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Magmatic interactions as recorded in plagioclase phenocrysts of quaternary volcanics in SE Bam (SE Iran)

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Abstract

In the southeast of Iran (SE Bam), there is a collection of volcanic rocks with andesite, basalt and trachyandesite composition. The textures of these rocks are often porphyritic with microlithic, porphyric cavity, and sometimes glomeroporphyritic, sore throat trachytic. Main minerals include olivine, clinopyroxene, plagioclase and secondary minerals including opaque minerals, Iddingsite, secondary biotite, chlorite and calcite. The analysis of magma textures gives us valuable information about magmatic processes. Micro textures in plagioclase of volcanic rocks in the region are divided into two groups: a) texture-linked to crystalline growth including: sieve texture, oscillatory zoning and degraded surfaces and b) Morphological textures such as glomerular crystals. Sieve texture and zoning in crystal represent processes such as magmatic mixing and abrupt reduction of pressure and, in general, unbalanced conditions in magmatic reservoirs. Based on electron microscope studies, plagioclase of igneous rocks of the region is within the boundaries of labradorite and bytownite.

Keywords: *Volcanic rocks, Plagioclase, Quaternary, Zoning, Sieve texture, Southeast of Iran, Bam*

1. Introduction

In an open-system volcanic process, the erupted magmatic products contain mixed crystal populations of xenocryst, antecryst, phenocryst and microlite (Jerram and Martin 2008). A mineral phase, in any of such forms, highly sensitive to the modifications in the volcanic system, and able to record the changes in thermodynamic equilibria in their textural and compositional zoning patterns, depending on the process they underwent, will be a power full tool in understanding the magma process. Specifically, several studies have concluded that texture and chemical zoning in plagioclase, in particular, may be an efficient tool for confining the dynamics and kinetics of magmatic process, due to its high sensitivity to changes in physical-chemical conditions (T, P, P(H_2O), f(O_2), melt composition) of the system (Stamatelopoulou-Seymour et al. 1990; Blundy and Shimizu 1991; Stimac and Pearce 1992; Singer et al. 1995; Tepley et al. 1999, 2000; Ginibre et al. 2002a,b; Humphreys et al. 2006; Ginibre and Wörner 2007; Smith et al. 2009; Viccaro et al. 2010 and 2012).

Sieve texture, glomero-porphyritic, and amigdaluidal matrix including the texture in the stomatal plagioclase of the region studied. Each texture is formed under a specific magmatic environment. The deduced micro-textural stratigraphy helped to draw the picture of progressive and systematic sequence of magma processes involved.

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2. Regional geology

The study area with an area of 800 km^2 in a distance of 120 kilometers southeast of Bam city and between latitudes 28° and 03' to 28° and 24' east and 58° and 49' longitude to 59° and 0' the north is located, and is structurally belonging to the tributary of the central Iran (Dehaj- Sarduieh belt) (Fig 1). The Dahej- Sarduieh belt has the largest volume of magmatic in the Urmia-Dokhtar Belt. Magmatic activity of this belt began as volcanic sedimentary and volcanic plutonic from Eocene and continues to quaternary (Abedian et al. 2010; Dabiri et al. 2011; Yazdi et al. 2017). One of the characteristics of the quaternary lava is the preservation of the relative cone and volcanic crater, and their dark color compared with other rock outcrops. quaternary volcanic rocks include olivine basalts to basaltic andesite, andesite, and companions of pyroclastic rocks. The texture of these rocks is porphyritic to aphanitic or glassy.

3. Petrography

Quaternary volcanic rocks include olivine basalts to basaltic andesite, andesite, and companions of pyroclastic rocks. Basic quaternary volcanic rocks include olivine basalt, basalt and alkali basalt, which account for a considerable amount of lava in the region. Plagioclase, olivine and augite phenocrysts as main minerals, and apatite and magnetite are secondary ascites of basaltic rocks that are located in glass jars, respectively. The dominant texture in these rocks are porphyritic, glomero-porphyritic, amygdaloidal, and microlitic. In the plagioclase mineral, these rocks are adjacent to the surrounding textures (sieve, zoning, and scaphoid). The andesitic rocks of the area are hyalopyroxene andesite, pyroxene andesite and trachyandesite. These rocks represent a variety of porphyritic, flow, glomero-porphyritic and sieve texture. The main minerals of these rocks include plagioclase and one or more mafic minerals such as hornblende and pyroxene. The plagioclase phenocrysts have a polypeptide concentration of oligoclase- andesine, and oscillatory zoning. In andesitic rooks, plagioclase is often decomposed into sericite, chlorite and clay minerals. Secondary quartz is also in the form of fine granules in the matrix and sometimes filler of rock drills. In andesitic rocks, magnetite and titanomagnetite (opaque minerals) are secondary minerals and apatite are accessory minerals.

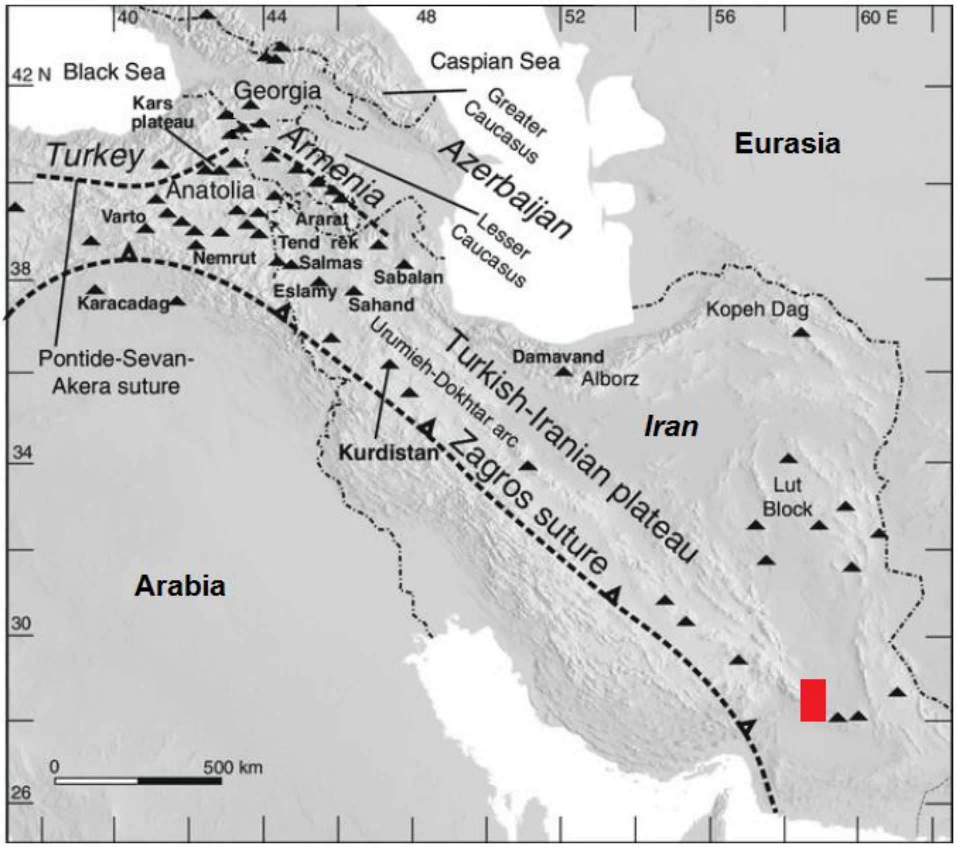

Fig 1. Map of the Turkish-Iranian plateau with shaded digital topography, showing locations of Late Miocene-quaternary volcanic centres (cones) (after Neill et al. 2013) and the study area (rectangle).

4. Study of microtextures in plagioclase of volcanic rocks in the region

The microtextures in the plagioclase are divided into two groups: a) texture-linked to crystalline growth including: sieve texture, oscillatory zoning and degraded surfaces such as texture due to imbalance in the crystalline-liquid phase, Changes in temperature, water pressure, and melt composition during crystallization and b) Morphological textures such as glomerular crystals, microlites, which are crystallized due to the interaction of crystalline magma dynamic processes, such as convection, get out of gas or explosive eruptions.

4.1. Sieve texture

The types of textures in the plagioclase of igneous rocks are: homogeneous, repeated, regular, and irregular sieve texture, and specially sieve texture with zoning.

One of the most important unbalanced textures are in the plagioclase crystals in quaternary volcanic rocks. This texture is formed due to the physical and chemical changes in the magmatic nests. In plagioclase phenocrysts, this texture is found on the margins, in the center of the crystal, and some in the margins and in the center. The size and number of sieves vary, depending on the magnitude of the rise of the magma and the increase in the content of magma during the ascent (Viccaro et al. 2010). The connection and magnitude of the sieves indicate intense or prolonged dissolution. Sieves texture coarse scales are divided into two groups, either individually or in association with each other. In separate screening sieve texture, the cavities are accidentally and irregularly located in the center of the crystal and do not follow a specific pattern. The sieve texture is associated in two ways. a. Extensively and in parallel with the plagioclase ligaments in which the cavitites with the holes are cut a part together and interconnected, b. loop-like screens in the center of the crystal, in which case they are in perfect contact. Sieve texture are observed in two coarse-scale and distinct (Fig 2a-b), and a small scale in plagioclase crystals of region samples. Small sieve texture is a very small incombustible of glass, and it has a dust-like appearance to crystallize and has a very good connection, and is mainly observed in the center and margins of small to medium grains or on the margins of large seeds (Fig 2c). In some plagioclase cases, in some regions of the region, sieve texture with zoning is observed (Fig 2d). In same samples, plagioclase is observed in which the whole surface of the crystalline cavity and shows a homogeneous sieve. The reason for creating this texture can be a homogeneous combination of minerals that, with changing conditions, all crystals begin to be crackup. According to Shelly (1993), sieve texture is created as result of the presence of interconnections between glasses or dusts and creates a porous appearance in the crystal. The spongy sieve texture in plagioclase in igneous rocks is thought to be the result of magmatic mixing (Tsuchiyama 1985).

The mixing process is possible either by mixing magmas with a different origin or magmatism of the same origin (Sterck 2008). The intensity and extent of this process can be as high as possible create a new magma (eg. andesitic magma) from the mixing of two different magmas (eg. basaltic and dacitic magmas) (Sterck 2008; Sayyari et al. 2008) or localized and less intensity, and only evidence of alien crystals in two mixed magma (Biabangard and Moradian 2009; Lee and Bachmann 2014). This phenomenon is carried out in different tectonic environments such as island arc and active continental margins due to the continious filling of the magma reservoir (Biabangard and Moradian 2009; Shahriari 2011).

In some cases, in the plagioclase crystals, the center of the crystalline region is healthy, and on the margin of the sieve texture is observed regularly and irregularly.

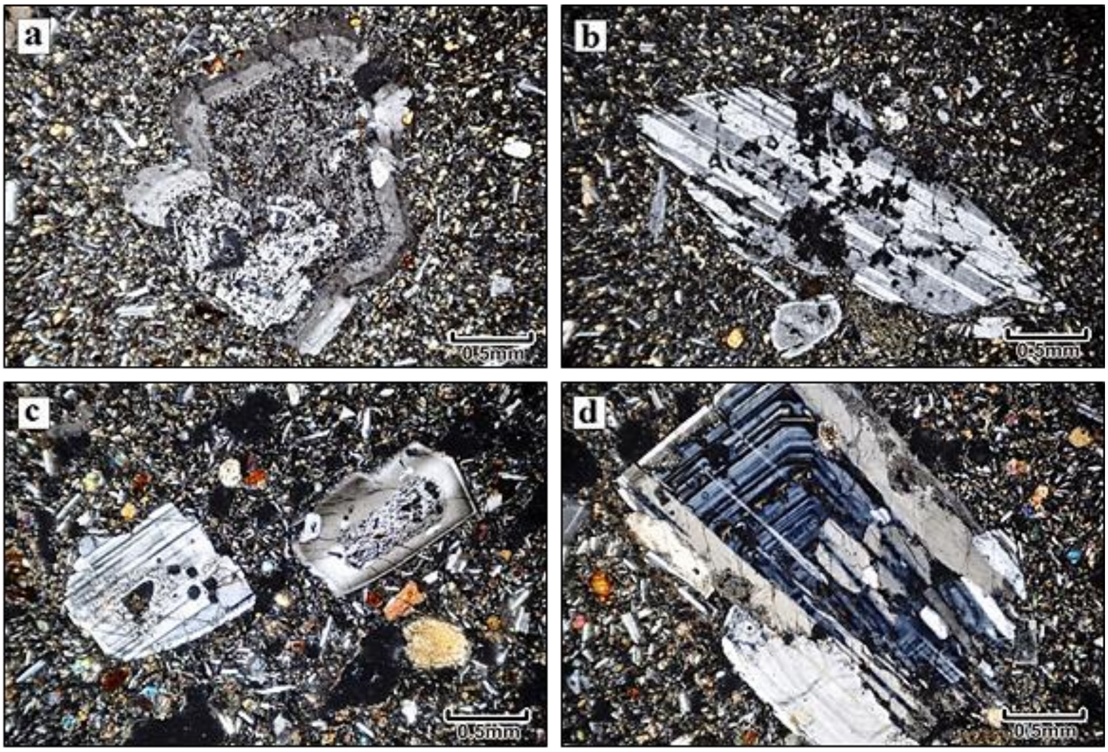

Fig 2. a) Sieve texture of the coarse- scale; b) Separate sieve texture in olivine basalt; c) Small sieve texture in olivine basalt; d) Small scale sieve texture with zoning in olivine basalt (light XPL).

If, on the sieve`s margin texture, it regularly captures the plagioclase crystals, these crystals are flat-shaped and plan- shaped plagioclase (Fig 3a and b). If the margin of sieve texture is irregular plagioclase, these plagioclase are known as iridescent nucleus. The reason for the formation of these plagioclase is the presence of a different composition in the crystalline structure. This combined difference causes the same variation in equilibrium conditions to occur in the anisotropic corrosion in the crystal, and then by the lateral magma penetration, a healthy margin appears around these crystals (Meghan 2006). According to Tsuchiyama (1985), in many cases, the plagioclase nucleus grows from a plagioclase- shaped ring that has more calcium than nucleus of these crystals. The existence of non-equilibrium conditions is the main cause for the creation of these rings, which are caused by the rapid growth of magma mixes that are hotter and rich in H_2O and Ca. in some cases, the photo mode (the normal crystalline margin and the center of the screen is screened) in plagioclase is observed, which can be seen from a sieve texture following a sudden decrease in the pressure under the saturated conditions of H_2O and during the ascent of magma from the depths to the surface of the earth occurs (Nelson and Montana 1992).

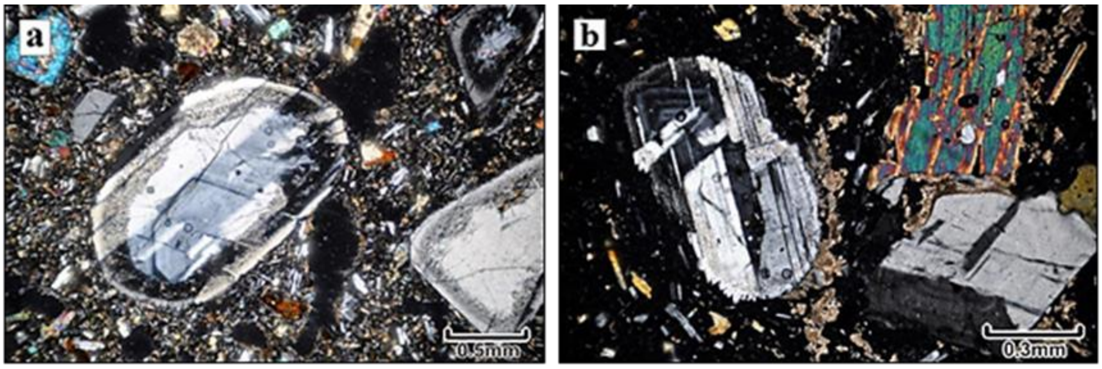

Fig 3. a) Coarse-scale sieve texture with a flat- shaped core in olivine basalt (Light XPL); b) Coarse- scale, flat-shaped in hornblende pyroxene andesite (light XPL).

Sieve textures consist of two causes:

1) During the processes of pressure reduction (Nelson and Montana 1992): during this process, when the magma is saturated with high velocity climbs into lower depths, the vapor pressure of the system increases, and the stability of the plagioclase crystals decreases and crystalline dissolution occurs (Blundy and Cashman 2005) filled with molten cavities, and after recrystallization, these cavities are encosed whitin the crystal and the sieve texture is formed in the crystal. Sieve texture is the result of this process of large size (Nelson and Montana 1992). Mainly large coagulants are observed in the center of plagioclase phenocrysts. (Stewart and Pierce 2004) argue that the instability of plagioclase crystals during the fast moving upward magma causes the formation of sieve texture in them. Because some parts of the plagioclase are melting partially and the products of melting inside the crystal begin to crystallize. Given that the temperature drop is rapid or slow, these product crystallize in the form of a glass or a new plagioclase inside the primary plagioclase, leading to the emergence of sieve texture.

2) Magma mixing or reaction with high temperature calcium-rich molten magmatic processes occur at lower depths. Due to this process, the phenocrysts tolerate dissolution in interaction with high-calcium molten liquid (Tsuchiyama 1985). After the dissolution, the crystals react in a new condition to stabilize the molten state and recrystallize. The size of the sieve produced by this process is small, and studies have shown that anorthite rich plagioclase crystals are in high temperature, low pressure, and in a high- Ca/Al, Al/Si, Ca/Na low water content it is crystallized (Blundy and Cashman 2005; Nelson and Montana 1992).

4.2. Zoning

Zoning is one of the other non-equilibrium textures observed in the Plagioclase is in the rocks of the region (Fig 4) and consists of two causes:

a) crystallization of plagioclase from a melt undergoing continuous variations in temperature, water vapour pressure and composition (Humphreys et al. 2006).

b) Increasing the growth rate of the crystalline-molten joint in response to equilibrium conditions (Ginibre et al. 2002a). In magmatic reservoir, magma is affected by dynamic activities such as convective flows or the entry of very hot calcium-rich magma or both. Following the effect of these processes, texture such small sieve texture, zoning and dissolution levels the facial shape is either in the margin of the previous crystals (Singer et al. 1995). In the long term, the crystal inside the molten is usually balanced between the combination of plagioclase and magma composition and no zoning. Conversely, the presence of zoning indicates a slowdown in the speed of equilibrium with respect to the crystallization rate (Shelley 1993). Therefore, the presence of zoning in plagioclase seems to be due to the rapid cooling of the mass margin and possibly due to rapid changes in temperature. Studies (Ustunik et al. 2013) on the zoning in plagioclase showed that by increasing or decreasing the pressure, the percentage of anorthite decreased or increased by about 3 mole per 1 Kb (Fig 5). Plagioclase phenocrysts with zonation of anorthite, strontium, iron, and magnesium represent magnesium rich in strontium in a volcanic system (Ginibre and Worner 2007).

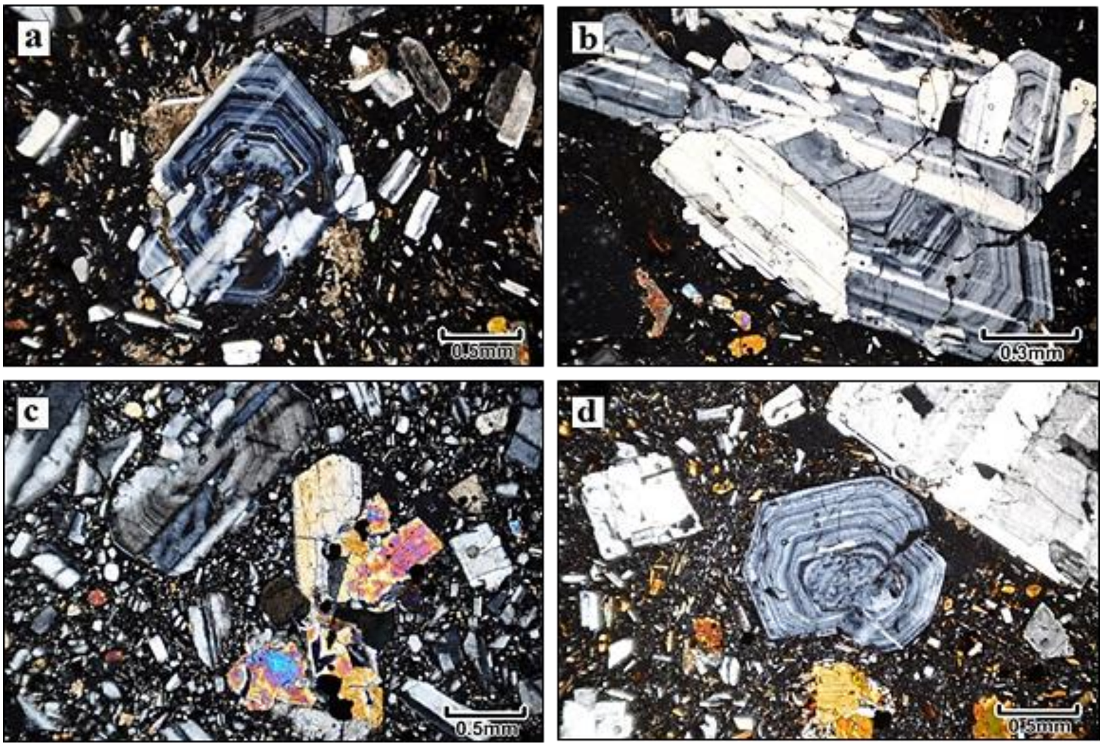

Fig 4. a, b, c) The presence of zoning in plagioclase in hornblende - pyroxene andesite (Light XPL); d) Presence of plagioclase zoning in hyalo andesite (Light XPL).

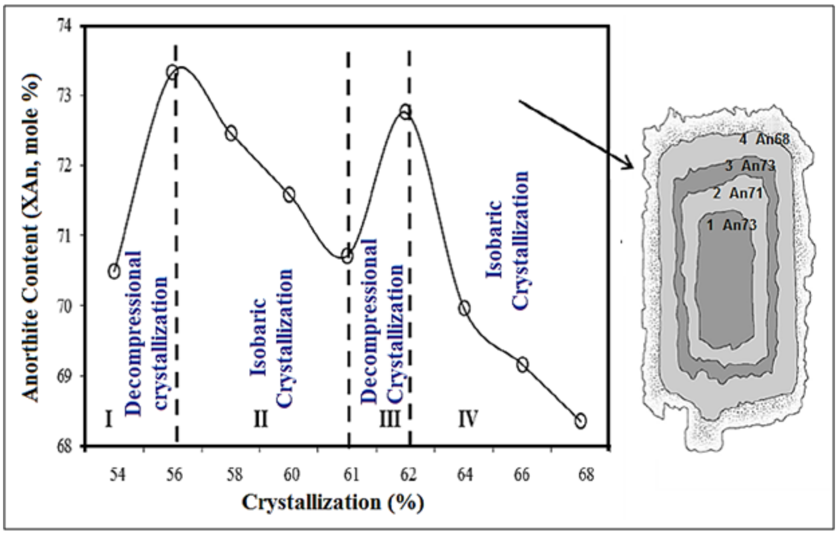

Fig 5. Changes in the amount of anorthite in plagioclase (in moles) with increasing crystallization percent under isobaric cooling condition (pressure) (Ustunisik et al. 2014).

4.3. Breakdown levels

This texture is seen on the margins of some of the plagioclase crystals of the region`s rocks (Fig 6a to d). These dissolution levels indicate changes in temperature, pressure, melt composition and magma water content. Because of the warming of the plagioclase above its freezing point or the re-magnetization of magma, crystals undergo a process of dissolution and melting. These crystals then reactivate and recrystallize with new magma. Significant changes in the composition and presence of levels of dissolution in plagioclase and pyroxene, and the presence of zinc oxides of magnesium and pyroxene-rich chromium olivine-rich Fe-Ti oxides indicate that magma mixing has been an important and influential process on the magma system (Sosa et al. 2014).

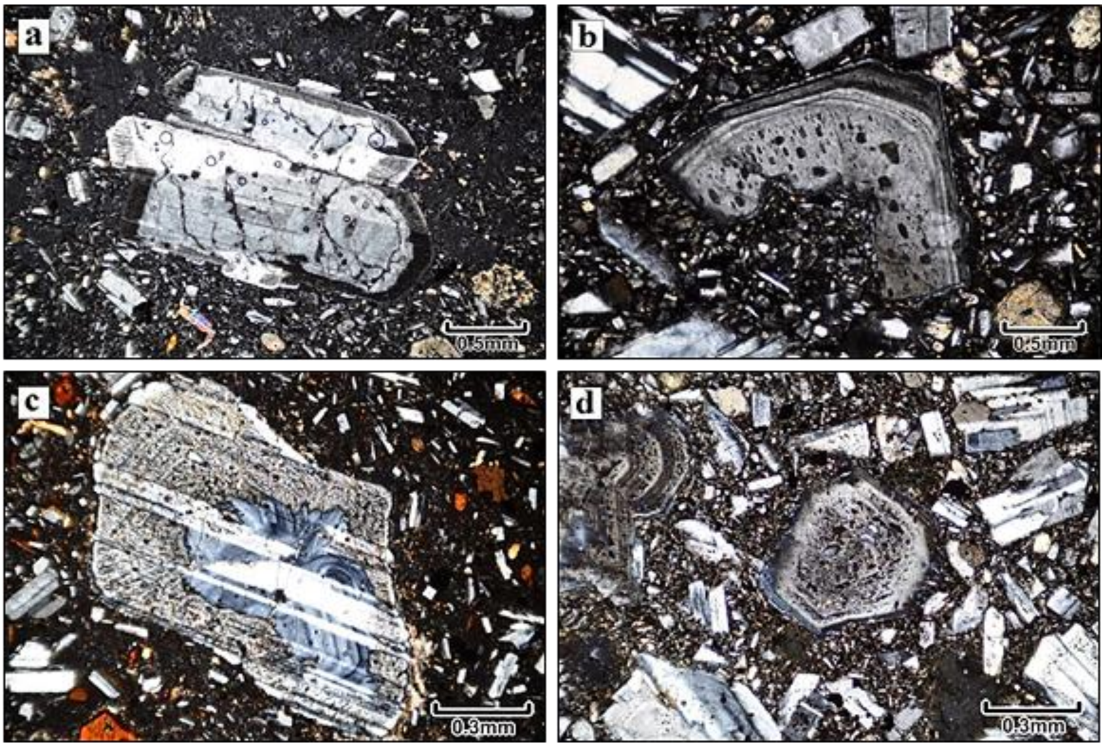

Fig 6. a) Collapse with Sieve texture in plagioclase crystals in trachy-andesite. b) Solubility with zoning and sieve texture of plagioclase crystal in pyroxene andesite (light XPL); c) Collapse with zoning and sieve texture of plagioclase crystal in pyroxene andesite (light XPL); d) Dissolution texture with zoning texture in plagioclase crystal in trachybasalt (light XPL).

4.4. Microlites

The presence of Microlites in samples may be due to the rapid cooling of lava (Lofgren 1980) or the increase in the temperature of liquidus magma during a magma eruption. In these conditions, the reduction of pressure causes the exhaust of gases, bubbles and solution of water, and this formation texture (Suzuki et al. 2007; Toramaru et al. 2008) (Fig 7a and b).

5. Plagioclase mineral chemistry

Plagioclase is the most abundant mineral in the rocks of the region, which is represented by both coarse crystalline and microlite forms. Petrographic evidence suggests a moderate alteration effect on this plagioclase, and as a result, secondary minerals can be found in sericite, calcite, chlorite, clay minerals and, as a result, sulfurization phenomenon. Five fine sections have been selected from the outcrops of the selected region and have been subjected to the Cameca Sx100 electron microprobe model at the Iranian Mining Research Center. In figure 8, spot analysis is shown in some of the region`s plagioclase on an electron microscope (BSE). On the Or-Ab-An diagram of (Deer et al. 1992), plagioclase of igneous rocks of the region is within the boundaries of labradorite and bytownite (Fig 9).

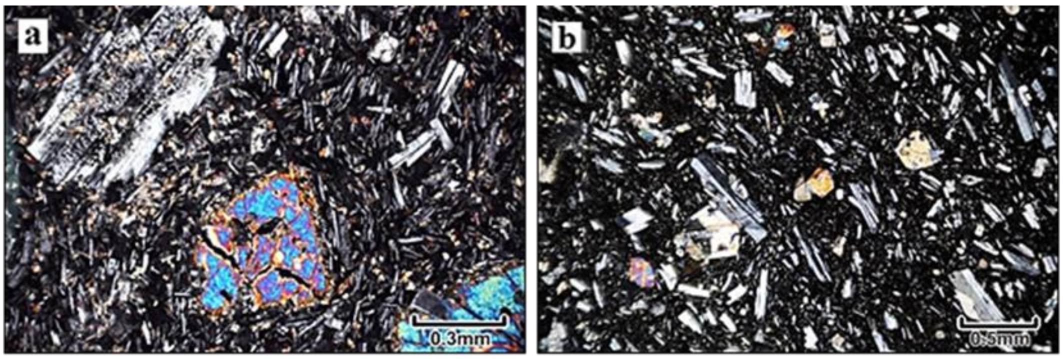

Fig 7. a) Phorphyritic texture with glassy ground mass to fluidal, corrosion of the plagioclase crystalline margin and pyroxene in alkali olivine basalts (light XPL); b) Microlitic fluidal texture in hyalo- pyroxene andesite (Light XPL).

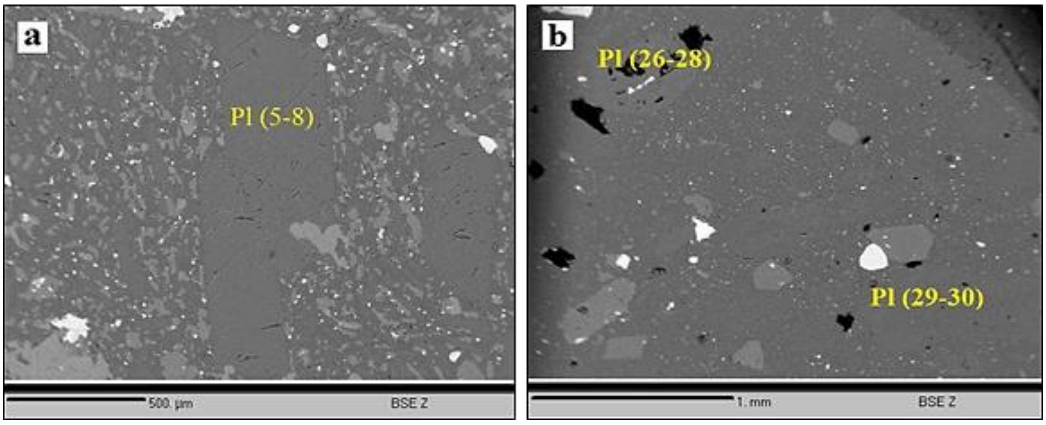

Fig 8. a) Electron microscopic (BSE) image of decayed plagioclase points in the A141 sample, which is related to the olivine basaltic rocks. b) and the A77 sample of the pyroxene andesite rocks.

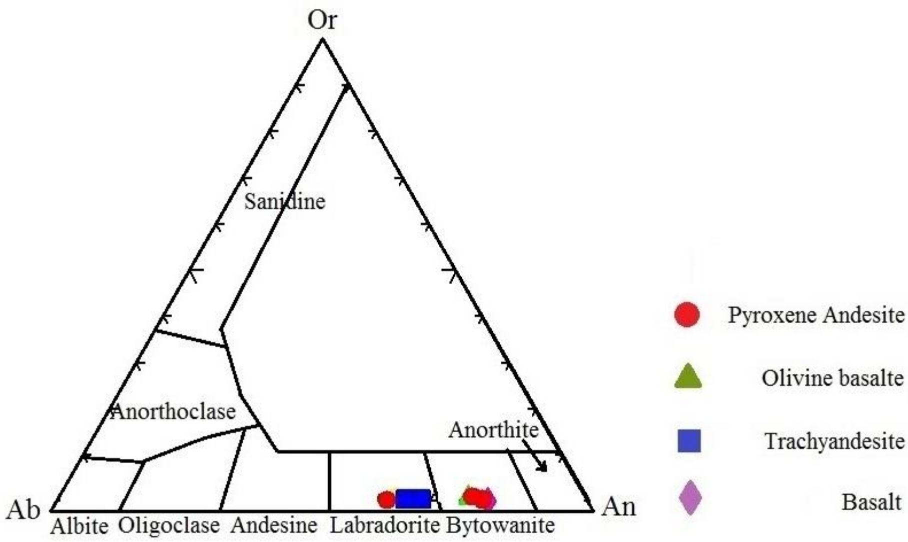

Fig 9. Determination of feldspar composition of igneous rocks in the area (Deer et al. 1992).

6. Discussion

The analysis of magma textures gives us valuable information about magmatic processes. The formation of non-equilibrium textures (sieve texture, zoning and reactive margin) usually depends on the change of independent variable (pressure, temperature, and chemical composition) that overlaps the previous state of equilibrium (Perugini et al. 2003). These textures are produced by chemical and thermal changes that are likely to result from the transfer of crystals to the other part of the magma, the melt flow between the earlier formed crystals or the progressive differentiation of the molten metal (Arvin et al. 2003). From the above textural observations a simplified magma plumbing model is envisaged for the studied lava unit. At the initial stage, water saturated high temperature magma have undergone extensive crystallization at deeper chamber in a stable magmatic environment produced optically clear An-rich plagioclase (Fig. 10). When this crystal-rich magma ascent to shallow chamber, these crystals have undergone varying rate of dissolution that causes the development of CS morphologies with varying size, shape and density. Just after the dissolution event many crystals have got unitedas glomerocrysts which subsequently re-grew as a single grain (Fig 10), while others have re-grown by manteling on CS cores. Crystals born after the decompression events are devoid of CS morphology as they represent smaller and medium size phenocrysts (low an content) in the lava unit. Some researchers believe that the reduction in combined combinational pressure and the presence of sieve and normal plagioclase in a sample cannot be justified (Kuscu and Floyd 1999; Ghaffari et al. 2014). There is a strong evidence that the imbalance in magma is heterogeneous, such as a large different in non-equilibrium textures in single-phase crystals (Perugini et al. 2003). Also, if the percentage of coarse- grained anorthite is less than the percentage of anorthitic plagioclase being in equilibrium with the molten material, the crushed layers in a sieve texture are rugged and prominent, and filled with magma (Tsuchiyama 1985). In this case, the plagioclase reacts and becomes calcite. If acidic magma and basic magma get mixed together, the feldspar sodic of the barely dissolved in acidic magma and the sieve texture emerges, and eventually the edges will be calcic by the reactions.

Plagioclase crystals are divided into two categories in size. Small crystals (<1mm) and large (3-5 mm), which is show respectively, younger and older crystals, the size and the way the crystals communicate, can be used to find out how they crystallize (Yu et al. 2012). The nucleus of the large plagioclase, the older plagioclase, is shown. The presence of the large sieve texture in the nuclei rich in large anions of plagioclase and the absence of this texture in the nucleus of small plagioclase indicate the crystallization of these crystals in the next stage. Some of the plagioclase crystals whit large sieve texture with magma are reacted and re-crystallize and comprise texture such as small sieve texture or volatile at the margin. Textures such as small Sieve, zoning and dissolution rates are formed following the change in the dynamic conditions of the lower magmatic nest through convection flows or the entry of very hot calcium magmas after texture such as glomerocryst and coarse-scale screening.

During the self-mixing process the magma chamber might have experienced undercooling by degassing or water exsolution followed by violent aerial eruption producing microlites, broken and swallow - tail crystals (Fig 10). Table 1, shows the type of plagioclase of the rocks of the area by the Spreadsheet. Increased water vapour pressure, sudden ascent of magma and the formation of unbalanced magma conditions reduce the amount of anthritis and increase Fe and Mg levels in plagioclase, respectively (Ahmadi et al. 2017).

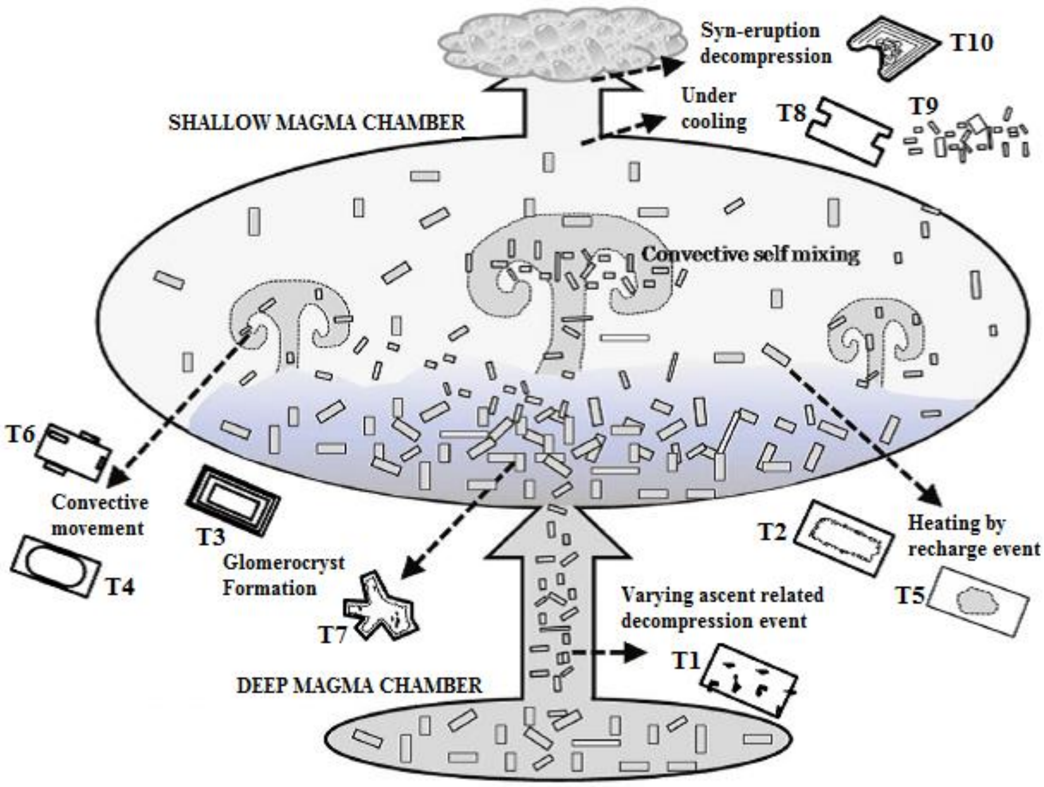

Fig 10. Cartoon illustrates model of crystallization dynamics and magma plumbing system for the aa lava erupted. A deep magma chamber feed crystal-rich magma into the base of a shallow chamber where the newly brought crystals and pre-existing crystals are undergoing dynamic crystallization in a convective self-mixing environment. Micro-textures (T1 to T10) developed in plagioclase at various stages of magmatic evolution are schematically illustrated (after Renjith 2014).

Table 1. Analysis of the plagioclase in volcanic rocks and determining the type of plagioclase using Spreadsheet.

Sample	A123	A141	A25.1	A25.2	A29	A77.1	A77.2	A77.3	A77.4
Analysis	Ol.Bas.	Ol.Bas.	Tr.And.	Tr.And.	Bas.	Px-And.	Px-And.	Px-And.	Px-And.
oxide	wt %	wt%	wt %	wt %	wt %	wt %	wt %	wt %	wt %
SiO_2	53.55	52.96	52.72	53.18	49.76	51.96	55.43	50.13	51.69
TiO_2	0.06	0.02	0.04	0.05	0.02	0.01	0.00	0.01	0.03
Al_2O_3	28	28.64	27.94	27.79	30.19	30.87	29.17	32.90	30.74
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	0.72	0.6	0.61	0.69	0.56	0.12	0.16	0.11	0.20
MnO	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.00	0.02
MgO	0.15	0.11	0.13	0.16	0.09	0.13	0.06	0.02	0.07
CaO	12.91	14.43	13.94	13.24	16.61	13.78	11.70	14.53	14.58
BaO	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	3.96	2.33	3.52	3.84	2.16	1.89	3.95	1.76	2.18
K_2O	0.17	0.1	0.09	0.09	0.03	0.05	0.03	0.00	0.16
total	99.54	99.2	98.99	99.08	99.44	98.83	100.50	99.47	99.67
Si	2.45	2.46	2.44	2.45	2.30	2.43	2.51	2.32	2.39
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.51	1.57	1.52	1.51	1.65	1.70	1.56	1.80	1.67
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2	0.03	0.02	0.02	0.03	0.02	0.01	0.01	0.00	0.01
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01
Ca	0.63	0.72	0.69	0.65	0.82	0.69	0.57	0.72	0.72
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.35	0.21	0.32	0.34	0.19	0.17	0.35	0.16	0.20
K	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01
An (%)	63.66	76.90	68.28	65.23	80.81	79.84	61.96	82.02	77.90
Ab (%)	35.34	22.47	31.20	34.24	19.02	19.82	37.85	17.98	21.08
Or (%)	1.00	0.63	0.52	0.53	0.17	0.34	0.19	0.00	1.02

7. Conclusion

Glomero-porphyritic, amigdaluidal and sieve are also the other textures in plagioclases of the rocks in the studied region. The study and interpretation of these textures provides information on the effect of magmatic processes on the crystallization of a crystal from a magmatic nest to magma eruption. The texture in the plagioclase of the region`s rocks of a large scale, irregular, and occasionally associated with zoning, and growth of the crystals. Of course, glomerular crystals, and microlites are also formed during magnetically dynamic processes such as convective flows, get out of gas or explosive eruptions, and in the final stage during or before the magmatic eruption. The coarse-grained texture is more common in the rocks of the region as a result of decreasing pressure, temperature and variation in the magma composition, while in the various types of intermediate rocks the region has a finely divided sieve texture due to the mixing of magma (the entry of calcium-rich magma in store intermediate magma).

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