Journal of Tethys: Vol. 2, No. 1, 055–069 *ISSN: 2345–2471 ©2014*

Magmatic evolution recorded by phenocrysts in volcanic rocks southeast of Isfahan

Moussa Noghreyan[1], Mahnaz Khodami[2]*

1- University of Isfahan, Isfahan, Iran
2- Yazd University, Yazd, Iran

* Corresponding Author: Khodami_m@Yahoo.com

Received: 16 December 2013 / Accepted: 21 February 2014 / Published online: 01 March 2014

Abstract

Late Miocene–Pliocene calc-alkaline volcanic rocks are exposed southeast of Isfahan in the Urumieh-Dokhtar magmatic belt. Volcanic rocks consist of lava flows and domes, chiefly basaltic andesites, andesites and dacites. Minerals in the volcanic rocks exhibit degrees of disequilibrium features. Plagioclase as dominant mineral in these rocks generally displays reverse and oscillatory zoning; sieve or dusty and clear populations, cores are unusually Ca-rich. Hornblende and biotitephenocrysts have reaction rims indicating disequilibrium growth during late stage crystallization. Quartz phenocrysts are corroded and embayed and a few show augite reaction rims. Criteria such as: a) development of sieve textures in plagioclase b) reaction rims in mafic minerals c) reverse zoning and heterogeneity of plagioclase rims d) the resorbed and embayed phenocrysts; support magma mixing as an important process in the evolution of these rocks.

Keywords: Volcanic Rocks, Magmatic Evolution, Mineral Chemistry, Magma Mixing.

1–Introduction

The studied area is located in130 km southeast of Isfahan city and belongs to Urumieh-Dokhtar Magmatic Belt (UDMB) in Iran Central structural zone. This magmatic belt is interpreted as a result of collision between the Eurasian and Arabian plates. Most of the Magmatic activities in the UDMB began in the Eocene and continued in Middle Eocene until Plio-Quaternary that includes varieties of igneous rocks (Berberian andBerberian, 1981; Hassanzadeh, 1993; Ghasemi and Talbot, 2006) and are generally represented by calc-alkaline rocks. The post-Miocene calc-alkaline volcanic rocks in the studied area are post-collision volcanism in Urumieh-Dokhtar magmatic belt (Berberian and Berberian, 1981; Hassanzadeh, 1993; Ghasemi and Talbot, 2006). This magmatism is characterized with acid intermediate to basic rocks with dominates of acidic rocks (Khodami *et al*., 2010). This work is mainly aimed at interpreting the processes related to their magmatic evolution that supported with petrographical evidences. Compositional and textural features of phenocrysts can give evidences about the composition and temperatures of magmas. The parts of volcanic rocks have disequilibrium textures that have studied as mixed lava. Magma mixing or mingling is the most common origin proposed for disequilibrium mineral assemblage (Sparks and Marshall, 1986; Feeley*et al*. 2002; Gencalioglu Kuscu and Floyd, 2001; Gerbe and Thouret, 2004). The role of magma mixing in the formation of some of the lavas in this research is supported by mineralogical and chemical characteristics.

2–Geological background

However, most of the magmatic activity occurred in Eocene that includes varieties of volcanic rocks, but Cretaceous units are also observable in north of this area (Fig. 1). The volcanic activity were extruded in Upper Miocene and continued up to Pliocene-Quaternary and is characterized by basaltic andesites, andesites and dacites as lava flows and domes and volcanic debris flow (Fig. 1).The age of emplacement of these rocks has not been determined by geochronological dating, but based on stratigraphical studies; these rocks are younger than late Miocene. Probably this volcanic activity began in the late Miocene and continued up to Pliocene.

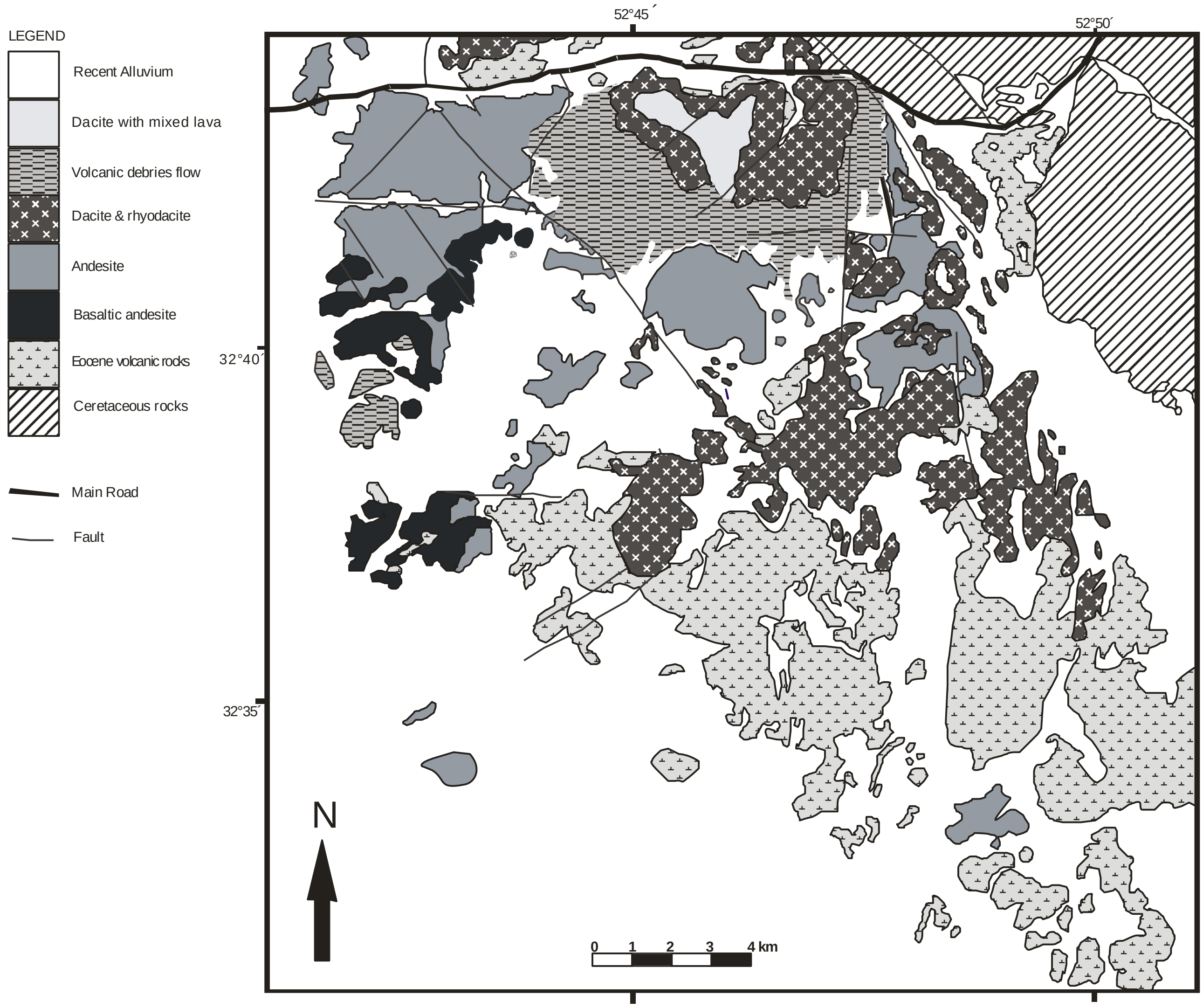

Figure 1) Geological map of the studied area (Simplified from the 1:100,000 geological map of Kajan Geological Survey of Iran).

3–Analytical methods

The major element compositions of the minerals were obtained by electron microprobe (EPMA) analysis of polished thin sections of rocks. The analyses were performed with a Cameca SX50 microprobe at the University of Oklahoma (USA) operated with a 20 kV accelerating voltage, a 15 nA beam current, a 30 s counting time, and a beam size of 5 μm utilizing both wavelength and energy-dispersive techniques (WDS and EDS). The mineral analyses were processed with the program PET (Dachs, 1998, 2004). Nomenclature of amphibolesand estimation of their Fe^{3+} contents follow the recommendations of Leake (1978). Mineral abbreviations are after Kretz (1983).

4–Discussion

4-1. Petrography and mineral chemistry

The Late Miocene, Pliocene volcanic rocks in the studied area range from basaltic andesite to dacite.

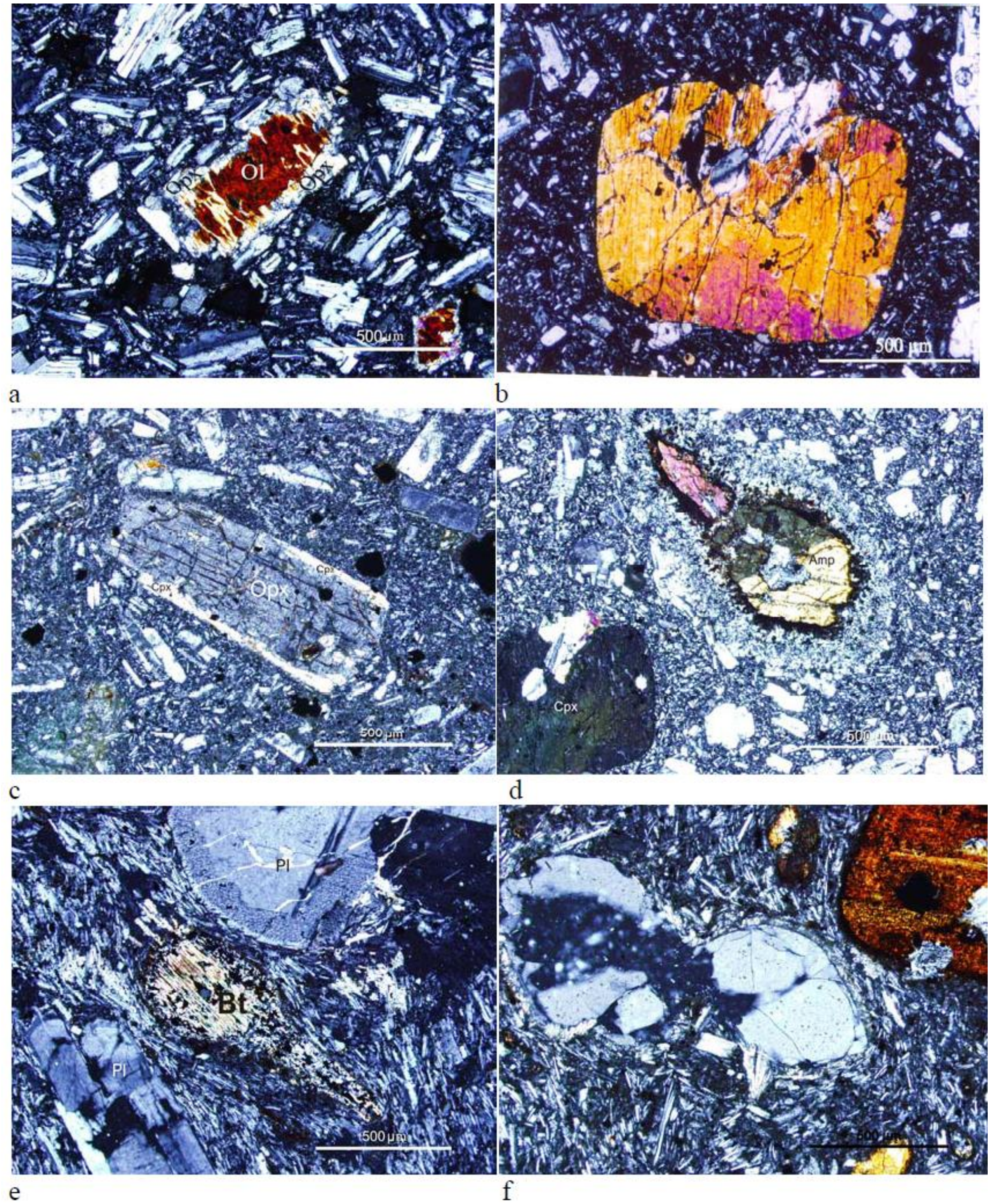

Figure2) Photomicrographs of thin sections of lavas a) Olivine phenocrysts with reaction rim of orthopyroxene in a basaltic andesite(XPL) b) Pyeoxene with hourglass zonation in andesite (XPL), c) Clinopyrpxene form parallel intergrowths with orthopyroxene (XPL).d) Amphibole phenocrysts with reaction rim (XPL) e)Plagioclase phenocrysts with sieve-textured, resorption-generated zone in mixed lavas. The development of a sieve zone surrounding a relatively clear core and rounded and embayed biotitephenocryst in andesite surrounded by reaction rim (XPL), f) Quartz phenocryst is partially resorbed, and shows reaction-rim (XPL).

These volcanic rocks show medium-K calc-alkaline compositional affinities (Khodami *et al*., 2010). These rocks are mainly porphyritic, with glassy and fine-grained groundmasses with plagioclase as the most abundant mineral phase, followed by pyroxene, and amphibole. Olivine is the main mafic phase in basaltic andesites, whereas orthopyroxene and clinopyroxene are abundant as mafic phenocrysts in the intermediate and felsic rocks.

The basaltic andesites consist of olivine phenocrysts and microphenocrysts with plagioclase, pyroxene and opaque oxides set in a dark brown glassy groundmass with plagioclase microlites. The scoria samples present in this region have vesicular texture.

The andesites contain abundant phenocrysts of plagioclase, orthopyroxene, clinopyroxene and opaque oxides, which can be accompanied by amphibole and biotite set in a brown glass with microlites of plagioclase and microphenocrysts of pyroxene or amphibole. The dacites are composed with plagioclase and the various amounts of orthopyroxene, amphibole, biotite, quartz and opaque oxides set in a colorless to pale brown glass. Some of the lavas are characterized by disequilibrium phenocryst assemblages and textures. Olivine phenocrysts (2.5 mm) and microphenocryst are present in basaltic andesite 5% -15% of the minerals population as main mafic phase. Olivine in basaltic andesites is euhedral to subhedral or skeletal crystal. Some of them are characterized by orthopyrpxene reaction rims which are common in calc-alkaline volcanic rocks (Fig. 2a). Orthopyroxenes and clinopyroxenes are abundant mafic mineral in these rocks. These minerals have wide range of size from microphenocryst to megacryst (Figs. 2b and 2c).

Table 1) Representative analyses of pyroxene in mixed lavas, 6 oxygen basis.
**Total iron as FeO, Mg# = $Mg^{2+}/(Mg^{2+}+Fe^{2+}+Fe^{3+})$*

	Clinopyroxene Phenocryst			*Orthopyroxene Phenocryst*				*Pyroxene corona on Quartz*	
Sample	GH10-Core1	2	Rim3	MA1-Core1	2	3	4	Rim-6	DH4-1
SiO_2	52.58	51.57	49.67	52.75	52.75	52.98	53.09	50.44	53.51
TiO_2	0.38	0.51	0.86	0.12	0.11	0.08	0.11	0.74	0.26
Al_2O_3	4.46	3.87	5.73	0.62	0.55	0.48	0.61	3.61	0.96
FeO^*	5.71	6.46	7.65	24.46	23.65	23.1	22.98	9.38	8.49
MnO	0.15	0.13	0.15	1.11	1.11	1	1.03	0.31	0.19
MgO	16.76	15.74	15.99	21.05	21.4	21.69	21.51	15.2	16.31
CaO	18.64	20.71	18.66	0.71	0.84	0.92	0.89	19.48	20.44
Na_2O	0.94	0.54	0.74	0	0	0	0	0.28	0.29
K_2O	0.01	0.01	0.22	0	0.01	0	0	0.01	0.04
Total	99.78	99.78	99.99	100.9	100.5	100.3	100.2	99.5	100.5
Si	1.99	1.88	1.78	1.97	1.97	1.98	1.98	1.87	1.96
Ti	0.01	0.01	0.02	0.003	0.003	0.002	0.003	0.02	0.01
Al	0.19	0.17	0.24	0.03	0.02	0.02	0.03	0.16	0.04
Fe^{3+}	0.09	0.15	0.23	0.04	0.04	0.02	0	0.11	0.01
Fe^{2+}	0.08	0.04	0	0.72	0.70	0.70	0.73	0.19	0.22
Mn	0.005	0.004	0.01	0.03	0.03	0.03	0.03	0.01	0.01
Mg	0.90	0.85	0.86	1.17	1.19	1.21	1.2	0.84	0.89
Ca	0.72	0.81	0.72	0.03	0.03	0.04	0.04	0.77	0.80
Na	0.07	0.04	0.05	0	0	0	0	0.02	0.02
K	0	0	0.01	0	0	0	0	0	0
Mg#	84.0	81.3	78.8	60.5	61.7	62.6	62.5	0.74	77.4
Name	Augite	Augite	Augite	Hypersthene	Hypersthene	Hypersthene	Boronzite	Augite	Augite
MolWo	40.05	43.36	39.70	1.424	1.68	1.84	1.79	40.41	40.95
MolEn	50.11	45.85	47.34	58.76	59.81	60.47	60.38	43.88	45.46
MolFs	9.83	10.77	12.95	39.81	38.50	37.68	37.82	15.69	13.57

On the pyroxene quadrilateral of Morimoto (1988), the pyroxenes plot in the augite field approaching diopside compositions, similar to pyroxenes from other orogenetic volcanic rocks

(Ewart, 1979, 1982). Orthopyroxenes are hypersthene to bronzite (Table 1 and Fig. 4).

Augite phenocrysts are generally subhedral to euhedral that occasionally show simple or lamellar twinning and sometime exhibit hourglass zoning (Fig. 2b). Clinopyroxene locally form parallel intergrowths with orthopyroxene (Fig. 2c). Amphibole exhibits green to pale brown pleochroism or orange-brown for oxyhornblende due to rock oxidation. They range in size from acicular microphencryst to phenocryst (4 mm). Amphibole phenocrysts are classified as calcic amphiboles. The range of compositions, vary from magnesio-hornblende, magnesio-hastingsite, hastingsite, ferri-tschermakite, tschermakite (Table 2).

*Table 2) Representative analyses of amphibole, 23 oxygen basis. *Total iron as FeO.*

Sample	Basaltic andesite		Dacite		mixed lavas	
	1	2	1	2	1	2
SiO_2	42.9	41.91	48.52	47.64	43.98	43.34
TiO_2	1.82	1.67	1.13	1.43	2.32	2.62
Al_2O_3	13.46	13.6	6.35	7.16	11.52	12.07
FeO^*	10.62	11.22	13.25	13.78	9.13	9.01
MnO	0.1	0.12	0.34	0.35	0.1	0.07
MgO	15.24	14.87	15.46	14.92	16.67	16.3
CaO	11.61	11.58	10.73	10.77	11.19	10.82
Na_2O	2.6	2.4	1.69	1.72	2.66	2.5
K_2O	0.63	0.67	0.22	0.3	0.75	0.78
F	0.21	0.38	0.31	0.06	0.54	0.16
Cl	0.03	0.01	0.07	0.1	0.03	0.05
Total	99.17	98.31	97.92	98.2	98.7	97.7
Si	6.07	5.98	6.96	6.85	6.22	6.21
Ti	0.19	0.18	0.12	0.15	0.25	0.28
Al	2.25	2.29	1.07	1.21	1.92	2.04
Fe^{3+}	0.87	1.12	0.77	0.67	0.92	0.62
Fe^{2+}	0.39	0.22	0.82	0.99	0.16	0.46
Mn	0.01	0.01	0.04	0.04	0.01	0.01
Mg	3.23	3.16	3.31	3.2	3.51	3.48
Ca	1.76	1.77	1.65	1.66	1.69	1.66
Na	0.71	0.66	0.47	0.48	0.73	0.69
K	0.11	0.12	0.04	0.05	0.13	0.14
F	0.09	0.17	0.14	0.03	0.24	0.07
Cl	0.01	0.002	0.02	0.02	0.007	0.01
$Mg\# = Mg^{2+}/Mg^{2+}+Fe^{2+}+Fe^{3+}$	71.9	70.3	67.5	65.9	76.5	76.3
Name	Magnesio hastingsite	Ferrimagnesio hastingsite	Magnesio hornblende	Magnesio hornblende	Magnesio hastingsite	Magnesio hastingsite
P (Kbar)						
Hammerstrom and Zen, 1986	7.4	7.6	1.5	2.2	5.7	6.3
Hollister et al., 1987	7.9	8.1	1.3	2.1	6.1	6.7
Johnson and Ruthersford, 1988	6.1	6.3	1.1	1.7	4.7	5.2
Schmidt, 1992	7.7	7.9	2.1	2.8	6.1	6.7
Average	7.3	7.5	1.5	2.2	5.6	6.2

Opaque rims are sometimes observed around amphibole phenocrysts that probably formed by oxidation on extrusion; locally opaque oxides entirely replaced phenocryst. The other texture in mineral is breakdown of amphibole (Figs. 2d, 3c and 3d). The common breakdown products consist of fine grained intergrowth of pyroxene, plagioclase and opaque. Plagioclase is the main mineral in all of the volcanic rocks as phenocrysts and microlites. Plagioclase phenocrysts are typically zoned. This mineral exhibits oscillatory, normal or reverse zoning. Two types of textures in plagioclase were observed in these rocks. The former of them are textures that have been referred to sieved, dusty, fritted, riddled, spongy plagioclase crystals (Tsuchiyama, 1985) orcellular plagioclase intergrowths (Andersson and Eklund, 1994). The second textural type is the normal or clear plagioclase. Plagioclase phenocrysts show sieve textured or dusty zones, although normal clear plagioclase is also common and two types of plagioclase are found together in mixed lavas (Figs. 2e and 3g, h, i). Sieved plagioclase crystals have observed either with a clear rim and a sieved core, or vice versa. EPMA results of plagioclases phenocrysts from the andesite and basaltic andesitic rocks yield the compositions of labradorite to anorthite (Table 3).

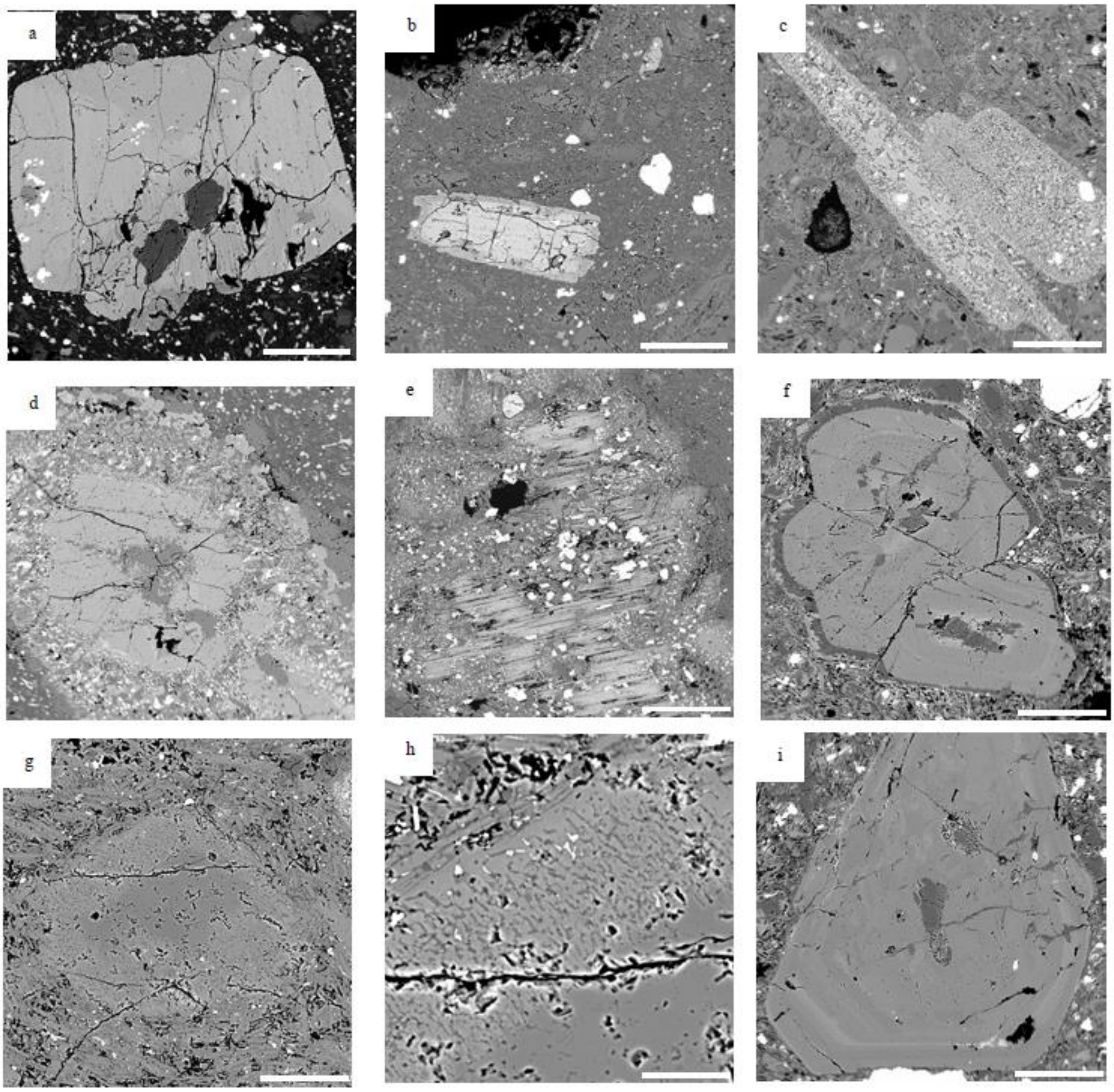

Figure 3) Backscattered electron images of phenocrysts in volcanic rocks in the SE area of Isfahan.a) Hourglass extinction in pyroxene phenocryst, the scale bar in the lower right is 80 µm, b) Orthopyroxene with the rim of clinopyroxene, the scale bar in the lower right is 80 µm, c-d) Amphibole phenocryst with a reaction rim. The reaction rim contains pyroxene, plagioclase, titanomagnetite and glass, the scale bar in the lower right is 80 µm, e) Biotitephenocryst decay to fine grain reaction products the scale bar in the lower right is 40 µm, f) Plagioclase phenocryst with thin resorption rim the scale bar in the lower right is 65 µm, g) Plagioclase phenocryst with dusty and sieve-textured zones, resorption generated zone and clear core in mixed lavas the scale bar in the lower right is 27 µm, h) The dusty zone in plagioclase of part g, the scale bar in the lower right is 8 µm, i) Oscillatory zoning in plagiaoclasephenocryst in dacite; the scale bar in the lower right is 80 µm.

Sieve zone have higher An content. The plagioclase phenocrysts from the dacitic rocks are oligoiclase to labradorite whereas this mineral in mixed lavas has large range in composition and An rich at the rim (Table 3). Biotite forms subhedral to resorbed phenocrysts

(1.5 mm) exhibiting green to dark brown pleochroism or reddish-orange where oxidized. Opacite rims and break-down fine grained products of biotite and amphibole are observed in these rocks (Figs. 2e and 3e). The analyzed biotitephenocrysts from the mixed lavas have a composition of 50%-65% F enriched phlogopite (Table 4). Quartz phenocrysts (1mm) are resorbed, rounded, embayed and cracked but have sharp boundaries without reaction rim. Occasionally this mineral has mafic reaction corona. Reacted quartz grains are surrounded by rims that consist of fine grained clinopyroxene and glass (Fig. 2f). The composition of clinopyroxene in reaction corona is augite (Table 1).

On the basis of the above observations on pyroxene, amphibole, biotite, quartz and plagioclase crystals, it is concluded that the disequilibrium textures and minerals represent magma mixing between a hotter mafic magma and a cooler more silicic magma. The lines of evidence for disequilibrium in mineral include:

Pyroxene: The most important feature to note about this mineral is the presence of high and low temperature pyroxene in the same sample interpreted as evidence for disequilibrium condition. In these lavas bronzite forms overgrowths on hypersthene phenocrysts and sometimes mantled by augite (Figs. 2c and 3b). Mg/Fe ratios in augite rim are too high to be equilibrium with orthopyroxene cores and resorbed hypersthenes saved as nucleation site for augite.

Similar textures are known to form in rapid cooling but in this case there aren't evidences of resorption at the core - rim boundary and heterogeneity in composition (Nixon, 1988). This zoning of pyroxene especially has been referred to open system (Gencalioglu Kuscu and Floyd, 2001; Sakuyama, 1981; Bloomfield, Arculus, 1989). In addition based on composition of pyroxenes these volcanic rocks are orogenic and calc-alkaline (Figs. 5 and 6).

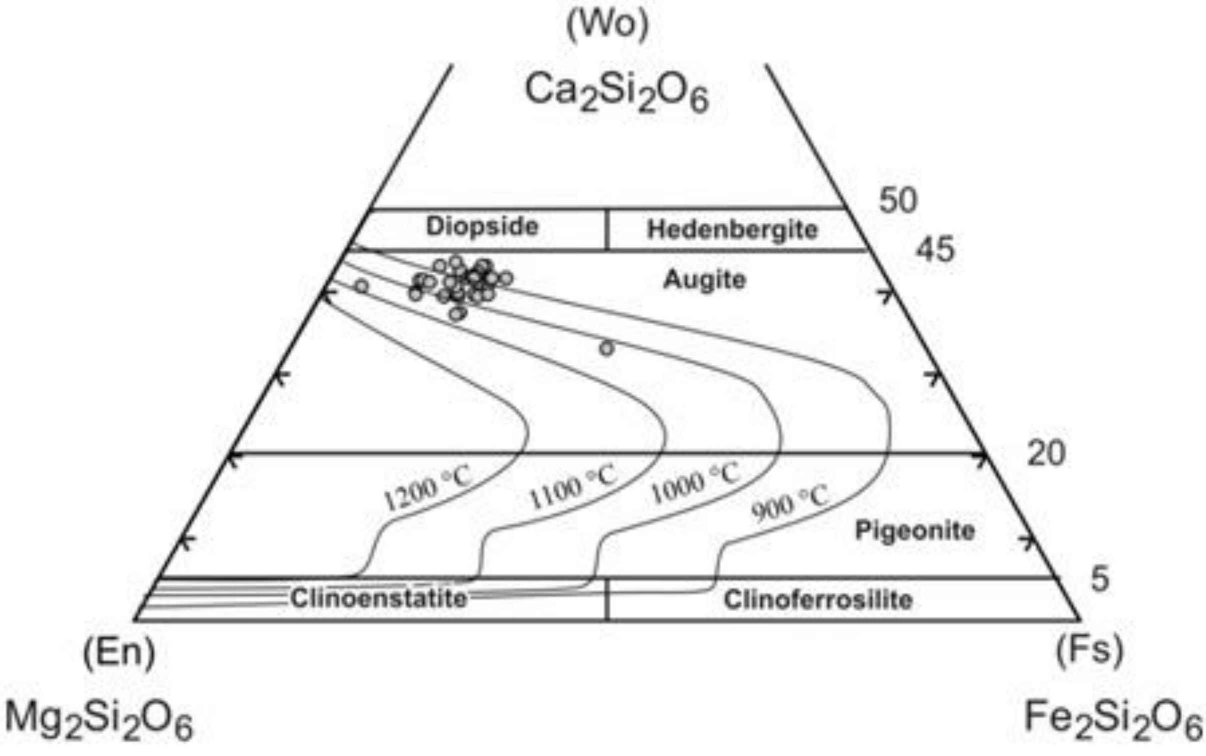

Figure 4) Composition of clinopyroxenes from SE Isfahan volcanic rocks are plotted in the En–Wo–Fsclinopyroxene classification diagram (after Morimoto, 1988).

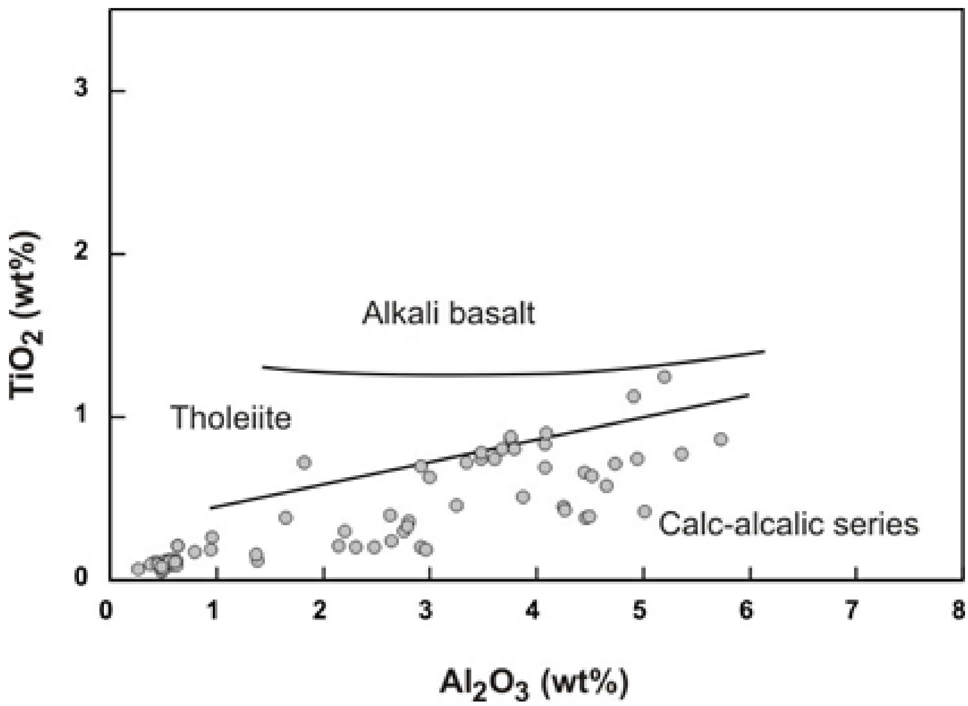

Figure 5) TiO2 v. Al_2O_3 binary diagram after Le Bas (1962) for pyroxene.

Amphibole: One of disequilibrium features of amphibole crystals are development of reaction rims, and pseudomorphs after amphibole. The opacite is characterized by the abundance of fine grain opaque minerals and formed by oxidation on extrusion and occasionally replaced entire phenocrysts (Rutherford and Hill, 1993). Opacite rims of amphibole don't relate to magma mixing events and may be produced by dehydration of a coexisting melt because of reduction of ambient pressure (Rutherford and Hill, 1993; Tepley *et al*., 1999). The other reaction rim is attributed to amphibole breakdown during slow magma ascent (Rutherford and Devine, 2003; Browne and Gardner, 2006).

The most common amphibole breakdown product is a fine grained intergrowth of clinopyroxene + orthopyroxene + plagioclase + Fe-Ti oxides and interstitial glass. These reactions involve an open chemical system with exchange of components with adjacent magma (Nixon, 1988; Tepley *et al*., 1999).

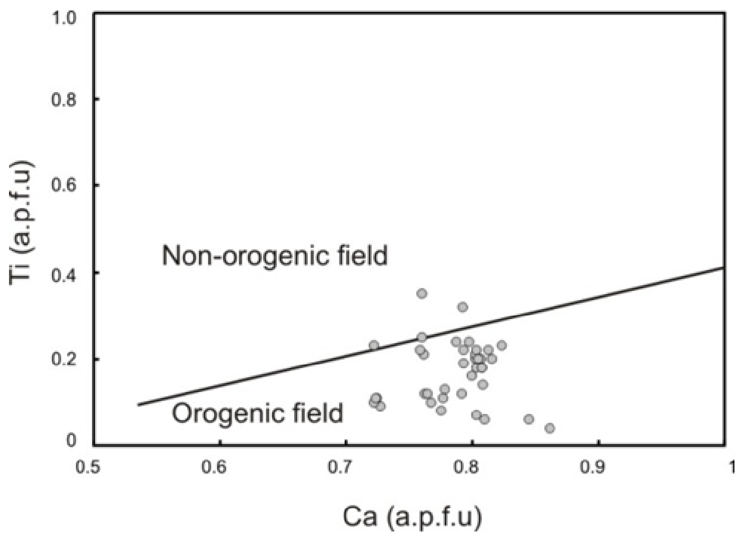

Figure 6) Ti vs. Ca binary diagram after Letterrieret al. (1982) modified by Sun and Bertrand (1991). a.p.f.u. atoms per formula unit for pyroxene.

Table 3) Representative analyses of plagioclase, 8oxygen basis. *Total iron as FeO.

Dacite							Phenocryst Core to Rim					
Sample	OG5-Pl--1	2	3	4	5	6	7	8	Rim9	OG5-Pl2- 1	2	Rim-3
SiO_2	57.6	55.4	56.2	57.2	54.0	59.0	58.2	53.3	54.5	53.0	57.0	52.5
Al_2O_3	26.9	26.8	27.9	27.3	29.2	25.8	26.4	29.5	28.7	29.6	27.3	29.8
FeO^*	0.23	0.23	0.24	0.25	0.29	0.24	0.23	0.58	0.45	0.24	0.22	0.54
CaO	8.74	8.99	9.66	8.98	11.1	7.41	8.21	11.9	10.8	11.6	8.98	12.2
Na_2O	6.61	5.94	5.99	6.37	5.12	7.11	6.82	4.74	5.26	4.55	6.30	4.47
K2O	0.38	0.30	0.25	0.29	0.18	0.38	0.33	0.21	0.23	0.16	0.29	0.20
Total	100.6	97.7	100.3	100.5	100.2	100.1	100.4	100.4	100.2	99.4	100.3	100.1
xAb	56.6	53.5	52.1	55.3	44.8	62.1	58.9	41.4	46.1	41.0	55.0	39.2
xOr	2.1	1.8	1.5	1.6	1.0	2.2	1.9	1.2	1.4	0.9	1.6	1.1
xAn	41.3	44.7	46.4	43.1	54.2	35.8	39.2	57.4	52.6	58.0	43.4	59.6
Mixed Lava			Phenocryst Core to Rim							Microlite		
Sample	DH4-Pl-Core1	Dusty zone 2	Dusty zone3	Rim4	GH10-Pl2-Core-1	2	3	4	5	Dusty zone6	Dusty zone7	8
SiO_2	61.34	68.36	58.18	52.01	60.53	61.19	60.58	61.74	53.91	53.13	51.99	55.53
Al_2O_3	24.65	16.94	25.91	29.41	24.97	24.80	25.11	24.38	24.59	29.34	30.34	27.46
FeO^*	0.15	0.69	0.60	0.72	0.14	0.14	0.15	0.15	3.36	0.51	0.57	0.77
CaO	5.84	3.35	8.63	12.35	6.11	5.96	6.15	5.54	7.40	11.98	12.62	9.74
Na_2O	7.80	3.87	4.73	4.24	7.93	8.01	7.89	8.07	5.77	4.62	4.16	5.48
K_2O	0.74	2.87	1.38	0.23	0.44	0.44	0.46	0.64	1.23	0.37	0.29	0.49
Total	100.67	96.78	99.68	99.39	100.30	100.65	100.47	100.66	96.87	100.24	100.34	99.84
xAb	67.8	50.8	45.4	37.8	68.4	69.1	68.1	69.8	54.1	40.2	36.7	49.0
xOr	4.2	24.8	8.7	1.4	2.5	2.5	2.6	3.7	7.6	2.1	1.7	2.9
xAn	28.0	24.3	45.9	60.8	29.1	28.4	29.3	26.5	38.3	57.6	61.6	48.1
Basaltic andesite												
Sample	TO4-Pl1-1	2	3	4	Rim-5	Rim-6	TO4-Pl2--1	2	3	4	5	Rim-6
SiO_2	47.19	46.63	46.89	50.90	53.76	53.16	47.43	47.46	46.50	47.97	47.52	52.33
Al_2O_3	33.33	33.80	33.81	30.78	28.85	29.47	33.24	32.95	33.89	33.03	33.15	30.13
FeO^*	0.62	0.58	0.63	0.70	0.77	0.74	0.64	0.66	0.64	0.62	0.59	0.81
CaO	16.27	16.93	16.69	13.59	11.36	12.40	16.19	16.19	16.87	16.06	16.31	12.6
Na_2O	1.87	1.63	1.89	3.62	4.88	4.37	2.04	2.24	1.67	2.29	2.06	4.20
K_2O	0.07	0.06	0.04	0.19	0.31	0.30	0.09	0.07	0.05	0.08	0.07	0.27
Total	99.65	99.93	100.31	100.13	100.33	100.83	99.96	99.86	99.99	100.34	100.08	100.7
xAb	17.16	14.76	16.98	32.14	42.93	38.28	18.5	19.9	15.2	20.4	18.5	37.0
xOr	0.43	0.32	0.25	1.09	1.80	1.74	0.6	0.4	0.3	0.5	0.4	1.6
xAn	82.41	84.92	82.77	66.76	55.27	59.98	81.0	79.6	84.6	79.1	81.1	62.4

Reaction rims developed where amphibole phenocrysts were in contact with melt. The rimmed crystals can indicate disequilibrium crystallization and formed by decompression during magma ascent and decrease of magmatic water content or thermal breakdown during magma mixing. The decrease of dissolved water results from either isothermal decompression during magma ascent or influx warmer or low-H_2O magma. Decompression experiments have demonstrated that amphibole without reaction rims could be formed only for very rapid ascent (Gerbe and Thouret, 2004, Rutherford and Hill, 1993).However the rimmed crystals are interpreted as the result of magma mixing during magma rising.

Plagioclase: The textural and compositional disequilibrium evidences in plagioclase are important. Sieve texture of plagioclase is noticeable in these volcanic rocks (Figs. 2e and 3f, g, h). This may be interpreted as resulting from either partial dissolution during the magma mixing process (Feeley and Dungan, 1996) or a decompression effect (Nelson and Montana, 1992). Plagioclase phenocrysts in mixed lavas develop a resorption zone in response to different temperature and composition of surrounding melt. Then the outer rim crystallizes with composition of new magma (Tsuchiyama, 1985; Halsor and Rose, 1991; Halsor, 1989; Browne *et al*. 2006). Tsuchiyama (1985) concluded from experimental data that "these textures were closely related to temperature and chemical compositions.

*Table 4) Representative analyses of biotite in mixed lavas, 11 oxygen basis. *Total iron as FeO. Mg# = Mg/ (Mg+Fe).*

	Mixed lava-1				*Mixed lava-2*			
	Core1	Core2	rim3	Rim4	Core1	Core2	Rim3	Rim4
SiO_2	36.41	35.68	34.53	36.50	37.89	37.20	37.35	36.97
TiO_2	3.49	3.51	3.65	3.63	3.64	3.68	3.73	3.53
Al_2O_3	13.84	13.81	13.65	13.96	13.84	13.86	13.90	13.79
FeO^*	17.57	20.78	23.20	17.46	17.94	17.86	17.86	18.13
MnO	0.22	0.24	0.18	0.18	0.34	0.37	0.30	0.32
MgO	14.91	13.88	12.98	15.68	12.83	13.45	13.74	13.43
CaO	0.02	0.03	0.02	0.03	0.04	0.02	0.05	0.03
SrO	0.03	0.01	0.02	0.01	0.02	0.00	0.00	0.01
BaO	0.32	0.32	0.32	0.41	0.68	0.48	0.29	0.29
Na_2O	0.40	0.31	0.54	0.53	0.59	0.61	0.66	0.67
K_2O	8.90	8.78	8.28	8.41	8.83	8.88	8.97	8.90
F	3.92	3.21	2.53	4.08	0.37	0.23	0.64	0.80
Cl	0.05	0.06	0.03	0.06	0.05	0.05	0.05	0.03
Total	100.07	100.61	99.92	100.95	97.05	96.70	97.53	96.90
Mg#	60.2	54.4	49.9	61.5	56.0	57.3	57.8	56.9
Si	2.087	2.035	1.980	2.073	2.076	2.041	2.046	2.050
Ti	0.150	0.151	0.157	0.155	0.150	0.152	0.154	0.147
Al	0.935	0.928	0.923	0.935	0.894	0.896	0.897	0.902
Fe	0.842	0.991	1.113	0.830	0.822	0.820	0.818	0.841
Mn	0.011	0.012	0.009	0.008	0.016	0.017	0.014	0.015
Mg	1.273	1.181	1.109	1.328	1.048	1.100	1.122	1.110
Ca	0.001	0.002	0.001	0.002	0.002	0.001	0.003	0.002
Sr	0.001	0.000	0.001	0.000	0.001	0.000	0.000	0.000
Ba	0.007	0.007	0.007	0.009	0.015	0.010	0.006	0.006
Na	0.044	0.034	0.060	0.058	0.062	0.065	0.070	0.072
K	0.651	0.639	0.606	0.609	0.617	0.622	0.627	0.630
F	0.711	0.580	0.459	0.733	0.064	0.040	0.110	0.141
Cl	0.005	0.006	0.003	0.006	0.004	0.005	0.004	0.003
Sum	6.001	5.979	5.965	6.007	5.702	5.724	5.757	5.775

A crystal became smaller and rounded above the plagioclase liquidus temperature and remained its original euhedral shape below the liquidus. If the crystal is less calcic than the plagioclase in equilibrium with the surrounding melt, the crystal-melt interface became rough and often more complicated (sieve-like texture; formation of mantled plagioclase) and the interface remained smooth if the crystal is more calcic than the equilibrium plagioclase. Therefore, sieved, dusty and spongy plagioclase textures are usually reported in magmatic rocks with magma mixing source. Sieve texture also forms due to decompression when magma ascends towards the surface (Nelson and Montana, 1992).

But in the decompression there should not be any compositional change on the crystal. Sieved zones should be more calcic than the earlier zones (Stimac and Pearce, 1992); and overgrowths zone on the resorption surfaces should be comparable in composition to groundmass microlites but a calcic, sieve-textured core should be followed by a resorption surface associated with a sudden change in An content (Gencalioglu Kuscu and Floyd 2001, Stamatelopoulou-Seymour *et al*., 1990).

Biotite: Reaction rims and Fe–Ti oxide pseudomorphs after biotite are disequilibrium features of biotites in mixed lava. Some of biotitephenocrysts show opacite rim and reaction rim like amphiboles (Fig. 2e). Breakdown of biotite forms opaque oxides or a granular intergrowth of orthopyroxene + Fe-Ti oxides ± K-feldspar. Reaction rims can be produced from heating during magma mixing (Nixon, 1988; Rutherford and Hill, 1993; Feeley and Sharp, 1996).

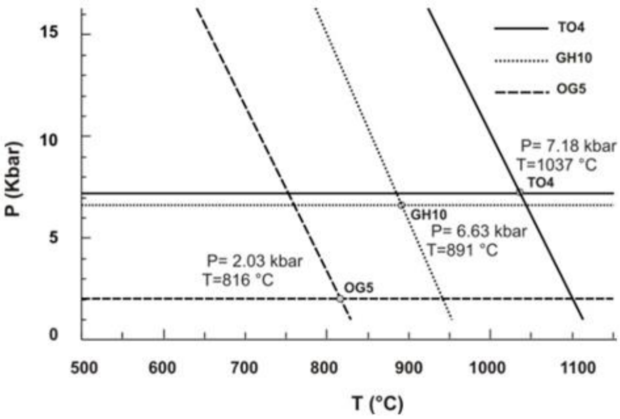

Figure 7) Application of Amph-Plaggeothermometry (Holland and Blundy, 1994) and barometery Al-in-amphibole (Schmidt, 1992) OG5 dacites, GH10 mixed lava, TO4 basaltic andesite.

Quartz: Resorbed, rounded, embayed quartz is common in the volcanic rocks. But rounded boundaries with evidence for reaction quartz with groundmass have been reported for magmatic contamination (Nixon, 1988). In the mixed lavas this mineral has mafic reaction corona. Reacted quartz grains are surrounded by rims that consist of fine-grained clinopyroxene and glass .The composition of clinopyroxene in reaction corona is augite. Augite rims on quartz phenocrysts form as a result of diffusion of Mg, Fe, and Ca into the zone of silicic melt surrounding the quartz when the mafic magma intruded to silicic magma (Nixon, 1988).

4-2. Geothermobarometric calculations

According to P–T calculations, mixed lavas have generally higher temperatures and pressures than dacite. Estimated Al–in hornblende (Schmidt, 1992) pressures are about 6.1-6.7 kbar for mixed lavas and 2-2.8 kbar for dacites and suggests shallow level magma chamber. Temperature calculations according to hornblende–plagioclase thermometer (Holland and Blundy, 1994) indicate that basaltic andesites are formed at 1037ºC and mixed lavas are formed at higher temperatures (891ºC) than the dacite lavas (816ºC) (Table 2, Fig. 7).

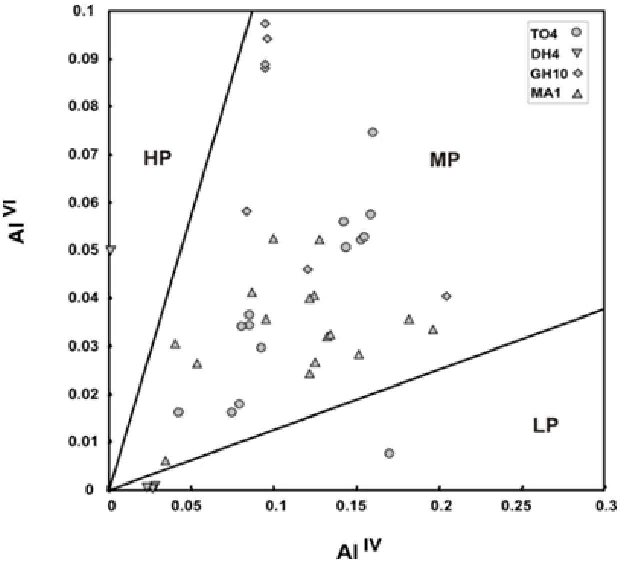

Figure 8)Al^{VI} vs. Al^{IV} diagram (Aoki andShiba, 1973) for pressure estimation of the clinopyroxenes of in SE Isfahan volcanic rocks. HP=High-pressure field, MP=Medium-pressure field, LP=Low-pressure field. Clinopyroxenes types are indicated by OG5 dacites, DH4, GH10 mixed lavas, MA1 andesite and TO4 basaltic andesite clinopyroxene; in DH4 is corona of quartz.

Dacite forming magma developed by the partial melting of the local continental crust and aggregate in a shallow level (about 7 km) magma chamber. However the pressure estimation of the clinopyroxenes based on AlVI vs. AlIV diagram indicates a medium crystallization pressure for this mineral (Aoki andShiba, 1973) but corona of pyroxene around quartz produced in low pressure (Fig.8). Actually the P-T estimations of minerals in mixed lavas suggest physical condition of mixing between two magmas.

4–Conclusions

Late Miocene–Pliocene to Quaternary volcanic rocks of Central Iranian volcanic belt in the southeast of Isfahan area display many disequilibrium features that imply the involvement of magma mixing processes. Disequilibrium textures and mineral compositions are the most effective evidence for the identification of magma mixing or mingling in silicic to intermediate rocks. However some of these features may be attributed to other mechanisms. But observed compositional changes, normal and reserve zoning in crystals together with in the samples and resorption surface of minerals cannot be explained by other mechanisms than mixing. Some of these evidences are following:

a) Occurrence of disequilibrium textures such as sieved or dusty plagioclase and clear and sieved plagioclases in the same sample.

b) Rounded and embayed crystals.

c) Reaction rims on amphibole and biotite and pseudomorphs after mafic phases.

d) Mineral zoning such as reverse, normal and oscillatory zoning in crystals in the same sample.

e) Resorbed and embayed quartz with augite reaction rim.

Partial melting of lower crust produces mafic magma then the magma batches cause to heating and melting of the higher level. These magmas are mixed together during ascending. All phases recorded disequilibrium textures and compositions, and overall these features are more than enough to demonstrate magma mixing. Based on observed disequilibrium textures, mineral compositions, interaction of dacite and more mafic magma batches are suggested. Basaltic or basaltic andesitic end member (as mafic magma) must have been presented in the mixing process. The volume proportion of mafic magma was small. Dacites are the other end member of mixing. Low temperature minerals such as amphibole, sodic plagioclase, biotite, quartz and minor pyroxene are crystallized from dacitic magma. The unreacted phenocrysts were derived from dacite magma. The reacted equivalents of these phenocrysts formed when this magma mixed with a mafic magma. Small volume of mafic magma intruded the magma chamber, losing heat to the surroundings. The felsic minerals became rounded, embayed or developed reaction rims and plagioclase crystals were sieved. Reaction rims on mafic minerals have developed responded to increasing temperature. The two end member magmas did not mix thoroughly before eruption due to large temperature difference between the two magmas and the relatively small volume proportion of the mafic magma. The addition of the volume of mafic magma to a felsic magma chamber may increase the total pressure to cause lava eruption. Therefore, detailed investigations may expose evidence for local magma mixing in the Late Miocene–Pliocene volcanic rocks in southeast Isfahan.

Acknowledgments:

The authors would like to thank Dr. Alba P. Santo, R.Cristofolini and Dr. F. Sarjoughian for their kind and careful comments that made the manuscript improved. They also would like to thank Dr M. Khalili in the University of Isfahan and Dr G. Morgan in University of Oklahoma (USA) for laboratory assistance during the microprobe analyses.

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