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PETROGRAPHY, IDENTIFICATION OF METASOMATIC TEXTURES AND ISOCHEMICAL REACTIONS FROM DARBA SUITE, SW JORDAN

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ABSTRACT

Hydrothermal fluids penetrated Darba rocks through their weak points in the solid state during the latest stage of their crystallization. Such fluid movement was facilitated by tectonic deformation. The Ediacaran rocks of Darba suite show metasomatic features and textures that were petrographically identified to be related to magmatism during the late stage of crystallization by isochemical hydrothermal fluids. The isochemical reactions are mostly grain boundary controlled changes ("metasomatic active fronts" or "reaction interfaces") represented by plagioclase crystals merging into one porphyroblast (megacryst), K-feld spathization equalizing albitization, sericitization, limited growth of apatite from plagioclase and the alteration of biotite and hornblende to chlorite.

KEYWORDS: *Shield, Jordan, Metasomatism, Petrography, Tectonics*

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INTRODUCTION

In solid state during the late stage of crystallization, hydrothermal fluids (HTF) related or unrelated magmatic processes may penetrate a rock body through weak points (e.g. micro fissures, grain boundaries, cleavage planes, and micropores) (Rong and Wang, 2016) and/or induced by the help of tectonic deformation (e.g. folding, fracturing, faulting, shear zones) (Collins, 2013). Such processes allow metasomatic fluids to become fully effective, producing new minerals under new physiochemical conditions either by ion-exchange (Yanagisawa et al., 1999) or dissolution–reprecipitation processes (Putnis, 2002). Petrographically metasomatic features can be identified by observing grain boundary relations, the orientation of crystals (co & hetero-orientated replacement) and the presence of relicts (Rong and Wang, 2016).

The Ediacaran rocks of Darba suite show metasomatic features and textures that were petrographically identified and attributed to the magmatic isochemical HTF which penetrated these rocks during their late stage of crystallization. The isochemical reactions are mostly grain boundary controlled changes ("metasomatic active fronts" or "reaction interfaces" in the sense of Rong (1982 and 2009).

Geological Setting

Darba suite is a plutonic intrusion in the northernmost part of the Arabian Nubian Shield (ANS) of the Aqaba Complex of Jordan (Figure.1) (McCourt and Ibrahim, 1990) that was exposed during the Cenozoic uplift (Kröner and Stern, 2004; Johnson et al., 2013). The ANS is generally regarded as an accretion of juvenile volcanic arc terrains and associated ophiolite remnants which were amalgamated during the assembly of Gondwana (Kröner and Stern, 2004).

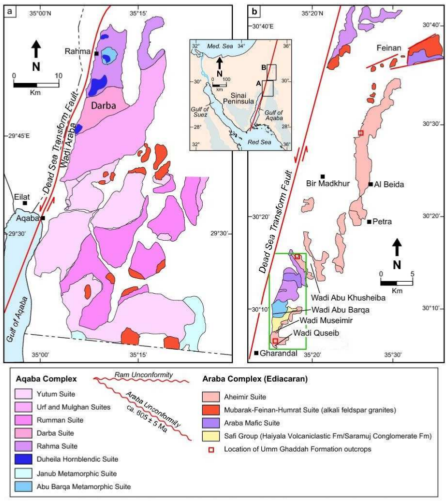

Figure 1: A+B Aqaba And Araba Complexes Respectively (Basement Rocks), Darba Tonalitic Suite, Which Includes Al-Muhtadi Area, Marked With "Darba", (After Mccourt And Ibrahim, 1990, Jarrar Et Al., 2003)

The rocks of Darba suite are part of the basement rocks of Jordan (Powell et al., 2015) and were formed during the East African Orogeny (EAO), an episode of intense tectonics that gave rise to one of the largest juvenile igneous provinces ever known (Bentor, 1985; Kröner and Stern, 2004).

The aim of this study is to petrographically investigate the Ediacaran rocks of Darba suite, in order to identify the metasomatic and other textures of these rocks and give them a specified petrographical nomenclature.

General Description

Darba tonalitic suite comprises two host units (Figure.2), the Muhtadi quartz monzodiorite unit and the Wa'ara granodiorite unit. The outcrops of both units are whitish grey colored tonalite, with idiomorphic plagioclase crystals, highly weathered and heavily diked rocks with fine-grained microdiorite enclaves (Abudayeh, 2018). Muhtadi is inhomogeneous black-white to gray in color characterized by a sudden increase in the grain size of its plagioclase to course pegmatitic megacrysts (Figure.3A). Wa'ara is homogenous, typified by its fine to medium pink to gray granodiorite rock, lacking such pegmatitic crystals (Figure.3B) and has fewer inclusions than Muhtadi. The enclaves are green to dark green in color characterized by the presence of large white plagioclase crystals with variable abundances.

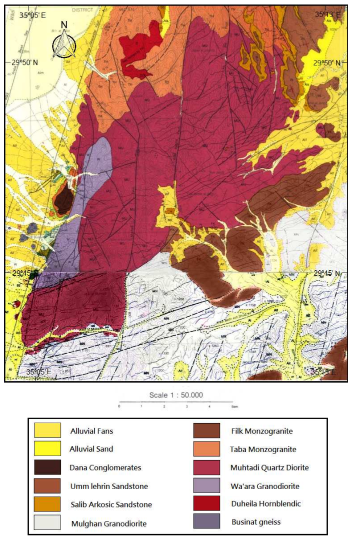

Figure 2: A Map Modified After Ibrahim (1991) Showing Darba Suite With Both of Its Units (Muhtadi in Crimson Red, Wa'ara in Lavender Color) and its Surrounding Units

Mineralogy and Textures of the Host Rocks

The mineralogy of the host rocks includes quartz, orthoclase, plagioclase, hornblende, and biotite. The accessory minerals are opaques, zircon, apatite, and titanite. A representative modal analysis for the minerals of the host rocks

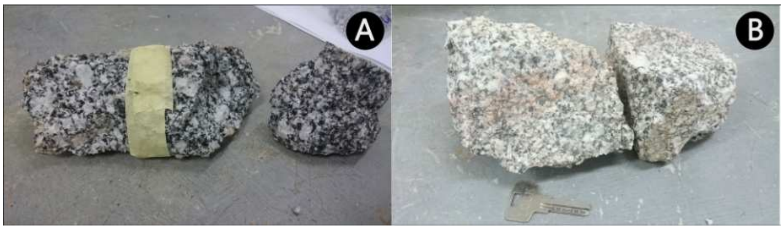

Figure 3 (A): Hand Specimen (Mu-28) Shows the Heterogeneity and General Appearance of an Unweathered Muhtadi Rock With Feldspar Megacrysts. Tape Width is 2 Cm. (B) Hand Spacemen (Wa-5) Shows the Homogeneity and the General Appearance of an Unweathered Wa'ara Rock. No Feldspar Megacrysts and Less Mafic Assembly.

Illustrated in Table-1. The anorthite content was obtained optically by using the Michel – Lévy method (explained in Kerr, 1977), so that plagioclase might range between oligoclase (An_{23}) to andesine (An_{42}).

The host granitoid rocks of both units generally have the following textures: holocrystaline, hypidiomorphic, medium-grained phaneritic in Wa'ara and medium to course porphyritic phaneritic in Muhtadi. Muhtadi shows the sudden pegmatitic increase in grain size caused mainly by some feldspar megacrysts, interlocking-massive granitic and is a leucocratic. The characteristic textures include micro-meso perthitic textures in orthoclase and poikilitic texture that is shown by the inclusions of accessory minerals with most of the other forming minerals or by the presence of small hornblende and biotite crystals in feldspars. Plagioclase shows normal and oscillatory zoning accompanied by polysynthetic twining with narrow and broad lamellae and compound (simple twins and polysynthetic), interpenetrate Carlsbad simple twining, pericline twins, sector twins, where most of the plagioclase crystals show high alteration in their middle parts indicating higher anorthite content. However, this is not the case for the pegmatitic feldspar crystals where the alteration is not selective. The closeness and presence of biotite around and adjacent to hornblende might indicate to the observer's eye what seems to be corona texture when it is not! It is a hetero-oriented replacement phenomenon known as metasomatism, which is the main suspect to explain the appearance of the pegmatitic sized plagioclase crystals. The presence of wavy extinction almost in feldspars, quartz and hornblende, besides the presence of slight fracturing and bending in mafic minerals along with the elongation in some of the primary oxides indicates that the rock was subjected to shear stresses. This is not surprising since the studied rocks were formed during the EAO and its associated tectonics.

Using the modal analysis data a varietal name of Hornblende Biotite Granodiorite can be given to the rocks of Wa'ara, and Hornblende Biotite Quartz Monzodiorite Porphyroid for Muhtadi.

Table 1: Statistical Data Acquired From Representative Thin Sections Made From the Host Rocks. (A: Average Grain Size in Mm, B: Standard Deviation, C: Modal Analysis Volume %)

Sample	Quartz			Alkali Feldspar			Plagioclase			Biotite			Hornblende		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
W A-1	1.79	0.72	17.0	2.50	1.04	12.0	2.81	0.93	47.0	1.45	0.58	16.0	1.26	0.35	7.3
W A-4	2.73	0.59	14.8	2.29	0.43	12.7	3.24	0.91	46.0	1.45	0.59	18.0	1.98	0.33	2.5
W A-7	1.96	1.15	15.3	2.87	1.26	17.3	2.89	0.94	53.5	1.43	0.35	11.3	1.98	0.33	2.5
MU-1	2.31	0.94	6.3	2.56	0.63	10.0	3.75	2.29	73.3	1.94	0.94	4.3	1.72	0.53	5.3
MU-3	1.51	0.92	7.0	3.17	1.04	12.5	4.26	1.94	71.5	1.23	0.39	6.0	1.74	0.43	2.0
MU-4	2.32	0.96	8.50	2.91	0.67	13.0	4.12	2.23	71.1	1.13	0.34	5.6	1.84	0.45	1.6
MU-6	4.29	0.21	15.6	1.21	0.13	7.2	3.49	1.16	52.2	2.53	0.64	11.0	2.13	0.82	13.0
MU-7	2.17	1.20	14.2	2.31	0.40	6.2	5.15	2.30	56.2	2.13	0.39	8.4	2.13	0.39	8.4
MU-26	3.88	0.57	12.0	2.94	1.21	7.0	6.67	2.26	62.6	1.43	0.34	7.6	2.53	1.39	10.0
MU-27	2.53	0.86	11.8	2.33	0.3	18.6	5.30	3.09	52.0	2.40	.05	11.2	2.27	0.73	56

Mineralogy and Petrography of the Enclaves

The mineralogy of the enclaves includes quartz, orthoclase, plagioclase, hornblende, and biotite. The accessory minerals are opaques, zircon, apatite, and titanite. Representative modal analyses for the minerals of the enclaves are illustrated in Table-2. The anorthite content of plagioclase might range between oligoclase (An_{26}) to andesine (An_{33}). This anorthite content is consistent with that of the host rock.

Hornblende shows an aggregate habit of anhedral crystals mainly in enclave -7. Two identified types of enclaved rocks are recognized, one is a dioritic in host rocks and the other as a rich hornblende xenolith in the enclaves themselves. The similarity in shape, size and color between the hornblende and biotite from the enclaves and those inclusions in hornblende and plagioclase crystals from the host rocks can point them out as relicts and may indicate assimilation processes.

Table 2: Statistical Data Acquired From Representative Thin Sections Made From the Dykes and Enclaves. (A: Average Grain Size in Mm, B: Standard Deviation, C: Modal Analysis %)

Sample	Quartz			Alkali Feldspar			Plagioclase			Biotite			Hornblende pyroxene*		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Enclave-1	0.31	0.1	2.0	-	-	0.0	1.67	2.26	69.6	0.22	0.05	4.3	0.47	0.44	24.0
Enclave-7	0.5	0.36	0.3	-	-	0.0	1.33	0.63	54.3	-	-	0.0	0.67	0.52	44.5
Enclave-9	0.36	0.1	2.0	-	-	0.0	0.81	0.71	66.6	0.36	0.09	2.6	0.45	0.08	28.0
Rh-Dyke-2	1.39	0.76	31.	1.87	0.76	37.3	1.04	0.73	30.0	0.35	0.08	1.3	-	-	0.0
Do-Dyke-1	0.21	0.1	1.0	-	-	0.0	0.33	0.05	71.6	-	-	0.0	0.36*	0.08*	23.0*
Do-Dyke-2	0.13	0.02	0.8	-	-	0.0	0.37	0.16	41.3	-	-	0.0	0.32*	0.05*	0.53*

The enclaves generally have the following textures: holocrystaline, allotriomorphic, fine-grained phaneritic with a sudden increase in grain size represented mainly by plagioclase megacrysts. The characteristic textures include antiperthitic textures in plagioclase surrounding remnant orthoclase, and poikilitic texture of accessory minerals in hornblende and plagioclase, or small hornblende grains in plagioclase megacrysts. The plagioclase shows the reverse and oscillatory zoning accompanied by polysynthetic twining with narrow and broad lamellae within the compound (simple twins and polysynthetic), also pericline twins. Most of the plagioclase crystals in Enclave-7 are totally altered and the appearance of saussurite reflects high anorthitic content. But that is not the case for the megacrysts crystals in Enclave-1 and Enclave-9, where the alteration is selective and targets the rings of the reverse zoning. These megacryst are mainly of uniform size. The absence of biotite and the appearance of muscovite which needs K & Al to form might indicate pseudomorphic replacement by metasomatic processes. Using the modal analysis a varietal name of Hornblende biotite microdiorite name is given to these enclaves.

Mineralogy and Textures of the Dikes

Dolerite Dikes

The mineralogy of the dolerites includes quartz, plagioclase, and pyroxene. The accessory minerals are opaques and titanite. A representative modal analysis for the minerals of the dolerite dikes is illustrated in Table-2.

The plagioclase is lath-shaped and highly weathered with fine crystals. The dolerites are metasomatized with abundant titanite and chloritization of pyroxene. These reactions are mostly described by many authors in other parts of the world as evidence of isochemical rock-magmatic fluid interaction (see Pollard, et al., 1983; Taylor and Pollard, 1988).

The general textures for these dolerite dikes are holocrystaline, hypidiomorphic, fine-grained phaneritic with ophitic, intergranular, felty or pilotaxitic and wavy extinction textures, plus being melanocratic in color. The characteristic textures were polysynthetic twining with narrow bands in plagioclase and sericite as an alteration product, also being veined by fine-grained quartz veins.

Rhyolite Dikes

The mineralogy of the rhyolite dikes includes quartz, sanidine, plagioclase, and biotite. The accessory minerals are opaques and titanite. A representative modal analysis for the minerals of the dolerite dikes is illustrated in Table-2. The quartz is porphyry, sericitization of plagioclase is the only alteration texture identified. No boundary controlled changes observed, where most probably this alteration is unrelated to the metasomatic stages from the surrounding host, enclaves and dolerite dikes.

The general textures of the rhyolite dikes are leucocratic, holocrystaline, hypidiomorphic to allotriomorphic, fine to medium grained porphyritic. Sanidine is granular, shows wavy extinction texture, micro-miso perthitic, poikilitic. Plagioclase is characterized by polysynthetic twining and normal zoning with sericite as an alteration product. Using the modal analysis data a varietal name of Alkali-Feldspar Rhyolite Porphyry can be given to the rhyolite dikes, and a basalt varietal name for the dolerite dikes.

Genetic Hypotheses of Metasomatic Mechanisms

The formation mechanism of co-oriented chloritization and muscovitization of biotite is of ion-exchange, because of their similar structure (cleavage and crystallographic lattices) (Kogure and Banfield, 2000). Muscovite can be of primary or secondary origins (Webster and Duffield, 1991). Myrmekite as a texture can be explained by a hetero-oriented dissolution-precipitation replacement process, where orthoclase is replaced by plagioclase (which needs less silica to form), leaving excess silica that takes the form of quartz vermicules inside the replacive plagioclase (Collins, 1988; Rong and Wang, 2016). The coarser the quartz vermicules the higher the anorthite value of myrmekitic plagioclase indicating that the replacive fluids were initially Na & Ca bearing fluids, but with lower anorthite value than the primary plagioclase (Rong and Wang, 2016). Sericitization and muscovitization are micropores-HTF infiltration controlled, where such fluids target the micropores in plagioclase (Smith and Brown, 1988; Que and Allen, 1996).

The perthitic albite in K-feldspar is mainly formed by either unmixing of solid solution or simultaneous crystallization of K-feldspar from a replacement origin (Collins, 1998).Whereas the Antiperthite observed is commonly seen in granites poor in potassium which is the case for some of the studied rocks (specifically the enclaves). Most researchers consider exsolution in the formation of antiperthite (Hubbard, et al., 1965; Vogel, 1970), others consider replacement processes involved in its formation where plagioclase is co-oriented replaced by K-feldspar (Collins, 2002).

Vernon (2002) studied a similar case but for K-feldspar megacrysts in granites and came up with the conclusion that these K-feldspar megacrysts are phenocrysts from a magmatic origin, based on the following criteria, (1) euhedral; (2) simple twin; (3) zonal inclusion of idiomorphic biotite and plagioclase; and (4) oscillatory zonal change of composition from inside to outside.

These major criteria of identification can be similarly applied to the plagioclase megacrysts, where these crystals are truly euhedral but their surfaces are still governed by preexisting surfaces of other types of crystals which are supposed to have been formed later on! The simple twining is there along with the oscillatory zoning, but the inclusions are not idiomorphic, plus they are not always in accordance with the zonal rims but occur randomly in the megacryst.

Plagioclase of Muhtadi shows a sudden increase to pegmatitic grain size which is generally inconsistent with the dominant grain sizes. This grain size occurs in their enclaves as well and resembles a porphyroblast instead of a phenocryst. Explained by plagioclase crystals merging into one porphyroblast (Figure.4) (Hippertt 1987, cited in Deer et al. 2001, page 585).

In the enclaves, textural features support two successive metasomatic episodes. The observations of Collins (2002) have been used to identify these episodes. First is magmatic Ca bearing melt forming the host rock plagioclases simultaneously injected into the enclaves through weak points and micro-fissures forming a micro-pocket melting and dissoluting crystals, producing new plagioclase crystals with primary (high) anorthite content. The second phase is a metasomatic Si, Ca and Na hydrothermal bearing fluids replacing the formerly produced magmatic plagioclase by metasomatic processes.

Observed Fluid-Rock Metasomatic Interactions and Textures in Darba Suite

The metasomatized studied rocks show locally a medium to intense degrees of (-ization or –ification), whereas if occurred noticing complete metasomatism is difficult since the presence of relics of replaced minerals is essential and key evidence in defining such replacement.

The observed types of replacement in the studied rocks include: (i) hetero-oriented albitization of K-feldspar forming a clear albite rim assuming the same crystallographic orientation as the adjacent plagioclase, (ii) co-oriented albitization (deanorthitization) of plagioclase producing dissolution–reprecipitation textures, (iii) co-oriented albitization of K-feldspar producing perthite by unmixing. (iv) the hetero-oriented K-feld spathization occurring at the grain boundary of plagioclase producing dissolution–reprecipitation textures, (v) the hetero-oriented K-feld spathization occurring at grain boundaries of two K-Feld spars producing swapped albite rims, (vi) the hetero- oriented replacement of plagioclase replacing alkali-feldspar forming myrmekite, (vii) the hetero-oriented muscovitization in the interior parts of plagioclase, (viii) the hetero-oriented biotitization of hornblende at grain boundary of K-feldspar, (ix) the co-oriented biotitization of hornblende, (x) the co & hetero-oriented chloritization and muscovitization of biotite and hornblende.

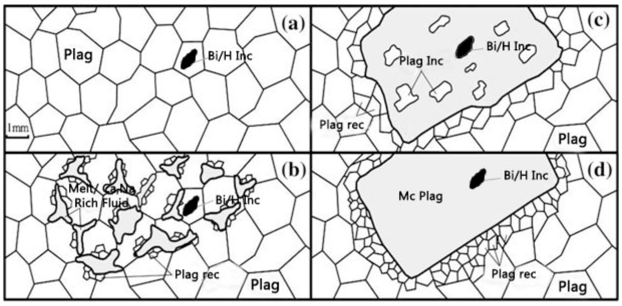

Figure 4: Steps of Solid Rock Crystals Recrystallizing and Merging into One Porphyroblast By Invading Metasomatic Fluids, Modified After Hippertt (1987, Cited In Deer Et Al. 2001). (Plag = Plagioclase, Bi/H Inc = Biotite/Hornblende Inclusion, Plag Inc = Plagioclase Inclusion, Plag Rec = Plagioclase Recrystallization, Mc Plag = Megacryst of Plagioclase)

Examples of Metasomatic and Other Textures in the Studied Host Rocks

Tectonism facilitates the passage of HTF, consequently becoming responsible for furthering the metasomatic processes and textures. This can be supported by chloritization of biotite through altered microfractures in K-feldspar (Figure.5-A). The same tectonics that fractured the K-feldspar caused simultaneously biotite to be deformed and later on to be chloritized. This indicates that the rock was shaped post-tectonically, emphasizing on the ideas of Collins (2013) focusing on the role of tectonic deformation in furthering the replacement process.

Figure.(5-B) shows coarse quartz vermicules of myrmekite, where plagioclase is leaning against and hetero-oriented nibble replacing the alkali-feldspar on its right causing the structure to need less silica to form itself. The excess silica from the replaced mineral crystallized as coarse quartz vermicules (CQV) (Rong and Wang, 2016).

Co and hetero-oriented biotitization of hornblende rims between H_1 and Bi_1 in Figure.(5-C; D) leaving intact hornblende (Bi_2) core takes place at the boundaries of K-feldspar (K_1). In addition, biotite subjected to chloritization can be seen in the same image adjacent to K-feldspar (K_2). K-feldspar forming swapped albite rims is present at the boundaries of two K-feldspars (K_1& K_2) by K-feldspathization. The relationship between P_2 and K_1 is of nibble replacement K-feld spathization, leaving the sericite core untouched since K-feldspar can't replace sericite. All of the used symbols in the micrographs are illustrated in Table-3.

Table 3: The Used Symbols in the Micrographs and their Meanings

Symbol	Meaning	Symbol	Meaning
Ab	Albite	Inc	Inclusion
Bi	Biotite	K	Alkali-Feldspar
Bi_{Chl}	Chloritized Biotite	Mus	Muscovite
Chl	Chlorite	P	Plagioclase
CQV	Coarse Quartz Vermicules	P_{Ab}	Albitized Plagioclase
G	Gypsum plate	Per	Perthite
H	Hornblende	P_{rec}	Recrystallized Plagioclase
H_{Agg}	Hornblende Aggregates	Q	Quartz
H_{Bi}	Biotitized Hornblende	Rel	Relict
H_{Chl}	Chloritized Hornblende	Ser	Sericite
HTF	Hydrothermal Fluids ppt	Sil	Silicification

Figure (5-E) shows wavy extinction texture in quartz, poikilitic texture, pericline twining in plagioclase and silicification of plagioclase, supported with a gypsum plate image (Figure.5-F) to show the orientation of crystals. Figure. (6-A; B) shows a part of the wavy extinction in quartz from Figure. (5-E), indicating tectonism. A sort of an optically continued, unidentified crystallized substance (either quartz or albite) surrounds quartz could be formed as a result of the passage of hydrothermal fluids (HTF) while invading the wavy texture. All these reaction interfaces were caused by chloritization and biotitization of hornblende (Figure.7). The sericitization of plagioclase along a micro-fracture in Figure. (8-A; B) indicates the passage of fluids through such fractures enhancing the metasomatic replacement.

The pericline twining is seen in (P_1, P_2, P_3) making contact with K-feldspar (K_1, K_2) hetero-oriented forming a clear albite rim (Figure.8-C). This reflects temperature conditions at which this texture was produced, and it is most definitely prior to the formation of albite rim i.e., pericline was formed during the melt stage at low temperatures and not from the metasomatic stage. Perthitic albite lamellae were formed from exsolution during an unmixing phase in the solid state (Collins, 1998), after K_1 hetero-oriented replaced plagioclase (P_1, P_2, P_3). This can be proved by observing the orientation of the optically continued pericline relicts in Figure. (8-D).

The hetero and co-oriented chloritization of biotite and biotitization of hornblende can be observed in Fig. (8-E; F), and can be proved by the relicts seen in image-F of the same Figure.

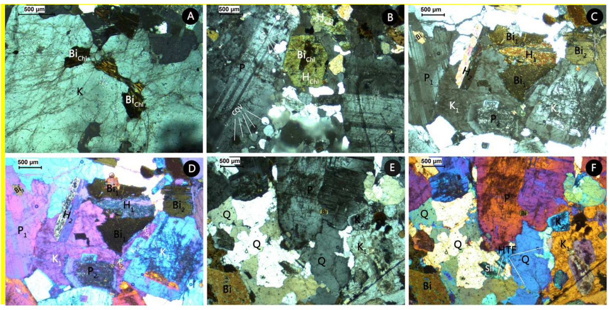

Figure 5: Microscopic Images of (A) Chloritized and Bended Biotite in Micro-Fractured Alkali Feldspar (XPL, Sample Wa-7). (B) Chloritization of Hornblende and Biotite Producing Adjacent Opaques, Coarse Quartz Vermicules of Myrmekite (XPL, Sample Wa-7). (C) Simple Twining in Hornblende, Polysynthetic and Poikilitic Textures in Plagioclase P_1, Biotitization of Hornblende H_1, Chloritization of Biotite Bi_2, Sericitization of Plagioclase Core P_2, K-Feld Spathization of Two K-Feldspars (K_1, K_2) Forming Swapped Albite Rows, K-Feld Spathization of Plagioclase P_2 Forming Albite Rim (XPL, Sample Wa-1). (D) Gypsum Plate of Image-C Showing Orientation of Crystals (G, Sample Wa-1). (E) Wavy Extinction Texture in Quartz, Poikilitic Texture And Pericline Twining in Plagioclase, HTF Invading Wavy Texture, Silicification of Plagioclase (XPL, Wa-1). (F) Gypsum Plate of Image-E Showing Orientation of Crystals (G, Sample Wa-1).

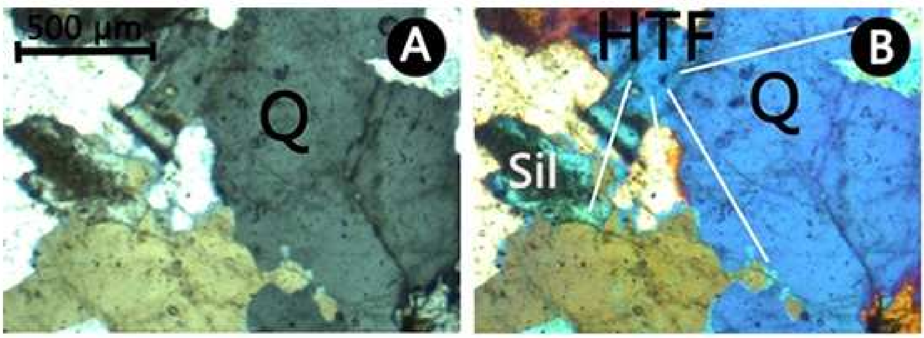

Figure 6: A Magnification of an Unidentified Crystallized Substance From an HTF Along Fractures in the Wavy Texture in Quartz From Figure. (6-E; F), Along With Silicification of Plagioclase

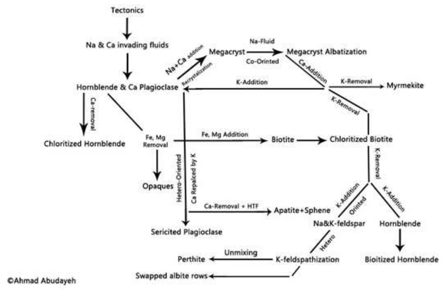

Figure 7: A Proposed Metasomatic Model Explaining The General Reactions in the Metasomatized Studied Rocks), Where the Arrowheads Broadness Represent How Intense is One Process Relative to all Others

Megacrysts

The proposed hypothesis for the metasomatic origin of the megacrysts in host rocks based on the optical observations in Figure.(9-A; B), where recrystallization of plagioclase crystals ceased mid-way indicating the end of hydrothermal phase before the crystals were fully recrystallized i.e., that the whole rock was not equally metasomatized but locally by the passage of fluids along fractures and weak points of different natures, resulting in Muhtadi's inhomogeneous appearance.

The co-oriented albitization epitaxially filling a micro-fracture almost sealing it, except for the sericited part that can't be replaced co-oriented by albite can be observed in Figure.(9-C; D). The hetero-oriented albitization of plagioclase P_1 by K_1 and K_2 to form P_{1Ab} can be observed in Figure.(9-C; D; E; F). This followed after the recrystallization of P_2&P_3 to form the megacryst P_1 by metasomatic processes. This can be proved by the sharp contact between the plagioclases (P_1, P_2, P_3), plus P_1 recrystallizing inside P_2& P_3 in Figure.(9-A; B), in addition, the presence of relicts from P_1 inside of the albitized P_{1Ab}. Figure.(9-A; B; C; D; E; F) are from the same megacryst.

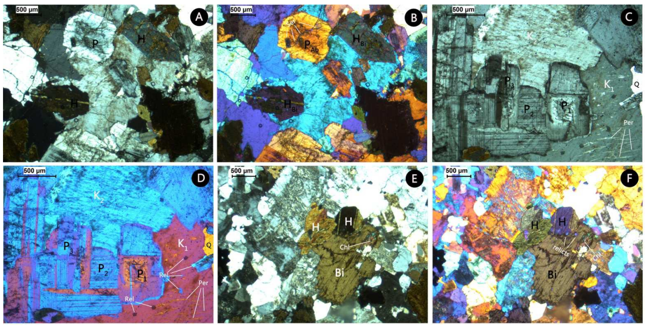

Figure 8: Microscopic Images of (A) Sericitization Along a Microfracture in Plagioclase Including a Sericited Apatite Crystal, Biotitization of Hornblende (XPL, Sample Wa-1). (H) Gypsum Plate of Image-A Showing Orientation of Crystals (G, Sample Wa-1). (C) Pericline Twining and Normal Zoning, Perthitic Albite in K-Feldspar, K_1-Feld Spathization of (P_1, P_2, P_3) Producing Dissolution-Precipitation Texture and Forming Albite Rim Between Plagioclase and K-Feldspar (XPL, Sample Mu-1). (D) Gypsum Plate of Image-C Showing Orientation of Crystals And Relicts (G, Sample Wa-1). (E) Simple and Polysynthetic Twining in Hornblende, Chloritization of Biotite, Co-Oriented Biotitization of Hornblende, Sericitization of Plagioclase (XPL, Sample Wa-7). (F) Gypsum Plate of Image-E Showing Orientation of Crystals and Relicts Inside Hornblende (G, Sample Wa-7).

Examples of Metasomatic and Other Textures in the Enclaves

Figure (10-A) shows pseudo-alignment of crystals (biotite and hornblende) along the rims of a relatively large reversely zoned plagioclase in microdioritic enclaved rock. This plagioclase contains inclusions of the same crystals. The pseudo-alignment of the outer crystals can be explained by the formation of this plagioclase from host rock melt that invaded the (solid) enclaves, simultaneously melting adjacent crystals (resorption surfaces) by dissolution, exerting an excess pressure or inducing stress during growth as force for crystallization on the neighboring minerals incubating their dissolution (Maliva and Siever, 1988; Merino, et al., 1993). Furthermore, interstitially causing the melt to become more calcic by melting hornblende (a local disequilibrium), crystallizing a reversely zoned ring. These dominant chemical changes didn't prevail long enough to complete the crystallization with higher calcic values, only for the melt to return to its previous composition crystallizing the rest of the zoning with less anorthite content. This is supported by the sericitization ring in the zoned plagioclase. The reverse zoning was only observed in the studied enclaves, strengthening the proposed metasomatic scenario.

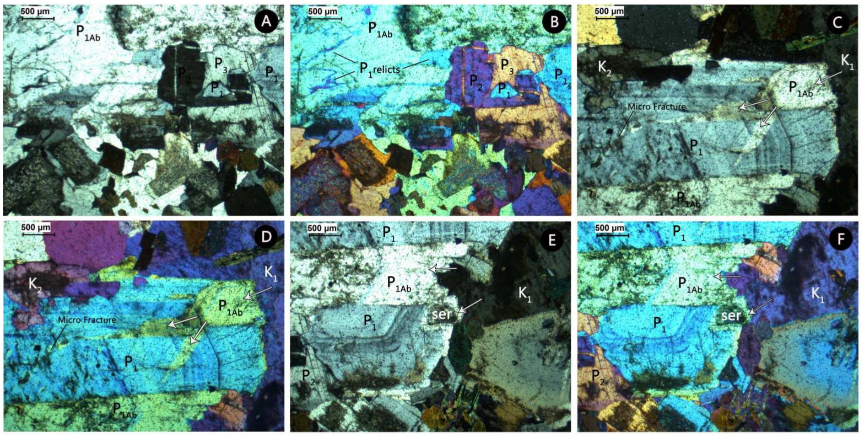

Figure 9: Microscopic Images of (A) Recrystallization of Former Plagioclase (P_2, P_3) To Build P_1. (B) Gypsum Plate of Images-A Showing the Orientation of Crystals, Relicts and Sharp Contact Between Plagioclase Crystals (G, Sample Mu-1). (C) & (E) Co-Ordinated Albitization of Plagioclase Feldspar Following Microfractures in the Crystal To Allow Passage of Fluids, Plus Minor Hetero-Oriented Albitization Forming Albite Rims that Couldn't Replace Sericite (XPL, Sample Mu-1). (D) & (F) Gypsum Plate of Images-C & E Showing the Orientation of Crystals and Relicts (G, Sample Mu-1).

Figure (10-B) shows the same process seen in Figure (5-B) &Figure. (8-E; F) but observed in the enclaved rocks, though such crystal sizes are from the host rock and not from enclave mineral crystal sizes, indicating that the enclaved rocks underwent the same metasomatic processes in solid state after being enclaved in and intruded by the host magma.

The highly altered view seen in Figure. (10-C) was formed by full saussuritization of plagioclase by invading HTF. These plagioclases are host melt produced crystals, highly anorthitic containing in the form of xenolith aggregates (accumulates) of finer hornblende that were metastable under prolonged exposure to hot circulating fluids surviving as alteration products (Gill, 2010). The partialmelting of these aggregates and the highly saussurited nature of plagioclase are features of altered mafic rocks (Gill, 2010). Plagioclase (Figure.10-C) which is highly anorthitic and completely saussurite is hetero-oriented producing muscovite in the process as a secondary alteration product.

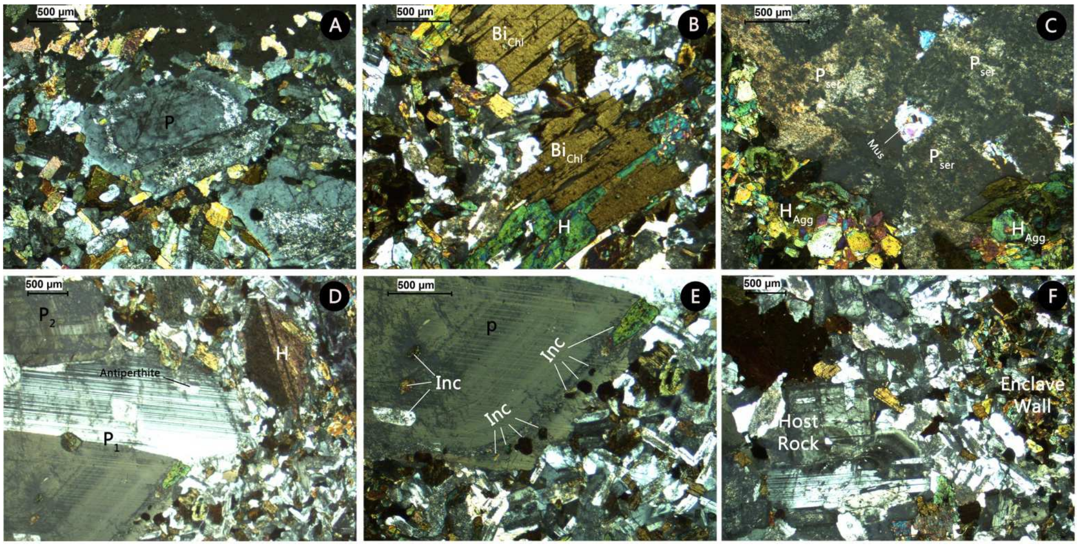

Figure 10: Microscopic Images of (A) Reverse Zoning in Plagioclase Marked By Sericitization Ring in the Zoned Plagioclase (XPL, Sample Enclave-9). (B) Biotitization of Hornblende and Chloritization of Biotite, Pleochroic Halos Caused By Zircon Mineral Inclusions Since it is a Metamict Mineral (XPL, Sample Enclave-9). (C) Muscovitization Of Calcic Plagioclase Crystals, Aggregates of Anhedral Hornblende Forming Xenolith in Melt Produced Crystals (XPL, Sample Enclave-7). (D) & (E) Polysynthetic Twining in Hornblende, Plagioclase Megacryst With Antiperthite, Reverse Zoning and Polysynthetic Twining in the Groundmass of Fine-Grained Enclave Rock Mineral Assemblage, The Megacryst Contains Inclusions Identical to the Nature of the Groundmass (XPL, Sample Enclave-1). (F) Invading Contact and Sudden Change in Crystal Sizes Between Host Rock and Wall Enclave (XPL, Sample Enclave-9).

The other representative enclave samples show less intense partial-melting of enclave minerals indicating that their hydrothermal episode was relatively briefer. The increasing in nucleation centers and decreasing of grain sizes in the newly formed crystals from the host magma arrested alteration products at an incipient stage. Preventing the preservation of these products as aggregates (accumulations) of hornblende (Gill, 2010), thus, produced poikilitic textures in newly formed crystals from the invading melt, which formed the same mineral assemblage in the host rock.

The crystal in Figure. (10-D) shows antiperthite texture in crystals with constant crystallographic orientation (co-oriented) strictly as that of the host plagioclase. The corroded plagioclase megacryst (Figure. 10-D; E) was formed from the injection of an invading melt into the enclave body through microfractures, grain boundaries, and other weak points. Only for the melt to fill the formed pocket by a megacryst, proposing that there was only one nucleation center in the pocket at that time. The partialmelting of hornblende xenolith crystals must have interstitially (a local disequilibrium) increased the calcic nature of the melt building up Ca in the melt to a point where the melt conditions formed very thin reverse zoning, indicating an increase in anorthite content by the sericitization of a zoned ring in the zoned plagioclase. This can also be seen in Figure. (10-A) by the reverse zoning in plagioclase in sample Enclave-9, noticing that the reverse zoning is thicker because of the smaller size of the crystal. This can be proved by the inclusions of similar crystals in Figure. (10-E) and reverse zoning only occurring in enclave rocks. Figure. (10-F) shows the invading contact and sudden change in crystal sizes between host rock and wall enclave.

DISCUSSIONS

The Ediacaran rocks of Darba suite are characterized by a unique appearance in hand specimens and under the microscope. Especially the megacrysts of Muhtadi, taking into consideration that grain size in a magmatic rock is proportional to the ratio of crystal growth rate to nucleation rate (Best, 2003). This is true only in the case of rocks unmodified by textural equilibration, fragmentation, or other secondary processes. The sudden or abrupt change in grain size in the plagioclases of Muhtadi can be attributed to merging of crystals under Ca & Na metasomatic fluids. These metasomatic processes are the secondary process that modified the shape of Muhtadi rocks during the late stages of crystallization. Therefore, the inhomogeneous appearance of Muhtadi compared to the homogeneous appearance of Wa'ara which didn't undergo such grain size modifications.

The statistical parameters of crystal size, average size and standard deviation (SD) of crystal sizes illustrated in Table (1&2) were measured to reflect the uniformity or the heterogeneity and show the degree of crystal size modifications.

The modal quantity of Wa'ara reflects Wa'ara uniformity in modal quantity. The quartz and the alkali-feldspar from the host rock show almost a uniform pattern in their average grain sizes and SD. This degree of uniformity reflects the metasomatic degree of modification in grain sizes. Quartz underwent no metasomatism and alkali-feldspar underwent a medium degree (albite rims, swapped albite rims/rows), minimizing the effect.

The partly biotitized and chloritized hornblende from Wa'ara shows an increasing pattern in average grain size. Such processes may increase the volume by 40% or decrease it by 30%, and happens simultaneously or with the sequence of biotitization of hornblende followed by the chloritization of biotite (Ferrow and Baginsk, 1998). On the other hand, the appearance of metasomatic hornblendes or biotites in Muhtadi is at the expense of each other.

The metasomatic plagioclase of Muhtadi causes its heterogeneous appearance (Figure.3-A). Plagioclase shows a uniform standard deviation with continues increase in average grain size. The sudden increase in some of the grain sizes (megacrysts) is at the expense of reducing the appearance of smaller others, by recrystallization of contiguous plagioclase crystals merging into a porphyroblast.

The latestage metasomatic reactions of Darba are mostly grain boundary controlled changes, also termed "metasomatic active fronts" or "reaction interfaces" (Rong, 1982; 2009). Such reactions have been described by many authors in other parts of the world as evidence of isochemical rock-magmatic fluid interaction (see Pollard, et al., 1983; Taylor and Pollard, 1988).

Metasomatic Model

In solid state during the late stage of crystallization, the invading metasomatic fluids attacked the mineral assemblage of the host rock after tectonic movements (Figure. 7), producing episodes of metasomatism post-tectonically reshaping the rock. The (Ca & Na) and K (two phases, texturally defined) metasomatic fluids attacked the most vulnerable of crystals that inhabit cleavage, fractures or incorporate Ca in their structures (e.g. hornblende, plagioclase). The invading fluids subtracted Ca, Fe and Mg from hornblende causing its chloritization and forming opaques adjacent or incorporated into its body, indicating that the fluids didn't carry the subtracted material far away, meaning that the mobility was limited to fractures and other weak points.

The chloritization of hornblende was simultaneously occurring when the fluid was subtracting Ca from plagioclase albitizing it by Na and/or replacing it by K forming sericite, simultaneously forming apatite and titanite. The chloritization of biotite could have happened along with hornblende if the invading fluids already contained Fe and Mg before entering the rock body. Though, not necessarily since it can happen not later on but simultaneously when Fe and Mg are subtracted from the hornblende and added to the fluid, and if biotite is close to hornblende then its chloritization can occur simultaneously indicated from the absence of opaques (Figure.5-B; C).

The k-feld spathization of plagioclase or two adjacent alkali-feldspars could have happened any time at low temperatures, producing perthite of unmixing from a solid solution depending on the availability of K carrying fluids and mobility along fractures leading to adjacent crystals of the same or similar nature. The metasomatic recrystallizing megacryst growth of plagioclase must have happened before all other metasomatic episodes based on textural relationships and its need of Ca and Na fluids to recrystallize into a megacryst. Proposing that the first metasomatic stage was when the fluid was still rich in Na and Ca was subtracted from other mafic minerals, for these megacrysts to be albitized by Na fluids later-on. The biotitization of hornblende could have happened along with the K-feld spathization of plagioclase. Figure. (8-A; B) represent a view where biotitized hornblende is adjacent to hetero-oriented K-feld spathized plagioclase.

CONCLUSIONS

The Following Conclusions Can Be Drawn From this Study

- A varietal name of Hornblende Biotite Granodiorite can be given to the rocks of Wa’ara, and Hornblende Biotite Quartz Monzodiorite Porphyroid for Muhtadi. The enclaved rocks are mafic microgranular enclaves of a hornblende gabbro-diorite composition, termed micro-diorites with a mixing nature.
- All of Darba suite rocks except the rhyolite dikes underwent late stage metasomatism by isochemical hydrothermal fluids
- The metasomatized studied rocks show locally a medium to intense degrees of (-ization or –ification).
- The plagioclase megacrysts of Muhtadi were as a result of merging into one porphyroblast after introducing Si, Ca and Na latestage hydrothermal fluids.
- Tectonics played a major role in facilitating the metasomatic hydrothermal fluids passage.
- The observed types of replacement in the studied rocks include: (i) hetero-oriented albitization of K-feldspar forming a clear albite rim taking the same crystallographic orientation as the adjacent plagioclase, (ii) co-oriented albitization (deanorthitization) of plagioclase producing dissolution–reprecipitation textures, (iii) co-oriented albitization of K-feldspar producing perthite by unmixing. (iv) the hetero-oriented K-feld spathization occurring at grain boundary of plagioclase producing dissolution–reprecipitation textures, (v) the hetero-oriented K-feldspathization occurring at grain boundaries of two K-Feld spars producing swapped albite rims, (vi) the hetero-oriented replacement of plagioclase replacing alkali-feld spar forming myrmekite, (vii) the hetero-oriented muscovitization in the interior parts of plagioclase, (viii) the hetero-oriented biotitization of hornblende at grain boundary of K-feldspar, (ix) the co-oriented biotitization of hornblende, (x) the co & hetero-oriented chloritization and muscovitization of biotite and hornblende.

The similarity in shape, size, and color between the hornblende and biotite from the enclaves and those inclusions in hornblende and plagioclase crystals from the host rocks can point them out as relicts and may indicate assimilation processes.

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