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Amygdaloidal and other Cavity Filling Zeolites of Kuh-e-Aradeh, Central Iran

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Abstract

Amygdaloidal, cavity- and fracture-filling zeolites in Eocene volcanic rocks from the Kuh-e-Aradeh of southern Kahrizak, in the northernmost part of Central Iran have been studied in some detail by optical, chemical analysis, SEM, and XRD techniques. The zeolites identified, in order of their relative time of formation from early to late, are tetranatrolite, analcime, natrolite, mesolite, stilbite-Ca, scolecite and heulandite-Ca. Formation of zeolites in the studied region began with a sodium zeolite of low Si/Al ratio and, with the gradual increase in calcium content and Si/Al ratio, ended with calcium zeolites. The zeolites were probably formed as a result of the late-stage hydrothermal activity in 60-150°C spans. Other associated secondary minerals in the region are calcite, opal, quartz, and pyrolusite. Chemical analysis of the host rocks showed that they are mostly andesitic, or, to a lesser extent basaltic, and the composition of one zeolite-bearing dyke is potassic trachybasalt.

Keywords: Zeolite; Hydrothermal; Sequence; Amygdaloid; Cavity; Kuh-e-Aradeh; Central Iran

1. Introduction

There are very few reports available in the literature concerning zeolites and associated minerals in amygdales, cavities, and veins in the mafic or intermediate volcanic rocks of Iran. Analcimite of the Teic Dam in the Eastern Azarbaijan, northwestern Iran, was first reported by Comin-Chiaramonti [8]. The zeolites of northeastern Azarbaijan in shoshonitic volcanics were then studied by Comin-Chiaramonti *et al.* [9]. Alberti *et al.* [1] have studied the mesolites of the Harbabkhandi region in Azarbaijan, Iran. Formation of analcite in volcanic rocks of Iran was studied by Darvichzadeh [11]. Natrolite and thomsonite were found in the Rude-Hen region of Demavand and later were reported by Hedjazi & Ghorbani [20]. Zeolitization in andesite of south Kahrizak at the northern-most part of Central Iran was studied by the authors [3]. We have also studied amygdaloidal- and vein-zeolites of Siahkuh, and Kuh-e-Davazdah Emam in Central Iran [4]. Some Iranian natural zeolites were characterized by Faghihian and Maccizadeh [13].

The present area of study, Kuh-e-Aradeh, is in a mountainous part of south Kahrizak. The aims of this study are zeolite recognition in amygdales, cavities in different andesitic and basaltic host rocks, finding the sequence of formation of zeolites and other associated minerals and giving an interpretation of their origins.

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Chemical analyses of the host rocks, their abundant zeolites, and that of one nearly pure stilbite sample are given. The chemical composition of the stilbite is compared with those in Oregon [22], Deccan Traps [33] and the Morden area [29].

2. Geological Setting and Field Relationships

Kuh-e-Aradeh, 900-1500 m above sea level, is located in the southern part of the Kahrizak region, 40 km from the old Tehran-Qom road (Fig. 1). In Central Iran, a post-Cretaceous, early Eocene diastrophism was very active, causing folding, magmatism, and uplifting [6]. The conspicuous basal conglomerates and breccias, including large boulders of underlying formations, indicate a pre-Middle Eocene relief. Angular unconformities up to 90° have been observed [15]. The Laramide orogenic movements are recorded in steep folding of Cretaceous deposits that are overlain by late Paleocene and Eocene rocks along prevalent angular unconformities [5]. No significant volcanic or plutonic events during the Paleocene are reported for the Central Iran.

The field relationships at the mountain have been studied in detail by Rieben [31] and Hajian [19]. Razavi [30] studied the field relationships and petrography of the volcanites and pyroclastics of the region. The Kuh-e-Aradeh consists of Eocene volcanites and pyroclastics which extend gently from base to peak. The field relationships and stratigraphic succession can be summarized as follows.

- The mountain constitutes mostly of about 300 m of dacitic to andesitic tuffs coloured white, gray to green and locally light brown to pink due to weathering. These tuffs continue north, south and locally west of Kuh-e-Aradeh. Many fractures at different directions were found in the tuffs. The fractures in the north and east contain calcite, barite, and pyrolusite.
- The zeolite-bearing andesite, basalt, andesitic- and basaltic-agglomerates are about 130 m thick and show locally conspicuous alteration that is mostly dark-gray to brown-gray and dark-green. The zeolite content of the rocks is as much as 15% by volume, approximately. Zeolites are mostly in amygdales, vugs of a few millimeters to 20 cm in size, veins of up to 2 m long and 10 cm thick, and veinlets (Fig. 2). Andesitic and basaltic agglomerates with breccias occur underneath of the rocks.
- More than 50 m thick of pyroxene-bearing andesite, dacite, trachyte and andesitic basalt occur with less alteration, and are coloured mostly gray, or light-brown to dark-brown.

The above mentioned assemblage is cut by several faults that trend almost northerly and west northwesterly. The vertical displacement of the faults is locally more than 30 m. The faults have not cut the marginal post-Eocene sedimentary rocks of Kuh-e-Aradeh.

The dykes of the Kuh-e-Aradeh region are silicic to mafic, coloured mostly dark-gray, burned-brown to dark-brown and variable in thickness up to 4 m. These dykes have cut most of the volcanic rocks, especially the zeolite-bearing andesites and basalts. Only one dyke of potassic trachybasalt composition and containing zeolite was found west of Kuh-e-Aradeh. No intrusive rock was apparent in the whole region. The rocks occurring above and below the zeolitized zones were dense without cavities.

Hydrothermal solutions in welded tuffs, fractures and faults formed deposits of pyrolusite and barite [30]. Several veins of barite, about one m thick, were found in the northern part of Kuh-e-Aradeh. The barite veins were exploited and then abandoned.

3. Material and Methods

More than 150 representative samples were hand picked from over an area of 50 km^2 at Kuh-e-Aradeh. Forty samples were selected to make thin sections for mineral sequence determination, and paragenesis studies by binocular microscope. Thirty five samples were ground to fine powder and analyzed by the powder X-ray diffraction method using Cu Kα radiation. The diffractograms were then compared with standard mineral diffractograms from PDFs. Each reported zeolite structure was initially confirmed by powder X-ray diffraction data on different zones, as schematically shown in Figure 3. Thin section surfaces of the minerals were coated with Au under vacuum conditions and examined by scanning electron microscopy (SEM) (Philips XL30), equipped with an EDX spectrometer. Electron microprobe analyses were done on the same samples already identified by binocular microscope and X-ray diffractometer whenever necessary. The water content of the zeolites were calculated based on their ideal stoichiometric chemical formulas. Wet chemical analysis was also performed on three host rock samples, one nearly pure stilbite and one heulandite specimen. Polished sections were made for the identification of a few ore mineral samples. X-ray diffractions and wet chemical analyses were done at Geological Survey of Iran. SEM experiments were performed at Tarbiat Modarres University.

4. Chemistry

Three typical zeolite-bearing host rocks, one from a

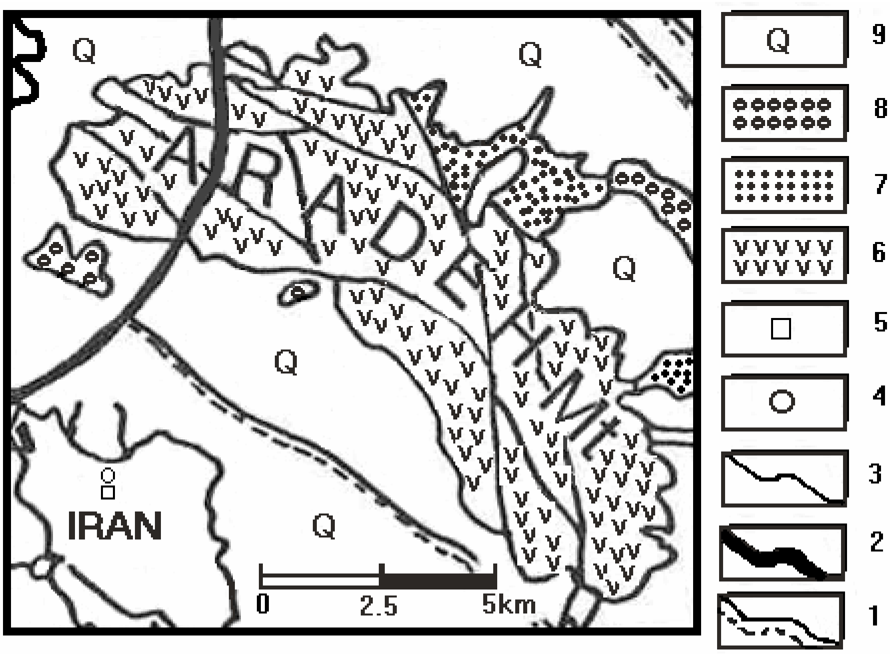

Figure 1. Index and geological sketch map of Kuh-e-Aradeh (Aradeh Mountain), south Tehran (modified from Geological quadrangle map of Iran No. F5, Tehran, 1987).

1) Asphalt road. 2) Old Tehran-Qom road. 3) Faults. 4) Tehran. 5) Location of the studied area. 6) Eocene volcanic and pyroclastic rocks. 7) Neogene sandstone and mudstone, gypsiferous. 8) Plio-Pleistocene conglomerate. 9) Quaternary alluvium.

Figure 2. Amygdaloids, veins and veinlets filled by zeolites in andesitic rocks.

zeolite-bearing dyke and the two others from the western part of Kuh-e-Aradeh, were chemically analyzed. The results of the chemical analyses are given in Table 1. Based on the classification of Le Bas *et al.* [24], the chemical analyses show that the host rock in the dyke is potassic trachybasalt, while the two others are basalt and basaltic trachyandesite.

Among the zeolites detected in the study area, stilbite was found in its almost pure form. Wet chemical analysis was then performed for the stilbite sample and compared with stilbites from other localities, viz; the Deccan Traps [33], Oregon [22], south Kahrizak [3], those reported by Gottardi & Galli [16] and those from the Morden area [29]. The comparative results are given in Table 2. The composition of the stilbite of Kuh-e-Aradeh, based on 72 oxygen atoms is $(Si_{26.66}\ Al_{9.41}\ Fe^{3+}_{0.02})\ (Ca_{4.04}\ Na_{0.65}\ Mg_{0.18}\ K_{0.04})\ O_{72}.28.61\ H_2O$. The calculated balance of errors for the stilbite is +3.45%, so the chemical analysis is reliable [16]. The comparative results show negligible variation in the major oxide contents. Ca is the most abundant extra framework cation. The measured T_{Si}, 0.74, is out of the T_{Si} ranges reported [10] for other zeolites of similar structures, stellerite (0.75-0.78) and barrerite (0.77, 0.78), while it is within the T_{Si} range reported for stilbite (0.71-0.78).

The results of chemical compositions, from electron microprobe analyses, and relevant unit cell contents of the more abundant zeolites from the Kuh-e-Aradeh are given in Table 3. The "balance of errors" calculated for the results show that all of them are within limits of permissible error (±10%).

The "balance of errors", E%, of the analyses have been calculated on the basis of formula adapted by Gottardi & Galli [16].

5. Secondary Mineral Assemblage

Zeolites and other secondary minerals of the study area were found in vugs, veins, and to a lesser extent in veinlets and in very rare cases as replacements of pyrogenic minerals. The veins were up to several centimeters thick and as much as few meters long. The samples were collected mostly from the northwestern and southeastern parts of Kuh-e-Aradeh on both sides of the old Tehran-Qom road. The drusy vugs are spheroid, ellipsoidal, and locally bottle- or grotesquely-shaped. They are generally about 1 cm in diameter but locally are up to 20 cm. The vugs are commonly in separate units but locally coalesce with each other. The zeolites present are tetranatrolite, natrolite, mesolite, scolecite, heulandite-Ca, stilbite-Ca, and analcime. Most amygdaloidal and vein zeolites are relatively coarse-grained and easily identified. However, most zeolites in altered plagioclase and veinlets were fine-grained aggregates and extremely difficult to identify.

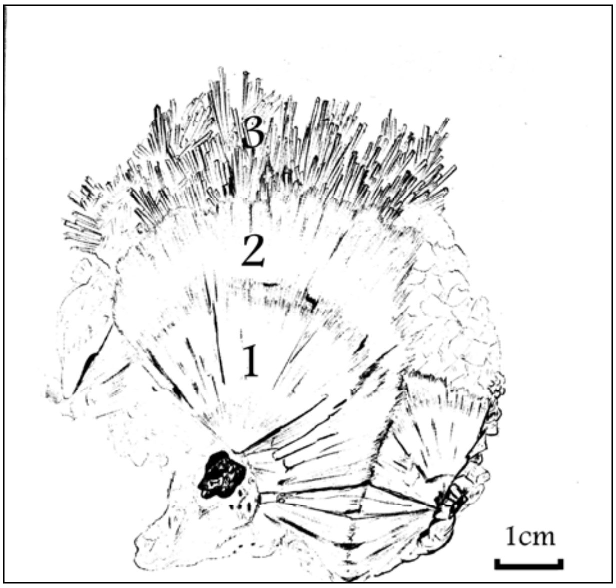

Figure 3. A pattern of a cavity zeolite. The black spot shows the starting point of formation of different zeolite zones. In this pattern Three different zones. natrolite (zone 1), tetranatrolite (zone 2) and mesolite (zone 3) are distinguishable. Each zone has a common region with next zone.

Table 1. Chemical analyses (wt.%) and classification* of host rocks of the zeolites in Kuh-e-Aradeh

Oxide	Potassic trachybasalt	Basalt	Basaltic trachyandesite
SiO_2	46.16	45.15	49.38
Al_2O_3	19.71	23.00	14.53
Fe_2O_3	9.92	7.47	13.93
TiO_2	1.10	0.83	1.14
MgO	3.29	4.50	4.47
MnO	0.17	0.11	0.18
CaO	7.32	9.60	2.43
Na_2O	3.42	3.00	5.39
K_2O	2.26	0.51	2.21
P_2O_5	0.10	0.26	0.62
SO_3	1.04	1.29	–
L.O.I	5.02	4.10	4.76
Total	99.51	99.82	99.04

* Based on the classification of Le Bas *et al.* [24]

Table 2. Chemical analysis and formula on the basis of 72 oxygens of the stilbite-Ca from Kuh-e-Aradeh and relevant analyses of stilbite from the literature

	K.A.	S.K.	Oregon	1	1	1	2	2	3	3
SiO_2	56.73	56.50	57.89	55.49	54.72	55.26	51.97	56.85	57.21	58.41
Al_2O_3	17.00	17.46	15.56	16.30	17.90	16.70	18.34	15.58	16.20	15.86
Fe_2O_3	0.07	0.00	0.08	0.00	0.00	0.00	0.03	0.08	n.d.	n.d.
MgO	0.25	0.00	0.00	0.55	0.40	0.45	0.03	0.06	n.d.	n.d.
CaO	8.03	8.63	7.76	7.85	7.90	7.95	7.88	7.89	8.20	7.75
Na_2O	0.71	1.06	0.86	1.00	1.10	1.20	2.73	1.00	0.59	1.12
K_2O	0.07	0.00	0.02	0.03	0.02	0.25	0.22	0.03	n.d.	n.d.
H_2O	18.25	16.33	18.43	18.70	18.92	18.44	18.85	18.55	-	-
Total	101.11	99.98	100.60	99.92	100.96	100.25	100.05	100.04	82.20	83.14
Si	26.65	26.40	27.33	26.64	26.06	26.43	25.34	27.14	27.02	27.26
Al	9.41	9.61	8.66	9.22	10.04	9.41	10.54	8.76	9.02	8.73
Fe^{3+}	0.02	0.00	0.03	0.00	0.00	0.00	0.01	0.03	n.d.	n.d.
Mg	0.18	0.00	0.00	0.39	0.28	0.32	0.02	0.04	n.d.	n.d.
Ca	4.04	4.32	3.92	4.04	4.03	4.07	4.12	4.03	4.15	3.88
Na	0.65	0.96	0.79	0.93	1.02	1.11	2.58	0.93	0.54	1.01
K	0.04	0.00	0.01	0.02	0.01	0.15	0.14	0.02	n.d.	n.d.
H_2O	28.61	25.46	29.04	29.96	30.07	29.44	30.68	29.55	-	-
Si/Al	2.83	2.75	3.16	2.89	2.59	2.81	2.40	3.10	3.00	3.12
E%	+3.45	+0.14	+0.42	-6.01	+4.03	-6.38	-4.04	-3.36	+2.04	-0.46

K.A.= Kuh-e-Aradeh, present study. S.K.= South Kahrizak, Iran [3]. Oregon, USA [22]. 1, Deccan Traps, India, [33]. 2, Gottardi & Galli [16]. 3, Morden area, Canada, Pe-Piper [29].

The rocks above and below the zeolitized zones were dense without any cavities. The zeolites and associated secondary minerals in andesite and basalt were sequentially deposited from the outer wall to the center of drusy vugs and veins. The description of the zeolites in order of decreasing abundance follows:

− Natrolite is closely associated with tetranatrolite and mesolite, and generally postdates tetranatrolite. This mineral characteristically forms compact aggregates of small acicular or, sometimes, bladed crystals, commonly hemispherical in form with a radiating structure and commonly associated with tetranatrolite and/or mesolite as a vug- or vein-lining. Natrolite is commonly white or colourless but locally is brownish or yellowish tufts coloured by iron oxide. The crystals are up to 1 cm long. Earthy natrolite samples were very fine-grained and occurred as yellow-brown aggregates of up to 3 mm.

− Tetranatrolite is considered to have a debatable structure [10]. Artioli and Galli [2] have reasoned for discreditation of tetranatrolite in favour of the gonnardite structure; whereas Evans *et al.* [12], have so proof of a validation of its structure. The results of this study seem to be in agreement with the assumptions of Evans *et al.* [12]. The T_{Si}=0.61 calculated for the analyzed tetranatrolite is slightly in excess to that of gonnardite, 0.52-0.59, [10]. If tetranatrolite is the same as gonnardite, as proposed by Artioli and Galli [2], the range of T_{Si} can be extended up to 0.62 [10]. The calculated T_{Si}, 0.61, thus will be within the reported range. Based on the discussion of Evans *et al.* [12], the ranges of Ca ion content of tetranatrolite and gonnardite are 0-4 and 0-8 per formula respectively. While the Ca ion content of the analyzed tetranatrolite in this study, 2.52 per 72 O atoms, is within the range of both zeolites; the Na ion content, 10.65, lies in the range of tetranatrolite (4-16), and not within that of gonnardite (12-16). This evidence seems to be in favor of the tetranatrolite structure.

Table 3. Selected electron microprobe analyses of abundant zeolites from Kuh-e-Aradeh

Oxide	Tet.	An.	Nat.	Mes.
SiO_2	48.65	52.90	50.62	48.89
Al_2O_3	26.15	24.85	26.38	24.95
Fe_2O_3	0.06	0.02	0.05	1.10
MgO	0.00	0.48	-	0.87
CaO	4.67	0.39	1.04	8.09
Na_2O	10.93	12.73	14.64	4.70
K_2O	0.06	0.09	0.08	0.34
H_2O	9.47	8.54	8.17	11.06
Total	100.00	100.00	100.98	100.00

Number of ions on the basis of:

	80 O	96 O	80 O	240 O
Si	24.50	30.92	24.79	75.92
Al	15.49	17.08	15.20	45.57
Fe^{3+}	0.02	0.01	0.02	1.28
Mg	-	0.42	-	2.02
Ca	2.52	0.24	0.54	13.46
Na	10.65	14.40	13.88	14.13
K	0.04	0.07	0.05	0.68
H_2O	15.90	16.54	13.34	57.25
Si/Al	1.58	1.81	1.63	1.67
E%	-1.40	+8.26	+1.40	+2.39

Tet. = tetranatrolite, An.= analcime, Nat.= natrolite, Mes. = mesolite

Tetranatrolite was the first zeolite to form on the wall of vugs and veins of the Eocene andesite and basalt of Kuh-e-Aradeh. It generally is formed after calcite deposition and is associated with fibrous species of natrolite and/or mesolite. Evans *et al.* [12] state that calcium-free natrolite first crystallizes; “paranatrolite, becomes the stable phase and begins to crystallize epitaxially on the prism faces of precursor natrolite” and, “paranatrolite will dehydrate to metastable tetranatrolite.” In the region of Kuh-e-Aradeh no calcium-free natrolite or paranatrolite species was found before tetranatrolite formation in all studied samples. It seems that the high Ca ion availability and other conditions in the samples studied has been facilitated the formation of tetranatrolite prior to any other relevant species. The Si/Al ratio in the analyzed sample of tetranatrolite, Table 3, is less than that of natrolite and all other zeolite samples formed sequentially after tetranatrolite. The trend of Si/Al ratio changes of the zeolites are discussed in the following section.

Tetranatrolite is locally abundant, forming irregular, chalk white aggregates and spherules up to 3 cm in diameter. Many samples show no crystal faces. Most specimens showed a succession of tetranatrolite-natrolite-mesolite. These three minerals commonly appeared as well-formed, large zeolite crystals. Only two specimens were tetranatrolite and/or analcime with natrolite.

- Stilbite-Ca was characterized by powder X-ray diffraction method and wet chemical analysis. The measured T_{Si}, 0.74, as described before, is very close to the lower limit reported [10] for stellerite (0.75-0.78), but far from that of barrerite (0.77, 0.78), of similar zeolite structures. Some other evidences such as X-ray single crystal data would probably resolve the complexity. However, at the moment it is beyond the scope of this study to resolve the complexity. So, it may thus be assigned as a probable structure of stilbite. The probable stilbite-Ca was commonly the last major zeolite to form in the vugs and veins of andesite and basalt of Kuh-e-Aradeh. It commonly occurs as very large tufts of nearly transparent lamellar crystals that are locally pink, red or black. The largest, up to 2 cm, and best-crystallized stilbite-Ca occurs with scolecite and/or heulandite-Ca that was deposited in the central part of cavities. The cavities were not completely filled but were still vugy. In one sample from the western part of Kuh-e-Aradeh, for example, a layer of stilbite covers the bottom of the cavity. In another sample, a coating of dark black stilbite was followed by calcite in the centre of the cavity. The dark black colour of the stilbite layer was attributed to the presence of manganese oxide, whereas pink, red or red to brown colours were attributed to the presence of iron oxide or iron hydroxide. Very rarely chalk white stilbite forms as radiating spherules up to 3 cm long. This type of sample was found in the western part of Kuh-e-Aradeh.
- Mesolite is generally associated with natrolite. Gunter *et al.* [18] also reported that “the crystals began growth as natrolite, and ended as mesolite”. This mineral normally developed as radiating acicular aggregates with 1-cm long fibres. It generally occurs as milky needles or tufts of delicate, silky fibres.
- Analcime was present as well-developed crystals, generally associated with tetranatrolite and natrolite. Fine specimens showed fresh transparent to milky crystals of up to 3 mm in diameter as found in the western part of Kuh-e-Aradeh. Only one specimen was recognized in a dyke at the western part of Kuh-e-Aradeh that contained analcime, tetranatrolite and natrolite.

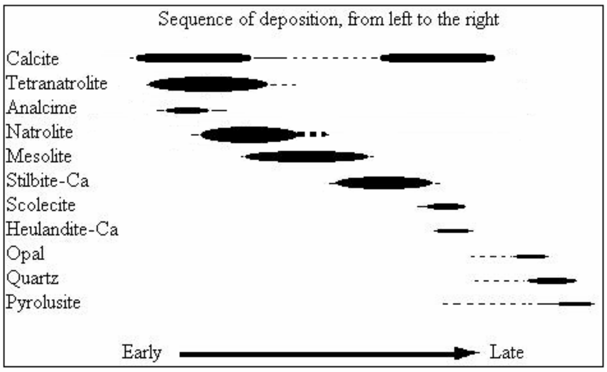

Figure 4. General paragenetic sequence of zeolites and associated secondary minerals in andesitic and basaltic veins and amygdales. Solid bars represent nesting shells of the minerals. The thickness of the bars show the relative amount of secondary minerals.

- Scolecite is a Ca-rich zeolite which occurs sporadically in the Kuh-e-Aradeh region. It seems to form in cavities after mesolite, either with or without stilbite.
- Heulandite-Ca seems to be the last zeolite to form in cavities with stilbite. It occurs as tabular, milky to pink glossy crystals of up to 3 mm in diameter. The Si/Al ratio for this sample is 2.88, which is the highest Si/Al ratio among all reported zeolites in this study.

It should be noted that there are also some very small amounts of other zeolite-like species which still require further investigation for their characterization. In the area studied, no regional zoning of zeolite assemblages was apparent.

Other secondary minerals present in the study area were calcite, types of crystalline and cryptocrystalline silica, and pyrolusite. Rhombohedral calcite was the first non-zeolitic secondary mineral to form in vugs, but scalenohedral calcite, when present, was always followed by the zeolites. Small amounts of crystalline and cryptocrystalline forms of silica occurred in association with zeolites, especially in the western part of Kuh-e-Aradeh. The silica minerals were quartz, chalcedony, opal, and a combination of chalcedony and quartz, termed zebra-banded silica. The colours varied from white, milky, gray to red. These silica phases were the last non-zeolitic secondary minerals to form in the vugs. However in one single sample pyrolusite was the last secondary mineral in the vug.

The whole paragenetic sequence of the secondary minerals was not observed in all samples of the study area (Fig. 3). The relative amount of minerals present in the samples was locally different in the east, west, and south parts of Kuh-e-Aradeh. The general paragenetic sequence in all samples, as shown in Figure 4, was invariant.

6. Discussion and Conclusions

A sequential formation of zeolites was demonstrated in an investigation on the zeolites and associated secondary mineral assemblages in samples taken from andesite and basalt of Kuh-e-Aradeh. From early to late, tetranatrolite, analcime, natrolite, mesolite, stilbite-Ca scolecite and heulandite-Ca were found sequentially in vesicles and vugs.

From chemical analyses of zeolites in the literature and those reported in this study, it seems that the formation of the zeolites began with a sodium zeolite of low Si/Al ratio (1.58), tetranatrolite, then by a gradual growth in calcium content and Si/Al ratio and ended with a calcium zeolite of relatively high Si/Al ratio (2.88), heulandite-Ca. The sequence of formation of the zeolites probably was in accord with the variation of Ca/Na, Si/Al ratios. It seems that any zeolite species, having a defined chemical composition, has been formed and stabilized in a definite temperature span. It also seems that the sequence of formation of zeolites was in accord with temperature gradient.

The zeolites are clustered in vugs and cavities without any evident reaction with the host-rocks. Our findings suggest that:

1) Chemical reactions were mainly achieved by thermal waters, common in volcanic areas [17]. Incipient alteration of andesitic and basaltic glass removed some Na, K, Ca and Si while Ti, Al and Fe were hardly mobilized [32]. A high activity of the carbonate ion caused the early precipitation of calcite, thereby removing much of Ca^{2+} ions and so leaving the water alkali rich [34]. Sodium zeolites, tetranatrolite, natrolite and analcime, were then deposited on the wall of vugs and veins, which in turn reduced the alkalinity of the solution. A decrease in alkalinity with a corresponding rise of silica activity, led to the formation of silica-rich phases as suggested by Comin-Chiaramonti, [8]. Mesolite, scolecite, stilbite-Ca and heulandite-Ca, with relatively higher silicon content, occurred as the next zeolite minerals deposited in vugs and veins. The latter zeolites which crystallized were indicative of a relatively lower temperature and, therefore, accumulation of more water and volatiles such as CO_2. Occurrence of a second generation of calcite, as the last sequence in crystallization of many cavities, may be interpreted as a result of higher CO_2 condensation at lower temperatures of the last stages of crystallization and thus more carbonate ion availability in Ca^{2+} -bearing solution.

2) Zeolite assemblages in amygdales, cavities and veins in intermediate and basic lavas have been interpreted as diagenetic [28, 27] or hydrothermal [22, 21]. Gottardi [17] believes that a continuum exists between these two, but prefers a hydrothermal hypothesis. Zeolitization in the Kuh-e-Aradeh region seems also to be hydrothermal. Evidence for the proposed hypothesis can be given as follows:

- Tetranatrolite was frequently found in the Kuh-e-Aradeh. Tetranatrolite is known only as a mineral of hydrothermal deposition [16],
- Fibrous zeolites, such as natrolite and tetranatrolite are frequent in the region in vesicles of andesites and basalts, but they are very rare as diagenetic minerals [17],
- The fine, large zeolite crystals are believed to have hydrothermal genesis [17]. Numerous fine, large zeolite crystals occurred in the study area [3].

3) Evidence for a temperature gradient come from the following.

The early formation of analcime and late formation of heulandite-Ca in the studied area suggest that the temperature of formation were less than 200°C and 150°C respectively [25,26]. The temperatures of formation for the type of zeolites of Kuh-e-Aradeh reported in literature are:

- laboratory experiments show that most Na-bearing zeolites are formed below 150°C [7]. Natrolite, tetranatrolite, and analcime are formed at the early stage of zeolite formation in vugs, and amygdales of the region studied.
- directly measured temperatures for analcime formation at Yellowstone Park were 125-155°C, [25].
- the temperature of mesolite/scolecite formation in the Iceland geothermal zone was estimated to be 65-80°C [23].
- stilbite-Ca, a common zeolite, forms at late-stage hydrothermal activity [14].
- the temperature range of heulandite formation reaches down to below 70°C [23].

It seems that the different zeolite species of Kuh-e-Aradeh were formed at different temperatures. The maximum and minimum temperatures of zeolite formation in Kuh-e-Aradeh region have been estimated to be around 150°C and 60°C, respectively.

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