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Petrography and petrology of The Yürekli (Balıkesir) volcanics: an example of post-collisional felsic volcanism in the Biga peninsula (NW Turkey)

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ABSTRACT

In this study, it is aimed to determine to petrographical, geochemistry and sources of the Yürekli volcanics (Biga Peninsula, NW Turkey). Tertiary volcanism is widespread in Western Anatolia (NW Turkey), is an important area where tectonic and magmatic events are observed together. Yürekli volcanic rocks composed of dacitic lavas and pyroclastics. Dacitic lavas show porphyric and hyalo-porphyric texture, and consisting of plagioclase, quartz, amphibole, biotite, sanidine and Fe-Ti oxide minerals with apatite and zircon accessory minerals. Petrologically, it is high-potassic and calc-alkaline in characteristic. Yürekli volcanics show enrichment in large ion litophile elements (LILE) while depletion in high field strength elements (HFSE) on the N-MORB normalized diagram. On the chondrite-normalized rare earth element (REE) plot, light rare earth elements are enriched but heavy rare earth elements are depleted in the rocks. Besides, REE patterns are concave shaped (mean LaN/LuN=16–25), and show a slight negative Eu anomalies (0.66–0.81). Plagioclase, amphibole and biotite fractional crystallization and crustal assimilation are important in the evolution of the Yürekli volcanics. According to all data, it can be argued that the Yürekli volcanics is formed in the post-collisional setting, and their parental magmas have derived from the melts of enriched lithospheric mantle.

1. Introduction

Turkey is divided into four main tectonic zones of the Sakarya zone, Tauride-Anatolide block, Intra-Pontide suture zone and Zagros suture zone (Okay and Tüysüz, 1999). The İzmir-Ankara-Erzincan suture zone (Figure 1a) is bounded by the Sakarya zone to the north and the Tauride-Anatolide block to the south (Şengör and Yılmaz, 1981; Yılmaz, 1990; Okay and Tüysüz, 1999). NW Anatolia is an important belt within the Alpine-Himalayan orogenic belt where magmatic activity is observed together with tectonic events (Aldanmaz et al., 2000; Altunkaynak and Genç, 2008).Thus, there are many studies performed on the general geology and petrology of the NW Anatolian Region (Bingöl, 1976; Ercan, 1979; Şengör and Yılmaz, 1981; Bingöl et al., 1982; Ercan and Günay, 1984; Yılmaz, 1990; Harris et al., 1994; Okay et al., 1996; Genç, 1998; Altunkaynak and Genç, 2008; Yılmaz et al., 2001; Altunkaynak and Dilek, 2013; Erdem, 2015; Aslan et al., 2017).

After closure of the Neo-Tethys Ocean, the Sakarya and Tauride-Anatolide continents collided in the Eocene period (Şengör and Yılmaz, 1981; Okay et al., 1996; Okay and Tüysüz, 1999; Altunkaynak and Dilek, 2006; Okay 2008) and as a result widespread magmatism formed in Northwest Anatolia (Yılmaz, 1989; Güleç, 1991; Ercan et al., 1995; Seyitoğlu and Scott, 1996; Genç and Yılmaz, 1997; Altunkaynak and Dilek, 2006; Okay and Satır, 2006; Karacık et al., 2008) (Figure 1b). In this period, intrusive rocks with granitic character and volcanic rocks with andesitic, dacitic and basalt character are commonly

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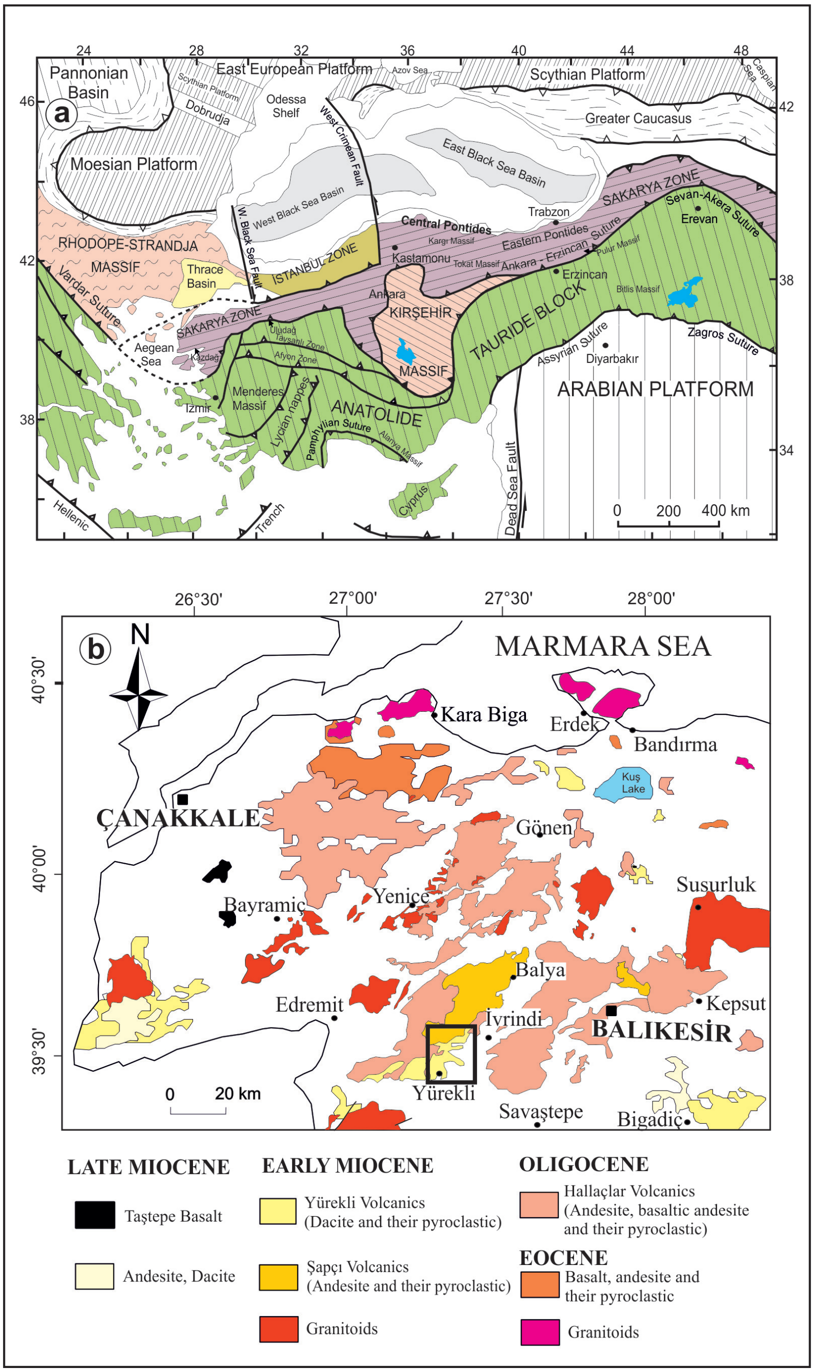

Figure 1- a) Tectonic zones of Turkey (Okay and Tüysüz, 1999) and b) The distribution of magmatic rocks in the Biga Peninsula (modified after Pehlivan et al., 2007).

found. Granitic plutons and the Edincik and Beyçayır volcanic rocks represent the first magmatism products in the Middle Eocene (Delaloye and Bingöl, 2000; Şengör et al., 1993; Köprübaşı and Aldanmaz, 2004; Altunkaynak and Dilek, 2006; Altunkaynak, 2007; Okay 2008; Altunkaynak et al., 2012, Erdem and Aslan, 2015; Aslan et al., 2017). In the Oligocene-Early Miocene period granitic intrusive rocks and genetically related volcanic rocks are found in the region (Altunkaynak and Yılmaz, 1999; Duru et al., 2004; Özgenç and İlbeyli, 2008; Altunkaynak and Dilek, 2006; Karacık et al., 2008; Akay, 2009; Prelević et al., 2012; Gülmez et al., 2013; Aslan et al., 2017). In the Biga Peninsula, Oligocene-aged volcanic products include the andesitic Yeniköy, acidic Atikhisar, basaltic Saraycık, and andesitic Bağburun and Hallaçlar volcanics (Dönmez et al., 2005). In the Lower Miocene period the andesitic Şapçı volcanic rocks and dacitic Yürekli volcanics are present. The Yürekli volcanics outcrop in a very limited area and generally have been altered. The final products in the region are the Upper Miocene-aged Taştepe basalts. All these units are unconformably overlain by the Lower Miocene aged Soma formation (Duru et al., 2004).

The topic of the study of the Yürekli volcanic rocks is located in the west of the Sakarya zone tectonically, 45 km southwest of Balıkesir (Figure 1b). There are many studies about Tertiary magmatism in the region, with the majority related to andesitic volcanism and granitic plutonic rocks (Ercan et al., 1995; Aldanmaz et al., 2000; Dönmez et al., 2005; Altunkaynak and Genç, 2008, Karacık et al., 2008; Prelević et al., 2015; Erdem, 2015; Aslan et al., 2017). There are limited studies about the Yürekli volcanics (Duru et al., 2004; Pehlivan et al., 2007) with studies only performed about general geology and petrography due to the small outcrop area. In this study, detailed petrographic and petrochemical properties of the Yürekli volcanics are determined in an attempt to investigate their position within collisional volcanism in NW Anatolia.

2. Stratigraphy

In the Biga Peninsula, sediments, metamorphic and widespread magmatic rocks are present in the Palaeozoic to Pliocene age interval (Krushensky, 1976; Duru et al., 2004; Dönmez et al., 2005). The basement rocks in the area comprise moderate-high degree Palaeozoic-aged Kazdağ Massif and the low-moderate degree Triassic-aged Karakaya Complex (Duru et al., 2004). In the nearly 160 km^2 study area, the Triassic Karakaya Complex, Tertiary volcanic rocks and the overlying Soma formation are present (Figure 2). The Karakaya Complex outcrops in a small area southeast of the study area. The uppermost unit of the Sakarya Zone basement, the Karakaya Complex, comprises light grey-brown sandstone and semi-crystallised limestone olistoliths within them (Duru et al., 2004; Pehlivan et al., 2007). The Hallaçlar volcanics unconformably overlying the Karakaya Complex have broad distribution in the region. According to K-Ar dating (Dönmez et al., 2005), the unit has Upper Oligocene age of 26.5±1.1 My and contains andesite, basaltic-andesite and pyroclastics. With excessive alteration, the unit experienced kaolinization and silicification (Erdem and Aslan, 2015). In altered outcrops the unit has light yellow-white colour, while it appears light brown-rose coloured in outcrops without alteration effects. The Early Miocene-aged Şapçı volcanics lie above

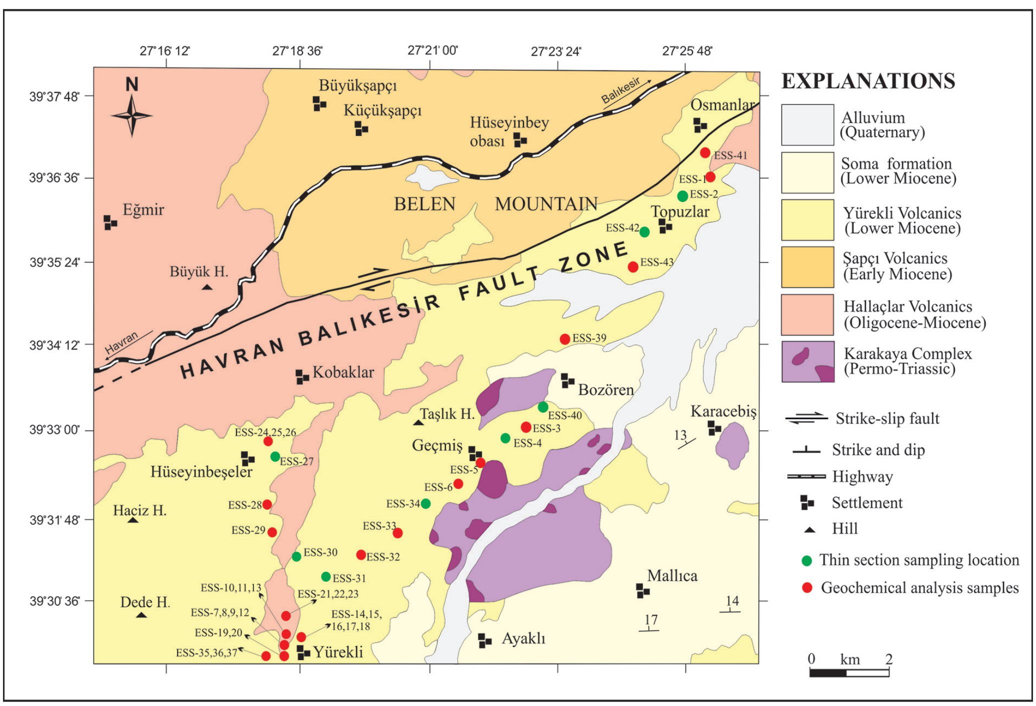

Figure 2- Geological map of the study area (modified after Pehlivan et al., 2007).

the Hallaçlar volcanics. The unit comprises andesite, trachy-andesite and their pyroclastics and is identified as 21.2±09 My by K-Ar dating (Dönmez et al., 2005) and as Early Miocene by zircon SHRIMP U-Pb dating (22.72±0.19 and 22.97±0.23 My) (Aslan et al., 2017). It outcrops in the north of the study area nearly Büyük and Küçük Şapçı villages. The unit, with light grey and light pink colour, has homogeneous hard and fractured structure.

Whole-rock K-Ar data of dacitic lava from the Yürekli volcanic rocks identified the unit as Lower Miocene (19.8±0.3, 19.5±0.1 and 20.3±0.6 My) (Krushensky, 1976). The unit is distributed along a line from northeast to southwest in the study area. The best outcrop in the region is near Yürekli village and environs (Figure 2). The Yürekli volcanics occur above the Şapçı and Hallaçlar volcanics. All units are covered by the Lowe Miocene aged Soma Formation comprising clay, marl, sandstone, tuffite, clayey limestone, siltstone and pebblestone alternations. The Soma Formation has white, grey and light-yellow colour, generally showing horizontal or close-to-horizontal bedding. It contains oolitic limestone with occasional diameters up to 2 cm. Quaternary-aged alluvium comprises the youngest unit in the study area.

3. Material and Method

Thin sections were made from 40 samples of dacitic lava from the Yürekli volcanics and 10 samples from surrounding rocks, for a total of 50 samples, investigated at Balıkesir University Department of Geological Engineering Research Laboratory using an Olympus CX31P brand polarizing microscope. A total of 21 dacitic lava samples found to be appropriate after petrographic investigations were send to ACME Laboratories (Vancouver, Canada) for main and trace-rare earth element analyses. After samples were powdered, the main and trace elements were analysed with ICP-AES, while rare earth elements were analysed with the ICP-MS method. In this analysis, main elements were measured with the ICP-AES method after $LiBO_2$ fusion. For trace and rare earth element analyses, 0.2 g powder sample was mixed with 1.5 g $LiBO_2$ in a graphite pot and heated to 1050 °C for 15 minutes. Melted samples were then dissolved in 5% HNO_3 and the solutions were analysed. With results given as weight %, main elements used SO-18/CSC as standard, while trace and rare earth elements given in ppm used the SO-18 standards.

4. Lithology and Petrography of Yürekli Volcanic Rocks

Yürekli volcanics comprise dacitic lava and pyroclastics. Pyroclastics are light-cream coloured tuffs, outcropping in very small areas east of Geçmiş village and south of Kobaklar village exposed to excessive alteration.

Dacitic lava outcrops in a large area from Osmanlar and Topuzlar villages north east of the study area continuing south to Yürekli village (Figure 2). Additionally, there are outcrops near Hüseyinbeşeler and Geçmiş villages and near Taşlık Hill, Haciz Hill and Dede Hill. The dacitic lavas form a dome structure especially near Yürekli village and surroundings (Figure 3a). In the centre of Yürekli village, the coarse-grained unit was identified to contain xenoliths of 1-3 cm dimensions. In spite of observing grey and beige tones (Figure 3b), sections affected by alteration are light yellow colour (Figure 3c). In areas affected by tectonism, there are abundant fracture-joint systems with slide surfaces. In locations with widespread alteration, there is enrichment in FeO, limonite and hematite observed, with abundant FeO accumulations on discontinuity surfaces (Figure 3d). Additionally, in sections with excessive amounts of alteration, kaolinization and silicification has occurred. Along shear fractures, there is occasional onion-peel structure formation present.

Samples taken from dacitic lava from the Yürekli volcanics generally have porphyric and hyaloporphyric texture, with occasional spherulitic texture observed. The Yürekli dacite contains the main minerals of plagioclase, quartz, amphibolite, biotite, sanidine and opaque oxides. Accessory minerals include apatite and zircon, with secondary minerals of chlorite, sericite and clay found. Plagioclases occur as euhedral and subhedral crystals and are found at different dimensions from very coarse phenocrystals to very small microliths observed in groundmass. An content is 9-25%, generally oligoclase with occasional albite. Some plagioclases show albite twinning or ring zoning (Figure 4a), while some have both characteristics. Plagioclases occasionally have cracked and fractured structure with sericitisation and kaolinization occurring. Quartz is in the form of anhedral crystals. Some quartz crystals have been corroded by groundmass (Figure 4b). Amphibole crystals are euhedral and subhedral, observed as small size microcrystals or phenocrystals (Figure 4c).

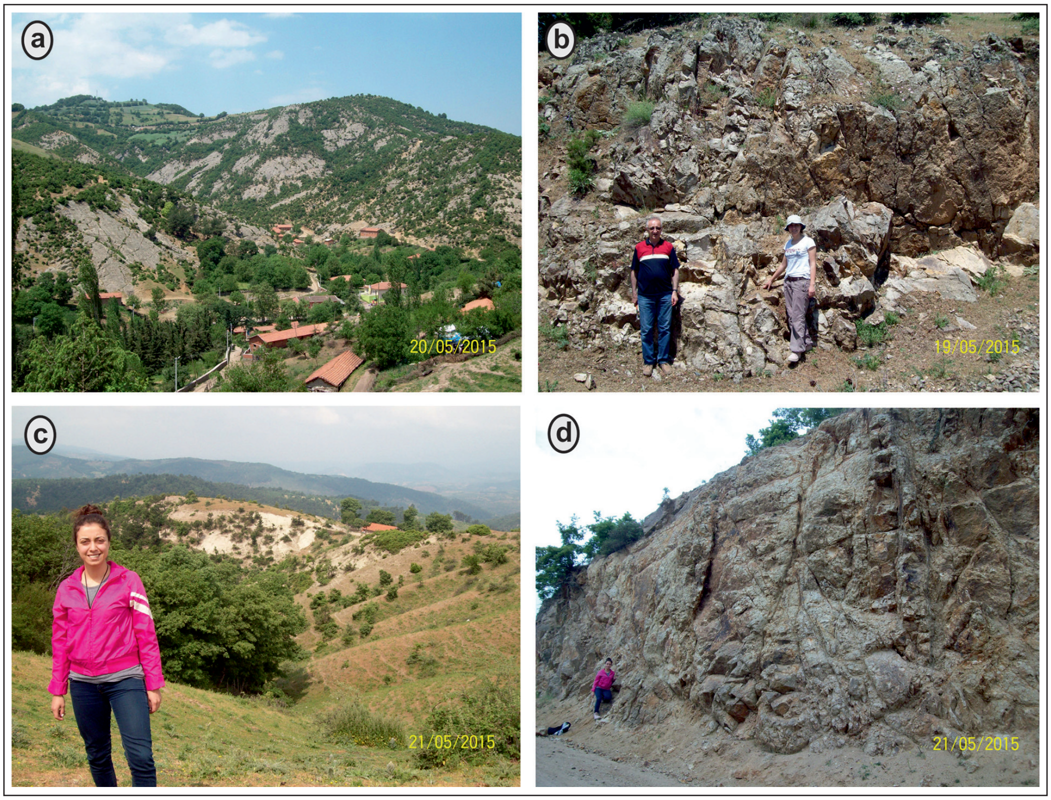

Figure 3- a) Dome shape dacitic lavas from the Yürekli volcanite (Yürekli village south slope), b) Gray colored hard and cracked dacite lava (North of Yürekli), c) Light yellow colored dacite lava affected by alteration (between Yürekli-Kobaklar), d) FeO enrichment along fractures (between Yürekli-Geçmiş villages).

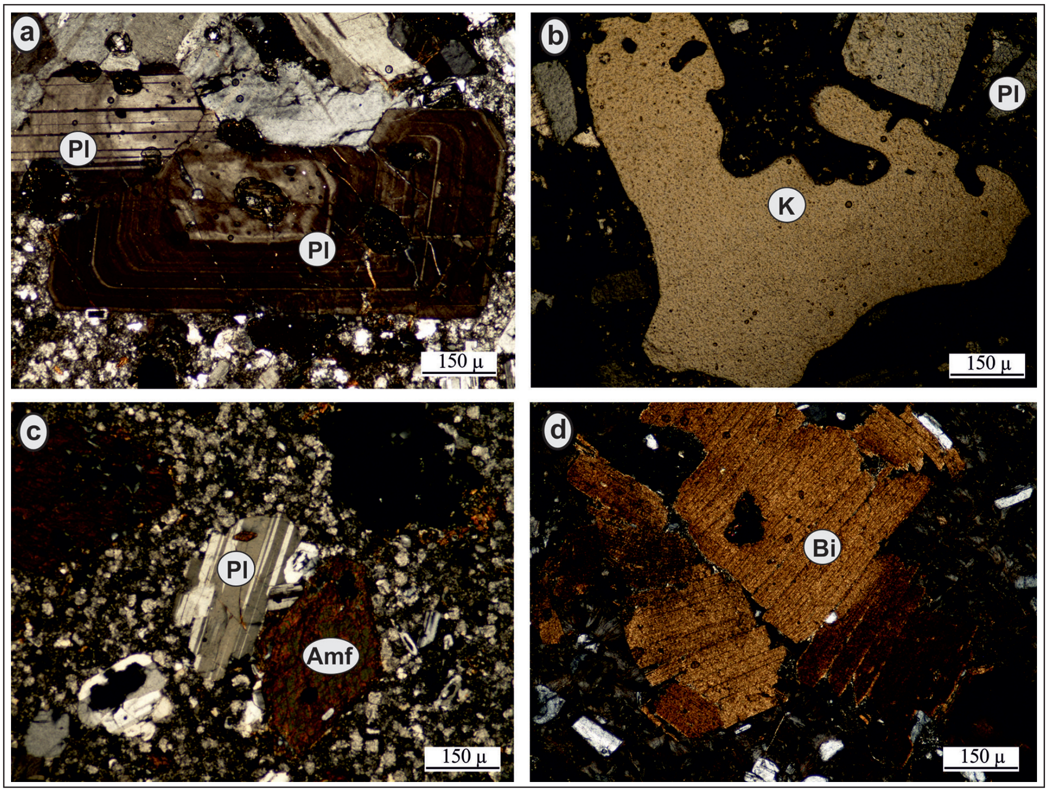

Figure 4- a) Oscillatory zoning plagioclase crystal, b) Quartz crystals corroded by groundmass, c) Euhedral amphibole crystals, d) Leaf-like biotite. Pl: Plagioclase, K: Quartz, Amf: Amphibole, Bi: Biotite.

They have pleochroism with dark brown and brown-yellow tones. Cracks and fractures have chloritisation observed. Biotites, in the form of semi-subhedral crystals, have rod-like or leaf-like (Figure 4d) shape. Generally, they have pleochroism in the light-dark or reddish-orange brown colour interval. Dark red and orange-brown colour tones show biotites have been oxidised. Some biotite minerals appear fully opaque, while some are enriched in iron but have not fully completed the opacification process. Chloritisation has occurred along the cleavage, fractures and cracks in biotites. Some biotites contain inclusions of opaque minerals and plagioclase. There are very small amounts of sanidine crystals, observed as prismatic or small microliths with clean faces. Opaque oxide minerals comprise 1-2% of the rock. Opaque minerals cluster around the edges of amphibole and biotite minerals and have irregular geometric shapes. The accessory minerals of apatite needles are found together with plagioclase, while zircons have very small size and mainly have euhedral form in groundmass. Sericite, calcite, chlorite and clay are present as weathering minerals. Groundmass contains microliths (plagioclase, sanidine and quartz), microcrystals (amphibole, biotite) and light-dark colour glass. There are plagioclase, amphibole, biotite and quartz minerals found as microliths and crystallites within the groundmass.

5. Geochemistry

The main, trace and rare earth element analysis results for dacitic lava samples from the Yürekli volcanic rocks are given in table 1. The variations in samples were SiO_2 values 60.67-73.46%, Al_2O_3 values 12.28-16.95%, MgO values 0.42-2.33%, Fe_2O_3 values 1.46-5.98%, CaO values 2.20-4.85%, K_2O values 3.17-5.87% and Na_2O values 1.94-6.65%. The LOI values were generally >1.5% due to alteration in the rocks, with these values reaching 5-5.8% for samples from between Yürekli and Geçmiş villages.

The SiO_2 against Zr/TiO_2 classification diagrams (Winchester and Floyd, 1977) for dacitic rocks of the Yürekli volcanics generally indicate dacite with some samples appearing to fall in the andesite or rhyolite areas (Figure 5a). Due to alteration of the rocks, some samples are located in different areas of the diagram. When the (Zr/TiO_2*0.0001) against Nb/Y diagram (Pearce, 1996) based on immobile elements is used, all samples appear to fall in the dacite/rhyolite area (Figure 5b). AFM triangle diagrams (Irvine and Baragar, 1971) indicate samples are in the calc-alkaline field (Figure 5c). On the Th-Co diagram (Hastie et al., 2007), all samples are located in the high-K and shoshonitic series fields (Figure 5d).

Diagrams of SiO_2 against main-trace elements observed negative and positive anomalies associated with fractional crystallisation of main mineral phases related to evolution of the investigated rocks. When variations according to increasing SiO_2 are investigated, there are negative trends for Na_2O, MgO, CaO, Al_2O_3, Fe_2O_3, P_2O_5, TiO_2, MnO, Rb and Zr, with a positive trend for K_2O while Sr, Ba, Th and Nb have irregular distributions (Figure 6). Main and trace element distributions appear to comply with the Early Miocene-aged Şapçı volcanics found in the region and similar to other volcanics (Figure 6). According to N-MORB normalised trace element distributions (Sun and McDonough, 1989), there is enrichment observed for large ion lithophile elements (LILE), Th, U and Ce values, with depletion of some high field strength elements (HFSE; Y and Ti), Nb, Tb and Ta distributions (Figure 7a). The investigated rocks are enriched in light rare earth elements and slightly less enriched in heavy rare earth elements (La_N/Lu_N= 16.77-25.67; La_N/Sm_N=4.79-7.07 and La_N/Yb_N=17.67-28.95) on rare earth element distributions (Figure 7b) normalised to chondrite (Sun and McDonough, 1989). The enrichment of light rare earth elements compared to heavy rare earth elements is typical of calc-alkaline volcanism (Wood and Joron, 1979; Wilson, 1989). Additionally, rare earth element distribution has a concave shape, indicating mineral differentiation of amphibole and plagioclase (Thompson et al., 1984; Thirlwell et al., 1994). Similarly, Eu has a very weak anomaly (Eu_N: 0.66-0.81); this situation shows differentiation of plagioclase and K-feldspar or high oxygen fugacity. The trace and rare earth element distributions for the Yürekli volcanics are similar to the Early Miocene-aged Şapçı volcanics (Figure 7a and b); thus, they may be said to have derived from the same source.

Table 1- Main oxide (weight %), trace element (ppm) and rare earth element (ppm) analyses of dacitic lava from the Yürekli volcanics.

	Yürekli volcanic rocks (dacite)									
Sample no:	**ESS-1**	**ESS-3**	**ESS-5**	**ESS-6**	**ESS-9**	**ESS-10**	**ESS-11**	**ESS-14**	**ESS-17**	**ESS-18**
SiO_2	60.67	73.46	65.61	66.18	66.79	70.00	64.6	63.03	62.89	70.96
TiO_2	0.69	0.40	0.47	0.49	0.50	0.43	0.49	0.54	0.56	0.47
Al_2O_3	16.82	12.28	15.31	16.18	16.24	13.71	15.8	16.46	16.93	15.06
Fe_2O_3(t)	5.98	1.62	2.68	2.20	2.33	1.87	4.14	4.86	4.79	1.46
MnO	0.10	0.02	0.10	0.01	0.01	0.08	0.05	0.06	0.06	0.07
MgO	1.37	0.57	0.77	0.72	0.49	0.42	0.56	0.97	1.13	0.42
CaO	4.85	2.21	2.20	2.27	2.26	2.91	3.35	2.72	2.75	2.62
Na_2O	3.65	2.21	2.07	2.48	2.94	2.15	2.99	2.93	2.96	2.80
K_2O	3.17	3.51	4.64	4.40	5.35	5.87	3.82	5.27	5.61	4.79
P_2O_5	0.25	0.14	0.16	0.10	0.17	0.14	0.17	0.19	0.19	0.17
LOI	2.10	3.30	5.80	4.70	2.60	2.20	3.70	2.60	1.80	0.90
Total	**99.65**	**99.72**	**99.81**	**99.73**	**99.68**	**99.78**	**99.67**	**99.63**	**99.67**	**99.72**
Zr	204	136	198	181	166	127	180	163	170	158
Y	21.0	14.2	13.9	15.3	16.3	15.9	17	15.4	16.3	16.6
Sr	732	502	503	559	561	465	577	592	648	628
Rb	106	111	162	160	172	183	135	162	174	137
Th	24.9	27.3	36.2	38.1	36.1	37.3	33.3	33.2	31.1	32.2
Ta	1.3	1.0	1.5	1.5	1.6	1.3	1.7	1.4	2.1	1.1
V	130	49	76	73	84	47	76	93	95	67
Pb	9.8	3.2	4.4	3.0	9.1	8.9	8.7	6.1	6.5	10.9
Ni	5.3	3.2	3.2	2.5	2.7	2.6	3.1	5.4	5.8	2.8
Co	14.2	3.6	3.6	3.6	5.3	5.5	6.3	10.9	10.5	3.4
Cs	4.9	4.2	5.2	5.5	4.1	6	3.9	7.2	7.5	6.6
Ba	1257	1109	1310	1345	1430	1294	1343	1470	1480	1342
Nb	14.9	11.3	14.4	14.0	14.3	12.7	14	13.2	13.2	12.6
Hf	4.9	3.3	5.3	4.8	4.6	3.3	4.5	4.4	4.7	4.0
La	54.90	44.40	55.10	56.10	61.00	53.70	53.60	55.70	56.80	54.10
Ce	98.90	76.70	96.40	95.80	107.20	90.20	97.60	101.40	97.90	97.50
Pr	10.43	7.98	9.60	9.71	10.64	8.79	9.58	10.06	9.90	9.97
Nd	35.70	28.70	33.90	33.90	37.60	30.80	32.50	35.00	34.80	36.60
Sm	6.43	4.73	5.51	5.39	5.80	4.97	5.51	5.90	5.71	6.11
Eu	1.56	0.96	1.11	1.20	1.33	1.06	1.28	1.27	1.33	1.43
Gd	5.65	3.70	4.42	4.27	4.77	4.21	4.98	4.54	4.48	4.97
Tb	0.78	0.47	0.56	0.58	0.64	0.58	0.64	0.60	0.59	0.69
Dy	4.12	2.68	2.85	3.16	3.18	3.03	3.33	3.33	3.1	3.39
Ho	0.75	0.49	0.55	0.55	0.60	0.52	0.64	0.64	0.56	0.63
Er	2.18	1.36	1.42	1.58	1.67	1.57	1.63	1.62	1.54	1.54
Tm	0.31	0.20	0.23	0.22	0.28	0.26	0.28	0.25	0.26	0.24
Yb	2.05	1.42	1.50	1.39	1.81	1.67	1.63	1.67	1.66	1.47
Lu	0.35	0.23	0.23	0.21	0.27	0.26	0.27	0.25	0.27	0.23
Eu_N/Eu^*	0.77	0.68	0.66	0.74	0.75	0.69	0.73	0.72	0.78	0.77
La_N/Lu_N	16.81	20.69	25.67	28.63	24.21	22.14	21.28	23.88	22.55	25.21
La_N/Yb_N	19.21	22.43	26.35	28.95	24.17	23.07	23.59	23.92	24.54	26.40
Mg#	18.64	26.03	22.32	24.66	17.38	18.34	11.91	16.64	19.09	22.34

Fe_2O_3(t): Total iron; LOI: loss on ignition; Mg# (Mg-number) =100 x MgO / (MgO+Fe_2O_3(t)), Eu*: (Sm+Gd)N/2

Çizelge 1- continued

	Yürekli volcanic rocks (dacite)										
Sample no:	**ESS-20**	**ESS-21**	**ESS-24**	**ESS-28**	**ESS-29**	**ESS-32**	**ESS-33**	**ESS-35**	**ESS-39**	**ESS-41**	**ESS-43**
SiO_2	62.00	65.00	65.92	65.13	65.23	65.47	64.95	64.48	63.01	66.66	68.03
TiO_2	0.52	0.54	0.49	0.55	0.53	0.51	0.41	0.46	0.50	0.48	0.46
Al_2O_3	16.45	16.59	15.61	16.52	16.95	16.34	14.54	14.86	15.62	15.05	14.36
Fe_2O_3(t)	4.86	3.37	3.91	3.09	3.14	3.35	3.73	4.11	3.85	4.34	4.26
MnO	0.08	0.03	0.03	0.03	0.02	0.01	0.03	0.05	0.46	0.05	0.05
MgO	0.93	0.73	0.73	0.98	0.73	0.59	1.54	2.33	1.13	1.09	1.07
CaO	3.06	2.68	2.92	3.13	2.78	2.98	3.31	3.76	3.47	3.24	3.12
Na_2O	2.74	2.96	2.84	2.91	2.94	3.07	1.94	2.51	3.10	3.33	3.22
K_2O	5.35	4.22	3.78	4.02	4.28	4.14	3.64	3.27	3.79	3.83	3.78
P_2O_5	0.19	0.18	0.17	0.17	0.07	0.17	0.22	0.15	0.17	0.13	0.13
LOI	3.50	3.40	3.30	3.20	3.00	3.10	5.30	3.70	4.50	1.50	1.20
Total	**99.68**	**99.70**	**99.70**	**99.73**	**99.67**	**99.73**	**99.61**	**99.68**	**99.60**	**99.70**	**99.68**
Zr	170	179	150	165	171	154	145	141	131	161	140
Y	15.8	19.2	14.9	24.4	12.9	13.3	14.5	16.6	18.5	19.1	13
Sr	607	559	578	604	579	608	964	681	663	578	545
Rb	168	141	130	122.6	144	138	116	101	139	138	134
Th	34.0	35.0	33.6	32.6	39.0	34.0	16.4	16.3	35.7	39.8	36.8
Ta	1.3	1.4	1.0	1.2	1.2	1.3	0.7	0.7	1.3	1.3	1.1
V	89	85	86	89	81	92	73	79	82	84	69
Pb	8.2	7.6	2.2	7.7	3.2	4.1	22.4	12.7	18.2	7.2	7.1
Ni	3.8	5.0	4.1	3.9	3.0	3.6	7.0	17.1	5.3	3.8	3.6
Co	17.7	7.4	6.1	5.2	3.9	5.5	6.5	10.1	15.7	8.8	8.8
Cr	7.1	3.6	6.0	3.6	5.0	4.0	10.0	1.4	10.4	5.9	7.1
Ba	1411	1270	1186	1215	1262	1262	1919	1231	1969	1167	1181
Nb	13.7	14	12.8	12.3	13.6	13.5	8.5	8.4	13.5	12.8	11.1
Hf	4.1	4.9	4.4	5.0	5.3	4.5	4.4	3.8	3.7	4.5	3.7
La	52.60	54.00	53.80	70.20	53.20	53.50	38.70	43.00	53.20	64.00	45.70
Ce	95.20	97.60	95.60	115.00	89.30	100.70	67.60	78.50	99.90	11.60	77.40
Pr	9.49	10.03	9.62	13.30	8.65	10.23	7.69	9.11	9.82	11.25	8.22
Nd	30.20	33.80	32.00	48.30	28.20	35.80	26.90	34.80	34.00	39.10	27.80
Sm	5.20	5.62	5.73	8.31	4.86	5.96	4.59	5.80	5.65	6.15	4.74
Eu	1.28	1.27	1.29	1.73	1.10	1.34	1.01	1.28	1.21	1.32	1.14
Gd	4.56	4.72	4.23	6.73	3.60	4.36	3.61	4.49	4.70	4.83	3.59
Tb	0.61	0.69	0.59	0.95	0.52	0.63	0.56	0.66	0.71	0.71	0.49
Dy	3.10	3.44	2.82	4.58	2.72	3.18	2.99	3.32	3.60	3.74	2.37
Ho	0.53	0.71	0.48	0.89	0.50	0.51	0.54	0.56	0.66	0.67	0.41
Er	1.69	1.82	1.44	2.76	1.40	1.20	1.49	1.65	1.93	1.85	1.19
Tm	0.24	0.31	0.20	0.36	0.21	0.20	0.21	0.24	0.30	0.30	0.21
Yb	1.66	1.83	1.37	2.42	1.30	1.37	1.46	1.59	2.16	1.97	1.37
Lu	0.27	0.30	0.23	0.40	0.23	0.19	0.22	0.23	0.34	0.33	0.22
Eu_N/Eu^*	0.78	0.73	0.77	0.68	0.77	0.77	0.73	0.74	0.70	0.71	0.81
La_N/Lu_N	20.88	19.29	25.07	18.81	24.79	30.18	18.85	20.04	16.77	20.79	22.26
La_N/Yb_N	22.73	21.17	28.17	20.81	29.35	28.01	19.01	19.40	17.67	23.30	23.93
Mg#	16.06	17.80	15.73	24.08	18.86	14.97	29.22	36.18	22.69	20.07	20.08

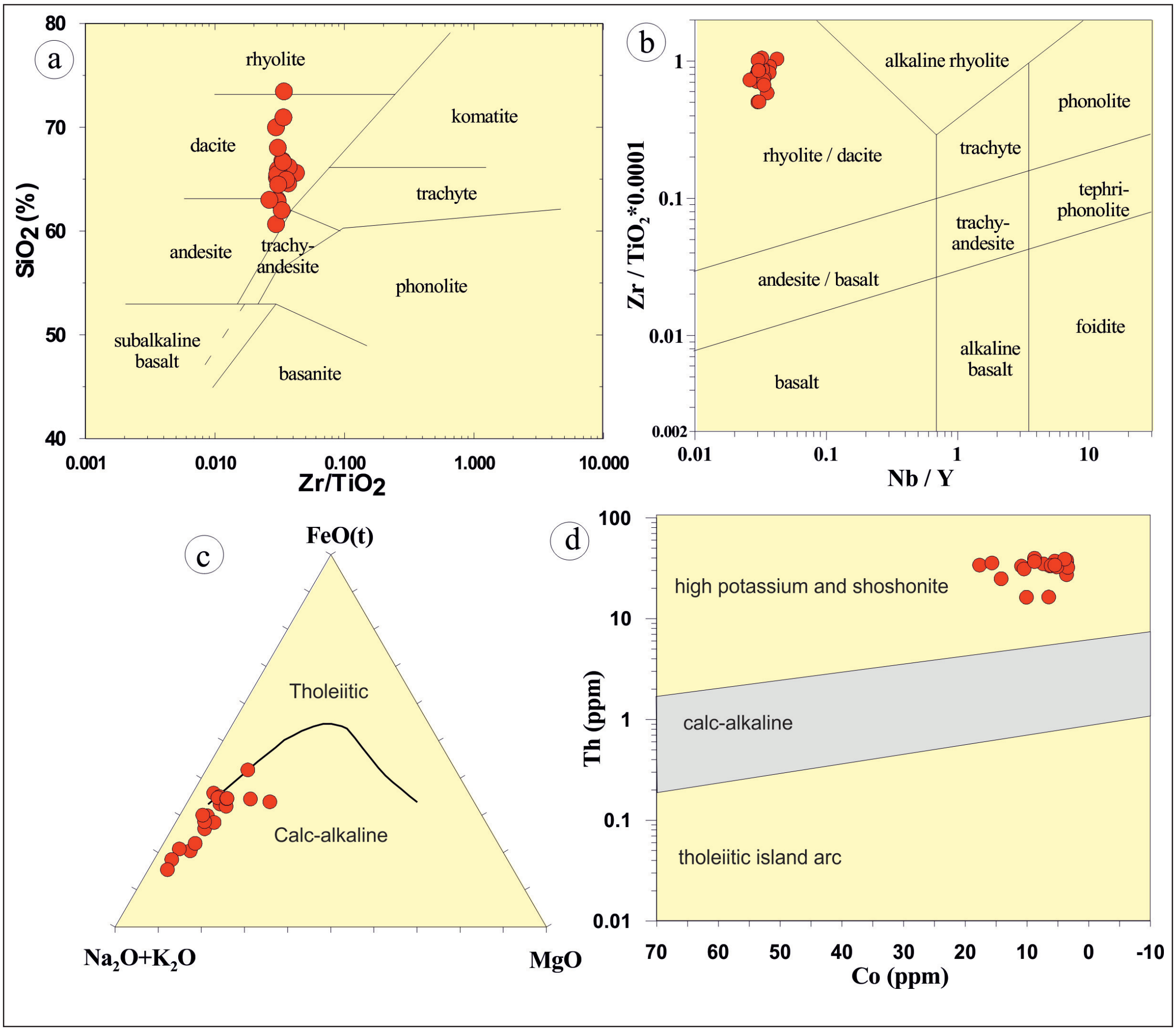

Figure 5- a) Dacitic lavas; SiO_2 vs. Zr/TiO_2 diagram (after Winchester and Floyd, 1977), b) Nb/Y vs. Zr/Ti classification diagram (Pearce, 1996), c) AFM ternary diagram (Irvine and Baragar, 1971), d) Th (ppm) vs. Co (ppm) diagram (Le Maitre vd., 2002) from the Yürekli volcanites.

6. Discussion

6.1. Source of Magma

Acidic composition magmas are derived from assimilation+fractional crystallisation of mantle-sourced basic magmas (Bacon and Druitt, 1988) or partial melts of mafic-intermediate composition magmatic or sedimentary rocks in the middle-lower crust (Stevens et al., 1997). The enrichment in large ion lithophile elements in the Yürekli volcanics (for example; Rb, Ba, Th and K) (Figure 7a) and high Ba/La and Th/Yb ratios show that the main magma for these rocks may be derived from a lithospheric mantle source containing subduction components (Pearce and Peate, 1995; Elburg et al., 2002; Zellmer et al., 2005; Baier et al., 2008; Aslan et al., 2017). Additionally the negative anomalies in Nb and Ta show subduction and/or crustal contamination (Pearce, 1983; Pearce and Peate, 1995; Elburg et al., 2002). The Ba/La ratio of the investigated rocks varies from 17.3-49.5, indicating a volcanic arc. Similarly, Ba/Nb, La/Nb, Ba/La, Sm/Nd and Nb/Th ratios show the rocks may be related to calc-alkaline volcanic rocks (Thompson et al., 1984; White and Patchett 1984; Bradshaw and Smith 1994; Smith et al., 1999; Elburg et al., 2002). The volcanic rocks display a pattern close to horizontal on heavy rare earth element distributions, which leads to the consideration that this main magma may have derived from a spinel lherzolite source containing

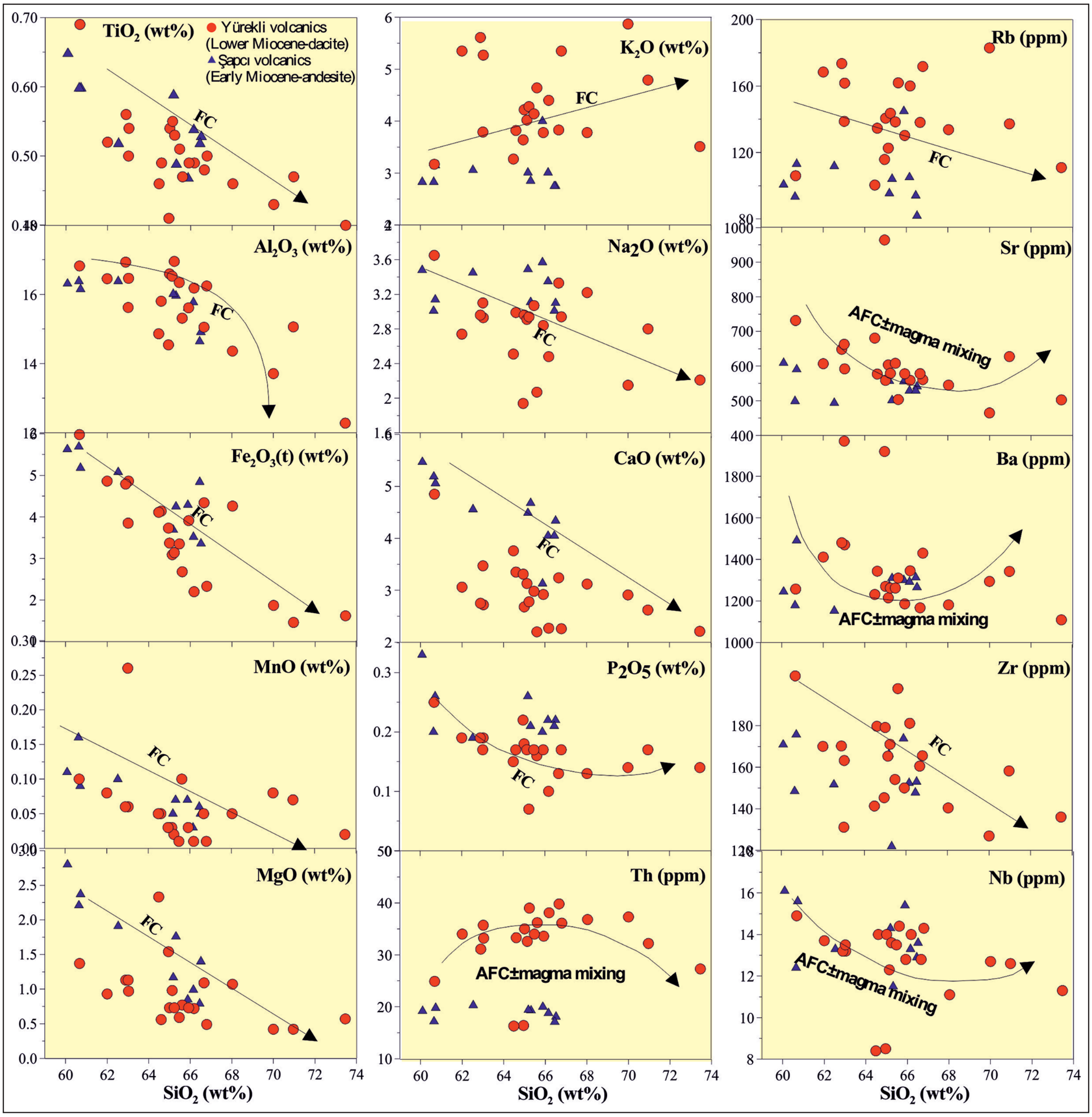

Figure 6- SiO_2 (wt%) vs. major oxide (wt%), trace (ppm) and rare earth element (ppm) variation plots of the Yürekli volcanic rocks. FC: fractional crystallization, AFC: assimilation fractional crystallization. Geochemical values of Şapçı volcanites were taken from Aslan et al., 2017.

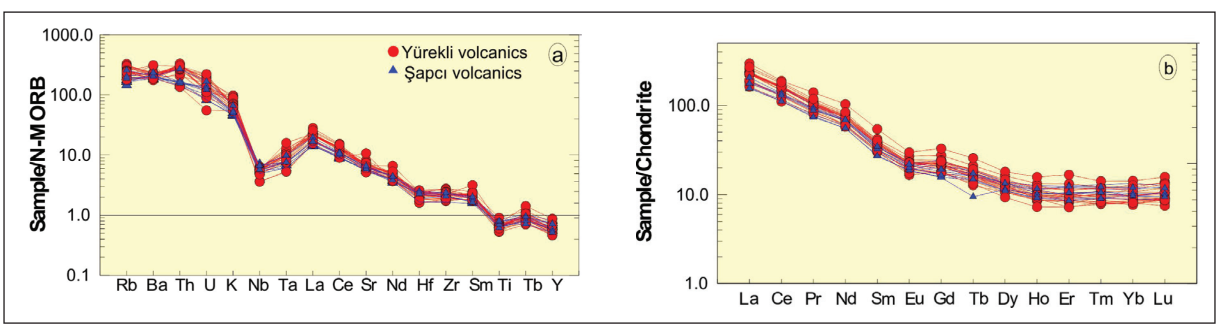

Figure 7- a) N-type MORB (Sun and Mcdonough 1989) normalized trace element spider diagram, b) chondrite (Sun and McDonough, 1989) normalized rare earth element pattern plots of the Yürekli volcanic rocks.

garnet, rather than a lherzolite source in the mantle (<50 km depth) (Wood and Joron 1979; Wilson 1989). The low Zr/Y (6-12) and Zr/Nb (10-13) values in the samples indicate sectional melt from a lithospheric mantle source.

Samples from the Yürekli volcanic rocks on the Nb_N/Zr_N–Zr diagram are located in the collision-related calc-alkaline volcanic rock field (Figure 8a). The Ta/Yb against Th/Yb diagram (Figure 8b) is used to determine whether additional components were added as a result of differentiation between mantle sources and subduction and/or crustal contamination. The analysed samples appear to show they were derived from magma evolving with fractional crystallisation (FC) and/or assimilation (AFC) events with subduction enrichment. On the same diagram, the high Th/Yb ratios in the volcanic rocks indicate subduction enrichment (Wilson, 1989). Samples from the Yürekli volcanic rocks fall in the volcanic arc area on the Ba/Nb-La/Nb diagram (Figure 8c). Similarly, on the Nb/La-La/Yb diagram (Figure 8d), samples appear to be in the lithospheric mantle area. The Lower Miocene Şapçı volcanic rocks with similar geochemical characteristics to volcanic rocks in the region (Aslan et al., 2017) are located in the same area of the diagram. This shows that Lower Miocene-aged volcanism in the region derived from main magmas with similar sources. The samples investigated have Zr/Sm values of 10-35, which similarly indicate an enriched lithospherice source (Wilson, 1989).

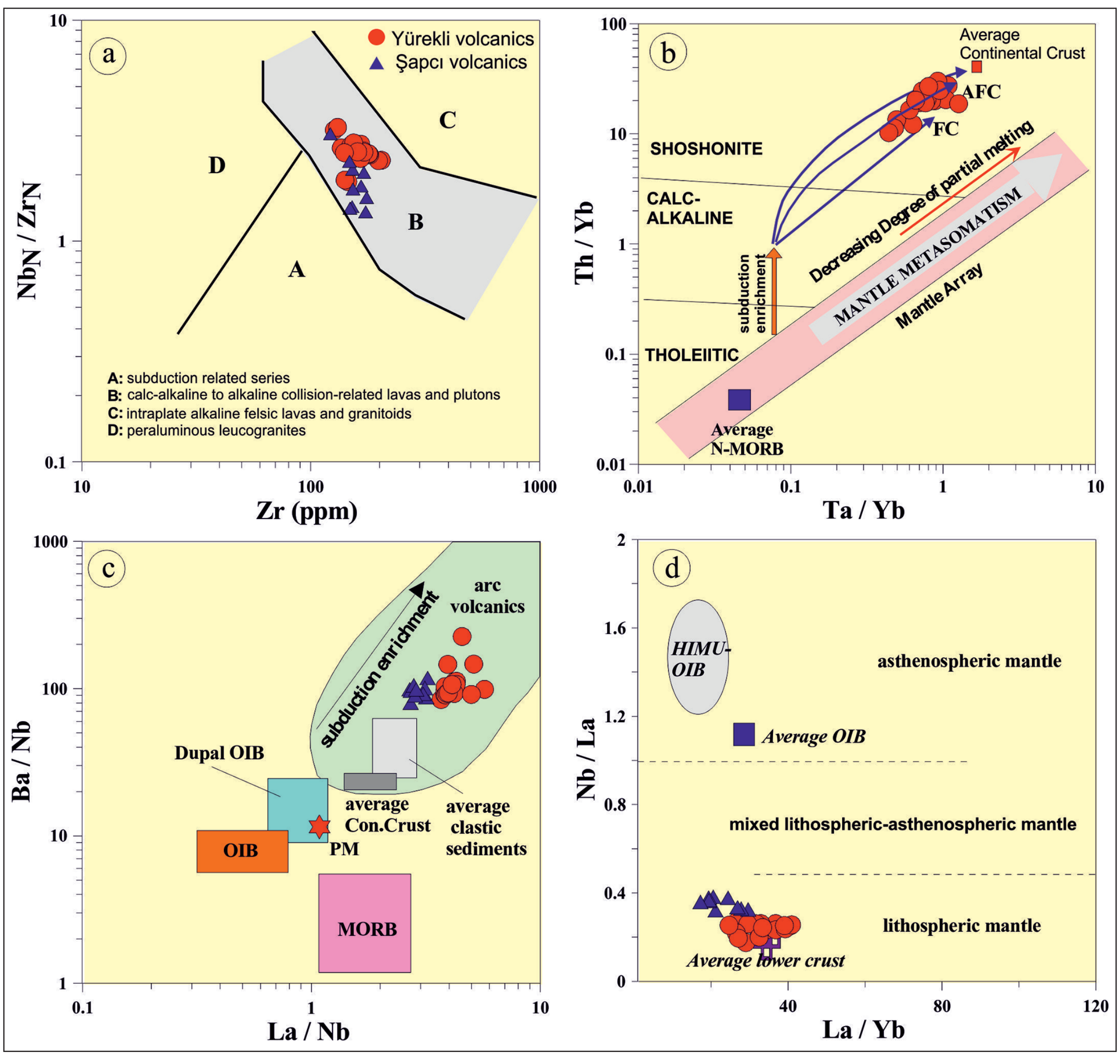

Figure 8- a) NbN/ZrN vs. Zr (ppm) diagram (Thieblemont and Tegyey 1994), (b) Th/Yb (ppm) vs. Ta/Yb (ppm) diagram (Pearce et al., 1990), (c) Ba/Nb (ppm) vs. La/Nb (ppm) diagram (Jahn et al., 1999), (d) La/Yb (ppm) vs. Nb/La (ppm) diagram (Jahn et al., 1999) for the Yürekli volcanic rocks. FC: Fractional crystallization; AFC: Assimilation-fractional crystallization; PM: Primary Mantle; MORB: Mid-Ocean Ridge Basalts; OAB: Ocean-Island Basalt.

6.2. Fractional Crystallisation and Assimilation

Negative or positive trends in SiO_2 against main and trace element variations indicate fractional crystallisation (FC) or assimilation fractional crystallisation (AFC) during evolution of the rocks (Figure 6). Variations of Na_2O, Al_2O_3, and CaO against SiO_2 are effective, especially in plagioclase crystallisation. Similarly, variation of SiO_2 against MgO ratios may be effective especially for amphibole differentiation, while the variation in SiO_2 against Fe_2O_3 ratios may be effective on amphibole and Fe-Ti oxide minerals. The variation in the trace element of Rb may be associated with amphibole crystallisation while the variation in Sr may be associated with plagioclase crystallisation (Thirlwall et al., 1994). Similarly, the reduction in TiO_2 and P_2O_5 against SiO_2 may be associated with crystallisation of titanomagnetite and apatite, respectively. The weak negative Eu anomaly indicates plagioclase and/or K-feldspar fractionation. Additionally, the negative Sr and Eu anomalies are the result of plagioclase fractionation, while negative Ba and Eu anomalies are caused by K-feldspar fractionation (Gill, 1981; Thirlwall et al., 1994). In this context, plagioclase, amphibole and biotite differentiation were effective during evolution of the investigated volcanic rocks.

Sr-MgO and Ba-Sr diagrams (Figure 9a and b) show plagioclase differentiation. Fractional crystallisation is also observed on the Zr-La diagram (Figure 9c). To identify mineral phases effective on fractional crystallisation, some binary diagrams are prepared using incompatible-compatible element associations. The negative Nb and Y variations against Zr (Figure 9d and f) represent biotite and amphibole differentiation. A positive trend of Zr against TiO_2 content indicates plagioclase and apatite differentiation, while a slight negative trend indicates Fe-Ti oxide and amphibole differentiation (Figure 9e). All these diagrams show that fractional crystallisation (FC) played an important role in the evolution of the Yürekli volcanics and differentiation of plagioclase, amphibole, biotite and Fe-Ti oxide were more effective compared to other phases. Additionally, the Ta/Yb against Th/Yb diagram (Figure 8b) shows fractional crystallisation (FC) with lower amounts of assimilation (AFC) were probably effective in the development of the Yürekli volcanics.

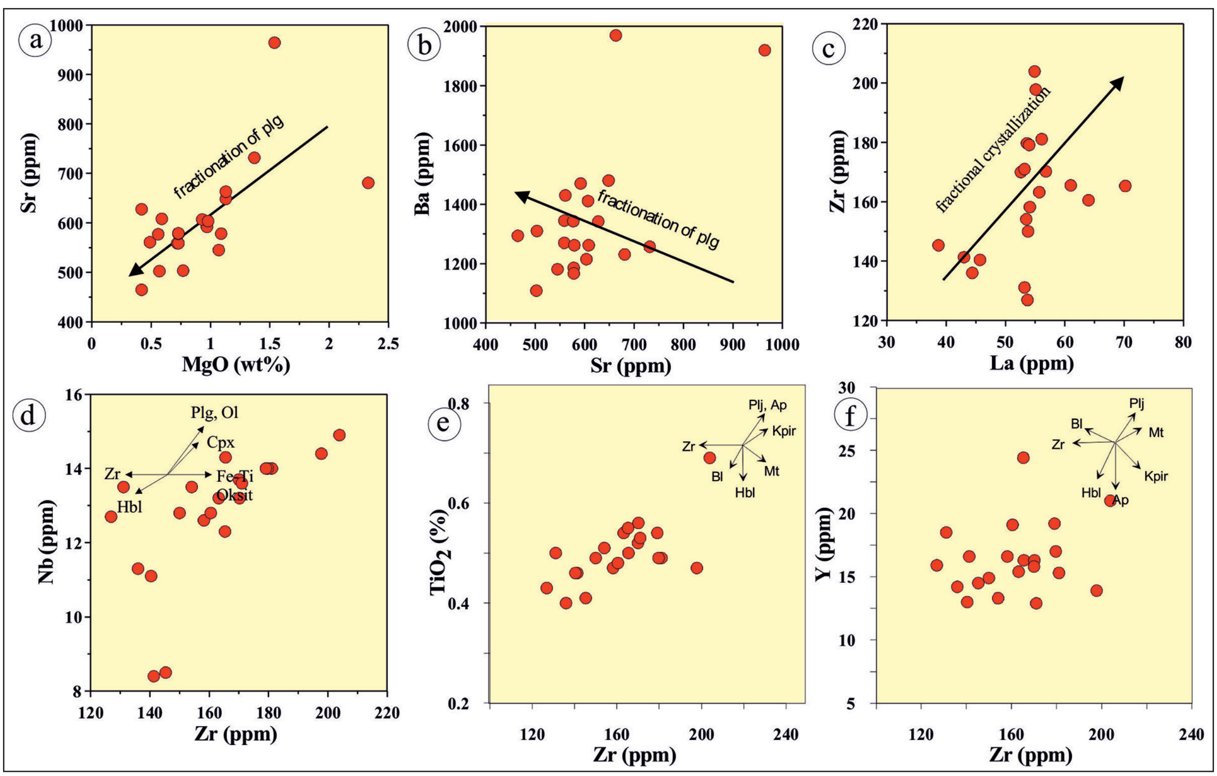

Figure 9- a) Sr (ppm) vs. MgO (wt%), b) Ba (ppm) vs. Sr (ppm), c) Zr (ppm) vs. La (ppm), d) Nb (ppm) vs. Zr (ppm) e) TiO_2 (%) vs. Zr (ppm), f) Y(ppm) vs. Zr (ppm) diagrams. Plj: Plagioclase, Kpir: Clinopyroxene, Ol: Olivine, Hbl: Hornblende, Bi: Biotite, Mt: Magnetite, Zr: Zircon, Ap: Apatite.

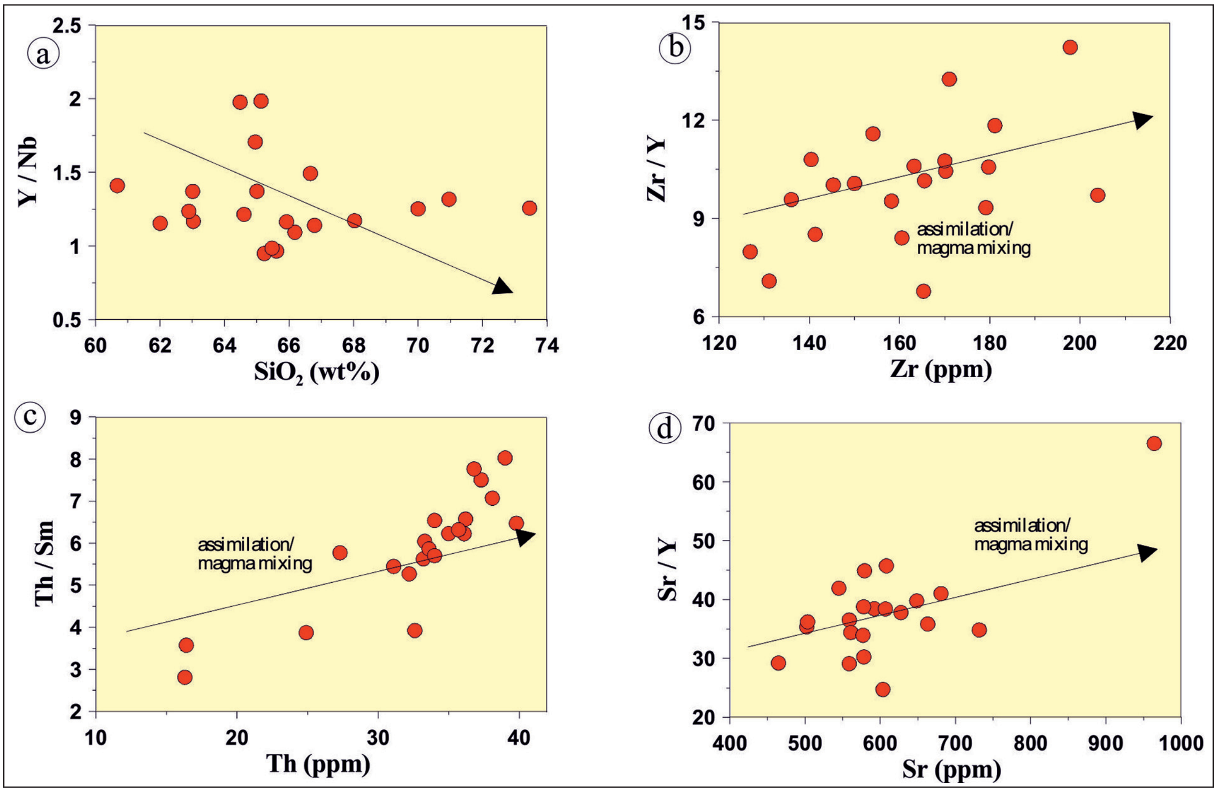

Figure 10- a) Y/Nb (ppm) vs. SiO_2 (%), b) Zr/Y (ppm) vs. Zr (ppm), c) Th/Sm (ppm) vs. Th (ppm) and d) Sr/Y (ppm) vs. Sr (ppm) diagrams.

The Zr/Y-Zr diagram shows the effect of assimilation (Figure 10b). The linear trend lines on Th/Sm-Th and Sr/Y-Sr variation diagrams (Langmuir et al., 1978) (Figure 10a, c, and d) indicate assimilation and/or low rates of magma mixing were effective in the evolution of the magma.

6.3. Magma-Tectonic Environment

The Yürekli volcanics have high potassium and calc-alkaline character. The investigated rock samples were located in the volcanic arc field (Figure 11a) on Rb/10-Hf-Ta*3 triangle diagrams (Harris et al., 1986). Additionally, the Rb/30-Hf-Ta*3 (Harris et al., 1986) diagram included a few samples in the precollisional and postcollisional area within the volcanic arc field (Figure 11b). In light of this data, we can say the Yürekli volcanic rocks are related to postcollisional magmatism.

Volcanism in Northwest Anatolia began in the Oligocene and is intensely observed in the Lower-Middle Miocene, continuing into the Upper Miocene with lower amounts in the Pliocene. Plutonism is generally not observed in the Early Miocene. Magmatism beginning with intermediate-potassium calc-alkali character in the Eocene became high potassium calc-alkaline in the Miocene and then intermediate-high potassium alkaline magmatism in the Pliocene. Tertiary magmatism played a significant role in the development of Western Anatolia. From the Upper Cretaceous to the Late Neogene, the NW Anatolian region was affected by a complex tectonic regime (Altunkaynak and Genç, 2008, Dilek and Altunkaynak, 2010; Prelević et al., 2012; Karaoğlu and Helvacı, 2014) and the Palaeogene-Neogene development of this belt is explained by complicated events like subduction, mantle metasomatism, crustal contamination and differentiation (Aldanmaz et al., 2000; Dilek and Altunkaynak , 2010; Altunkaynak et al., 2012; Seghedi et al., 2013; Prelević et al., 2012 and 2015). Studies in recent years have stated the south branch of the Neotethys Ocean developed a roll-back event and the magmatism developing from the Lower Miocene was associated with this event (Biryol et al., 2011; Ersoy et al., 2011; Prelević et al., 2012 and 2015). Magmatic rocks in the region were derived from enriched lithospheric mantle and crust (Dilek and Altunkaynak, 2010, Aslan et al., 2017). Oligocene-Middle Miocene magmatism developed as a result of the collision of the Sakarya continent with the Tauride-Anatolide continent (Ercan et al., 1995).

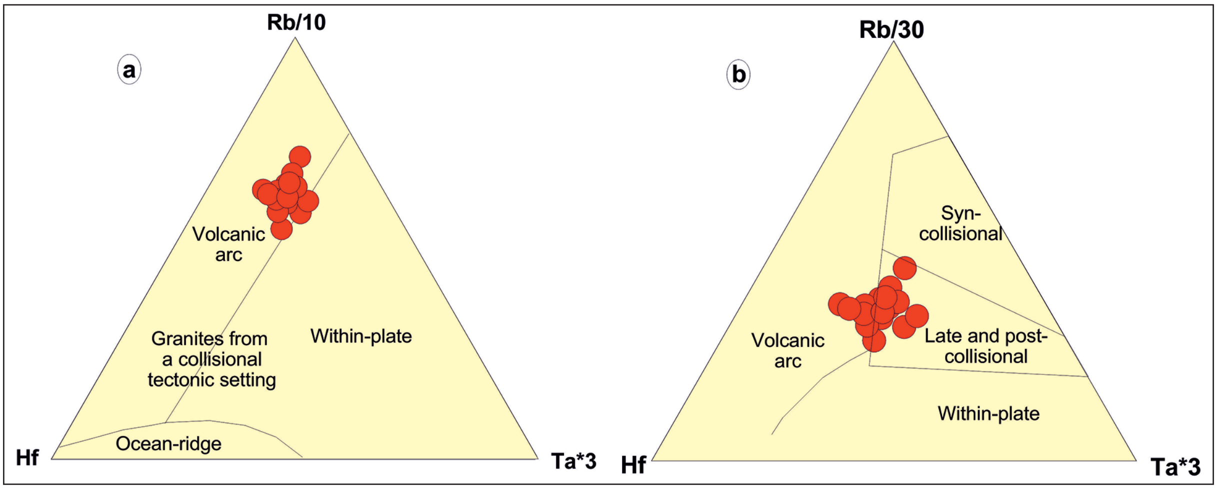

Figure 11- a) Rb/10-Hf-Ta*3 (Harris et al., 1986), b) Rb/30-Hf-Ta*3 (Harris et al., 1986) diagrams of the Yürekli volcanics rocks.

Magmatism after collision began in the Middle Eocene associated with subduction and produced intermediate-potassic calc-alkali plutonic and volcanic rocks. Post-collisional roll-back of the south branch of the Tethys Ocean crust caused elevation of the asthenosphere and melting of enriched lithospheric mantle and thus led to calc-alkali magmatism in the Middle-Late Miocene (Biryol et al., 2011; Prelević et al., 2012; Ersoy et al., 2011). The continuing extensional regime in Western Anatolia caused elevation of the asthenospheric mantle and formation of alkali magmatism linked to this.

7. Conclusion

This study determined detailed petrography of the Yürekli volcanic rocks outcropping southwest of Balıkesir, with attempts to determine the petrochemical characteristics, source and magmatic-tectonic environment of the rocks. Within the scope of this study, the basic results are summarised below:

1. Yürekli volcanic rocks comprise dacitic lava and pyroclastics. Petrographically dacitic lava has porphyric and hyaloporphyric textures, with occasional spherulitic texture. The main minerals forming the rocks are plagioclase, quartz, amphibole, biotite, sanidine and opaque oxides, with accessory minerals of apatite and zircon.

2. The Yürekli volcanics have calc-alkaline character, indicating post-collisional volcanic properties. Distribution normalised to N-MORB show enrichment in large ion lithophile elements (LILE), Th and Ce with depletion in some high field strength elements (HFSE), Nb and Ta content. Chondrite-normalised rare earth element distributions have concave form (mean La_N/Lu_N=16–25) with weak negative Eu anomaly (Eu/Eu*=0.66–0.81).

3. The main magma source for the Yürekli volcanic rocks was enriched lithospheric mantle with fractional crystallisation (FC) and low amounts of assimilation (AFC) effective during evolution.

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This study comprises the Master's Thesis of Geological Engineer Ece Simay Saatçi. Born in 1990, Ece Simay Saatçi graduated from Dumlupınar University Kütahya Technical Sciences Vocational School Department of Natural Construction Stone Technology and then enrolled in Balıkesir University Department of Geological Engineering after external transition examinations. Graduating in 2014, Saatçi began Master's degree study at Balıkesir University Institute of Science and Technology the same year. After completing her Master's thesis and while preparing for her defence, Saatçi was killed in a terrible traffic accident in İzmir on 08 August 2017. Displaying exemplary behaviour in her personality and academic success, Saatçi is commemorated by dedicating this study to her memory. This study was supported by Balıkesir University Scientific Research Projects Unit (Project no: 2015/179). I thank the reviewers for their constructive criticism and valuable opinions.

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