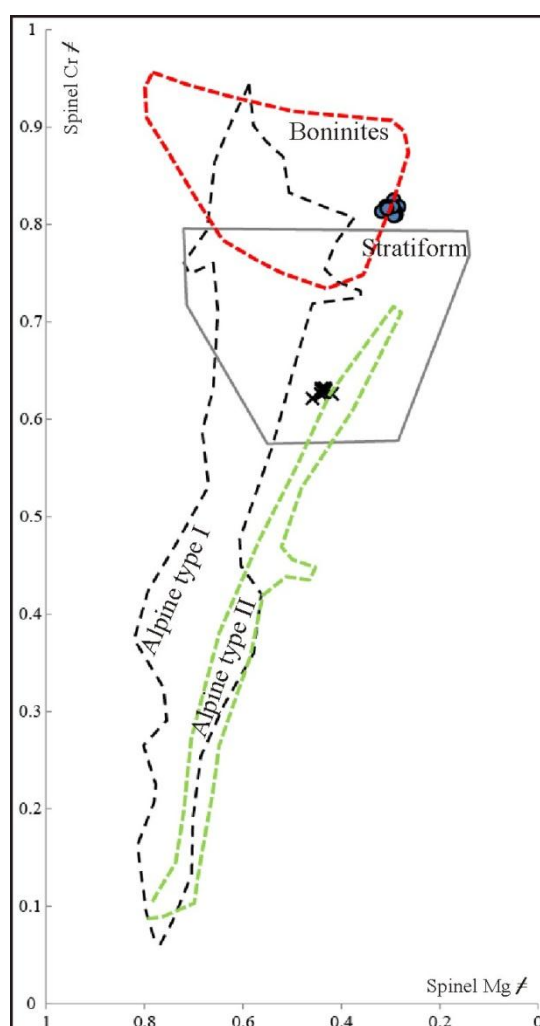as a result of intersections of two sets of joints

Fig.8: Cr# vs. Mg# diagram for chromian spinels from tectonites and cumulate dunites rocks
from the Mawat ophiolites. Compositional fields for spinels in boninites and different
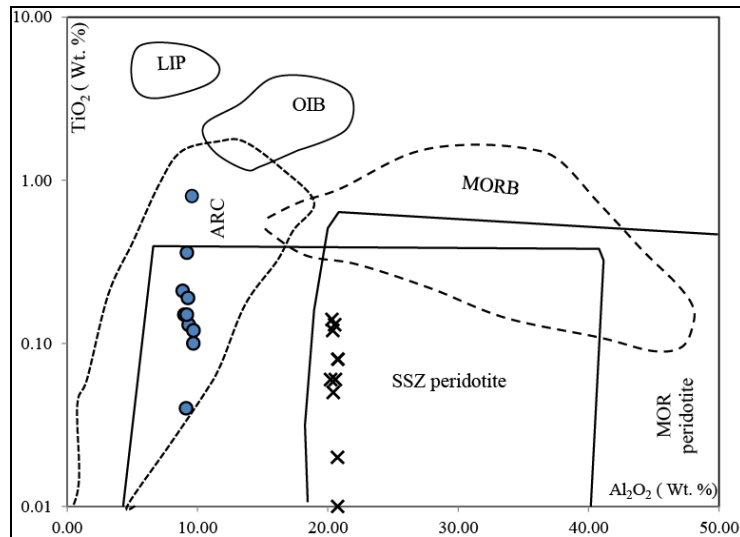types of perdotites from (Dick and Bullen 1984, Kepezhinskas *et al*., 1993;
Barnes and Roeder, 2001)

Fig.9: TiO_2 versus Al_2O_3 in chromite from the Mawat ophiolite complex. Fields are after Kamenetsky *et al*. (2001). SSZ; Supra-subduction zone; LIP, large igneous province; MORB, mid-ocean ridge basalt; OIB, ocean island basalt
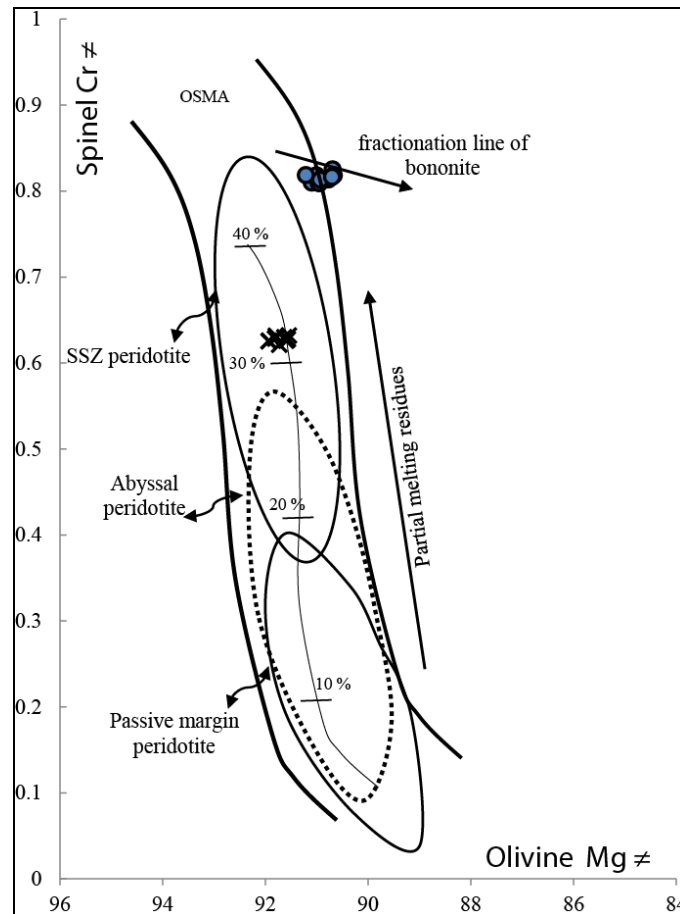

Fig.10: Mg# of olivinevs. Cr# of spinel in tectonite and cumulate dunites from the Mawat ophiolite. The olivine-spinel mantle array (OSMA) is shown by the two solid lines. Fields are after (Dick and Bullen, 1984; Arai, 1994; Pearce *et al*., 2005)
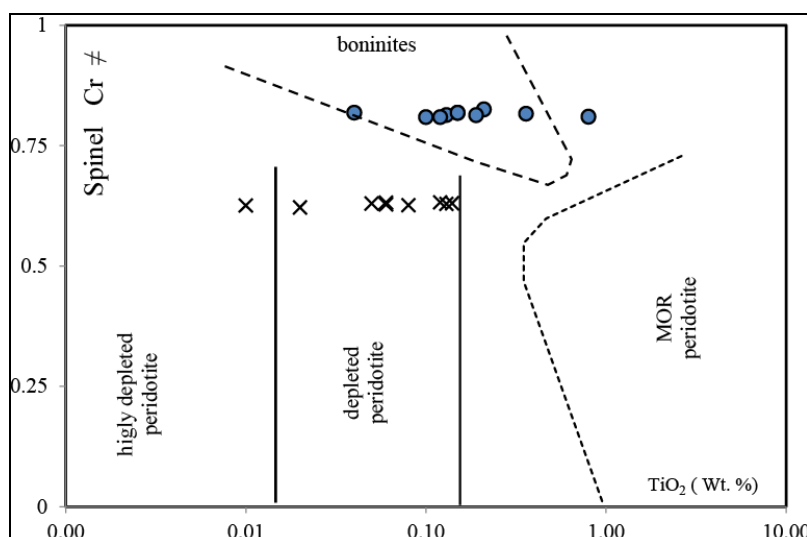
Fig.11: Cr# vs. TiO$_2$ (wt.%) diagram of chromian spinel from tectonites and cumulate dunites rocks from the Mawat ophiolites. Fields after Kepezhinskas *et al*., 1993. The blue circles symbol represents data from cumulate while the multiples symbol represents data from tectonite dunites

CONCLUSIONS

The reappraisal of the petrology of the ultramafic unit of the Mawat ophiolite shows that the unit can be divided into two contrasting members: the tectonite member and the cumulate member. Their stratigraphic succession, petrographical, and mineralogical features support the proposal that the unit represents the lower ultramafic portion of the ophiolite. The tectonite member is composed dominantly of harzburgite, dunite and less commonly lherzolite. This member is overlain by the cumulate member and has the same characteristics as ultramafic tectonites of other ophiolites in the Zagros Orogenic Belts. The cumulate member is composed of dunite interlayered by pyroxenite vein. Rare types of olivine have been recognized in the cumulate dunite; characterized by coarse black colored grains. BSE and EDS spectral analyses suggest that the black color of the olivine might be attributed to minute inclusions of magnetite+spinel+diopside. Dunites in the Mawat ophiolite are of bimodal origin showing that they may have formed by a combination of crystal fractionation and high degrees of partial melting in a suprasubduction zone environment. Stratigraphically the upper cumulate dunites have originally formed by crystal fractionation from boninitic magma chambers in the last stage of evolution of the Mawat ophiolite, whereas the lower tectonite, reflects refectory residual product of high degrees of partial melting of the upper mantle peridotite. The occurrences of new types of dunite in associations with Ni-Cu rich pyroxenite vein open a new window for reconsideration of mineral potential of the Mawat ophiolite especially for platinum group elements.

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