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Chemical composition of biotite as a guide to petrogenesis of granitic rocks from Maherabad, Dehnow, Gheshlagh, Khajehmourad and Najmabad, Iran

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Abstract: Biotite, the dominant ferromagnesian mineral in granitoid rocks, can be used to discriminate tectonic setting, magma types and magnetite- ilmenite series. In this study, we analyzed biotite with an electron microprobe (wavelength dispersion) from different granitoids. Intrusive rocks from Maherabad porphyry Cu-Au prospecting are meta-aluminous. Biotite from Maherabad are Mg-rich type and the ratio of Fe/(Fe+Mg) is 0.286-0.309. Maherabad biotite compositions fall in the field of (sub-alkaline) calc-alkaline orogenic suites. Based on High TiO_2 and low Al_2O_3 in biotites, Maherabad also belongs to magnetite series. Intrusive rocks from Najmabad, Dehnow, Gheshlagh and Khajehmourad (NDGK) are classified as belonging to the ilmenite-series of reduced S-type granitoids. Biotite from NDGK areas are Fe-rich and the Fe/(Fe+Mg) ratio in Najmabad is 0.491-0.511, in Dehnow-Kuhsangi 0.583-0.675, Gheshlagh 0.56-0.58, and Khajehmourad 0.705-0.720. respectively NDGK biotite compositions fall in the field of peraluminous granite (P) suites (S-type). Based on low TiO_2 and high Al_2O_3 in biotites, Najmabad, Dehnow and Gheshlagh biotite belong to ilmenite series.

Keywords: *Biotite, Najmabad, Maherabad, Khajehmourad, susceptibility.*

Introduction

Biotite from five plutons (Maherabad, Najmabad, Gheshlagh, Dehnow and Khajehmourad) are selected for this study (Fig. 1). At the early stages of mica studies, evaluations were mainly focused on the chemical composition of different types of host rocks. For example, Heinrich [1] used the mica composition to investigate the variation with rock types from granites to diorites. Later, Foster [2] observed that there were important overlaps from different rock types when octahedral mica composition plotted on ternary Al^{VI}+Fe^{3+}+ Ti^{4+}-Fe^{2+}+Mn^{2+}-Mg^{2+} diagram. In those studies, there was no emphasis on the rock names for mica composition. For that reason, Neilson and Haynes [3] proposed a plot comparable to Foster's [2] biotite composition.

In recent years, Nachit [4] used mica composition in granitoids to relate magma types in which biotite crystallized. In Altot vs. Mg classification diagram, the nature of granitoid magmas grouped into four types such as peraluminous (P), calcalkaline (C), subalkaline (SA), and alkaline–peralkaline (A–PA). Abdel-Rahman [5] gave discrimination diagrams between alkaline (A), calc-alkaline (C), and peraluminous (P) granite suites based on the biotite chemistry. Rieder et al., [6] has written an article regarding the nomenclature of the micas. Yavuz [7] wrote a program for estimating Li from electron-microprobe mica analyses and classifying trioctahedral micas in terms of composition and octahedral site occupancy. Yavuz [8] has written a program for evaluating and plotting microprobe analyses of biotite from barren and mineralized magmatic suites.

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Analytical Techniques

All elemental analyses of biotites were obtained from polished thin sections using a JEOL JXA-8900R electron microprobe at the University of Colorado Boulder (USA). Element determinations (Si, Al, Fe, Mg, Ti, Mn, Total Ba, Na, K, F and Cl) were carried out using a beam size of 3 mμ, an accelerating potential voltage of 15 kV, a probe current of 15 nA, and a counting time of 20 s for each element analyzed. Natural biotite, amphibole, sandine, tugtupite, and willemite standards were used in the analytical procedure for F, Si, Al, Fe, Mg, Ti, Cl, Ba, and Mn. Matrix effects were corrected using the ZAF software provided by JEOL. The accuracy of the reported values for the analyses is 1%–5% in 1s. Depending on the abundance of the element. A microprobe analysis is defined as the arithmetic mean of five spot analyses of a biotite grain. The OH values are calculated on the basis of 11 oxygen formula units. The X and X values Mg Fe are determined from cation fractions and are defined as Mg/Fe + Mg and (Fe +Al^{VI})/(Mg +Fe + Al^{VI}), respectively (Zhu and Sverjensky, 1992). The X, X, and X are the mole fractions of F, Cl, F, Cl. OH and OH in the hydroxyl.

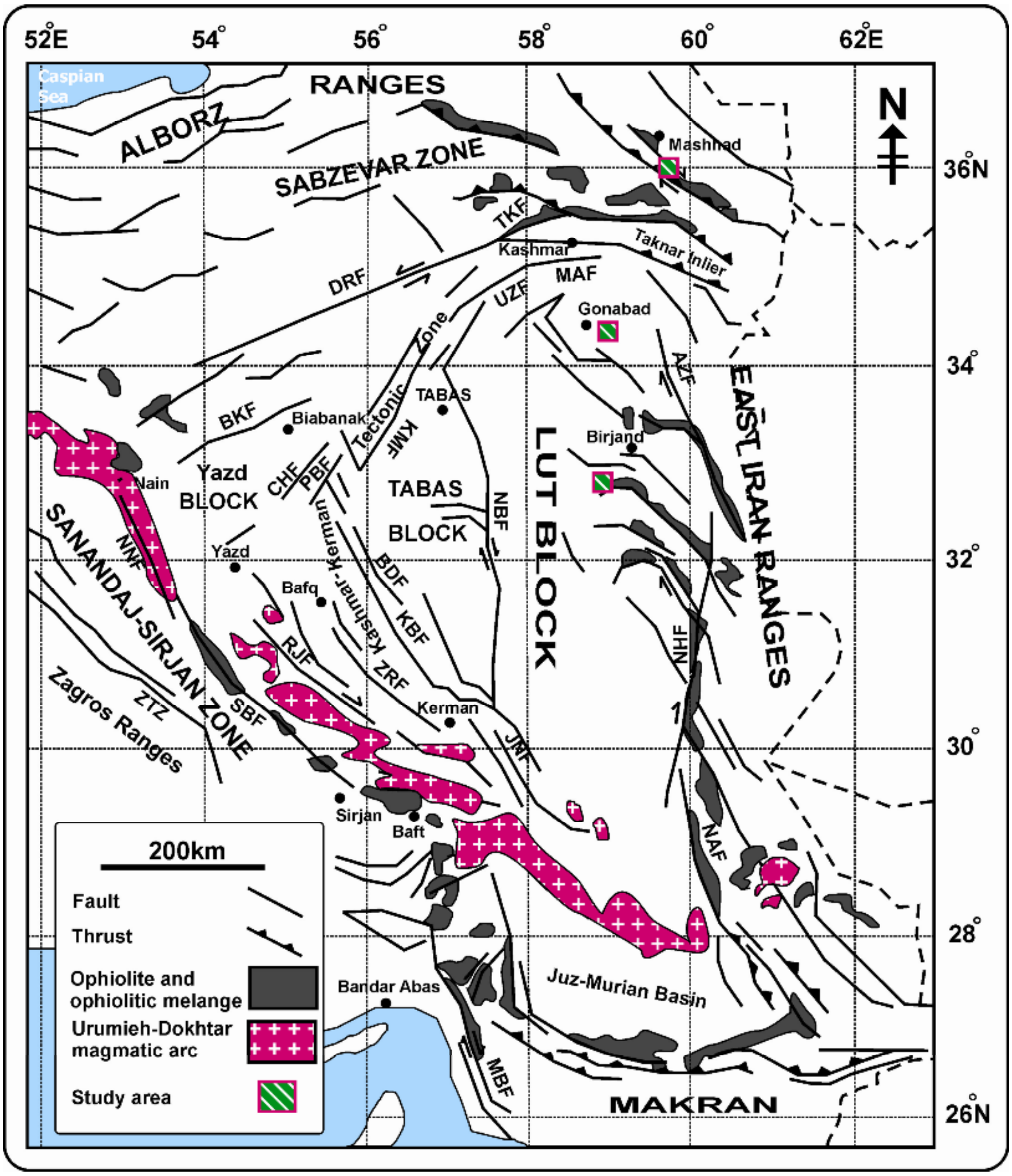

Fig 1. Map shows location of the study areas.

Petrography & Whole rock geochemistry

Maherabad

The Maherabad porphyry copper-gold prospect area is located about 70 km SW of Birjand city (center of South Khorasan Province), eastern Iran. It is located in the eastern part of Lut block. Fifteen intrusive rocks (Upper Eocene) range in composition from diorite to monzonite have been distinguished [9, 10].

Based on mineralogy and high values of magnetic susceptibility [(300 to 2000) × 10^{-5} SI], these intrusive rocks are classified as belonging to the magnetite-series of I-type granitoids. Chemically, they are met-aluminous (Fig. 2), high-K calc-alkaline to shoshonite intrusive rocks which were formed in island arc setting. These rocks are characterized by average of SiO_2 > 59 wt%, Al_2O_3 > 15 wt%, MgO < 2 wt%, Na_2O > 3 wt%, Sr > 870 ppm, Y < 18 ppm, Yb < 1.90 ppm, Sr/Y > 55, moderate LREE, relatively low HREE and enrichment LILE (Sr, Cs, Rb, K and Ba) relative to HFSE (Nb, Ta, Ti, Hf and Zr). They are chemically similar to some adakites, but their chemical signatures differ in some ways from normal adakites, including higher K_2O contents and K_2O/Na_2O ratios and lower Mg#, $(La/Yb)_N$ and $(Ce/Yb)_N$ in Maherabad rocks [9, 10]. Maherabad intrusive rocks are the first K-rich adakites that can be related to subduction zone.

Najmabad

Najmabad is located about 15 Km southeast of Gonabad. An east-west trending biotite granodiorite porphyry pluton, 26×4 km^2 in size, intruded Jurassic slates and quartzites. The granodiorite has porphyry texture with 35 to 55 percent phenocrysts. The mineral content, based on the phenocrysts, are: 15%–20% plagioclase, 10%–15% K-feldspar, 10%–15% quartz, 5%–10% biotite and less than 2% accessory phases. Based on mineralogy and low values of magnetic susceptibility [(5 to 11) × 10^{-5} SI], this granodiorite is classified as belonging to the ilmenite-series of reduced S-type granitoids. Chemically it is met-aluminous (Fig. 2), with relative enrichment in LILE = Rb, Ba, Zr, Th, Hf, K and LREE, and depletion in Sr, P, Ti and HREE. Based on REE content and low $(La/Yb)_N$ = 7-11.5, this pluton originated from melting of continental crust during the Jurassic-Cretaceous orogeny that caused regional metamorphism [11].

Dehnow Kuhsangi

The Dehnow Kuhsangi quartz diorite to granodiorite is situated within the Binaloud Mountains, south and west of Mashhad city in northeastern Iran, between Longitude 59°23'55" to 59°33'41"E and Latitude 36°16'19" to 36°22'55"N. Its composition ranges from hornblende biotite quartz diorite to granodiorite. The quartz diorite contains 35%–50% plagioclase, 10%–14% K-feldspar, 9%–14% quartz, 15%–11% biotite, 2% hornblende and less than 2% accessory phases. Plagioclase shows minor weak zoning [12]. Quartz is in anhedral form is and found as interstitial grains. Accessory minerals are apatite, zircon, and ilmenite. Xenoliths within the hornblende biotite diorite mainly represent the country rocks such as slates, meta-peridotite, and meta-gabbro.

Based on mineralogy and low values of magnetic susceptibility [(5 to 20) × 10^{-5} SI], this diorite to granodiorite are classified as belonging to the ilmenite-series of reduced S-type granitoids. Chemically, the Dehnow diorite and Kuhsangi granodiorite are moderately per-aluminous (Fig. 2) S-type plutons with $(La/Yb)_N$ = 7 to 22 and no, or only small, negative Eu anomalies (Eu/Eu* = 0.55 to 1.1) [12].

Khajehmourad

The Khajehmourad leucogranite batholith is located in northeastern Iran and it lies between Longitude 59°33′ to 59°42′ E and Latitude 36°08′ to 36°13′ N. The biotite-muscovite leucogranite batholith is an NW/SE-elongated body with maximum dimensions of ~17 km length and ~7 km width. The batholith comprises of different Zones: The border zone is mainly a tourmaline bearing aplite granite, but the bulk of the batholith is made up of biotite-muscovite leucogranite. Pegmatite dykes, which are locally very abundant, are the youngest intrusive rocks and cutting the biotite-muscovite leucogranite [13].

The biotite-muscovite leucogranite has fine-grained equigranular texture and is poorly foliated. It contains 35-38 % quartz, 25-29 % K-feldspar, 27-32 % albite, 2.5-5 % muscovite and 1.5-2.5 % biotite. Common accessory minerals include tourmaline, garnet, apatite and zircon [13].

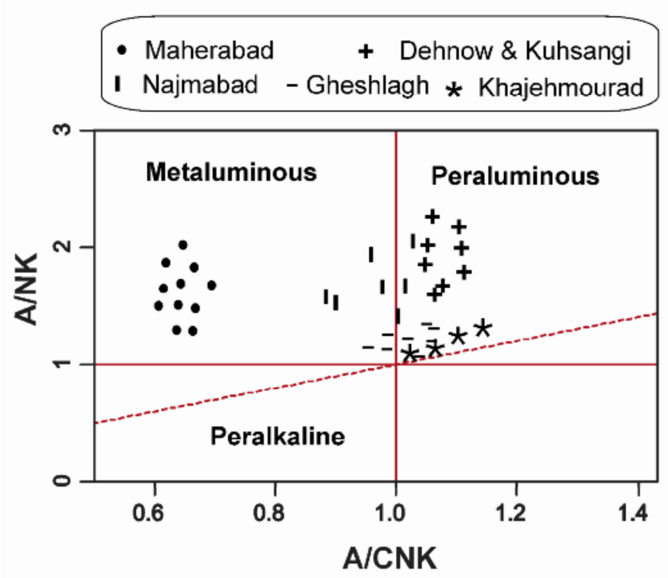

Fig 2. Plot of A/CNK versus Na_2O+ K_2O [15].

Chemically, biotite muscovite leucogranite and aplite granite are per-aluminous S-type pluton (Fig. 2). Magnetic susceptibility of biotite muscovite leucogranite and aplite granite are between than [(0 to 5) × 10^{-5} SI] and the ratio of ferric to ferrous ratio (< 0.35), therefore they are classified as belonging to the ilmenite-series (reduced type) (Fig. 3). The low field strength elements (LFSE) (Rb, Ba and Sr) content of biotite-muscovite leucogranite are in general high. Leucogranite has the highest Rb ≈ 235-261 ppm. The Rb/Sr is in the range of 1.07 to 1.27 in biotite muscovite leucogranite. The Ba content of biotite-muscovite leucogranite ranges from 550 to 708 ppm. The total REEs content of biotite muscovite leucogranite is between TREEs = 130-176 and aplite is very low is Total REEs = 50.79. They have small negative Eu anomalies (Eu/Eu*= 0.52 to 0.76) [13].

Gheshlagh

Gheshlagh Monzogranite is exposed in the southeastern plutonic belt of Mashhad. It lies between Longitude 59° 35′ to 59° 51′ E and Latitude 36° to 36° 10′. It contains 32 to 40 %, quartz, 32 to 42 %, K-feldspar, 8 to 17 %, plagioclase, 5 to 10 %, biotite and minor muscovite [14]. Accessories phases are zircon and apatite. Monzogranite has a coarse grained texture with typically coarse pink K-feldspar phenocrysts (2-3 cm long).

Chemically, monzogranite is moderately per-aluminous S-type granitoids (Fig. 2). It has low values of magnetic susceptibility [(5 to 11) × 10^{-5} SI] therefore it is classified as belonging to the ilmenite-series of reduced type granitoids (Fig. 3)[14]. Rock/orogenic normalized spidergrams of monzogranite show well defined negative anomalies for Ta, Hf, Y and Yb. Rb, Th, Nb, Sm and Ce show positive anomalies. Rb shows the highest positive anomaly. High Rb indicates that the magma originated from a source with high feldspar and most of the feldspar was melted. Monzogranite contains high K_2O, with high potassium feldspar. Th content of this rock is very high.

Monzogranite is characterized by strong light rare earth element (LREE) enrichment and low heavy REE (HREE). All samples have very small negative Eu anomalies (Eu/Eu* = 0.62 to 0.88). Total REE content of monzogranite ranges from 212-481 ppm [14].

Magnetic susceptibility

Magnetic susceptibility is the degree of magnetization of a material in response to an applied magnetic field. Granitic rocks were classified into magnetite-series and ilmenite-series by Ishihara [16]. Ishihara [16] recognized that in Japan there is a distinct spatial distribution of granitic rocks that contain magnetite coexisting with ilmenite and those that contain ilmenite as the only Fe–Ti oxide. He recognized that the magnetite-series granitoids are relatively oxidized whereas the ilmenite-series granitoids are relatively reduced. Granites show magnetic susceptibility of > 3.0 ×10^{-3} (SI units) are classified as belonging to the magnetite-series (Fig. 3) [17].

The magnetic susceptibility (MS) measurements of intrusive rocks from the study areas were carried out in the field on smooth rock surfaces using hand-held GM–S2 magnetic susceptibility meter. Magnetic susceptibility data are plotted in Figure 3, Maherabad with high magnetic susceptibility is plotted in the field of Magnetite series (Fig. 3), while Najmabad, Dehnow, Khajehmourad and Gheshlagh with low magnetic susceptibility [(5 to 20) × 10^{-5} SI], are plotted in the field of ilmenite series (Fig. 3).

Biotite mineral chemistry

Biotite from five plutons (Maherabad, Najmabad, Khajehmourad, Gheshlagh, and Dehnow), with different chemical and physical properties, were analyzed with electron-microprobe. Representative chemical analyses of biotite are given in Table (1a-d.).

Using the spreadsheet excel program designed by Tindle and Webb [18], structural formulae of biotite were calculated on the basis of 24 (O, OH, Cl, F) and 8 cations (Table 1a-d). According to the nomenclature of Deer [19], the biotite of the Maherabad pluton is classified biotite of Mg–rich (pholotopite) and Dehnow, Gheshlagh and Najmabad are as biotite (Annite- siderophyllitic) (Fig. 4). The Fe/(Fe+Mg) ratio in Maherabad biotite is 0.286-0.309, in Najmabad 0.491-0.511, in Dehnow-Kuhsangi 0.583-0.675, Gheshlagh 0.56-0.58, and Khajehmourad 0.705-0.720 respectively.

Foster [2] suggested discrimination diagrams on the basis of Mg, Fe^{+2} +Mn and Al^{VI}+Fe^{+3}+Ti (Fig. 5). He classified biotite into: siderophyllites, Fe-biotites, Mg-biotites and phlogophite (Fig. 5). Based on this classification, Khajehmourad is plotted in field of siderophyllites, Gheshlagh and Dehnow in the field of Fe-biotites, Najmabad in the field of Mg-biotite and Maherabad in the field on phlogophite (Fig. 5).

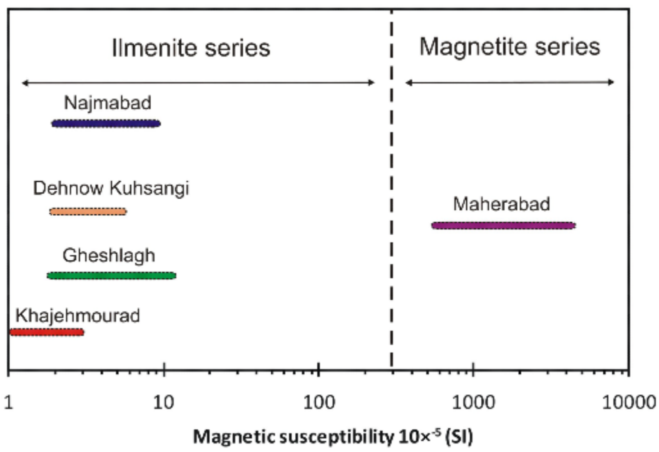

Fig 3. Based on Magnetic susceptibility, Najmabad, Dehnow-Kuhsangi, Gheshlagh and Khajehmourad are belonging to Ilmenite series and Maherabad is magnetite series.

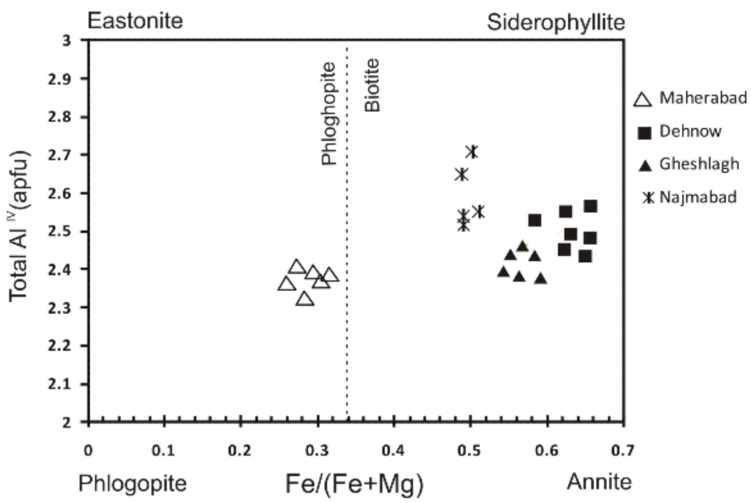

Fig 4. Classification of biotite based on Deer (1992).

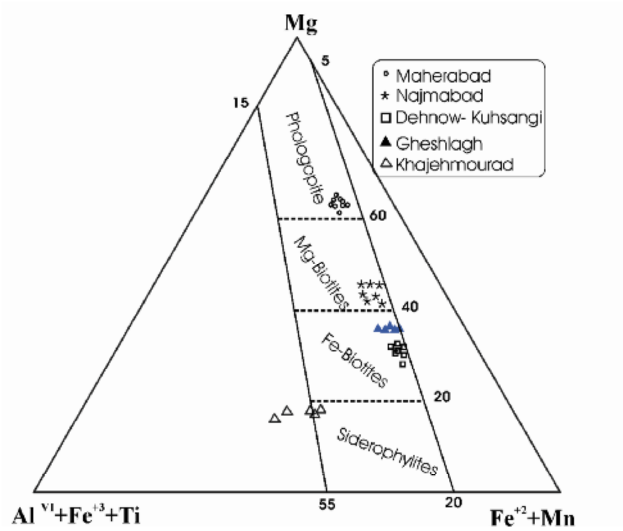

Fig 5. Plot of biotite from the study areas on Foster's [2] classification diagram.

Table 1a. Representative electron-microprobe analyses of biotite from Maherabad-Khopik Cu-Au porphury prospecting areas.

	Maherabad-Khopik										
SiO_2	37.51	36.86	37.08	37.1	37.3	37.45	37.25	37.3	36.95	37.3	36.98
TiO_2	5.54	5.26	5.59	5.3	5.35	5.45	5.29	5.45	5.37	5.29	5.31
Al_2O_3	13.54	13.88	13.6	13.62	13.6	13.56	13.67	13.67	13.85	13.76	13.47
FeO	12.1	12.04	12.71	12.2	12.23	12.09	12.32	12.15	12.2	12.15	12.18
MnO	0.208	0.194	0.268	0.207	0.201	0.256	0.209	0.208	0.234	0.206	0.198
MgO	16.69	16.83	15.93	16.7	16.57	16.72	16.55	16.45	16.7	16.45	16.67
CaO	0.023	0.057	0.027	0.025	0.023	0.027	0.026	0.024	0.025	0.023	0.067
Na_2O	0.27	0.249	0.262	0.259	0.269	0.264	0.246	0.258	0.245	0.266	0.259
K_2O	11.14	10.56	11.12	11.12	11.01	10.89	11.13	11.14	10.98	10.98	11.12
Cl	0.18	0.23	0.19	0.19	0.19	0.17	0.20	0.19	0.16	0.17	0.21
H_2O*	4.04	3.99	4.00	4.01	4.01	4.03	4.01	4.02	4.02	4.02	3.99
O = F, Cl	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.05
Total	101.2	100.1	100.7	100.6	100.7	100.8	100.8	100.8	100.7	100.5	100.4
Si	5.507	5.460	5.490	5.482	5.504	5.509	5.495	5.500	5.455	5.506	5.483
Al iv	2.343	2.423	2.373	2.372	2.365	2.351	2.377	2.376	2.410	2.394	2.354
Al vi	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.612	0.586	0.622	0.589	0.594	0.603	0.587	0.604	0.596	0.587	0.592
Fe	1.486	1.491	1.574	1.508	1.509	1.487	1.520	1.498	1.506	1.500	1.510
Mn	0.026	0.024	0.034	0.026	0.025	0.032	0.026	0.026	0.029	0.026	0.025
Mg	3.652	3.716	3.516	3.678	3.645	3.666	3.639	3.616	3.675	3.620	3.684
Ca	0.004	0.009	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.011
Na	0.077	0.071	0.075	0.074	0.077	0.075	0.070	0.074	0.070	0.076	0.074
K	2.086	1.995	2.100	2.096	2.072	2.043	2.094	2.095	2.068	2.068	2.103
OH*	3.956	3.942	3.953	3.953	3.951	3.958	3.950	3.953	3.961	3.959	3.946
Cl	0.044	0.058	0.047	0.047	0.049	0.042	0.050	0.047	0.039	0.041	0.054
TOTAL	19.79	19.78	19.79	19.82	19.79	19.77	19.81	19.79	19.81	19.78	19.84
Y total	5.776	5.818	5.746	5.801	5.773	5.789	5.772	5.744	5.807	5.733	5.812
X total	2.166	2.076	2.180	2.174	2.153	2.123	2.169	2.173	2.142	2.147	2.188
Al total	2.343	2.423	2.373	2.372	2.365	2.351	2.377	2.376	2.410	2.394	2.354
Fe/Fe+Mg	0.289	0.286	0.309	0.291	0.293	0.289	0.295	0.293	0.291	0.293	0.291
Luhr et al. 84	1347.3	1307.7	1313.1	1303.2	1308.7	1333.7	1294.1	1329.5	1313.7	1304.9	1306.0

Table 1b. Representative electron-microprobe analyses of biotite from Dehnow-Kuhsangi Areas

	Dehnow onalite		Vakilabad Granodiorite		Kuhsangi Granodiorite		
	V5-1	V5-2	T3-1	T3-2	X2-1	X2-2	X2-3
SiO_2	35.75	34.75	35.76	35.98	35.4	34.17	34.96
TiO_2	3.02	2.72	0.51	2.51	2.26	2.18	2.42
Al_2O_3	16.3	16.6	17.61	16.84	17.47	16.85	16.6
FeO	22.94	23.65	21.73	22.8	23.42	24.41	24.1
MnO	0.356	0.381	0.486	0.519	0.399	0.499	0.22
MgO	7.89	7.99	8.73	7.72	6.86	6.59	6.83
CaO	0.031	0.19	0.046	0.041	0.01	0.076	0.047
Na_2O	0.14	0.135	0.07	0.088	0.046	0.061	0.12
K_2O	9.38	8.27	8.749	9.277	9.47	9.3	9.4
Cl	0.121	0.094	0.092	0.12	0.086	0.09	0.07
H_2O*	3.85	3.81	3.81	3.86	3.83	3.74	3.79
O = F, Cl	0.03	0.02	0.02	0.03	0.02	0.02	0.02
Total	99.75	98.57	97.57	99.72	99.23	97.95	98.54
Si	5.529	5.439	5.591	5.552	5.510	5.442	5.510
Al iv	2.471	2.561	2.409	2.448	2.490	2.558	2.490
Al vi	0.500	0.501	0.836	0.615	0.716	0.605	0.593
Ti	0.351	0.320	0.060	0.291	0.265	0.261	0.287
Fe	2.967	3.096	2.841	2.942	3.049	3.251	3.176
Mn	0.047	0.051	0.064	0.068	0.053	0.067	0.029
Mg	1.819	1.864	2.035	1.776	1.592	1.564	1.605
Ca	0.005	0.032	0.008	0.007	0.002	0.013	0.008
Na	0.042	0.041	0.021	0.026	0.014	0.019	0.037
K	1.850	1.651	1.745	1.826	1.880	1.889	1.890
OH*	3.968	3.975	3.976	3.969	3.977	3.976	3.981
Cl	0.032	0.025	0.024	0.031	0.023	0.024	0.019
TOTAL	19.581	19.556	19.610	19.551	19.569	19.670	19.625
Y total	5.683	5.832	5.836	5.692	5.674	5.749	5.691
X total	1.897	1.724	1.774	1.859	1.896	1.921	1.934
Al total	2.971	3.062	3.245	3.063	3.205	3.163	3.084
Fe/Fe+Mg	0.620	0.624	0.583	0.624	0.657	0.675	0.664
Luhr et al. 84	915.5	900.8	827.6	896.5	885.0	879.0	888.3

Table 1c. Representative electron-microprobe analyses of biotite from Gheshladh and Khajehmourad

	Monzogranite (Gheshlagh)							Leucogranite (Khajehmourad)				
	FG1	FG2	FG3	FG4	FG5	FG6	FG7	MG-1	MG-2	MG-3	MG-4	MG-5
SiO_2	35.77	36.04	35.67	35.78	36.01	35.89	35.76	30.9	26.21	30.78	26.23	30.89
TiO_2	2.583	2.47	2.197	2.67	2.56	2.48	2.68	2.92	2.3	2.91	2.25	2.87
Al_2O_3	15.874	15.33	17.263	16.45	15.68	16.11	15.97	29.34	37.94	30.1	37.56	30.2
FeO	21.77	22.1	20.1	21	21.1	21.56	21.34	20.2	17.65	19.98	17.57	19.56
MnO	0.587	0.5	0.685	0.48	0.52	0.51	0.48	0.588	0.354	0.45	0.32	0.31
MgO	8.77	8.87	8.867	8.78	8.89	8.82	8.8	4.62	4.25	4.34	4.23	4.59
CaO	0.159	0.001	0.04	0.01	0.02	0.01	0.02	0.096	0.0718	0.07	0.06	0.05
Na_2O	0.069	0.07	0.115	0.08	0.09	0.07	0.11	0.112	0.189	0.16	0.19	0.11
K_2O	9.08	9.76	9.1	9.3	9.3	9.45	9.21	8.196	7.01	8.21	7.05	8.14
Cl	0.018	0.008	0.013	0.01	0.01	0.01	0.01	0.001	0.045	0.03	0.02	0.03
H_2O*	3.85	3.85	3.86	3.86	3.84	3.86	3.84	4.03	4.05	4.03	4.04	4.03
O = F, Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01
Total	98.52	99.00	97.91	98.42	98.02	98.76	98.20	101.00	100.06	101.05	99.51	100.78
Si	5.569	5.610	5.537	5.554	5.620	5.572	5.574	4.600	3.868	4.570	3.892	4.582
Al iv	2.431	2.390	2.463	2.446	2.380	2.428	2.426	3.400	4.132	3.430	4.108	3.418
Al vi	0.483	0.423	0.695	0.563	0.504	0.520	0.508	1.748	2.467	1.837	2.461	1.863
Ti	0.302	0.289	0.256	0.312	0.300	0.290	0.314	0.327	0.255	0.325	0.251	0.320
Fe	2.835	2.877	2.609	2.726	2.754	2.799	2.782	2.515	2.178	2.481	2.180	2.427
Mn	0.077	0.066	0.090	0.063	0.069	0.067	0.063	0.074	0.044	0.057	0.040	0.039
Mg	2.036	2.058	2.052	2.032	2.068	2.041	2.045	1.025	0.935	0.961	0.936	1.015
Ca	0.027	0.000	0.007	0.002	0.003	0.000	0.000	0.015	0.011	0.011	0.010	0.008
Na	0.021	0.021	0.035	0.024	0.027	0.021	0.033	0.032	0.054	0.046	0.055	0.032
K	1.803	1.938	1.802	1.841	1.851	1.871	1.831	1.556	1.319	1.555	1.334	1.540
OH*	3.995	3.998	3.997	3.997	3.997	3.997	3.997	4.000	3.989	3.992	3.995	3.992
Cl	0.005	0.002	0.003	0.003	0.003	0.003	0.003	0.000	0.011	0.008	0.005	0.008
TOTAL	19.584	19.673	19.546	19.563	19.577	19.610	19.577	19.293	19.264	19.272	19.267	19.243
Y total	5.733	5.714	5.703	5.696	5.695	5.718	5.712	5.689	5.879	5.660	5.868	5.663
X total	1.851	1.959	1.843	1.867	1.882	1.893	1.864	1.604	1.385	1.612	1.399	1.580
Al total	2.913	2.813	3.158	3.010	2.884	2.948	2.934	5.148	6.599	5.267	6.569	5.280
Fe/Fe+Mg	0.582	0.583	0.560	0.573	0.571	0.578	0.576	0.710	0.700	0.721	0.700	0.705
Luhr et al. 84	904.0	898.0	895.9	911.5	906.3	900.8	910.1	927.3	914.3	928.3	912.3	929.3

Table 1d. Representative electron-microprobe analyses of biotite from Najmabad.

	Najmabad						
SiO_2	36.39	36.21	35.56	34.94	36.40	36.36	36.39
TiO_2	2.89	3.64	2.50	2.49	2.45	2.37	2.89
Al_2O_3	16.38	15.80	17.33	17.73	16.78	16.98	16.56
FeO	18.29	19.05	18.61	18.95	18.00	18.34	18.55
MnO	0.29	0.33	0.31	0.33	0.33	0.31	0.32
MgO	10.65	10.23	10.92	10.54	10.45	10.56	10.57
CaO	0.011	0.002	0.003	0.004	0.002	0.002	9E-04
Na_2O	0.011	0.015	0.001	0.001	0.011	0.009	0.01
K_2O	11.35	11.25	11.28	11.70	11.12	11.09	11.34
Cl	0.14	0.14	0.15	0.12	0.11	0.12	0.10
H_2O*	3.96	3.95	3.95	3.93	3.95	3.96	3.98
O = F, Cl	0.03	0.03	0.03	0.03	0.02	0.03	0.02
Total	101.22	101.43	101.22	101.19	100.47	100.96	101.58
Si	5.463	5.450	5.353	5.293	5.486	5.460	5.447
Al iv	2.537	2.550	2.647	2.707	2.514	2.540	2.553
Al vi	0.361	0.252	0.428	0.459	0.467	0.465	0.368
Ti	0.326	0.412	0.283	0.283	0.278	0.268	0.325
Fe	2.296	2.398	2.344	2.400	2.269	2.303	2.322
Mn	0.037	0.042	0.040	0.043	0.042	0.039	0.041
Mg	2.383	2.296	2.451	2.380	2.348	2.364	2.358
Ca	0.002	0.000	0.000	0.001	0.000	0.000	0.000
Na	0.003	0.004	0.000	0.000	0.003	0.003	0.003
K	2.172	2.161	2.166	2.260	2.138	2.124	2.165
OH*	3.965	3.963	3.963	3.969	3.972	3.969	3.975
Cl	0.035	0.037	0.037	0.031	0.028	0.031	0.025
TOTAL	20.119	20.073	20.107	20.116	20.087	20.100	20.120
Y total	5.942	5.908	5.941	5.855	5.946	5.973	5.952
X total	2.177	2.165	2.166	2.262	2.141	2.127	2.168
Al total	2.898	2.802	3.075	3.166	2.981	3.005	2.922
Fe/Fe+Mg	0.491	0.511	0.489	0.502	0.491	0.494	0.496
Luhr et al. 84	939.7	972.5	918.0	915.2	919.6	913.4	937.8

Nachit [4] used mica composition in granitoids to relate magma types in which biotite crystallized. In Al(tot) vs. Mg classification diagram, the nature of granitoid magmas was grouped into four types such as peraluminous, calc-alkaline, sub-alkaline, and alkaline–peralkaline (Fig. 6). Biotite from Gheshlagh, Dehnow, Khajehmourad, and Najmabad are plotted in the field of peraluminous but Maherabad is plotted in the field of sub-alkaline (Fig. 6). The negative correlation between Al and Mg observed among biotite compositions is usually accounted for a number of substitutions operating between four end-members (Fig. 6).

Abdel-Raham [5, 20] suggested MgO-Al_2O_3 diagram of biotite chemistry for discriminating between alkaline magma (A), peraluminous magma (P) (including S-type), and calc-alkaline magma (C) (Fig. 7).

Khajehmourad, Najmabad, Gheshlagh and Dehnow biotite compositions fall in the field of peraluminous granite (P) suites (S-type) in the biotite discrimination diagrams of Abdel-Rahman [5] (Fig. 7). This is consistent with the aluminum saturation index of intrusive rocks (Fig. 2). Maherabad biotite compositions fall in the field of calc-alkaline orogenic suites (Fig. 7). This is consistent with the aluminum saturation index of intrusive rocks (Fig. 2).

Abdel-Rahman [5] suggested discrimination diagrams on the basis of major - elements (FeO, MgO, Al_2O_3) of biotites in igneous rocks crystallized from A, P and C magma types. Based on his classification; Biotite from Khajehmourad, Najmabad, Gheshlagh and Dehnow belong to peraluminous granite (P) suites (S-type) (Fig. 8). Biotite from Maherabad belongs to calc-alkaline orogenic suites (Fig. 8).

Biotites from Maherabad are calc-alkaline orogenic suites (field C) and are moderately enriched in Mg (with an average FeO*/MgO 0.85, near phlogophite), while Najmabad, Gheshlagh, Khajehmourad and Dehnow are peraluminous (including S- type) suites (field P) and are siderophyllitic in composition and have an FeO*/MgO ratio of 2-3.

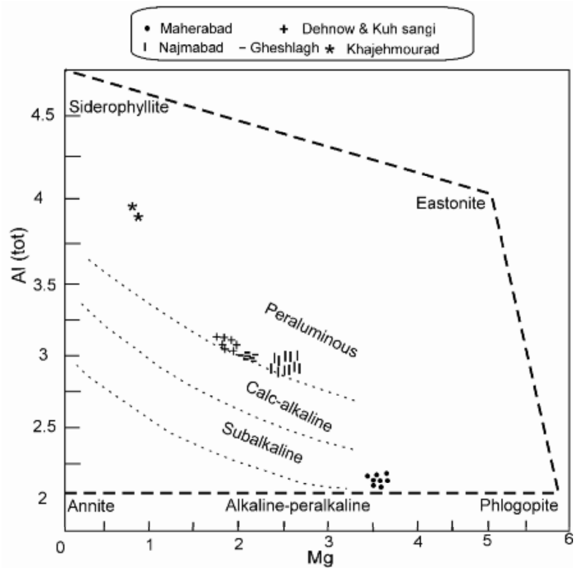

Fig 6. Biotite from the study areas plotted in Nachit [4] diagram to find out the type of magma.

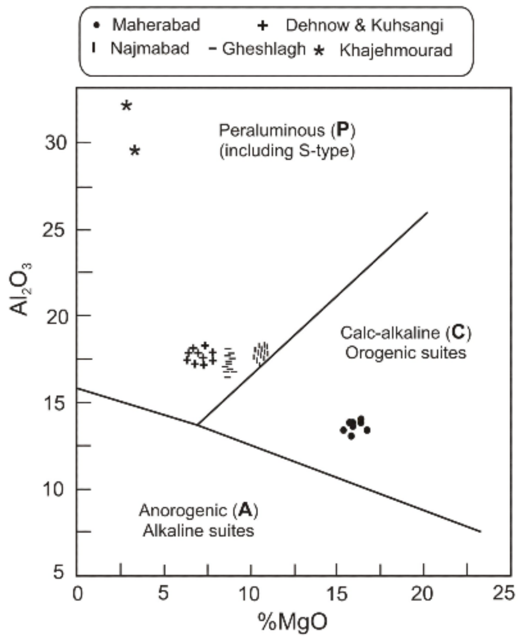

Fig 7. Al_2O_3-MgO biotite discrimination diagram, Abdel-Rahman [5].

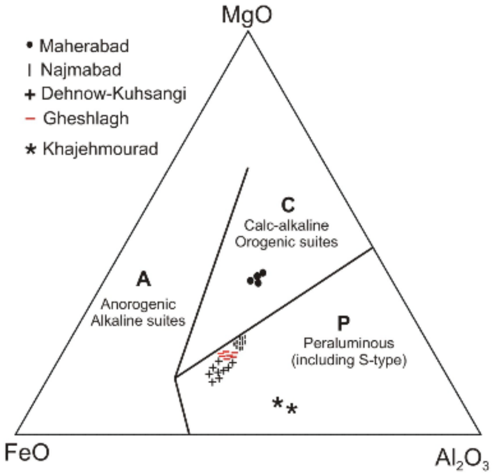

Fig 8. Distribution of micas on Abdel-Rahman's [5] ternary MgO–FeOtot–Al_2O_3 tectonomagmatic discrimination diagram.

Biotites from Maherabad has high TiO_2 and low Al_2O_3 but Najmabad, Dehnow and Gheshlagh have low TiO_2 and high Al_2O_3 (Fig. 9). The Ti content of biotites is believed to be dependent on the temperature of crystallization of biotite and the oxygen fugacity (fO_2) [21] and possibly on the volatile content of the magma. A low Ti content correlates with low temperature of crystallization and low oxygen fugacity [22].

Maherabad with high magnetic susceptibility [> 500 × 10^{-5} SI], belong to Magnetite series (Fig. 3). Based on High TiO_2 and low Al_2O_3 in biotites, Maherabad is also belonging to magnetite series (Fig. 9). Najmabad, Dehnow, Khajehmourad and Gheshlagh with low magnetic susceptibility [(5 to 20) × 10^{-5} SI], they are plotted in the field of ilmenite series (Fig. 3). Based on low TiO_2 and high Al_2O_3 in biotites, Najmabad, Dehnow and Gheshlagh are also belonging to ilmenite series (Fig. 9).

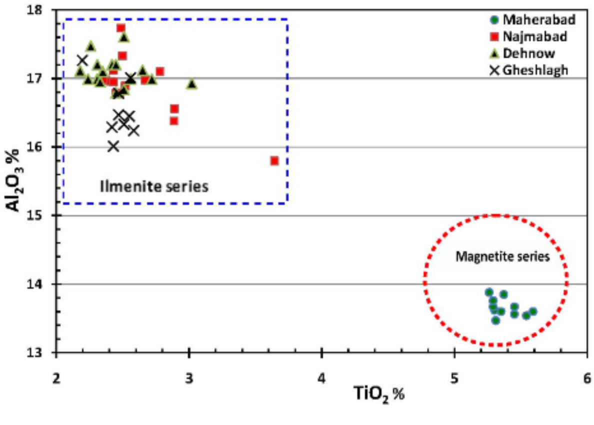

Fig 9. plot of TiO_2 v.s Al_2O_3.

Discusion & Conclusions

The processes responsible for chemical variations in the biotites are primary magmatic. Gathering evidence from studies of natural systems [23, 24, 25] and experimental systems [26, 27] suggest that compositions of biotites are very sensitive to prevailing magmatic physico-chemical conditions, especially oxygen fugacity (fO2). The availability of oxygen leads to early crystallization of iron-rich amphibole and iron oxides (typically magnetite), which in turn precludes the build-up of iron in calc-alkaline melts from which a moderately Mg-rich biotite crystallizes. Biotites from Maherabad are Mg-rich and the ratio of Fe/(Fe+Mg) is 0.286-0.309. Based on high TiO_2, low Al_2O_3, and low FeO, these biotites were crystallized from calc-alkaline orogenic granitoids magma belonging to magnetite series. Biotite from Gheshlagh, Dehnow, Khajehmourad and Najmabad are Fe-rich, low TiO_2, high Al_2O_3, and low MgO. These biotites were crystallized from peraluminous S-type granitoids magma belonging to ilmenite series

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