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Thermobarometry of the Astaneh Pluton and its Related Subvolcanic Rocks (Sanandaj-Sirjan Zone, Western Iran)

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Abstract: The Astaneh area belongs to the Sanandaj-Sirjan Zone (SSZ) in Western Iran. The igneous rocks in this area consist of tonalite, granodiorite, monzogranite and subvolcanic rocks (rhyodacites). 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 of minimum pressure is estimated at 1.37 kbars in tonalites whereas the maximum pressure is 6.58 kbars in pargasite in dacitic enclaves. The maximum temperature is 767°C in pargasitic amphibole crystallized in dacitic enclave whereas the minimum temperature is 650°C in tonalite. All analyzed samples have log fO_2 in the range between -13 (in dacitic enclave) to -18.3 (in tonalite) and -15 (in tonalitic enclave), respectively, which show this magma crystallized in high fO_2. The presence of phenocrysts of plagioclase (An = 80-90) together with plagioclase (An = 35-40), pargasitic amphibole in dacitic enclave and oscillatory zoned plagioclase in rhyodacites might be accounted for by a magma mixing model in the subvolcanics of Astaneh.

Key words: Sanandaj-Sirjan zone, I-type granite, metaluminous, calc-alkaline

INTRODUCTION

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

Berberian (1983) considered this zone as a Mesozoic magmatic arc and a Tertiary fore-arc. 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 Astaneh 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 *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 observed field relationships of the Astaneh 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. The analyses 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 feldspar and hornblende are shown in Table 1 and 2.

RESULTS AND DISCUSSION

Geological setting: The Astaneh pluton is a NNW-SSE trending body covering an area of 30 km^2, approximately 10 km in length and 3 km in width, which lies between 33°30'-34° N and between 49°15'-49°, 25' E (Fig. 1b).The

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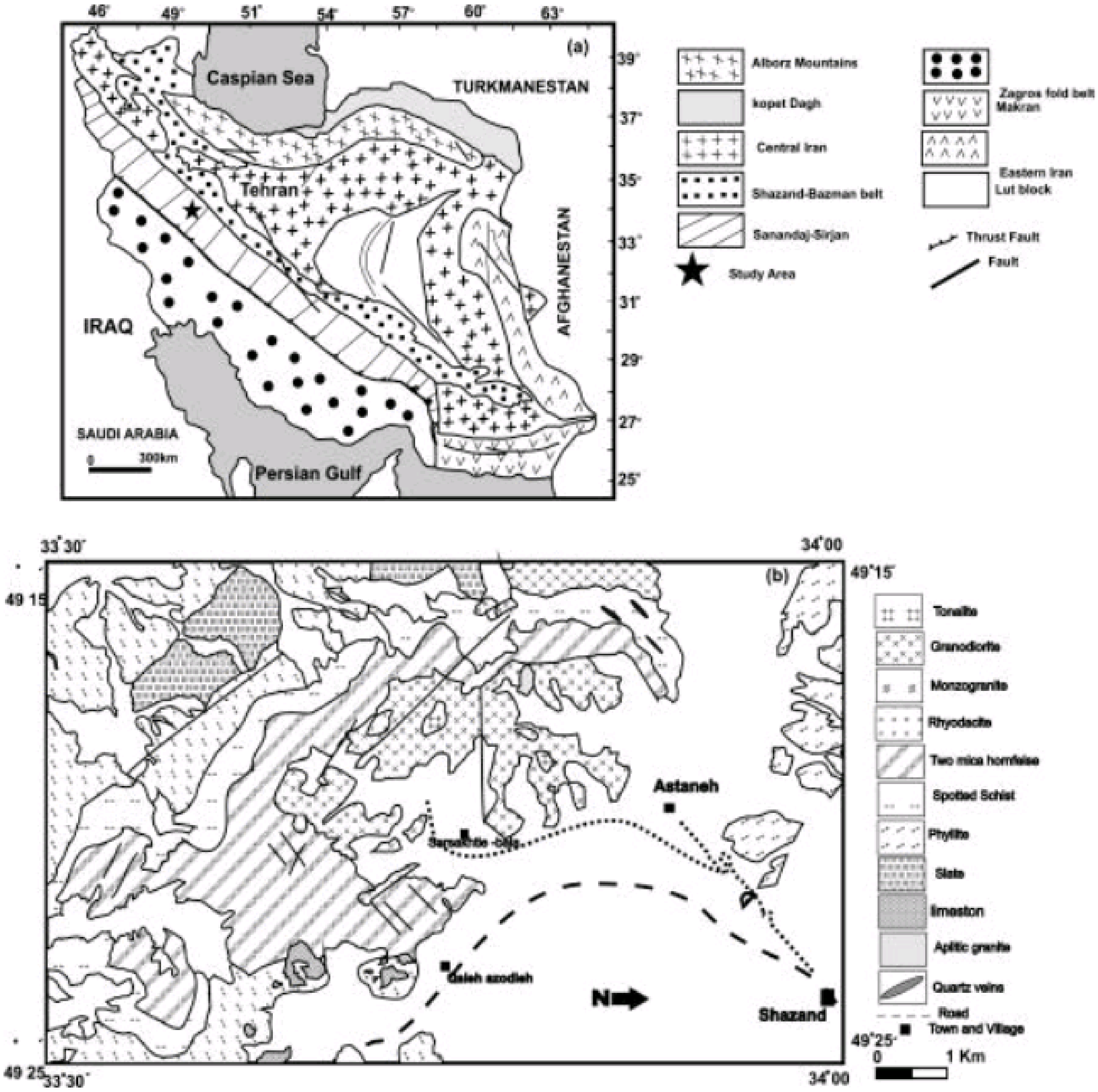

Fig. 1: (a) Geological map of Iran (Shahabpour, 1994), showing major lithotectonic units and (b) the Astaneh area, Western Iran

Astaneh area is characterized by the predominance of metamorphic rocks of Jurassic age (Baharifar *et al*., 2004) and the presence of the Astaneh pluton. Metamorphic rocks subdivided in to 2 groups based on their setting: Dynamothermal and Contact. Dynamotermal metamorphism has affected a vast area which is composed of slate, phyllite and schist (Ahmadi *et al*., 2007). By the injection of the Astaneh pluton, a contact metamorphic aureole developed which can be assigned to the albite-epidote facies. Contact metamorphism rocks consist of spotted schist and hornfelses (Ahmadi *et al*., 2007). U-Pb zircon geochronological data from Astaneh granitoid rocks indicate episode of magmatic activity 170 Ma ago during the middle Jurassic (Ahmadi *et al*., 2007) while Masoudi (1997) has earlier described them to the upper Cretaceous (about 99Ma) time. The compositional variation found in this major pluton, usually range from quartz-diorite-tonalite to monzogranite and subvolcanic rocks to rhyodacite composition. However, tonalite and more basic rocks are included large xenoliths in this pluton. A very common feature of Sanandaj-Sirjan zone granitic type is conspicuous presence of mafic microgranular enclave dispersed, especially in the granodiorites and monzogranites of Astaneh. The granitoids occurring in Astaneh show close similarities with those described elsewhere in the Sanandaj-Sirjan zone, exceptionally occurrence subvolcanic rocks in Astaneh. In general, mineral assemblage in Astaneh pluton and its related subvolcanic is same to other calc-alkaline granites in Sanadaj-Sirjan zone.

Table 1: Representative electron microprobe analysis of amphibole in granodiorite, monzogranite, tonalite, dacitic enclave and mafic microgranular enclave (MME, tonalite) from Astaneh pluton (No. of ions on the basis of 23 oxygen)

	Actinolite in granodiorite and monzogranite					Magnesio-hornblende in tonalite										
Samples	As5-1	As5-3	As5-5	As5-7	As-5-9	4	6	9	11	14	15	16	EK-1	EK-2	EK-3	EK-4
SiO_2	50.4	51.9	50.0	51.3	51.5	49.8	49.5	49.8	49.5	49.9	49.6	49.9	49.5	49.3	48.7	48.6
TiO_2	0.3	0.1	0.5	0.2	0.2	0.5	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.4	0.5	0.6
Al_2O_3	4.5	3.1	4.6	3.9	4.1	4.6	4.6	4.3	4.6	4.5	4.0	5.0	4.6	4.2	5.1	5.1
FeO*	16.1	15.1	16.1	15.8	15.6	14.3	14.4	14.2	14.5	14.2	14.3	14.6	15.7	15.5	15.9	16.1
MgO	13.0	13.3	12.6	13.0	12.6	14.4	14.7	14.3	14.3	14.5	14.5	14.5	13.9	14.1	13.2	13.3
MnO	0.5	0.6	0.7	0.0	0.6	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
CaO	10.4	11.5	10.9	10.9	11.4	11.2	11.0	11.3	11.1	11.2	11.1	11.1	10.8	10.8	10.8	10.9
Na_2O	0.6	0.3	0.5	0.4	0.4	0.6	0.7	0.6	0.6	0.5	0.5	0.7	0.7	0.7	0.8	0.8
K_2O	0.3	0.2	0.4	0.2	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.5
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	96.3	96.2	96.4	96.5	96.9	96.1	96.3	96.0	96.1	96.3	95.3	97.0	96.5	95.9	95.9	96.4
T-sites																
Si	7.5	7.7	7.5	7.6	7.6	7.4	7.4	7.4	7.4	7.4	7.4	7.3	7.4	7.4	7.3	7.3
Aliv	0.5	0.3	0.5	0.4	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6	0.7	0.7
Al (total)	0.8	0.5	0.8	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.9	0.8	0.7	0.9	0.9
M1, 2, 3 sites																
Alvi	0.3	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2
Ti	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1
Fe^{3+}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mg	2.9	2.9	2.8	2.9	2.8	3.2	3.3	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.0	3.0
Mn	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe^{2+}	1.7	1.7	1.8	1.8	1.8	1.5	1.5	1.6	1.5	1.5	1.5	1.5	1.6	1.6	1.7	1.7
Ca	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
M4 site																
Fe	0.3	0.1	0.2	0.2	0.1	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ca	1.7	1.8	1.7	1.7	1.8	1.8	1.7	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Na	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
A site																
Ca	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0
Na	0.1	0.0	0.1	0.0	0.0	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2
K	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sum A	0.2	0.1	0.2	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4
Fe/Fe+Mg	0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6
$Mg/Mg+Fe^{2+}$	0.6	0.6	0.6	0.6	0.6	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4

	Magnesio hornblend in tonalitic enclave												
Samples	11	13	15	17	19	21	23	25	28	30	31	33	35
SiO_2	47.74	47.76	47.26	47.59	47.87	47.62	47.31	47.96	47.43	48.13	47.10	47.36	47.10
TiO_2	1.32	1.37	1.38	1.30	1.27	1.35	1.36	1.38	1.41	1.29	1.40	1.47	1.44
Al_2O_3	6.83	6.59	6.94	6.78	6.70	6.84	7.02	6.38	6.89	6.66	6.86	7.15	7.14
FeO*	15.21	15.64	15.35	15.06	14.93	15.58	15.03	15.51	15.42	14.77	15.80	14.97	15.30
MgO	12.31	12.28	12.23	12.50	12.51	12.48	12.15	12.55	12.46	12.77	12.39	12.49	12.11
MnO	0.28	0.29	0.29	0.33	0.35	0.31	0.25	0.27	0.29	0.32	0.23	0.27	0.26
CaO	11.08	11.10	11.11	11.06	11.13	11.06	11.37	11.07	10.87	11.17	10.92	10.88	11.20
Na_2O	0.61	0.60	0.67	0.49	0.59	0.62	0.60	0.59	0.78	0.65	0.52	0.65	0.65
K_2O	0.48	0.50	0.58	0.50	0.50	0.59	0.53	0.50	0.60	0.47	0.58	0.56	0.51
F	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
Cl	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
Sum	96.01	96.21	95.89	95.69	96.02	96.58	95.65	96.34	96.33	96.28	95.90	95.85	95.90
T-sites													
Si	7.15	7.15	7.10	7.14	7.16	7.11	7.11	7.17	7.10	7.16	7.09	7.09	7.08
Aliv	0.85	0.85	0.90	0.86	0.84	0.89	0.89	0.83	0.90	0.84	0.91	0.91	0.92
Al (total)	1.21	1.16	1.23	1.20	1.18	1.20	1.24	1.12	1.22	1.17	1.22	1.26	1.27
M1, 2, 3 sites													
Alvi	0.35	0.31	0.33	0.34	0.34	0.31	0.35	0.29	0.32	0.33	0.30	0.35	0.34
Ti	0.15	0.15	0.16	0.15	0.14	0.15	0.15	0.16	0.16	0.14	0.16	0.17	0.16
Fe^{3+}	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
Mg	2.75	2.74	2.74	2.79	2.79	2.78	2.72	2.80	2.78	2.83	2.78	2.79	2.71
Mn	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.03
Fe^{2+}	1.71	1.76	1.74	1.68	1.68	1.72	1.74	1.73	1.71	1.65	1.73	1.66	1.75
Ca	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
	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

Table 1: Continued

	Magnesio hornblend in tonalitic enclave												
Samples	11	13	15	17	19	21	23	25	28	30	31	33	35
M4 site													
Fe	0.19	0.20	0.19	0.21	0.19	0.22	0.15	0.21	0.22	0.19	0.26	0.22	0.18
Ca	1.78	1.78	1.79	1.78	1.78	1.77	1.83	1.77	1.74	1.78	1.74	1.75	1.80
Na	0.03	0.02	0.02	0.01	0.03	0.01	0.02	0.02	0.04	0.03	0.00	0.04	0.02
	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
A site													
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
Na	0.14	0.15	0.17	0.14	0.14	0.17	0.15	0.15	0.19	0.16	0.15	0.15	0.17
K	0.09	0.10	0.11	0.09	0.09	0.11	0.10	0.10	0.11	0.09	0.11	0.11	0.10
Sum A	0.23	0.25	0.28	0.23	0.24	0.29	0.25	0.25	0.31	0.25	0.28	0.26	0.27
Mg/(Mg+Fe)	0.62	0.61	0.61	0.63	0.62	0.62	0.61	0.62	0.62	0.63	0.62	0.63	0.61
Fe/Fe+Mg	0.41	0.42	0.41	0.40	0.40	0.41	0.41	0.41	0.41	0.39	0.42	0.40	0.41

	Pargasite in dacitic enclave									
Samples	AE-38-30	AE-38-32	AE-38-34	AE-38-40	AE-38-44	AE-38-45	AE-38-79	AE-38-80	E-38-15	E-38-16
SiO_2	42.31	43.42	41.51	41.70	42.12	42.24	42.37	42.50	42.59	41.74
TiO_2	3.27	2.67	2.98	3.32	3.29	3.20	3.06	3.18	3.24	2.73
Al_2O_3	11.83	11.02	11.36	11.55	11.58	11.57	11.53	11.50	11.95	11.27
FeO*	10.36	11.77	16.80	11.78	13.37	11.81	10.67	10.95	10.44	16.21
MgO	15.27	14.35	10.37	14.00	12.89	14.02	15.08	14.39	14.38	10.35
MnO	0.14	0.22	0.22	0.19	0.17	0.19	0.16	0.14	0.15	0.30
CaO	11.33	11.01	11.15	11.19	11.27	11.31	11.24	11.24	11.25	11.48
Na_2O	2.40	2.41	2.28	2.71	2.39	2.34	2.52	2.61	2.56	2.08
K_2O	0.64	0.49	0.65	0.62	0.63	0.62	0.63	0.63	0.59	0.76
F	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	98.42	97.76	97.74	97.59	98.17	97.95	97.98	97.84	98.04	97.54
T-sites										
Si	6.20	6.39	6.29	6.20	6.25	6.25	6.24	6.27	6.26	6.34
Aliv	1.80	1.61	1.71	1.80	1.75	1.75	1.76	1.73	1.74	1.66
Al (total)	2.05	1.91	2.03	2.02	2.03	2.02	2.00	2.00	2.07	2.02
M1, 2, 3 sites										
Alvi	0.25	0.31	0.32	0.22	0.28	0.27	0.24	0.27	0.34	0.35
Ti	0.36	0.30	0.34	0.37	0.37	0.36	0.34	0.35	0.36	0.31
Fe^{3+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	3.34	3.15	2.34	3.10	2.85	3.09	3.31	3.17	3.15	2.34
Mn	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.04
Fe^{2+}	1.04	1.22	1.98	1.28	1.48	1.26	1.09	1.19	1.13	1.96
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
M4 site										
Fe	0.23	0.23	0.15	0.19	0.17	0.20	0.23	0.16	0.15	0.10
Ca	1.77	1.74	1.81	1.78	1.79	1.79	1.77	1.78	1.77	1.87
Na	0.00	0.04	0.04	0.03	0.03	0.01	0.00	0.06	0.08	0.03
	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
A site										
Ca	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.68	0.65	0.63	0.75	0.65	0.66	0.72	0.69	0.65	0.58
K	0.12	0.09	0.13	0.12	0.12	0.12	0.12	0.12	0.11	0.15
Sum A	0.81	0.75	0.76	0.87	0.77	0.78	0.84	0.81	0.76	0.72
(Na+K)A	0.80	0.75	0.76	0.87	0.77	0.78	0.84	0.81	0.76	0.72
Fe/Fe+Mg	0.28	0.32	0.48	0.32	0.37	0.32	0.28	0.30	0.29	0.47
Mg/Mg+Fe^{2+}	0.76	0.72	0.54	0.71	0.66	0.71	0.75	0.73	0.74	0.54

Field description and petrography: Astaneh granitoids include quartz-diorite-tonalite, granodiorite, monzogranite and a small apophys-like body of semicircular morphology (maximum length 2 km), outcrops NW of study area. The granodiorite is the most dominant rock in this pluton.

Quartz-diorite and tonalite: The quartz-diorite and tonalite are exposed within the granodiorite and have gradual boundaries with them. These rocks have granular texture to porphyritic with plagioclase megacrysts and composed predominantly of plagioclase (40-45 vol. %), amphibole (5-10 vol. %), biotite (10-15 vol. %), alkali feldspar (<5 vol. %), quartz (15-20 vol. %) and in one sample Orthopyroxene (En = 50-64), replaced to anthophyllite in rim (Fig. 2a). Plagioclase is anhedral to subhedral plates, zoned and altered to sericite, epidote

Table 2: Representative electron microprobe analyses of plagioclase in dacitic enclave (phenocryst and matrix), tonalitic enclave, tonalite and granodiorite from Astaneh pluton (No. of ions on the basis of 8 oxygen)

Samples	Plagioclase in granodiorite			Plagioclase in tonalitic enclave			Plagioclase in tonalite			Plagioclase in rhyodacite			Plagioclase in dacitic matrix		Plagioclase in Phenocryst dacite		
SiO_2	54.5	54.4	56.8	53.3	52.5	52.3	58.3	57.6	58.1	58.9	61.8	63.1	61.6	61.6	46.8	46.9	47.2
TiO_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1
Al_2O_3	29.1	28.7	27.1	28.7	29.5	29.6	26.0	26.3	25.9	25.5	24.0	22.9	23.6	23.8	33.3	33.4	33.1
Cr_2O_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0
FeO	0.1	0.2	0.1	0.0	0.1	0.2	0.2	0.2	0.3	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.2
MnO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MgO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CaO	10.5	10.4	8.6	11.1	11.9	12.3	8.0	8.5	7.8	6.9	4.9	3.7	4.5	4.7	16.1	16.3	16.2
Na_2O	5.5	5.6	6.6	5.3	4.6	4.7	7.1	6.6	6.8	7.0	8.4	9.2	9.3	9.1	2.4	2.2	2.3
K_2O	0.1	0.1	0.3	0.1	0.1	0.0	0.1	0.1	0.1	0.5	0.3	0.2	0.2	0.2	0.1	0.1	0.1
NiO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	99.4	99.6	98.6	98.7	99.3	99.7	99.4	99.4	99.0	99.7	99.2	99.5	99.6	99.4	99.5	99.3
Cations based on 8 oxygen																	
Si	2.5	2.5	2.6	2.4	2.4	2.4	2.6	2.6	2.6	2.7	2.8	2.8	2.8	2.7	2.2	2.2	2.2
Al	1.5	1.5	1.4	1.6	1.6	1.6	1.4	1.4	1.4	1.4	1.3	1.2	1.2	1.3	1.8	1.8	1.8
Ti	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe^{++}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mn	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ni	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ca	0.5	0.5	0.4	0.5	0.6	0.6	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.8	0.8	0.8
Na	0.5	0.5	0.6	0.5	0.4	0.4	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.2	0.2	0.2
K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Xab	0.5	0.5	0.6	0.5	0.4	0.4	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.2	0.2	0.2
XAn	0.5	0.5	0.4	0.5	0.6	0.6	0.4	0.4	0.4	0.3	0.2	0.2	0.2	0.2	0.8	0.8	0.8
Xor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

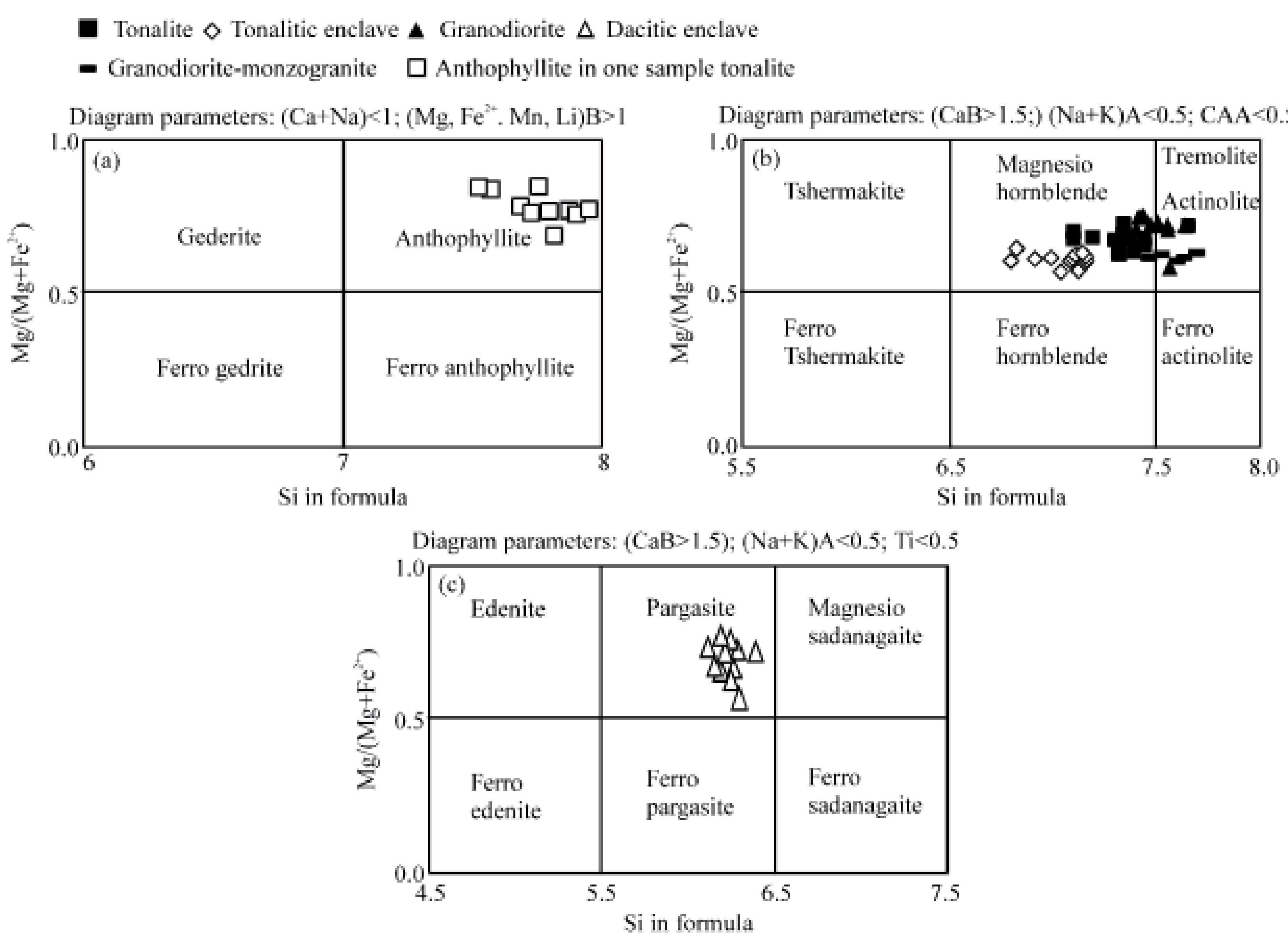

Fig. 2: Classification of Amphibole in tonalite, granodiorite, monzogranite, tonalitic and dacitic enclaves in Astaneh pluton according to Leake *et al*. (1997). Showing crystallization of magnesio-hornblende in tonalite and tonalitic enclave, magnesio-hornblende-actinolite in granodiorite and monzogranite; pargasite in dacitic enclave and anthophyllite in rim of orthopyroxene in one sample tonalite and dacitic enclave

and calcite. Biotite occurs as brown kinking flakes and altered to chlorite. Amphibole shows a euhedral prismatic habit, green colour and altered to biotite, chlorite, epidote and prehnite (Fig. 2a-c). 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 hypidiomorphic texture. The main minerals are plagioclase, (30-40 vol. %), that usually euhedral, more or less with variable degrees of sericitisation, shows zoning and the first felsic mineral to crystallize. K-feldspar (<10 vol. %) forms anhedral to subhedral crystals and includes microcline-perthites. Quartz (25-30 vol. %) forms anhedral crystals. Amphibole (5-10 vol. %), shows a euhedral prismatic habit, green colour and altered to biotite, chlorite, epidote and prehnite. Biotite, the most abundant mafic mineral (5-15 vol. %) appears in brown flakes. Apatite and the less abundant zircon and allanite occur in all samples.

Monzogranite: The monzogranites are exposed within the granodiorites and have gradual boundaries with them. The mineral assemblages include perthitic alkali feldspar (20-25 vol. %), plagioclase (15-25 vol. %), quartz (30-35 vol. %), biotite (7-10 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. Euhedral zircon may be considered as magmatic zircons as opposed to anhedral ones which can be partially melted restitic crystals (Pitcher, 1993).

Rhyodacite pluton: The subvolcanic rocks (rhyodacites) show a considerable range of colours, varying from gray to dark gray.

In these rocks, quartz, plagioclase and biotite occurs as phenocrysts in a seriate texture. Normal alteration is to aggregates of chlorite, opaque minerals and epidote.

These rocks contain numerous dacitic xenoliths that show phenocrysts of pargasitic amphibole to CaB>1.5 (1.71-1.77), (Na+K) A>0.5 (0.55-0.7) (Fig. 2b), plagioclase and biotite.

MINERAL CHEMISTRY

Amphibole: Representative major elements EPMA of unaltered magmatic hornblende from Astaneh pluton is shown 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.

Based on the electron microprobe analyses, four different types of amphibole are identified in the Astaneh plutonic and its related subvolcanic rocks: 1. magnesio-hornblende in tonalite and tonalitic enclaves, 2. Actinolite in granodiorite to monzogranite, 3. pargasite in dacitic enclave and 4. Anthophyllite formed by orthopyroxene in tonalitic and dacitic samples.

All amphibole (except two sample of anthophyllite) are mainly magnesio-hornblende with a few actinolitic hornblends on the (Si. P. f.u.) Versus ($Mg/Mg+Fe^{2+}$). Amphiboles show (CaB> 1.5 (1.7- 1.85), (Na+K) A <0.5 (0.12-0.25) and thus are calcic amphiboles occurring to Leake *et al*. (1997) classification (Fig. 3), that usually in calc-alkaline granitoids.

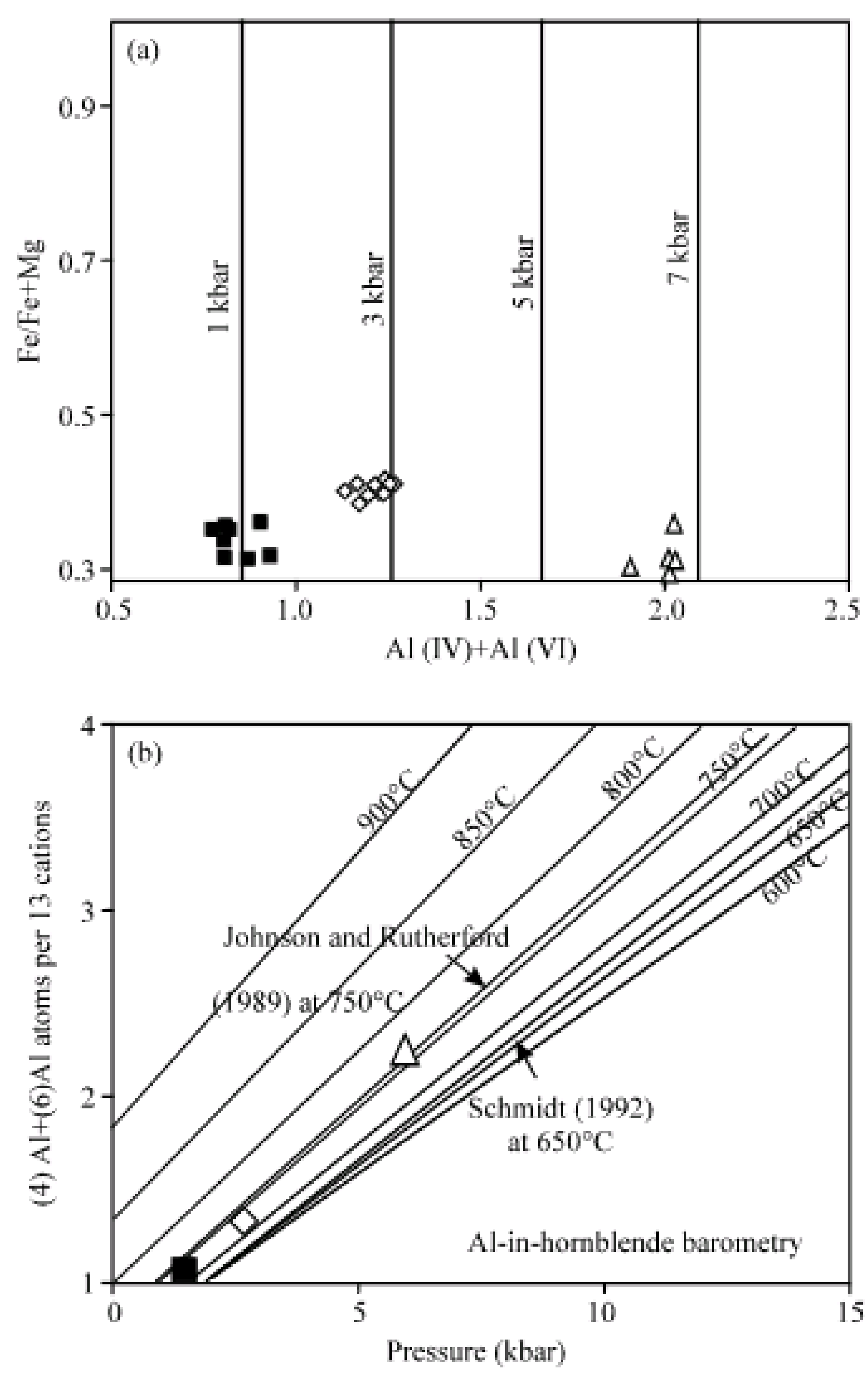

Fig. 3: (a): Fe/ (Fe + Mg) vs. (4) Al + (6) Al. Isobars are based on the calibration of Schmidt (1992). (b): Graphical expression of revised Al in hornblende barometer calibration. The calibrations of Johnson and Rutherford (1989) and Schmidt (1992) are shown for comparison

The most important feature to note the amphiboles is the presence of pargasitic composition in Astaneh dacitic enclaves. Pargasitic amphibole is more typical of andesitic, basaltic-andesitic and basaltic magmas than to dacitic magmas. Presence of pargasite and magnesio-hornblende compositions in volcanic rocks has been interpreted by researchers as result of mixing between basaltic and rhyolitic magma (Nakada, 1991).

Feldspars: Plagioclase in dacitic enclave commonly shows a strong zonation, most of the compositions range from An 23 to An 75. High Ca cores (An 75) are observed in some samples. Because the calcic plagioclase is unlikely crystallize entirely from surrounding Ca-poor matrix, the andesitic to bytownitic cores may be derived from an external origin such as basaltic to andesitic magmas. They (plagioclase in matrix) generally show SiO_2 (51.72-57.5), Al_2O_3 (25.2-29.55), Na_2O (5.23-8.66), CaO (5.4-11.96) and K_2O (<1.0) contents (Table 2).

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. 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. We also ensured that 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 Astaneh 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) conclude 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 enclaves (except some analyzed points), tonalites and pargasite in dacitic enclave 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; Hollister *et al*., 1987; Johanson and Rutherford, 1989). The most recent (Schmidt, 1992) was chosen in this study because of the smaller margin of error in the equation:

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

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 Astaneh pluton and related subvolcanic rocks (dacitic enclave), the minimum pressure is estimated at 1.78±0.6 kbars in tonalitie whereas the maximum pressure is 6.58±0.6 kbars in pargasite in dacitic enclave and 2.75± 0.6 kbars in tonalitic enclave.

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 [±313] = {79.44+Yab-an −33.6XNaM4−(66.8−2.92P [kbar]) XAlM2+78.5XAlT1+9.4XNaA}/0.0721-RLn [(27XNaM4XSiT1XAnplg)/(64XCaM4XAlT1 XAbplg)]

where, T is expressed in °C, R = 0.0083144 kJ/K/mol, Yab = 0 for Xabplag >0.5 or else

XalT1	=	(8-Si)/4
XalM2	=	(Al+Si-8)/2
XKA	=	K
XvacA	=	3-Ca-Na-K-Cm
XnaA	=	$Ca+Na+Cm^{-2}$
XnaM4	=	(2-Ca-Cm)/2
XcaM4	=	Ca/2
Cm	=	$Si+Al+Ti+Fe^{3+}+Fe^{2+}+Yab$ = 12.0 (1-Xabplag) 2-3.0 kJ and various X terms (molar fractions) are defined by Holland and Blundy (1994)

The maximum temperature is 767°C in pargasitic amphibole crystallized in dacitic enclave, minimum temperature is 708°C in the tonalites and in the tonalitic enclave intermediate between the dacitic enclave and tonalite. Magnesio-hornblende in tonalitic enclave crystallized in 734°C. Indeed according to diagram of

Fe/(Fe+Mg) versus (4) Al+(6) Al (Schmidt, 1992), (Fig. 3a) pargasite in dacitic enclave crystallized in higher pressure than magnesio- hornblende in tonalitic enclave and tonalite. For calculation of temperature we have utilized calibrations of Johanson and Rutherford (1989) and Schmidt (1992) (Fig. 3b). The Johanson and Rutherford (1989) and Schmidt (1992) calibrations are p = 4.23 Altot- 3.46 and p = 4.76Altot-3.01, respectively. In this study, pargasite in dacitic enclave crystallized between 750-770°C, magnesio hornblende in tonalitic enclave 700-720°C and in tonalite 630-660°C, respectively.

The approximate temperature of emplacement confirmed by the petrology of the hornfels zone that surrounds the pluton and its subvolcanic zone. The mineral assemblages in contact metamorphism of granodiorites and tonalites are albite-epidote hornfels but in the subvolcanic rocks by noted to occurrence mineral assemblage corundum and spinel in its hornfels may be in accommodate to higher temperature.

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 Mg-rich pargasitic, magnesio-hornblende and Fe^{2+} biotite in Astaneh 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. Wones (1989) 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.

In this study, used equilibrium expression to estimate the prevailing oxygen fugacity in the Astaneh pluton.

Temperature and pressure estimated from hornblende-plagioclase thermometry and aluminum in hornblende barometer were used in these calculations. The all of the sample analyzed have $\log fO_2$ in limitation between -13 (in dacitic enclave), -18.3 (in tonalite) and -15 bars (in tonalitic enclave) that show that magma crystallized in high fO_2.

CONCLUSIONS

The igneous rocks in the Astaneh area consist of tonalite, granodiorite, monzogranite and subvolcanic rocks (rhyodacites). The results of microprobe analysis in different rocks and their minerals indicate that Astaneh pluton and its related subvolcanic rocks 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 Astaneh 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 minimum pressure is 1.37 kbars in tonalites whereas the maximum pressure is 6.58 kbars in dacitic enclaves. The maximum temperature is 767°C in dacitic enclave, whereas the minimum temperature is 608°C in tonalites. The analyzed samples have $\log fO_2$ in limitation between -13 to -18.3 that show this magma crystallized in high fO_2 and related to arc-magmatism.

The presence of plagioclase with two distinct compositional range (An = 80-90) and (An = 35-40), pargasitic amphibole in dacitic enclave and oscillatory zoned plagioclase in rhyodacites would account for magma mixing model in the subvolcanics of the Astaneh pluton.

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