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GEOCHEMISTRY AND MINERALOGY OF ZEOLITIC TUFFS FROM THE ALAÇATI (ÇEŞME) AREA, TURKEY

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Abstract—Silicic vitric tuffs of the Alaçatı (Çeşme) area, west of Izmir (Turkey), are partly altered to authigenic zeolites and clay minerals. Mordenite and clinoptilolite-heulandite accompanied by smectite are the main alteration products of the tuffs. Scanning electron microscope examination indicates that mordenite forms mainly from a gel-like precursor and to a lesser degree from volcanic glass. Mordenite and clinoptilolite-heulandite have formed by the hydrolysis and dissolution of silicic vitric tuffs by thermal waters which circulated through the fracture zone into porous vitric tuffs. These thermal waters, which resulted from mixing of thermal (Na-Cl type) and groundwaters, provided the extra Na and Ca that are necessary for the formation of mordenite. Various percentages of calcite are present in the altered tuffs. The enrichment of calcite in the altered tuffs indicates that thermal waters supply Ca, sourced from dissolution of Triassic carbonate rocks.

The alteration minerals in the Alaçatı (Çeşme) area do not seem to be laterally zoned. The occurrence of the zeolites seems to be related to inferred fracture zones trending NE−SW. These fracture zones are important because they provide porosity and permeability in the tuffs for zeolite formation. The large glass content and permeability of tuffs accompanied by the favorable hydrochemical condition resulted in zeolitization of the Alaçatı (Çeşme) area.

Key Words—Alaçatı, Alteration, Clinoptilolite-heulandite, Mordenite, Tuff, Turkey.

INTRODUCTION

Many deposits of volcanic ash have undergone diagenetic alteration to zeolites. Important zeolite deposits are associated with such materials in volcano-sedimentary environments. Phillipsite, clinoptilolite, heulandite and erionite are widespread in deposits of saline-alkaline lakes, in burial diagenetic environments, and in deep-sea sediments. Mordenite rarely occurs in these environments (Hay, 1978). In contrast, mordenite commonly forms as an alteration mineral in many geothermal areas, and its formation temperature is known to range from ~60 to 160ºC (Mas, *et al*., 2000). An example of mordenite formation was given by Mas *et al*. (2000) from the El Humazo geothermal area. Mordenite formation, described by Kitsopoulos (1997) in Polyegos Island in Greece, originated from the circulation of Na-rich hydrothermal fluids through volcaniclastic materials.

Sedimentary zeolite occurrences are widespread in Central and Western Anatolia. The most common zeolite occurrences are at Beypazar, Yozgat, Nevşehir (Cappadocia), Kırka, Emet, Şile, Bigadiç, Gördes and Keşan. In all these occurrences, except that located in the Şile area, the volcanic protoliths were deposited in lacustrine environments (Birsoy, 2002). The common zeolites reported in Turkish deposits are clinoptilolite, heulandite and analcime. Mordenite is a less common mineral and has been reported only from the Şile area. Until now, there has been no evidence to support the formation of zeolite in tuffs at the Alaçatı (Çeşme) area. This study is the first comprehensive investigation of tuffs in this area.

The aim of our study was to characterize the geochemistry, mineralogy and texture of the tuffs in the Alaçatı (Çeşme) area, to determine the degree of zeolitization, and to elucidate the processes that may be related to the zeolitization.

GEOLOGY AND HYDROGEOLOGY

Geology

Since the Neogene, an extensional tectonic regime has prevailed in western Turkey. Evidence for this is provided by the West Anatolia graben system. Geothermal fields in W. Turkey are associated with the fault zones of the grabens. The Çeşme geothermal field is one of these. The general tectonic lineaments are N−S- and NE−SW-striking gravity faults, forming grabens and horsts, which allow the hot waters to discharge along fault zones in the study area (Conrad *et al*., 1995; Gemici and Filiz, 2001).

Alaçatı (Çeşme) is located 70 km west of Izmir (Figure 1). The study area covers nearly 30 km^2 and the lithostratigraphic sequence is composed mainly of three

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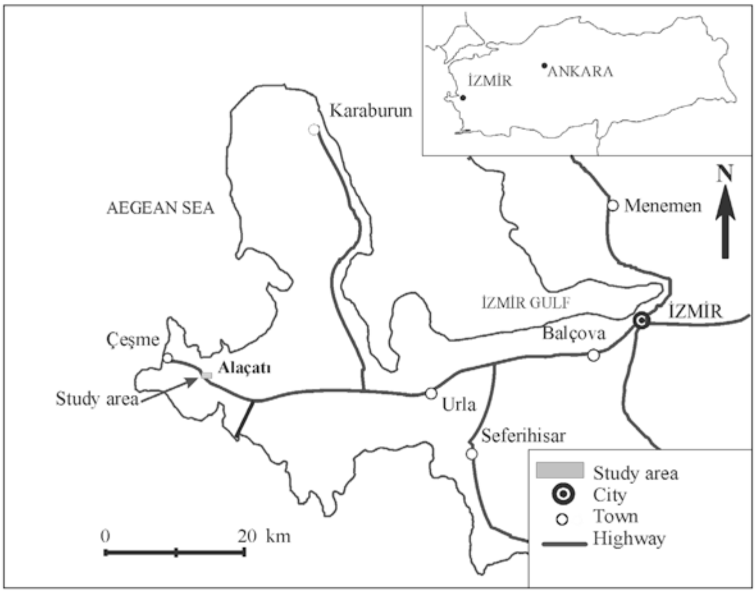

Figure 1. Location map of the study area.

units: (1) the Karadağ unit; (2) the Neogene unit; and (3) the Quaternary unit.

The Karadağ unit is the oldest unit and consists of late Triassic limestone. This limestone is highly fractured and has karstified morphology. It is overlain unconformably by the Neogene unit which occupies the lower elevation areas and covers most of the study area. The Neogene unit consists, from bottom to top, of sedimentary and volcanic rocks. The sedimentary rocks include clayey limestones and sandstones and the volcanic rocks consist chiefly of tuffs, tuffites and agglomerates. The contact between the sedimentary and volcanic rocks is transitional. The Quaternary unit is composed of slope wash and alluvium covers other units unconformably (Türkbileği and Aşıcı, 1988).

The tuffs are the most widespread pyroclastic rocks in the study area. The igneous protolith was acidic, probably of rhyolitic or dacitic composition (Türkbileği and Aşıcı 1988). The abundance of the tuffs increases towards the south, east and west of Alaçatı (Çeşme). The tuffs are white to light gray in color and range in thickness from a few m to 200 m. According to Türkbileği and Aşıcı (1988), although fractures are common in tuffs, they are difficult to identify due to the softness of the tuffs. They strike N–S and NE–SW in direction and are considered important because they increased the secondary porosity and permeability of the tuffs.

Hydrogeology

Previous studies (Conrad *et al.*, 1995; Gemici and Filiz, 2001) concluded that the thermal waters of the Çeşme geothermal field are heated in reservoir rocks, and then penetrate through faults and karstic structures and move towards the surface along the N–S and NE–SW striking fractures. Triassic karstified limestones are the main reservoir rocks and Neogene sediments and volcanic rocks are the cap rock of the system. The heat source probably arises through increasing geothermal gradient caused by the magma which came closer to the surface because of faulting during graben tectonism. Discharging of thermal springs is directly associated with N–S trending fractures. Thermal springs emerge in the northern part of the study area along these fractures which are the contacts between reservoir and cap rocks. In the southern part of the area, the thickness of the cap formation reaches ~300 m. The clayey sediments are relatively impermeable (Gemici and Filiz, 2001).

ANALYTICAL METHODS

About 40 samples were collected from outcrops of the Alaçatı tuffs; the sampling locations are shown in Figure 2. The mineralogy of the bulk samples was determined by powder X-ray diffraction (XRD) analysis with a JEOL JSDX 100 S4 diffractometer. Pulverized powders were scanned from 4 to 60º2θ at a speed of 2º2θ/min using Ni-filtered CuKα radiation. All powder samples were prepared using an automatic agate mortar.

Chemical analyses of the bulk samples were carried out by atomic absorption spectrometry (AAS Pye-Unicam SP9) and by X-ray fluorescence (XRF) using a Jeol JSDX 100 S4 spectrometer. Chemical analyses of the bulk samples were performed using the Li tetraborate fusion method (Perkin-Elmer, 1976). Loss on ignition (LOI) was determined by dehydrating the samples at 110ºC and subsequent calcination at 1000ºC for 1 h. Samples were prepared as pressed powder pellets for trace element analysis. Four international geochemical

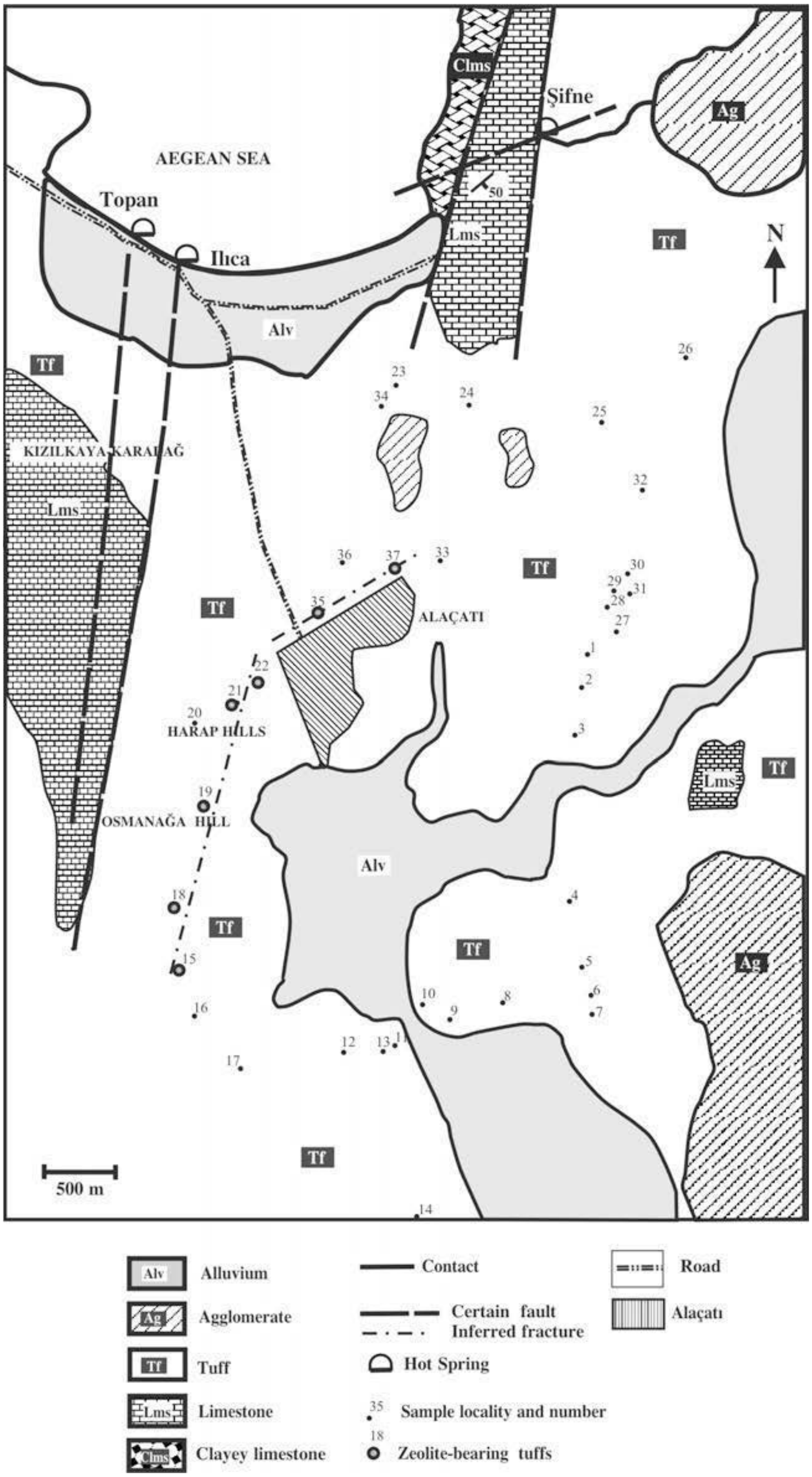

Figure 2. Geological map of the Alaçatı (Çeşme-İzmir) area (modified from Türkbileği and Aşıcı, 1988), showing the sample locations.

standards were used for calibration, and accuracy was monitored by repeated measurement of JR1 (rhyolite) reference material (Imai *et al*., 1995).

The textures of the tuffs were examined in thin-section by optical microscopy. The micromorphological features of zeolites were examined in gold-coated, fresh

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surfaces of the selected samples with a JEOL SXA 733 scanning electron microscope (SEM).

RESULTS

Petrography-mineralogy

Alaçatı tuffs consist of ash and minor amounts of lapilli-sized pyroclastic fragments which range in size from 0.1 to 1 mm, so that the tuffs in the Alaçatı area are classified as 'fine tuffs' (Fisher and Schmincke, 1984). The pyroclastic fragments consist mainly of feldspar, lesser quartz, minor biotite, pyroxene and volcanic rock fragments composed of plagioclase and minor pyroxene. Microlaths of plagioclase are often present in the rock fragments. The tuffs are made up of various proportions of glass, crystal and lithic fragments and lithic fragments commonly make up 10% of the silicic tuff.

According to the classification of Pettijohn (1957), the tuffs are classified as 'vitric tuffs'. The vitric material consists mainly of pumice, which has a fibrous or cellular structure comprising minute elongate or circular cavities. Spheroidal bubbles are also common.

The mineralogical composition of the tuffs, as determined by XRD analysis, is given in Table 1. Plagioclase is the most common phenocryst making up 50% of the phenocrysts. It is partially altered to clay minerals. Minor quartz and orthoclase are also present. Although biotite was not detected by XRD, it is occasionally observed by optical microscopy. In addition to the phenocrysts, XRD analysis showed the presence of mordenite, clinoptilolite-heulandite, smectite and calcite. Mordenite is found in seven samples and is the predominant component. Mordenite-rich samples are A15, A18, A19, A21, A22, A35 and A37. A representative XRD pattern of a mordenite-rich tuff (A37) is shown in Figure 3. The most distinctive reflections of the Alaçatı mordenite are 200, 202, 150 and 530 with *d* spacings of 9.1 Å, 3.45 Å, 3.98 Å and 3.21 Å, respectively. The X-ray data from the Alaçatı mordenite match those of Na-rich mordenite (Na-Al-Si-O.H_2O). In addition, some X-ray data of Alaçatı mordenite match those of (Ca,Na,K)-rich mordenites. However, there are no microanalytical data to verify zeolite composition. Clinoptilolite-heulandite is associated with mordenite. The clay mineral in the Alaçatı (Çeşme) tuffs was identified in air-dried samples as smectite, based on its 001 XRD reflection at 15 Å. Secondary carbonate formation is also common in the matrix. Calcite is commonly found as an open-space filling in vesicles and along fractures, and as a replacement product of feldspar and a product of the alteration of the groundmass in the tuffs, its abundance ranging from traces to 15 vol.% of the tuffs (Kaçmaz, 2001). Non-volcanic fragments exhibit fractured textures which in some cases are filled with secondary calcite.

The SEM examination confirmed the XRD results that the tuff samples from the Alaçatı (Çeşme) area are dominated by mordenite and revealed the morphological features of this mineral (Figure 4). Mordenite is present as long, delicate, acicular or filiform crystals. Examination by SEM suggests that some mordenite formed as a result of direct alteration of volcanic glass (Figure 4a,b). Interlaced mordenite fibers are widespread (Figure 4c) forming a mat which covers the surface of tuffs. Some interlaced mordenite fibers are also present showing "rats-nests" features (Figure 4d) (Mumpton and Ormsby, 1976). The filiform mordenite is usually present as a tangle of curved fibers (Figure 4e).

Table 1. Mineralogy of tuff samples determined by powder XRD.

Sample number	Mo	Clin-Heul	Smec	Feld	Qtz	Calc
A1	–	–	–	T	T	–
A2	–	–	–	P	T	P
A3	–	–	P	T	–	T
A4	–	–	T	P	P	A
A5	–	–	P	–	–	P
A6a	–	–	T	P	T	P
A6b	–	–	T	P	T	P
A7	–	–	T	T	–	T
A 8	–	–	P	P	T	T
A 9	–	–	P	T	–	P
A 10	–	–	P	–	T	P
A 11a	–	–	P	P	T	P
A 11b	–	–	P	P	T	P
A 12	–	–	–	T	T	A
A 13	–	–	P	T	T	P
A 14	–	–	P	T	T	–
A 15	A	P	A	P	P	P
A 16	–	–	P	T	T	P
A 17	–	–	–	T	T	A
A 18	A	P	A	P	T	P
A 19	A	P	A	P	P	P
A 20	–	–	P	T	T	P
A 21	A	P	A	P	P	P
A 22	A	P	A	P	P	P
A 23	–	–	A	P	T	P
A 24	–	–	P	–	T	A
A 25	–	–	–	T	T	–
A 26a	–	–	T	T	T	P
A 26b	–	–	T	T	–	P
A 27	–	–	–	P	T	A
A 28	–	–	P	P	–	A
A 29	–	–	T	P	T	A
A 30	–	–	–	T	–	–
A 31	–	–	–	P	T	P
A 32a	–	–	–	P	T	A
A 32b	–	–	–	–	T	A
A 33	–	–	P	T	–	P
A 34	–	–	A	–	T	P
A 35	A	P	A	P	–	P
A 36	–	–	A	P	–	P
A 37	A	P	A	P	–	P

Symbols: A = abundant, P = present, T = trace, – = not detected, Mo = mordenite, Clin = clinoptilolite, Heul = heulandite, Smec = smectite, Feld = feldspar, Qtz = quartz, Calc = calcite

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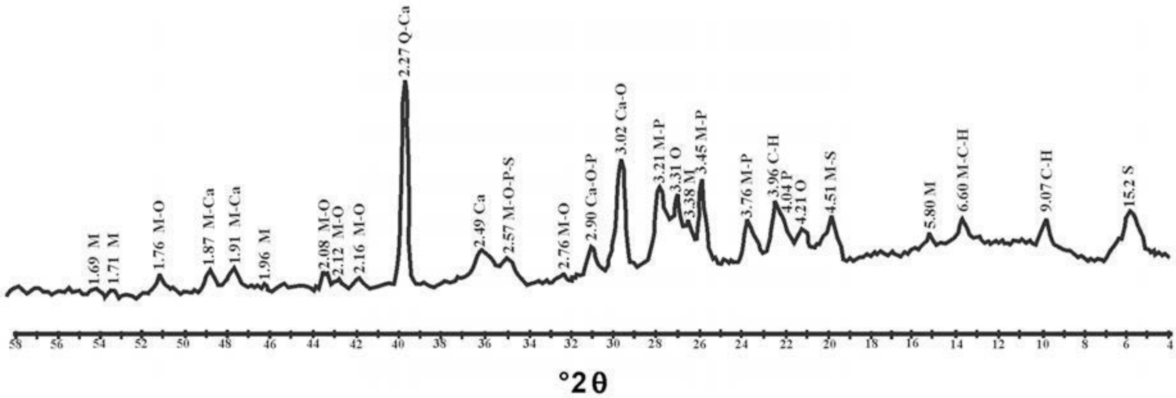

Figure 3. Powder XRD pattern of sample 37. M = mordenite, C-H = clinoptilolite-heulandite, S = smectite, P = plagioclase, Q = quartz, O = orthoclase, Ca = calcite.

Mordenite generally coexists with smectite (Figure 4f), and is associated with clinoptilolite-heulandite which is present as well-formed platy and tabular cyrstals (Figure 4g). The typical honeycomb structure, a common crystal habit of smectite, is obvious in Figure 5a,b.

Host-rock composition

Table 2 lists the major and trace element compositions of the zeolite-rich and zeolite-free tuff samples from the Alaçatı (Çeşme) area. Twelve representative samples were selected to demonstrate the geochemical features of the tuffs in the Alaçatı area. The smectite and zeolite-bearing tuffs have greater LOI values than fresh tuffs (*e.g.* samples A18 and A1, Table 2). Sample A23 has a higher LOI value despite being a zeolite-free tuff. Mordenite-rich tuffs have higher Na and Ca contents.

The analyses were plotted on the Zr/TiO_2 *vs.* Nb/Y diagram (Winchester and Floyd, 1977). The geochemical diagrams, which use fewer mobile elements such as Zr, Ti, Nb and Y, are more suitable for the purposes of description and classification of altered volcanic rocks. The tuffs have geochemical compositions varying between rhyodacite-dacite and trachyandesite (Figure 6), implying that the chemical composition of these tuffs is compatible with parent magma of a rhyodacitic–dacitic composition (see Discussion).

DISCUSSION

The tuffs in the Alaçatı (Çeşme) area were partly altered to smectite and zeolites, namely mordenite and clinoptilolite-heulandite. The stages of alteration leading to the formation of zeolite-bearing tuffs are shown by comparing samples with different degrees of alteration (Table 2). No data are available for the original bulk composition of the tuffs, the alteration of which led to

Table 2. Chemical composition of representative zeolite-bearing and zeolite-free tuffs from the Alaçatı area.

	Zeolite-bearing tuffs					Zeolite-free tuffs						
	A15	A18	A21	A35	A37	A20	A33	A25	A23	A6	A1	A30
SiO_2 (wt.%)	61.50	60.21	63.50	63.20	61.10	60.2	59.4	67.09	58.5	60.9	67.7	66.4
TiO_2	0.09	0.08	0.12	0.08	0.09	0.08	0.10	0.14	0.08	0.13	0.18	0.15
Al_2O_3	11.82	9.48	11.44	9.74	9.04	11.66	10.18	12.13	8.92	11.26	16.5	12.84
Fe_2O_3	0.49	0.65	0.16	0.93	1.13	0.18	0.75	1.45	0.16	1.89	1.53	2.09
MnO	0.05	0.04	0.04	0.05	0.07	0.05	0.09	0.03	0.05	0.07	0.11	0.1
MgO	0.09	0.09	0.10	0.07	0.08	0.09	0.07	0.1	0.08	0.08	0.11	0.09
CaO	7.84	9.66	8.44	8.63	9.88	9.98	11.32	5.57	11.90	7.88	1.13	5.36
Na_2O	3.50	3.89	3.41	3.08	3.21	2.35	2.50	3.27	2.24	2.92	3.25	2.96
K_2O	2.95	2.70	3.06	2.96	2.63	3.36	3.19	3.77	2.68	3.64	4.28	3.97
P_2O_5	–	–	–	0.02	–	–	–	0.03	–	–	0.02	0.01
LOI	12.34	13.79	10.05	11.17	13.20	12.45	11.67	6.29	15.97	10.71	4.90	5.94
Total	100.67	100.59	100.32	99.93	100.43	100 .40	99.27	99.87	100.58	99.48	99.71	99.91
Zr ppm	38.80	79.10	72.10	57.90	55.50	70.90	80.10	85.00	40.90	63.50	102.40	86.20
Y	31.40	27.00	32.20	25.90	27.10	41.50	36.50	66.50	34.50	51.80	61.30	59.00
Nb	13.70	18.80	29.80	18.10	17.40	22.00	19.60	35.60	18.90	17.00	30.70	27.80
Zeolite	Mo, Clin-Heul											

Sample locations A15, A18, A21, A35, A37, A20, A33, A25, A23, A6, A1, A30 are shown in Figure 2
LOI = loss on ignition
Mo = mordenite; Clin-Heul = clinoptilolite-heulandite

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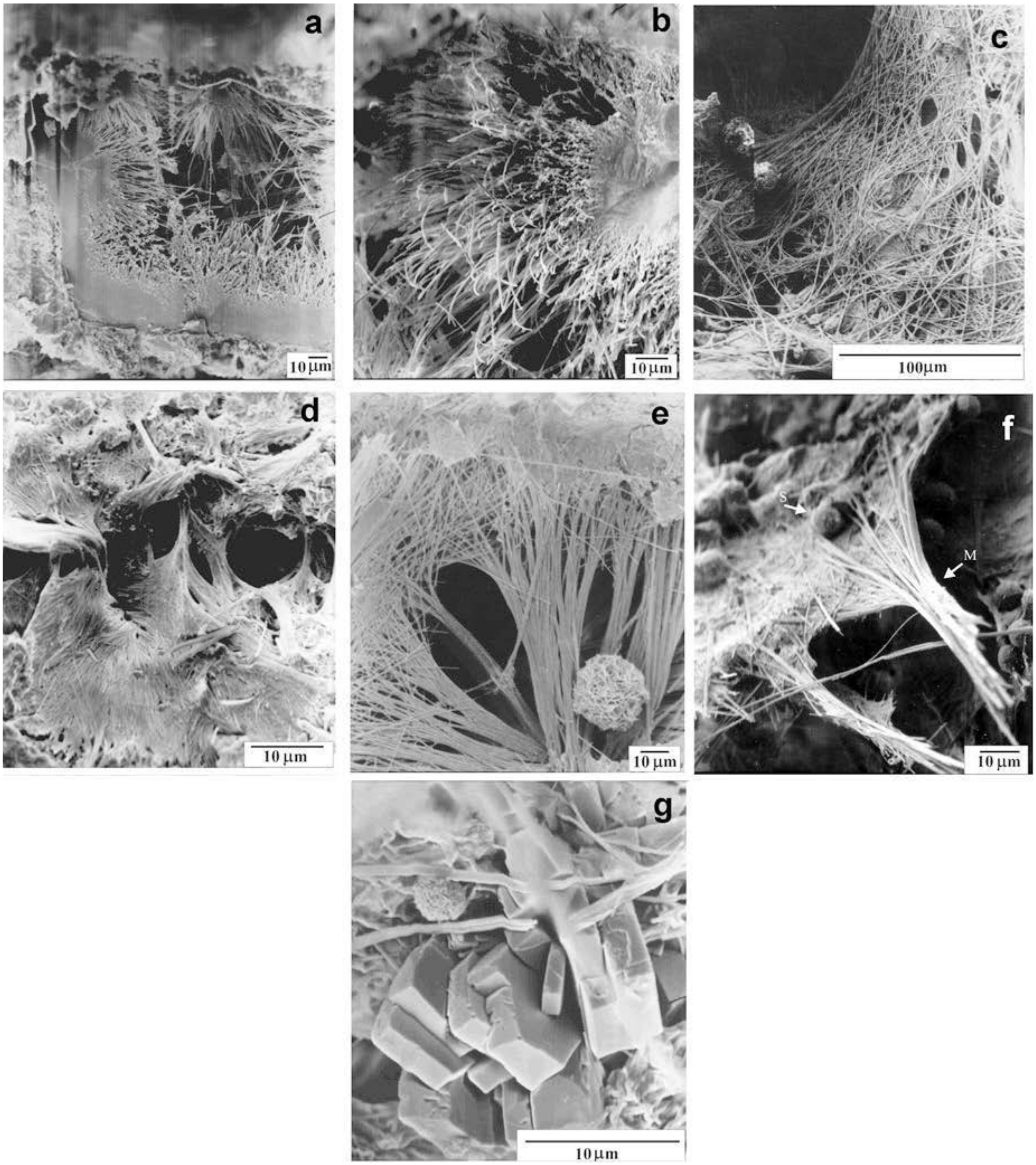

Figure 4. SEM images of (a,b) sample A15 showing mordenite fibers that formed after the direct alteration of volcanic glass; (c) sample A22 showing interlaced mordenite fibers. (d) sample A37 showing a 'rat-nest' feature of mordenite fibers; (e) sample A37 showing 'spider-web'-type mordenite forming a tangle of curved filiform mordenite; (f) sample A18 showing acicular mordenite (M) associated with smectite (S); and (g) clinoptilolite-heulandite.

the (Na,Ca)-rich mordenite-bearing tuffs. Inasmuch as no diagnostic XRD peaks for an authigenic phase were determined in samples A1, A25 and A30 (Table 2), their bulk chemistry probably reflects the original bulk composition of the tuffs. The alteration of tuffs to mordenite and clinoptilolite-heulandite (*e.g.* sample A15, Table 2) resulted in an increase in H_2O, Na_2O and CaO. The high Ca and Na contents of the mordenite-rich samples are correlated with the Ca and Na content of thermal waters. Since smectites and zeolites adsorb water, high LOI values in our samples are an indication of smectite and zeolite content (Table 2). One zeolite-free tuff (sample A23), has a larger LOI value than other zeolite-free tuffs. A correlation between LOI and CaO is

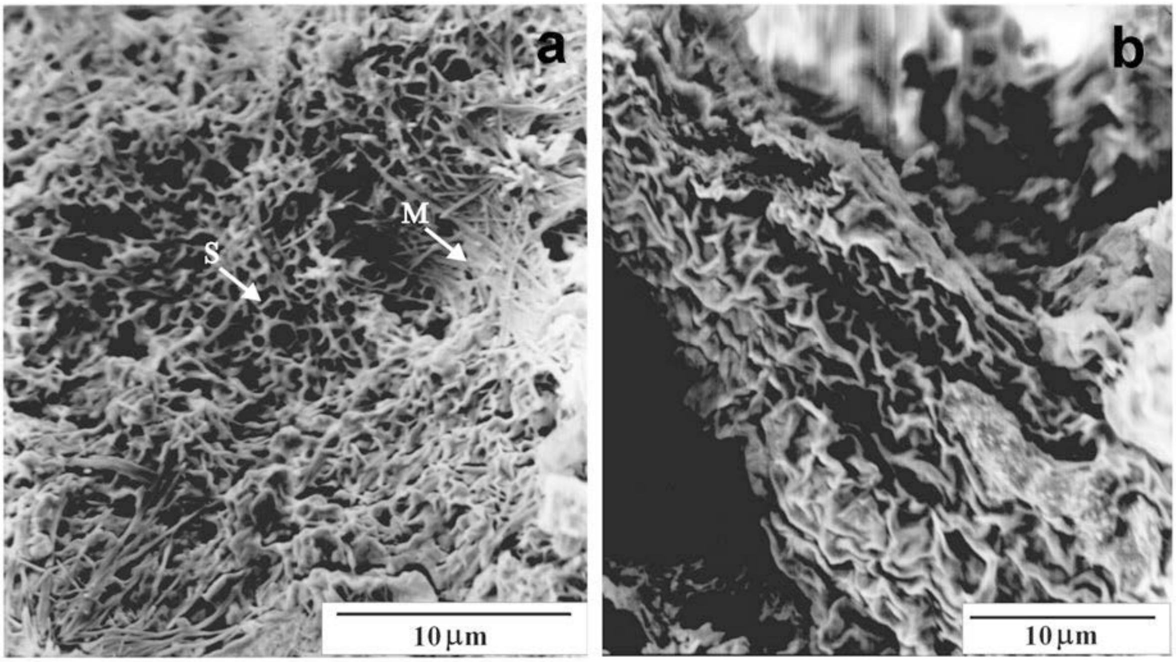

Figure 5. SEM images (a) of mordenite and smectite. Smectite (S), showing characteristic honeycomb structure, coexists with filiform mordenite (M); (b) the honeycomb structure of smectite.

clearly seen in sample A23 (Table 2) meaning that its LOI value may be attributed to the presence of calcite because of the large amount of CaO.

The formation of zeolites in pyroclastic rocks is influenced by various factors. The chemical composition of the host rocks controls the zeolite species (Iijima, 1980). For ultrabasic and basic rocks, zeolites with a low Si/Al ratio are characteristically gismondine, harmotome, mazzite and others. High-silica zeolites such as mordenite, clinoptilolite and heulandite are most often associated with acidic rocks. By using less mobile elements, it was revealed that the parent precursors to the Alaçatı tuffs were rhyodacitic to dacitic in composition (Figure 6), thus affecting the chemical composition and type of zeolites formed. Although the samples are interpreted as sourced in rhyolite-dacites, their projection on the Zr/TiO_2 *vs*. Nb/Y diagram (Winchester and Floyd, 1977) is affected by the mobilization of Y during the alteration of glass to bentonites and zeolites (Christidis, 1998). It is obvious from Table 2 that the zeolite-bearing samples have a lower Y content than others (*e.g*. sample A18). Therefore, the composition of the parent rocks is shifted towards the field of trachyandesite (Figure 6).

The principal requirements for zeolitization are: (1) a high proportion of volcanic glass in the parent rocks; (2) a large internal surface area and high permeability; and (3) favorable hydrological conditions. Petrographic study has shown that pumice and comminuted pumice were major constituents of the volcanic ashes that have been zeolitized (Hall, 1998). The silicic tuff is vitric in the study area but also contains varying amounts of crystal and rock fragments. Vitric material consists mainly of pumice. There is strong evidence to support the formation of minor amounts of mordenite directly from dissolution of volcanic glass (Figure 4a,b). Filiform mordenite was found to have been formed from a gel-like type material (Figure 4d). Figure 4a shows the dissolution texture of glass and mordenite that has grown on the inside of the glass. The mordenite shown in Figure 4d has developed from a gel-like material that was probably derived from alteration of glass. The SEM examination of sample A15 shows that some of the mordenite fibers apparently grew by

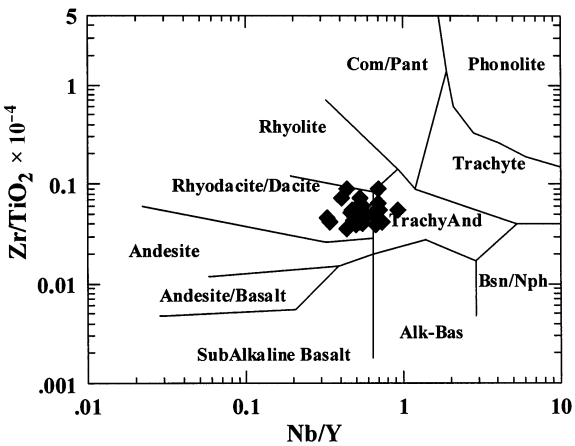

Figure 6. Plot of Zr/TiO_2 *vs*. Nb/Y for the tuffs in the Alaçatı (Çeşme) area (Winchester and Floyd, 1977).

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replacing glass (Figure 4a,b), which could have been hydrated and leached of Al, as suggested by Hawkins *et al*. (1978).

Mordenite is the most abundant zeolite in tuffs of the Alaçatı (Çeşme) area and always coexists with smectite and clinoptilolite-heulandite. Mordenite and clinoptilolite-heulandite were found in only seven samples (A15, A18, A19, A21, A22, A35 and A37) out of 40. The distribution of the zeolites would appear to be related to fracture zones trending NE–SW (Figure 2). However, fracture zones are poorly defined in the tuffs. Samples A20, A33 and A36 close to the zeolite-bearing tuffs are zeolite-free. The lack of zeolites and the presence of smectite and calcite in these tuffs suggest that zeolite occurrences disappear with increasing distance from the inferred fracture zones. No diagnostic XRD peaks for zeolite minerals were determined in other samples (Table 1) away from these fracture zones.

Recent investigations of the hydrochemical characteristics of thermal waters discharged from springs and wells suggests that in the Çeşme geothermal field there are two types of waters (Gemici and Filiz, 2001). The first type originated from a lower aquifer within the Triassic karstic limestone which is the main potential reservoir of the system. Thermal waters from the Triassic karstic limestone have a large sea-water component; they are rich in NaCl, and have temperatures of 37–62ºC and total dissolved solids (TDS) up to 35.000 mg/L. The second type includes thermal waters derived from an upper aquifer formed by Neogene volcanic and sedimentary rocks which cap the geothermal system. These waters have a lower discharge temperature (37–40ºC) and smaller TDS contents due to their mixing with local groundwater before emergence. Mixing of these thermal waters with the local groundwaters in different proportions gives rise to Na-Ca-Cl-HCO_3 thermal waters. The composition of the vitric material and the characteristics of the solutions may have dictated which zeolite species precipitated (Sheppard and Simandl, 1999). Mordenite is typically a very siliceous zeolite with a Si/ (Al+Fe^{3+}) ratio of 4.5 to 5.3; Na and Ca are generally the dominant exchangeable cations (Tsitsishvili *et al*., 1992). We conclude that the Alaçatı (Çeşme) tuffs are dominated by mordenites (Na- and Ca-rich mordenites) with clinoptilolite-heulandite. In this respect, we accept that the Na-Ca-Cl-HCO_3 thermal waters have provided the excessive Na and Ca necessary to form the Na- and Ca-rich mordenites. Besides, the outcrop distribution of zeolite minerals in tuffs of the Alaçatı (Çeşme) area was recognized only in a specific area. A conspicuous alteration and a considerable amount of zeolites were only found in the western part of the study area (Figure 2), where the thermal spring is present. The Na-Cl thermal springs from the Ilıca and Şifne areas, 3 km NW and 4 km NE of Alaçatı area, respectively (Figure 2), have high concentrations of Na. According to the experimental work of Conrad *et al*. (1995), the Na^+ concentration of the thermal spring waters ranged from ~6100 to 12,100 mg/L, with maximum Na^+ concentrations in the waters from the Ilıca area, comparable to that of the local sea-water (12,780 mg/L).

Solution pH is the main factor affecting the Si/Al ratio in zeolites during their formation (Wilkin and Barnes, 2000; Bernhard and Barth-Wirsching, 2002). Mordenite is a highly siliceous zeolite and requires high silica activity for its formation. Experimental work by Mariner and Surdam (1970) indicates that the concentration of dissolved Al increases and the Si/Al ratio decreases with increasing pH. This indicates that at moderately alkaline pH values, zeolites such as mordenite which has relatively high Si/Al are favored over zeolites with low Si/Al ratios such as chabazite and phillipsite. Mordenite is the predominant zeolite at Alaçatı, due to the favorable pH (~7, 5) reported in drill holes in the western part of Alaçatı (Gemici and Filiz, 2001). Mordenite formation is favored in mildly alkaline pH of 7–9 (Phillips, 1983).

Calcite is present in most of the samples examined. The enrichment of calcite is attributed also to the increased Ca content of thermal waters which circulate through the Triassic carbonate rocks that are present at depth as reservoir rocks. On the other hand, by using the saturation index approach it is possible to predict the reactive minerals in the subsurface from the groundwater data without examining samples of the solid phases (Deutsch, 1997). It is important to know saturation indices for some minerals (calcite, quartz, *etc*.) to predict which ones may precipitate during the extraction and use of the fluids. Geothermal investigations in the study area show that all thermal waters from deep wells and springs are oversaturated or close to equilibrium with respect to calcite (Gemici and Filiz, 2001) indicating that this mineral occurs in the reservoir.

CONCLUSIONS

The formation of zeolites in the Alaçatı (Çeşme) area is related to the reaction between silicic vitric tuffs and thermal waters which circulate through permeable tuffs along NE–SW-trending fracture zones, resulting in hydrolysis and dissolution of silicic vitric glass. The existence of NE–SW-trending fracture zones is assumed here to be the most important factor controlling the distribution of zeolites in the study area.

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