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Petrographic and geochemical characteristics of the Tertiary Bağburun volcanites around Sarıalan (Altıeylül, Balıkesir)

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Abstract

The Bağburun volcanites, located in Altıeylül, Balıkesir, were examined for their petrographic and geochemical properties to enhance the understanding of Neogene volcanism in western Anatolia. These rocks predominantly comprise plagioclase, amphibole, biotite, sanidine, and altered clinopyroxene. Textural features, such as sieve-textured plagioclase and the presence of xenoliths, indicate complex crystallization processes, including magma mixing and assimilation. The major element geochemistry reveals a high-K calc-alkaline nature, characterized by decreasing MgO and TiO_2 and increasing K_2O content. Variations in Na_2O and Sr contents are likely indicative of alteration. Trace element patterns exhibited LILE enrichment, HFSE depletion, negative Eu anomalies, and elevated La/Yb (13.5–18.2) and Th/Nb (13.5–18.2) ratios, suggesting a multicomponent magma source involving mantle melts, subplate fluids, and continental crustal contributions. Their spatial distribution implies that magma ascent was facilitated by local fault systems. In summary, the Bağburun volcanites represent a localized yet significant manifestation of Neogene magmatism in western Anatolia, contributing to a more comprehensive understanding of the tectonic evolution of the region.

Keywords: *Bağburun volcanites, Balıkesir, geochemistry, petrography, Sarıalan.*

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Sarıalan (Altıeylül, Balıkesir) civarındaki Tersiyer yaşlı Bağburun volkanitlerinin petrografik ve jeokimyasal özellikleri

Öz

Balıkesir, Altıeylül'de bulunan Bağburun volkanitleri, Batı Anadolu'daki Neojen volkanizmasının anlaşılmasını geliştirmek amacıyla petrografik ve jeokimyasal özellikleri açısından incelenmiştir. Bu kayaçlar ağırlıklı olarak plajiyoklaz, amfibol, biyotit, sanidin ve altere klinopiroksenden oluşmaktadır. Elek dokulu plajiyoklaz ve ksenolitlerin varlığı gibi dokusal özellikler, magma karışımı ve asimilasyon da dahil olmak üzere karmaşık kristalleşme süreçlerini göstermektedir. Ana element jeokimyası, MgO ve TiO_2'de azalma ve K_2O içeriğinde artış ile karakterize yüksek K'li kalk-alkali bir yapı ortaya koymaktadır. Na_2O ve Sr içeriklerindeki değişimler muhtemelen alterasyonun göstergesidir. İz element örüntüleri, LILE zenginleşmesi, HFSE tükenmesi, negatif Eu anomalileri ve yüksek La/Yb (13,5-18,2) ve Th/Nb (13,5-18,2) oranları sergileyerek, manto eriyikleri, levha altı sıvıları ve kıtasal kabuk katkılarını içeren çok bileşenli bir magma kaynağına işaret etmektedir. Mekânsal dağılımları, magma yükselişinin yerel fay sistemleri tarafından kolaylaştırıldığını göstermektedir. Özetle, Bağburun volkanitleri, Batı Anadolu'daki Neojen magmatizmasının yerel ancak önemli bir tezahürünü temsil etmekte ve bölgenin tektonik evriminin daha kapsamlı bir şekilde anlaşılmasına katkıda bulunmaktadır.

Anahtar kelimeler: *Bağburun volkanitleri, Balıkesir, jeokimya, petrografi, Sarıalan.*

1. Introduction

The volcanic formations in the vicinity of the Sarıalan neighborhood, situated in the Altıeylül district of Balıkesir province, serve as a representative example of Neogene volcanism in Western Anatolia. These formations are characterized as high-potassium volcanic products associated with the extensional tectonic regime of the region (Figure 1). However, comprehensive petrographic and geochemical analyses of this unit are limited and data on magma sources and tectonic settings remain insufficient.

Previous investigations of Neogene high-K calc-alkaline volcanism in Western Anatolia (e.g., Kula [1], Bayramiç [2], Alaçamdağ [3], Şuhut: [4]) have revealed that these magmas record complex processes of fractional crystallization, crustal assimilation, and mantle metasomatism under an extensional geodynamic regime. In the Balıkesir region, volcanic formations of similar ages and compositions have been documented in the Bigadiç and Sındırgı areas [5], [6]. Nonetheless, Bağburun volcanic rocks in the Sarıalan area have not been investigated in detail.

The geodynamic framework of Western Anatolia is governed by the Menderes Massif, ophiolitic mélanges, and Neogene graben systems, which developed in response to slab rollback and the post-collisional extensional regime following the closure of the Neotethys [7], [8]. Within this tectonic context, the Bağburun volcanites offer a localized yet significant opportunity to evaluate the interplay between lithospheric mantle melting, crustal interactions, and structural controls such as fault zones.

Accordingly, this study addresses the following research question: How did fractional crystallization, crustal assimilation, and mantle metasomatism interact to generate Bağburun volcanites within the post-collisional extensional regime of Western Anatolia? To address this question, we examined the lithological, petrographic, and geochemical characteristics of the Bağburun volcanites and evaluated their petrogenesis within the broader framework of the Neogene magmatism in the Aegean region. In doing so, this work aims to fill a gap in the literature by providing the first integrated petrographic and geochemical dataset from Bağburun, thereby contributing to both local geological understanding and regional geodynamic models.

Figure 1. General locator map showing the location of the study area in Turkey and Western Anatolia.

2. Materials and methods

The study area was situated in the vicinity of the Sarıalan neighborhood within the Altıeylül district of Balıkesir Province, encompassing an area of approximately 10 km^2. During the field investigations, geological mapping was conducted at a scale of 1:25. 000, allowing for the detailed determination of lithologic boundaries, distribution of volcanic units, and structural elements. A Garmin GPS device was employed for positioning and a Brunton geologist's compass was used for structural measurements.

For petrographic analyses, 65 fresh rock samples were collected from the site, of which 46 were prepared as thin sections. These sections were prepared at the Department of Geological Engineering, Pamukkale University, and microscopic examinations were conducted at the optical microscope laboratory of the Department of Geological Engineering, Balıkesir University, using an Olympus CX31-P polarizing microscope. Mineral paragenesis, textural features, and alteration types were evaluated thoroughly.

For geochemical analysis, six representative samples with minimal petrographic alteration were selected and sent to the Bureau Veritas Laboratory in Canada. Major element analyses were performed using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES), whereas trace elements and rare earth elements were analyzed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Internationally certified reference materials (e.g., OREAS and GSR) were employed in the analyses; each analysis group was supplemented with control samples and reported with a margin of error of ± 2-5%.

The obtained data were evaluated using rock classification diagrams, Harker correlations, normalized spider, and rare earth element diagrams, and inferences regarding magmatic processes were made based on trace element ratios (La/Yb, Th/Nb, and Zr/Y).

3. Regional geology

Western Anatolia is recognized as one of the most tectonically active and geologically intricate regions in Turkey. The geological framework of this area comprises Paleozoic metamorphic rocks of the Menderes Massif, Mesozoic ophiolitic and pelagic units, and Tertiary–Quaternary volcanic and sedimentary deposits [7], [8]. This assemblage resulted from extended plate interactions and structural evolution.

Ophiolitic complexes and mélange belts, formed during the closure of the Tethys Ocean in the Mesozoic era, are located along the İzmir–Ankara–Erzincan suture zone and are key geological features influencencing tectonic segmentation in the region [9]. The extensional tectonic regime, initiated post-Eocene, facilitated the development of graben systems across much of Western Anatolia and the emergence of extensive Neogene volcanism along these systems [10].

The volcanic products of this activity are predominantly high-potassium calc-alkaline and comprise trachyandesite, andesite, trachyte composite lavas, and ignimbrites [1], [2], [3]. Crustal extension along normal fault zones is considered a principal factor governing the distribution of igneous formations [11].

The study area, Sarıalan (Altıeylül, Balıkesir), is situated in the northwestern sector of Western Anatolia, within the zone where the Neogene extensional regime was predominant (Figure 2). Regionally, volcanic succession is associated with the Bigadiç and Sındırgı graben systems, which reflect the east–west and northeast–southwest trending fault zones that provide conduits for magma ascent.

Locally, the Bağburun volcanites overlie Neogene sedimentary deposits and cut through older metamorphic and ophiolitic units exposed in the Balıkesir region, indicating structural control of their emplacement. Although direct geochronological data are not available for the Bağburun volcanites, a comparison with geochemically and petrographically similar volcanic suites in Western Anatolia suggests a Middle–Late Miocene age [1], [5]. Recent syntheses [6] have emphasized the role of fault-bounded basins and localized extensional domains in channeling Neogene volcanism across the Aegean province. Within this broader framework, the Bağburun volcanites represent a local manifestation of regionally widespread high-K calc-alkaline magmatism in post-collisional Western Anatolia.

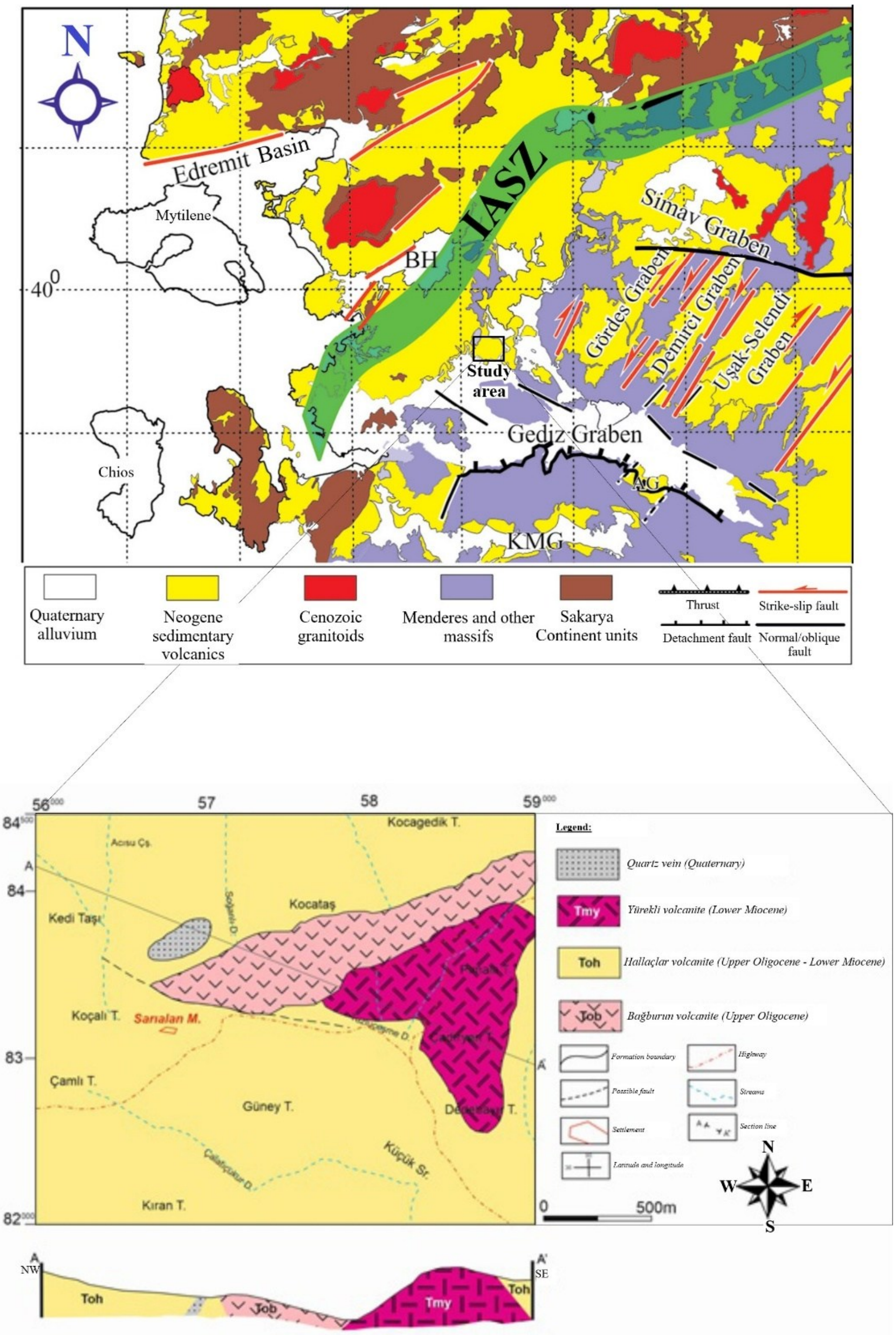

Figure 2. A simplified geological map of Western Anatolia (simplified from [6]) and the general geological map of Sarıalan and its vicinity (modified from [12]).

3. Findings

3.1. Lithological characteristics of the Bağburun volcanites

The surface of the Bağburun volcanites within the study area exhibits complex facies comprising lava and pyroclastic volcanic products. Volcanoclastic agglomerates, tuffitic sandstones, and clastic tuffs were present in the lower stratigraphic levels of the unit, whereas ignimbrites and porphyritic lava flows were observed in the middle and upper levels (Figure 3). This stratigraphic succession indicates that volcanism is multi-stage and variable in nature.

Figure 3. Field view of the Bağburun volcanites.

The clastic units in the lower stratigraphic levels are characterized by a dark red burgundy coloration, heterogeneous textures, and coarse clastic agglomerates. These levels are interpreted as products of explosive first-stage volcanism and display tuffitic characteristics in certain areas.

The ignimbritic strata frequently identified in the intermediate sections of the unit exhibit the characteristics of welded tuff and contain flattened volcanic clasts with fiyamme structures. These layers are indicative of derivatives formed through the in-situ deposition of hot volcanic ash clouds and subsequent compression by syn-deformational processes (Figure 4).

Porphyritic lava flows were discernible in the upper strata of the volcanite. These lavas exhibit light-gray, greenish, or yellowish hues and contain phenocrysts of plagioclase, amphibole, biotite, quartz, and sanidine. Dark-colored basic rock fragments (xenoliths), frequently observed within lavas, predominantly manifest as lenticular structures with poor contact with the surrounding lava. This observation suggests that these fragments were incorporated into the lava at a later stage and subsequently entrained in the magma (Figure 5).

Figure 4. Field observations of ignimbritic strata at intermediate levels and welded tuff formations.

Figure 5. Xenoliths, which are basic rock fragments, were identified within the lavas at the upper stratigraphic levels of the Bağburun volcanites.

Alterations were evident in the majority of volcanic products. Specifically, processes such as carbonation, hematitisation, and limonitisation have markedly influenced rock textures, predominantly occurring along the fracture zones. Additionally, exfoliation structures, commonly referred to as onion peel weathering, were observed in certain sections. This suggests that the volcanites were subjected to both physical and chemical weathering (Figure 6). The lithological diversity observed in the Bağburun volcanites indicates that this unit is not the result of a singular igneous phase. Instead, it reflects a multi-stage volcanic process characterized by the concurrent development of successive lava flows and pyroclastic activities.

Figure 6. The Bağburun volcanites exhibits several alteration features including carbonation, hematitization, exfoliation structures, and fracture-filled weathering.

3.2. Petrography of the Bağburun volcanites

Petrographic analysis of the Bağburun volcanites revealed a predominantly semicrystalline porphyritic texture. The primary phenocrysts identified include plagioclase, amphibole, biotite, quartz, sanidine, and opaque minerals, such as magnetite and pyrite. These minerals are embedded within a glassy or microlithic matrix, and the rocks exhibit trachytic, glomeroporphyritic, and occasionally poikilitic textures (Figure 7).

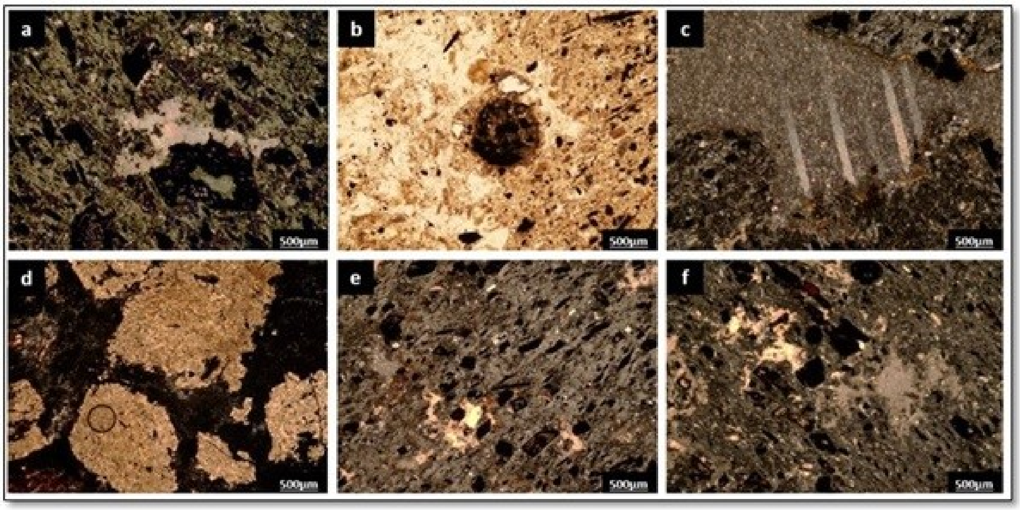

Figure 7. The presence of alterations in thin sections was observed as follows: (a) opacified amphibole and biotite, (b) opacitization in biotite mineral, (c) carbonation with mesh twins, (d) complete formation of carbonation, and (e) and (f) opacitized amphibole and biotite minerals.

Quartz minerals, commonly found in lava samples, manifest as large phenocrysts engulfed, fractured, or eroded by the surrounding matrix. These characteristics indicate thermal or chemical instability during quartz crystallization. Some quartz fragments were of detrital origin and may represent primary crystals.

Although sanidine crystals are less abundant, they are significant indicators of the magma's elevated potassium content. Their partial retention within the glassy groundmass suggests crystallization at a later stage under relatively low-undercooling conditions. Clinopyroxene, present in some samples, frequently exhibits signs of alteration at the crystal margins, such as chloritization and clayification, which may indicate hydrothermal alteration that postdates the magmatic phase and affects the primary magmatic textures. The occurrence of poikilitic textures in certain thin sections indicates late-stage crystallization, whereas sieve-textured plagioclases are consistent with processes of magma mixing and/or dissolution–recrystallization (cf. [13]). Collectively, these petrographic features reveal a complex magmatic history involving both crystallization differentiation and interactions between magmas.

The biotite and amphiboles are needle-like crystals that predominantly exhibit euhedral or subhedral forms. Biotites display cateye extinction and frequently contain fracture marks. Amphiboles become opaque over time and exhibit weathering marks along their margins. These minerals demonstrate growth textures often accompanied by plagioclase microliths (Figure 8).

Plagioclase phenocrysts were observed as zoned inclusions, microliths, and sieve-textured crystals. These crystals were found both as phenocrysts and microliths within the matrix, forming trachytic textures with the surrounding material. Glomeroporphyritic structures were also observed in some of the samples.

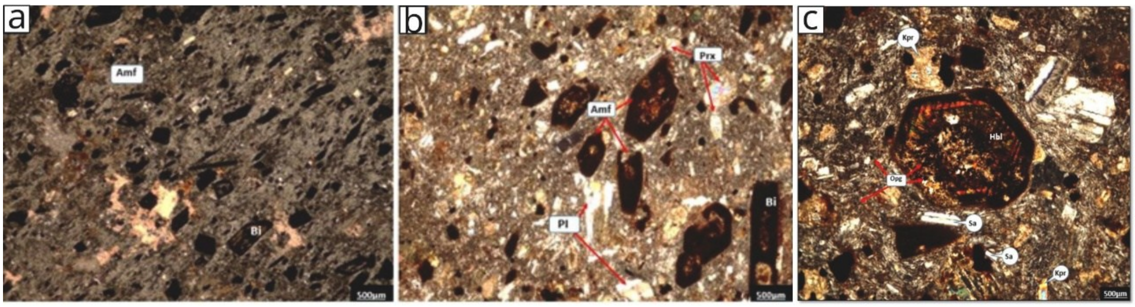

Figure 8. (a) Biotite mineral exhibiting cat's-eye extinction, (b) Idiomorphic to hypidiomorphic amphibole minerals, (c) Observation of an opacified self-formed amphibole, carbonated clinopyroxene, and sanidines (Kpr: Clinopyroxene, Hbl: Amphibole, Sa: Sanidine, Opg: Opaque Mineral, Pl: Plagioclase, Bi: Biotite, Amf: Amphibole, Prx: Pyroxene).

Foreign rock fragments, known as xenoliths, are frequently encountered in lava deposits and can be categorized into two primary types: quartzaceous fragments and those with basic composition. The quartzaceous fragments are characterized by large crystals with abraded edges and lack self-figured forms, whereas the basic fragments exhibit significant alteration. These observations indicate the presence of a multicomponent magma system and suggest the possibility of magmatic mixing (Figure 9).

In certain samples, pyroxene minerals were distinctly identifiable. Xenomorphic pyroxenes display evidence of clayification and chloritization at their edges, and these minerals are dispersed within a glassy matrix. Additionally, sanidine crystals were observed to be partially preserved within the glassy groundmass.

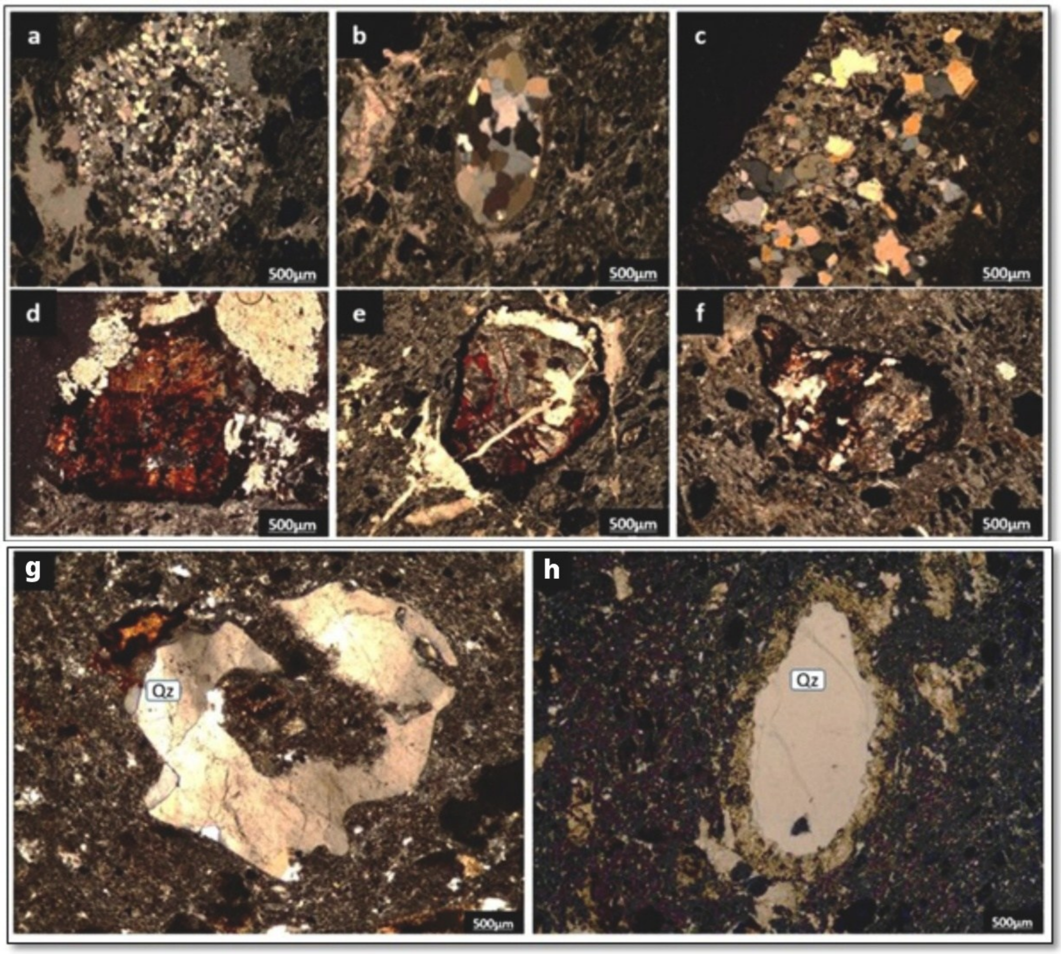

Figure 9. Examination of foreign rock fragments in thin sections revealed the following: (a), (b), and (c) depict quartz rock fragments; (d), (e), and (f) illustrate rock fragments with a basic composition; (g) shows a corroded, self-morphosed quartz phenocryst; and (h) presents a fractured quartz phenocryst that has been partially consumed by paste (Qz: Quartz).

The secondary minerals that have developed include calcite, chlorite, and epidote. Notably, calcites that have formed as fracture fillings are distinguished by their carbonation structures, which exhibit straw twinning. These carbonates are predominantly concentrated around the sericitized plagioclase and opacified mafic minerals (Figure 10).

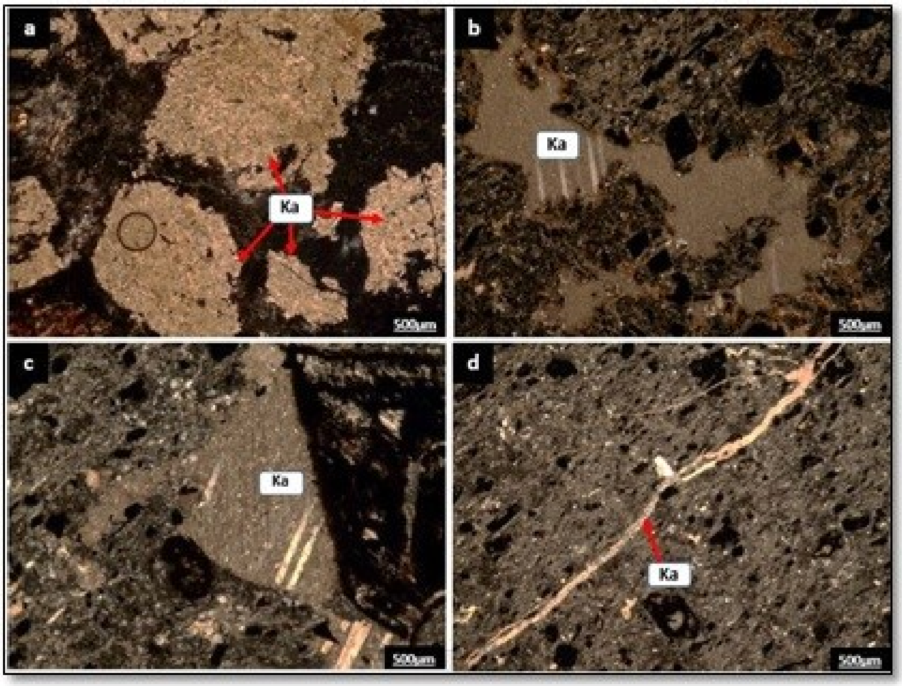

Figure 10. Thin-section analysis of carbonation reveals the following: (a) fully carbonated minerals, (b) and (c) straw twin formations, and (d) carbonation occurring along the fracture (Ka: Carbonate).

3.3. Geochemistry of the Bağburun volcanites

3.3.1. Major element geochemistry

ICP-AES analyses of six representative samples from the Bağburun volcanites reveal that these rocks exhibit volcanic characteristics with an intermediate composition. The SiO_2 content ranged from 59.31% to 61.43%, whereas the K_2O content varied between 2.51% and 6.87% (Table 1). These values indicate a high-potassium calc-alkaline nature in the samples.

In the TAS diagram, which employs the total alkali (Na_2O + K_2O) and SiO_2 ratios [14], most samples were located within the trachyandesite field, with some positioned on the andesite–trachyandesite boundary (Figure 11a). When assessing the SiO_2 to K_2O ratio, the samples fell within the high-potassium series and were classified as subalkaline (Figure 11b). In the AFM diagram developed by [15], all the samples were grouped within the calc-alkaline field (Figure 12). These classifications suggest a potential association between the volcanites and arc-type magmatism.

Significant correlations were evident in the Harker diagrams, illustrating the relationship between SiO_2 and other major elements. Notably, as the SiO_2 content increased, the MgO and TiO_2 ratios decreased, which can be attributed to the early crystallization and fractionation of mafic phases such as olivine, clinopyroxene, and amphibole. Similarly, the observed increase in K_2O with SiO_2 likely reflects the crystallization of K-bearing minerals, such as sanidine and biotite, consistent with petrographic observations. Positive trends were also observed in the SiO_2 vs. Al_2O_3, Na_2O, and K_2O diagrams, suggesting that the samples evolved towards more felsic compositions with alkali enrichment playing a significant role (Figure 13).

In contrast, the Na_2O values exhibited a wide range (0.66–5.33 wt. %), which is interpreted as the result of alteration processes (e.g., albitization or alkali mobilization) rather than primary magmatic differentiation. Similarly, the Sr contents (310–1044 ppm) display large variations, likely reflecting mobility during secondary processes. Relatively high LOI values (3.4–7.5 wt. %) further indicate that volatile-driven alteration has influenced mobile elements such as Na_2O, CaO, and Sr. Consequently, petrogenetic interpretations in this study primarily rely on immobile elements, such as HFSE (e.g., Nb, Ta, Zr, Y) and REE, which are considered more robust against alteration effects.

Table 1. Major oxide (%) contents of Bağburun volcanites (LOI: Loss of ignition).

	B1	B6	B5	B7	B9	B4
SiO_2	61.43	59.31	60.74	59.52	59.43	60.91
Al_2O_3	13.48	14.41	16.18	14.43	15.41	14.72
Fe_2O_3	6.01	5.11	7.10	5.11	6.33	5.97
MgO	3.11	0.65	1.90	0.61	2.32	3.68
CaO	3.05	4.48	1.00	4.14	2.82	1.92
Na_2O	3.73	0.66	4.98	0.69	5.33	3.83
K_2O	2.51	6.86	3.39	6.87	2.63	2.60
TiO_2	0.64	0.65	0.74	0.66	0.67	0.65
P_2O_5	0.18	0.18	0.19	0.17	0.13	0.17
MnO	0.07	0.05	0.06	0.03	0.07	0.06
Cr_2O_3	0.038	0.036	0.028	0.028	0.024	0.020
LOI	5.4	7.4	3.4	7.5	4.5	5.1
Total	99.79	99.88	99.80	99.87	99.77	99.78
Mg#	34.10	11.28	21.11	10.66	26.82	38.13

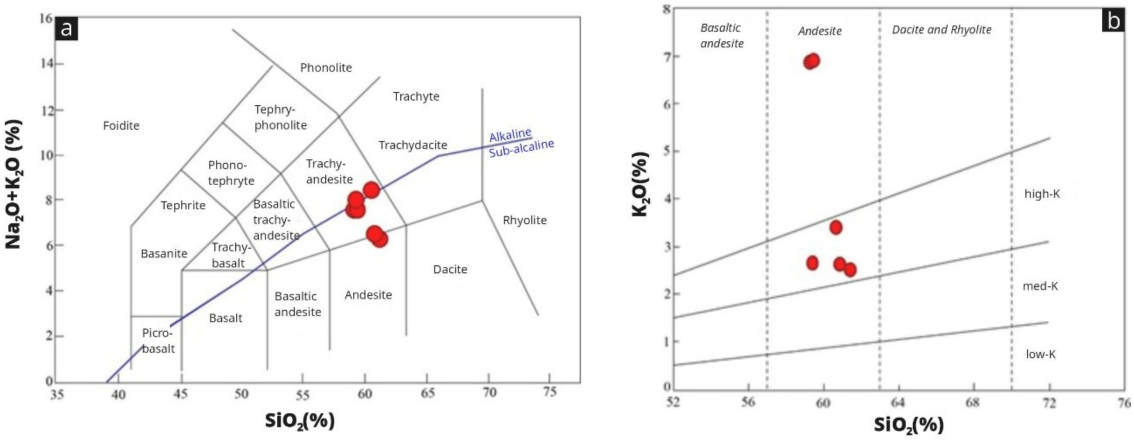

Figure 11. (a) The Total Alkali-Silica (TAS) diagram of the Bağburun volcanites, as delineated by [14], with the alkali–subalkali curve following the criteria established by [15], and (b) the SiO_2 (%) versus K_2O (%) diagram of the Bağburun volcanites, as presented by [16].

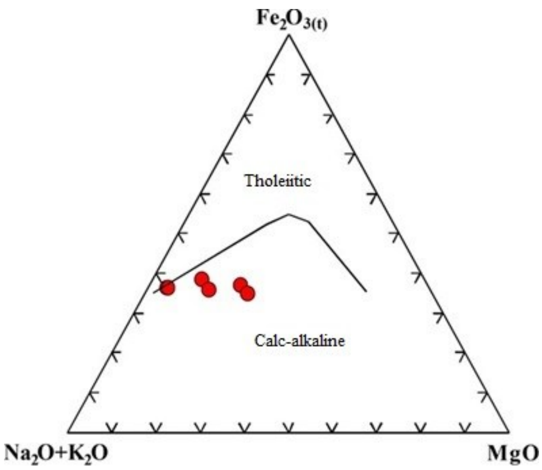

Figure 12. AFM (Na_2O+K_2O, $Fe_2O_{3(t)}$, MgO) diagram of the Bağburun volcanites [15].

Given the limited number of samples (n=6), these results can be regarded as preliminary indicators of magmatic processes. Although general fractionation and compositional evolution trends can be recognized, additional analyses are required to confirm the representativeness of these geochemical signatures.

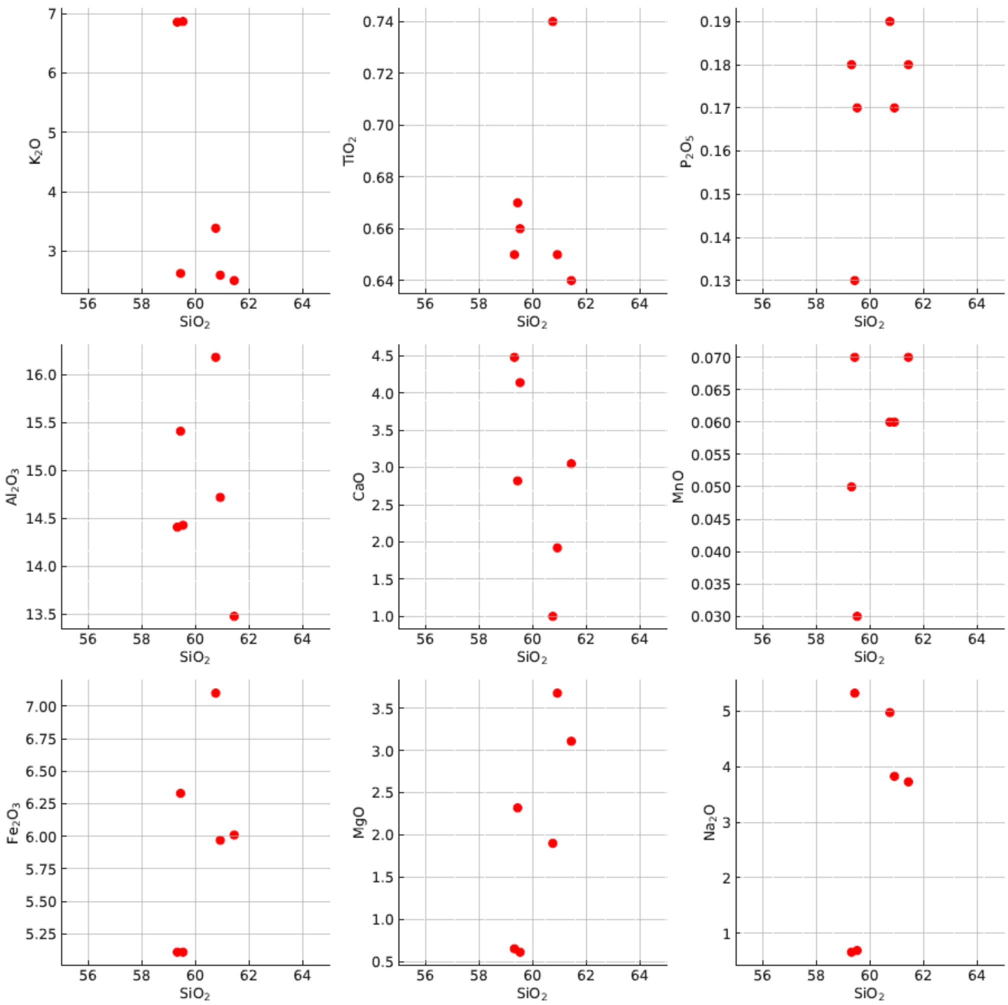

Figure 13. Harker (variation of major oxides versus SiO_2) diagrams of the Bağburun volcanites.

3.3.2. Trace and rare earth element geochemistry

ICP-MS analysis of six samples of the Bağburun volcanites revealed notable variations and distinct patterns in trace element and rare earth element (REE) content (Tables 2 and 3). REE ratios further quantify the LREE–HREE fractionation: $(La/Lu)_n$ = 10.52 ± 0.90 (9.18–11.48), $(La/Sm)_n$ = 4.42 ± 0.32 (4.01–4.84), and $(Gd/Lu)_n$ = 1.62 ± 0.13 (1.41–1.73) (n=6). Together with the negative Eu anomaly (Eu/Eu* = 0.76 ± 0.04; 0.69–0.78), these values indicate plagioclase fractionation and LREE-enriched melt evolution. Specifically, there is an enrichment in large ion lithophile elements (LILE) such as Rb, Sr, and Ba, alongside a depletion in high field strength elements (HFSE) such as Nb, Ta, Zr, and Y. Elevated La/Yb (13.5–18.2) and Th/Nb (1.70–1.93), together with Zr/Y (4.75–6.91), point to crustal input and modified mantle sources.

Table 2. Trace element (ppm/ppb) contents of Bağburun volcanites.

	B1	B6	B5	B7	B9	B4
Be	2	<1	3	3	<1	<1
Co	16,6	10,1	14,7	10,0	14,9	15,9
Cs	1,1	5,2	0,5	4,3	0,3	1,2
Ga	10,9	14,0	13,4	15,8	14,8	13,9
Hf	3,1	3,1	3,8	3,3	3,4	3,9
Nb	6,7	6,7	7,7	6,9	7,5	7,5
Rb	45,2	149,3	61,2	144,9	45,7	48,1
Sn	<1	<1	1	1	1	1
Sr	866,5	310,7	881,1	306,2	1043,6	849,8
Ta	0,4	0,3	0,5	0,4	0,4	0,5
Th	12,9	12,4	13,1	12,5	12,8	12,9
U	2,0	2,3	2,2	2,3	1,7	2,4
V	84	122	75	121	96	81
W	0,5	0,7	1,4	0,8	0,8	1,1
Zr	118,6	113,3	129,9	117,9	113,1	136,5
Y	21,6	18,2	18,8	17,6	23,8	20,6
Mo	0,3	0,3	0,3	0,2	0,2	0,1
Cu	4,5	14,1	9,3	13,7	6,8	3,5
Pb	16,0	13,7	14,3	12,3	14,0	17,9
Zn	68	68	45	66	53	59
Ni	81,0	38,6	37,4	31,4	57,4	60,4
As	8,3	13,7	17,5	13,2	24,6	9,7
Cd	<0.1	0,2	<0.1	0,2	<0.1	<0.1
Sb	0,4	2,8	5,3	2,4	1,0	0,1
Bi	0,2	<0.1	<0.1	<0.1	<0.1	<0.1
Hg	0,02	0,08	0,01	0,06	0,02	<0.01

Table 3. Rare earth element (ppm) contents and additional ratios of Bağburun volcanites.

	B1	B6	B5	B7	B9	B4
La	32,5	30,9	37,0	30,6	40,9	29,9
Ce	52,4	56,9	66,2	56,9	62,5	59,1
Pr	6,86	6,36	7,67	6,41	8,01	6,59
Nd	27,6	24,3	30,1	24,8	30,4	25,6
Sm	5,23	4,30	5,52	4,31	5,46	4,68
Eu	1,13	1,08	1,25	1,04	1,37	1,09
Gd	4,68	4,01	4,32	3,82	5,06	4,21
Tb	0,67	0,58	0,64	0,56	0,71	0,61
Dy	3,73	3,28	3,79	3,21	4,23	3,70
Ho	0,78	0,67	0,74	0,65	0,84	0,78
Er	2,28	1,91	2,25	1,92	2,59	2,27
Tm	0,33	0,27	0,33	0,28	0,35	0,33
Yb	2,09	1,74	2,42	1,68	2,38	2,22
Lu	0,33	0,28	0,37	0,27	0,37	0,33
(Eu/Eu^*)	0.69	0.78	0.77	0.77	0.78	0.74
$(La/Lu)_n$	9.97	11.18	10.13	11.48	11.19	9.18
$(La/Sm)_n$	4.01	4.64	4.33	4.58	4.84	4.12
$(Gd/Lu)_n$	1.71	1.73	1.41	1.71	1.65	1.54
La/Yb	15.55	17.76	15.29	18.21	17.13	13.47
Th/Nb	1.93	1.85	1.70	1.81	1.71	1.72
Zr/Y	5.49	6.23	6.91	6.70	4.75	6.63

In the spider diagrams normalized to Ocean Island Basalt (OIB), there are notable enrichments in Sr, Rb, Ba, and Th, along with depletion in Nb, Ta, Zr, and Y (Figure 14a). This pattern aligns with the characteristic trace element behavior associated with arc-type magmatism. Patterns normalized to E-type and N-type mid-ocean ridge basalts (MORB) exhibit relative enrichment in elements such as Ce and Zr (Figure 14b), suggesting the potential involvement of crustal material in the magma source.

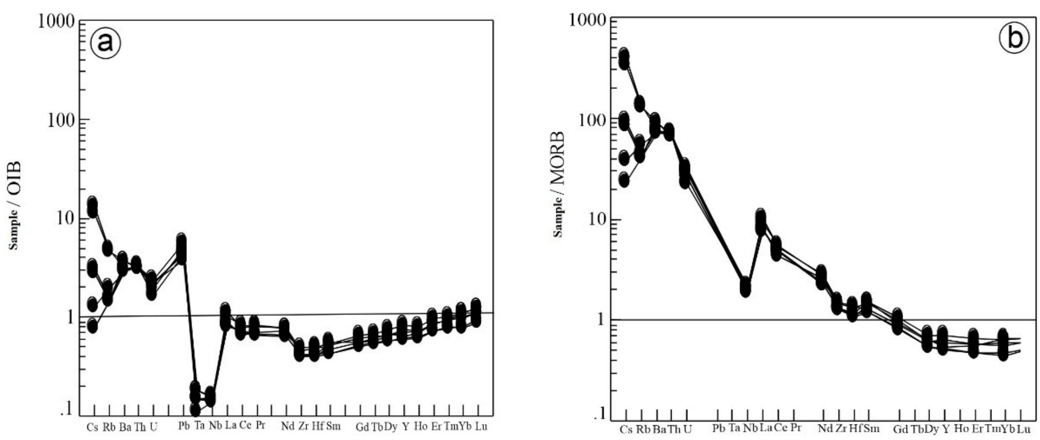

Figure 14. The Bağburun volcanic rocks are represented in a normalized spider diagram, with normalization to (a) the Ocean Island Basalt (OIB) using values from [17] and (b) Mid-Ocean Ridge Basalt (MORB) using values from [18].

The chondrite-normalized rare earth element patterns exhibited a pronounced negative europium (Eu) anomaly across all samples (Figure 15). This anomaly is attributed to the extraction of Eu^{2+} from the system owing to plagioclase segregation. The marked enrichment of light rare earth elements (LREE), such as lanthanum (La), cerium (Ce), and neodymium (Nd), relative to heavy rare earth elements (HREE), suggests processes of low-grade partial melting or contributions from the crust.

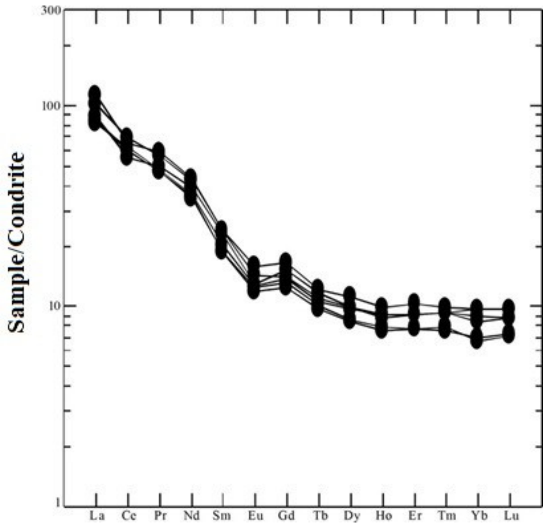

Figure 15. Chondrite-normalized REE distributions of the Bağburun volcanites (normalized values were obtained from [19]). All samples show a negative Eu anomaly (Eu/Eu* = 0.69–0.78; mean 0.76).

The imcompatible element ratios provide substantial insights into magma development. The La/Yb ratio in the samples was predominantly elevated, suggesting crustal contribution to mantle-induced melting. The Th/Nb ratios are at medium-low levels, potentially indicating subplate fluid contribution and/or contamination (Figure 16a). The Zr/Y ratios exhibited limited variation (Figure 16b).

Although derived from a limited number of samples, these data suggest that the Bağburun volcanites underwent complex magma evolution, exhibited characteristics of arc-type magmatism, and that crustal components may have influenced the magma source.

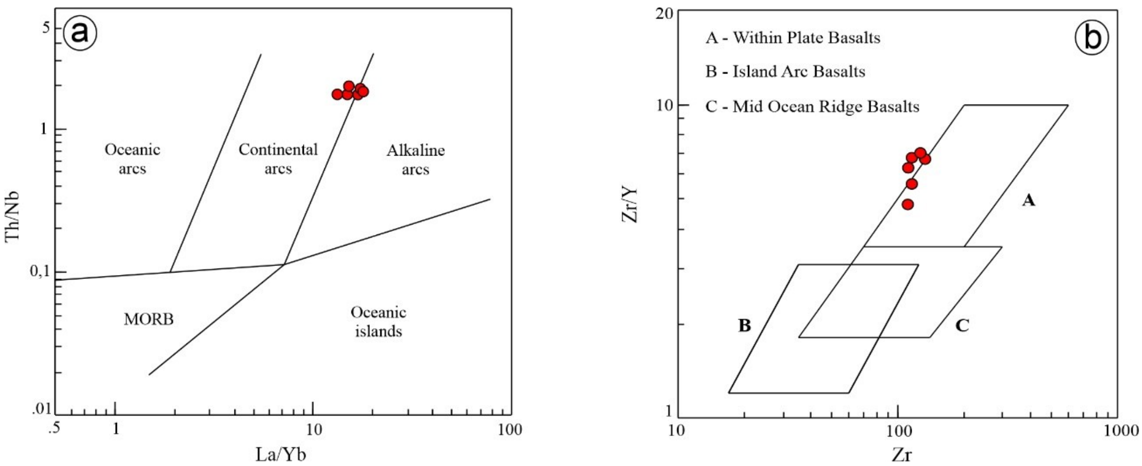

Figure 16. (a) La/Yb versus Th/Nb diagram, (b) Zr versus Zr/Y diagram of the Bağburun volcanites.

4. Discussion

4.1. Geochemical classification and magma character

According to the TAS and AFM diagrams, the Bağburun volcanites are situated within the high-potassium calc-alkaline series and exhibit trachyandesite-andesite composition. This compositional range aligns with the characteristic features of arc-type volcanism, which was extensively developed during the Neogene period in Western Anatolia [1], [3]. The SiO_2 and alkali contents indicated that these rocks originated from magmas that evolved under the influence of continental crust.

The vertical trends observed in the major element data, such as the increase in SiO_2 and decrease in MgO and TiO_2, suggest that fractional crystallization was a significant magmatic process. However, given that these inferences were based on data from only six samples, these assessments should be regarded as interpretations within the context of limited data.

Although the Bağburun volcanic rocks demonstrated relatively consistent patterns in both major and trace elements, the potential for alterations due to post-magmatic processes cannot be dismissed. LOI values, ranging from 3.4 to 7.5 wt.% (Table 1), suggest a limited yet discernible presence of volatiles. Alkali elements such as Na_2O and K_2O, along with large-ion lithophile elements like Sr, are particularly susceptible to secondary alterations. Consequently, this study primarily emphasizes immobile elements, including HFSE, REE, and specific trace-element ratios, as they are deemed more reliable against alteration effects. Therefore, petrogenetic conclusions regarding the mantle source and tectonic environment are derived from these stable indicators rather than components that may be more prone to mobility.

Substantial variation in Na_2O (0.66–5.33 wt. %) and Sr (310–1044 ppm) concentrations is attributed to secondary alteration, as evidenced by the elevated LOI values (3.4–7.5 wt.%). These elements are recognized for their mobility during hydrothermal processes, which implies that they may not accurately reflect the original magmatic compositions. Therefore, this study primarily emphasizes immobile elements such as HFSE (e.g., Nb, Ta, Zr, Y) and REE, which are considered more resistant to alteration effects [20], [21]. This approach mitigates the bias introduced by secondary processes, thereby facilitating more reliable petrogenetic interpretation.

4.2. Igneous processes: partial melting, fractional crystallization and contamination

The negative correlations observed in the Harker diagrams, particularly for MgO, TiO_2, and Fe_2O_3, along with the zoned-sieve textured crystal forms of plagioclases, suggest the active role of fractional crystallization within the magma system. These petrographic features serve as evidence of magma evolution at a microscopic scale.

Elevated $(La/Lu)_n$ (~10.5) and $(La/Sm)_n$ (~4.4), coupled with $(Gd/Lu)_n$ (~1.6) and a negative Eu anomaly ($Eu/Eu^* \sim 0.76$), are consistent with fractionation dominated by plagioclase ± amphibole and limited HREE-compatible phase accumulation.

Negative Eu anomalies can be interpreted as a chemical indication of extensive plagioclase segregation, while significant enrichment in light rare earth elements (LREE) suggests low-grade partial melting or crustal contributions. Notably, elevated La/Yb ratios imply heterogeneity in the melting depth or crustal material contribution to mantle-derived magmas [22].

These findings are consistent with both geochemical and petrographic observations. However, owing to the limited number of samples, these results should be interpreted as indicative of general trends in the volcanism of the region.

4.3. Tectonic environment assessment

Trace element patterns, particularly the depletion of Nb and Ta and the enrichment of LILE, suggest that volcanites formed within a continental arc setting. These trends, as observed in the normalized spider diagrams, align with the established geochemical signatures characteristic of arc-type magmatism [17], [20]. Moreover, when normalized patterns are compared with MORB and OIB, it is evident that these volcanites do not originate from a singular oceanic source; instead, the mantle source has been altered by crustal contributions.

The ratios of Zr/Y (4.75–6.91), Th/Nb (1.70–1.93), and La/Yb (13.5–18.2; mean 16.2 ± 1.8) indicate a complex composition within the magma system. Th/Nb values exceeding one suggest sources modified by subduction processes [20], while elevated Zr/Y ratios in comparison to intraplate basalts (typically <3; [21]) imply source enrichment. Similarly, increased La/Yb ratios suggest either melting in garnet-bearing mantle or assimilation of crustal material. These geochemical indicators collectively suggest contributions from mantle melt, subduction-related fluids, and the continental crust. Further sampling and isotopic analysis are required to substantiate this interpretation.

In addition to these geochemical markers, the spatial configuration of the Bağburun volcanic rocks is significantly associated with local fault systems in the Altıeylül–Balıkesir region. Notably, the east–west and NE–SW oriented faults, such as the Bigadiç and Sındırgı fault zones, are posited to have functioned as conduits for magma ascent. Consequently, the emplacement of volcanic materials was likely influenced not only by regional extensional processes but also by specific structural weaknesses. These tectono-magmatic interactions are consistent with observations from other Neogene volcanic sites in Western Anatolia, where fault-guided magma pathways have been documented [5], [22].

Although trace-element ratios provide valuable preliminary insights into magma sources, they are inadequate for definitively distinguishing between mantle enrichment, slab-derived fluids, and crustal assimilation. Radiogenic isotope data (such as Sr–Nd–Pb and Hf) are essential to resolve this ambiguity. For instance, the combined application of Sr–Nd isotope systematics is a widely used approach to differentiate between depleted mantle characteristics and crustal contamination, whereas Pb isotopes can identify contributions from subducted sediments [5], [22]. Consequently, future isotope studies on the Bağburun volcanites would provide a more robust framework for assessing the relative influences of the lithospheric mantle, subduction-related metasomatism, and crustal assimilation in their formation.

4.4. Comparison with literature and regional context

The geochemical and petrographic characteristics of the Bağburun volcanites are largely consistent with the prevalent calc-alkaline volcanic activity of the late Neogene period in Western Anatolia [2], [5]. In contrast to the ultrapotassic lavas found in certain volcanic regions of the area, the Bağburun samples were distinguished by their elevated quartz content and ignimbrite-tempered structures [4].

The trace element ratios depicted in the discrimination diagrams further substantiate this interpretation. Th/Nb values exceeding 1 are typically indicative of a subduction-related influence [19], and the Bağburun volcanites, with values ranging from 1.70 to 1.93, fall within this category. Similarly, Zr/Y values between 4.75 and 6.91 exceed those of typical intraplate basalts (<3; [21]), suggesting source enrichment. High La/Yb ratios (13.5–18.2) imply partial melting in the presence of residual garnet and/or crustal material assimilation. Petrographic observations of xenoliths within the lavas further support magma–crust interaction, consistent with these geochemical indicators.

This combination of petrographic and geochemical evidence aligns with regional studies of other Neogene volcanic centers in Western Anatolia, such as Kula, Şuhut, and Bayramiç, where fractional crystallization and crustal contributions have also been noted [1], [3], [4]. Thus, the Bağburun volcanites exemplify a local manifestation of arc-type magmatism within a broader extensional regime.

The spatial configuration of these volcanic formations highlights the impact of the tectonic features. The Bağburun volcanic rocks are intimately associated with the Bigadiç and Sındırgı fault zones, which functioned as conduits for magmatic ascent during the Miocene period of extension. This association is consistent with observations from other regions of Western Anatolia, where fault-guided magma pathways have been documented [5], [22]. Within this geodynamic framework, the Bağburun volcanic rocks exemplify the interaction between mantle-derived magmas and localized extensional structures in Western Anatolia.

5. Results

The Tertiary volcanic rocks at Bağburun near Sarıalan comprise a complex assemblage of porphyritic lava flows and pyroclastic deposits. Petrographic analyses have identified semi-crystalline porphyritic textures characterized by plagioclase, amphibole, biotite, quartz, and sanidine, along with xenoliths and sieve-zoned plagioclase, indicative of magma mixing and intricate crystallization processes.

A whole-rock chemical analysis (SiO_2 59–61 wt.%, K_2O 2.5–6.9 wt.%) classifies these rocks as high-K calc-alkaline trachyandesite–andesite. Harker diagrams demonstrate fractionation trends, such as a decrease in MgO and TiO_2 with increasing SiO_2, which is consistent with the crystallization of mafic minerals observed in petrographic analysis. However, a substantial variation in Na_2O (0.66–5.33 wt. %) and Sr (310–1044 ppm), along with elevated LOI values (3.4–7.5 wt.%), suggests that these elements were variably altered, necessitating reliance primarily on immobile elements (HFSE, REE) for interpretations.

Trace-element patterns exhibit enrichment in LILE and depletion in HFSE (e.g., Nb–Ta), which are characteristic of arc-type signatures. REE data revealed LREE-enriched patterns with a negative Eu anomaly (Eu/Eu* ~ 0.76), consistent with plagioclase fractionation. High La/Yb (13.5–18.2), Th/Nb (1.70–1.93), and Zr/Y (4.75–6.91) ratios imply interactions between mantle-derived magmas, subduction-related fluids, and crustal materials. The presence of xenoliths further corroborates the magma-crust interaction. Regionally, the Bağburun volcanic rocks share numerous characteristics with other Neogene high-K calc-alkaline volcanic centers in Western Anatolia (e.g., Kula, Bayramiç, Şuhut), yet they are distinguished by their relatively high quartz content and ignimbrite intercalations. Despite the limited number of samples analyzed (n=6), the combined petrographic and geochemical evidence supports the interpretation that the Bağburun volcanic rocks originated from a metasomatized lithospheric mantle source modified by subduction-related components and subsequently influenced by fractional crystallization and crustal assimilation.

These findings enhance our understanding of the magmatic evolution of the Bağburun volcanic rocks, which represents a local but significant expression of Neogene arc-related volcanism in Western Anatolia.

Author contributions and acknowledgment

This article is derived from the M.Sc. thesis of Ferat Savci, conducted under the supervision of Gökhan Büyükkahraman, and submitted to the Balikesir University Institute of Science. The study reflects a part of his graduate research on the petrographic and geochemical characteristics of the Bağburun volcanites. As the authors, we declare that this study does not require Ethics Committee approval.

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