PETROLOGY OF GABBROIC ROCKS OF MAWAT OPHIOLITE COMPLEX (CENTRAL SECTOR), NE IRAQ

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ABSTRACT

The gabbroic members of the igneous rocks from the Mawat Ophiolite Complex are located in the Zagros Suture Zone at the boundary between the Arabian and Iranian Plates. They are related to post collision event with emplacement into the continental crust after collision (during Tertiary) between the Arabian and Iranian Plates.

Three types of gabbroic rocks were recognized and studied: 1) The layered gabbros, which are the dominant type; 2) The marginal gabbros are the most affected by alteration and deformation among the three types of the gabbros, and 3) The dyke pegmatoid gabbros. The layered gabbros exhibit two types of layering; compositional layering and grain size layering. Mechanical crystal settling is considered as the main process of layering.

In this study, the petrographic study of 100 thin sections showed that these rocks consist of calcic plagioclase, bytownite in composition (An 85), clinopyroxene (augite) and rarely orthopyroxene, as the major mineral phases. Iron oxides, mainly magnetite is found as an accessory primary phase and as secondary after the Fe-Mg bearing mineral phases. The rocks in general, experienced alteration with the formation of different secondary minerals. Amphibole (Tremolite – Actinolite) is abundant as alteration product of the primary pyroxenes; associated with chlorite, epidote, sericite and secondary magnetite. Plagioclase attained relatively variable degrees of alteration. Three types of deformations were recognized; crystal-plastic, semi-brittle and brittle. Pseudomorphic and non-pseudomorphic alterations were distinguished. The marginal gabbros are most affected by alteration and granulation. Primary magmatic textures include hypediomorphic granular, intergranular, poikilitic, ophitic and sub ophitic textures, whereas deformation textures are evident by granulation, secondary twinning, and schistose textures.

دراسة صخارية الصخور الگابروية لمعقد ماوات الأوفيولايتي (القاطع الأوسط)، شمال شرق العراق

عماد كاظم الصافي، آيتن هادي و أحمد محمد عقراوي

المستخلص

تقع وحدة صخور الگابرو لمعقد ماوات الأوفيولايتي ضمن نطاق زاگروس التصادمي على الحدود بين الصفيحتين العربية والإيرانية، وهي مرتبطة بأحداث ما بعد التصادم وتموضعها ضمن القشرة القارية بعد التصادم خلال عصر المايوسين. تتألف صخور الگابرو من الگابرو المتطبق الذي يمتاز بكونه الأكثر انتشارا والگابرو الطرفي الذي يكون أكثر تأثراً بالتشوه، وتجمعات من قواطع الگابرو البغمتايتي.

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أثبتت الدراسة الصخارية لمائه شريحة بأن الصخور المدروسة تتكون من معادن أساسية: پلاجيوكليس (لابرادورايت – بايتونايت) وكلاينوپايروكسين (أوجايت) وفي حالات نادرة أورثوپايروكسين. أما المعادن الثانوية فتشمل الأمفيبول (تريمولايت – أكتينولايت)، كلورايت، أپيدوت، سيريسايت ومغنتايت ثانوي، بالإضافة الى ذلك فان الأخير يتواجد أيضاً كطور أولي مساعد. تعاني صخور الگابرو لمعقد ماوات من التحلل والتحول وبدرجات متفاوتة، مع إحلال معادن الأمفيبول الثانوي والكلورايت محل معادن الپايروكسين الأولي. إن معدن الپلاجيوكليس يبقى نسبياً بصورة نقية في هذه الصخور. لوحظت العديد من الأنسجة الصهيرية، حيث تعكس الصخور المدروسة النسيج الحبيبي ناقص الأوجه والنسيج البيني والنسيج "اليويكليتي" والنسيج الأوفيتي وشبه الأوفيتي. أما الأنسجة التشوّهية فتكون مرتبطة بتواجد وزيادة عملية التحبب، التوئمة الثانوية وانتشار الأنسجة النضيدية. تعاني صخور الدراسة ثلاثة أنواع من التشوه: التشوه المرن والتشوه شبه المرن والتشوه الهش، أما أنماط التحلل فتشمل التحلل الشكلي الكاذب، والتحلل الشكلي غير الكاذب. وتعتبر صخور الگابرو الطرفي من أكثر أنواع الصخور تأثيراً بالتشوه والتحلل.

INTRODUCTION

The Mawat Ophiolite Complex (MOC) is a part of the Zagros Fold – Thrust Belt, which extends about 2000 Km from southeastern Turkey through northern Syria and Iraq to western and southern Iran (Alavi, 2004). MOC represents one of the Tethyan ophiolites, and it is considered to be part of the Le Crossant Ophiolitique peri-Arabe (Ricou, 1971). From the base to the top, the typical rock types of MOC include ultrabasic rocks, mafic intrusives, subvolcanic, volcanic igneous rocks, and overlain by oceanic sediments; called Gimo Group.

Basic igneous rocks were classified globally by different authors, the most important is of Streikeisen's classification (1976). It is based on the abundance of primary minerals, when modal analysis can be reliably obtained. Rock names are assigned based on the primary phases present prior to alteration. All studied rocks in the present study showed variable degrees of alteration, when so extensive; the estimation of the primary mineral assemblages is not possible. In this case, it is difficult to use this global classification.

In general, the studied rocks are partially or completely replaced by secondary minerals. The rock name used here is based on the reconstructed primary minerals and is termed either urilite or amphibolized (i.e. urilite gabbros, and amphibolized gabbros).

- **Previous Works**

- Jassim (1973) investigated the geology of the central sector of the Mawat Igneous Complex. He indicated that this sector comprises the basic and ultrabasic igneous rocks and minor intrusions. He also recognized various types of banding in gabbro; they are: rhythmic, injection, and alteration banding.
- Al-Mehaidi (1974) mapped the Mawat – Chwarta area through the regional geological mapping of Iraq. He prepared a geological map of the area with detail description of all rock units. He also indicated that the Mawat nappe consists of Mawat Ophiolite Complex and Gimo Sequence.
- Al-Hassan (1975) conducted a comparative study between Mawat and Penjwin Igneous Complexes and found similarities in the mineralogy, texture and chemistry of both igneous complexes, and he indicated that these complexes had suffered similar post magmatic history.
- Al-Hassan (1982) introduced the division of the Penjwin gabbros into layered gabbro, marginal gabbro, and the pegmatoid gabbro.
- Buday and Jassim (1987) concluded that Mawat Ophiolite Complex (Upper Cretaceous) lies within the Penjwin Walash Subzone and they concluded that banded gabbro is the main basic intrusion in the area.

- **Sampling Locations**

Topographic maps at scale of 1: 20 000 of the study area, which is covered by sheet nos. 75/700 and 75/710 in the Mawat region have been used.

Three locations were chosen for sampling (Fig.1); the first lies about 1 Km north of Konjrin village (K-location) extending NE – SW and is about 4670 m in length. The second is located west of Waraz village in the Kard Zubair valley (W-location) extending NE – SW and is about 5300 m in length. The third (R-location) extends N – S and it lies about few kilometers north of Kanaro village near Root Peak, with 1330 m length. The sampling included 47 samples from K-location, 35 samples from W-location and 18 samples from R- location.

FIELD DESCRIPTION

The gabbros, in the study area are light greenish grey to dark greenish grey in colour. Field observations showed that most gabbros had experienced deformation. This is clearly shown by abundant evidence of jointing, fracturing, and crushing (Fig.2). These rocks were affected by shearing stress due to tectonic contact along the boundaries of the gabbros unit, and in the shear zones, which are within the gabbroic rocks (Jassim, 1973).

According to the field relations in the present study, the gabbroic rocks can be subdivided into three groups; layered gabbro, marginal gabbro, and the dyke swarms pegmatoid gabbro (Al-Saffi, 2008). The layered gabbro is the most abundant type, in the study area and covers the major parts of the three locations, where it shows alternating layers of light and dark minerals. Two main types of igneous layering are recognized in the layered gabbro; the first is the grain size layering and second is the compositional layering, typically with variation from mafic to more felsic minerals. Both types of layering are commonly present together (Fig.3). The graded layers occur where the proportion of dark to light minerals decreases. This leads to the succession of metagabbro, gabbro, and leucogabbro. The layering is well developed and ranges in thickness from few centimeters to 60 cm.

Megascopic features in layered gabbros, within this study, such as ratio layering, size layering, graded bedding, as a result from early igneous processes of the layered gabbros; these features suggest that this type of layering is due to crystal settling mechanism (Campbell, 1978 and Irvine, 1980). The layered gabbros also show narrow shear zones not exceeding few meters. In these zones, the rocks are highly deformed and are light greenish gray in colour.

In the northeastern part of the study area (upper parts of all three locations), the layered gabbro has a sharp contact with the ultrabasic rocks; in Ser Shiw area and it is a remarkable feature in this area, where numerous pyroxenite dykes cut the gabbroic rocks. These dykes decrease in occurrences and in thicknesses toward the gabbro's body with a thickness ranging from (1.5 – 3) m.

The marginal gabbro is restricted in the southern part of the study area. It is found in the lower part of W-location, near Waraz village. These rocks were intensively deformed with light green to dark green in colour and medium to low toughness. The transition from the layered gabbro to marginal gabbro is gradual.

In the upper part of K-location, the ultrabasic body in Ser Shiw area shows a dyke of pegmatoid gabbros, which occurs within the ultrabasic rocks and they are about 1.1 m, in thickness. These pegmatoid gabbros are coarse-grained (about 2.5 cm) and generally, show no trace of layering.

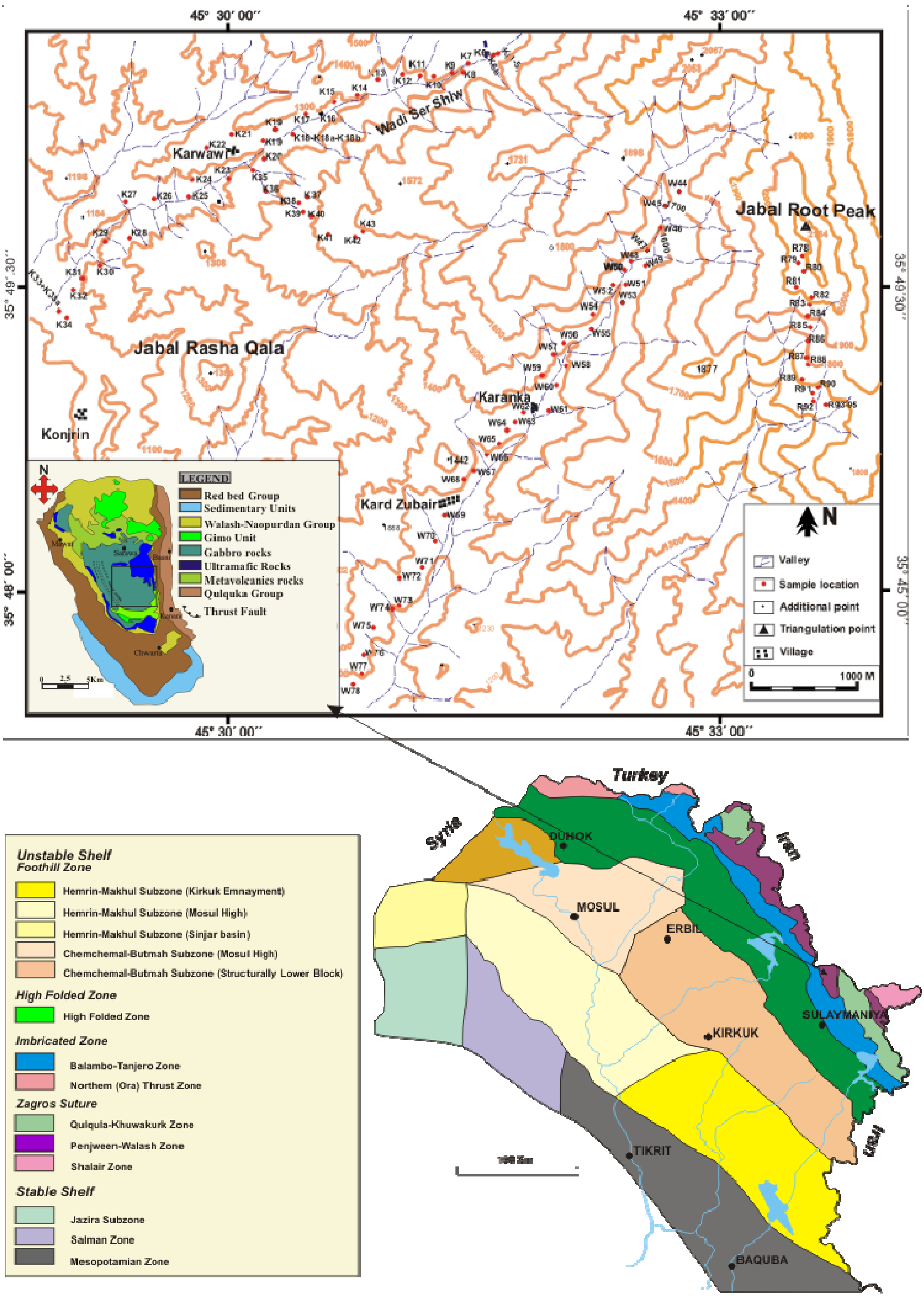

Fig.1: Tectonic zones of the Unstable Shelf Units (Jassim and Goff, 2006), with location and Topographic map of the study area

Fig.2: Jointing, fracturing, and crushing in layered Gabbro

Fig.3: Graded layers, the proportion of dark to light minerals decreases upward

PETROGRAPHY

Thin sections of 100 representative samples from the three sampled locations were examined using polarized microscope to find out the mineral composition and textures, and to clarify the effects of deformation and alteration/ and or low grade metamorphism on these rocks.

Basic rocks, in the present study are composed of primary minerals of plagioclase and pyroxene (clinopyroxene and in rare cases orthopyroxene), secondary mineral assemblages include secondary amphiboles, chlorite, epidote, sericite, and opaque minerals. Mineral and texture modifications in the studied rocks are the result of variable degrees of deformation and alteration. Many cumulus fabrics may be obscured by deformation and recrystallization during obduction (Best, 1982). Some of the studied rocks retained their original textures despite of alteration and deformation. Three types of deformation were recorded including crystal-plastic deformation, semi-brittle deformation and brittle deformation.

Crystal-plastic deformation is marked by increasing abundance of mechanical twins, sub-grains due to granulation in plagioclase (Miller *et al*., 2003). Brittle deformation includes localized zones of highly deformed features, whereas semi-brittle deformation was assigned to features of both brittle and crystal-plastic structures (Blackman *et al*., 2006).

Two types of alteration can be distinguished in the studied rocks; pseudomorphic and non-pseudomorphic. Both alteration types are pervasive, but the former indicates that the primary features are preserved, whereas in the latter are destroyed.

The modal mineral abundances, which are estimated by point counting, are shown in Table (1) and they show microscopic visual estimates of the extent of alteration intensities; according to ratio of secondary mineral assemblages. In addition, granulations were estimated by point counting, as shown in Table (2a, b and c).

Depending on field observations, three types of basic igneous rocks are recorded in the study area: layered gabbro, marginal gabbro, and dyke of pegmatoid gabbros. The description of these rocks is given hereinafter.

Table 1: Model and analysis of Mawat Gabbros; **(A):** K-Location; **(B):** R-Location and **(C):** W-Location

(A)

Rock name	**Pegmatoid Gabbros**				**Layered Gabbros**												
Sample No.	K3	K4	K6a	K6b	K7	K9	K11	K13	K19	K20	K24	K26	K32	K33	K43	K41	K36
Plagioclase %	42.3	53.1	45.3	49.3	62.3	52.9	52.9	44.3	39.3	53.4	50.1	42	56	26	58.6	46.1	40.3
Amphibole %	31.6	31.9	30.8	29.3	33	37.8	37.8	39.9	52.2	39.1	46.4	53.1	38	46.2	36.6	51.2	55
Chlorite %	11.9	8.8	9.2	10.2	1.6	4.3	4.3	5.6	4.5	7.3	1.0	1.1	3.1	6.5	1.9	2.4	1.2
Clinopyroxene %	13.1	4.1	12.1	8.4	0	0	0	4.3	0	0	0	0	0	0	2.4	0	0
Orthopyroxene %	0	0	0	0	0	0	0	2.3	0	0	0	0	0	0	0	0	0
Opaque Minerals %	1.3	2.1	1.7	2.8	3.1	5	5	3.6	4	0.2	2.2	3.8	2.9	18.5	0.5	0.3	3.5
Quartz %	0	0	0	0	0	0	0	0	0	0	0.3	0	0	2.8	0	0	0
Sum %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

(B)

Rock name	**Layered Gabbros**							
Sample No.	R78	R80	R81	R85	R87	R88	R91	R93
Plagioclase %	18.6	49.9	50.2	45.4	32.1	51.1	40.3	65
Amphibole %	74.5	40.6	43.5	44.4	55.8	42.6	51.3	28.2
Chlorite %	6.2	8.9	5.9	4.2	11.3	6	7.5	6.1
Opaque Minerals %	0.7	0.6	0.4	6	0.8	0.3	0.9	0.7
Sum %	100	100	100	100	100	100	100	100

(C)

Rock name	**Layered Gabbros**				**Marginal Gabbros**														
Sample No.	W45a	W45b	W46	W51	W55	W57	W61	W60	W62	W64	W67	W71	W72	W73	W74	W75	W76	W77	W78
Plagioclase %	51	49.4	58.1	34.9	50	32.4	45.9	45.7	44.2	64.1	50.2	35.6	52.2	39.6	50.5	33.3	38.3	45.1	38.6
Amphibole %	42.2	43.9	93.6	58	41	56	41.1	43	38	31.9	46.2	52.7	30	40	41.7	46.1	43.2	46	46.6
Chlorite %	5.3	5.8	2	6.6	7	11.3	12	2.1	11	3.7	2.8	2.2	7.4	1.7	2.3	2.1	1.6	1.8	2.8
Clinopyroxene %	0	0	0	0	0	0	0	8.4	6	0	0	0	0	0	0	0	0	0	0
Orthopyroxene %	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0
Opaque Minerals %	1.5	0.9	0.3	0.4	2	0.3	1	0.8	0.5	0.3	0.8	9.5	10.4	8.2	4.5	6.7	5.9	6.2	9.8
Epidote %	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	1.8	1.3	0.9	2.2
Sum %	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 2a: Granulations (%) of Mawat gabbros (K-location)

Rock types	Layered gabbros				Pegmatoid gabbro	
Sample No.	K20	K13	K11	K7	K3	K6
Granulated	9	39.6	74.4	100	25.6	23.2
non-granulated	91	60.4	25.3	0	74.4	76.8
Sum	100	100	100	100	100	100

Table 2b: Granulations (%) of Mawat gabbros (W-location)

Rock types	Layered gabbros				Marginal gabbro	
Sample No.	W60	W46	W45b	W7b	W76	W78
Granulated	8.2	18.7	51.5	100	70.3	75.9
non-granulated	91.8	81.3	48.5	0	29.7	24.1
Sum	100	100	100	100	100	100

Table 2c: Granulations (%) of Mawat gabbros (R-location)

Rock types	Layered gabbros			
Sample No.	R93	R88	R79	R78
Granulated	5.5	15	36.8	100
non-granulated	94.5	85	63.2	0
Sum	100	100	100	100

- **Layered Gabbro**

Layered gabbro is composed of alternating plagioclase rich and pyroxene rich layers. The pyroxene has been completely or partially altered to secondary amphibole (urilite) and chlorite. Under the microscope, most of the pyroxene minerals in these rocks are observed as relicts within the amphibole minerals. Urilitization and sussuritization are typical alteration types in these rocks. Variable degrees of deformation are observed and hence the layered gabbro displays wide varieties of microstructure; ranging from crystal-plastic to brittle features. The samples of the layered gabbro show several narrow shear zones. In these zones and at the contact with the ultramafic body, the plagioclase and to lesser extent secondary amphiboles are granulated, and in many cases, they are impregnated with opaque minerals. Most of these zones have undergone extensive mineralogical and textural modifications. Quartz occurs in a few samples. It is found in the western part of the studied area in the lower part of K-location.

Petrographic study of the studied rocks shows two types of textures; primary and deformational igneous textures that are completely free of any crystal-plastic pseudomorphic (overprint), and are mainly found and preserved in the fine grained rocks. In the more common coarser grained rocks, the most pristine igneous texture consists of plagioclase with secondary twins, undulose extinction, and/ or sub-grains, which are described hereinafter.

─ **Layered Gabbros:** Show a hypediomorphic granular texture (Fig.4.1). Most intrusive basaltic magmas crystallize by slow sequential growth of minerals producing hypediomorphic granular texture (Best, 1982). This texture has been found and described in many arc plutonic complexes, like Vizcono Peninsula, California (Kimbrough and Moore, 2003), Oman Ophiolite Suite (Shastry *et al*., 2001) and in Sazava Intrusion, Central Bohemian Pluton (Janousek *et al*., 2004).

─ **Poikilitic Texture:** Is also observed where secondary amphiboles oikycrysts enclose plagioclase chadacrysts (Fig.4.2) and shows plagioclase with reactional margins surrounding them. Sapountzis, (1979) suggested in his study of the Ssalaniki Gabbros that the plagioclase and clinopyroxene have been partially replaced by amphibole through reaction of the primary crystals with the liquid. The poikilitic texture is considered a common textural feature in Jormua Ophiolite, Finland (Peltonen *et al*., 1998), and in gabbros from Aksaray and Kayseri regions, Turkey (Kocak *et al*., 2005).

Figure (4.3) shows intergranular texture, where the secondary amphiboles form grains interstitial with the plagioclase. Layered gabbro's samples also have ophitic texture. Figure (4.4) illustrates subhedral and anhedral crystals of plagioclase, which are randomly arranged and completely enclosed in the secondary amphibole. Often, the plagioclase crystals penetrate into, but are not enclosed in the secondary amphibole. In this case, the sub-ophitic texture is developed (Fig.4.5). The ophitic and sub-ophitic textures have been described in many ophiolites of the world such as; Gabbroic Pluton, Yildizeisivas Region, Turkey (Boztug *et al*., 1998), the Poanti – Karsanti Ophiolite, Southern Turkey (Parlak, 2000).

Plagioclase is the most important constituent of the layered gabbro. Modal proportions of plagioclase vary between (18.6 – 65) %. The wide range of modal plagioclase is due to sampling related to layering nature. Plagioclase has mostly undergone granulation, which affects grain size and shape, and its morphology ranges from subhedral, unaffected by fracturing or granulation to anhedral. The grain size ranges from fine (mean size = 0.3 mm) to relatively coarse (4.0 mm). Petrographic examination (using Michel-Levy estimates) showed that most of plagioclases are Bytownite in composition (An 85). Figure (5.1) shows relatively fresh plagioclase crystals, almost without a trace of deformation.

The layered gabbro's samples show crystal-plastic deformation, where plagioclase displays undulose extinction, deformation twins, and sub-grian formation, where local patches of plagioclase sub-grains on the margins of large grains were observed, particularly where the larger grains impinge on each other (Fig.5.2), where annealing recrystallization with sutured boundaries of smaller sub-grains are obvious. Figure (5.3) clearly shows granulation of plagioclase into narrow zones along grain boundaries and internal cracks.

The semi-brittle deformation processes began at the end of crystal-plastic deformation, in some cases; several of the most highly deformed samples contain plagioclase with tails of polygonal smaller sub-grains (Fig.5.4). Samples near the contact between layered gabbro and ultramafic body and near shear zones show more intense granulation by the influence of brittle deformation, which affected plagioclase by the formation of fine crystals. In addition, these rocks show a schistose texture (Fig.5.5). Where the deformation intensity increases, the mortar texture is developed (Fig.5.6). It also shows completely granulated plagioclase crystals and acicular secondary amphiboles are more abundant.

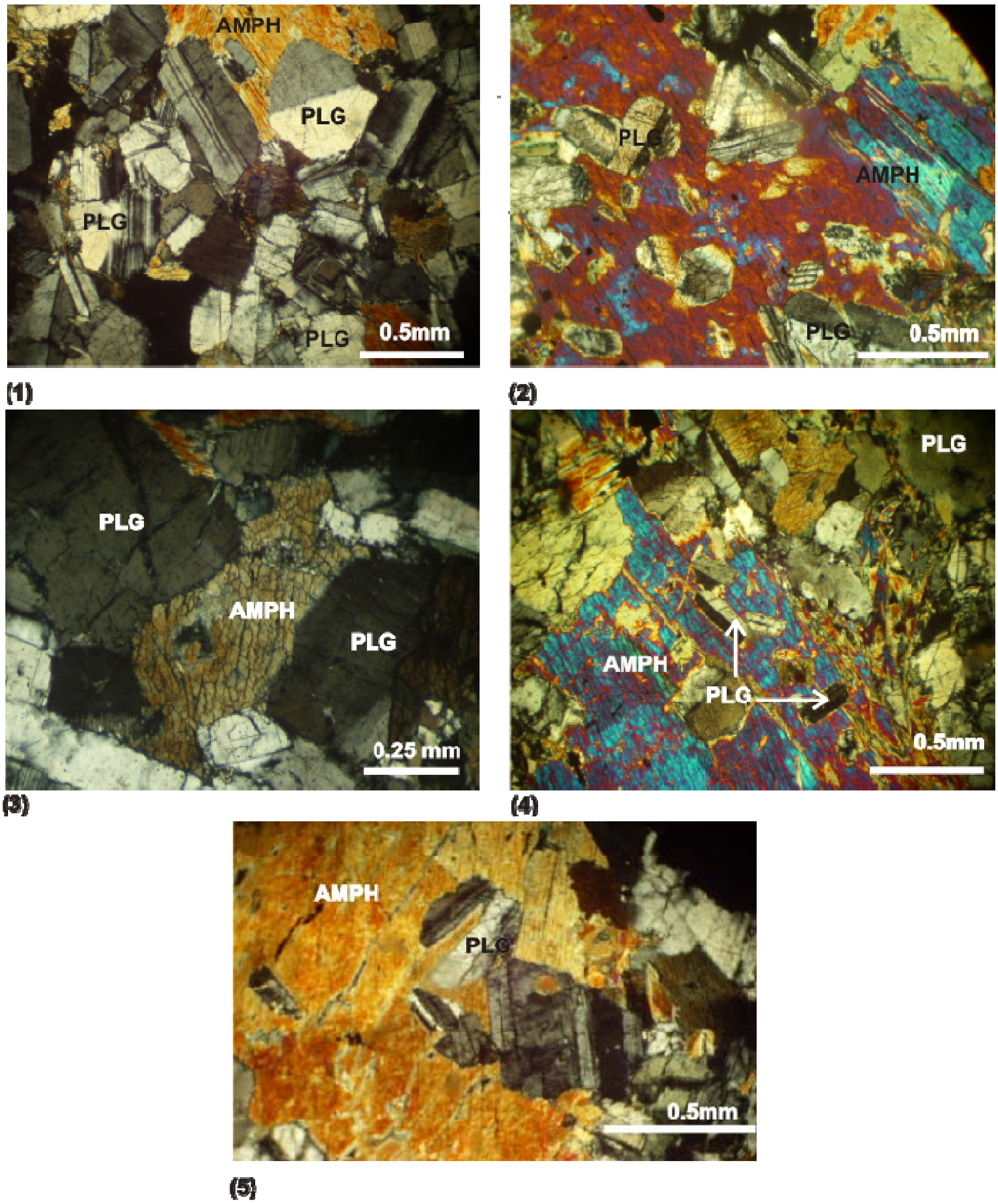

Fig.4:

1) Photomicrograph of sample K43 (X.N.), showing hypediomorphic granular texture in layered gabbro

2) Photomicrograph of sample K36 (X.N.), poikilitic texture consisting of secondary amphiboles oikycrysts enclose plagioclase chadacrysts

3) Photomicrograph of sample K40 (X.N.), exhibiting intergranular texture including amphibole grains interstitial to the plagioclase

4) Photomicrograph of sample K41 (X.N.), showing ophitic texture, plagioclase crystals which are completely enclosed in the amphibole

5) Photomicrograph of sample W64 (X.N.), showing sub-ophitic texture, plagioclase crystals are partially enclosed in the amphibole

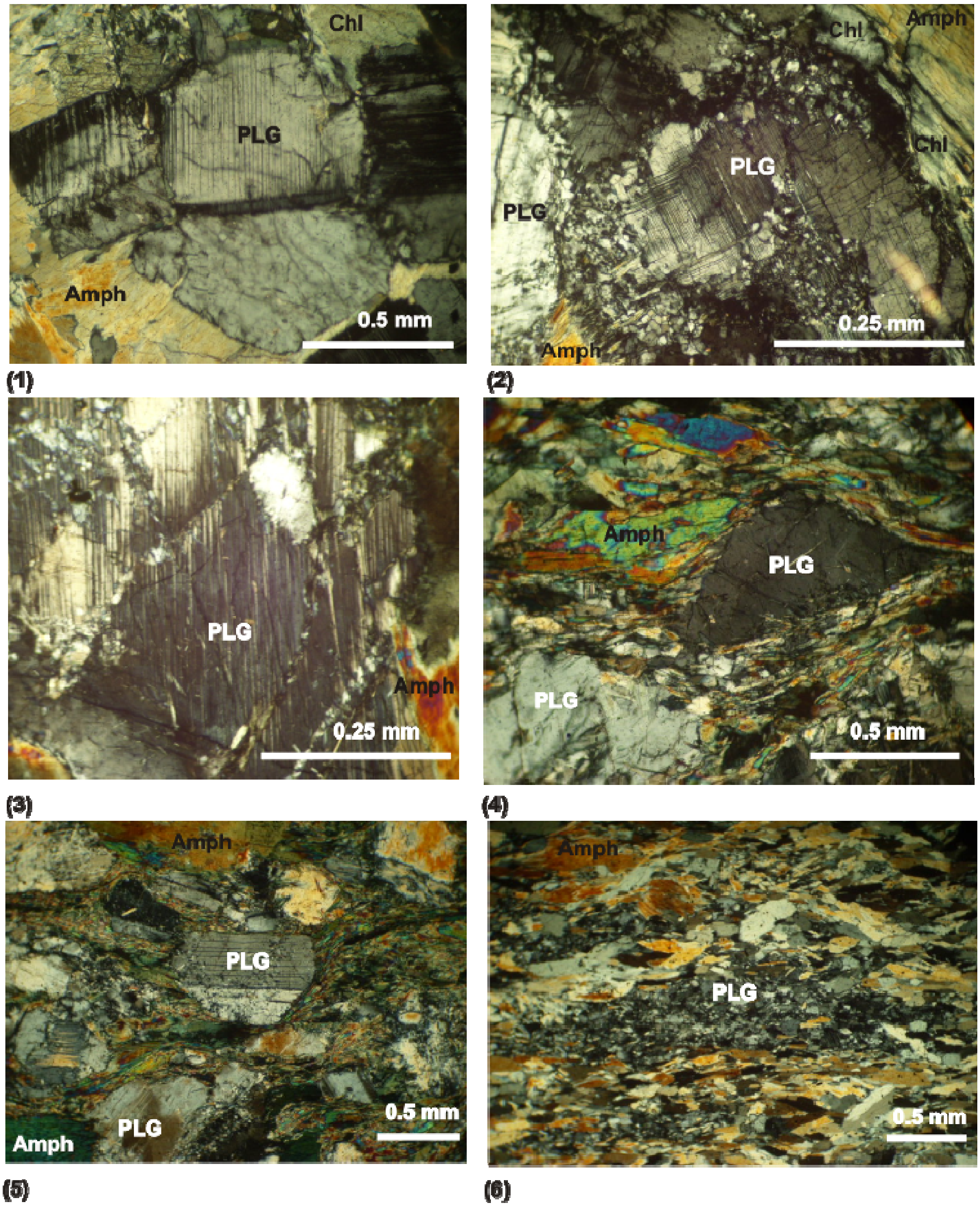

Fig.5:

1) Photomicrograph of sample W61 (X.N.), showing relatively fresh plagioclase crystals
2) Photomicrograph of sample K22 (X.N.), exhibiting granulation of plagioclase along grain boundaries
3) Photomicrograph of sample K25 (X.N.), showing granulation in to narrow zone along internal cracks
4) Photomicrograph of sample R86 (X.N.), showing plagioclase with tails of polygonal subgrains due to deformation
5) Photomicrograph of sample R88 (X.N.), exhibiting schistose texture
6) Photomicrograph of sample R85 (X.N.), exhibiting mortar texture with completely granulated plagioclase crystals

Deformation twining is also observed (Fig.6.1), showing the curvature of the twin lamellae. The twin lamellae also show tapering away toward undeformed area, which is noted by cross twin lamellae (Fig.6.2). Some plagioclase crystals can distinctly show displacement of twins lamellae along micro fracture, which have developed within the crystal (Fig.6.3). Figure (6.4) illustrates uralitic amphibole, which is invaded by a plagioclase lath.

Some plagioclase grains are clouded by abundant disseminated opaque minerals, acicular secondary amphibole and sericite (Fig.6.5). In all examined specimens, plagioclase is the most stable phase, over large intervals of the layered gabbro; alteration of plagioclase is limited to narrow zones and enclose variable amounts of chlorite along cracks and grain boundaries (Fig.6.6). The most extensive alteration of plagioclase occurs in sheared rocks where the original grains are granulated, within these zones the plagioclase crystals may also be replaced by minor epidote due to sussuritization process.

Urilite is the major secondary mineral after pyroxene in the layered gabbros. It is green in colour and strongly peleochroic in thin sections, from brownish green to deep green.

Two types of secondary amphibole were distinguished; less fibrous with anhedral to subhedral, and the distinctly fibrous amphibole. Both types are secondary in origin formed by urilitization product of pre-existing pyroxenes.

Throughout most of the studied rocks, the pyroxene is variably affected by alteration, more intense alteration is usually adjacent to the contact between layered gabbro and dunite body and in the shear zone, and hence, it is difficult to distinguish fresh pyroxene crystals, where relicts of pyroxene are present within secondary amphiboles. Pyroxenes are mainly represented by augite, which is colorless with weak peleochroism and an extinction angle of 42°.

The amphiboles form (25 – 74.5) % of the total volume of the studied rocks, depending on the percentage of original pyroxenes. The distinctly fibrous secondary amphiboles occur mainly in the shear zones and along contacts with dunite bodies, where the rocks have been deformed, but occur elsewhere as well, in contrast, the less fibrous secondary amphibole, which occurs in slightly deformed rocks. Shear zones are characterized by bands of granulated original plagioclase and elongated secondary amphibole. In many instances, the pyroxene grains are completely altered to fibrous secondary amphiboles (Tremolite – Actinolite). Figure (7.1) shows bending along cleavage planes in amphiboles due to deformation.

The alteration occurs almost exclusively along the margins of the pyroxene grains and penetrates into the crystals along cleavage planes and/ or along fractures, alteration also extends into adjacent plagioclase grains along fractures. The secondary amphibole might be accompanied by small amounts of pale green chlorite showing kink bands (Fig.7.2).

The secondary amphibole is also present as pale green acicular (needle-like) crystals; this amphibole shows weak peleochroism and varies from pale green to very pale green. Acicular crystals of amphiboles also appear within coarse plagioclase crystals (Fig.7.3). In some samples, the secondary amphibole has frayed margins penetrating into the adjacent plagioclase crystals, particularly where the grains impinge on each other due to deformation (Fig.7.4). These frayed margins are resulted from slipping along cleavage planes. Figure (7.5) shows fractures cutting plagioclase crystals, which are filled with green amphiboles, occasionally, with minor amount of chlorite. Secondary amphiboles, generally show undulose extinction, displacement along microfractures, microfaults, slipping along cleavages and secondary twining; all of which are deformational features (Fig.7.6).

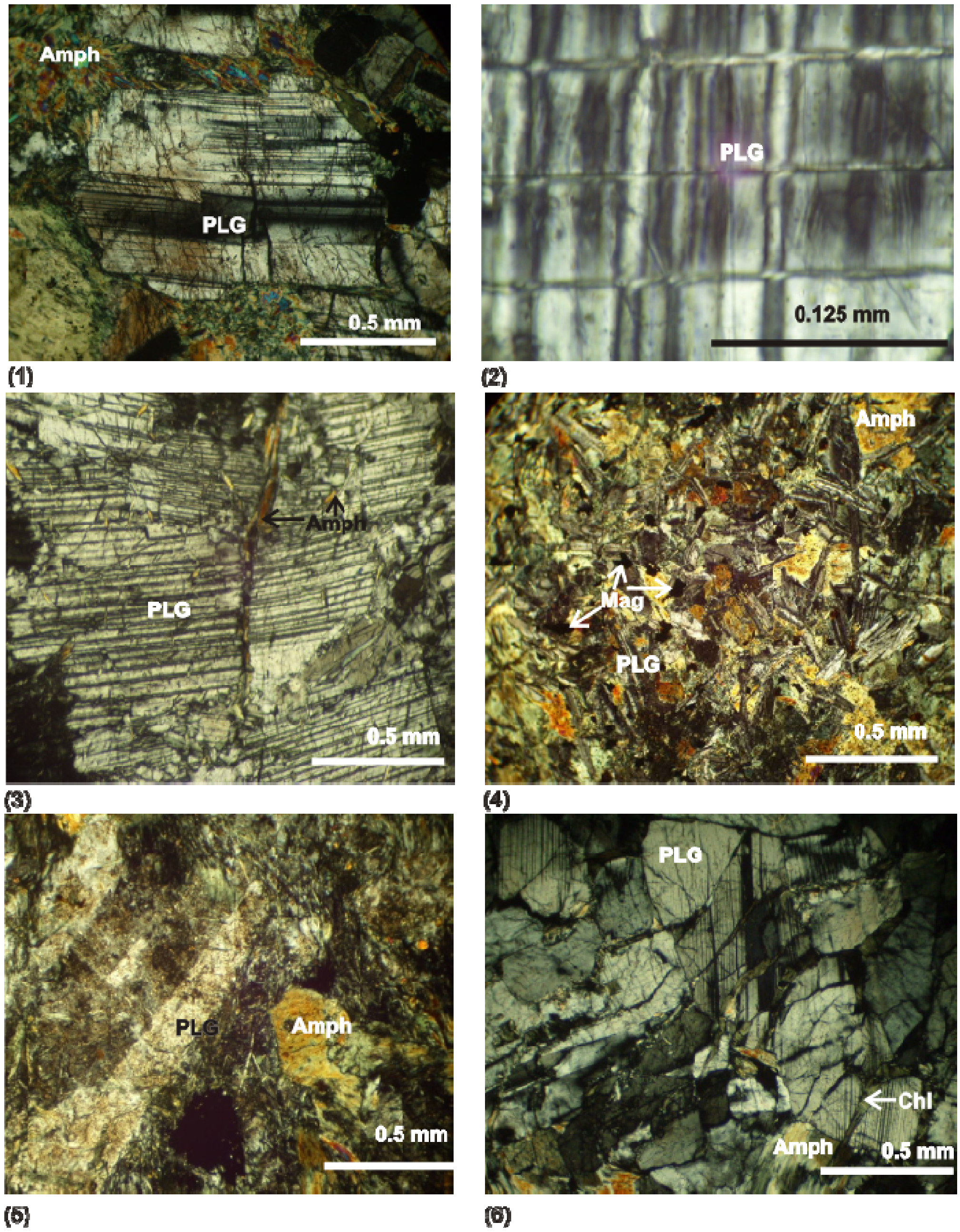

Fig.6:

1) Photomicrograph of sample K37 (X.N.), showing secondary twinning in plagioclase with tapering and curvature of the lamellae
2) Photomicrograph of sample K43 (X.N.), showing cross lamellae in plagioclase due to deformation
3) Photomicrograph of sample K13 (X.N.), showing displacement of twins lamellae along micro fractured in plagioclase
4) Photomicrograph of sample W67 (X.N.), showing amphiboles which is invaded by plagioclase lath
5) Photomicrograph of sample W55 (X.N.), showing plagioclase grains clouded by abundant disseminated opaque minerals, acicular secondary amphibole and sericite
6) Photomicrograph of sample W64 (X.N.), showing alteration of plagioclase is limited to narrow zones and enclose minor amounts of chlorite along cracks and grain boundaries

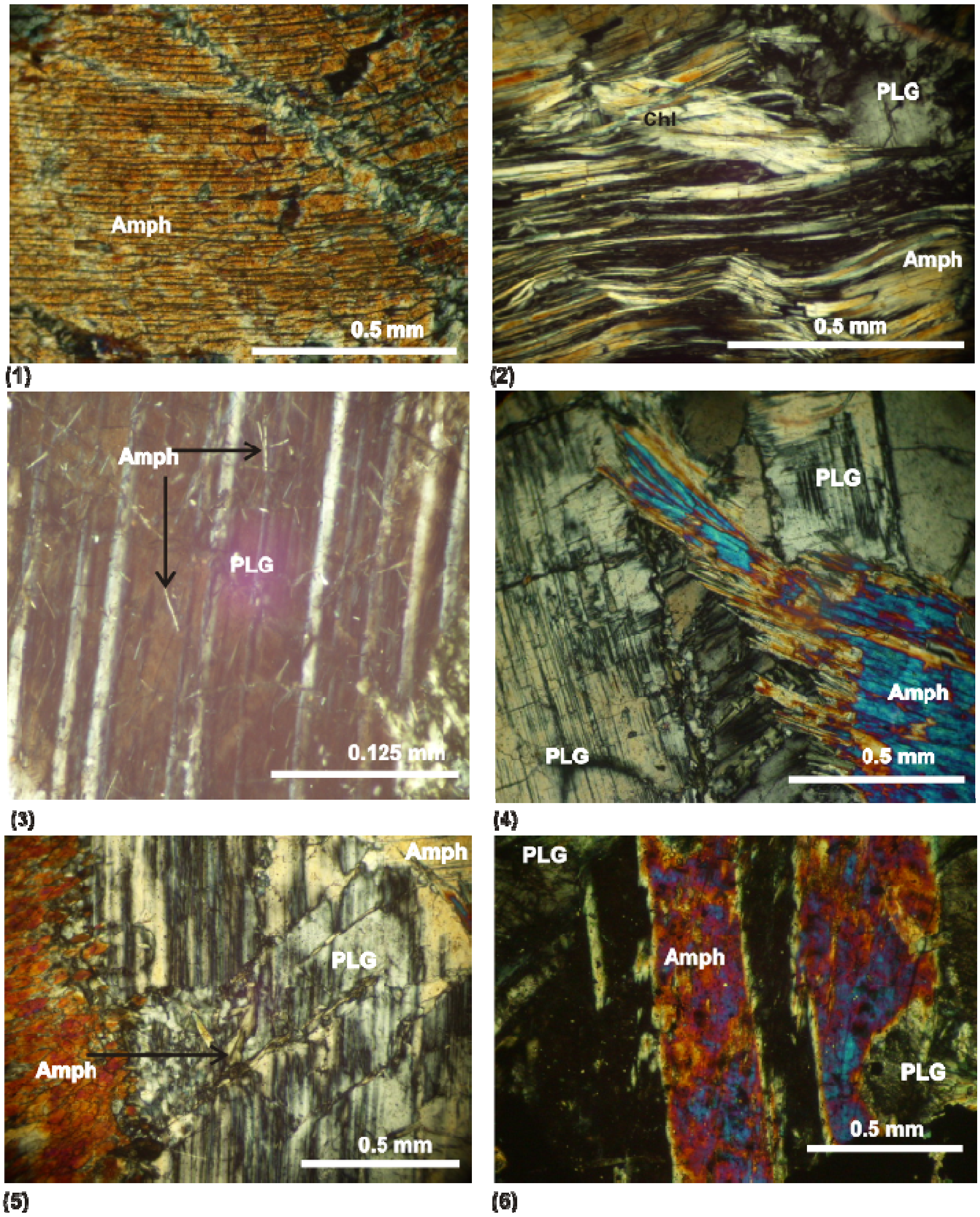

Fig.7:

1) Photomicrograph of sample R45b (X.N.), showing bending along cleavage planes due to deformation in amphibole

2) Photomicrograph of sample W45a (X.N.), showing the secondary amphibole which are accompanied by small amounts of pale green chlorite with kink bands

3) Photomicrograph of sample K20 (X.N.), showing acicular crystals of secondary amphibole appear in coarse plagioclase crystals

4) Photomicrograph of sample K35 (X.N.), showing the secondary amphibole has frayed margins and penetrating into the adjacent plagioclase crystals

5) Photomicrograph of sample K19 (X.N.), showing fractures cutting plagioclase crystals, which are filled with green amphibole

6) Photomicrograph of sample K37 (X.N.), showing secondary twining and micro-fault in amphibole

Chlorite ranges from (1 – 12) % of the total volume of the layered gabbros, with pale green colour and faint pleochroism. Chlorite occurs as patches and present in many thin sections; subordinate to secondary amphibole. It occurs as an alteration product (chloritization) after the pyroxenes and secondary amphiboles minerals. Its occurrence in the deformed plagioclase grains is rather restricted to the cracks, fractures, and grain boundaries.

Epidote commonly occurs in small amount (Table 1). It is rare and restricted in the layered gabbros. It is usually found as an alteration product of the plagioclase due to sussuritization (epidotization) within sheared rocks.

Opaque minerals are mostly magnetite ranging in amount from (0.2 – 10.4) %. They form disseminated aggregates of very fine grained or in some cases, occur as single grains and is commonly associated with alteration of pyroxenes to secondary amphiboles (Fig.8.1). There is generally a strong association between oxide-rich regions and highly deformed and altered regions.

- **Marginal Gabbro**

Modal analysis of the samples of marginal gabbro is shown in Table (1b). It is composed of plagioclase, fibrous secondary amphibole, chlorite, epidote, and secondary oxides.

Distinctly fibrous secondary amphiboles are mainly (Tremolite – Actinolite), depending on extinction angle (13 – 21)°, they range in colour from colourless – yellowish green to strongly pleochroic; ranging from deep green to yellowish green probably due to the higher Fe-content, and have elongated shape. The following minerals were found in the marginal gabbro.

Plagioclase varies in grain size from (0.2 – 1.0) mm and shape due to granulation. It is An 80 in composition depending on extinction angle (36)°.

Acicular secondary amphibole is also common in the samples of marginal gabbro. In many cases, the plagioclase crystals are invaded by acicular crystals of amphiboles, which might indicate that deformation took place after solidification of the marginal gabbro rocks.

Chlorite is flaky in shape and mainly found as alteration product, also the marginal gabbros show abundant magnetite (Fig.8.2).

Epidote is in general, more abundant than in the layered gabbro and pegmatoid gabbro, it is found as single crystals and small grain aggregates (Fig.8.3).

Samples of marginal gabbro show higher alteration intensity than the layered gabbro and dyke of pegmatoid gabbro rocks, whereas the non-pseudomorphic alteration type is the most common. The samples of marginal gabbro show orientation forming a weak foliation manifested by the alternating of plagioclase and ferromagnesian minerals (distinctly fibrous secondary amphibole and/ or chlorite). In this case, a schistose texture is formed. This tectonic texture is the most common texture and is observed in all thin sections of the samples of marginal gabbro.

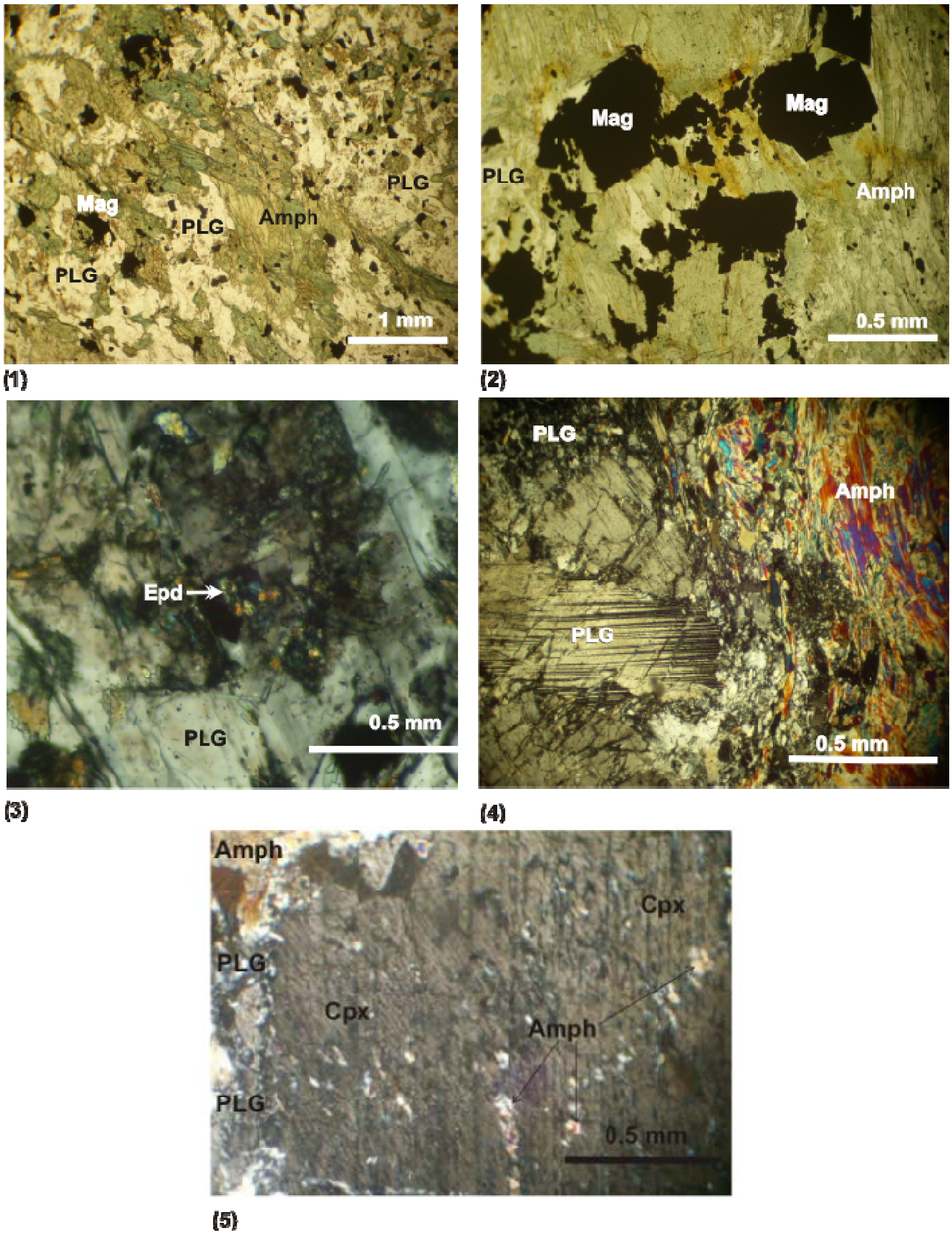

Fig.8:

1) Photomicrograph of sample W71 (P.P.L.), showing opaque minerals in the layered gabbro
2) Photomicrograph of sample W78 (P.P.L.), showing opaque minerals in the marginal gabbro
3) Photomicrograph of sample W78 (X.N.), showing a single crystals and small grain aggregates of epidote in marginal gabbro
4) Photomicrograph of sample K3 (X.N.), showing limited granulation near boundaries of large plagioclase grains
5) Photomicrograph of sample K3 (X.N.), showing the secondary amphiboles which occur along cleavage planes and veins

▪ **Dyke of Pegmatoid Gabbro**

The primary minerals in pegmatoid gabbro include calcic plagioclase, which is the most abundant mineral in the studied samples of the pegmatoid gabbro, followed by clinopyroxene and magnetite. The secondary mineral assemblages include secondary amphiboles and chlorite. Modal analysis of the samples of a dyke of pegmatoid gabbro is shown in Table (1a).

The majority of plagioclases are fresh without any traces of alteration and they show limited granulation near boundaries of large plagioclase grains (Fig.8.4). In general, plagioclase grains of the pegmatoid gabbro; display undulose extinction, sub-grain formation and deformation twins.

The samples of pegmatoid gabbro are slightly altered, where the style and intensity of alteration in these rocks is different from that in layered gabbros and marginal gabbros, which show partial to complete alteration. The pseudomorphic alteration is most common in the samples of pegmatoid gabbro and strongly related to crystal-plastic deformation. Moreover, the studied rocks of pegmatoid gabbro are slightly granulated (Table 2a).

Pyroxene forms (4.1 – 13.1) % of the modal, and it is relatively fresh without alteration, colorless with weak pleochroism, and it is augite in composition according to extinction angle (44°).

Amphiboles are secondary, by replacement after pyroxene minerals. It is less fibrous and green in color and strongly pleochroic, varying from green to brownish green. In some cases, the secondary amphiboles occur as small blebs within the pyroxene grains, some of which are aligned along cleavage planes, as well as, vein fillings by secondary amphibole (Fig.8.5).

Chlorite is pale green in color, flaky in shape, occurs as an alteration product (chloritization) after the pyroxene.

Opaque oxide occurs within secondary amphibole as alteration product of Fe-rich minerals.

Dykes of pegmatoid gabbro rocks have been found and described in many parts of ophiolite complex in the world; such as, a polygenetic ophiolite complex, Central Iran (Ghasemi *et al*., 2002), Mayari – Baracoa Ophiolite belt, Eastern Cuba (Marchesi *et al*., 2006), Southern Albanian Ophiolites (Koller *et al*., 2006), and Trinity Ophiolite (Stremmel and Suhr, 2007).

RESULTS AND DISCUSSION

The study area exhibits deformation, alteration and/ or metamorphism and hence shows complex manifestations. The studied samples are mainly composed of mineral assemblages including plagioclase, pyroxene (clinopyroxene and in rare cases orthopyroxene), secondary amphiboles, chlorite, epidote, sericite, and magnetite.

Based on field observations, three groups of gabbroic rocks are recognized; the layered gabbro, which is found in the three sections; the marginal gabbro, which appears in the lower part of W-location, and dyke of pegmatoid gabbro, which is found in the upper part of K-location.

The three groups show partial to complete alteration. The alteration is pervasive with conversion of pyroxene to secondary amphibole (Tremolite – Actinolite), in many cases, rough optical continuity with minor amount of chlorite. Coish *et al*. (1986) assumed that the dominance of Actinolite – Chlorite suggests that clinopyroxenes are the principle original minerals. Plagioclase remains relatively fresh in appearance; it is un-zoned with variable grain size and shape due to granulation.

The observations described concerning gabbros of the Mawat Ophiolite Complex resulted from the evolution of deformation conditions with time and range from magmatic textures to deformation textures. The former includes hypediomorphic granular, intergranular, poikilitic, ophitic, and sub-ophitic textures. The deformation textures are most common in the studied samples, where cumulus fabrics may be obscured by deformation during obduction (Best, 1982). Deformational twining of plagioclase is common, where the studied samples show bending, tapering, and crossing of different sets. Augustithes (1978) indicated that most polysynthetic deformation twins of plagioclase takes place by post solidification processes.

The samples of layered gabbro show crystal-plastic deformation, where the transition from igneous textures to crystal-plastic deformation texture is marked by increasing of abundance deformation of twins, and subgrain boundaries in plagioclase. These types of deformation took place under high temperature, which more likely were deformed at temperature near solidus (Blackman *et al*., 2006). It is important to note that the gabbros of ophiolites are related to derivation from fast-spreading ridges, such as Oman Ophiolite (Nicolas, 1989), which have no extensive crystal-plastic fabrics.

Some of plagioclase crystals are clouded by microscopic inclusions of iron oxide, sericite, epidote, and acicular amphibole. This is attributed to the introduction of some component or to exsolution due to metamorphism (Whintney, 1972).

In few samples, e.g. samples no. K33, K24, K30 and K33a; quartz is present as a fine grain aggregate and vein-filling, as observed by Jassim (1973) in the western part of the banded gabbro of the Mawat Ophiolite Complex near Amadin village, representing zones of minor acidic intrusions and he concluded that this mineral was introduced after the crystallization of gabbro due to the emplacement.

Urilitization and sussuritization are most common in gabbros of the studied samples. Moreover, Jassim (1973) assumed that urilitization of the Mawat Ophiolite Complex took place before the deformation.

The microscopic textural features of gabbroic rocks, the un-zoned nature of minerals and their modal variation in abundance strongly suggest that they are cumulate in origin. The pseudomorphic habit of secondary minerals clarifies that this alteration is hydrothermal in origin. Such type of alteration had been described in many worldwide ophiolites; in gabbro of North Cape, New Zealand (Hopper and Smith, 1996), in Troods Massif, Cyprus (Gass and Swewing, 1973), and has been attributed to hydrothermal circulation of hot sea water.

All samples of the marginal gabbro, at ultramafic/gabbro contacts and in narrow shear zones within the layered gabbro had undergone shearing. In this case, schistose texture is well developed. Al-Hassan (1982) indicated that the schistose texture in Penjwin gabbros reflects the emplacement and thrusting movement. Williams *et al*. (1954) and Hatch *et al*. (1961) assumed that in sheared and schistose rocks, much of the feldspars might be granulated to smaller size and much or all pyroxenes are replaced by fibrous amphiboles. Such types of processes are attributed to low-temperature/ high stress, i.e. upper green schist farcies conditions (Blackman *et al*., 2006).

In general, the marginal gabbros have absence of annealing in these textures indicating a solid state deformation (Agar and Liod, 1997). This type of deformation has been recorded by many authors, e.g. Terry and Heidelbach (2006) and Ilnicki (2002). The pervasive of deformation in solid state and schistosity, and in some rocks overprint of metamorphism effects were recorded in the fabrics of Alpine ultramafic rocks (Best, 1982).

Sheared zones are commonly impregnated with iron oxide minerals, and are typically associated with alteration of ferromagnesian minerals, which causes expulsion of iron. The alteration processes are facilitated by fluid penetrating along shear zones, as also recorded by Mevel and Cannat (1991) in the oceanic gabbros from slow-spreading ridges and in the gabbros from Indian Ocean (Stakes *et al*., 1991).

The dykes of pegmatoid gabbro sit as schlieren within the ultramafic body (Ser Shiw area). These dykes also were recognized by Al-Hassan (1982) in Penjwin Complex and his conclusion was that they represent pockets of the anatectic basaltic melt, which were not released to high levels. Cannat (1995) indicated that these dyke swarms gabbros were observed in Mid-Atlantic Ridge, and he suggests that the crust in these settings is a complicated mixture of gabbroic plutons and partially serpentinized peridotite and that these observations are related to slow-spreading ridges. It is important to note that the dykes of Mawat gabbros, which are observed in the present study, were not recorded before among the studies concerning the Mawat Ophiolite Complex.

CONCLUSIONS

This study has come to the following conclusions.

- Depending on field observations, three groups of gabbroic rocks were recognized: **1) Layered gabbro**, which covers the major part in all rocks of the three studied locations. Two main types of igneous layering are recognized in the layered gabbros. The first is the grain size layering; and the second one is the compositional layering. Both types of layering are commonly associated with each other. **2) Marginal gabbro** is restricted in the southern part of the study area, it is found in the lower part of W-location near Waraz village, and these rocks are intensely deformed. **3) D**y**ke of pegmatoid gabbro**, which occurs within the ultrabasic body (Ser Shiw area). The Megascopic features in the layered gabbros; such as graded bedding, dimensions, and thicknesses of layering indicate gravitational crystal settling mechanism.
- Petrographically, the Mawat gabbros, in general, are mainly composed of mineral assemblages including Ca-rich plagioclase (Labradorite to Bytownite), pyroxene {clinopyroxene (Augite) and in rare cases orthopyroxene}, whereas the olivine is absent. Secondary minerals include amphiboles (Tremolite – Actinolite), chlorite, epidote, sericite, and magnetite. The Mawat gabbros exhibit deformation and alteration and/ or metamorphism with conversion of pyroxenes to secondary amphibole (Tremolite – Actinolite). Plagioclase remains relatively fresh in appearance.
- Three types of deformations were recorded in the studied rocks including crystal-plastic deformation, semi-brittle deformation and brittle deformation. Crystal-plastic deformation occurs in the layered gabbro, while brittle deformation is most common in the marginal gabbro.
- Based on the petrographical observations, urilitization is the most common alteration process. Urilitization took place during the deformation, as is showed petrographically.
- Both magmatic and deformational textures were observed. The magmatic textures include hypediomorphic granular, intergranular, poikilitic, ophitic and sub-ophitic textures.

The deformation textures are the most common in the studied samples, and the cumulus fabrics may be obscured by deformation probably during emplacement and thrusting. All samples of the marginal gabbros, at ultramafic gabbro contacts and in narrow shear zones within the layered gabbro have undergone shearing. In such cases, a schistose texture is developed, which is attributed to low-temperatures/ high stress. The transition from igneous texture to crystal-plastic deformation texture is marked by the increasing abundance of deformation twins, sub-grain boundaries in plagioclase. These types of deformation took place under high temperature; almost at temperature near solidus.

- Sheared gabbros are commonly impregnated with iron oxide minerals, and they are typically associated with alteration of ferromagnesian minerals, which causes explosion of iron during alteration.
- Deformation twins of plagioclase took place by post solidification of primary twins due to dynamic deformation. The studied samples show bending, tapering, and crossing of different sets.
- The microscopic textural features of the studied rocks, the un-zoned nature of minerals and their modal variation in abundance strongly suggest that they are cumulate in origin.
- The pseudomorphic habit of secondary minerals suggests that the alteration is hydrothermal in origin**.**

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