



Petrographic and geochemical characteristics of late cretaceous volcanic rocks in the vicinity of Avliyana (Gümüşhane, NE Turkey)

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Abstract

In this study, the Late Cretaceous volcanic rocks outcropping in Avliyana (Gümüşhane-NE Turkey) and its surroundings in the Southern Zone of the Eastern Pontides were investigated as petrographically and geochemically. The Late Cretaceous Avliyana volcanic rocks are basalt, basaltic andesite and andesite in composition, and are mainly composed of plagioclase, alkali feldspar, hornblende, biotite and minor augite minerals. Volcanic rocks have calc-alkaline character and have low to high-K content. They are enriched with large ion lithophile elements (LILEs) and light rare earth elements (LREEs) and depleted in terms of elements with high-field strength elements (HFSEs). The chondrite-normalized rare earth element distributions are concave with low to moderate enrichment ($La_N/Lu_N=3-12$), indicating that the volcanic rocks originated from the same source. Fractional crystallization and a lesser assimilation played an important role in the development of volcanic rocks. All these data indicate that the studied volcanic rocks were possibly derived from the partial melting of a subcontinental lithospheric mantle (SCLM), which was enriched by fluids and/or sediments from a subduction of oceanic crust.

Keywords Eastern pontides, Gümüşhane, late cretaceous, whole-rock geochemistry, petrography, Avliyana volcanic rocks.

1. Introduction

Eastern Pontides (NE Turkey), also known as Sakarya Zone, located in the Alpine-Himalayan orogenic belt, is one of the areas where volcanic and plutonic rocks are widely observed [1–9] and important mineral deposits are located. Three main volcanic cycles have been identified in the Eastern Pontides: Liassic, Cretaceous, and Eocene (and later) [10,11]. The Eastern Pontides were divided into two zones, Northern and Southern Zones, by [12] because the Cretaceous aged rocks differ lithologically in the northern and southern regions. Accordingly, the

study area is located to the Southern Zone of the Eastern Pontide.

Although many detailed studies have been carried out on the Late Cretaceous plutonic rocks in the Eastern Pontides [5,13–15], studies on their volcanic equivalents are limited [16–22]. Radiometric age data for Late Cretaceous volcanic rocks in the Eastern Pontides are limited and are given in Table 1. According to Table 1, the ages of the Late Cretaceous volcanic rocks range from 75 to 92 Ma.

Table 1. Crystallization ages of Late Cretaceous volcanic rocks in the Eastern Pontides (After [23])

Name	Formation	Rock Types	Age (Ma)	Dating	Reference
Değirmentaş (Torul/Gümüşhane)	Kızılkaya	Dacite	77.99±3.76	K-Ar	[23]
Artvin	Kızılkaya Tirebolu	Rhyolite	83.04±0.39 86.51±0.35	²⁰⁶ Pb/ ²³⁸ U	[22]
Murgul (Artvin)	Çatak Kızılkaya	Basalt Dacite	92.1±1.2 88.8±0.9	⁴⁰ Ar/ ³⁹ Ar	[24]
Rize	Çayırbağ	Dacite	83.2±1.0	⁴⁰ Ar/ ³⁹ Ar	[25]
Akçaabat (Trabzon)		Basalt	82.61±0.34	⁴⁰ Ar/ ³⁹ Ar	[26]
Ordu		Basalt	86.02±0.52	²⁰⁶ Pb/ ²³⁸ U	[20]

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		Rhyo-dacite	75.34±0.10		
Tekke (Gümüşhane)		Felsic tuff	84.05±0.94 81.09±0.62 77.1±1.0	²⁰⁶ Pb/ ²³⁸ U	[27]
Tirebolu (Giresun)	Kızılkaya Çayırbağ	Dacite Rhyolite	91.1 ± 1.3 83.1 ± 1.5	²⁰⁶ Pb/ ²³⁸ U	[28]
Maden (Bayburt)		Trachy- andesite	80.9 ±0.9	⁴⁰ Ar/ ³⁹ Ar	[18]
Zigana (Gümüşhane)	Kızılkaya	Dacite	78.7 ± 2.3 75.3 ± 2.4	K-Ar	[17]

In the Avliyana (Gümüşhane) region, detailed studies have been carried out mainly on general geology and mineral deposits [29–34], and studies on the petrology of Late Cretaceous volcanic rocks are limited in this area.

2. Regional geology and stratigraphy

The pre-Late Cretaceous rocks are represented by early Carboniferous metamorphic rocks [35], Middle to Late Carboniferous plutonic rocks [4,9,36–39], Jurassic volcanics, volcanoclastic and plutonic rocks [40, 41] and Late Jurassic-Early Cretaceous carbonates [42]. The Late Cretaceous series that unconformably overlie carbonate rocks consist of volcanic, plutonic and sedimentary rocks [22, 43–46], and overlain by the Cenozoic units. The Cenozoic units in the region are represented by Late Paleocene-Early Eocene adakitic rocks [47], Middle Eocene volcanic, sub-volcanic and sedimentary rocks [2, 3, 21, 45, 48–52], Middle Eocene plutonic rocks [6, 44, 53–57], Neogene volcanic rocks [58], Late Miocene-Pliocene adakitic volcanic-subvolcanic rocks [59]. The youngest units in the region are Quaternary alluvium and terraces.

3. Analysis methods

Within the scope of the study, thin sections of rock samples collected from the field were prepared and detailed petrographic properties were determined under polarizing microscope. Subsequently, whole-rock major, trace and rare earth element analyzes of 11 rock samples belonging to the study area were carried out at the BC Analysis (ACME) Laboratory in Vancouver, Canada. Major and trace elements were analyzed by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometer), and rare earth elements (REE) were analyzed by ICP-MS (Inductively Coupled Plasma-Mass Spectrometry). While SO-18/CSC standards were used in the

In this study, the petrographic, geochemical and petrological properties of the Late Cretaceous aged Avliyana (Gümüşhane) volcanic rocks will be revealed, and the development of the Eastern Pontide Late Cretaceous magmatism will be tried to be clarified.

The study area located in the south zone of the Eastern Pontides and is generally dominated by plutonic and volcanic rocks (Figure 1). The oldest units in the study area are Middle-Late Carboniferous plutonic rocks. Early-Middle Jurassic volcano-clastic rocks unconformably overlie these units. These rocks are overlain by Late Jurassic-Early Cretaceous limestones. These units are overlain by a Late Cretaceous sedimentary sequence interbedded with andesite, basalt and their pyroclasts. In places, diabase dykes also cut this sedimentary sequence. All these units are unconformably overlain by Eocene andesite, basalt and their pyroclasts. Upper Eocene aged quartz porphyry and granodiorite intrusive rocks cut all these units (Figure 1).

analysis of major oxides, SO-18 standard was used in trace element analysis. For main oxide and trace element analysis, 0.2 g powder sample was mixed with 1.5 g LiBO₂ and analyzed after dissolving it in a liquid containing 5% HNO₃, while for rare earth element analysis, 0.250 g powder sample was dissolved in four different acids and analyzed. Major oxides were measured in wt%, trace elements and rare earth elements in ppm. While the detection limits of the major elements vary between 0.001 and 0.04%, the detection limits of trace and rare earth elements vary between 0.01 and 0.5 ppm.

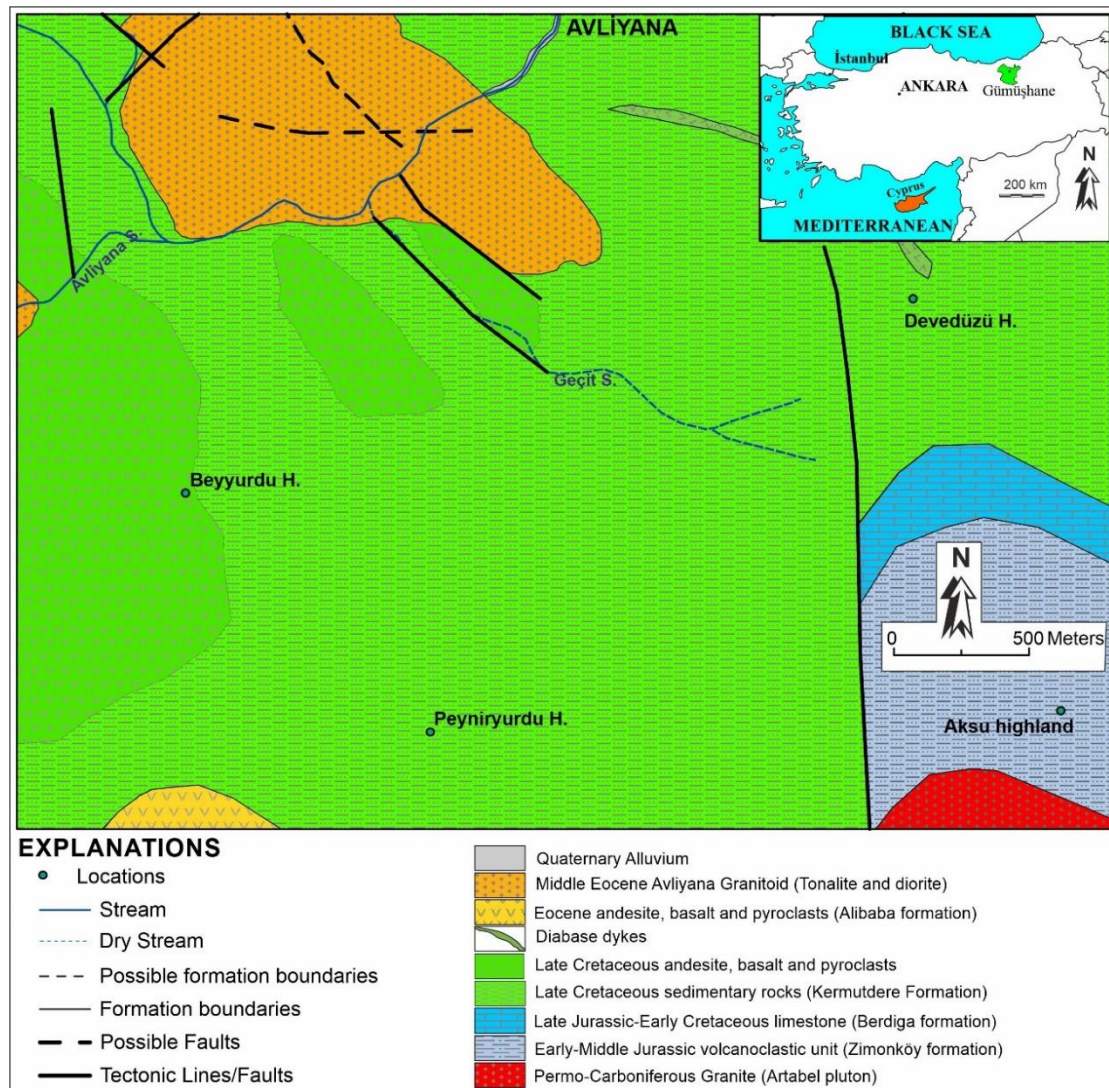


Figure 1. Geological map of the study area (modified after [4, 30, 55, 60])

4. Mineralogy and petrography

The studied Late Cretaceous volcanic rocks mainly consist of basalt, basaltic andesite and andesites. Microlitic, microlitic porphyric, porphyric, and partially cumulo-phric textures were observed in microscopic examinations. The main minerals of the rocks are plagioclase, hornblende, augite, biotite and opaque minerals. Plagioclase is observed as large, mainly subhedral lath-shaped crystals and small crystals in the matrix. Coarse crystals usually show a zoned texture. The An (anorthite) contents ranged from 32 to 57 (optically). Plagioclase phenocrystals show albite and polysynthetic twinning, while small crystals show albite twinning. The most common alteration products are calcite, chlorite and clay minerals. Hornblendes were observed as large,

euhedral and subhedral prismatic crystals, and as small crystals in matrix. Some large hornblende minerals contain plagioclase and opaque mineral inclusions. Pleochroism colors are brownish green-green-light yellowish green. Some minerals are generally altered into calcite and opaque minerals have developed in the mineral margins. Augites are generally seen as coarse prismatic crystals in some sections. Secondary minerals consist of calcite, chlorite, sericite and epidote minerals. Opaque minerals are found as coarse crystals and scattered. The matrix is composed of micro and cryptocrystals of plagioclase, augite, hornblende and biotite minerals with opaque mineral grains.

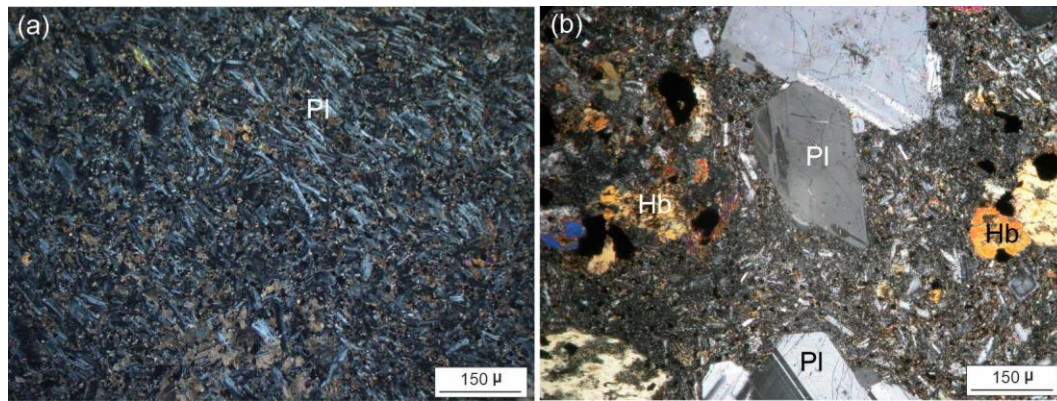


Figure 2. Microphotographs of Avliyana volcanic rocks. a) Microlithic texture in basalts b) Porphyritic texture in andesites (Crossed Polar, Pl: Plagioclase, Hb: Hornblende)

5. Geochemical features of the late cretaceous Avliyana volcanic rocks

5.1. Major and trace elements

Major, trace and rare earth element analyzes of 11 samples of Avliyana volcanic rocks are also given in Table 2 and 3.

SiO₂ values of the examined samples are between 48-63%, the lowest in basalts (48-51%) and the highest

in andesites (58-63%). The K₂O/Na₂O ratios of the samples vary between 0.13 and 0.96, and the magnesium numbers [Mg#=100*(MgO/MgO+Fe₂O₃^T)] vary between 36 and 67 (Table 2).

Table 2. Major (%) and trace (ppm) element analyzes of Avliyana volcanic rocks

Rock	Basalt				Basaltic andesite		Andesite				
Sample	GT-23	GT-6	GT-31	AVL-7	GT-30	AVL-17	GT-3	GT-29	GT-2	AVL-10	AVL-4
SiO ₂	48.33	48.70	50.73	51.11	54.17	56.24	58.06	59.24	61.94	62.49	62.90
TiO ₂	1.36	1.15	0.88	1.07	0.81	0.49	0.55	0.66	0.47	0.78	0.69
Al ₂ O ₃	16.44	19.56	18.10	11.50	17.94	17.06	18.19	17.83	15.67	18.01	17.21
Fe ₂ O ₃ ^T	10.75	9.11	8.85	8.62	9.46	6.26	6.12	7.22	5.36	2.43	5.44
MnO	0.21	0.08	0.20	0.29	0.08	0.12	0.08	0.08	0.07	0.06	0.09
MgO	7.38	5.31	5.18	7.36	3.95	3.05	3.71	1.85	3.40	2.21	2.17
CaO	9.82	8.92	8.95	15.61	7.86	6.87	4.47	5.34	3.33	4.58	1.09
Na ₂ O	3.59	3.58	3.81	2.34	2.88	3.19	4.11	3.25	2.57	3.67	4.16
K ₂ O	0.45	0.58	0.96	0.37	1.36	1.46	1.08	2.24	2.47	2.68	2.33
P ₂ O ₅	0.33	0.18	0.12	0.16	0.18	0.13	0.11	0.19	0.09	0.21	0.10
LOI	1.00	2.60	2.00	1.30	1.10	4.80	3.30	1.90	4.40	2.70	3.70
Total	99.66	99.77	99.78	99.73	99.79	99.67	99.78	99.80	99.77	99.82	99.88
Co	35.80	25.30	25.70	23.60	17.30	17.90	13.60	11.30	11.90	4.10	2.00
Ni	49.20	34.60	9.10	15.60	4.70	3.60	8.60	6.00	8.20	2.60	1.80
V	177.00	211.00	302.00	152.00	208.00	175.00	108.00	146.00	107.00	131.00	172.00
Cu	7.30	3.80	32.20	14.80	62.20	42.10	3.10	3.90	13.00	12.50	12.70
Pb	8.10	4.00	1.90	6.20	9.20	11.50	5.80	7.60	45.50	5.40	2.20
Zn	20.00	25.00	48.00	24.00	27.00	45.00	71.00	39.00	57.00	9.00	37.00
W	1.20	0.50	0.50	1.00	2.20	0.50	2.20	2.00	2.80	2.00	0.50
Sc	24.00	25.00	30.00	18.00	23.00	17.00	17.00	14.00	17.00	17.00	17.00
Rb	9.80	10.10	24.70	10.60	52.60	35.10	32.60	78.00	116.00	54.30	74.20
Ba	118.00	115.00	251.00	89.00	228.00	785.00	494.00	1024.00	663.00	710.00	555.00
Sr	619.90	616.90	378.30	398.80	477.70	725.50	399.60	404.80	219.60	322.40	195.90
Ta	0.50	0.80	0.20	0.80	0.30	0.30	0.60	0.70	0.50	0.60	0.40
Nb	2.60	5.30	3.80	5.20	5.30	5.20	7.10	7.90	6.10	8.30	7.00
Hf	2.70	2.40	2.30	3.30	2.90	2.10	3.70	3.30	3.10	4.40	4.10
Zr	118.90	100.70	79.20	124.70	107.30	81.30	129.50	127.50	113.70	161.60	142.50

Y	35.50	21.50	21.30	18.90	23.60	12.50	13.00	18.70	15.00	26.20	20.50
Th	1.40	0.90	2.00	5.40	3.10	5.70	10.70	8.40	12.50	8.90	5.00
U	0.20	0.20	0.20	1.30	0.60	2.00	3.40	1.90	3.70	3.10	1.20
Ga	16.10	17.70	15.80	11.30	16.90	14.50	19.30	15.70	16.50	16.10	17.50
La	10.60	11.50	10.70	20.00	15.40	17.50	18.30	22.60	28.00	28.30	16.10
Mg #	60.18	56.20	56.30	65.27	47.90	51.75	57.17	36.07	58.27	66.69	46.76
K₂O/Na₂O	0.13	0.16	0.25	0.16	0.47	0.46	0.26	0.69	0.96	0.73	0.56
Th/Yb	0.47	0.43	0.94	2.80	1.26	4.60	8.56	4.24	7.02	3.03	2.00
Ce/Pb	3.16	6.80	12.63	6.63	3.89	2.82	6.74	6.28	1.08	10.69	15.27
Nb/La	0.25	0.46	0.36	0.26	0.34	0.30	0.39	0.35	0.22	0.29	0.43
La/Nb	4.08	2.17	2.82	3.85	2.91	3.37	2.58	2.86	4.59	3.41	2.30
Ba/Nb	45.38	21.70	66.05	17.12	43.02	150.96	69.58	129.62	108.69	85.54	79.29
Mg# (mg-number) = molar 100xMgO/(MgO+ Fe₂O₃^T). LOI is loss on ignition											

Table 3. Rare earth element (ppm) analyzes of Avliyana volcanic rocks

Rock	Basalt				Basaltic andesite		Andesite				
	GT-23	GT-6	GT-31	AVL-7	GT-30	AVL-17	GT-3	GT-29	GT-2	AVL-10	AVL-4
La	10.60	11.50	10.70	20.00	15.40	17.50	18.30	22.60	28.00	28.30	16.10
Ce	25.60	27.20	24.00	41.10	35.80	32.40	39.10	47.70	49.00	57.70	33.60
Pr	3.27	3.29	2.79	4.71	4.14	3.39	4.21	5.06	5.27	6.62	4.08
Nd	16.90	14.50	13.50	18.70	18.30	13.00	14.80	19.60	18.40	25.70	16.20
Sm	5.22	3.45	3.28	3.89	3.79	2.67	2.73	3.70	3.18	5.42	3.22
Eu	1.80	1.23	0.94	1.04	1.32	0.78	0.75	0.86	0.80	1.26	0.92
Gd	6.38	3.73	3.64	3.83	4.05	2.49	2.61	3.32	3.06	5.25	3.36
Tb	1.10	0.64	0.59	0.66	0.65	0.37	0.39	0.53	0.44	0.80	0.56
Dy	6.63	3.97	3.76	3.46	4.09	1.93	2.35	3.23	2.65	5.02	3.46
Ho	1.26	0.83	0.84	0.81	0.81	0.45	0.42	0.69	0.49	0.93	0.73
Er	3.32	2.22	2.34	2.12	2.57	1.15	1.29	1.89	1.80	2.93	2.37
Tm	0.50	0.34	0.34	0.30	0.38	0.19	0.18	0.32	0.24	0.44	0.35
Yb	2.95	2.07	2.12	1.93	2.46	1.24	1.25	1.98	1.78	2.94	2.50
Lu	0.38	0.34	0.34	0.28	0.40	0.22	0.21	0.30	0.24	0.43	0.44
(Eu/Eu*)_n	0.95	1.04	0.83	0.81	1.02	0.91	0.85	0.74	0.77	0.71	0.85
(La/Lu)_n	2.89	3.50	3.26	7.40	3.99	8.24	9.02	7.80	12.08	6.81	3.79
(La/Sm)_n	1.28	2.10	2.05	3.24	2.56	4.13	4.22	3.84	5.54	3.29	3.15
(Gd/Lu)_n	2.08	1.36	1.33	1.70	1.26	1.41	1.54	1.37	1.58	1.52	0.95
(La/Yb)_n	2.43	3.75	3.41	7.00	4.23	9.54	9.89	7.71	10.63	6.50	4.35
Eu*=(Sm+Gd)_n/2											

In the SiO₂ versus (Na₂O+K₂O) diagram [61], Avliyana volcanic rocks consist of subalkaline basalt, basaltic andesite and andesite in composition (Figure

3a). In the SiO₂ vs. Zr/TiO₂ diagram of [62], it is seen that the samples correspond to subalkaline basalt and andesite rocks (Figure 3b).

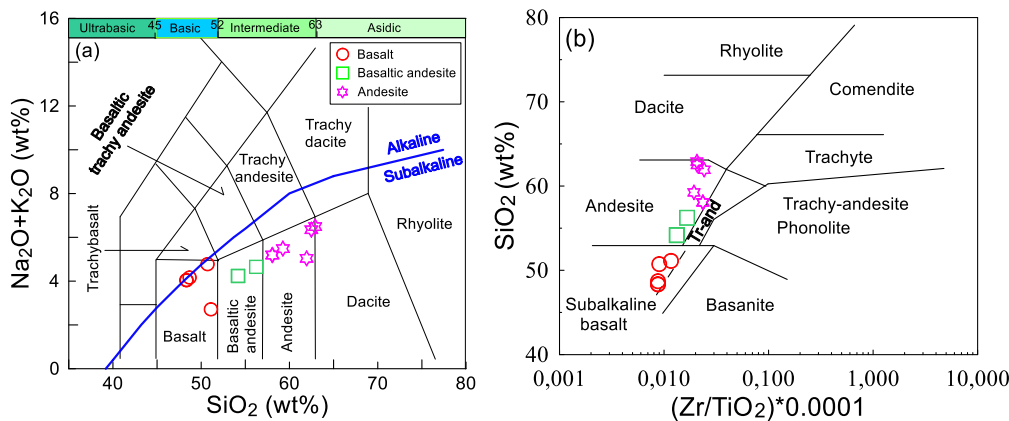


Figure 3. a) SiO₂ vs. total alkali (Na₂O+K₂O) diagram [61] b) SiO₂ vs. Zr/TiO₂ classification diagram [62] for samples from the Avliyana volcanic rocks (Alkali/subalkali separation curve from [63]).

All of the samples in the AFM diagram have calc-alkaline character (Figure 4a). When the rock samples are transferred to the K₂O vs. SiO₂ diagram

[61], it is seen that the samples have low to high-potassium content (Figure 4b).

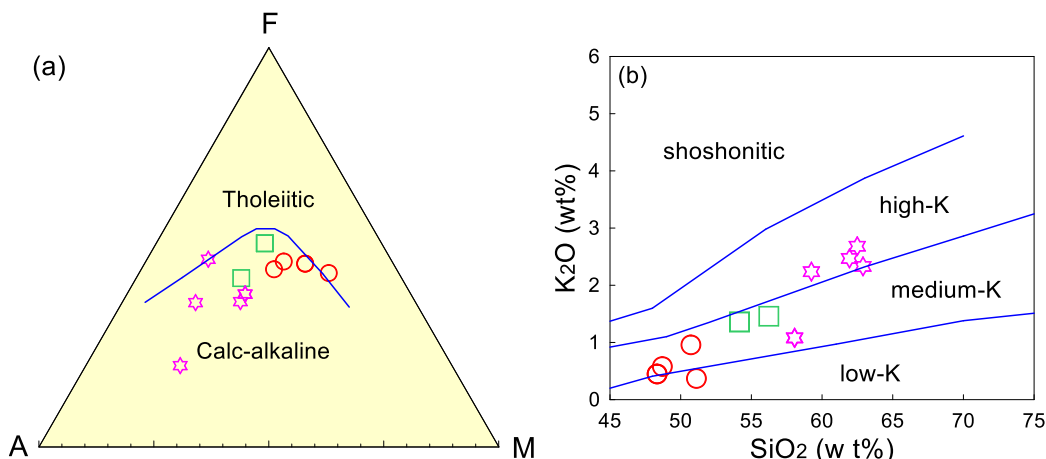
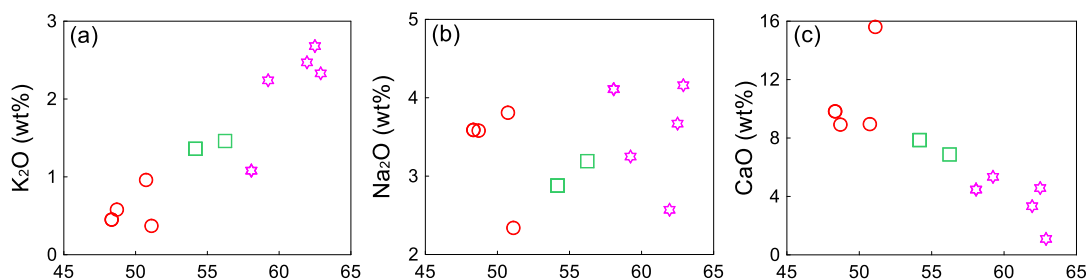


Figure 4. For samples from the Avliyana volcanic rocks a) AFM diagram (Tholeiitic-calc alkaline separation curve taken from [63]), b) SiO₂ vs. K₂O diagram (The field boundaries between medium-K, high-K and shoshonitic are from [64]).

Although irregular distributions for some samples are partially observed in the SiO₂ versus major and trace element variation diagrams (Figures 5 and 6), good correlations observed in most of the samples indicate that fractional crystallization played an important role in the development of Late Cretaceous volcanic

rocks. In the SiO₂ versus major element variation diagrams, as SiO₂ values increase, CaO, MgO, Fe₂O₃^T, TiO₂ and P₂O₅ decrease and show a good negative relationship (Figure 5). In parallel with the increase in SiO₂, a positive correlation is observed in K₂O values (Figure 5).



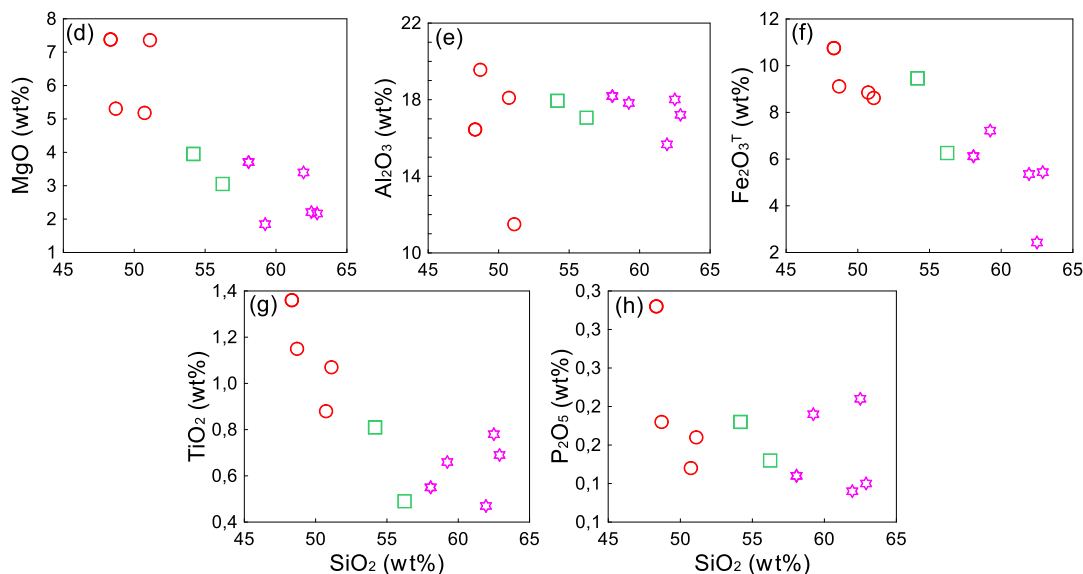


Figure 5. SiO₂ versus major element variation diagrams of Avliyana volcanic rocks samples

In the SiO₂ versus trace element variation diagrams, a positive correlation is observed for Ba, Zr, Rb, Th, Nb and La values as SiO₂ increases, while a negative

correlation is observed for Sr, Ni and Y contents (Figure 6).

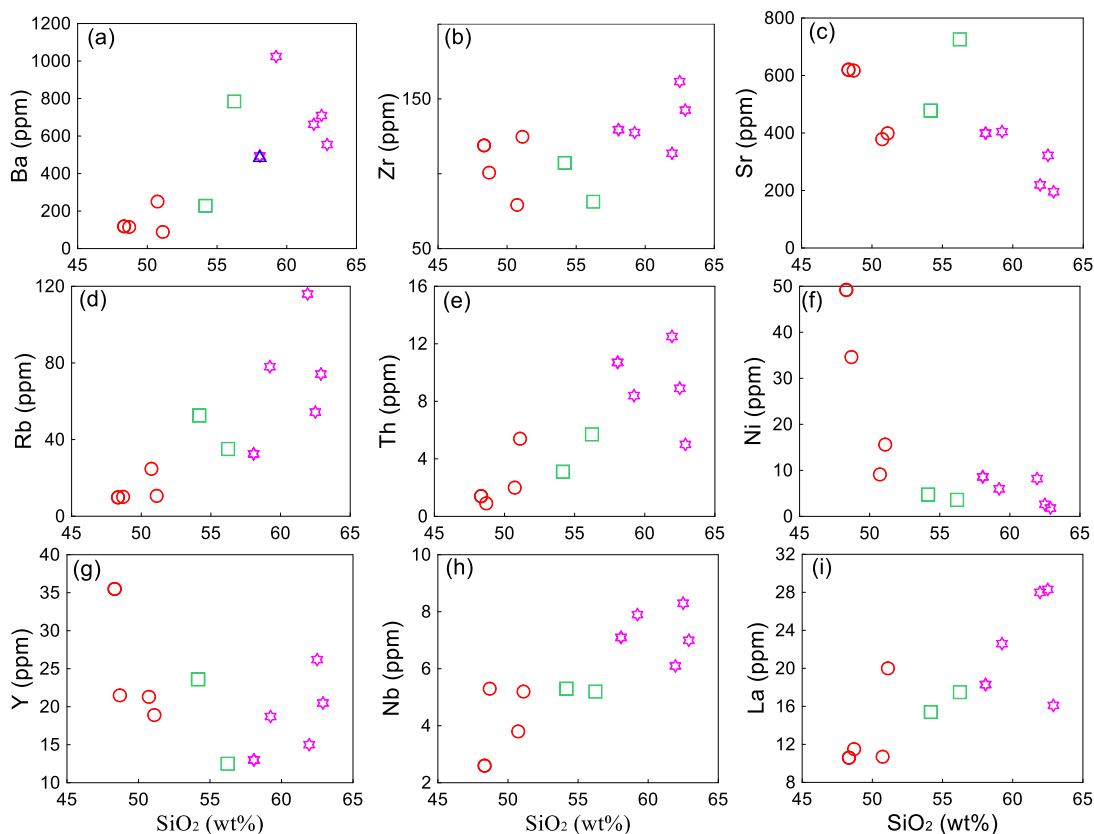


Figure 6. SiO₂ versus trace element variation diagrams of samples of Avliyana volcanic rocks

In the trace element variation diagram normalized to the primary mantle [65], an enrichment is observed in incompatible elements, while depletion is observed in compatible elements such as Ti, Nb and Ta (Figure 7). The negative Nb and Ta anomaly

indicates that the subduction component plays an active role in the development of the main magma of the rocks.

The chondrite-normalized [66] rare earth element

(REE) distribution patterns of the investigated volcanic rocks are generally similar to each other (Fig. 7). This indicates that the volcanic rocks in the study area are derived from a similar source. In the chondrite normalized rare earth element distribution

diagrams of the studied samples (Fig. 7), light rare earth elements are more enriched than heavy rare earth elements. The $(La/Lu)_N$ ratios of the samples are between 2.89 and 12.08, and the $(Eu/Eu^*)_n$ ratios are between 0.71 and 1.04 (Table 3, Fig. 8).

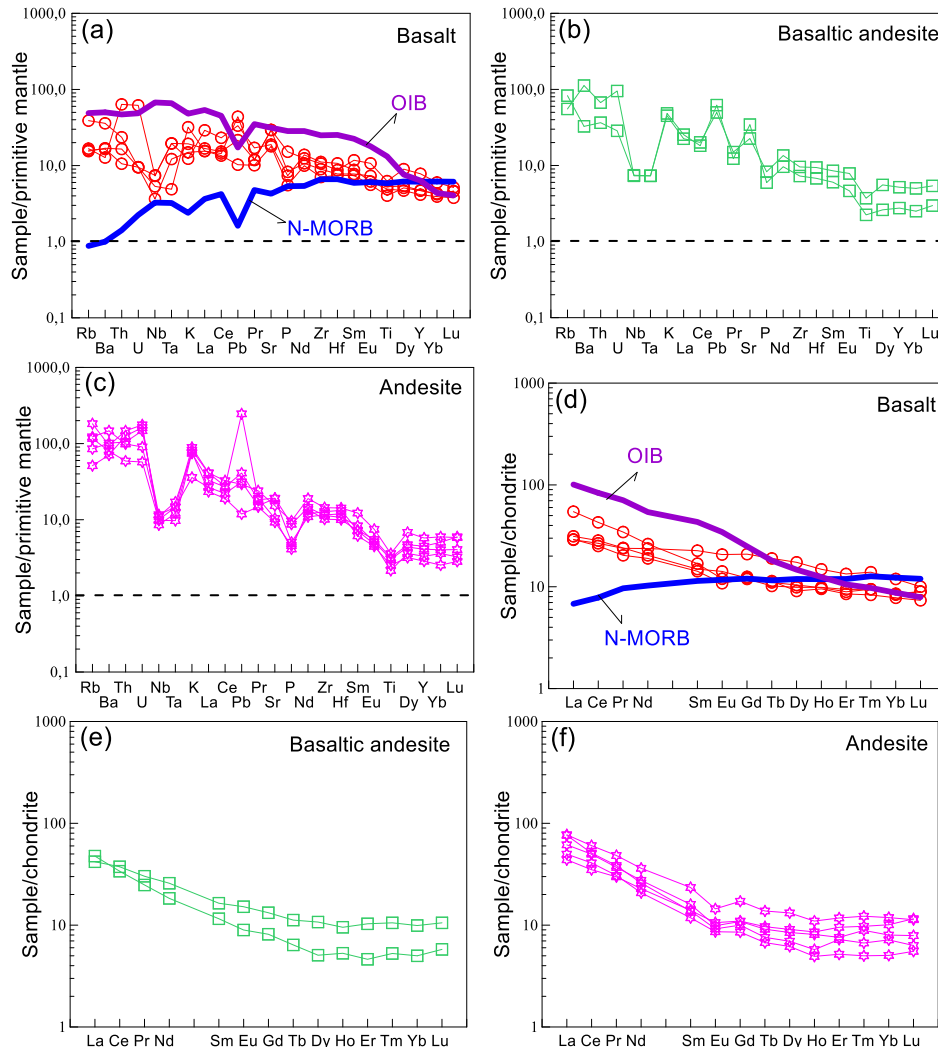


Figure 7. Trace element variation diagrams of Avliyana volcanic rocks (a-c) Primitive mantle normalized trace element patterns [65], (d-f) Chondrite normalized trace element patterns [66]

According to the Ce/Pb vs. Ce [67] tectonic discrimination diagram, the samples fall into the arc volcanics area and nearby (Figure 8a). In the Sr/Y vs.

Y [68] discrimination diagram, the samples are located in the area of the normal arc volcanic series (Figure 8b).

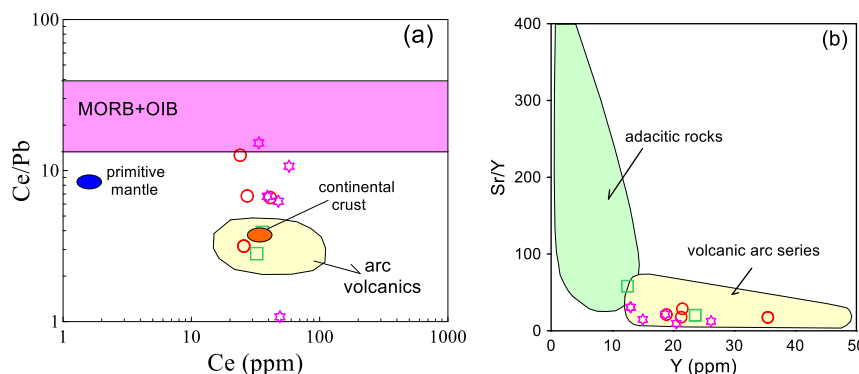


Figure 8. Tectonic discrimination diagrams of Avliyana volcanic rocks. (a) Ce/Pb vs. Ce diagram (primary mantle values from [69], continental basalt-MORB+OIB and arc volcanic areas from [70]). (b) Sr/Y-Y discrimination diagram [68].

6. Discussion

The Avliyana volcanic rocks possess MgO values of 1.8–7.4%, Mg# values of 36–67 and Ni values of 2–49 ppm (Table 2). These values indicate that the Avliyana volcanic rocks substantially differ from the magmas derived from primitive mantle composition (Mg# = ~ 66 to 75, Ni = ~ 400 to 500 ppm; [71]).

The distribution pattern of the some major and trace

elements of the studied samples (Figures 5 and 6) support plagioclase ± amphibole + Fe-Ti oxide + apatite fractionations.

In the Y versus Rb diagram (Figure 9), Late Cretaceous volcanic rocks have a low-Y series trend, indicating that plagioclase and hornblende fractionation is effective in the rocks.

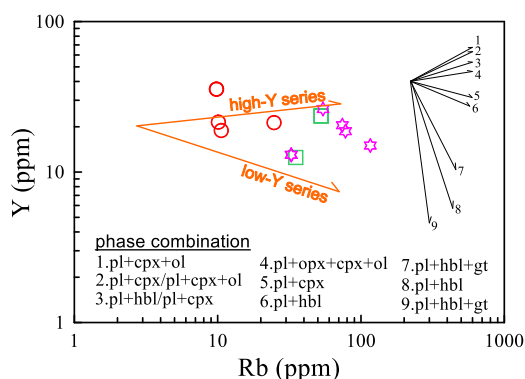


Figure 9. Y (ppm) versus Rb (ppm) diagram of Avliyana volcanic rocks

Enrichments of LILEs and LREEs, and negative Ta and Nb anomalies (Figure 7) together with low $(La/Yb)_N$ (2.4-10.6) ratios and high Th/Yb (0.4-8.6) ratios (Table 3) of the studied samples indicate

subduction-related metasomatised mantle source [72]. Sr/La vs. La/Yb and Ba/Th vs. La/Sm diagrams show that the melt was enriched in the fluids [73] during the Late Cretaceous subduction (Figure 8).

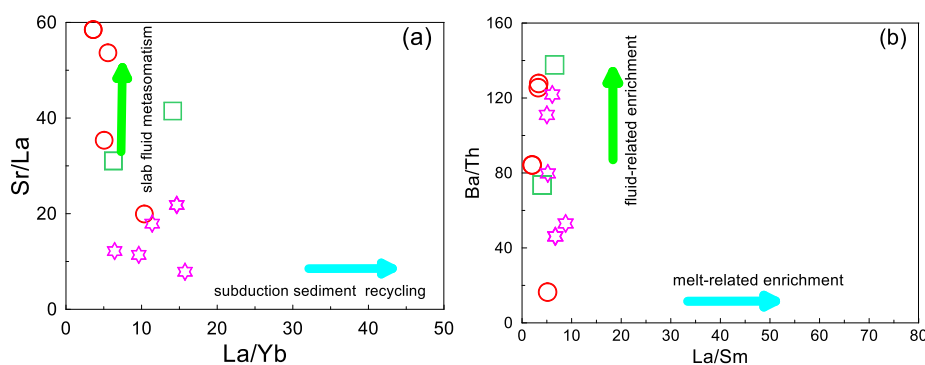


Figure 10. For the Avliyana volcanic rocks, (a) Sr/La vs. La/Yb and (b) Ba/Th vs. La/Sm diagrams

In the Nb/Th versus Nb diagram (Figure 11a), the samples of the studied volcanic rocks are located in the arc volcanics area. The low Ce/Pb ratios (1.1 to 15.3) observed in the samples differ from oceanic basalts (20 to 30) [69], indicating that the studied volcanic rocks did not derive from an asthenospheric mantle source. Nb/La ratios are useful in determining the partial melting point and source composition of volcanic rocks [74]. High Nb/La ratios (>1) indicate

an ocean island basalt (OIB)-like asthenospheric mantle source, while low ratios (<0.5) indicate a lithospheric mantle source [75]. The Nb/La ratios of the studied volcanic rocks range from 0.22 to 0.46 (Table 2), indicating a spinel lherzolitic lithospheric mantle source (Fig. 11b). The studied volcanic rocks (Figure 11c) are located in or near the arc volcanics area. La/Nb (2.3 to 4.6) and Ba/Nb (17 to 151) ratios of volcanic rocks indicate the source of subduction

zone enrichment. At the time of subduction, LILE and LREE elements are transported upwards via fluids derived from the slab [76,77]. Therefore, significant LILE and LREE enrichments observed in the studied volcanics indicate an enriched mantle source rather than a depleted mantle source [78,79].

The Th/Y versus Nb/Y diagram (Figure 11d) proposed by [72] is used to distinguish between

melting enrichment products and subduction enrichment product. In addition, Th/Y and Nb/Y ratios can be used to distinguish crustal contamination and homogenization at the magma source. The investigated volcanic rocks trend parallel to the OIB and MORB lines (Figure 11d), but have higher Th/Y ratios compared to them, indicating that the mantle source is metasomatized by subduction zone fluids.

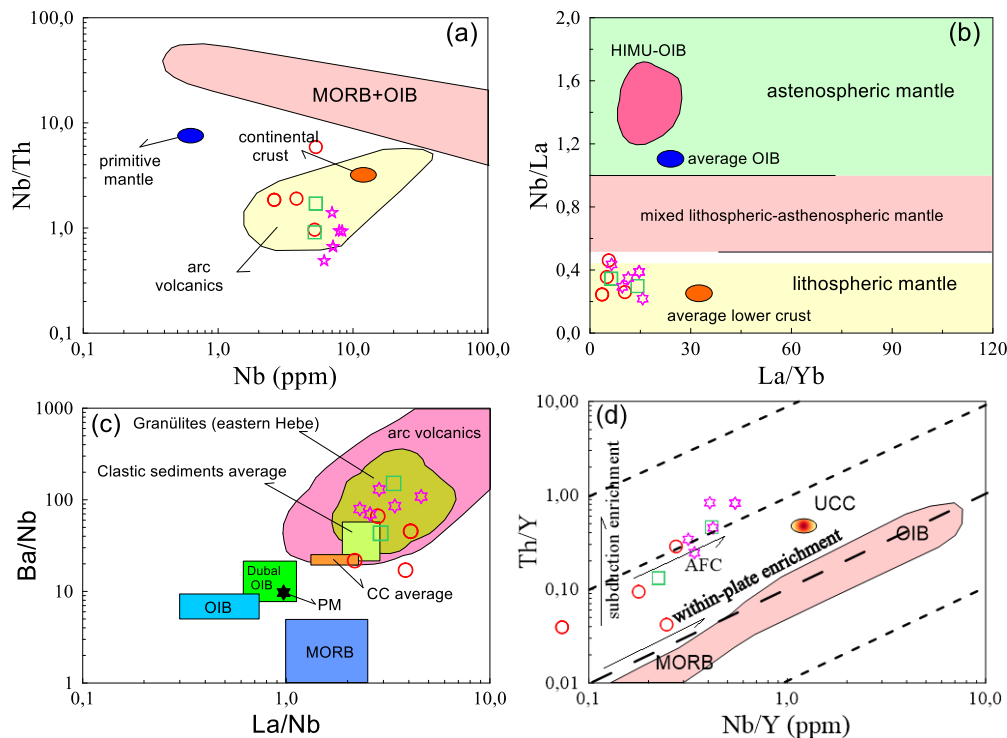


Figure 11. For the Avliyana volcanic rocks; (a) Nb/Th versus Nb diagram, (b) Nb/La versus La/Yb diagram, (c) Ba/Nb versus La/Nb diagram [74] and (d) Th/Y versus Nb/Y diagram [72]. For reference values in diagrams, see Figure 9 caption in [49].

7. Conclusions

1. The studied Avliyana volcanic rocks vary from basalt to andesite in composition defining a calc-alkaline series.
2. All of the samples display similar geochemical features characterized by enrichment in large-ion lithophile elements and light rare earth elements, with pronounced depletion in high-field-strength elements indicating similar sources and petrogenetic processes.
3. The main solidification processes involved in the evolution of the volcanics consist of fractional crystallization with minor amounts of crustal contamination.
4. Plagioclase, hornblende and Fe-Ti oxides are the most important fractionating mineral phases.
5. The studied volcanic rocks were derived from a subcontinental lithospheric mantle enriched by fluids in a subduction-related geodynamic setting.

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