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Mineralogy, metamorphism and geothermobarometry of the Ghandab metamorphic Complex, SE Fariman, NE Iran

F. Ranjbar, S. M. Homam*, K. Ebrahimi Nasr Abad, B. Rahimi

Graduate of Petrology at Department of Geology – Ferdowsi University of Mashhad

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Abstract: The study area is located about 110 kilometers southeast of Mashhad and approximately 40 kilometers southeast of Fariman. The area is considered to be a part of the central Iran zone. It includes metamorphic rocks with different protoliths consisting of pelitic, carbonate and quartz - feldspathic rocks. The metamorphism in the study area is considered to be a contact regional metamorphism with a low pressure - high temperature grade. According to petrographic studies, the metamorphism in the region reached the upper limit of amphibolite facies. On the basis of different mineral assemblages, three zones were recognized, including Andalusite-Cordierite, Sillimanite - Andalusite, and Sillimanite – K-Feldspar zones. Using Thermocalc software, the average temperature and pressure for the peak of metamorphism in the metapelitic rocks are 664 ºC and 2.5 Kbar respectively. Based on calculated maximum pressure (2.5 Kbar), the depth of ~7.8 Km for the metamorphism is estimated.

Keyword*: amphibolite facies; contact regional metamorphism; Fariman; low P-high T; Thermocalc.*

Introduction

Low pressure- high temperature metamorphism has been recognized in several different areas around the world. This type of metamorphism occurs in various tectonic iettings such as active continental margins and continental tension zones, in which intense heat is dominant in relatively lower depths**.** Previous researches in the study area concentrated mostly on field relationships and petrographical aspects and no detail studies on mineral and whole rock chemistry, parageneses and P-T conditions of metapelites have been done. The first and most comprehensive documented work on Ghandab metamorphic complex was done by [1] who provided the 1:100000 geological map of Kariz Now in 1979 (Fig 1). Economic potential of andalusites studied by [2] and a low pressure – high temperature metamorphism introduced by [3] in the Ghandab region. It is believed [3] that the rocks in this area have end7ure two phases of metamorphism, first phase is regional and second phase is a type of contact metamorphism.

Pelites, psammites, limestones and cherts are the protoliths of the metamorphic rocks. The most important rock units in the region are mica schists with andalusite, cordierite, garnet and sillimanite porphyroblasts. The study of mineralogy, textural relationships, progressive changes of paragenetic relationships and P-T condition of formation of the Ghandab metamorphic complex may provide valuable information for understanding the geological history of Iran, specially the central Iran structural zone.

Method

This study carried out in two parts including field and laboratory works. During field works, systematic sampling from 5 sections from NE to SW across the metamorphic complex and in contact of metamorphic rocks with conglomerate in north and recrystalized dolomites in south of the study area has been done. During laboratory works 87 thin and polished thin sections for petrographical purpose were studied. In addition,

* Corresponding author: Tel-fax: (0513) 8797275, E-mail: homam@um.ac.ir

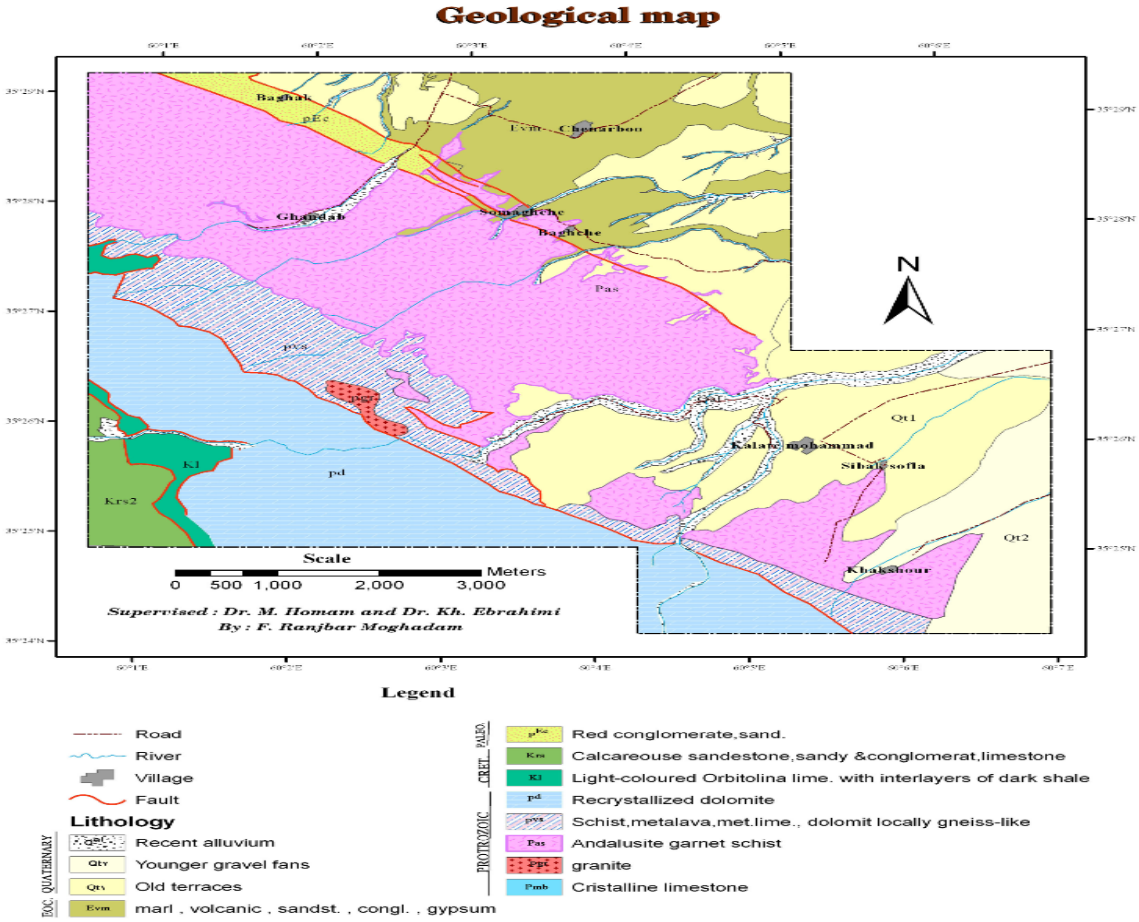


Fig 1 The geological map of the study area (Modified 1:100000 Kariznow map from Ranjbar,1389).

X-ray fluorescence (XRF) and X-ray diffractometry was performed using a Bruke axs-S4 Explorer for recognition of the unknown minerals and identification of whole rock chemistry. For characterizing the exact mineral composition and calculating temperature and pressure of metamorphism peak, some samples were analyzed using an electron microprobe analyzer (Cameca SX100) housed in Advanced Research Institute of Mineral Processing of Iran (Karaj).

Geological setting

The study area is located about 110 km southeast of Mashhad and approximately 40 km southeast of Fariman with geographic coordinates of 35º 24′ to 35º 28′ N and 60º 02′ to 60º 07′ E. There is a great disagreement about the geological and structural situation of the study area in the main structural units of Iran. According to [4] the Ghandab metamorphic complex constitutes a part of the central Iran zone. However, [5] considered the study area as a part of Naien- Sabzevar zone. On the basis of the 1:100000 geological map of Kariz Now, [1], metamorphic terrains of Proterozoic age are exposed in a narrow elongated belt, widening to the north-west on the north-western flank of the main range. The most complete section of the metamorphic terrains in the northwestern corner of the Kariz Now sheet (Ghandab region) which is composed of thick series of mica schists, characterized by the presence of large crystals of andalusite, sillimanite, cordierite and garnet. Small lenses of pegmatite-like bodies with large crystals of tourmaline also can be locally seen in this series. Horizons of highly recrystallized limestones interlayered with the mica schists. Gneissos rocks, lighter-colored and finer-grained than the mica schists, roughly show the same mineral composition (biotite, muscovite, sillimanite, garnet, cordierite), but are richer in quartz. A volcano-sedimentary complex (Sibak complex) including various types of rocks consisting of schists, recrystallized carbonate rocks, meta-lavas (acidic and basic), meta-gabbros and granitoid rocks, locally exhibiting gneissose texture, are located as a narrow elongated belt (about 1 km thick), extending from the north-west to the south-east. A dark-colored recrystallized dolomite (Infracamberian Soltanieh Dolomite) overthrusted on the cretaceous formations. A NW-SE trending, sub-vertical, post-overthrusting fault system separates the Sibak complex and andalusite schists from the uplifted dolomite unit [6]. Intrusive rocks, frequently showing a gneissose, blastomylonitic texture and ranging in composition from granite to quartz diorite, form a part of the Sibak complex. On the basis of an absolute age measurement made on zircons from a granite from the Sibak complex, a Late Proterozoic age (630-650 Ma) suggested by [1] for this formation.

Petrography

As mentioned earlier, metamorphic rocks in the study area have various protoliths, however metapelites are the most abundant and important metamorphic rocks of the region. Quartzite and quartz-feldspathic schists form irregular interlayers. Metapelites can be seen as mica schists that are characterized by the presence of large andalusite porphyroblasts. According to petrographic studies, three different mineralogical assemblages can be distinguished from the northeast towards the southwest. These mineral assemblages are discussed below. In this study the mineral symbols and abbreviations are taken from [7] and suggested reactions are taken from [8]

A: Assemblage Qtz+BT+Pl+Ms +and+Crd+Grt

In the north part of the study area, a band of andalusite micaschist is seen with approximately 2.5 km length with a very fine-grained (~0.01 mm), graphite-rich matrix. Cordierite, andalusite and garnet form the main porphyroblasts of the rock. Cordierite porphyroblasts show elliptical shape and mostly sector twin shapes (Fig 2-a). Cordierite porphyroblasts mostly are replaced, completely or partially, by micaceous aggregates, rich in biotite, muscovite and quartz. This assemblage has created a bird´s eye structure in the matrix (Fig 2-a). According to textural evidence, the micaceous assemblage is not resulted from retrograde reactions. As reported by [9], it is believed that during prograde metamorphism, cordierite was consumed to produce andalusite. In some examples, cordierite crystals show the process of retrograde cordierite decomposition, pinitization, in which cordierite is replaced by extremely fine-grained chlorite, sericite and iron oxides. Where cordierite is completely changed to pinite, the crystal core is became optically isotropic (Fig 2-B). In some samples the micaceous aggregate are folded (Fig.2-C).

Andalusite porphyroblasts are distinguished by their low birefringence and gray to yellow interference color and the presence of sector zoning (Fig.2-D). The size of andalusite crystals varies from 0.2 to 2 mm. The alteration of some andalusite porphyroblasts to sericite can be seen. However, unlike the cordierite crystals, the andalusite crystals are relatively fresh.

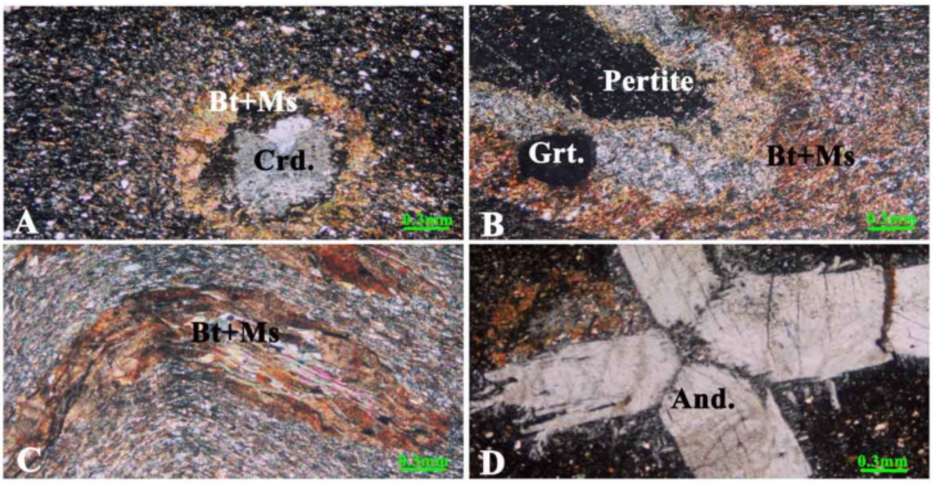


Fig 2 A: Cordierite crystal with sector twining changing to micaceous assemblage (bird ´s eye structure) (XPL) B: Pinitic alteration in the core of cordierite that replaced by biotite, muscovite, and garnet (XPL) C: Andalusite crystal with cross twining (XPL) D: Folded micaceous assemblage after cordierite.

The small-grained, xenoblastic garnets are present in the matrix. Idioblastic, medium-grained garnets can be seen in biotite-muscovite-quartz assemblages after cordierite. Microprobe analysis shows no considerable chemical differences between these two kinds of garnet.

B: Assemblage Qtz + Pl + Bt + Ms + And + Fib ± Grt ± Crd

In this mineralogical assemblage, the abundance of graphite and quartz are less than the previous mineral assemblage. The size of biotite and muscovite crystals increases and preferred orientation is more obvious. The size of andalusite porphyroblasts in this assemblage is larger (>10 cm) than those in the first assemblage. Andalusite porphyroblasts appear in two forms, including poikiloblastic andalusite with no well formed crystal faces and idioblastic chiastolite. Progressive metamorphism in cordierite porphyroblasts produced aggregates of biotite, muscovite, and quartz. In some samples, remained cordierite crystals can be seen in the core of micaceous aggregates (Fig 2-B). Garnet crystals show different sizes and form idioblastic to xenoblastic crystals. In some samples garnets are seen as aggregates of small individual grains. Fibrolites commonly can be seen as intergrowths with biotite flakes (Fig 3-A & B), muscovite and plagioclase. It also is present as needles, concentrated in, and radiating out from quartz and feldspar grain boundaries. Accessory minerals in these schists include zircon, epidote, apatite, tourmaline and iron oxides.

C: Assemblage Qtz + Pl + Bt + Kfeld + And + Fib + Sil ± Grt ± Crd

The rocks with this assemblage are characterized by dark brown hornfelses with biotite, garnet, andalusite and sillimanite visible in hand specimens. Under the microscope, the overall textures of the rock, suggest transformation of the rocks with the previous mineral assemblages by a wholesale textural reconstitution. The red-brown biotite with quartz and feldspar of the groundmass defines the hornfelsic textures. Primary muscovite is absent in this assemblage and it normally occurs as randomly oriented plates, mostly replacing andalusite porphyroblasts produced during retrograde metamorphism. Sillimanite appears as long prisms growing from the groundmass. In some samples, sillimanite is formed by coarsening of fibrolite (Fig. 3-F). In many samples, andalusite recrystallizes topotaxially into diamond-shaped and euhedral prismatic sillimanite (Fig. 3-D & E), up to 2 mm long. In many samples, when andalusite is replaced by sillimanite, a symplectite of plagioclase, cordierite, biotite and K-feldespar can be seen around the replaced mineral. Garnet generally can be seen as idioblastic inclusion-free porphyroblast. They generally have larger sizes (from 0.5 to 7 mm) than those in lower grade schists (previous mineral assemblages). In this mineral assemblage, cordierite can be seen but these cordierite grains are high temperature type of cordierites with low relief and lack of cycling twining. They are full of inclusions such as biotite, zircon and apatite. Large-grained perthitic K-feldspar crystals with inclusions of biotite, quartz and muscovite can be seen. They sometimes show candle flame structure (Fig. 3-D). According to Pryer and Robin`s model [10] the necessary conditions for the formation of candle flame perthite is the presence of subtraction stress and relatively dry situation.

Metamorphic reactions

Based on petrographic studies, porphyroblasts in the Ghandab metamorphic complex are not grown simultaneously but their growth were sequentially. According to textural evidence cordierite first appears by the following reactions:

(1) Ms+Chl = Crd+Bt+H_2O

(2) Chl+Ms+Qtz = And+Bt +Crd+H_2O

Considering the petrographic evidence**,** micaceous aggregate around the cordierite was not a product of retrogressive reaction but they formed during prograde metamorphism by following reaction:

(3) Crd+Ms = And+Qtz+Bt+H_2O

A sequence of reactions performed in low-grade metamorphism of Cooma complex studid by [9] how concluded that the general lack of andalusite alteration compared with the almost complete alteration of cordierite suggest that andalusite grew later than cordierite. This also may confirm that andalusite produced as a result of progressive reactions of cordierite consumption. Since reaction (3) is a continuous reaction, coexistence of cordierite and andalusite in these rocks is common. Reaction (1) can be considered for andalusite crystallisation at low temperatures.

As mentioned earlier, garnet in metapelites from the study area, can be observed in matrix as well as micacoeus aggregate after cordierite. It seems that micacoeus aggregate provided suitable site for garnet growth by the following reaction (in base of Thermocalc reaction):

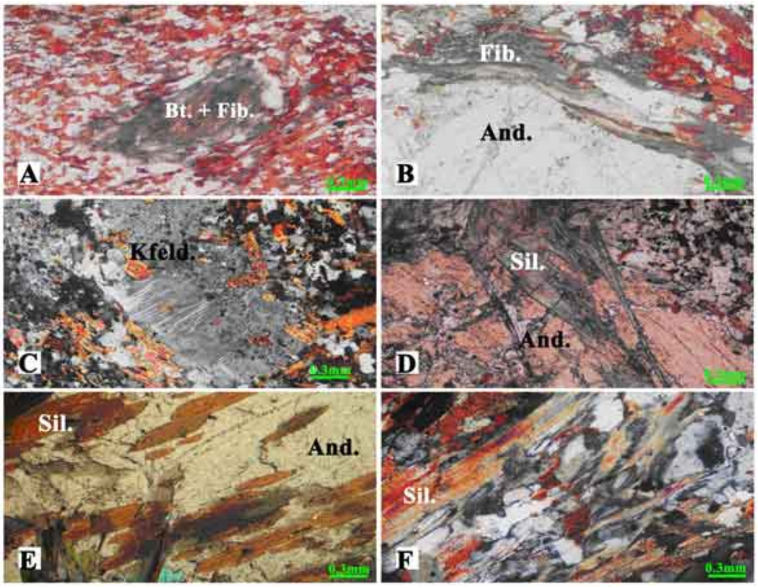


Fig 3 A: High Ti biotites that due to being coarser in this section, the schitosity is weaker, epitaxial growth of fibrolite on the biotit can been observed (PPL**)** **B**: Fibrolites with graphite around the andalusite (PPL). **C**: Replace of prismatic sillimanite in andalusite (XPL). **D**: Replacement of diamond shape sillimanite in andalusite (XPL)**.E:** Thicking of fibrolite and transformation to sillimanite: (XPL). F: Candle Flame shape pertite.

(4) Qtz + Ms + Crd + Chl (daphynite) = Bt + And + Grt (almandine-rich) + H_2O

Reaction 5 also can be suggested for garnet formation from matrix materials:

(4) Qtz + Ms + Fe - Chl = Fib + Bt + Fe –Grt + H_2O

It is concluded by [11] that Fe-rich garnets may form from iron-rich chlorite at 500°C under pressures more than 4 Kbar and at 600°C under pressures more than 5 Kbar. However, they realized that if garnet contain large amount of spessartine it may form under pressures less than 2 kbar which is consistent with the amounts of pressure estimated in study area (see section on thermobarometry).

Reaction 6 is one of the most important reactions that produced sillimanite in the study area rocks:

(6) And = Sil

Sillimanite at temperatures higher than the muscovite breakdown reaction (in muscovite-free rocks) may be produced by the following reaction:

(7) Qtz + Bt + Ms = Sil + Alm + Kfeld + H_2O

High grade cordierites can be seen in some rocks in the third mineral assemblage may have formed by the following reaction:

(8) Qtz + Sil + Bt = Kfeld + Crd + H_2O

Bulk rock and mineral chemistry

To investigate total composition of metamorphic rocks in the study area and examine the relationship between mineral assemblage and whole rock chemical composition, 4 representative samples were analyzed by X-ray fluorescence (XRF). Analysis was performed by a Bruke axs-S4 Explorer machine. Chemical analysis of pelitic rocks indicate that Na_2O varies from 1 to 1.8 Wt%, whereas K_2O is between 3.5 and 6 Wt%. Al_2O_3 varies from 17 to 19 Wt% that indicates the argillitic origin of the rocks. FeO/ (FeO+MgO) ratio in samples is from 0.54 to 0.57 similar to Dalradian metapelites in Scotland. (MgO + FeO)/Al_2O_3 ratio is between 0.21 and 0.26. The average X_{Mn} (X_{Mn}=MnO/MnO + FeO+MgO) ratio is ~0.015 that lies in its normal range (0.01 to 0.04) in metapelites [12].

The mineral paragenesis in pelitic rocks can be a function of the whole rock composition. However, the plot of analyzed samples of the Ghandab metamorphic complex in AFM diagram indicates that protolith composition had no control on the occurrence of mineral paragenesis. The composition of these rocks is very similar to composition of amphibolite facies schists and schists of North America [13]. To characterize the exact mineral composition and evaluation of temperature and pressure conditions of metamorphism, 10 samples (from 3 thin sections) were analyzed using a electron microprobe Analyzer(Cameca SX100) housed in Advanced Research Institute of Mineral Processing, Iran (Karaj) with instrument setting at 15 kV accelerating voltage, 15µA beam current and 5µm beam diameter. The chemical characteristics of the analyzed minerals are discussed below.

Garnet in metapelites of southeast Fariman shows different textural characteristics including garnets in matrix, garnets associated with plagioclase, muscovite, quartz, biotite around andalusite porphyroblasts, and garnets that formed in micacouse assemblage after cordierite. To find if there are any chemical differences between above-mentioned garnets, they were analyzed in three samples X_{Fe}, X_{Ca}, X_{Mn}, X_{Mg} are listed in Table 1. Garnet formulas were calculated based on 12 atoms of oxygen. The position of garnets in Mg, Fe, Mn+Ca diagram are shown in Fig. 4, 5. Garnets are solid solution of almandine-spessartine and their spessartine proportion is between 19 to 35%. Chemical profiles for the garnet porphyroblasts indicate that they are relatively homogeneous and shows no zoning (Fig.6). Chemical zoning in garnet is controlled by several functions such as temperature, diffusion-controlled growth [14] and effect of multiple nucleations [15]. Biotite porphyroblasts show different textural relations, including biotites in matrix and those from micaceous aggregates after cordierites. Biotite formula was calculated based on 22 oxygens. Chemical composition of biotites in all samples in eastonite-sidrophillite-phlogopite-annite diagram lies in the vicinity of the annite-phlogopite line and have nearly annite composition. X_{Fe} in samples has average of ~0.6. Mg/(Mg+Fe) ratio is between 0.38 and 0.43. As it can be seen in Table 2, there is no clear chemical difference in amounts of Al and Mg/(Mg+Fe) ratio between matrix biotites and biotites in micaceous aggregate. However, the Ti content in sample 7, a high grade metamorphic sample, is significantly more than other samples. Since this sample is from sillimanite-andalusite zone and therefore experienced high-grade metamorphism, the high amount of Ti can be attributed to temperature effect. Mole fraction of albite in plagioclase was calculated as X_{ab} = Na/(Na + Ca + K) (Table 3). The average of X_{ab} is 0.97 for sample 1C and 0.87 for sample 7A. No significant changes of Na and Ca can be seen from rim to core of analyzed plagioclases, which indicates the homogeneity (Fig.7). White mica occurs in all mineral assemblages with a variety of textural features. Microprobe analyses of white mica from metapelites are plotted on the MgO + SiO_2, Al_2O_3, FeO diagram (Fig. 8) .According to this diagram, analyzed white micas are muscovite.

Table 1 Fe, Mg, Mn + Ca content obtained based on microprobe analyses of garnets in the study area.

sample	Fe	Mg	Mn+Ca
7-5A	0.4257	0.0572	0.13431
7-3A	0.4356	0.0572	0.12656
1C	0.3652	0.0270	0.20807
6G	0.4071	0.0332	0.16504

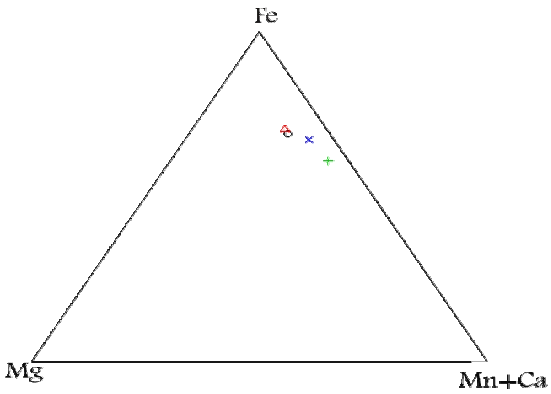


Fig 4 The Composition of garnets in analyzed samples plot on Fe, Mg, Mn diagram.

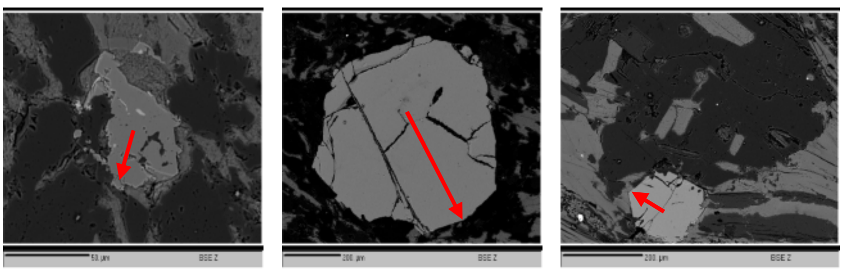
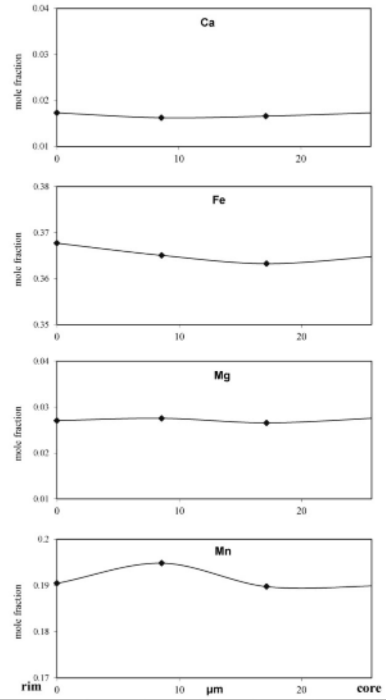
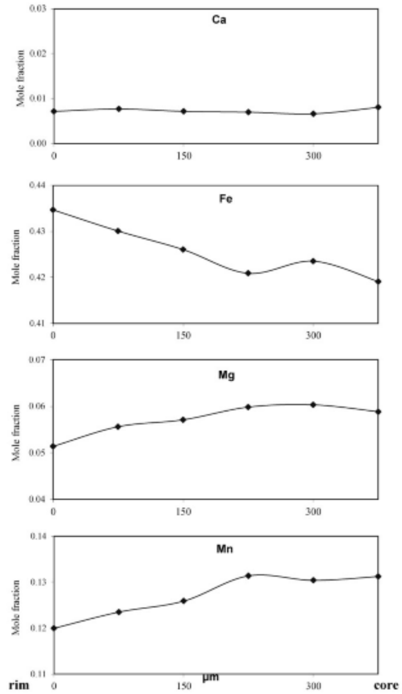


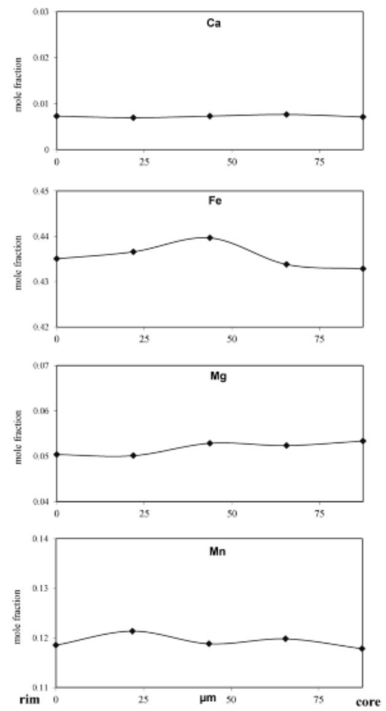
Fig 5 The BSE images of analyzed garnets with three different textural relations 1- Garnet in micaceous assemblage 2- Garnet in matrix 3- Garnet adjacent to andalusite crystal (from left to right).

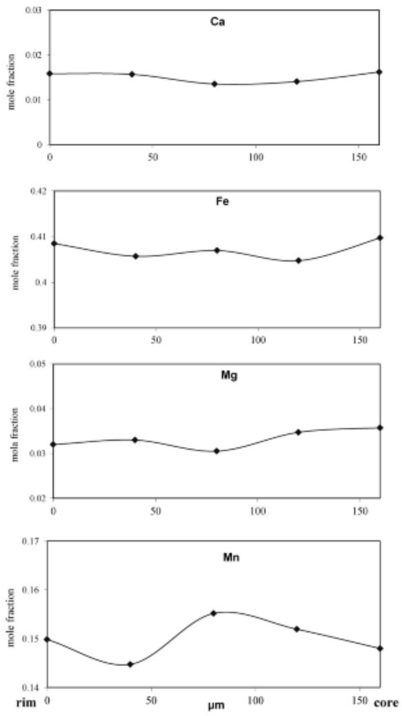




No.	sample	point	dist.	Ca	Fe	Mg	Mn
1	1c	4	0.000	0.0173	0.3677	0.0270	0.1904
2	1c	3	8.571	0.0162	0.3651	0.0275	0.1948
3	1c	2	17.143	0.0166	0.3633	0.0266	0.1897
4	1c	1	25.714	0.0173	0.3648	0.0275	0.1899

No.	sample	point	dist.	Ca	Fe	Mg	Mn
1	7-5	6	0	0.007	0.4347	0.0514	0.1200
2	7-5	5	75	0.008	0.4301	0.0556	0.1235
3	7-5	4	150	0.007	0.4260	0.0571	0.1259
4	7-5	3	225	0.007	0.4209	0.0598	0.1314
5	7-5	2	300	0.007	0.4235	0.0603	0.1304
6	7-5	1	375	0.008	0.4191	0.0588	0.1312





No.	sample	point	dist.	Ca	Fe	Mg	Mn
1	g7-3	5	0.000	0.0073	0.4351	0.0504	0.1186
2	g7-3	4	21.875	0.0070	0.4366	0.0501	0.1214
3	g7-3	3	43.750	0.0073	0.4397	0.0529	0.1188
4	g7-3	2	65.625	0.0077	0.4338	0.0524	0.1198
5	g7-3	1	87.500	0.0071	0.4328	0.0533	0.1178

No.	sample	point	dist.	Ca	Fe	Mg	Mn
1	6g	5	0.000	0.0159	0.4085	0.0320	0.1498
2	6g	4	40.000	0.0157	0.4057	0.0330	0.1448
3	6g	3	80.000	0.0136	0.4070	0.0305	0.1552
4	6g	2	120.000	0.0141	0.4047	0.0347	0.1520
5	6g	1	160.000	0.0162	0.4097	0.0357	0.1480

Fig 6 The zoning profiles of Ca, Mg, Fe, and Mn in analyzed garnets.

Table 2 Representative amounts of Al, Mg/Mg+Fe and Ti based on microprobe analyses of biotites of metapelites (7-A and C4 biotites of matrix in high grade and low grade metamorphism, C3 biotite of micaceous assemblage).

sample no.	M/FM	AL	Ti
$C4bio_1$	0.41622	0.38843	0.13398
$C4bio_2$	0.40297	0.39627	0.13011
$C4bio_3$	0.40703	0.36000	0.12944
$C4bio_4$	0.40557	0.38118	0.14174
7Abio-1	0.39664	0.38667	0.38742
7Abio-2	0.38630	0.38078	0.37175
7Abio-3	0.38877	0.38039	0.37234
7Abio-4	0.39784	0.39314	0.39316
$C3bio_1$	0.41003	0.38275	0.12615
$C3bio_2$	0.39798	0.37196	0.15008
$C3bio_3$	0.43877	0.39412	0.13338
$C3bio_4$	0.42363	0.38333	0.12571

Table 3 Calculated mole fraction of Na, Ca, and K for plagioclases in analyzed samples.

sample No.	Na	K	Ca
1C-1	0.9673	0.0011	0.0316
1C-2	0.9735	0.0021	0.0244
1C-3	0.9708	0.0011	0.0281
1C-4	0.9708	0.0022	0.0270
1C-5	0.9746	0.0016	0.0238
7A-1 1	0.8731	0.0163	0.1106
7A-1 2	0.8791	0.0140	0.1069
7A-1 3	0.8787	0.0120	0.1093
7A-1 4	0.8763	0.0125	0.1112
7A-1 5	0.8806	0.0092	0.1103
1C3-1	0.9420	0.0016	0.0564
1C3-2	0.9580	0.0027	0.0392
1C3-3	0.9929	0.0027	0.0045
1C3-4	0.9895	0.0022	0.0083
1C3-5	0.9802	0.0022	0.0176
7A-6 1	0.8917	0.0118	0.0965
7A-6 2	0.8880	0.0081	0.1038
7A-6 3	0.8800	0.0128	0.1072
7A-6 4	0.8686	0.0168	0.1146
7A-6 5	0.8833	0.0115	0.1051
7A-6 6	0.8978	0.0065	0.0957

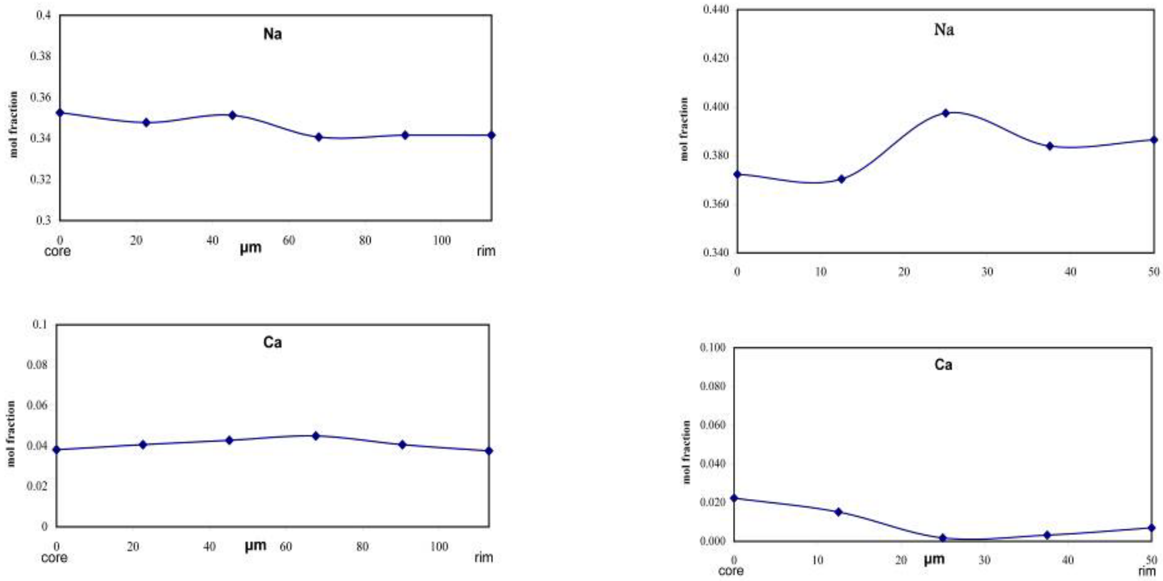


Fig 7 Zoning profile of Na and Ca for analyzed plagioclase in 1C and 7A samples.

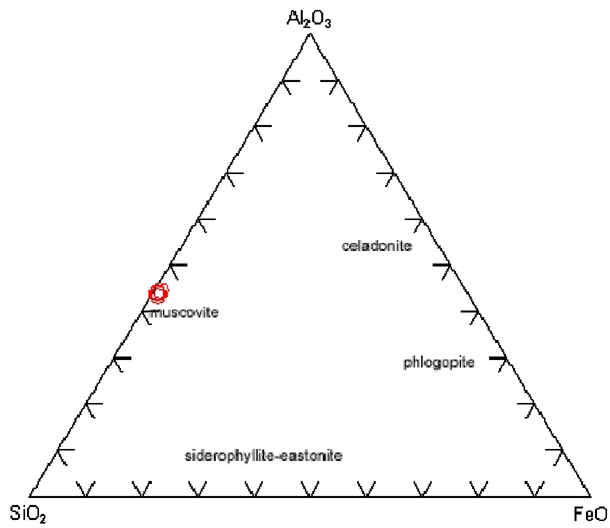


Fig 8 The composition of white mica based on Fe, Al and Si oxides plotted on SiO_2, Al_2O_3, FeO + MgO diagram

Thermobarometry

THERMOCALC program [16] is the most common software to calculate P-T conditions in metamorphic rocks. Therefore, it is used to estimate P-T conditions of metamorphism for the selected samples from the Ghandab metamorphic complex. In Thermocalc software, the end members of mineral solid-solutions are considered to participate in reactions and in the first step the mineral end-member activities are calculated [17]. Using the activities of the mineral end members, a series of reactions are recognized:

1- Sil = And

2- Qtz + Ms = And + Kfeld + H_2O

3- Qtz + Ms = Sill + Kfeld + H_2O

4- Alm + 2Ms = 3And + Bi + Kfeld + H_2O

5- 3Qtz + Ms + Bi = Alm + 2 Kfeld + $2H_2O$

6- Alm + 2Ms = Bi + 3Sil + Kfeld + H_2O

The T and P position for each reaction is calculated on a P-T window (Table 4), then the position of each reaction is drawn on P-T diagram (Fig. 9). Intersection of reaction curves of the reactions indicate the maximum temperature of ~700 ^{oC} and pressure of ~2.6 kbar The lowest temperature is ~620 ºC. The average of pressure and temperature calculated are around 664 °C and 2.5 Kb with uncertainties ±28 ºC and ± 0.6Kbar, respectively.

Table 4 The calculated ΔG for 1-6 reactions in 1-4 Kbar pressure.

P(kbar) / Reactions	1	1/5	2	2/5	3	3/5	4	sdT	sdP
1	791	753	717	681	646	611	578	16	0.22
2	592	619	643	666	688	710	731	30	0.74
3	599	624	656	667	686	705	723	30	0.81
4	607	652	696	740	785	_	_	17	0.19
5	583	600	614	625	635	644	652	9	0.44
6	625	662	698	733	768	_	_	15	0.22

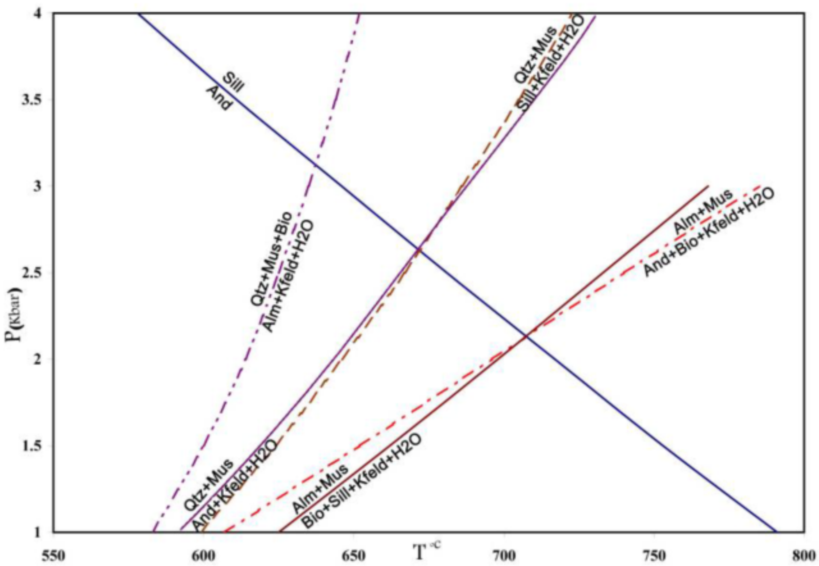


Fig 9 P-T diagram based on P-T calculation on the studied samples.

Discussion

Petrographical evidence from the Ghandab metamorphic complex show features of low-pressure high temperature metamorphic field gradient. The development of cordierite + andalusite + garnet at low to medium grade, appearance of sillimanite at lower grade than the muscovite breakdown and presence of garnet + biotite + sillimanite + cordierite + orthoclase at high grade metamorphism, are completely consistent with type 2a facies series of [18] that are formed approximately at 2-3 kbar pressure. This also is confirmed by average temperature and pressure, calculated by THERMOCALC software for peak of metamorphism in the study area (664 °C at a pressure of ~2.5 Kbar). In addition, many studies on high temperature-low pressure metamorphic terrains show that there is undeniable relationship between this type of metamorphism and granitoid intrusions, particularly in the terrains with Early Proterozoic and Archean ages [19]. Granitoids may intrude in arc tectonic setting, simultaneous or after metamorphism. Also in continental rifting areas, thinning of the crust or lithosphere causes the upward heat flux originating from the mantle or asthenosphere rise and this can lead to the formation and ascent of granitic magmas. A certain field and age relationship between metamorphic rocks and granite plutons in the study area is recognized by Ranjbar [20]. Mineralogical and textural features as well as P-T conditions of the Ghandab metamorphic complex are very similar to those from high temperature-low pressure regional contact metamorphisms reported from the Cooma complex in south Australia [21] [22]. Cooma complex granite plutons are considered to be generated by partial melting in center of a contact metamorphic complex [22]. Based on field observations and petrographic studies in the Cooma complex, [21] suggested that Cooma granodiorite rocks were generated as a consequence of the regional metamorphism that resulted from the large-scale emplacement of a batholith. At the peak of this kind of regional metamorphism, partial melting at depth at the center of the complex formed the granodiorite, which was then emplaced within the complex [23]. Due to the very numerous similarity such as sequential growth of porphyroblasts, the field relations particularly between metamorphic rocks with S-type granitic masses and similar ages for of the Cooma and Ghandab complexes, more likely the type of metamorphism in the study area is regional contact metamorphism of high temperature–low pressure type that occurred by pervasive emplacement of granitic plutons of Proterozoic in ~8 km deep of the crust.

Conclusions

According to petrographic studies there are three different mineralogical assemblages and these assemblages change from northeast to southwest with increasing of metamorphic grade The microprobe analysis shows that garnets are chemically homogeneous and rich iron (almandine). Biotites are annite and composition of plagioclase is albite-oligoclase.

Coexistence of cordierite and andalusite and absence of kyanite indicate that metamorphism in this area was Buchan type. Based on mineral assemblages, three zones can be distinguished including andalusite – cordierite zone, sillimanite-andalusite zone and upper sillimanite zone. P-T calculation were carried out by determining chemical composition of garnet, biotite and plagioclase and using THERMOCALC software. The results show that average P and T are 660ºC and 2.5 kbar, respectively. According to the maximum pressure obtained (~2.6 kbar) and with regard to each kilobars pressure equals approximately 3 km depth, the depth of metamorphism is estimated 7.8 km that means the depth of metamorphism is in the upper crust. comparing the characteristics of Ghandab and cooma complexes and many similarities of these two areas indicates high temperature-low pressure regional cantact metamorphism for this area.

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