Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 10 (2), December 2021, pp 1774-1788
ISSN 2147-3471 © 2021

Petrographic and geochemical characteristics of carboniferous plutonic rocks around Erenkaya (Gümüşhane, NE Turkey)

A. Kaygusuz[1,a], E. Aydınçakır[1], C.Yücel[2], H.E.Atay[1]

[1]Gümüşhane University, Geological Engineering, Gümüşhane, Turkey.
[2]Gümüşhane University, Mining Engineering, Gümüşhane, Turkey.

Accepted 17 July 2021

Abstract
In the Eastern Pontides, there are many plutonic rocks of different ages and compositions from Paleozoic to Tertiary. Although Carboniferous plutonic rocks are widely observed as large bodies in the Southern Zone of the Eastern Pontides, they are less common in the Northern Zone and consist of smaller bodies. In this study, Carboniferous plutonic rocks cropping out in Erenkaya (Gümüşhane) and surrounding area in the Southern Zone of the Eastern Pontides were investigated petrographically and geochemically. The studied Carboniferous plutonic rocks are in granodiorite and granite composition and mainly consist of plagioclase, orthoclase, quartz, biotite and hornblende minerals. These plutonic rocks have calc-alkaline character and have high K content. The samples have peraluminous to metallumin characters and have high SiO_2 contents (67-75 wt%). They are enriched in-large ion lithophile and light rare earth elements, and depleted in high-field strenght elements. Chondrite-normalized rare earth element distributions are characterized by concave-upwardly shapes (La_N/Yb_N = 3.57 to 6.90) and show negative Eu anomalies (Eu_N/Eu^* = 0.32 to 0.62). All these features with low molar $(Na_2O+K_2O)/(FeO^T+MgO+TiO_2)$, K_2O/Na_2O, ASI and high $(CaO+FeO^T+MgO+TiO_2)$ and Na_2O contents indicates that the studied Carboniferous rocks may have been formed by partial melting of meta-magmatic lower crustal source rocks.

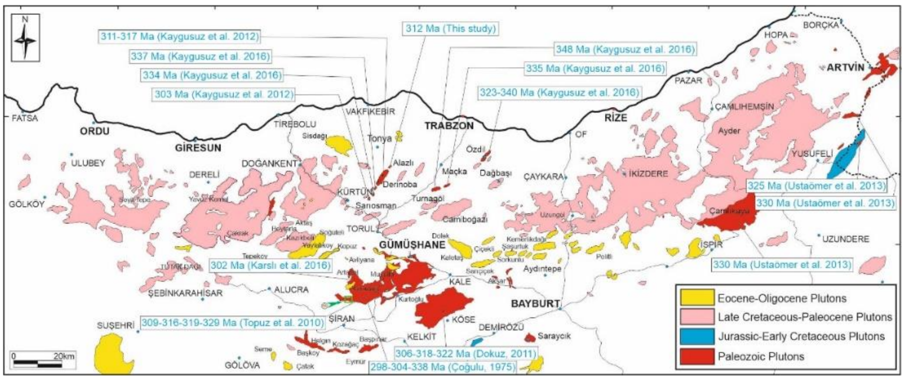
Keywords: Eastern pontides, Erenkaya (Gümüşhane), carboniferous, whole-rock geochemistry, plutonic rocks.

1. Introduction

Eastern Pontides (NE Turkey), located in the Alpine-Himalayan orogenic belt and also known as the Sakarya Zone, is one of the areas where plutonic and volcanic rocks are commonly observed [1-12].

The plutonic bodies observed in the Eastern Pontides between Paleozoic and Cenozoic period are represented by mafic to felsic products of the magmatic rocks varying from gabbro to granite in compositions. The emplacement periods of these plutonic rocks in the belt range from Paleozoic [4-5, 13-20] through Jurassic [21-23], Late Cretaceous-Paleocene [10, 24-27] to Eocene-Oligocene [1, 11, 28-34].

Radiometric age data for the Carboniferous aged plutonic rocks in the Eastern Pontides are limited and are given in Figure 1 and Table 1. Accordingly, the ages of the Carboniferous plutonic rocks vary between 302 and 348 Ma (Table 1).



[a] Corresponding author; abdullah.kaygusuz@gmail.com

Figure 1. Simplified geological map showing the main pluton distribution and geochronological ages in the Eastern Pontides (modified after [20, 35]).

Table 1. Geochronological ages of Carboniferous plutons in the Eastern Pontides (changed from [20])

Era/Age	Pluton/Location	Age (Ma)	Method	Reference
Carboniferous	Köse (Gümüşhane)	322.2±3.8	Ar-Ar	[5]
Carboniferous	Köse (Gümüşhane)	306.6±4.2	Ar-Ar	[5]
Carboniferous	Köse (Gümüşhane)	318±2.4	Ar-Ar	[5]
Carboniferous	Gümüşhane	298	U/(Th-Pb)	[13]
Carboniferous	Gümüşhane	304	U/(Th-Pb)	[13]
Carboniferous	Gümüşhane	338	U/(Th-Pb)	[13]
Carboniferous	Gümüşhane	309.2±5.3	Ar-Ar	[4]
Carboniferous	Gümüşhane	316.8±2.9	Ar-Ar	[4]
Carboniferous	Gümüşhane	319±5	U-Pb	[4]
Carboniferous	Gümüşhane	329±6	U-Pb	[4]
Carboniferous	Çamlık (Gümüşhane)	302.01±0.68	U-Pb	[17]
Carboniferous	Alazlı (Tonya-Trabzon)	312.1±2.1	U-Pb	[20]
Carboniferous	Derinoba (Tonya-Trabzon)	317.2±3.5	U-Pb	[15]
Carboniferous	Derinoba (Tonya-Trabzon)	311.1±2.0	U-Pb	[15]
Carboniferous	Kayadibi (Kürtün-Gümüşhane)	303.8±1.5	U-Pb	[15]
Carboniferous	Özdil (Yomra-Trabzon)	340.7±1.8	U-Pb	[16]
Carboniferous	Özdil (Yomra-Trabzon)	323.1±1.5	U-Pb	[16]
Carboniferous	Seslikaya (Maçka-Trabzon)	335.4±1.4	U-Pb	[16]
Carboniferous	Soğuksu (Maçka-Trabzon)	348.4±1.6	U-Pb	[16]
Carboniferous	Şahmetlik (Tonya-Trabzon)	334.5±1.4	U-Pb	[16]
Carboniferous	Kızılağaç (Tonya-Trabzon)	337.2±0.69	U-Pb	[16]
Carboniferous	Çamlıkaya (Yusufeli-Artvin)	330±4.0	U-Pb	[14]
Carboniferous	Demirkent (Yusufeli-Artvin)	325±3.0	U-Pb	[14]
Carboniferous	Narlık (Yusufeli-Artvin)	330±19	U-Pb	[14]

Despite the petrological and geochemical studies have been conducted in recent years on Carboniferous plutons in the region [15-20], the investigations of the Erenkaya (Gümüşhane) and surrounding area are mainly based on the geological mapping affords [35].

The Carboniferous aged plutonic rocks in Erenkaya (Gumushane) and its surroundings, which are the subject of this study, form a part of the Gümüşhane Pluton. The Gümüşhane Pluton (according to some authors, Gümüşhane Granitoid, Gümüşhane Granite), which spreads over an area of approximately 400 km^2, was studied in parts, not as a whole. Although there are detailed studies [4; 17-18, 22, 36] in different parts of the Gümüşhane Pluton, no study has been conducted on the petrographic, geochemical and petrological properties of the Carboniferous aged plutonic rocks in Erenkaya (Gümüşhane) and its surrounding. Therefore, in this study, it was aimed to examine the petrographic, geochemical and petrological properties of the Carboniferous aged plutonic rocks in the Erenkaya (Gümüşhane) and surrounding areas.

2. Regional geology and geological setting

Based on lithological and structural differences, the Eastern Pontides are generally divided into a southern and a northern zone [37-38]. Carboniferous plutons are observed both northern and southern zones (Figure 1).

The basement rocks of the Eastern Pontides consist of Early Carboniferous metamorphic rocks [39] and Late to Early Carboniferous Plutonic rocks [4, 15-16, 18, 20]. These Pre-Jurassic basement rocks are overlain by the Early and Middle Jurassic volcano-sedimentary rocks [40-43] and are cut by Mid to Late Jurassic plutons [14, 21, 23, 44]. All these rocks are overlain by the Late Jurassic to Early Cretaceous carbonates [45]. The Late Cretaceous units that unconformably overlie these carbonate rocks consist of plutonic, volcanic and sedimentary rocks [46-49] and overlain by the Cenozoic units consisting of plutonic, volcanic and sedimentary rocks [1, 8, 11-12, 31, 47, 50-63]. The youngest units in the region are Quaternary alluvium and terraces.

The study area located in the south zone of the Eastern Pontides and is generally dominated by plutonic and volcanic rocks (Figure 2). The oldest units in the study area are the Mid to Late Carboniferous Gümüşhane Pluton. This pluton is observed in a very large part of the study area. The Early to Middle Jurassic Şenköy Formation unconformably overlies the Gümüşhane Pluton (Figure 2). This formation is found in the northern and southern parts of the Gümüşhane Pluton in the study area and has faulty contacts with the Gümüşhane Pluton.

3. Analytical techniques

Within the scope of this study, thin sections of rock samples collected from the field were prepared and detailed petrographic properties were determined under a polarizing microscope.

Based on the petrographical studies determined under a polarizing microscope, fresh and mostly representative rock samples were selected for whole-rock major, trace and rare earth element (REE) analyzes. These analyses were made in ACME (Vancouver, Canada) Analytical Chemistry Laboratory. Major and trace elements were analyzed by ICP method, and rare earth elements (REE) by ICP-MS method. For the major and trace element analyzes, 0.2 grams of powder sample was mixed with 1.5 grams of $LiBO_2$ and analyzed after dissolving in a liquid containing 5% HNO_3, while 0.250 grams of powder sample for rare earth element analyzes was dissolved in four different acids and analyzed. Detection limits range from 0.002 to 0.04 wt% for major oxides, 0.1 to 8 ppm for trace elements, and 0.01 to 0.3 ppm for REE.

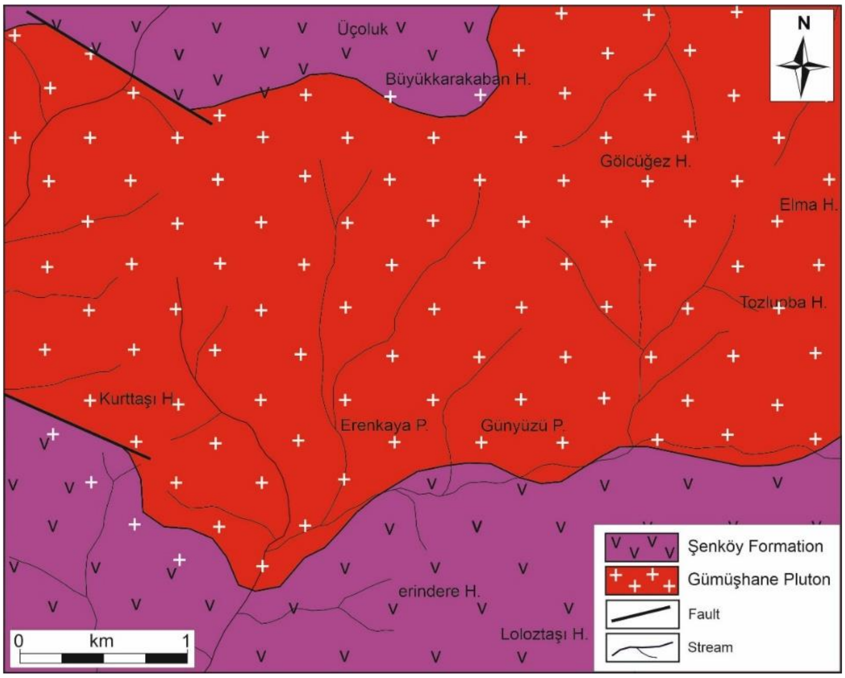


Figure 2. Geological map of the study area

4. Mineralogy and petrography

The studied plutonic rocks are composed of granodiorite and granite. Granodiorites are observed in the marginal parts, wherease granites are observed in the central parts. While granites form a large part of the pluton, granodiorites are observed in a smaller area. Although the contact of granites and granodiorites cannot be observed very well due to intense alteration and vegetation, the contacts are sharp, and the granites cut the granodiorites. They are generally holocrystalline, medium to coarse grained, poikilitic, micrographic and rarely micrographic in texture. Main minerals are plagioclase, quartz, orthoclase, biotite, hornblende, muscovite and opaque minerals (Figure 6).

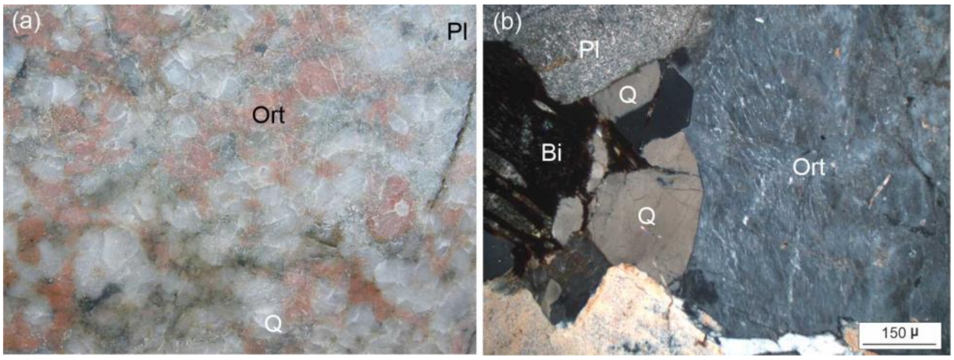


Figure 3. The polished hand sample (a) and thin section view (b) of the studied rocks (Pl: Plagioclase, Ort: Orthoclase, Q: Quartz, Bi: Biotite)

Plagioclases forms euhedral and subhedral coarse grained crystals. They show polysynthetic twinning, and some of them are zoned. The compositions of the crystals showing albite twins are andesine (An_{33-38}). Quartz is anhedral with irregular cracks and interstitial to the other minerals. K-feldspars forms anhedral to subhedral crystals of perthitic orthoclase. Karlspad twins are observed in some of the large and semi-euhedral orthoclases. In some sections, large orthoclase crystals form a poikilitic texture including smaller plagioclase, biotite and opaque minerals. Biotite is observed as subhedral crystals and generally chloritized. They show greenish pleochroism due to chloritization. There are also small amounts of opaque mineral formations with chloritization. Hornblendes are in the form of elongated euhedral prismatic crystals and contains small biotite, apatite, zircon and opaque mineral inclusions. Chloritization is common in some minerals. Muscovites are found in rare and as small crystals. There are opaque minerals of varying sizes and anhedral shape.

5. Whole-rock geochemistry

The minimum (min), maximum (max), average (avg) and standard deviation (SD) values of whole-rock major, trace and rare earth element analyzes of seven samples of the studied plutonic rocks are given in Table 2 and 3. SiO_2 values of the studied samples are between 67 and 75%. Granodiorites have the lowest SiO_2 values (66-67), while granites have the highest SiO_2 values (72-74). The K_2O/Na_2O ratios of the samples vary between 0.64 and 1.06, and the magnesium numbers [$Mg\#=100*(MgO/MgO+Fe_2O_3^T)$] vary between 33 and 39 (Table 2**).**

Table 2. Minimum (min), maximum (max), average (avg) and standard deviation (SD) values of whole-rock major and trace element analyzes of the studied rocks

Rock	**Granodiorite**				**Granite**			
	min	max	avg	SD	min	max	avg	SD
SiO_2	66.52	68.87	67.61	1.18	72.35	75.06	73.81	1.21
TiO_2	0.18	0.23	0.21	0.03	0.14	0.18	0.16	0.02
Al_2O_3	16.36	17.97	16.99	0.86	11.72	12.85	12.38	0.48
$Fe_2O_3^T$	2.16	2.96	2.62	0.41	2.21	2.85	2.53	0.28
MnO	0.06	0.08	0.07	0.01	0.03	0.05	0.04	0.01
MgO	0.58	0.85	0.73	0.14	0.53	0.70	0.61	0.09
CaO	2.26	3.05	2.59	0.41	1.77	2.18	1.92	0.18
Na_2O	3.58	4.20	3.89	0.31	3.25	3.51	3.39	0.11
K_2O	2.65	2.82	2.71	0.09	3.34	3.46	3.40	0.06
P_2O_5	0.07	0.11	0.09	0.02	0.04	0.08	0.06	0.02
LOI	1.40	2.90	2.23	0.76	1.30	1.80	1.50	0.22
Total	99.67	99.86	99.74	0.10	99.66	99.86	99.79	0.09
Co	3.90	7.60	6.00	1.90	1.70	2.30	1.93	0.29
Ni	10.60	24.20	16.10	7.16	8.70	15.30	11.53	2.79
V	13.00	38.00	26.00	12.53	8.00	12.00	10.00	1.83
Cu	15.90	38.40	26.57	11.30	14.30	127.70	46.93	54.30

Pb	5.70	6.90	6.47	0.67	9.60	13.40	11.93	1.63
Zn	25.00	33.00	30.00	4.36	23.00	31.00	27.50	4.12
W	1.30	3.60	2.37	1.16	0.50	4.30	1.70	1.75
Rb	94.00	101.00	97.00	3.61	102.40	109.60	105.63	3.23
Ba	523.00	615.00	574.67	47.04	536.00	793.00	642.00	117.52
Sr	58.00	92.00	78.33	17.95	45.00	53.80	50.40	4.02
Ta	1.70	1.90	1.80	0.10	1.70	1.90	1.83	0.10
Nb	7.30	8.90	8.17	0.81	9.00	11.10	10.05	0.93
Hf	3.10	4.60	4.00	0.79	4.80	5.30	5.13	0.22
Zr	125.00	163.00	145.33	19.14	149.10	174.90	157.73	11.82
Y	35.70	49.90	42.63	7.11	34.10	39.90	37.45	2.46
Th	5.60	8.40	6.70	1.49	6.30	9.40	8.15	1.31
U	0.90	1.40	1.13	0.25	1.30	1.80	1.53	0.22
Ga	13.60	15.30	14.37	0.86	14.30	16.00	15.23	0.74
Mg #	37.15	38.73	37.80	0.83	32.71	36.77	34.56	1.74
K_2O/Na_2O	0.64	0.79	0.70	0.08	0.95	1.06	1.00	0.05
ASI (A/CNK)	1.08	1.31	1.22	0.12	0.95	0.99	0.97	0.02
Nb/Ta	3.84	5.24	4.56	0.70	5.29	5.84	5.50	0.25
Y/Nb	4.30	6.84	5.30	1.35	3.59	3.90	3.73	0.13
Rb/Sr	1.02	1.74	1.30	0.39	1.93	2.28	2.10	0.16
Ce/Pb	6.24	7.58	6.98	0.68	4.42	7.69	5.75	1.55
Mg# (mg-number) = molar 100xMgO/(MgO+ $Fe_2O_3^T$). LOI is loss on ignition.								

Table 3. Minimum (min), maximum (max), average (avg) and standard deviation (SD) values of rare earth element analyzes of the studied rocks

Rock	**Granodiorite**				**Granite**			
	min	max	avg	SD	min	max	avg	SD
La	23.30	31.60	26.53	4.44	30.30	42.70	36.20	5.95
Ce	40.60	52.30	45.10	6.30	56.10	78.80	66.98	11.03
Pr	5.59	7.68	6.58	1.05	6.26	8.82	7.57	1.17
Nd	25.10	31.50	28.03	3.23	23.60	31.10	27.38	3.43
Sm	3.45	4.62	3.98	0.59	4.74	6.44	5.60	0.72
Eu	0.76	0.89	0.82	0.07	0.61	0.71	0.66	0.05
Gd	4.13	5.45	4.95	0.71	5.15	6.51	5.88	0.61
Tb	0.85	0.95	0.89	0.06	0.91	1.06	0.99	0.06
Dy	5.82	6.39	6.05	0.30	5.55	6.73	6.14	0.48
Ho	1.32	1.56	1.44	0.12	1.22	1.38	1.32	0.07
Er	3.43	4.17	3.80	0.37	3.58	4.26	4.00	0.29
Tm	0.42	0.58	0.50	0.08	0.57	0.64	0.62	0.03
Yb	3.42	4.41	3.89	0.50	3.53	4.27	4.01	0.33
Lu	0.52	0.64	0.58	0.06	0.56	0.66	0.63	0.05
$(La/Lu)_n$	3.77	6.29	4.82	1.31	5.04	6.80	5.94	0.78
$(La/Sm)_n$	4.02	4.31	4.19	0.15	3.78	4.27	4.06	0.22
$(Gd/Lu)_n$	0.99	1.13	1.06	0.07	1.06	1.24	1.16	0.08
$(La/Yb)_n$	3.57	6.24	4.72	1.38	5.08	6.90	6.09	0.82
$(Eu/Eu^*)_n$	0.51	0.62	0.57	0.06	0.32	0.38	0.35	0.02
$Eu^*=(Sm+Gd)_n/2$								

In the SiO_2 versus (Na_2O+K_2O) diagram (Figure 4a), the studied plutonic rocks consist of subalkaline granodiorite and granite composition rocks. In the Ce/Yb vs. Ta/Yb diagram, all of the samples are calc-alkaline in characters (Figure 4b).

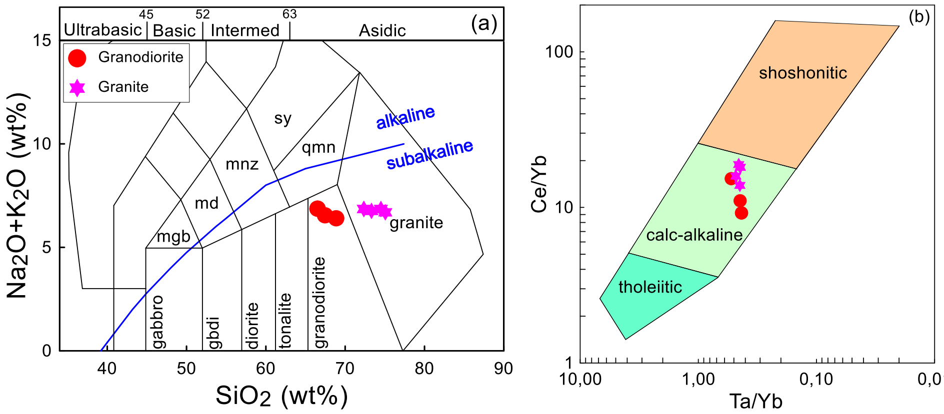


Figure 4. a) Chemical nomenclature diagram [63], b) Ce/Yb vs. Ta/Yb diagram [64] of the rock samples from the studied plutonic rocks (field boundaries alkaline/subalkaline series, according to [65])

Rock samples are located in the high potassium area in the K_2O vs. SiO_2 diagram [63] (Figure 5a). The A/CNK values of the samples are between 0.95-1.31 and they show metallumin to peralumin properties (Figure 5b).

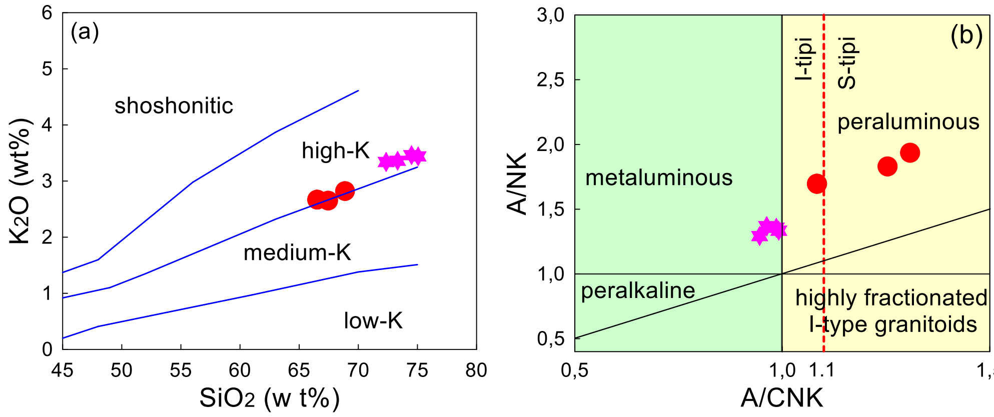
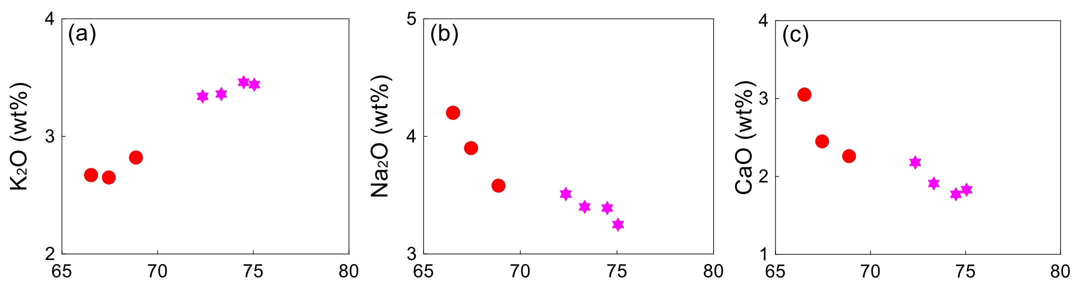


Figure 5. a) SiO_2 vs. K_2O diagram (field boundaries between the medium-K, high-K and shoshonitic series, according to [66]), b) A/CNK vs. A/NK diagram [66] of the rock samples from the studied plutonic rocks

Although irregular distributions are observed in some of the major and trace element vs. SiO_2 diagrams (Figures 6 and 7), they give good correlations indicates that fractional crystallization plays an important role in the development of rocks. In the SiO_2 versus major element diagrams, the SiO_2 values increase, wherease Na_2O, CaO, MgO, Al_2O_3, $Fe_2O_3^T$, TiO_2 and P_2O_5 decrease (Figure 6). A positive correlation is observed in K_2O vs. SiO_2 diagram (Figure 6).



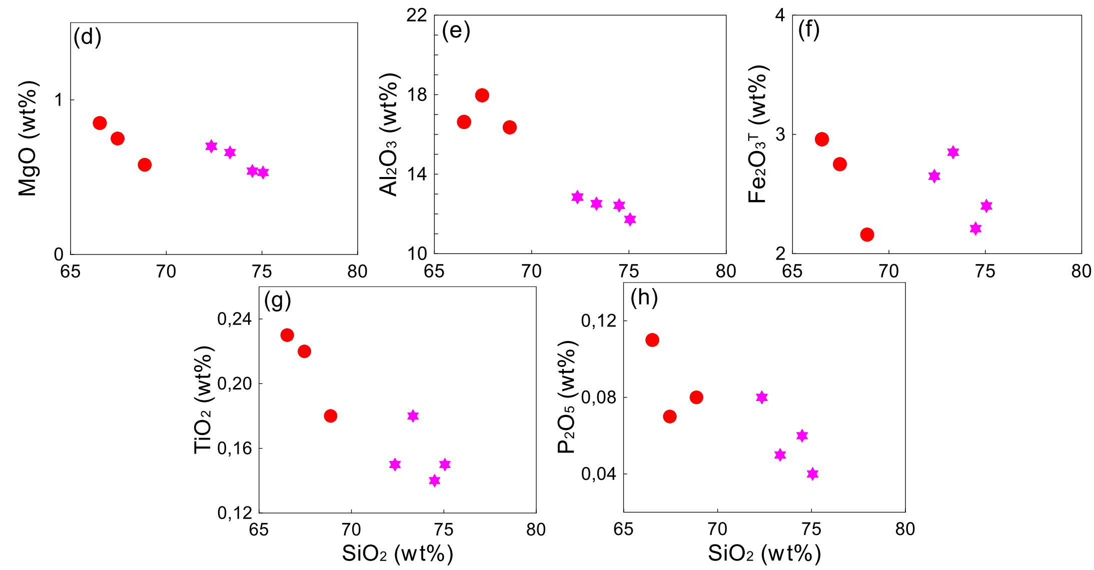


Figure 6. Variation diagrams of SiO_2 (wt.%) vs. major oxides (wt.%) for the rock samples from the studied plutonic rocks

In the trace element vs. SiO_2 diagrams (Figure 7), a positive correlation is observed in Ba, Zr, Rb, Th, Nb and Pb values as increasing SiO_2, wherease a negative correlation is observed for Sr, Ni and Y contents (Figure 7).

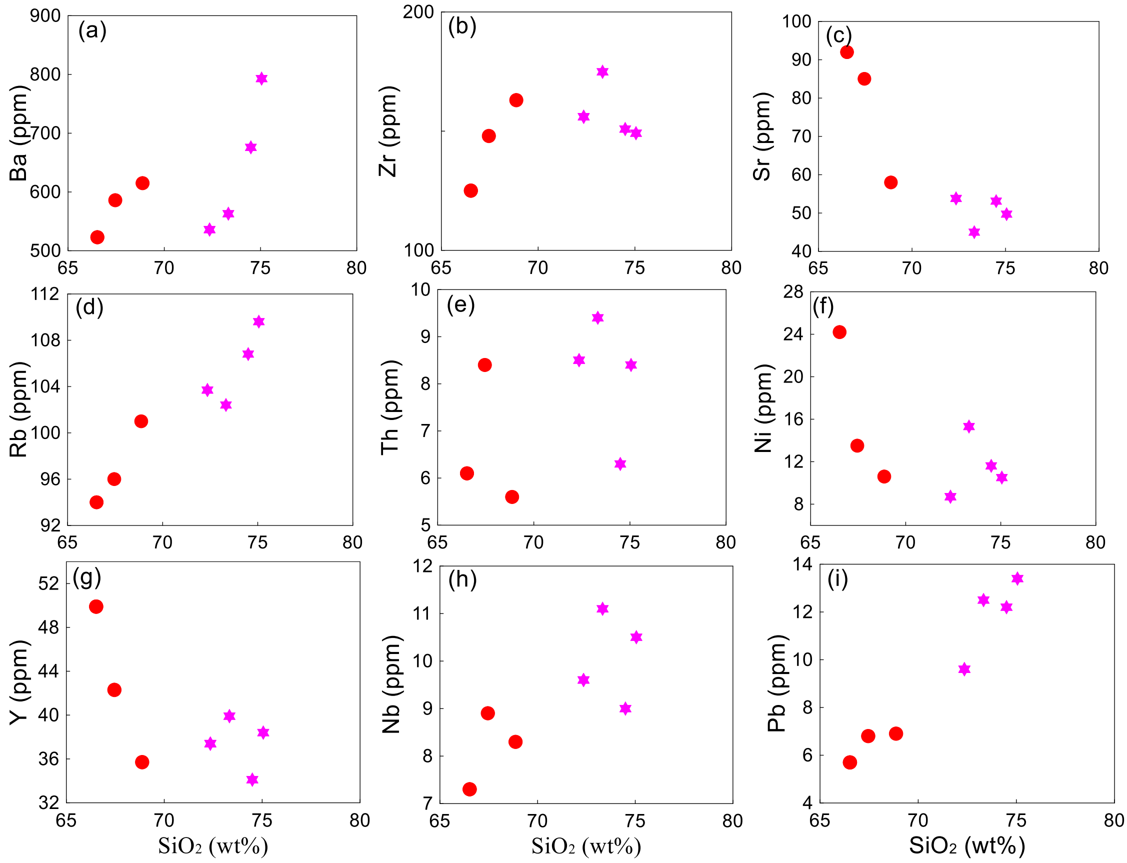


Figure 7. Variation diagrams of SiO_2 (wt.%) vs. trace elements (ppm) for the rock samples from the studied plutonic rocks

In the primitive mantle-normalized [67] multielement variation diagrams (Figure 8a and b), while the enrichment is observed in incompatible elements of the samples, the depletion is also observed in compatible elements such as Ti, Nb, Ta, Sr and P.

The chondrite-normalized rare earth element (REE) distributions [68] of the studied rocks are generally similar to each other (Figures 8c and d). This indicates that the rocks in the study area are derived from a similar source.

In the chondrite-normalized REE diagrams (Figure 8), light rare earth elements (LREEs) are more enriched than heavy rare earth elements (HREEs). While the $(La/Lu)_N$ ratios of the samples vary between 3.77 and 6.80, the $(La/Yb)_N$ ratios are between 3.57 and 6.90 (Table 3). The $(Eu/Eu^*)_N$ ratios of the samples are between 0.32 and 0.62 and they show negative Eu anomalies (Figure 8).

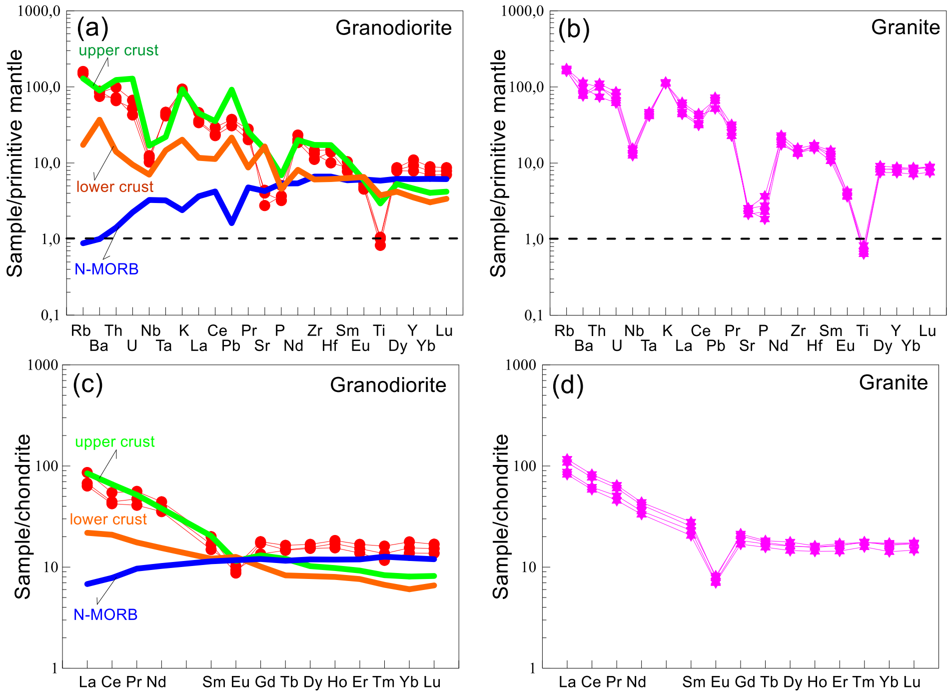


Figure 8. (a-b) Primitive mantle-normalized [67] trace element patterns, (c-d) Chondrite-normalized [68] rare earth element patterns for the rock samples from the studied plutonic rocks

In the SiO_2 versus molar A/CNK diagram [69], some of the samples are located in the area of I-type and some of them in the area of S-type granitoids (Figure 9a). When compared with the I and S-type granites [69] of the Lachlan Belt, it is seen that all of the samples fall in the same area with I-type granites of the Lachlan Fold Belt (Figure 9b).

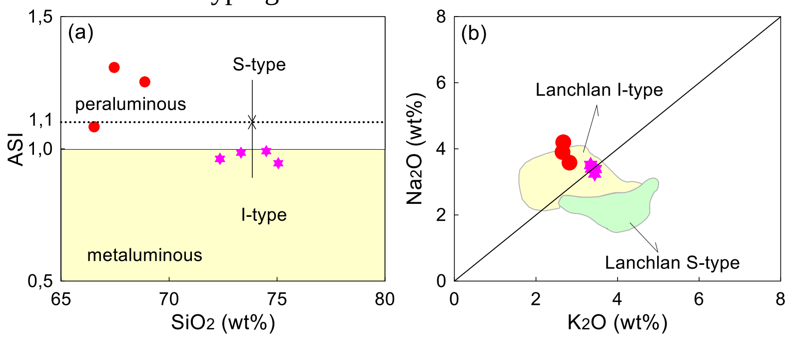


Figure 9. (a) SiO_2 vs. ASI (A/CNK) diagram [69], (b) Na_2O vs. K_2O (%) diagram for the rock samples from the studied plutonic rocks

In the Nb vs. 10000Ga/Al diagram developed by [70], all of the samples are located in the I-type granite area (Figure 10a). In the multicationic diagram of [71], it is seen that the samples mostly fell into the syn-collision area (Figure 10b).

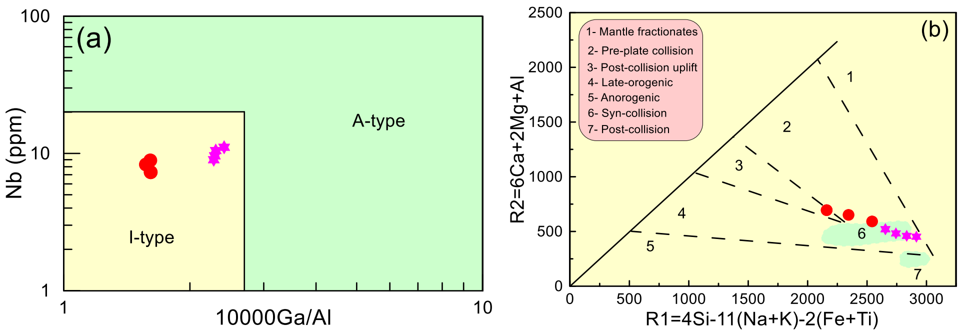


Figure 10. (a) Nb vs. 10000 Ga/Al classification diagram [70], (b) R1-R2 diagram [71] for the rock samples from the studied plutonic rocks. R1=4Si–11(Na+K)–2(Fe+Ti); R2= 6Ca+2Mg+Al

In the Rb vs. (Y+Nb) diagram [72], the studied samples are located close to the triple intersection point of volcanic arc granitoids (VAG), intraplate granitoids (WPG) and syn-collision granitoids (Syn+COLG) areas (Figure 11a). In this diagram, it is seen that the grouping has shifted a little more to the collision granites (syn-COLG) region. The samples falling at the triple intersection characterize the post-collisional granitoids (Post-COLG) [72]. In the Zr vs. $(Nb/Zr)_N$ diagram, all samples are located in the collision-related area (Figure 11b).

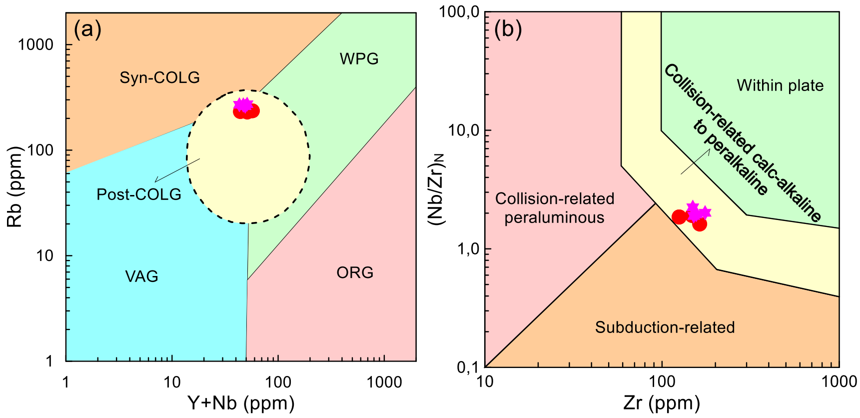


Figure 11. (a) Distributions of Rb vs. (Y+Nb) in the tectono-magmatic diagram [72], (b) Zr vs. $(Nb/Zr)_N$ diagram for the rock samples from the studied plutonic rocks

6. Discussion

The studied plutonic rocks are of high K calc-alkaline character, has low Ni content (9-24 ppm) and relatively low Mg# (33-39) values. All these features indicate that the main magma of the studied rocks is not in equilibrium with the primary mantle composition (Mg# = ~ 66 to 75, Ni = ~ 400 to 500 ppm; [73]).

As seen in the Harker diagrams (Figures 5 and 6), while SiO_2 increases with K_2O and Rb in the samples, whereas the decrease in TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO and P_2O_5 contents indicate fractional crystallization.

The studied plutonic rocks are of calc-alkaline character and do not contain any basic composition in their geochemical data (SiO_2 = 67-75, MgO = 0.5-0.9, Ni = 9-24). They have negative Nb, Ta, P, Sr and Ti anomalies in the primitive-mantle normalized diagrams and are enriched in Rb and K. Medium to high Rb/Sr ratios (1.02-2.28), high SiO_2 (66-75) and K_2O (2.7-3.5) contents indicate that these rocks may derive from metamagmatic, metasedimentary or felsic micaceous crustal source rocks [74].

The average Nb/Ta ratios of the samples are 17.5 for mantle-derived magmas and 11-12 for crust-derived magmas [75]. The Nb/Ta ratios of the samples are between 4 and 6, and these values indicate magmas derived from the crustal rocks. [76] suggested that the Y/Nb ratio can distinguish between granitoids with mantle (Y/Nb $<$ 1.2) and crustal (Y/Nb $>$ 1.2) origins. The Y/Nb ratios of the samples are between 3.6 and 6.8, indicating crustal origin.

In spider diagrams normalized chondrite and primitive mantle, the samples show negative Nb, Ta, Ti and positive Rb, Th, K, Pb anomalies and are enriched with LILE and LREE elements. These features are generally characteristic of crustal rocks. In experimental studies of [77] showed that I-type high-K granitoids can be derived from meta-magmatic rocks with calc-alkaline mafic to intermediate composition in the crust by partial melting in hydrated environments. According to [78], tonalitic and trondjemitic magmas can be formed by the hydrous melting of basalt. These magmas may produce granitic composition rocks (acidic) through fractional crystallization (FC) and/or crustal contamination.

The magmas forming the granitic rocks can generally be formed by partial melting of the lower continental crust as a result of dehydration of metasedimentary and/or metamagmatic rocks [79]. The compositional differences of magmas formed by the partial melting of different source rocks such as metabasalts, metagraywackes, metapelites and amphibolites under variable melting conditions may be visualized by the molar oxide ratios [79]. The studied samples have low molar K_2O/Na_2O, (Na_2O+K_2O) / $(FeO^T+MgO+TiO_2)$, ASI and high $(CaO+FeO^T+MgO+TiO_2)$, Na_2O contents indicates the origin by dehydration melting from mafic lower crustal rocks (e.g. amphibolites) (Figure 12).

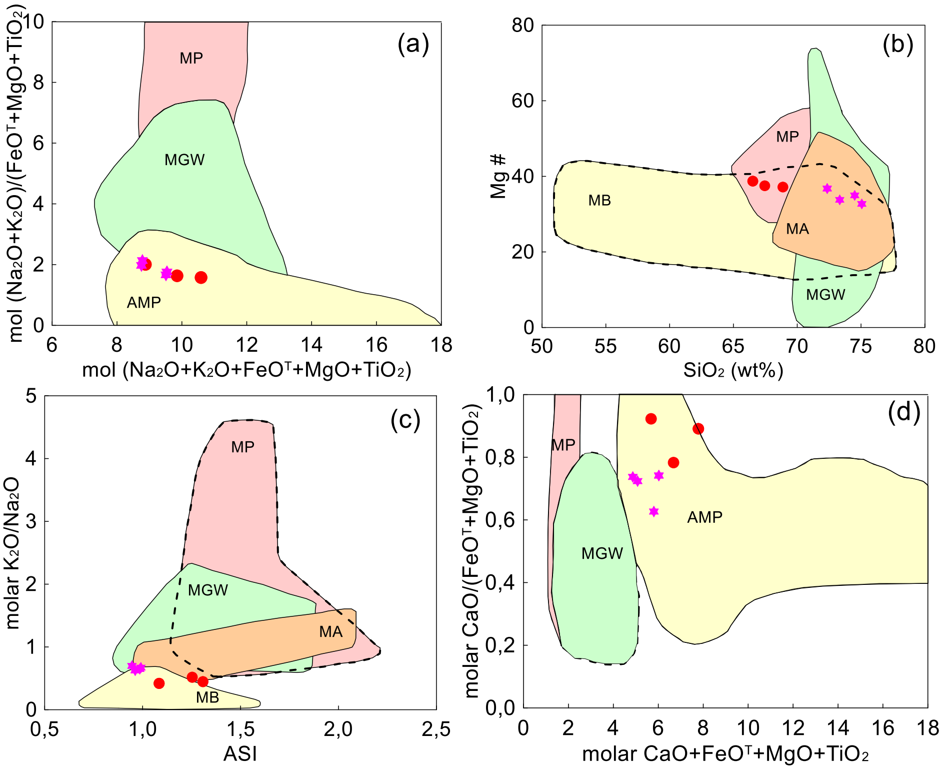


Figure 12. Chemical composition of the studied plutonic rocks. Outlined fields denote compositions of partial melts obtained in experimental studies by dehydration melting of various bulk compositions. MB, metabasalt; MA, metaandesite; MGW, metagrasswack; MP, metapelite; AMP, amphibolite. Data source fields from [79]

7. Conclusions

1. The studied plutonic rocks are granodiorite and granite in composition defining a calc-alkaline series.
2. The samples have peraluminous to metalluminous characters and have high SiO_2 contents (67-75 wt%).
3. All of the samples display similar geochemical features characterized by enrichment in large-ion lithofile elements and light rare earth elements, with pronounced depletion in high-field-strength elements indicating similar sources and petrogenetic processes.
4. The main solidification processes involved in the evolution of the plutonic rocks consist of fractional crystallization.
5. The geochemical composition of the studied plutonic rocks is broadly compatible with an origin by dehydration melting from a metabasaltic (amphibolitic) source rocks.

Acknowledgement

This study was financially supported by Gümüşhane University Scientific Research Projects Unit (GUBAP Project No: 20.F5114.01.01). Zikrullah Samet Güloğlu, Muhammet Emin Ay and Mertcan Yılmaz are thanked for their help during fieldwork. We thank the editor and referees for their contributions during the review and evaluation phase of the manuscript.

References

[1] Karslı, O., Chen, B., Aydın, F., Şen, C. Geochemical and Sr-Nd-Pb isotopic compositions of the Eocene Dölek and Sarıçiçek Plutons, Eastern Turkey: Implications for magma interaction in the genesis of high-K calc-alkaline granitoids in a post-collision extensional setting, Lithos 2007; 98: 67-96.
[2] Kaygusuz, A., Siebel, W., Şen, C., Satır, M. Petrochemistry and petrology of I-type granitoids in an arc setting: The Composite Bayburt Pluton, Eastern Pontides, NE Turkey. International Journal of Earth Sciences 2008; 97: 739-764.
[3] Eyüboğlu, Y. Late Cretaceous high-K volcanism in the eastern Pontides orogenic belt, and its implications for the geodynamic evolution of NE Turkey, Int Geol Rev 2010; 52 (2-3): 142-186.
[4] Topuz, G., Altherr, R., Wolfgang, S., Schwarz, W.H., Zack, T., Hasanözbek, A., Mathias, B,. Satır, M., Şen, C. Carboniferous high-potassium I-type granitoid magmatism in the Eastern Pontides: The Gümüşhane Pluton (NE Turkey). Lithos 2010; 116: 92-110.
[5] Dokuz, A. A slab Detachment and delamination model for the generation of Carboniferous high-potassium i-type magmatism in the Eastern Pontides, NE Turkey: Köse Composite Pluton. Godwana Research 2011; 19: 926-944.
[6] Akaryalı, E., Tüysüz, N., The genesis of the slab window-related Arzular low-sulfidation epithermal gold mineralization (Eastern Pontides, NE Turkey). Geoscience Frontiers 2013; 4-4: 409-421.
[7] Aydınçakır, E. The Petrogenesis of Early Eocene non-adakitic volcanism in NE Turkey: Constraints on the geodynamic implications, Lithos 2014; 208-209: 361-377.
[8] Aslan, Z., Arslan, M., Temizel, İ., Kaygusuz, A. K-Ar dating, whole-rock and Sr-Nd isotope geochemistry of calc-alkaline volcanic rocks around the Gümüşhane area: implications for post-collisional volcanism in the Eastern Pontides, Northeast Turkey. Mineralogy and Petrology 2014; 108: 254-267.
[9] Maden, N., Akaryalı, E. A review for genesis of continental arc magmas: U, Th, K and radiogenic heat production data from the Gümüşhane Pluton in the Eastern Pontides (NE Türkiye). Tectonophysics 2015; 664: 225–243.
[10] Temizel, İ., Arslan, M., Yücel, C., Abdioğlu Yazar, E., Kaygusuz, A., Aslan, Z. U-Pb geochronology, bulk-rock geochemistry and petrology of Late Cretaceous syenitic plutons in the Gölköy (Ordu) area (NE Turkey): Implications for magma generation in a continental arc extension triggered by slab roll-back, Journal of Asian Earth Sciences 2019; 171: 305–320.
[11] Temizel, İ., Arslan, M., Yücel, C., Abdioğlu Yazar, E., Kaygusuz, A., Aslan, Z. Eocene tonalite–granodiorite from the Havza (Samsun) area, northern Turkey: Adakite-like melts of lithospheric mantle and crust generated in a post-collisional setting. International Geology Review 2020; 62 (9): 1131-1158.
[12] Vural, A., Kaygusuz, A. Geochronology, petrogenesis and tectonic importance of Eocene I-type magmatism in the Eastern Pontides, NE Turkey. Arabian Journal of Geosciences 2021; 14: 467. doi.org/10.1007/s12517-021-06884-z.
[13] Çoğulu, E. Gümüşhane ve Rize bölgelerinde petrografik ve jeokronolojik araştırmalar. İTÜ Kütüphanesi 1975; 1034, İstanbul.
[14] Ustaömer, T., Robertson, A.H.F., Ustaömer, P.A., Gerdes, A., Peytcheva, I. Constraints on Variscan and Cimmerian magmatism and metamorphism in the Pontides (Yusufeli–Artvin area), NE Turkey from U–Pb dating and granite geochemistry. In: Robertson, A.H.F., Parlak, O., Ünlügenç, U.C., (eds.), Geological development of Anatolia and the easternmost Mediterranean Region. Geological Society of London Special Publications 2013; 372: 49-74.
[15] Kaygusuz, A., Arslan, M., Wolfgang, S., Sipahi, F., İlbeyli, N. Geochronological evidence and tectonic significance of Carboniferous magmatism in the southwest Trabzon area, Eastern Pontides, Turkey.

International Geology Review 2012; 54 (15): 1776-1800.

[16] Kaygusuz, A., Arslan, M., Sipahi, F., Temizel, İ. U–Pb zircon chronology and petrogenesis of Carboniferous plutons in the northern part of the Eastern Pontides, NE Turkey: Constraints for Paleozoic magmatism and geodynamic evolution. Gondwana Research 2016; 39: 327-346.

[17] Karslı, O., Dokuz, A., Kandemir, R. Subduction-related Late Carboniferous to Early Permian Magmatism in the Eastern Pontides, the Camlik and Casurluk plutons: Insights from geochemistry, whole-rock Sr-Nd and in situ zircon Lu-Hf isotopes, and U-Pb geochronology. Lithos 2016; 266-267: 98-114.

[18] Vural, A., Kaygusuz, A. Petrology of the paleozoic plutons in Eastern pontides: artabel pluton (Gümüşhane, NE Turkey). Journal of Engineering Research and Applied Science 2019; 8 (2): 1216-1228.

[19] Gücer, M.A., Sarı, E. Petrography, geochemistry and petrological characteristics of the Carboniferous Pamuktaş Pluton, Bayburt (NE Turkey). Yerbilimleri 2020; 41 (2): 85-120.

[20] Kaygusuz, A. Geochronological age relationships of Carboniferous Plutons in the Eastern Pontides (NE Turkey). Journal of Engineering Research and Applied Science 2020; 9 (1): 1299-1307.

[21] Dokuz, A., Karslı, O., Chen, B., Uysal, İ. Sources and petrogenesis of Jurassic granitoids in the Yusufeli area, northeastern Turkey: implications for pre- and post-collisional lithospheric thinning of the Eastern Pontides. Tectonophysics 2010; 480: 259-279.

[22] Aydınçakır, E., Gündüz, R., Yücel, C. Emplacement conditions of magma(s) forming Jurassic plutonic rocks in Gümüşhane (Eastern Pontides, Turkey). Bulletin of the Mineral Research and Exploration 2020; 162: 175–196.

[23] Karslı, O., Dokuz, A., Kandemir, R. Zircon Lu-Hf isotope systematics and U–Pb geochronology, whole-rock Sr-Nd isotopes and geochemistry of the early Jurassic Gokcedere pluton, Sakarya Zone-NE Turkey: a magmatic response to roll-back of the Paleo-Tethyan oceanic lithosphere, Contributions to Mineralogy and Petrology 2017; 172/31: 1–27.

[24] Yılmaz, A., Adamia, S., Chabukiani, A., Chkhotua, T., Erdoğan, K., Tuzcu, S., Karabıyıkoğlu, M. Structural correlation of the southern Transcaucasus (Georgia), Eastern Pontides (Turkey): In: Bozkurt, E., Winchester, J.A., Piper, J.D.A., (Eds), Tectonics and Magmatism in Turkey and surrounding area: Geological Society of London, Special Publication 2000; 173: 171–182.

[25] Boztuğ, D., Erçin, A.İ., Kuruçelik, M.K., Göç, D., Kömür, İ., İskenderoğlu, A. Geochemical characteristics of the composite Kaçkar batholith generated in a Neo-Tethyan convergence system, Eastem Pontides, Turkey, Journal of Asian Earth Sciences 2006; 27: 286–302.

[26] Karslı, O., Dokuz, A., Uysal, I., Aydin, F., Bin, C., Kandemir, R., Wijbrans, R.J. Relative contributions of crust and mantle to generation of Campanian high-K calc-alkaline I-type granitoids in a subdution setting, with special reference to the Harşit pluton, Eastern Turkey. Contributions to Mineralogy and Petrology 2010; 160: 467-487.

[27] Kaygusuz, A., Arslan, M., Siebel, W., Sipahi, F., İlbeyli, N., Temizel, İ. LA-ICP MS zircon dating, whole-rock and Sr-Nd-Pb-O isotope geochemistry of the Camiboğazı pluton, Eastern Pontides, NE Turkey: Implications for lithospheric mantle and lower crustal sources in arc-related I-type magmatism, Lithos 2014; 192-195: 271–290.

[28] Sipahi, F., Saydam Eker, Ç., Akpınar, İ., Gücer, M.A., Vural, A., Kaygusuz, A., Aydurmuş, T. Eocene pluton and associated Fe-Cu mineralization in northeastern Turkey: The Karadağ Fe-Cu skarn example, International Geology Review 2021; doi.org/10.1080/00206814.2021.1941323.

[29] Topuz, G., Alther, R., Schwarz, W.H., Siebel, W., Satır, M., Dokuz, A. Post-collisional plutonism with adakite-like signatures: the Eocene Saraycık Granodiorite (Eastern Pontides, Turkey), Contributions to Mineralogy and Petrology 2005; 150: 441–455.

[30] Arslan, M., Aslan, Z. Mineralogy, petrography and whole-rock geochemistry of the Cenozoic granitic intrusions in the Eastern Pontides (Turkey), Journal of Asian Earth Sciences 2006; 27: 177–193.

[31] Kaygusuz, A., Öztürk, M. Geochronology, geochemistry, and petrogenesis of the Eocene Bayburt intrusions, Eastern Pontide, NE Turkey: implications for lithospheric mantle and lower crustal sources in the high-K calc-alkaline magmatism. Journal of Asian Earth Sciences 2015; 108: 97-116.

[32] Kaygusuz, A., Yücel, C., Arslan, M., Sipahi, F., Temizel, İ., Çakmak, G., Güloğlu, Z.S. Petrography, mineral chemistry and

crystallization conditions of Cenozoic plutonic rocks located to the north of Bayburt (Eastern Pontides, Turkey). Bulletin of the Mineral Research and Exploration 2018; 157: 75-102.

[33] Kaygusuz, A., Yücel, C., Arslan, M., Temizel, İ., Yi, K., Jeong, Y-J., Siebel, W., Sipahi, F. Eocene I-type magmatism in the Eastern Pontides, NE Turkey: Insights into magma genesis and magma-tectonic evolution from whole-rock geochemistry, geochronology and isotope systematics. International Geology Review 2020; 62 (11): 1406-1432.

[34] Eyüboğlu Y., Dudas, F.O., Thorkelson, D., Zhu, D.C., Liu, Z., Chatterjee, N., Yi, K., Santosh, M. Eocene Granitoids of Northern Turkey: Polybaric magmatism in an evolving arc-slab window system, Gondwana Research 2017; 50: 311-345.

[35] Güven, İ.H. 1:25000-Scale Geological and Metallogenical Map of the Eastern Black Sea Region (in Turkish); Mineral Research and Exploration Institute of Turkey (MTA) Publications, Ankara, Turkey 1993; 98 pp.

[36] Yılmaz, Y. Petrology and structure of the Gümüşhane Granite and surrounding rocks, north-eastern Anatolia. PhD Thesis 1972; University of London (unpublished).

[37] Okay, A., Şahintürk, Ö. Geology of the eastern Pontides. In: Robinson AG (Ed.) Regional and petroleum geology of the Black Sea and surrounding region: American Association of Petroleum Geologists (AAPG) Memoir 1997; 68: 291–311.

[38] Özsayar, T., Pelin, S., Gedikoğlu, A. Doğu Pontidler'de Kretase, KTÜ Yerbilimleri Dergisi 1981; 2: 65–114.

[39] Topuz, G., Altherr, R., Kalt, A., Satır, M., Wemer, O., Schwarz, W.H. Aluminous granulites from the Pulur complex, NE Turkey: A case of partial melting, efficient melt extraction and crystallization, Lithos 2004; 72: 183-207.

[40] Ağar, U. Demirözü (Bayburt) ve Köse (Kelkit) Bölgesinin Jeolojisi. Doktora Tezi 1977, İstanbul Üniversitesi, İstanbul (unpublished).

[41] Kandemir, R., Yılmaz, C. Lithostratigraphy, facies, and deposition environment of the lower Jurassic Ammonitico Rosso type sediments (Arts) in the Gümüşhane area, NE Turkey: Implications for the opening of the northern branch of the Neo-Tethys Ocean. Journal of Asian Earth Sciences 2009; 34: 586-598.

[42] Saydam Eker, Ç., Sipahi, F., Kaygusuz, A. Trace and rare earth elements as indicators of provenance and depositional environments of Lias cherts in Gumushane, NE Turkey. Chemie der Erde Geochemistry 2012; 72: 167-177.

[43] Gücer, M.A., Arslan, M., Sherlock, S., Larry M. Heaman. Permo-Carboniferous granitoids with Jurassic high temperature metamorphism in Central Pontides, Northern Turkey. Miner Petrol 2016; 110: 943–964.

[44] Eyuboğlu, Y., Dudás, F.Ö., Santosh, M., Zhu, D.C., Yi, K., Chatterjee, N., Jeong, Y.J., Akaryalı, E., Liu, Z. Cenozoic forearc gabbros from the northern zone of the Eastern Pontides Orogenic Belt, NE Turkey: implications for slab window magmatism and convergent margin tectonics. Gondwana Research 2016; 33: 160-189.

[45] Pelin, S. Geological study of the area southeast of Alucra (Giresun) with special reference to its petroleum potential. Karadeniz Teknik Üniversitesi Yayın No. 87, Trabzon 1977; 103 pp.

[46] Aydınçakır, E. Subduction-related Late Cretaceous high-K volcanism in the Central Pontides orogenic belt: Constraints on geodynamic implications. Geodinamica Acta 2016; 28 (4): 379-411.

[47] Temizel, İ., Abdioğlu Yazar, E., Arslan, M., Kaygusuz, A., Aslan, Z. Mineral chemistry, whole-rock geochemistry and petrology of Eocene I-type Shoshonitic plutons in the Gölköy area (Ordu, NE Turkey), Bulletin of the Mineral Research and Exploration 2018; 157: 121-152.

[48] Kaygusuz, A., Arslan, M., Temizel, İ., Yücel, C., Aydınçakır, E. U–Pb zircon ages and petrogenesis of the Late Cretaceous I-type granitoids in arc setting, Eastern Pontides, NE Turkey, Journal of African Earth Sciences 2021; 174: 104040. doi.org/10.1016/j.jafrearsci.2020.104040.

[49] Aydın, F., Saka, S.O., Şen, C., Dokuz, A., Aiglsperger, T., Uysal, İ., Kandemir, R., Karslı, O., Sarı, B., Başer, R., Temporal, geochemical and geodynamic evolution of the Late Cretaceous subduction zone volcanism in the eastern Sakarya Zone, NE Turkey: implications for mantle-crust interaction in an arc setting, Journal of Asian Earth Sciences 2020; 192, 104217. https://doi.org/10.1016/j.jseaes.2019.104217.

[50] Tokel, S. Doğu Karadeniz Bölgesi'nde Eosen yaşlı kalk-alkalen andezit1er ve jeotektonizma, TJK Bülteni 1977; 20/1: 49-54.

[51] Aydın, F., Karslı, O., Chen, B. Petrogenesis of the Neogene alkaline volcanics with implcations for post collisional lithospheric

thinning of the Eastern Pontides, NE Turkey: Lithos 2008; 104: 249–266.
[52] Topuz, G., Okay, AI., Altherr, R., Schwarz, WH., Siebel, W., Zack, T., Satır, M., Şen, C. Post-collisional adakite-like magmatism in the Ağvanis Massif and implications for the evolution of the Eocene magmatism in the Eastern Pontides (NE Turkey). Lithos 2011; 125: 131–150.
[53] Eyuboğlu, Y., Dudas, F.O., Santosh, M., Yi, K., Kwon, S., Akaryalı, E. Petrogenesis and U-Pb zircon chronology of adakitic porphyries within the Kop ultramafic massif (Eastern Pontides Orogenic Belt, NE Turkey). Gondwana Research 2013; 24 (2): 742-766.
[54] Arslan, M., Temizel, İ., Abdioğlu, E., Kolaylı, H., Yücel, C., Boztuğ, D., Şen, C. 40Ar-39Ar dating, whole-rock and Sr-Nd-Pb isotope geochemistry of post-collisional Eocene volcanic rocks in the southern part of the Eastern Pontides (NE Turkey): Implications for magma evolution in extension-induced origin, Contributions to Mineralogy and Petrology 2013; 166: 113–142.
[55] Kaygusuz, A., Şahin, K. Petrographical, geochemical and petrological characteristics of Eocene volcanic rocks in the Mescitli area, Eastern Pontides (NE Turkey), Journal of Engineering Research and Applied Science 2016; 5 (2): 473-486.
[56] Kaygusuz, A., Arslan, M., Wolfgang, S., Şen, C. Geochemical and Sr–Nd isotopic characteristics of post-collisional calc-alkaline volcanics in the eastern Pontides (NE Turkey). Turkish Journal of Earth Sciences 2011; 20: 137-159.
[57] Kaygusuz, A., Merdan Tutar, Z., Yücel, C. Mineral chemistry, crystallization conditions and petrography of Cenozoic volcanic rocks in the Bahçecik (Torul/Gümüşhane) area, Eastern Pontides (NE Turkey). Journal of Engineering Research and Applied Science 2017; 6 (2): 641-651.
[58] Kaygusuz, A., Gücer, M.A., Yücel, C., Aydınçakır, E., Sipahi, F. Petrography and crystallization conditions of Middle Eocene volcanic rocks in the Aydıntepe-Yazyurdu (Bayburt) area, Eastern Pontides (NE Turkey). Journal of Engineering Research and Applied Science 2019; 8 (2): 1205-1215.
[59] Yücel, C., Arslan, M., Temizel, İ., Yazar, E.A., Ruffet, G. Evolution of K-rich magmas derived from a net veined lithospheric mantle in an ongoing extensional setting: Geochronology and geochemistry of Eocene and Miocene volcanic rocks from Eastern Pontides (Turkey): Gondwana Research 2017; 45: 65–86.
[60] Yücel, C. Geochronology, geochemistry, and petrology of adakitic Pliocene–Quaternary volcanism in the Şebinkarahisar (Giresun) area, NE Turkey. International Geology Review 2019; 61 (6): 754-777.
[61] Kaygusuz, A., Selvi, D. Crystallization conditions and petrography of eocene volcanic rocks in the Gümüşdamla-Erikdibi area (Bayburt, NE Turkey). Journal of Engineering Research and Applied Science 2020; 9 (2): 1529-1537.
[62] Çakmak, G., Kaygusuz, A. Petrography and crystallization conditions of the Pelitli Pluton in the Bayburt area, Eastern Pontides (NE Turkey). Journal of Engineering Research and Applied Science 2021; 10 (1):1658-1669.
[63] Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R., Zanettin, B.A Classification of ıgneous rocks and glossary of terms, Blackwell, 1989; Oxford.
[64] Pearce, J.A. Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe, R.S. (eds) Andesites. Orogenic andesites and related rocks, John Wiley and Sons 1982; 525-548.
[65] Irvine, T.N., Baragar, W.R.A. A guide to the chemical c1assification of common volcanic rocks, Canadian Journal of Earth Sciences 1971; 8: 523-548.
[66] Peccerillo, R., Taylor, S.R. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology 1976; 58: 63–81.
[67] Sun, S., McDonough, W.F. Chemical and ısotopic systematics of oceanic basalt: Implications for mantle composition and processes, In: A. D. Saunders, ve M.J. Norry, (eds.), Magmatism in the Ocean Basins, Geological Society of London, Special Publication 1989; 42: 313-345.
[68] Taylor, S.R., McLennan, S.M. The continental crust, its composition and evolution. Blackwell, Oxford 1985; 312 pp.
[69] Chappell, B.W., White, A.J.R. Two contrasting granite types. Pac. Geol 1974; 8: 173–174.
[70] Whalen, J.B., Currie, K.L., Chappell, B.W. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contribution to Mineralogy Petrology 1987; 95: 407–419.
[71] Batchelor, B., Bowden, P. Petrogenetic

interpretation of granitoid rock series using multicationic parameters: Chemical Geology 1985; 48: 43–55.
[72] Pearce, J.A., Harris, N.B.W., Tindle, A.G. Trace element discrimination diagram for the tectonic interpretation of granitic rocks. J. Petrol 1984; 25: 956–983.
[73] Frey, F.A., Green, D.H., Roy, S.D. Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from South Eastern Australia utilizing geochemical and experimental petrological data. J Petrol 1978; 19: 463-513.
[74] Jung, S., Masberg, P., Mihm, D., and Hoernes, S. Partial melting of diverse crustal sources - constraints from Sr-Nd-O isotope compositions of quartz diorite-granodiorite-leucogranite associations (Kaoko Belt, Namibia): Lithos 2009; 111: 236–251.
[75] Green, T.H. Significance of Nb/Ta as an indicator of geochemical processes in the crust–mantle system: Chemical Geology 1995; 120: 347–359.
[76] Eby, G.N. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. Geology 1992; 20: 641–644.
[77] Roberts, M.P., Clemens, J.D. Origin of high-potassium, calc-alkaline, I-type granitoids. Geology 1993; 21: 825–828
[78] Wyllie, P.J. Constraints imposed by experimental petrology on possible and impossible magma sources and products. Transactions of the Royal Society of London 1984; A310: 439–456.
[79] Patiño Douce, A.E. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas? In: Castro A, Fernandez C, Vigneresse JL (eds) Understanding granites: intergrating new and classical techniques. Geol Soc London, Spec Pub 1999; 168: 55–75.
..