Geology of Zagros metamorphosed volcaniclastic sandstones: a key for changing the Mawat Ophiolite Complex to a metamorphic core complex, Kurdistan Region, NE-Iraq

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Abstract. Mawat Ophiolite Complex is located about 36 km to the northeast of Sulaimani city and directly to the east-northeast of Mawat town near the border of Iran in the northeastern Iraq. The complex has about 600-km² surface area and consists of high mountain terrains that subjected to intense geological investigations from the fiftieth of previous century till now. According to previous studies, the complex contains tens of igneous rocks such as basalt, metabasalt, tuff, diabase, metabasalt, diorite dykes, peridotite, serpentinite, serpentinite-matrix melange, gabbro, metagabbro, harzbergite, pyroxenite, plagiogranite, pegmatite, granitoid rocks and dunite. They added occurrences of the volcanic and subvolcanic rocks in the form of dykes or basaltic flows. The present study tries to change the petrology and tectonics of whole complex from Ophiolite Complex to Metamorphic Core Complex. The revision includes refusal of all the above igneous rocks, instead they considered as medium grade regional metamorphism of different types of volcaniclastic sandstones (volcanic wackes), arenites and greywackes (impure sandstones) which sourced predominantly from remote volcanic source area inside Iran. The revision depended on several conjugate field and laboratory evidences inside the complex. These evidences such as absence of pillow basalt, volcanic flows, glass shards, volcanic cones, dykes, sills, contact metamorphism, dilatational structures and flow structures. Other evidences are presence of cross beddings, erosional surfaces, lensoidal channel fills, metamorphosed conglomerate, exposures of thousands of laminated planar beds and transition from fresh volcaniclastic sandstones to its medium grade metamorphosed counterparts, which previously considered as igneous rocks of ophiolite types. Another, evidence, in contrast to ophiolite section, the basalt location is at the base of the claimed ophiolite section while plutonic (dunite and peridotite) rocks located at its top. These locations of the two rocks contradict the definition of ophiolites. Accordingly, the present study changed the geological map of the whole Mawat area from igneous outcrops to metamorphosed volcaniclastic sandstones, arenites and greywackes that belong to Walash-Naoperdan Series. The parent rocks of the series transformed to different types of regionally metamorphosed rocks by deep burial during Eocene. During the burial, diageneses and metamorphisms enhanced by complex mixture of materials from different source areas and seawaters environments. Later, they uplifted, unroofed and exhumed during Pliocene as a core complex.

1. Introduction
According to Buda and Al-Hashimi (1977[1]), the Mawat Ophiolite Complex consist of plutonic complex of ultrabasics, pyroxenite, layered and coarse gabbros, diorites, dolerite dykes and late stage plagiogranite differentiates. Buday (1980) [2], Al-Mehaide (1975) [3], Jassim et al. (1983) [4], described
the complex under the name of Mawat Massif and Mawat Nape. According to the above authors, complex consists of two parts, the first is metabasalts and diabases that located at the boundary of the complex, the second is mafic and ultramafic rocks that exposed in the core of the complex (Figure 1). These two parts surrounded by Walash-Naoperdan Series which compriseds, according to Buday and Jassim (1987) [5], Aswad et al. (2014) [6] of volcanic and sedimentary (clastic and carbonate) rocks. Buday (1980) [2]; Jassim and Goff (2006) [7] referred to the volcanic rocks inside the series as the Walash Volcanic Group and its type section located at Walash village (near Choman town) where it consists of 1000 m of mainly volcanic rocks. Buday (1980) [2] further added that the Walash group exposed, around the Mawat Massif to the northeast of Mawat and Choarta towns. Buday and Jassim (1987, p175) [5] detailed about volcanic rocks in the Mawat area (Mawat Group) and considered the volcanic rocks as a roof or mantle of the Mawat Intrusive Complex. According to the above authors and Koyi (2009) [8], the group consists of acidic lavas, pillow lavas, and pyroclastics, dykes, lava flows and intermediate volcanics such as pyroxene andesite, pyroxene-amphibole andesite, amphibole andesite and altered andesites) which pass laterally into volcano sedimentary sequences with tuffs, tuffaceous rocks, red mudstones, radiolitaries and white limestones. Koyi (2009) [8] classified the volcanic rocks of Walash-Naoperdan Series as diabase, metadiabase, pelitic basalt, and andesite of high 87Sr/86Sr ratio with the age of Early Eocene (44.3Ma). Aziz et al. (2011) [9] referred to occurrence of two serpentinite-matrix mélangé sheets under Mawat Ophiolite Complex and bound the Walash-Naoperdan Series.

Azizi et al (2013) [10] studied the Mawat Ophiolite Complex and determined that the Mawat area was an extensional basin during Late Paleozoic to younger age along the Arabian passive margin and added that in this basin huge volumes of mafic lava were intruded into its sediments. While Aswad et al. (2014) [6] concluded that Mawat was separated from Penjween Nappe (Ophiolite Complex) by gravity sliding and transferred for about 60 km toward west. Othman and Gloague (2014) [11] observation, in the field that the Walash sequence involve serpentine bodies and comprised of sedimentary shale, greywacke, limestones, volcanic basalt, andesite, tuffs, volcanic cones, and agglomerates.

Ghazal et al (2018) [12] studied metamorphosed porphyritic textures of the Walash-Naoperdan Series at the Betwat village and mentioned inheritance of the textures from texture of original rocks. Ali et al (2014) [13] indicated by diagram that Eocene-Oligocene volcano-sedimentary rocks of the latter series developed as an intra-oceanic island-arc within the intervening Neotethys Ocean. They added that the continuous tectonic activity ultimately produced an island-arc and back-arc (island-arc tholeiite and calc-alkaline to alkaline rocks) as origin of series that developed in an intraoceanic setting bordering the Arabian continent during the Paleogene.

2. Materials and methods
The study concerned with the Mawat area that located in Kurdistan Region, Northeast Iraq (Figure 1). The area is part of the Thrust Zone of (Buday, 1980) [2] and Jassim and Goff (2006) [7] and called Mawat Massif by Jassim et al., (1983) [4], Mawat igneous complex by Jassim and AL-Hassan (1977) [14]; Buda and Al-Hashimi (1977) [1]. Al-Mehaidi (1975) [3] called the area „Mawat Nappe” and Buday and Jassim (1987) [5] mentioned it as “Mawat Group” while it described under the name of Mawat ophiolite Complex by Aswad and Elias (1988) [15] and Mirza and Ismail (2007) [16]. According to above authors, the massif is composed of mixture of igneous, metamorphic and Meta-volcanic rocks that has 20 and 30 kms of width and length respectively. In this area, we selected many sections on the outcrops of previous volcanic rocks of Walash Group, metabasalts and plutonic igneous rocks of the Mawat Igneous Complex (Figure 1). Additionally, the study surveyed all the above outcrops for finding evidences of volcanic rocks such as pillow Lava, ropy (pahoehoe) structure, dykes, volcanic cones, chilled boundary, dikes, dilatational structures and others. In the same time, searches for sedimentary origin of claimed igneous rocks wassierously under consideration during which hundreds of samples are prone to inspection in the field for lithologies and textures and structures. The study described the samples with 10X hand lens and under stereomicroscopes with taking suitable photographs. For petrographic study, 20 thin sections are prepared and studied under
polarizer microscopes for identifying of the petrographic constituents. I checked and evaluated all the previous studies and compared their data with the results of the present one.

3. Results

3.1. Volcaniclastic sandstones versus volcanic and plutonic rocks in the WNS

Volcaniclastic sandstones as type of volcanic detritus include clastic materials composed in part or entirely of volcanic fragments, formed by any particle-forming mechanism (e.g. pyroclastic, epiclastic), transported by any mechanism, deposited in any physiogeographic environment or mixed with any other volcaniclastic type or with any nonvolcanic fragment types in any proportion (Fisher, 1961[17] and Marsaglia et al, 2016) [18]). Grower (2007) [19] discussed in detail difficulties of identifying metamorphosed volcaniclastic rocks from metamorphosed igneous intrusions and mentioned their presence in metamorphic regions.

In the studied area, I found relatively fresh (but locally slightly recrystallized or metamorphosed) thick succession of fine and coarse grain volcaniclastic sandstones, siltstones and conglomerates for the first time around the Mawat Ophiolite Complex. This succession well exposed along western side of Satur valley (or gorge) at three km west of Mawat town, where the new road cut is available between Dasti Tile and Gabarwa villages at the south and north of the succession respectively (Figure 2). It exposed on the road that passes through villages such as Zhazhla, Hanjira, Awakurte, Azmak, Grgasha, Shanakhse and Dere. A small outcrop is located on the Peak of Sarsir Mountain at 3 km northeast of Chwarta town too.

The succession is about 1500 m thick and mainly consist of dark grey, black (weathering grey or brown), well bedded (occasionally laminated) volcaniclastic sandstones with intervals of siltstone and siliceous-ferruginous shales in addition to few beds of conglomerate (volcaniclastic conglomerate) (Figure 3). The succession ends with about 40 m of fossiliferous Naoperdan limestone. When the terminology of Bailey (1996) [20] is applied, it can be named “island-arc detritus succession” which derived from the forearc inside Iran that developed after subduction of the Arabian plate under the Iranian one and continued during late Jurassic and whole Cretaceous.

Under polarized and stereoscopic microscopes, the sandstones and conglomerates consist of different clasts (grains) of volcanic rocks and the clasts have porphyritic and aphanitic textures in addition to broken and unbroken crystals of plagioclase and amphiboles. The iron oxides mostly replaced the latter crystal while calcite replaced the former partially (Figures 4 and 5a). The succession contains trace fossils and ripple marks (Figure 3), both imprinted on fine grain volcaniclastic sandstone (Figure 5b). The paleocurrent (evident from the ripples) indicate the southwest direction of transport and the same direction is obtainable by grain size analysis whereas the grain size decreases toward latter direction.

Previously Ali et al. (2017) [21] found marine clastic rocks in the Walash-Naoperdan Series in the Hasanbag and Qalander areas, which consist of lithic arenites with high proportions of volcanic rock fragments. Therefore, these volcaniclastic sandstones in the series are not volcanic rocks as previously considered by tens of authors but they are sedimentary rocks transported from northern remote volcanic source areas and deposited as volcaniclastic sandstone (as possible turbidites) in deep basin. Serious field works failed to find any signs of volcanic intrusions or extrusions while the aforementioned evidences indicated sedimentary nature of the succession.
Figure 1. a) location of the studied area, b) Geological map of Chwarta-Mawat area shows the Walash group (as a part of Walash Naoperdan Nappe), metabasalt, metadiabases and plutonic rocks (modified from Al-Mehaidi, 1975) [3].
Figure 2. Satur Gorge at the 5 km west of the Mawat town where thick succession of the greywackes (volcanic detritus) are exposed at the latitude and longitude 35° 51' 57.97" and 45° 26' 37.73".

Figure 3. Apart of volcaniclastic sandstone succession (as a thick parasequence) in Satur gorge at the latitude and longitude 35° 52' 06.66" and 45° 26' 33.83" with ripple marks at the base.

Figure 4. a, b and c) Fresh volcaniclastic sandstone in the Satur gorge contains volcanic clasts, the metamorphism of these rock produce igneous-like rocks in the core of Mawat Complex.
3.2. Metamorphosed volcaniclastic succession inside Mawat ophiolite Complex

As mentioned before, the boundary of the Mawat ophiolite Complex consists of the outcrops of fresh volcaniclastic sandstones of Walash-Naoperdan Series (or Walash Group). However, at the north and east they disrupted by the Main Zagros Thrust and the outcrops disappear. When one walks, from this boundary toward the center of the complex, he observes after 500 m, a gradual increase of the grade of the metamorphism of the volcaniclastic sediments and it increases more toward the core (center). Due to the slight metamorphism near the boundary, it is possible that the previous studies applied “metabasalt and metadiabase of Mawat Ophiolite complex (see Aswad et al., 2014) [6] for these rocks. These rocks are observable north and northwest of Qarababa Mountain and areas around Gabarwa, Chinar, Spyiara, Shasho villages (see Figure 1). More advancing ahead toward the center the grade metamorphism increase and the greywakes and arenites are called “Gabbro or peridotite” in or near the core. Island-arc detritus (Bailey, 1996) [20] is the word can be applied for these metamorphosed sediments.

There are three evidences for sedimentary origin of the above rocks, the first is observing, in these areas, clear exposure of thousands of thin and thick layers of coarse or fine grain rocks of black, light green, grey and brown of different alternations. These layers (beds) have planar bedding surface, sharp lower and upper contacts, mostly laminated and in some places cross bedded (Figures 6, 7 and 8). These rocks are previously called banded metabasalts or banded gabbros but they neither extrusion nor intrusions due to lacking of pillow basalts, ropey (pahoehoe) structures, glass shards, volcanic cones, amygdales, dilatational structures, digitation, cross cutting relations and contact metamorphisms, chilled boundaries (thermally metamorphosed border of the host rocks). Close insight shows similarities the layers (successions) of the claimed metabasalts, metadiabases and gabbros of previous Mawat Ophiolite Complex to the layers of the volcaniclastic sandstones of Walash-Naoperdan Series. The differences shaped by different grades of regional metamorphism of different lithologies. The structures such as alternation of laminae and beds with different lithologies and sharp bedding surfaces inherited from their deposition in aqueous media where the system was open for rapid changing of energy and materials influxes.

The second evidence is occurrence of buried channel (lenticular body) (most possibly turbidite submarine channel) which has lensoidal shape and covered from the top by drape of finer grain sediment (Figure 7). The channel is confined type and has erosional base on metamorphosed fine and soft volcaniclastic deposits. It is located near Waras village on the outcrops of metabasalt of Mehaidi (1975) [3]; Othman and Gloague (2014)
Mohammad and Qaradaghi (2016) [22]; Al Humadi et al. (2019) [23] and banded gabbro, volcanic basic igneous rocks and intermediate igneous of Mirza (2008, p.7) [24]. According to cross section, the channel has elongation of north-south which is the direction of sediment transport toward the south. The shape of this channel is similar to channels recorded by Woods (2014) [25] and Rebesco et al. (2014) [26] in the submarine turbidite channels. The coarseness of the channel fill relative to the surroundings rocks is direct evidence for its sedimentary origin since turbidite channels sediments are normally coarser than their hosting rocks. There is another proof that is impossibility of intrusion of small gabbroic body (but coarse grain) to intrude in fine grain basalt. Tens of smaller lensoidal channels are observable on outcrops of the claimed metabasalts, gabbros and peridotites around Gabarwa, Kuradawe, Saraw and Daraban villages (Figure 8). The boundaries of these channels are so sharp that there are no even a millimeters of chilled (thermal metamorphosed zonation) of the border of the claimed metabasalt or diabase, therefore, all the lensoidal bodies are sedimentary and they are neither volcanic flow nor intrusion as claimed previously. The rocks of the channels and beds show clear granular and poorly sorted textures that resemble porphyritic texture of volcanic rocks. Jassim and Al-Hassan (1977) [14] observed granulation of plagioclase in the banded gabbro of Mawat and Penjween complexes and confirmed similarity of the granularity in the two complexes. Nevertheless, they attributed this type of texture to shearing and thrusting. They also mentioned (p.86) absence of chilled margin of the dikes in Mawat Ophiolite Complex.

The third is widespread laminations and bandings in the claimed metabasalts and pultonic rocks. In this regard, Jassim and Al-Hassan, 1977, p.173) [14] mentioned that banded (layered) gabbro covered main part of the Mawat complex and the bands show local laminations due to mineralogical and textural variation in the gabbro. Buday and Jassim (1987) [5] recorded banded and laminated gabbro, which attributed to crystal accumulation. In the same context, Abdulzahra (2008) [27] concluded that layered gabbro covers the major part in all rocks of the central sector of Mawat Complex. He added that two main types of the igneous layering are recognizable in the layered gabbron. They are grain size layering and the compositional (mineralogical) layering and he added that both types of layering are commonly associated with each other. He farther added that graded bedding and thicknesses of layering in layered gabrons indicate gravitational crystal settling mechanism.

The findings of the present study in addition to lamination and graded bedding of previous studies are evidence of the sedimentary origins of the gabrons and metabasalts of Mawat Ophiolite Complex. Magma cannot generate channels, erosional surfaces; ripple marks, cross bedding and thousands of laminated planar beddings (Figures 7, 8 and 9). The magma or lava is 100,000 times more viscous than water, therefore, deposition, erosion, flow regime changes of solid particles such as crystals or detrital grains are more common and faster thousand times in water than lavas or magmas.

**Figure 6.** a) Faulted and tilted alternation of dark and light color coarse grain metamorphosed volcaniclastic sandstones (previously metavolcanic rocks of Mawat ophiolite complex). b) Same alternation but with fine grain metamorphosed volcaniclastic sandstones, at 1 km south of Gabarwa village.
Figure 7. A submarine turbidite channel filled with metamorphosed coarse grain volcaniclastic sandstones, it originally scored in fine grain volcaniclastic sediments (see shale or siltstone at the base) at the 500 m southwest of Waraz village, at the latitude and longitude 35° 47' 13.87'' and 45° 30' 18.41'' respectively.

Figure 8. a) Small channel scored in volcaniclastic and filled with laminated plagioclase and hornblende (black rocks) rich coarser sediments (now metamorphosed) at 200 m south of the Gabarwa village at the head of Satur valley, at the latitude and longitude 35° 52' 40.70'' and 45° 26' 45.46'' respectively. b) Cross bedding and lamination in the previous gabbro, present metamorphosed volcaniclastic sandstone 1 km south of Kuradawe Village.
Figure 9. a) Bedding (most possibly cross bedding) in the metamorphosed volcaniclastic sandstones and conglomerate (previously considered as gabbro), b) Ripple marks on fine grain volcaniclastic siltstone (now recrystallized to pyroxenite-like rock), their troughs are filled with felsic volcaniclastic sandstone (now recrystallized to Gabbro-like rock) at 1 km south of Rasha Kani village north central part of Mawat Ophiolite Complex.

3.3. Absence of discordant (cross cutting) basaltic or gabbroic

Although volcanic vents and dykes (sheet dykes), pillow lavas are main component of any volcanic and ophiolite terranes, yet no single one of these structures are found in the previous “basalts, gabbros and peridotites” of Mawat Complex and Walash Group. These discordant basaltic and gabbroic (dark color) dykes are missing in whole northeastern Iraq since the present author tracked hundreds of kilometer inside the outcrops of Mawat, Chwarta and Bulfat (Qaladiza) and Penjween areas without observing discordant small or large dark or light color bodies. All the internal and exterior (boundary condition) properties of the claimed diabase or felsic dykes are inspected in the fields, nevertheless, no single sign of dykes are observed. All the claimed basaltic intrusions and dykes are concordant to the beds (strikes or beds elongation) of the surrounding host rocks and they never cut vertical or horizontal surrounding layers but all elongate parallel to layers of host rocks (Figure 10). Even the elongations of the claimed dykes are not normal to the long axes of the elongate grains (crystalloclasts) of the host rocks but they are parallel.

Figure 10. a, d) hand drawing of discordant basaltic bodies (black horizontal and vertical zones) which are never found either in Mawat or Bulfat or Penjween complexes.

In the same manner, nearly all previous granitoid bodies (pegmatites, lecogranites and other light color igneous rocks) are concordant. These bodies are studied by Mirza and Ismail (2007) [16]; Kareem
(2015, p.17) [28], Othman and Gloague, (2014) [11]; Mohammad et al. (2014) [29]; Mohammad and Qaradaghi, (2016) [22]; Al Humadi et al. (2019) [23]. The photos of the last four articles show clearly elongation of the bodies parallel (concordant) to layers of host rocks (Figures 11, 12 and 13a). The bodies boundaries are sharp and don’t show contact metamorphism. In Mawat area, the granitoid bodies, dykes and their host rocks are deformed (tilted) to nearly 75 degrees of dip and in the direction of northeast in the northern boundary of the complex while in the southern boundary the dip attitude is opposite (Figures 11a and 12). Therefore, these bodies are felsic thick beds of volcanic clastic wackes or arenites, which are prone to regional metamorphism together with the host rocks (gabbro, diorite or peridotite). In the many places, there are thin (3-30cm) and 1-10 m long albite or Quartz veins cutting concordantly or discordantly the layers of the host rocks of the claimed igneous rocks with wedge shaped, with sharp boundaries (Figure 13b). The author think that these small veins are tectonic fractures formed during tectonic burial, deformation and later filled with secondary calcite but they replaced with plagioclase and quartz during metamorphism in elevated temperatures and pressure.

Figure 11. a) a photo of Kareem (2015, p.17) [28] for claimed pegmatite dyke which elongates parallel to layers of host rocks, on the peak of Sarshyw mountain (the photo looks northeast), b) another bodies with same attitude by Othman and Gloague, (2014) [11]. In the present study, red lines indicate the elongation of the two bodies and layers.

Figure 12. a) Lecogranite dyke in ultramafic rocks (Mohammad and Qaradaghi, 2016) [22], the parallelism of its strike to the layering of the hosted rock (the red line, of the present study) is clear, the photo looks northeast. b) Same condition is true for the claimed dyke of (Al Humadi et al. 2019) [23].

In this regard, Spotl et al., (1999) [30] concluded that replacement of calcite by albite occurs in deep burial and high temperature diagenetic environment (in presence of brine fluid), ranging from high-grade diagenesis (150-200 °C) to lower green schist facies (300-350 °C). They added that in siliciclastic sediments this replacement begin more early and more prevalently. In thin section partial
and total replacement of plagioclase by calcite is very clear (Figure 13b and 14). However, under high temperature and pressure of the metamorphism, the present author think that the process of replacement can be reversal especially in marine sedimentary rocks in which, Al, Si and Na available (from seawaters and clays) for replacement of calcite by albite and other plagioclases.

**Figure 13.** a) a concordant (parallel) folded and metamorphosed limestone bed replaced mainly by albite (previous granitoid bodies) near the tower of communication, on Qarababa mountain at west of Amadin village, b) both discordant and concordant calcite veins (replaced by silicate minerals) between Amadin and Mirawa village

**Figure 14.** a) Two crystal of plagioclase (inside volcaniclastic succession) replaced partially by calcite (ca), the plagioclase crystals are in extinction position, b) same two crystal are in bright position after rotation of the stage about 30 degrees while the calcite became in extinction position, s.no.15, Satur gorge, at 1km north of Bard Pan village should explore the significance of the results of the work, not repeat them.

3.4. The topography of the Mawat area does not aid presence of igneous bodies

When one walks inside the valleys and on hills of the area of the Mawat Complex, he observes two geomorphologic features, the first is all high mountain peaks and ridge summits are covered by limestone rocks (e.g. fresh or metamorphosed limestone of Walash-Naoperdan Series). The main mountain peaks are: Gimo, Hazar Kani, Hawra Barza, Qashan, Qarababa, Sar Shiwi and Sarsir.

In contrast to limestone terrain, the igneous one are consist mainly of smooth undulating and rolling hills that are barren from high cliffs and elevate peaks as shown the figure (15) which shows
the central part of the Mawat Ophiolite Complex that according to all authors, mentioned in the introduction, consist of Gabbroic rocks. As mentioned before, this terrane consists of the alternation of thousands of thin and thick beds of fine grain (siltstone and shale) and coarse grain (sandstones) of metamorphosed volcaniclastic rocks. In most case, each two coarse grain competent beds of parasequences separated by fine grain soft incompetent sediments (Figures. 6, 7, 12 and 13a). Therefore, these rocks are not massive and each two beds interfaces acts as zone of weakness (discontinuities surface) so they don’t shape high contrast topography. Although several rock types are mapped by Al-Mehaidi (1975) [3], but in the field the boundaries of these rocks are unclear due to intense deformation. These properties are manifested in the highly zigzag boundaries and spotty distribution of all outcrops of the claimed igneous rocks in the map of the latter author (Figure 1) and by (Othman and Gloague, 2014) [11] (Figure 16a).

Another evidence absence of ophiolite rocks is overlying of what called ophiolite by shallow marine nummulitic Eocene carbonate of Naoperdan Formation in Mawat and Bulfat Complexes (areas). In Mawat area the, the limestone is fresh in the periphery (at southwest, south and southeast) of the complex while in the north and northeast it metamorphosed which called in Gimo Sequence (Figures 15 and 23). If these two complexes are Ophiolite (oceanic crust and upper mantle rocks), they must been topped or fronted by both pillow basalt and pelagic ooze limestone or radiolarites. In spite of presence of radiolarite rocks at the east and northeast of the Mawat Complex (Figure 1), yet they have not relation with the complex and they located at the back of the complex not at the top or front. It was known that previous studies considered development of Penjween ophiolite by uplift of the Oceanic floor and obduction on to Arabian Continental Margin. If this is true, it must carry radiolarites and pillow lava to Mawat area on its top and front during it climbing the margin.

3.5. Mawat Ophiolite Complex and presence of sharp erosional surfaces

Although crystallization during diageneses (in the source area and in a basin of the deposition and metamorphism destroyed many depositional structures and textures yet many of them can be found. One of them is erosional surfaces which are common feature of detrital (clastic) sediments of both carbonate and siliciclastic types. In the field of the studied area, tens of them can be observable in fresh and metamorphosed volcaniclastic sandstones (previous volcanic rocks, gabbro, diabase, dunite and peridotite). These structures appear as sharp planar, irregular, or concave surfaces with overlying and underlying by coarse and fine grain sediments (Figures 7, 8 and 17). The sediment fill of these erosional
structures are appear as small lensoidal bodies which represent small channels that filled with graded coarse sediments, changed upward to fine ones. In the figure (17a) the clasts (plagioclases) and interstices matrix (amphiboles) are clear. The high-energy flow turbidity currents scored the channels in soft volcaniclastic sediments and filled with deposits when the flow velocity decreased.

Figure 16. Result of remote sensing mapping of the rock types of the Mawat Ophiolite Complex (Othman and Gloague, 2014) [24] shows irregular and spotty outcrop of claimed ophiolite.
Due to high viscosity of magma, it cannot flow so speedily to erode and deposit small-scale (few centimeters to decimeters wide) channel–like and ripple-like structures. In water medium, earthquakes, volcanic eruptions, landslides, waves, and turbidity current can energize high speed turbid flow responsible for erosion in one place and deposition in another one but the magma behave differently due to its high viscosity and closed system. Previously, Jassim and Al-Hassan, 1977, p.173) [14] mentioned trough banding and graded layers but they interpreted these structures as crystals accumulation.

3.6. Extremely wide range of the age of the claimed Plutonic rocks of Mawat complex

The previous evidence about sedimentary origin of the previous basalts gabbros and peridotites of the Mawat complex are the achievement of present authors while very recent literature published the best evidence. Very strong indirect evidence is included in the study of the Al Humadi et al. (2019) [23] in which there are four direct signs for sedimentary origins of the rock of the complex although the authors not attributed these evidences to sedimentary origin of their samples.

The first is recording wide ranges of zircon grains ages in the felsic and gabbroic rocks of the complex and these ages are 222, 94, 81, 40 and 38. We attribute these wide ranges of ages to sedimentary mixing of zircons from different source area and depth when the volcanic arc in Iran (most possibly Urumieh-Dukhtar Magmatic Arc) was prone to deep, old and new rocks erosion successively. They mentioned that one of their samples contained zircons of different ages that cannot occur in igneous rocks due to their closed systems.

The second is showing photos (Figure 18) zircons of Gabbro and felsic dykes that contain spongy and pitted surfaces with pores, in addition to intergrowth with xenotime and monazite minerals. They added that according to Tomaschek et al., (2003) [31]; Hay and Dempster, (2009) [32] such textures can be produced in low temperature aqueous fluid-rich environment through a coupled dissolution-reprecipitation process. The third is their referring to the very low whole-rock Zr content in D1 and D3 (19.7 and 34.3ppm) and they added that according to Watson (1979) [33] it is hard for zircon to crystallize from such a melt. Therefore, it is clear that the origin of felsic is sedimentary and the zircons transported to a side of deposition as detrital grain by turbidity currents. The fourth is their observing sharp crosscutting of host rocks (gabbro and peridotite) by the felsic dykes and they (Al Humadi et al., 2019) [23] concluded that the dyke is older than the host rocks and the age of the gabbro is > 10 Ma younger than the felsic dykes that crosscut the ultramafic mantle section. This type of crosscutting is never exists in igneous rocks because the dyke must be younger than the host rock.
This disagreement of ages proves the sedimentary origin of the claimed Mawat ophiolite especially the dykes boundary does not show contact metamorphism or forceful emplacement.

**Figure 18.** Spongy and pitted surfaces of zircons with intergrowth of xenotime and monazite minerals from Gabbro and felsic dykes of Mawat Ophiolite Complex used for age determination of by Al Humadi et al. (2019) [23].

4. Discussions
In the valleys and galleys, on hills and mountains, the landscapes of the Mawat Ophiolite Complex shows thousands of beds of either fresh or metamorphosed sedimentary volcanioclastic sandstone, siltstone and shale which previously considered as the igneous rocks. In one meters of thickness, one can see several types of rocks that are impossible for magma to differentiate such high numbers of rocks due to closed system of magma in contrast to sedimentary basins in which energy and source areas (materials) changes temporally and spatially ten times quicker than magma. Abdulzahra, (2008) [27] referred to tholeitic nature of Mawat gabbros that show small degree of differentiation (FeO₂/MgO) which is less than 2. Therefore, if there is little differentiation, how all the aforementioned igneous rocks formed in successive layered pattern in Mawat Ophiolite Complex? The sedimentary origin is our answers for the question.

Toward southeast of Mawat Ophiolite Complex, the influx of plutonic igneous and limestone clasts increase at the expense of volcanioclastic sediments. They all derived mainly from volcanic source areas with subsidiary plutonic and limestones ones, which deposited in deep marine basin as volcanioclastic sandstones, greywackes and arenites. Previous authors treated the fresh layers as basalts, diabases, while metamorphosed ones considered as gabbros, peridotites, pyroxenite, plagiogranite, lecogranite, pegmatite, dunite by tens of authors worked on the complex.
Most of the rocks of the Mawat Ophiolite Complex show planner beds and laminations, except the pulverized and intensely sheared ultrabasic volcanioclastic sandstones. These sheared and hydrated rocks are mainly located in the periphery of the complex where reverse faults prevail due to nearly vertical uplift of the complex as metamorphic core complex. Many authors called these sheared rocks “serpentinites” while both thin sections and had specimens of the present study show that the serpentine mineral exist only on sheared surface and around olivine grains while the rest of the claimed serpentinite consists of amphiboles and pyroxenes with subsidiary olivine and iron oxides.

Othman and Gloague (2014) [11] mentioned volcanic cones in the Mawat area, while we think that the fresh or metamorphosed thick parasequences (packages) of sandstones successions that are underlain and overlain by finer clastics are what called “volcanic cone”. These parasequences are very common in all type of rocks of previous Mawat Ophiolite Complex; one of them is observable in the figure (19) at 1km to the north of Kanaru village and about 65 m thick. It consists of tens of planner beds of metamorphosed coarse greywackes and interbedded by siltstones and shales. It considered by Al-Mehaïdi, 1974) [3] as metamorphosed volcanic rocks inside Mawat Ophiolite Complex (Figure 1). Mirza et al.(2016, p.33) [34] studied podiform (lensoïdal) chromitites inside Mawat Ophiolite Complex and observed close relation between the dip of the bedding planes of the country rocks (38°) while that of the chromitites podiforms is 25° with dip direction of both toward NE.

The field observations of present study depicted the elongation of the granitoid bodies, felsic dykes (described in the previous section) and chromite bodies. These bodies are nearly have same strikes (elongations) of the sedimentary beds and the minor differences are attributed to tectonic deformations by which component and incompetent bodies might have differently responded to dislocation by stress. The most serious criticism against the present work is occurrence of few podiform chromite and local dunite thick bodies in Mawat Complex. We justify this critic in four points, the first is the equality of strikes of both chromite and dunite bodies with strike of their country rocks as shown in many articles. These articles are such as Kareem (2015) [28] (Figure 11a), Othman and Gloague, (2014) [11] (Figure 15b), Mirza et al. (2016) [34] (Figure 13b) and Al Humadi et al. (2019) [23] (Figure 12a), therefore, most signals refer to sedimentary deposition. The photos of thin sections published by Mirza et al.(2016) [34] show granular clasts of chromite in fine matrix (groundmass) with irregular peripheries (Figure 16 c and d). The same type of photo is published by Mohammad (2013, p.5013) [35] too for massive lenses (60×60 cm in dimension) of dunite in Penjween Ophiolite Complex.

The second is high friability and coarseness of the dunite in the outcrops which about 20 m thick and according to Mohammad (2008) [36], its grains are anheral and located on the highest peak in the area. This location contradicts igneous dunite origin because it must be located at the base of ophiolite rock sequence at an elevation lower than gabbros and basalts. Mohammad (2020) [37] and Mohammad and Cornell, (2017) [38] observed this stratigraphic feature of Mawat Ophiolite Complex but they attributed it to overturning of the ophiolite without giving any evidence of their overturn idea. The present study does not aid this reversal of stratigraphy since there are no any field evidences for this process, all sedimentary structures such as graded bedding, channel shapes and paleocurrents refer to normal stratigraphic condition. Compatible with this study, in the past Jassim and Goff (2006, p.302) [7] mentioned that basalt (with marble) built up the roof (top) of the Mawat Complex. Another problem is inference of Aswad et al. (2014) [6] in which they considered that Mawat Ophiolite Complex was separated from Penjween Nappe (Penjween Ophiolite Complex) by gravity sliding and transferred for about 60 km toward west nearly along the plateostrike. The present study not found any signal of this process of Mawat area and contrary aids vertical uplift with more or less horizontal movement along paleodip normal to Zagros Thrust Fault.

The third is texture of the dunite, under stereo- and polarizer microscope, which composed of discrete transparent grain, surrounded by thin white fine grain matrix and shows more or less subroundness,
sorting and mechanical abrasion of the edges (Figures 20, 21 and 22a). The same wearing can be seen under scanning electronic microscopic (Figure 22b), moreover, the dunite contains sporadic anhedral black grains of spinel chromium (Figure 20). The fourth is southwestward decrease of the percentage and sizes of the olivine and increase of the ratios of pyroxene (Mohammad, 2020) [37]. On the map of Othman and Gloague (2014) [11] and Mohammad and Cornell (2017) [38] peridotite changed to gabbro in the same direction (Figure 16a). These means that olivine beds (dunite) is sedimentary and relatively near to the source by which attained coarse and clean texture while toward south (more distal area) it decreased in grain size and mixed with other components from other local source areas or feeder channels. Therefore, Olivine arenite (Pettijohn et al. 1987, p160) [39] (as a type of sandstone) most possibly derived from a source area of the olivine basalt and transported to the present location, and deposited as channel fill sediments (volcaniclastic olivine arenite). In this connection, Mohammad (2020, p.25) [37] found lensoidal body of dunite in side harzburgite, however, he called it tabular body while his photo show clear lensoidal shape not tabular one. In the present study, this type of dunite shape is considered as channel deposit which is similar to the channel recorded by Karim and Al-Bidry (2020) [40] in Mawat Ophiolite Complex and assumed as deposition of the deep marine turbidite channels (Figure 7). According to Karim and Abioui, (2021) [41] these sediments were transported to Mawat area in two stages, in the first they sourced from Urumieh-Dokhtor Magmatic Arc t and deposited inside the Sanandij-Sirjan Zone during Jurassic and Early Cretaceous, later they uplifted and eroded during Paleocene inside Iran reworked to the Mawat area during the latter age.

Now clean olivine sands are accumulating on the Huwaii beaches (see green sand on the Hawaii beach in web), these sands can transport to deep basin hundreds of kilometers far from the beach by turbidity currents during tsunamis and typhoons. In the basin, they underwent gravity and shape sorting by which pure olivine arenite can deposit as placer deposits in deep submarine channels. The same processes are true for iron, chromium mineral accumulations in certain places in Mawat and Penjween areas. All circumstance evidences reveal its sedimentary origin but it needs further future study for finding an unequivocal evidences about the dunite origins.

![Figure 19](image1.png)

**Figure 19.** Very thick parasequences (about 65 m thick) of metamorphosed coarse volcaniclastic sandstones at 1km to the north of Kanaru village. It consists of planner beds interbedded by siltstone and shale, it considered by Al-Mehaidi (1974) [3] and other authors as metamorphosed volcanic rocks inside Mawat Ophiolite Complex.
Figure 20. a, b) previous dunite under stereomicroscope show discrete, subrounded and sorted grains (crystals) of olivine (olivine arenite) white fine grain matrix occupy interstices between the grains, it contains randomly distributed black spinel chromium grains (sc), the pin needle head is for scale.

Figure 21. a, b) previous dunite under polarizer microscope shows discrete, subrounded and sorted grains (crystals) of olivine under XP and normal lights.
4.1. Absence of contact metamorphism and pillow basalt
Several authors published researches on Mawat Ophiolite Complex and mentioned tens of igneous rocks, which surrounded by sedimentary rocks but without refereeing to contact metamorph-ism in the complex or without showing photos of it. Jassim and Goff (2006) [7] reviewed the contact metamorphism in Bulfat and Penjween complexes, but the field works of the present authors could not prove the occurrence of contact metamorphisms in both complexes. Recently, Karo (2015, p.91) [42] concluded important result by biotite isotopic ages and mentioned that the age of claimed contact metamorphism and the Qandil Metamorphic Series, about 13 km far from the intrusion, gave the same metamorphic age. He farther added that both localities should affected by the same metamorphic events. This equality of ages of two remote samples proves that there are not contact metamorphisms even in Bulfat Igneous Complex and all the rocks of the two complexes were prone to deep burial and regional metamorphism. Naoperdan limestone (as part of Walas-Naoperdan Series) in many localities is in contact with previously claimed gabbro and volcanic rocks in Mawat and Bulfat complexes. The present study investigated these contacts and not observed any evidences of the contact metamorphism, even in centimeter scale. The same condition is true for Gimo Sequence (metamorphic limestone) which consist originally of metamorphosed limestone of later series (Figure 23).

Pillow lava is one of the main part of the ophiolite sequence but among ten of studies on the Mawat area no one found the true pillow lavas, this is true for the present study. Another feature that contradicts the ophiolite is its overlying by shallow water carbonate and clastic sediments of the Walash-Naoperdan Series and Red Bed Series (Figures 1 and 24). The previous studies supposed that uplift (obduction) of the ophiolite exhume pillow lava and deep oceanic sediments. There are radiolarites in northeast and east of the Mawat ophiolite complex but it has not stratigraphical relations with the rock of the complex (Figures 1 and 24).

4.2. Types of the rocks in the Mawat Ophiolite Complex
In the Mawat Ophiolite Complex, if experts mention all the names of previously identified igneous rocks, they are more than ten, in some case in one meter of thickness, several different rocks are observable and they alternated with each other. These rocks are result of diagenesis and metamorphism of complex sediments mixtures of different grain sizes and mineralogy that deposited from several energy regimes and source areas such as felsic and mafic volcanic source area in addition to subsidiary plutonic and limestones-sources. These mixtures received additional material from open
seawaters such as Na, Ca, Mg and others. The sediments of the Mawat Core Complex (previous Mawat Ophiolite Complex), at first step took laminations, bedding and alignment of the platy grains parallel to depositional surface (on the sea bottom) during the deposition. In the second step, they are prone to burial and attained more grains alignments (by pressure) in addition to more mineralogical alterations (by diagenetic processes). The burial associated with folding, faulting, fracturing, and entrapment of the seawaters rich in Na, Ca and Mg. In the third step, they metamorphosed differentially and regionally which got main changes of textures, mineralogy of the parent rocks.

The differential metamorphism is due to differences of thermal and mechanical conductivity of different sediments successions, degree of porosity, thickness and mineralogy. Therefore, diagenesis, (during burial and deposition) and metamorphism affected the present rocks in different scale. However, the original beddings, laminations and most of the textures preserved in the present days rocks (Figures 6, 7, 8, 9, 17 and 19). Due to these preservations, the rocks of Mawat Ophiolite Complex looks like hornfels that are tens but for local areas, the names such as, phyllite, schist and gneiss are suitable but we propose abandoning using igneous terms because their origins are not igneous although their apparent appearances and mineralologies are similar to igneous rocks. Other terms such as metamorphosed coarse or fine volcaniclastic sandstones (greywackes and arenites), metamorphosed volcaniclastic conglomerate, metamorphosed olivine sandstone (arenite), metamorphosed plagioclase and pyroxene sandstone and others can be used (Figure 24). These later terms are most correct naming but their acceptance are difficult due to their absence in the previous literatures.

![Figure 23](image)

**Figure 23.** Gimo Sequence (calcisilicate marble or metamorphic limestone) on top of Gmo mountain which consist originally of metamorphosed limestone of WNS. The photo is taken from Kani spyia village

4.3. Changing the geological map of the Mawat Metamorphic Core Complex

According to the above renaming of the rocks of the Mawat area, this study changed the name of previous “Mawat Ophiolite Complex” to Mawat Metamorphic Core Complex (MMCC) due to prevalence of metamorphic rocks and applicability of the definition of “metamorphic core complex” on it. Recently Karim and Al-Bidry (2020) [40] studied in detail Bulfat Ophiolite Complex (10km west of Mawat Complex) and proved that the origin of all its rocks are sedimentary and changed its tectonic setting to metamorphic core complex.

The previous tectonic models cannot answer all questions about the origins of all crowded diverse rocks that arranged in successions of thousands of layers in small geographic area. As mentioned in the previous sections, the succession contains relict of planar bedding, erosional surfaces, laminations, crossbedding and small or large channels. Moreover, the grains (texture) show sorting, sub-roundness and abrasion. The best supporting literature to present study is that of Al-Saffi et al. (2012) [43] who published a photo of graded layers (graded bedding) in the gabbro of the Mawat Ophiolite Complex and they attributed them to crystal settling (Figure 25c). However, the present study considers it as
sedimentary graded bedding. Another significant property of the complex is tilting of all its layers 30-80 degrees to either northeast or southwest or east or west that similar to bell mouth since nearly all beds dip toward central part of the complex (Figure 24c). This property contradict the ophiolite obduction (thrusting on Arabian Plate) because thrusting of very thick and heavy oceanic floor rocks for long distant and with low tilting angle (Figure 27) must give nearly same tilting to the host rock.

The field and office works in addition to literatures reviews (extremely wide age range of rocks) persuaded the present author to propose a new tectonic model of metamorphic core complex (Figure 24). This model can explain reasons for the mixture of numerous dissimilar sedimentary, metamorphic and igneous-like rocks in highly sheared and uplifted small area.

![Figure 24. a) New rock names of the Mawat Metamorphic Core Complex, b) geologic cross section the complex (Mehaidi,1975) [3], c) A Cross section of the Mawat Metamorphic Core Complex of the present study.](image)
Fossen (2010) [44] defined metamorphic core complex as a core of metamorphic rocks (gneisses) cropped out in a window through non-metamorphic rocks (sedimentary rocks) of considerably younger age. These two rock types of the crust (upper and lower crust) are separated by a detachment, which exhibit evidence of significant shear offset. This detachment is brittle, overprinting mylonitic non-coaxial fabrics in the underlying gneissic lower unit. He added the control of the core complex by a low-angle extensional detachment or shear zone that thins the upper plate (hanging wall) so that metamorphic lower-plate rocks ascend isostatically and eventually become exposed at the surface.

These complexes are defined by Lister and Davis (1989) [45] as structure of the crust that are resulted from major extension of continents, when the middle and lower continental crust is pulled out from beneath the fracturing, extending upper crust. Deformed rocks in the footwall are uplifted through a progression of different metamorphic and deformational environments, producing a characteristic sequence of (overprinted) meso- and microstructures. Huet et al. (2011) [46] stated that the genesis of MCCs resulted from a mode of lithospheric continental stretching that follows collision. They added that the rheological layering of the crust (inherited from collision) is a first-order parameter controlling the development of extensional structures in post-orogenic settings.

On the outcrop of the MMCC, we observed widespread of brittle deformation such as shearing (as polished surfaces and slickensides), brecciation, fracturing and faulting on the micro, meso and large scales (Figures 6a and 13b). Due to these deformations, the complex surrounded nearly from sides by streams such as upstream of Littile Zab River and Qalachuwan-Mokaba stream (Figure 24). The ductile deformations are common too in the metamorphosed volcanioclastics sediments that are evident from folding and foliation (Figure13a). The periphery of the complex contains common and extreme sheared rocks that appear as fissile lensoidal chips of hornblende covered by shiny and polished serpentine minerals. These chips show shearing in the scale of millimeters and in some place about 4 meters thick (Figures 1 and 24). These chips manifest brittle brecciation and hydration of the volcaniclastic sandstones of mafic or ultramafic composition by which transformed partially to hornblende and serpentine. In the Qutabiyan Gorge (near Qutanbiyan village), at the southeast boundary of the complex, the thickness of sheared volcaniclastic sandstone is about 100 m and only partially sheared on the scale of decimeters. In microscopic scale, the brittle deformation is very clear in the forms of grain suturing, kink banding, wavy extinction and fossil fracturing and faulting (Figure 25).

According to these facts, the present study, modified the geological map of the Mawat area by Meahidi, (1975) [3] and renamed the outcropped rocks (Figure 24). However, an accurate geological map of the area needs future detail geological fieldworks for plotting the contact of the exposed rocks precisely. Due to vertical uplift of the MMCC, the present study refuses the nappe, presence of ophiolite and the thrust fault changed to reverse faults.

In literature, analogous to the deep root is discussed in detail by Azizi et al. (2013) [10] who refuse nape setting of the Mawat Ophiolite Complex (Mawat Massif) and considered that the Mawat ophiolite developed as an intrusion of mantle plume into an extensional tectonic regime on the thinned lithosphere of the Arabian passive margin (Figure 26). In contrast to Arabian passive, Aswad et al. (2011) [47] considered Mawat area as an island arc on the periphery of a back arc basin (Figure 27) while Mohammad and Cornell (2017) [38] imagined the complex as an area of the volcanic Arc and ophiolite obduction (Figure 28). Karim and Al-Bidry (2020) [40] considered the Mawat area as basin of deep marine sedimentation of volcaniclastic sandstones (greywacke) and finer clastics. Moreover than that, Karim et al. (2020) [48] concluded deep root of Mawat Complex and they stressed on the effect of Main Zagros Thrust on deformation of the complex and its rotation clockwise for about 20 degrees. Therefore, the present study does not ignore more or less modification of the shape and deformations of the Mawat Metamorphic Core Complex by the Main Zagros Thrust (or reverse fault).
Figure 25. a) faulting and bending of nummulites inside limestone Walash-Naoperdan series at the southern boundary of the MMCC on the Qarababa mountain, b) fracturing of the alveolinas in the latter series and on the latter mountain, c) graded bedding in the gabbro of Mawat Ophiolite Complex (Al-Saffi et al. (2012) [3].

Figure 26. Tectonic model of Azizi et al. (2013) [10] in which Mawat area considered as intrusion of mantle plume into an extensional tectonic regime on the thinned lithosphere of the Arabian passive margin.

Figure 27. Cross section and map view of the Mawat area during Eocene by Aswad et al. (2011) [47] in which Mawat area is considered as an island arc on the periphery of back arc basin.
5. Conclusions

1- Field and lab works failed to find basalts, metabasalt-, metadiabase and plutonic igneous rocks in previous Mawat Ophiolite Complex.

2- All exposed rocks in the complex consist of either fresh volcaniclastics sediments (sandstone, conglomerate, shale, greywakes) and their metamorphosed equivalents rocks.

3- The complex consists of thousands of layers of more than ten rocks which all metamorphosed regionally to green schist and amphibolite facies.

4- In most metamorphosed rocks original sedimentary structures, textures such as planar beddings, laminations, cross beddings and granular textures are preserved.

5- Due to preservation of these structures, the metamorphic rocks looks like different types of hornfels, schists and gneisses.

6- All the previously considered dykes are neither dyke nor sill but they are metamorphosed impure limestone or feldspar rich sediments.

7- The study changed the Mawat Ophiolite Complex to Mawat Metamorphic Core Complex and not proved presence of ophiolite and igneous rocks in Mawat area.

8- The volcaniclastic sediments (greywakes) sourced from remote volcanic source area inside Iran and transported to Mawat area during Paleocene-Eocene by turbidity currents.

9- No evidences of overturning and lateral movement are found.

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