Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 9 (5): 843-853, 2009
ISSN 1812-5654

Petrography and Mineral Chemistry of the Boroujerd Pluton (Sanandaj-Sirjan Zone, Western Iran)

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Abstract: The Boroujerd pluton is chiefly constituted of quartz-diorite, granodiorite and monzogranite. The mineral chemistry and microprobe analysis of mineral assemblages in these rocks indicate that the magma in this area has a metaluminous to slightly peraluminous composition, related to calc-alkaline, arc-type magmas and displays features typical of I-type granitoids. Also, the average pressure and temperature is estimated at 1.093±0.6 k bars and 785±40 in quartz-diorites, respectively. All analyzed samples have log FO_2-14.1 which show this magma crystallized in high oxygen fugacity. Also, the occurrence of magnesio-hornblende and Fe^{2+}biotite in Boroujerd rocks suggest relatively oxidized magma.

Key words: I-type granite, metaluminous, calc-alkaline, geothermometry

INTRODUCTION

The Sanandaj-Sirjan zone, which is the host of the Boroujerd pluton, has a length of 1500 km and a width up to 200 km from the Northwest to the Southeast in Iran (Fig. 1). This tectonic zone is mainly composed of Mesozoic and some Paleozoic rocks and separates the stable Central Iranian block, from the Afro-Arabian plate (Stöcklin, 1968).

The presence of a narrow arc-trench gap in this belt is an indication of steep subduction (Isacks and Barazangi, 1977; Berberian and Berberian, 1981). The Sanandaj-Sirjan calc-alkaline magmatic arc, including the Boroujerd pluton, formed over a high angle subducting oceanic slab in the Neotethyan subduction zone during Late Triassic to Late Cretaceous time (Berberian and Berberian, 1981; Shahabpour, 2005).

So far exceptionally a few age determinations (Ahmadi-Khalaji *et al*., 2007; Arvin *et al*., 2007), no detailed studies especially mineral chemistry have been carried out on any of the mesozoic plutonic rocks, in the Sanandaj-Sirjan zone.

The main aims of this study are to use petrography and mineral chemical characteristics, as well as observe

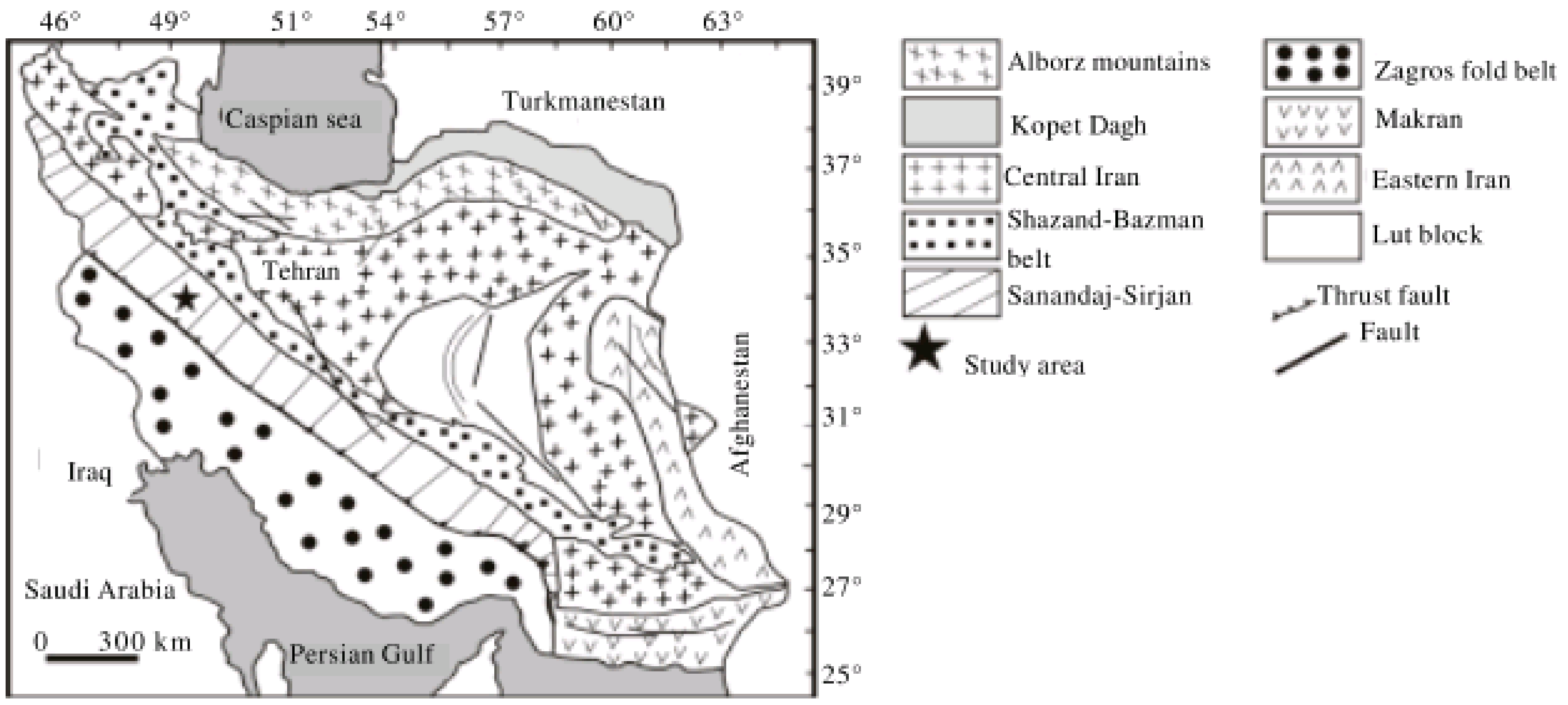

Fig. 1: Geological map of Iran (Shahabpour, 1994), showing major lithotectonic units

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field relationships of the Boroujerd pluton, to determine its origin and to shed light thermobarometer and related magmatism in Iran, an area for which little information has been available so far.

MATERIALS AND METHODS

The major element compositions of the minerals were determined by electron microprobe analysis of polished thin sections. Some mineral compositions were determined using a Cameca SX-100 electron microprobe at the University of Hamburg (institute mineralogy and petrology), in June 2005 during 6 months, Germany. Also, the analysis were performed with JXA-8200 Super Probe at university of Huelva in March 2006 during 6 months, Spain, operated with an accelerating voltage 15 keV and a probe current of 5 nA. Silicate standards were Jadeite for Na, Wollastonite for Ca, Alkali Feldspar for K and Al, Enstatite for Mg, Fayallite for Fe and Mn and apatite for P. Chemical composition and structural formula of hornblende, biotite and feldspar are shown in Table 1-3.

RESULTS

Geological setting: The Boroujerd pluton is a NW-SE trending body covering an area of 600 km^2, approximately 60 km in length and 8-10 km in width, which lies between 33°38'-34°N and between 48°45'-49°20' E (Fig. 2). The Boroujerd area is characterized by the predominance of metamorphic rocks of Jurassic age (Baharifar *et al*., 2004) and the presence of the Boroujerd pluton. Metamorphic rocks subdivided in to 2 groups based on their setting: Dynamothermal and contact. Dynamothermal metamorphism has affected a vast area which is composed of slate, phyllite and schist (Ahmadi-Khalaji *et al*., 2007). Contact metamorphic rocks, consisting of spotted schists, cordierite-andalusite and cordierite-silimanite hornfelses, are evident only to the North of the pluton, because the southern margin of the complex is controlled by a fault system parallel to the contact and the granitoid rocks are thrusted onto the metamorphic rocks (Ahmadi-Khalaji *et al*., 2007).

Table 1: Representative electron microprobe analysis of amphibole in quartz-diorite of the Boroujerd pluton (number of ions on the basis of 23 oxygen)

Specimen	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	49.250	49.270	49.710	49.890	49.880	50.320	50.120	52.270	49.620	49.830	49.340	49.690
TiO_2	0.700	0.850	0.790	0.270	0.230	0.230	0.300	0.150	0.420	0.450	0.410	0.210
Al_2O_3	5.420	5.660	5.530	4.440	4.500	4.460	4.430	2.430	4.970	4.680	5.140	4.810
FeO^{+}	15.740	14.610	15.370	16.680	16.930	16.700	16.770	15.480	16.560	16.310	16.780	16.510
MgO	13.570	13.450	13.410	12.370	12.830	12.840	12.850	12.600	13.470	12.770	12.640	12.490
MnO	0.480	0.310	0.420	0.600	0.530	0.530	0.430	0.480	0.480	0.490	0.650	0.680
CaO	10.690	11.370	11.400	10.420	10.650	10.550	10.660	12.540	10.810	10.870	10.820	10.690
Na_2O	0.710	0.790	0.700	0.600	0.590	0.600	0.620	0.170	0.650	0.640	0.730	0.590
K_2O	0.420	0.500	0.430	0.340	0.350	0.360	0.360	0.060	0.430	0.390	0.460	0.370
F	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cl	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sum	97.110	96.900	97.830	95.710	96.510	96.710	96.610	96.250	96.530	96.560	95.890	96.240
T-sites												
Si	7.29	7.280	7.29	7.51	7.45	7.48	7.47	7.76	7.41	7.43	7.39	7.450
Al^{IV}	0.71	0.720	0.71	0.49	0.55	0.52	0.53	0.24	0.59	0.57	0.61	0.550
Al (total)	0.95	0.990	0.96	0.79	0.79	0.78	0.78	0.43	0.88	0.82	0.91	0.850
M 1, 2, 3 sites												
Al^{Vi}	0.24	0.270	0.25	0.29	0.24	0.27	0.25	0.19	0.29	0.25	0.30	0.300
Ti	0.08	0.090	0.09	0.03	0.03	0.03	0.03	0.02	0.05	0.05	0.05	0.020
Fe^{3+}	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Mg	2.99	2.960	2.93	2.77	2.86	2.85	2.85	2.79	2.78	2.84	2.82	2.790
Mn	0.06	0.040	0.05	0.08	0.07	0.07	0.05	0.06	0.06	0.06	0.08	0.090
Fe^{2+}	1.63	1.640	1.68	1.83	1.81	1.79	1.81	1.92	1.83	1.79	1.75	1.800
Ca	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.000
M4 site	5.00	5.000	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.000
Fe	0.32	0.170	0.21	0.27	0.30	0.29	0.28	0.00	0.24	0.24	0.22	0.270
Ca	1.68	1.800	1.79	1.68	1.70	1.68	1.70	1.98	1.73	1.74	1.74	1.720
Na	0.00	0.030	0.00	0.05	0.00	0.03	0.02	0.02	0.03	0.02	0.04	0.020
A site	2.00	2.000	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.000
Ca	0.02	0.000	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Na	0.20	0.200	0.20	0.13	0.17	0.14	0.16	0.02	0.16	0.16	0.17	0.150
K	0.08	0.090	0.08	0.06	0.07	0.07	0.07	0.01	0.08	0.07	0.09	0.070
Sum A	0.30	0.290	0.28	0.19	0.25	0.21	0.23	0.04	0.24	0.24	0.26	0.220
Vac A	0.70	0.710	0.72	0.81	0.75	0.79	0.77	0.96	0.76	0.76	0.74	0.780
$Mg/Mg+Fe^{2+}$	0.65	0.640	0.64	0.60	0.61	0.61	0.61	0.59	0.60	0.61	0.62	0.610
Fe/Fe+Mg	0.35	0.360	0.36	0.40	0.39	0.39	0.39	0.41	0.40	0.39	0.38	0.390

Table 2: Representative electron microprobe analysis of biotite quartz- diorite, granodiorite and monzogranite from Boroujerd pluton (Number of ions on the basis of 11 oxygen

	Biotite in quartz diorite							Biotite in granodiorite			Biotite in monzogranite			
Specimen	1	2	3	4	5	6	7	1	2	3	1	2	3	4
SiO_2	36.59	36.75	36.65	36.42	36.71	36.81	34.25	34.55	34.61	33.41	33.59	33.80	34.31	33.85
Al_2O_3	14.99	15.24	15.01	15.14	15.00	15.18	18.87	18.70	18.63	18.38	18.22	18.33	17.75	17.34
MgO	11.71	11.88	11.63	11.72	11.68	11.73	7.08	7.45	7.48	7.93	5.77	5.84	6.21	5.82
FeO	14.97	15.39	14.95	14.99	14.67	15.20	18.96	18.59	18.61	19.43	20.23	20.00	19.85	20.67
Fe_2O_3	3.79	3.90	3.78	3.80	3.72	3.85	4.69	4.61	4.62	4.65	4.96	4.86	4.91	5.09
TiO_2	3.51	3.38	3.68	3.75	3.45	3.29	2.34	2.00	1.92	1.75	2.24	1.97	1.68	2.47
MnO	0.17	0.19	0.19	0.16	0.14	0.18	0.18	0.23	0.21	0.18	0.52	0.50	0.54	0.57
CaO	0.04	0.01	0.04	0.01	0.05	0.01	0.00	0.05	0.02	0.12	0.03	0.03	0.03	0.03
Na_2O	0.12	0.16	0.15	0.11	0.18	0.17	0.19	0.22	0.15	0.15	0.06	0.03	0.06	0.03
K_2O	8.57	8.48	8.48	8.71	8.53	8.43	8.57	8.49	8.49	7.17	8.49	7.93	8.55	8.64
Cr_2O_3	0.11	0.13	0.02	0.04	0.07	0.10	0.03	0.06	0.03	0.06	0.08	0.03	0.00	0.00
NiO	0.00	0.00	0.03	0.06	0.05	0.06	0.03	0.02	0.00	0.02	0.00	0.00	0.00	0.04
Total	94.58	95.51	94.63	94.90	94.24	95.00	95.20	94.97	94.78	93.26	94.20	93.32	93.89	94.55
	1-bit1	1-bit2	1b-bit1	1b-bit2	2a-bit1	2a-bit2	1-bit	1-bit	3b-1	3b-2	a1-1	a3-2	a4-2	a5-3
Formula calculated on the basis of 11 oxygen atom														
Si	2.79	2.78	2.80	2.78	2.81	2.80	2.66	2.68	2.69	2.64	2.67	2.69	2.73	2.69
Al_{IV}	1.21	1.22	1.20	1.22	1.19	1.20	1.34	1.32	1.31	1.36	1.33	1.31	1.27	1.31
Total	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Al_{VI}	0.14	0.14	0.15	0.14	0.16	0.16	0.39	0.40	0.40	0.36	0.37	0.41	0.39	0.32
Mg	1.33	1.34	1.32	1.33	1.33	1.33	0.82	0.86	0.87	0.94	0.68	0.69	0.74	0.69
Fe	1.20	1.22	1.20	1.20	1.18	1.21	1.54	1.51	1.51	1.59	1.67	1.66	1.64	1.71
Ti	0.20	0.19	0.21	0.21	0.20	0.19	0.14	0.12	0.11	0.10	0.13	0.12	0.10	0.15
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	2.90	2.92	2.89	2.90	2.89	2.91	2.90	2.90	2.91	3.02	2.88	2.90	2.88	2.88
Na	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.01	0.00	0.01	0.01
K	0.84	0.82	0.82	0.85	0.83	0.82	0.85	0.84	0.84	0.72	0.86	0.81	0.87	0.88
Total	7.75	7.76	7.74	7.76	7.75	7.75	7.78	7.78	7.77	7.77	7.75	7.71	7.76	7.76
FeO														
FeO/MgO	0.561	0.564	0.563	0.561	0.557	0.564	0.728	0.714	0.713	0.710	0.778	0.774	0.762	0.78

Table 3: Representative electron microprobe analysis of plagioclase in quartz- diorite, granodiorite and monzogranite from Boroujerd pluton (Number of ions on the basis of 8 oxygen)

	Plagioclase in quartz diorite												
Specimen	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	56.34	54.75	54.9	54.87	52.67	54.47	54.82	55.23	55.86	60.74	53.80	53.85	53.67
Al_2O_3	27.75	29.12	28.97	28.75	30.08	28.84	28.77	28.01	28.01	24.78	29.30	29.25	28.98
MgO	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
FeO	0.02	0.09	0.00	0.05	0.02	0.05	0.07	0.00	0.05	0.04	0.02	0.02	0.10
TiO_2	0.03	0.02	0.03	0.00	0.00	0.03	0.00	0.00	0.01	0.01	0.01	0.02	0.01
MnO	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.00	0.00	0.00	0.00
CaO	9.53	10.91	10.80	10.80	12.16	11.01	10.67	9.92	9.66	5.96	11.30	11.28	11.22
Na_2O	6.06	5.39	5.41	5.37	4.59	5.39	5.42	5.80	6.08	8.16	4.98	5.21	5.17
K_2O	0.07	0.07	0.05	0.08	0.08	0.06	0.05	0.06	0.05	0.13	0.09	0.09	0.08
Cr_2O_3	0.04	0.00	0.00	0.03	0.00	0.00	0.02	0.02	0.00	0.01	0.00	0.02	0.02
NiO	0.00	0.03	0.00	0.00	0.01	0.00	0.01	0.00	0.05	0.00	0.00	0.03	0.00
Total	99.85	100.40	100.20	99.96	99.61	99.84	99.84	99.08	99.81	99.84	99.50	99.76	99.25
	1-plg1	1-plg2	1b-plg1	1b-plg2	2a-plg1	2a-plg2	2a-plg3	2b-1	2b-2	2b-3	3a-plg1	3a-plg2	3a-plg3
Formulae calculated on the basis of 8 oxygen atoms													
Si	2.53	2.46	2.47	2.47	2.39	2.46	2.47	2.51	2.52	2.70	2.44	2.44	2.44
Al	1.47	1.54	1.54	1.53	1.61	1.54	1.53	1.50	1.49	1.30	1.57	1.56	1.55
Ca	0.46	0.53	0.52	0.52	0.59	0.53	0.52	0.48	0.47	0.28	0.55	0.55	0.55
Na	0.53	0.47	0.47	0.47	0.40	0.47	0.47	0.51	0.53	0.70	0.44	0.46	0.46
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tot	5.00	5.00	5.00	5.00	5.01	5.01	5.00	5.00	5.01	5.00	5.00	5.01	5.01
Xab	0.53	0.47	0.47	0.47	0.40	0.47	0.48	0.51	0.53	0.71	0.44	0.45	0.45
Xan	0.46	0.53	0.52	0.52	0.59	0.53	0.52	0.48	0.47	0.29	0.55	0.54	0.54
Xor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3: Continued

	Plagioclase in granodiorite									
Specimen	1	2	3	4	5	6	7	8	9	10
SiO_2	57.15	55.90	58.08	55.68	55.89	56.59	55.00	56.49	56.55	55.55
Al_2O_3	27.63	28.50	27.26	28.54	28.32	28.25	29.10	28.00	27.75	28.76
MgO	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01
FeO	0.03	0.03	0.02	0.00	0.02	0.04	0.04	0.02	0.04	0.04
TiO_2	0.02	0.01	0.01	0.00	0.03	0.00	0.04	0.03	0.00	0.00
MnO	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.03
CaO	9.07	10.00	8.62	10.20	10.07	9.55	10.60	9.54	9.36	10.48
Na_2O	6.48	5.80	6.64	5.82	5.80	6.05	5.41	6.04	6.21	5.63
K_2O	0.09	0.11	0.13	0.07	0.10	0.10	0.09	0.10	0.10	0.06
Cr_2O_3	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
NiO	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.01
Total	100.50	100.00	100.80	100.40	100.30	100.60	100.00	100.24	100.04	100.60
								2b-1	2b-2	
Formulae calculated on the basis of 8 oxygen atoms										
Si	2.55	2.50	2.58	2.5	2.51	2.52	2.47	2.53	2.54	2.49
Al	1.45	1.50	1.43	1.51	1.50	1.49	1.54	1.48	1.47	1.52
Ca	0.43	0.48	0.41	0.49	0.48	0.46	0.51	0.46	0.45	0.50
Na	0.56	0.50	0.57	0.51	0.50	0.52	0.47	0.52	0.54	0.49
K	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tot	5.00	5.00	5.00	5.01	5.00	5.00	5.00	5.00	5.00	5.00
Xab	0.56	0.51	0.58	0.51	0.51	0.53	0.48	0.53	0.54	0.49
Xan	0.43	0.49	0.41	0.49	0.49	0.46	0.52	0.46	0.45	0.51
Xor	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.00
Tot	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

	Plagioclase in monzogranite					
Specimen	1	2	3	4	5	6
SiO_2	59.15	58.50	57.09	62.10	56.20	55.79
Al_2O_3	25.22	25.80	26.97	22.80	27.50	27.55
MgO	0.00	0.00	0.00	0.01	0.00	0.01
FeO	0.00	0.03	0.00	0.01	0.00	0.02
TiO_2	0.00	0.00	0.02	0.00	0.01	0.04
MnO	0.01	0.00	0.00	0.00	0.00	0.00
CaO	6.12	6.69	8.09	3.78	8.80	9.18
Na_2O	5.72	4.43	5.81	5.93	5.60	5.40
K_2O	0.13	0.14	0.11	0.11	0.11	0.09
Cr_2O_3	0.00	0.00	0.02	0.00	0.03	0.00
NiO	0.01	0.02	0.00	0.02	0.01	0.03
Total	96.37	95.60	98.10	94.80	98.20	98.11
	a2-1	a3-1	a5-1	a5-2	a6-1	a6-2
Formulae calculated on the basis of 8 oxygen atoms						
Si	2.70	2.69	2.59	2.85	2.55	2.54
Al	1.36	1.40	1.44	1.23	1.47	1.48
Ca	0.30	0.33	0.39	0.19	0.43	0.45
Na	0.51	0.39	0.51	0.53	0.49	0.48
K	0.01	0.01	0.01	0.01	0.01	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.88	4.82	4.95	4.80	4.96	4.96
X_{ab}	0.62	0.54	0.56	0.73	0.53	0.51
X_{an}	0.37	0.45	0.43	0.26	0.46	0.48
X_{or}	0.01	0.01	0.01	0.01	0.01	0.01
Total	1.00	1.00	1.00	1.00	1.00	1.00

U-Pb zircon geochronological data from Boroujerd granitoid rocks indicate episode of magmatic activity 170 Ma ago during the middle Jurassic (Ahmadi-Khalaji *et al*., 2007). The compositional variation found in this major pluton, usually range from quartz-diorite-granodiorite to monzogranite. The granitoids occurring in Boroujerd show close similarities with those described elsewhere in the Sanandaj-Sirjan zone. In general, mineral assemblage in Boroujerd pluton is same to other calc-alkaline granites in Sanadaj-Sirjan zone.

Field description and petrography: Detailed mapping of the Boroujerd area (Fig. 2) distinguished three main rock types; include quartz-diorite, granodiorite and monzogranite which are locally associated with acidic dikes. The granodiorite is the most dominant rock in this pluton.

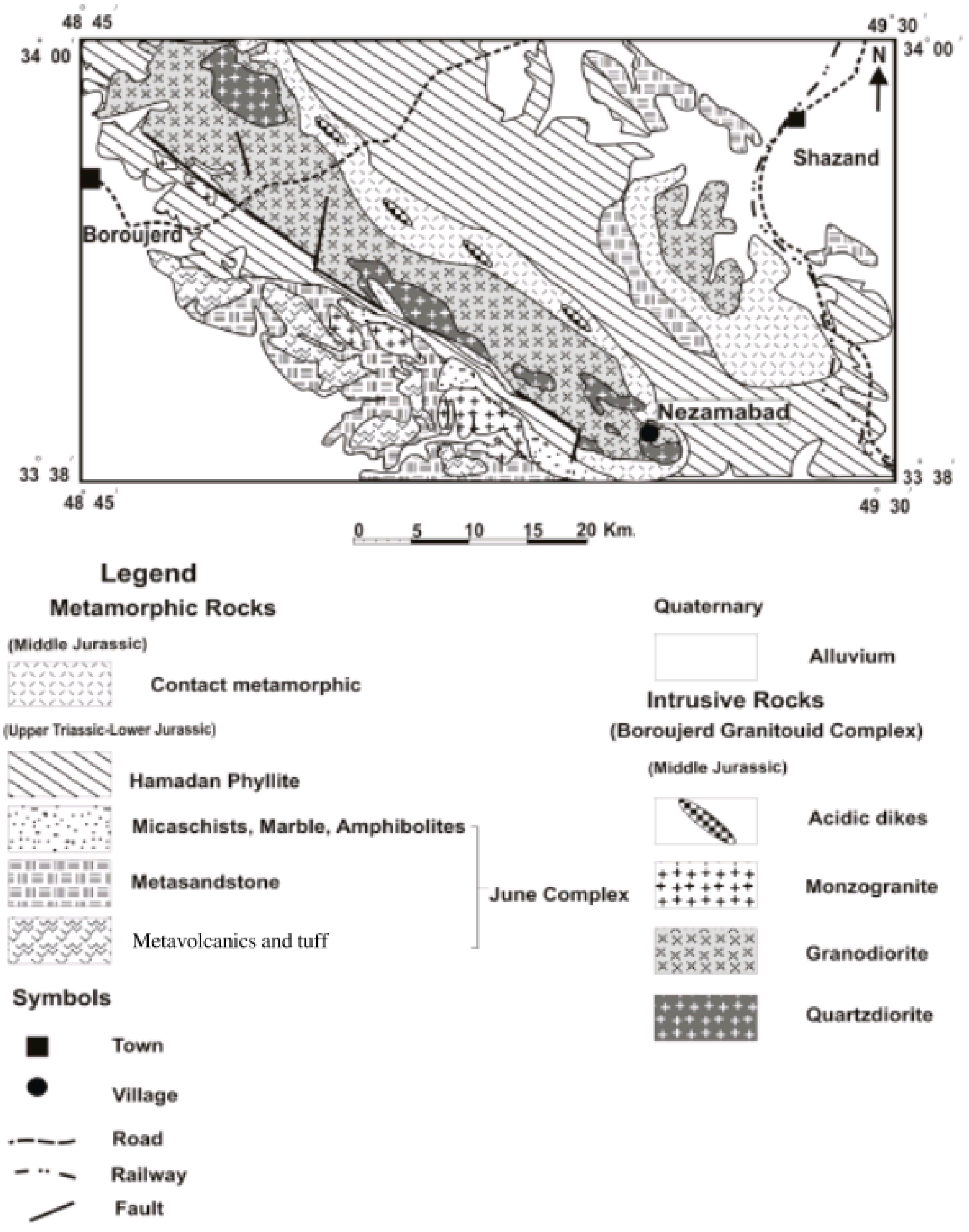

Fig. 2: The Boroujerd area, western Iran

Quartz-diorite: The quartz- diorite and tonalite are exposed within the granodiorite and have gradual boundaries with them (Fig. 3A). These rocks have granular texture (Fig. 3B) to porphyritic with plagioclase megacrysts and composed predominantly of plagioclase (40-50 vol.%), amphibole (10-15 vol.%), biotite (15-20 vol.%), alkali feldspar (<5 vol.%), quartz (<15 vol.%). Plagioclase is anhedral to subhedral plates, zoned and altered to sericite, epidote and calcite. Biotite occurs as brown kinking flakes and altered to chlorite and prehnite (Fig. 3D). Amphibole shows a euhedral prismatic habit, green colour and altered to biotite, chlorite, epidote and prehnite. Quartz crystals occur as anhedral to subhedral with adulatory extinction and a late interstitial phase. Alkali feldspar is anhedral to subhedral crystals. Zircon, sphene, apatite are conspicuous accessory minerals.

Granodiorite: The granodiorites are medium to coarse-grained rocks and have a granular to

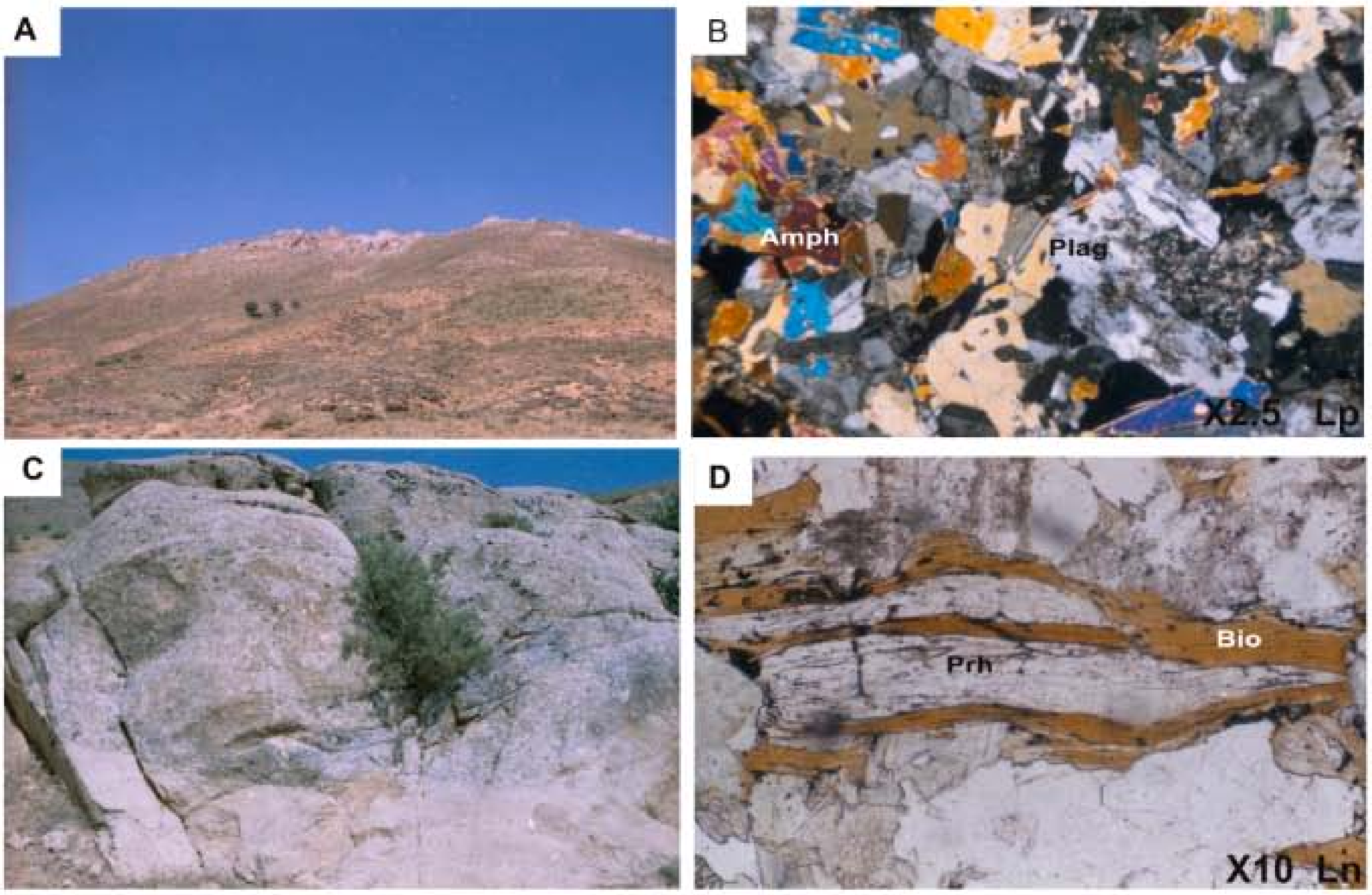

Fig. 3: Field and microscopic photos in quartz- diorite, granodiorite and monzogranite: Bt = Biotite; Amph = Amphibole; Prh = Prehnite; Mineral abbreviations are according to Kretz (1983)

hypidiomorphic texture. The main minerals are plagioclase, (30-40 vol.%), are usually euhedral, more or less with variable degrees of sericitisation, shows zoning and the first felsic mineral to crystallize. K-feldspar (<20 vol.%) forms anhedral to subhedral crystals and includes microcline-perthites. Quartz (25-30 vol.%) forms anhedral crystals. Biotite, the most abundant mafic mineral (10-20 vol.%) appears in brown flakes. Apatite, zircon, allanite and opaques are common accessory minerals and some muscovite is present as a secondary mineral.

Monzogranite: The monzogranites are widely scattered as separate and small outcrops through the southern part of the area (Fig. 3B). These rocks are light in colour (Fig. 3C), fine to coarse-grained, with a granular texture. The mineral assemblages include perthitic alkali feldspar (30-35 vol.%), plagioclase (25-35 vol.%), quartz (30-35 vol.%), biotite (5-10 vol.%). Zircon, allanite and apatite are common accessory minerals. Plagioclase forms subhedral to euhedral plates and altered to sericite. It is commonly zoned and the first felsic mineral to crystallize. Quartz grains occur as anhedral crystals or interstitial and may be recrystallized. Biotite occurs as anhedral flakes. Most it has altered to chlorite. Euhedral zircon, with clear haloes and prismatic, needle-like apatite are abundantly contained in plagioclase and quartz.

Acidic dikes (aplites and pegmatites): A series of NW trending aplites and pegmatites (Fig. 3B), varying from a few meters to tens of meters in length and a few meters in width, occur in the area studied. The aplites are characterized by fine equigranular assemblage of quartz, alkali feldspar and some muscovite, tourmaline and opaque oxides. These rocks are the main manifestation of the final phase of magmatic activity. Pegmatites are mainly present in the granodiorites and its aureole. They show a simple mineralogy with graphic texture. These are characteristically composed of quartz, feldspar, muscovite, tourmaline, zircon and apatite with some andalusite and garnet in the aureole samples. Pegmatites are similar in age with the main units (Ahmadi-Khalaji *et al*., 2007) and again, could be final phase of magmatic activity.

Mineral chemistry

Amphibole: Amphibole is common in the quartz- diorites, but rare in the granodiorites and absent from the monzogranites. Representative major elements EPMA of unaltered magmatic hornblende from Boroujerd pluton (Fig. 4 A, B) is presented in Table 1. Major element EPMA compositions were calculated to an apfu 23 oxygen and normalized to total cations (Ca+Na+K) = 13, with Fe $^{3+}$/Fe^{2+} ratios calculated by charge balance.

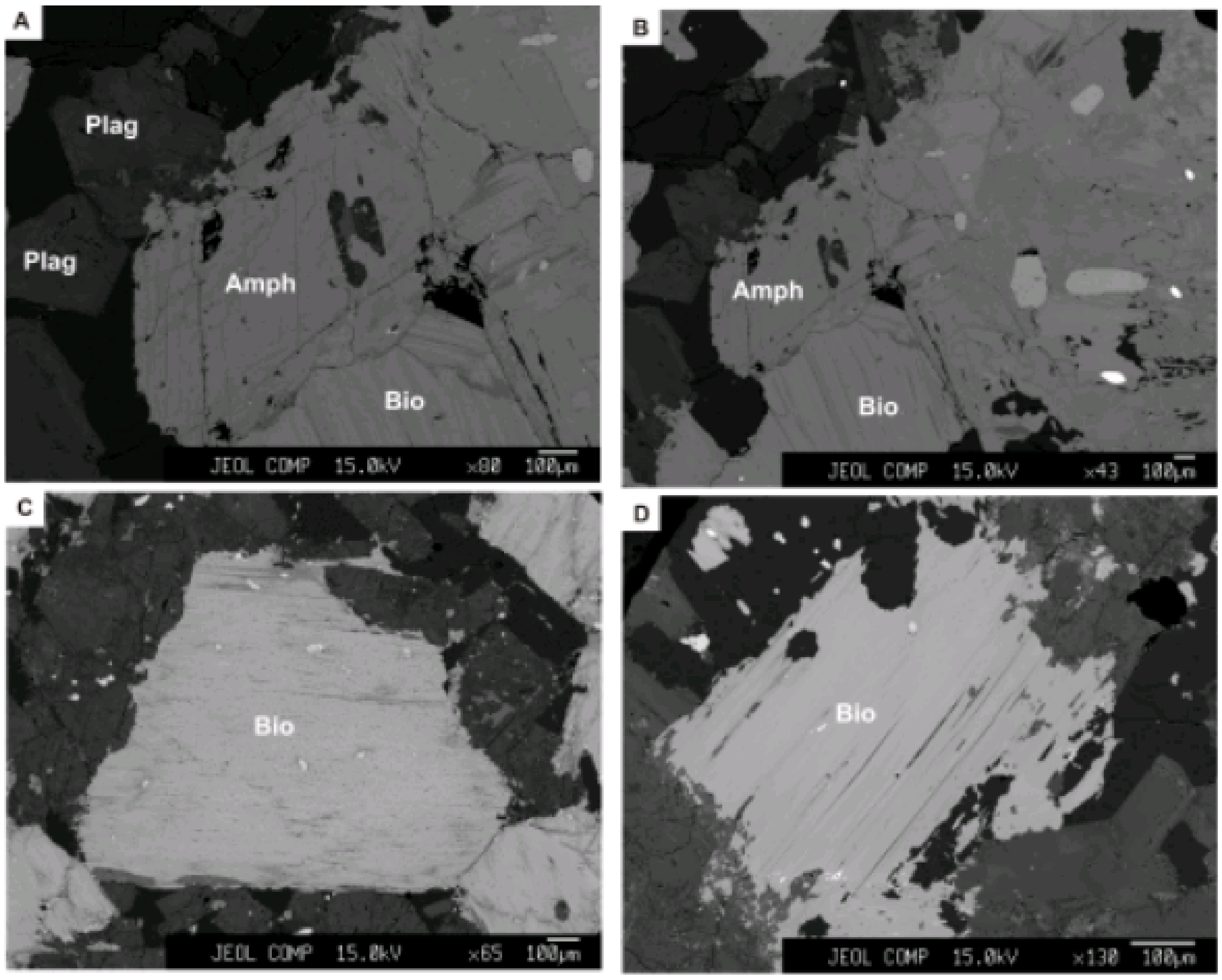

Fig. 4: Backscattered electron image (BSE) to representative samples, (A), (B), Amphibole, Plagioclase and Biotote in quartz- diorite, (C) Biotite in granodiorite and (D) Biotite in monzogranite

Based on the electron microprobe analysis, all amphibole are mainly magnesio-hornblende with a few actinolitic hornblendes on the (Si.P.f.u.) versus ($Mg/Mg^{+}Fe^{2+}$) (Fig. 4A). Amphiboles show (CaB> 1.5 (1.68-1.98), (Na+K) A<0.5 (0.03-0.29) and thus are calcic amphiboles occurring to Leake *et al*. (1997) classification (Fig. 5A), that usually in calc-alkaline granitoids.

Biotite: Biotite is the most abundant mafic mineral in the Boroujerd pluton and it is the only mafic silicate in the monzogranites. Electron microprobe analysis of selected biotites (Fig. 4C, D) are shown in Table 2. Electron micrpoprobe analysis of biotite mineral is a quick and easy method, allowing on this basis, the distinction between unaltered primary magmatic biotites and more or less reequilibrated, possibly neoformed ones by post-magmatic hydrothermal fluids. For use of the ternary diagram $10TiO_2$-FeO+MgO-MgO (Nachit *et al*., 2005) is a necessary preliminary to the typological study of granitoids based on the biotite chemistry. All the analyzed biotites of the Boroujerd pluton are primary magmatic biotites (Fig. 5B).

According to the revision of mica classification (Rieder *et al*., 1999) the Boroujerd micas plot in the biotite field, at low to medium FeO/FeO+MgO ratios (0.56-0.77), (Fig. 5C). The low Fe/Fe+Mg ratio in biotites is described by Czamanske and Wones (1973) as reflecting increasing FO_2 conditions during magmatic evolution. The alumina saturation index of biotite (Altot/Ca+Na+K, ASI) is significantly increase quartz-diorite to monzogranite (1.56 to 2.26) and reflected increased alumina activity in the crystallizing magma of each area (Zen, 1988).

Nachit *et al*. (1985) developed some diagrams for identification of biotites belonging to rocks of different magma series (Fig. 5D). In general, biotites in quartz-dioritic rocks have compositions similar to those of subalkaline series, granodiorite in calc-alkaline series and monzogranite in calc-alkaline series to aluminopotassic field. The most important feature to note the biotites is the presence of prehnite (parallel to biotite cleavage) compositions in Boroujerd granitoids (Fig. 3D, 4D).

Growth of prehnite within biotite is interpreted as a secondary process, probably as a result of deuteric reactions. The biotite is intergrowth with prehnite and is

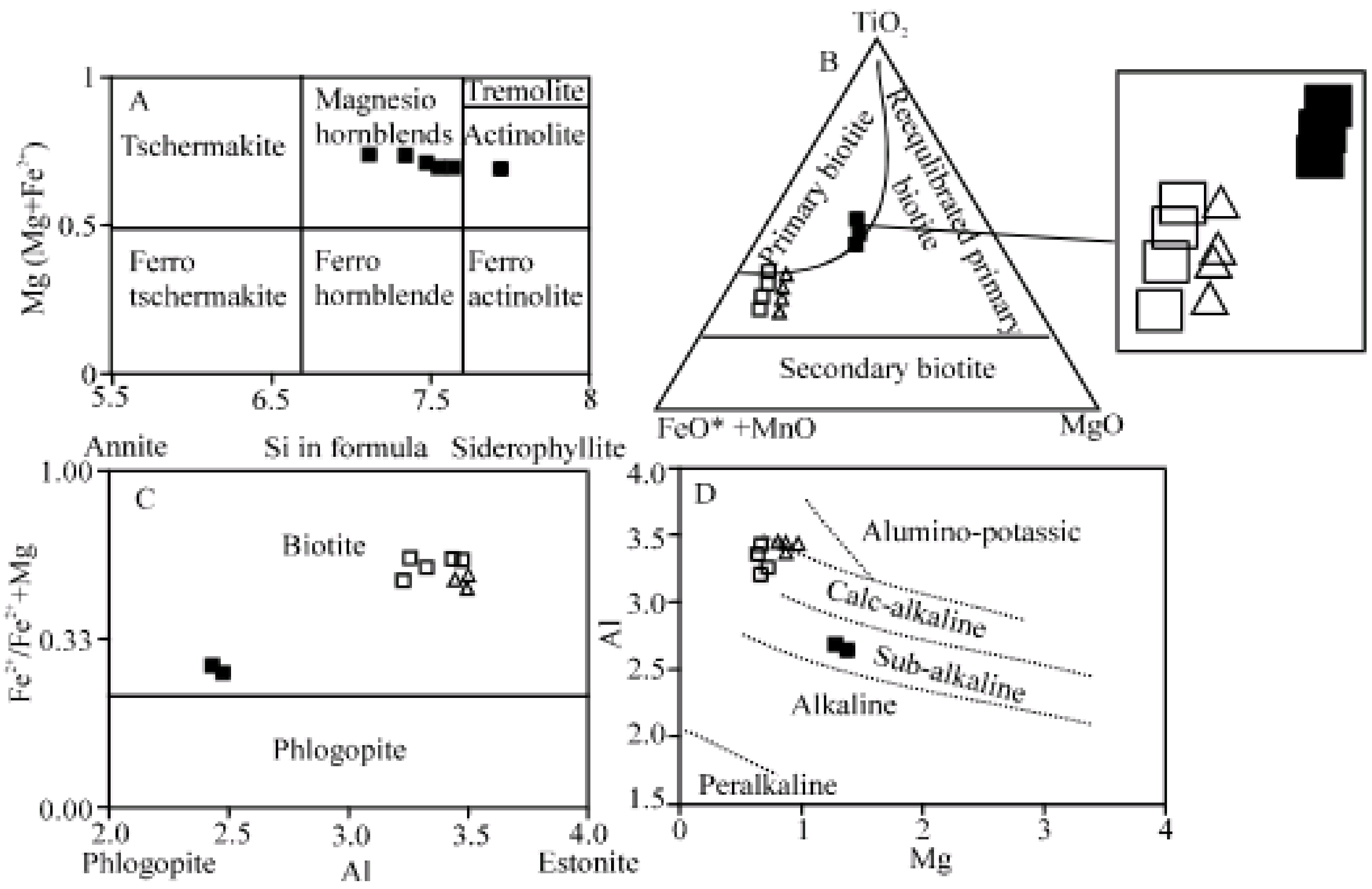

Fig. 5: (A) Classification of Amphibole in quartz-diorite according to Leake *et al.* (1997). Showing crystallization of magnesio-hornblende and actinolite in quartz-diorite, (B) The ternary diagram TiO_2-FeO*-MgO (Nachit *et al.*, 2005). Showing all biotites of the Boroujerd pluton are primary magmatic biotites, (C) The mica classification (Rieder *et al.*, 1999) for biotites of the Boroujerd pluton and (D) Total Al versus Mg diagram adapted from Nachit *et al.* (1985) for biotites of the Boroujerd pluton

partly altered to chlorite. Biotite cleavages and the margins of some crystals, locally bow around the pod like outline of the prehnite. About source of prehnite, Liou (1971) indicated that prehnite is unstable above 393°C at 5 Kbars; thus implies that a primary origin for prehnite in igneous rocks such as tonalites is unlikely. The possible reaction is (Phillips and Rickwood, 1975):

Biotite+labradorite+water = prehnite+sericite+albite+ magnetite+quartz

Feldspars: Locally plagioclase is oscillatory zoned in three main rock types of the Boroujerd pluton indicating probably disequilibrium melting in the generation of granitoid rocks (Castro, 2001). Plagioclase is the main mineral in the granodiorites, with the crystals occurring mainly as subhedral laths. Myrmekitic intergrowths with quartz are occasionally present in some granodiorites and monzogranites. Plagioclase generally appears as zoned crystals, often with a patchy core and overgrowths indicative of distinct crystallization periods. In the granodiorites, compositions span the whole andesine interval from An52 to An41, similar to the compositions in the quartz- diorites (An59 to An46). Alteration, mostly restricted to An-rich zones, is commonly to sericite, clay and saussuritic minerals. Plagioclase is less abundant in the monzogranites and shows less zonation than in the granodiorites. Compositions range from andesine to oligoclase (An48 to An26), partly straddling the compositions analyzed in the monzogranites. Representative analysis are given in Table 3.

Geothermobarometry hornblende and plagioclase: The recent application of Al (IV) and Al (tot) in hornblende, as both a geothermometer and geobarometer respectively, provides new information on the likely temperatures and pressures that exited during the emplacement of the granitic magma within the crust.

Wones (1989) suggested the chemical variability in amphiboles and also other mafic silicates to be potential indicators of intensive variables in granitic magmas.

None of the analyzed hornblendes are zoned, although only EPMA from amphibole rims were used for hornblende-plagioclase geothermometry. Al values for actinolitic-hornblende and actinolites were disregarded because of their probable post-magmatic nature. The primary phases of quartz, plagioclase feldspar, alkali feldspar, biotite, sphene and magnetite were present together with hornblende. Magnetite is a common mineral in the Boroujerd pluton. Many arc-related plutons crystallize at elevated FO_2 (magnetite series of Ishihara 1977), whereas anorogenic plutons are often emplaced at low FO_2 (Anderson, 1983). Low FO_2 decreases the Mg/Fe and Fe^{3+}/Fe^{2+}ratios in hornblende (Czamanske *et al.*, 1981). Generally it can be concluded, that hornblende crystallizing under high FO_2 gives better and more reliable geothermobarometry result than those growing under low FO_2 (Stein and Dietl, 2001).

Anderson and Smith (1995) concluded that temperature and, in particular, FO_2 are parameters that should be carefully evaluated before the application of a given geobarometer. The following considerations were made prior to the application of the Al-in-Hbl geobarometer to the analyzed rocks. The all of the magnesio-hornblende in quartz-diorites have Fe/ (Fe+Mg) <0.65, Si <7.5 and Ca> 1.6 (apfu). Thus there used for geobarometry (Hammarstrom and Zen, 1986).

There are several empirical Al-in-hornblende barometers that have been used to determine solidus pressures in calc-alkaline plutons (Hammarstrom and Zen, 1986; Holliste *et al*., 1987; Johnson and Rutherford, 1989). The most recent (Schmidt, 1992) was chosen in this study because of the smaller margin of error in the Eq:

$$P\ (\pm 0.6)\ \text{kbar} = -3.01 + 4.76\ \text{Al}\ (T)$$

where, P is in kbar and Al (T) is the total Al content of hornblende in atoms per formula unit.

From the all of the analyzed amphiboles of the Boroujerd pluton pressure is 1.09±0.6 kbars in quartz-diorites.

For estimation of temperature in above rocks, Blundy and Holland (1990) first proposed a very simple, empirical thermometer on the basis of the edenite-tremolite reaction; which could be applied only to quartz-bearing, intermediate to felsic igneous rocks with plagioclase An < 0.92 and Si in hornblende < 7.8 atoms pfu. In this study for calculation temperature we used Holland and Blundy (1994) following thermometer,

It now is:

$$T[\pm 40] = \frac{-76.95 + 0.79P[\text{kbar}] + Y_{ab} + 39.4X_{Na}^{A} + 22.4X_{K}^{A} + (41.5 - 2.89P[\text{kbar}])X_{Al}^{M2}}{-0.0650 - RLn[\frac{27X_{vac}^{A}X_{Si}^{T1}X_{Ab}^{Plag}}{256X_{Na}^{A}X_{Al}^{T1}}]}$$

where, T is expressed in °C, R= 0.0083144 kJ K^{-1} mol^{-1}, Yab = 0 for Xabplag > 0.5 or else Yab = 12.0(1-Xabplag) 2-3.0 kJ and various X terms (molar fractions) are defined in Holland and Blundy (1994). The estimated temperature is 785°C±40 in magnesio hornblende crystallized in quartz-diorite.

The approximate temperature of emplacement confirmed by the petrology of the hornfels zone that surrounds the Boroujerd pluton. Contact metamorphic rocks, consisting of spotted schists, cordierite-andalusite and cordierite-silimanite hornfelses.

Oxygen fugacity estimation: The oxygen fugacity of magma is related to its source material, which in turn depends on tectonic setting. Sedimentary-derived granitic magmas are usually reduced, while I-type granities are relatively oxidized. It is difficult to estimate the original oxygen fugacity of primary magmas from the study of granitoids, as magnetite usually becomes Ti free during slow cooling and ilmenite undergoes one or more stages or oxidation and exsolution (Haggerty, 1976). However, some inferences on the oxidation state of magma can be made using the rock mineral assemblage and mineral chemistry. The occurrence of magnesio-hornblende and Fe^{2+} biotite in Boroujerd rocks suggest relatively oxidized magma.

According to Wones (1989) the assemblages of titanite+magnetite+quartz in granitic rocks permit an estimation of relative oxygen fugacity. He made quantitative estimation of fugacity based on the equilibrium expression.

$$\text{Log}\ FO_2 = -30930/T + 14.98 + 0.142\ (P-1)/T$$

where, T is temperature (in Kelvin) and P is pressure (in bars). We used this equilibrium expression to estimate the prevailing oxygen fugacity in the Boroujerd pluton.

Temperature and pressure estimated from hornblende -plagioclase thermometry and aluminum in hornblende barometer were used in these calculations. Quartz-diorites analyzed have log FO_2-14.1 that show that magma crystallized in high FO_2.

DISCUSSION

The Boroujerd granitoids include quartz diorite, granodiorite and monzogranite. They cut by numerous acidic dikes. So, the Boroujerd granitoids consist of two different suites (types); a monzogranitic (more felsic, leucocratic type) and a quartz-dioritic to granodioritic (more mafic or mesocratic type).Whereas the mesocratic type occurs as an ellipsoid large intrusion and form elongated SE-NW trending complexes, leucocratic type as small intrusions show round shapes suggesting a change in the crustal stress field.

The results of microprobe analysis in different rocks and their minerals indicate that Boroujerd pluton have a metaluminous and slightly peraluminous character and I-type magma. The based on analyzed biotite and magnesio-hornblende, this pluton has calc-alkaline magma.

Coexisting mineral phases and their compositions from the granitoid rocks of Boroujerd in Sanandaj-Sirjan Zone were used to estimate the physicochemical parameters of their crystallizing parent magma. The samples contain the suitable assemblage for Al-in hornblende barometry (Hbl-Pl-Qtz-Kfs-Ttn-Fe, Ti oxide).

The aluminum in hornblende barometer, hornblende-plagioclase thermometer and estimation of FO_2, were used to calculate pressure, temperature and oxygen fugacity, respectively. The pressure and temperature is 1.093±0.6 kbars and 785°C±40 in quartz-diorites respectively. The analyzed samples have log FO_2-14.1 that show this magma crystallized in high FO_2 and related to arc-magmatism.

ACKNOWLEDGMENTS

M. Mirmohammadi is thanked for his assistance in determination some mineral compositions at the University of Hamburg (institute mineralogy and petrology), Germany. The mineral chemical study was carried out in the University of Huelva (Spain) during a study leave of Z.T.

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