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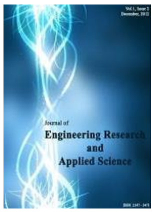

Petrography and crystallization conditions of Middle Eocene volcanic rocks in the Aydıntepe-Yazyurdu (Bayburt) area, Eastern Pontides (NE Turkey)

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Abstract

Mineralogical, petrographic and mineral chemistry properties are presented for the Middle Eocene aged Aydıntepe-Yazyurdu volcanics in the Eastern Pontides (NE Turkey). The studied volcanic rocks are composed of basalt, basaltic andesite, andesite and dacite and their pyroclastic. These rocks contain plagioclase ($An_{39\text{-}86}$), alkali feldspar, quartz, clino-pyroxene ($Wo_{38\text{-}48}En_{38\text{-}46}Fs_{9\text{-}23}$), ortho-pyroxene ($Wo_{02\text{-}03}En_{71\text{-}73}Fs_{25\text{-}26}$), amphibole (Mg# = 0.68-0.79), biotite and Fe-Ti oxide minerals. Crystallization temperatures calculated from amphibole-plagioclase and clinopyroxene minerals are 819 °C to 1157 °C, pressure values are 0.14 to 7.79 kbar. Oxygen fugacity (log10 fO_2) are -11.0 to -12.1 and estimation of water content is between 3.9 and 5.9% calculated by using amphiboles. Based on the obtained data, it is suggested that the magmas had undergone anhydrous and hydrous crystallizations in the shallow to mid-crustal magma chambers.

Keywords: mineralogy-petrography, geothermobarometer, Middle Eocene, Aydıntepe-Yazyurdu volcanics, Eastern Pontides, Bayburt, NE Turkey.

1. Introduction

The Eastern Pontides are represented by three main volcanic phases developed during Liassic, Late Cretaceous and Early Eocene to Miocene [1, 2]. Although some researchers have demonstrated the evolution of the Middle Eocene volcanic rocks in the Eastern Pontides [3-11], studies on the crystallization conditions and magma chamber processes of the volcanic rocks in the Aydıntepe-Yazyurdu area are limited [12]. In this study, mineralogical, petrographic and mineral chemistry data for volcanic rocks exposed in the Aydıntepe-Yazyurdu (Bayburt) area are reported to provide thermobarometer (pressure-temperature) conditions during the crystallization and to determine settlement of the volcanics.

2. Regional geology and stratigraphy

The Eastern Pontides are subdivided into the southern and northern parts [13-14]. The study area is located within the southern part of the Eastern Pontides.

The basement rocks of the Eastern Pontides consist of Early Carboniferous metamorphic rocks [15] and Late Carboniferous Plutonic rocks [16-19]. These Pre-Jurassic basement rocks are transgressive overlain by the Early and Middle Jurassic volcano-sedimentary rocks [20-21] and are cut by Mid- to Late Jurassic intrusions [22-24]. All these rocks are overlain by the Late Jurassic to Early Cretaceous carbonates. The Late Cretaceous units that unconformably overlie these carbonate rocks consist of sedimentary, plutonic and volcanic rocks [25-28]. Late Cretaceous alkaline igneous rocks and Early Paleocene plagioleucitites formed related to the closure of the Neo-Tethys Ocean [29-30]. From the Paleocene to the Early Eocene, the Eastern Pontides was above sea level probably because of the collision between the Tauride-Anatolide block and the Pontides magmatic arc [14, 31].

The Eocene volcanic and volcanoclastic rocks overlie the Late Cretaceous series [6-9, 32], and are intruded by plutons of similar age [33-40]. Post-Eocene uplift and erosion brought clastic input into locally developed basins [41]. In the Late Eocene, the region has remained largely above sea level with continuous minor volcanism and terrigenous sedimentation [14]. The Miocene and post-Miocene magmatism are characterized by calc-alkaline to mildly alkaline compositions [5, 9, 11, 42], while the Miocene to Pliocene volcanism in the Ilıca-Kandilli area, near

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the North Anatolian Fault Zone (NAFZ), is represented by calc-alkaline in compositions [43-44]. In the Aydıntepe-Yazyurdu region (Figure 1), the basement rocks are formed by Ardıç Volcanites [45] consisting of andesite, basalt, agglomerate, tuff and tuffite alternations.

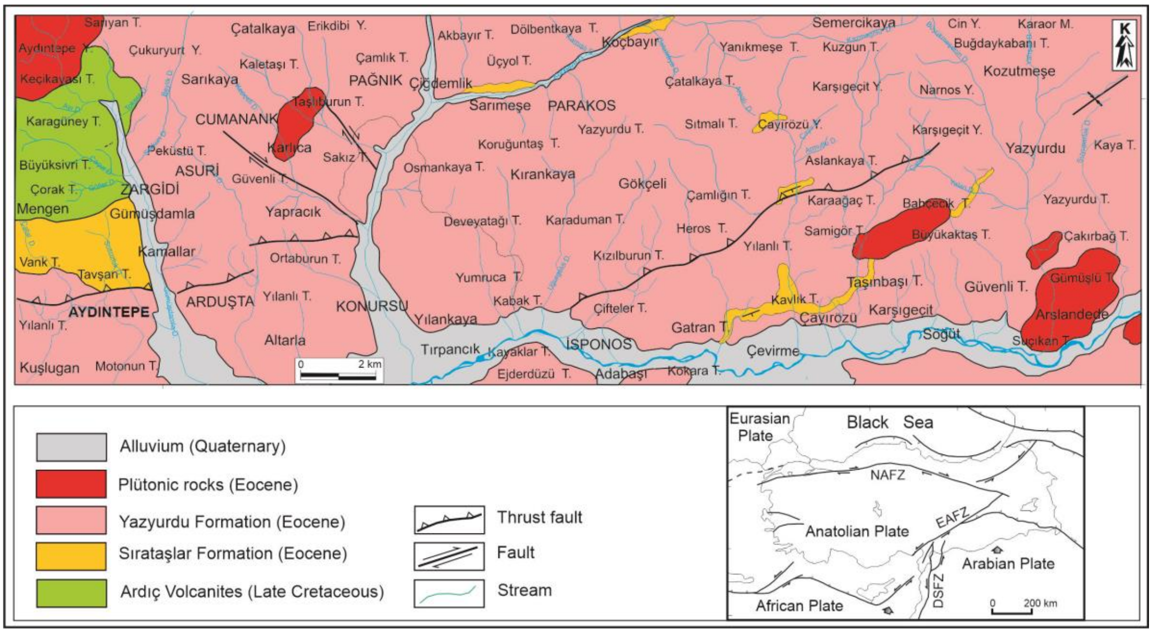

Figure 1. Geological map of the Aydıntepe-Yazyurdu area. Modified after [12].

Eocene Sırataşlar Formation [20] which consists of Nummulites-bearing limestone, sandstone, marl and sandy limestone overlie these rocks conformably, and are overlined conformably by Eocene Yazyurdu Formation [45] which consists of andesite, basalt and pyroclastics including sandstone intermediate levels. Eocene plutons cut these lithologies. Quaternary Alluvium are the youngest units of the study area.

The andesites and basalts forming the studied Yazyurdu Formation have a greenish gray to yellowish gray in color, and brown color in the altered sections. Clinopyroxene and plagioclase minerals can be recognized macroscopically. The volcanic breccias are dark gray and green in color, and andesitic pebbles are connected by a matrix. Andesitic pebbles are between 2 to 50 cm in size and have a semi-angular shape. The tuffs are gray and green in color and are generally altered and cavities. The cavities are sometimes filled with secondary calcite, epidote and quartz minerals. Exfoliation structures are observed in places where the rocks are altered.

3. Analytical techniques

In this study, 100 samples were collected in the Aydıntepe-Yazyurdu (Bayburt) area. The modal mineralogy of these samples was examined by Leica type polarizing microscope, and 5 representative samples being selected for electron microprobe analyses.

Electron microprobe analyses on carbon-coated polished sections were carried out at the Ifermer Epma laboratories, Brest (France), using a Cameca SX-100 electron microprobe. Polished sections were examined using back-scattered electron imagery, and selected minerals were quantitatively analyzed. An accelerating voltage of 15 kV and a sample current of 15 nA. Peak and background counting times ranged from 10s to 20s and 5s to 10s, respectively. Natural minerals and synthetic/compounds were used as standards. The matrix effects were corrected by using Phi (r) z Peak Sight© software from Cameca™. Typical standard deviations (1σ) ranged from 0.03 to 0.1 wt.% for Fe, Cr, K, Ti, Mg and Mn, and 0.1 to 0.3 wt.% for Si, Ca, Na and Al.

4. Petrography and mineral chemistry

The volcanic rocks consist of basalt, basaltic andesites, andesites and minor dacites (Figure 2). Basalts and basaltic andesites show microlithic to microlithic–porphyric textures characterized by plagioclase, pyroxene, olivine and amphibole phenocrysts. Their groundmass is composed of plagioclase, pyroxene, olivine and amphibole microlites, and Fe–Ti oxide. Andesites have hypo-crystalline porphyritic and glomeroporphyritic textures. They have phenocrysts of plagioclase, K-feldspar, pyroxene, amphibole and biotite in a groundmass of microlites including the same minerals and Fe–Ti oxide. Dacites exhibit holocrystalline- and microgranular textures with plagioclase, K-feldspar, quartz, amphibole and minor biotite phenocrysts. Their groundmass contains the microlites of plagioclase, amphibole, biotite, Fe–Ti oxide, and glass (Figure 2).

The minimum and maximum values of the microprobe compositions for plagioclase, pyroxene, amphibole and Fe-Ti oxide are given in Table 1. Plagioclase occurs as subhedral to euhedral normal and reverse zoned crystals. Some of them show oscillatory zoning (Figure 2a). The compositions of the plagioclase phenocrysts ranging from bytownite to andesine ($An_{88–31}$) (Figure 3, Table 1).

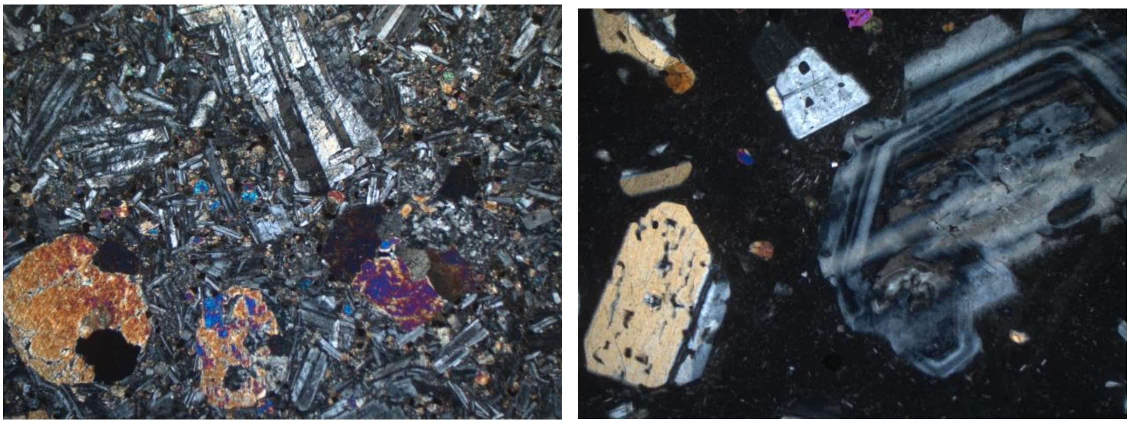

Figure 2. Photomicrography showing textural relationship of the Aydıntepe-Yazyurdu volcanic rocks: (a) large clino-pyroxene crystals in basalt, (b) oscillatory zoning plagioclase in andesite.

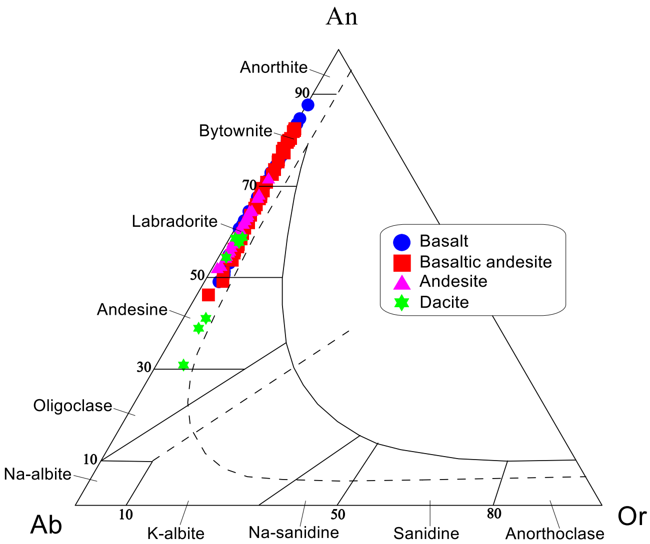

Figure 3. Classification diagram of feldspars [46].

Pyroxene forms subhedral to euhedral crystals, and mainly forms zoned phenocrysts. All the pyroxenes are of calcic clinopyroxene (Wo_{38-48}) except for the orthorombic pyroxenes of the clinoenstatite (En_{71-73}) (Figure 4a). Calcic pyroxenes are generally augite, and minor diopside in composition. Mg number (Mg#) of clino-pyroxenes range from 0.6 to 0.8 (Table 1). They are placed in the CATS field in the Ti-Na-Al^4 diagram [47] (Figure 4b, Table 1).

Table 1. Maximum and minimum values of microprobe analyze for plagioclase, pyroxene, amphibole and Fe-Ti oxide.

	Plagioclase (n=101)			**Clino-pyroxene (n=66)**			**Ortho-pyroxene (n=8)**			**Amphibole (n=28)**			**Fe-Ti oxide (n=29)**	
	min	max		min	max		min	max		min	max		min	max
SiO_2	46.37	60.02	SiO_2	48.82	52.80	SiO_2	53.36	54.86	SiO_2	44.95	47.28	SiO_2	0.05	2.46
Al_2O_3	22.27	34.24	TiO_2	0.29	1.02	TiO_2	0.15	0.24	TiO_2	1.63	2.33	TiO_2	1.99	16.42
FeO	0.36	2.71	Al_2O_3	1.45	5.40	Al_2O_3	1.07	3.47	Al_2O_3	7.54	9.27	Al_2O_3	0.58	4.78
CaO	6.36	17.77	Cr_2O_3	0.00	0.71	Cr_2O_3	0.00	0.00	FeO	12.02	13.02	Cr_2O_3	0.00	0.95
Na_2O	1.33	7.32	FeO	5.32	13.91	FeO	15.72	16.75	MnO	0.31	0.56	FeO	75.77	86.55
K_2O	0.04	0.90	MnO	0.07	0.46	MnO	0.34	0.49	MgO	13.79	15.26	MnO	0.05	4.33
Total	97.40	100.90	MgO	13.41	16.32	MgO	25.96	26.78	CaO	10.84	11.39	MgO	0.00	1.87
Si	2.13	2.73	CaO	18.67	23.14	CaO	1.42	1.69	Na_2O	1.35	1.73	CaO	0.01	1.41
Al	1.19	1.85	Na_2O	0.13	0.45	Na_2O	0.00	0.05	K_2O	0.53	0.80	Total	90.23	96.25
Fe(ii)	0.01	0.11	K_2O	0.00	0.23	K_2O	0.00	0.02	Total	95.89	98.56	Si	0.02	0.96
Ca	0.31	0.88	Total	98.70	101.12	Total	100.58	101.33	Si	6.60	6.86	Ti	0.59	4.30
Na	0.12	0.64	Si	1.84	1.96	Si	1.91	1.97	Ti	0.18	0.26	Al	0.26	1.98
K	0.00	0.05	Ti	0.01	0.03	Ti	0.00	0.01	Al	1.29	1.59	Cr	0.00	0.28
An	30.76	87.82	Al	0.06	0.24	Al	0.05	0.15	Fe(ii)	1.45	1.58	Fe(ii)	22.10	27.94
Ab	11.91	64.05	Cr	0.00	0.02	Cr	0.00	0.00	Mn	0.04	0.07	Mn	0.01	1.30
Or	0.24	5.18	Fe(ii)	0.16	0.44	Fe(ii)	0.47	0.51	Mg	2.98	3.30	Mg	0.00	0.98
Structural formula based on 8 oxygen atoms			Mn	0.00	0.01	Mn	0.01	0.01	Ca	1.68	1.76	Ca	0.00	0.53
			Mg	0.75	0.90	Mg	1.39	1.43	Na	0.76	0.97	Fe#	0.96	1.00
			Ca	0.75	0.92	Ca	0.05	0.07	K	0.10	0.15	Structural formula based on 32 oxygen atoms		
			Na	0.01	0.03	Na	0.00	0.00	Mg#	0.68	0.79			
			K	0.00	0.01	K	0.00	0.00	Structural formula based on 23 oxygen atoms					
			Wo	38.24	48.09	Wo	2.75	3.31						
			En	38.21	45.87	En	70.69	72.49						
			Fs	8.70	22.71	Fs	24.53	26.01						
			Mg#	0.63	0.84	Mg#	0.74	0.75						
			Structural formula based on 6 oxygen atoms											

n= sample number, max: maximum values, min: minimum values, Mg#: Mg number

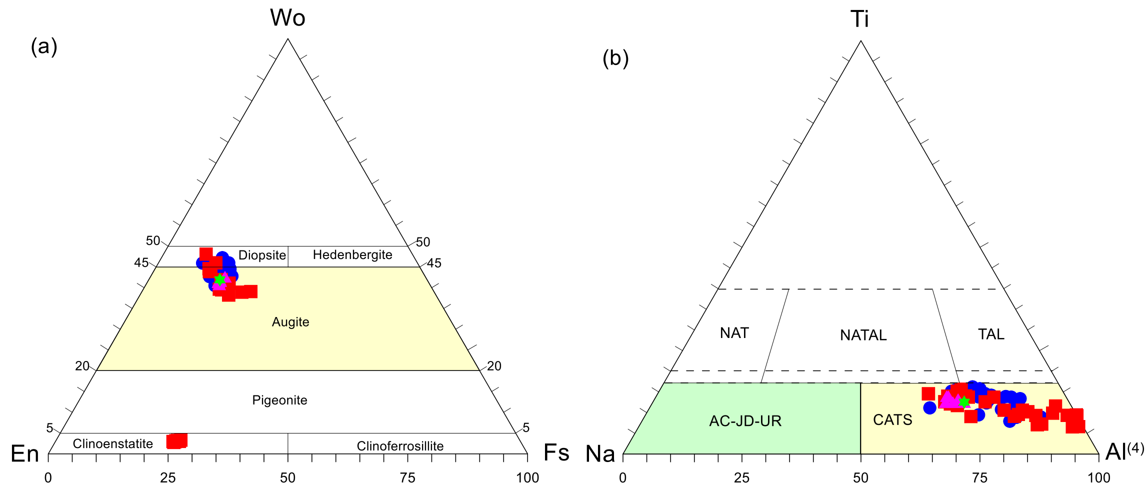

Figure 4. Classification diagrams of pyroxene, a) Wo-En-Fs [48], b) Ti-Na-Al(4) [47].

Amphibole occurs as subhedral to euhedral phenocrystals and microlites in groundmasses. They have $(Ca+Na)_B$ values greater than 1.0, and are calcic in composition (Figure 5a). Amphiboles from the studied rocks are classified as magnesio-hornblend in composition with $Ca_A < 0.50$ (Figure 5b). The Mg# of amphiboles varies from 0.68 to 0.79 (Table 1).

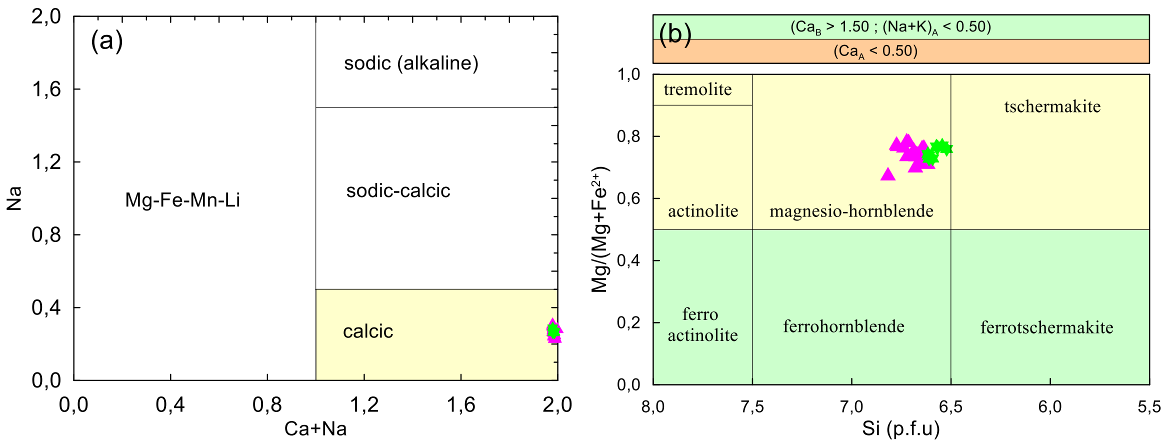

Figure 5. (a and b) The compositions of amphiboles [49].

K-Feldspar is found in andesitic and dacitic rocks as anhedral to subhedral micro phenocryst. K–feldspar phenocrysts are sanidine and anorthoclase in compositions. Biotite occurs in dacitic and andesitic rocks as phenocrysts and as a dispersed groundmass. Quartz is found only in dacitic rocks. Embayed quartz crystals are common. Fe–Ti oxides are anhedral to euhedral in shape and are in many cases adjacent to plagioclase or pyroxene phenocrysts. They are the product of the ulvospinel-magnetite solid solution and show compositions close to the magnetite in the ternary TiO_2-FeO-Fe_2O_3 diagram [50] (Figure 6).

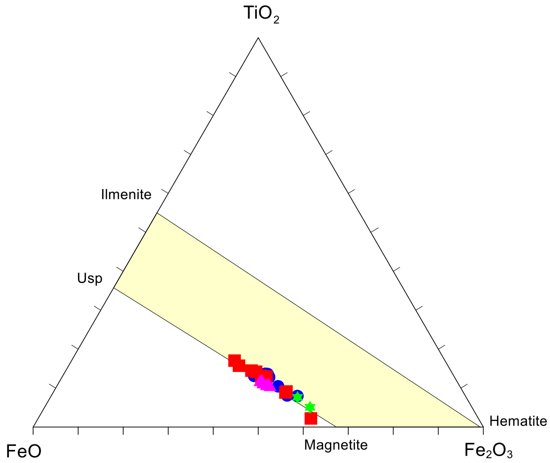

Figure 6. Ternary FeO-Fe2O3-TiO2 diagram [50].

5. Intensive parameters

5.1. Clinopyroxene thermobarometry

Estimates of quantitative pressure and temperature on the clinopyroxene composition re-evaluated by using Ref. [51]. The Reference [51] gave an equilibrium constant using the Fe–Mg exchange and $K_D(Fe\text{-}Mg)^{cpx\text{-}melts}$ = 0.27±0.03. The calculated results of the studied rocks show pressures ranging from 0.14 to 7.79 kbar and temperatures ranging from 1121 to 1188 °C (Table 2).

Table 2. Clinopyroxene temperature and pressure calculations

	P (32a. kbar)	P (32b. kbar)	P (32c. kbar)	T (^{0}C)	KD $_{(Fe\text{-}Mg)}$
min	0.14	0.53	2.40	1121	0.26
max	6.53	5.73	7.79	1188	0.28
avg	2.78	2.59	4.64	1157	0.27
std	1.54	1.16	1.49	14	

Eqn. 32a: only cpx barometers, for anhydrous magmas; Eqn. 32b: only cpx barometers, for hydrous magmas; Eqn. 32c: cpx-melts barometers

5.2. Amphibole-plagioclase thermobarometer

Microprobe data for the amphibole and plagioclase phenocrysts from the Aydıntepe-Yazyurdu volcanics were used to calculate temperature using the equations suggested by [52]. Pressures were calculated using Al-in-amphibole method and equations proposed by [53] for volcanic rocks. The results obtained from the amphibole-plagioclase thermometer and Al-in-amphibole geobarometer are given in Table 3. Calculated pressures and temperatures give values of 2.5 to 4.5 kbar and 833 to 872 °C for the studied volcanic rocks (Table 3).

Table 3. Amphibole-plagioclase pressure and temperature calculations.

	P1 (kbar)	P2 (kbar)	P3 (kbar)	T °C
min	2.51	3.26	3.76	833
max	3.98	4.10	4.46	872
avg	3.14	3.54	4.00	849
sp	0.35	0.29	0.24	15

P1: [54], P2: [55], P3: [56]

5.3. Amphibole thermobarometry, oxygen fugacity, and hygrometer

[57-58] estimated that the P, T, H_2O contents, ΔNNO and fO_2 of volcanic rocks using microprobe analysis of amphiboles. The calculated crystallization temperatures and pressures of amphiboles in the Aydıntepe-Yazyurdu volcanics were 1.2 to 2.4 kbar and 819 to 893 °C, respectively (Table 4). The relative oxygen fugacity (ΔNNO) ranged from 1.03 to 1.72 for the studied rocks (Table 4). The oxygen fugacity (log10 fO_2) values of

the studied rocks varied between -11.0 and -12.1 (Table 4). Calculation results by using the formula of [57-58] denote that the H_2O_{melt} contents of melts changed from 3.9 to 5.8 wt.% for the studied volcanic rocks (Table 4).

Table 4. Amphibole pressure, temperature, H_2O contents and oxygen fugacity calculations.

	[57]					[58]			
	T (°C)	P (kbar)	DNNO	fO_2	H_2O	T (°C)	P (kbar)	DNNO	H_2O
min	819	1.21	1.03	-12.09	3.86	829	1.47	1.08	4.49
max	869	1.84	1.70	-11.01	5.78	893	2.41	1.72	5.35
avg	847	1.45	1.44	-11.46	4.46	866	1.83	1.42	4.80
sp	13	0.15	0.17	0.22	0.36	16	0.20	0.17	0.20

6. Discussion and conclusions

Cenozoic magmas had post-collisional characteristics and were derived from a sub-continental lithospheric mantle source that was previously modified by fluids and/or sediments [6, 59-60]. In addition, the crustal structure throughout the Eastern Pontides is not homogeneous with varying thicknesses of 29 to 40 km [61-62]. For this reason, petrographic and mineral chemical properties of the volcanic rocks would be changed depending on the magma chamber processes at different crustal levels.

The petrographic and mineral chemistry properties of the Aydıntepe-Yazyurdu volcanic suggest that they developed in hydrous and anhydrous environments. The content of water in the amphibole-containing magma is controversial at rates ranging from 2 to 3 wt.% [63] to 5 wt.% [64-65] and then up to 6 wt.% [66]. The estimated H_2O_{melt} content ranges from 3.9 to 5.8 wt.% for the Aydıntepe-Yazyurdu volcanics rocks. The calculated crystallization temperatures and pressures in the studied volcanic rocks using the chemical analysis of amphibole and orthopyroxenes are 819 to 1157 °C and 0.1 to 7.8 kbar, respectively. The oxygen fugacity (log10 fO_2) values of the Aydıntepe-Yazyurdu volcanics varied between -11.0 and -12.1. The combined petrographic, mineral chemistry, and thermobarometric features indicate that the magmas had undergone anhydrous and hydrous crystallizations in shallow to mid-crustal levels (~ 1 to 12 km).

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