Bull. Min. Res. Exp. (2018) 157: 75-102

Bulletin of the Mineral Research and Exploration

http://bulletin.mta.gov.tr

Petrography, mineral chemistry and crystallizatıon conditions of cenozoic plutonic rocks located to the north of Bayburt (Eastern Pontides, Turkey)

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Research Article

Keywords:
Mineral chemistry, geothermobarometer, Cenozoic plutonic rocks, eastern Pontides, Bayburt, Turkey.

Received Date: 18.06.2017
Accepted Date: 09.04.2018

ABSTRACT

The Eastern Pontides comprise many intrusive bodies varying in composition, size and age from Palaeozoic to Cenozoic. Especially Cenozoic aged bodies are commonly observed in the southern part, while they are rarely exposed in the northern part of the Eastern Pontides. In this study, the petrography and mineral chemistry of the Cenozoic aged Çiçekli, Somarova, Sorkunlu, Şaşurluk, Aydıntepe, Kemerlikdağı and Pelitli plutons located to the north of Bayburt are determined, and the crystallisation conditions of the studied bodies were estimated by means of thermobarometer calculations. The studied plutons extend mostly in NE-SW directions and are approximately ellipsoid in shape. The contacts between the plutons and surrounding rocks are sharp, and plutons commonly contain mafic microgranular enclaves (MMEs) of different sizes. Petrographic and mineral chemistry studies reveal some disequilibrium textures reflecting the magma mixing process. Based on modal mineralogy, the plutonic rocks are gabbroic diorite, diorite, tonalite, granodiorite and monzogranite in composition. The rocks have fine to medium granular, porphyric, monzonitic, poikilitic, occasionally myrmekitic and micrographic textures. The main minerals are labradorite and albite (An_{68-02}), magnesiohornblende and actinolite (Mg# = 0.6-0.9), diopside and augite (Wo_{44-46}), clinoenstatite (En_{53-57}) and Fe-Ti oxide minerals. Crystallization temperatures calculated from amphibole, biotite, clinopyroxene, magnetite and ilmenite minerals are 405°C to 1161°C, pressure values are 0.1 to 2.7 kbar, and oxygen fugacity (log10 fO_2) is -20 to -12. Estimation of water content calculated by using amphiboles is between 2.9 and 6.8%. Based on obtained data, it is suggested that the studied plutons were emplaced at shallow depths (~ 1-8 km).

1. Introduction

The Eastern Pontides (NE Turkey), located within the Alpine-Himalayan orogenic belt, are a significant area where volcanic and plutonic rocks are commonly observed (Arslan et al., 2000, 2013; Kaygusuz et al., 2006; Kaygusuz, 2009; Saydam Eker et al., 2012; Aslan et al., 2014; Sipahi et al., 2014; Aydınçakır, 2014; Alemdağ, 2015; Temizel et al., 2012, 2016; Kaygusuz and Şahin, 2016; Özdamar, 2016; Yücel et al., 2014, 2017). There are numerous various sized plutons in the region with a broad age range varying from Permo-Carboniferous to Eocene in the region and types varying from mainly gabbro to granite (Figure 1). These plutons intruded mainly at three different time period including Paleozoic, Cretaceous and Eocene. Of these Palaeozoic-aged plutons intruded

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http://dx.doi.org/10.19111/bulletinofmre.427829

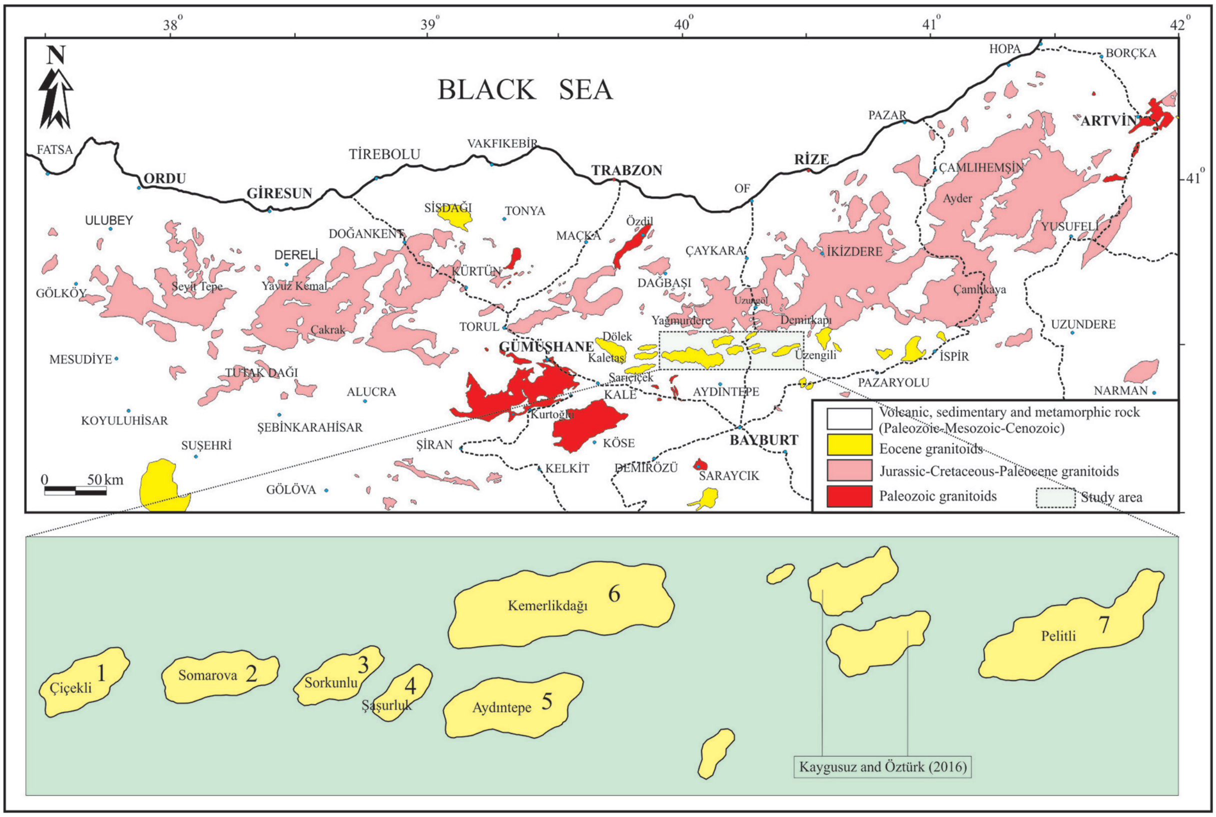

Figure 1- Geologic map showing distribution of Cenozoic-aged plutons in the Eastern Pontides and investigated plutons (1: Çiçekli, 2: Somarova, 3: Sorkunlu, 4: Şaşurluk, 5: Aydıntepe, 6: Kemerlikdağı, 7: Pelitli) (based on 1/500,000 scale MTA map).

into the metamorphic rocks (Yılmaz, 1972; Çoğulu, 1975; Topuz et al., 2010; Dokuz, 2011; Kaygusuz et al., 2016; Karslı et al., 2017), Cretaceous plutons intruded into the subduction-related volcanic and/or volcanoclastic rocks (Köprübaşı et al., 2000; Şahin et al., 2004; Boztuğ et al., 2006; İlbeyli, 2008; Kaygusuz et al., 2010, 2013; Karslı et al., 2010; Kaygusuz and Aydınçakır, 2011; Kaygusuz and Şen, 2011; Sipahi et al., 2017), and Eocene and later plutons are intruded in a narrow area cutting all former series (Yılmaz and Boztuğ, 1996; Aslan et al., 1999; Topuz et al., 2005; Arslan and Aslan, 2006; Karslı et al., 2007; Kaygusuz and Öztürk, 2015; Eyüboğlu et al., 2013, 2017; Özdamar et al., 2017).

There are limited studies about Eocene-aged plutons in the Eastern Pontides (Figure 1), where the age of many plutons relatively identified according to contact relations and stratigraphic relationships. The age of the Saraycık Pluton situated south of the study area was determined as 66 Ma (Rb-Sr, Aslan, 1998) and 52 Ma (Ar-Ar, Topuz et al., 2005); in the west of the study area, the age of the Kaletaş Pluton is 44 Ma (U-Pb, Arslan and Aslan, 2006), the age of the Dölek Pluton is 44 Ma (U-Pb, Arslan and Aslan, 2006), with ages of the Dölek and Sarıçiçek plutons 42-43 Ma (K-Ar, Karslı et al., 2007) and the age of the Sarıçiçek Pluton is 44 Ma (U-Pb, Eyuboğlu et al., 2017).

The Eocene-aged intrusive rocks located within the area of the studied plutons were named the Rize Pluton by Keskin et al. (1989) and Önenç et al. (2005). Çakmak and Kaygusuz (2014), reported the age of the Pelitli Pluton as 46 Ma (U-Pb). Kaygusuz and Öztürk (2015) reported the age of the Kılıçkaya and Kozluk Plutons located in the study area as 46 Ma (U-Pb). Eyuboğlu et al. (2017) reported the age of the Sorkunlu Pluton as 44 Ma (U-Pb), the age of the Üzengili Pluton as 45 Ma (U-Pb) and the age of the Kozluk Pluton as 44 Ma (U-Pb).

The aim of this study is to determine the petrographic and mineral chemistry features of the Cenozoic-aged plutonic rocks outcropped north of Bayburt, and to determine thermobarometer conditions (pressure (P) – temperature (T)) during the crystallisation of the pluton with mineral chemistry data and to contribute to the literature about emplacement conditions.

2. Geological Setting and Field Characteristics of Plutons

The basement of the study area, located south of the Eastern Pontides and dominated by generally sedimentary, volcanic and plutonic rocks, is formed by conglomerates, marl, shale, sandstone, siltstone, tuff, tuffite, and red-coloured fossiliferous limestones along with acidic-basic lava, dykes and sills of the Liassic-aged Hamurkesen formation (Ağar, 1977). The Hozbirikyayla formation, comprising Dogger-Malm-Lower Cretaceous-aged oolitic limestone, dolomitic limestones, sandy limestone, limestone with sandstone-siltstone interlayers, carbonates with chert bands and nodules, conformably overlies this formation (Ağar, 1977). The Upper Cretaceous-aged Çatıksu formation, comprising sandstone, pelagic limestone, mudstone and claystone alternations overlies the Hozbirikyayla formation with an angular unconformity (Keskin et al., 1989). The Arduç Volcanic rocks comprising Upper Cretaceous andesite and basalt lavas, andesitic-basaltic agglomerates, tuff and tuffite (Keskin et al., 1989) lies above the Çatıksu formation. The Eocene-aged Sırataşlar formation comprising nummulitic limestone, sandstone, occasional marl and sandy limestone, unconformably overlies the Arduç Volcanic rocks (Ağar, 1977). The Ypresian-Lutetian-aged andesite-basalt lavas, andesitic-basaltic agglomerates and tuff alternations of the Yazyurdu formation (Keskin et al., 1989) unconformably overlie the Sırataşlar formation. The Cenozoic-aged plutonic rocks cut the Yazyurdu formation (Figure 3) and the youngest unit in the study area is Quaternary-aged alluvium (Figure 2).

The long axes of the studied plutons extend in the northeast-southwest direction and are generally ellipse in shapes (Figure 2). Çiçekli and Somarova plutons contain small sized (0.5-2 cm) and minor amount of mafic microgranular enclaves; whereas Sorkunlu, Şaşurluk, Aydıntepe, Kemerlikdağı and Pelitli plutons contain large amounts of angular, partially rounded mafic magmatic enclaves ranging in size from 1 to 10 cm. The enclaves are finer grained and darker than the host rock.

The Çiçekli Pluton outcrops over an area of about 6 km^2, with 3-4 km length and 1-2 km width. The pluton intruded into the Eocene-aged Yazyurdu formation at northern boundary, while intruded into the Upper Cretaceous-aged Arduç Volcanic rocks at the east-west and southern boundaries (Figure 2 and 3a). At contacts with the wall rocks, volcanic rocks have been transformed to metavolcanics, while at contacts with sedimentary rocks, limestone has been transformed into crystallised limestone and occasionally marble. The Somarova Pluton, which extends an area of about 8 km^2 (4-5 km in length, 2-3 km in width), cuts the Eocene-aged Yazyurdu formation at north- northwest boundary, and cuts the Upper Cretaceous-aged Arduç Volcanic rocks at the south-southeast boundary (Figure 2 and 3b). The Sorkunlu Pluton is of the same size as the Çiçekli Pluton, with length of 3-4 km and width of 1-2 km (about 6 km^2). The pluton cuts the Eocene-aged Yazyurdu formation at the northern boundary, cuts the Upper Cretaceous-aged Arduç Volcanic rocks at the east-west boundary, and cuts the Liassic-aged Hamurkesen formation at the southern boundary (Figure 2 and 3c).

The Şaşurluk Pluton has the smallest size of these intrusive rocks, and outcrops about 3 km^2 area (2-3 km long, 1-2 km wide). The pluton cuts Eocene-aged Yazyurdu formation at its northern boundary, cuts

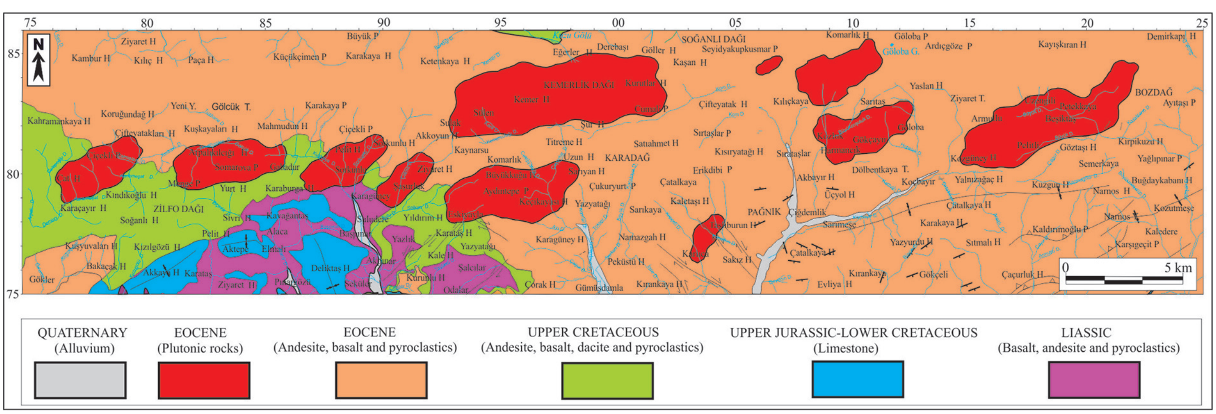

Figure 2- Geologic map showing plutonic and surrounding rocks (adapted from Keskin et al., 1989).

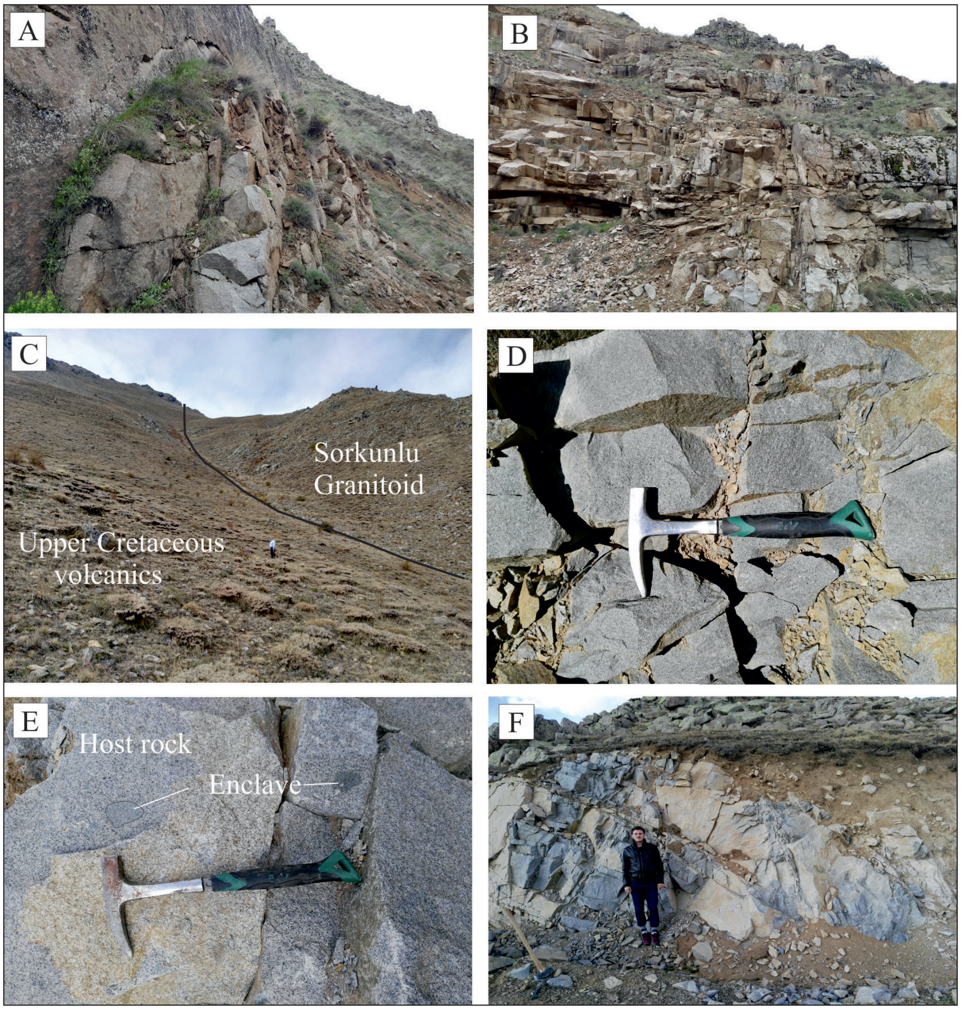

Figure 3- Field photograps of the studied plutonic rocks (a) Çiçekli, (b) Somarova, (c) Sorkunlu, (d) Aydıntepe, (e) Kemerlikdağı, (f) Pelitli.

Upper Cretaceous Arduç Volcanics at its east-west boundaries and cuts the Liassic-aged Hamurkesen formation at its southern boundary. The Aydıntepe Pluton outcrops over an area of about 12 km^2 with 5-6 km length and 2-3 km width. The pluton cuts the Eocene-aged Yazyurdu formation at the north-east and west edges, while cuts the Upper Cretaceous-aged Arduç Volcanic rocks at the south edge (Figure 2 and 3d). The Kemerlikdağı Pluton has the largest outcrop in the study area (nearly 22 km^2) with 7-8 km length and 2-3 km width. The pluton cuts the Eocene-aged Yazyurdu formation where the metavolcanics developed along contacts with volcanic wall rocks. The Pelitli Pluton outcropping over nearly 16 km^2 area, the length is 5-6 km with width of 3-4 km. The pluton cuts the the Eocene aged Yazyurdu formation with metavolcanics developed along the contacts (Figure 2 and 3f).

3. Analytical Methods

Under the scope of this study, thin sections were prepared from 450 rock samples obtained in the field and detailed petrographic characteristics were determined with a polarising microscope and modal analyses of 162 samples were performed. For modal analyses, in samples with grain size 0.5-0.8 mm 1000-1300 points were counted, and for samples with grain size 1.0-1.5 mm, 1300-1700 points were counted. Counted samples had counts calculated with the count error formulae and 8 samples had counts repeated.

Microprobe analyses performed on twenty samples from the studied intrusives at the Geology and Mineral Research Laboratory of the New Mexico Institute of Mining and Technology (USA). Microprobe analyses were performed on plagioclase, K-feldspar, biotite, amphibole, pyroxene and Fe-Ti oxide minerals using a CAMECA-SX 100 brand microprobe-3 wavelength dispersive (WD) spectrometry device. The working conditions of the device were 15 kV voltage and 20 nA. Analyses were completed with a 10 µm laser diameter and the count time was fixed at 10 s for Si, Al, Ti, Fe, Mn, Mg, Ca, Na and K elements. Point laser of 1 µm was chosen for amphibole and pyroxene analyses. Considering sodium evaporation in feldspar and plagioclase analyses, very slightly defocused light (10 µm) was used to prevent or reduce losses to a minimum. During measurements, caersuitite (UCB), diopside (UCB), orthoclase (UCB), albite (UCB), anorthite (UCB), biotite and magnetite (UCB) standards were used.

4. Results

4.1. Petrography of Plutons

The general petrographic characteristics of the studied plutonic rocks are given in table 1, QAP diagrams based on modal analysis shown in figure 4. The zoning map prepared based on modal composition of rocks forming the plutons is shown in figure 5.

The modal analysis results of the samples from the Çiçekli Pluton show monzogranite, granodiorite and tonalite composition in the QAP diagram (Streickeisen, 1976) (Figure 4). Monzogranites are located in zones close to the centre of the pluton, while tonalite and granodiorite are located in the margin zones. Monzogranites cut granodiorite and tonalites, with less distribution (Figure 5a). The rocks of the Somarova Pluton are granodiorite, tonalite and diorite in composition (Figure 4). The granodiorites are mainly in the central zone, with diorites located around the edges. The granodiorites

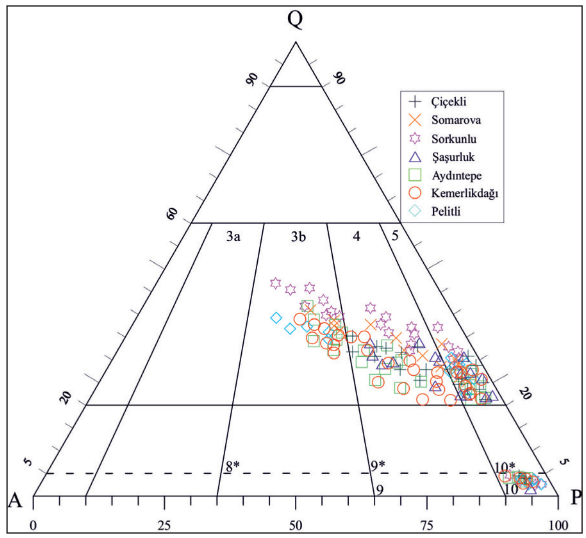

Figure 4- Location of rock samples from the plutons on QAP diagram (Streckeisen, 1976).

Table 1- General petrographic characteristics of studied plutonic rocks.

Pluton	Çiçekli (n=15)	Somarova (n=22)	Sorkunlu (n=19)	Şaşurluk (n=16)	Aydıntepe (n=34)	Kemerlikdağı (n=29)	Pelitli (n=27)
Rock unit	mg, gd, to	gd, to, di	gd, to, di, gbrdi	mg, to, di	mg, gd, to, di, gbrdi	mg, gd, to, di, gbrdi	mg, gd, to, di
Texture	granular, porphyric, monzonitic, poikilitic, myrmekitic	granular, porphyric, poikilitic, myrmekitic	granular, porphyric, poikilitic, myrmekitic, micrographic	granular, porphyric, monzonitic, poikilitic, myrmekitic, micrographic	granular, porphyric, monzonitic, poikilitic, myrmekitic, micrographic, graphic	granular, porphyric,, monzonitic, poikilitic, myrmekitic, micrographic, graphic	granular, porphyric, monzonitic, poikilitic, myrmekitic, micrographic
Grain size	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric	fine-moderate, occasionally porphyric
Modal min (%)	min-max (mean)	min-max (mean)	min-max (mean)	min-max (mean)	min-max (mean)	min-max (mean)	min-max (mean)
Plagioclase	29-59 (46)	38-81 (57)	41-79 (55)	25-81 (53)	30-79 (53)	29-80 (52)	23-80 (51)
Quartz	21-37 (28)	3-31 (22)	1-29 (19)	2-37 (20)	2-37 (22)	3-38 (21)	2-46 (29)
Ortoclase	4-24 (11)	1-22 (9)	1-18 (7)	2-32 (11)	1-28 (13)	2-26 (12)	2-30 (12)
Amphibole	1-8 (3)	2-14 (7)	3-17 (9)	1-14 (7)	2-16 (7)	1-14 (8)	0-9 (4)
Biotite	4-10 (7)	1-5 (3)	1-10 (5)	1-9 (5)	1-10 (4)	1-10 (4)	0-5 (2)
Pyroxene	3-5 (4)	4 (4)	2-10 (5)	1-4 (3)	1-5 (3)	2-3 (3)	2-4 (3)
Opaque minerals	1-5 (2)	1-4 (2)	1-4 (2)	2-6 (3)	1-4 (2)	1-4 (3)	0-4 (2)
Accessory Minerals	apatite, zircon	apatite, zircon, sphene	apatite, zircon, sphene	apatite, zircon, sphene	apatite, zircon, sphene, allanite	apatite, zircon, sphene, allanite	apatite, zircon, sphene
Secondary Minerals	Sericite, chlorite, epidote, calcite, clay minerals	Sericite, chlorite calcite, clay minerals	Sericite, chlorite clay minerals	Sericite, chlorite clay minerals	Sericite, chlorite calcite, clay minerals	Sericite, chlorite calcite, clay minerals	Sericite, chlorite calcite, clay minerals
mg: monzogranite, gd: granodiorite, to: tonalite, di: diorite, gbrdi: gabbrodiorite, n: number of samples							

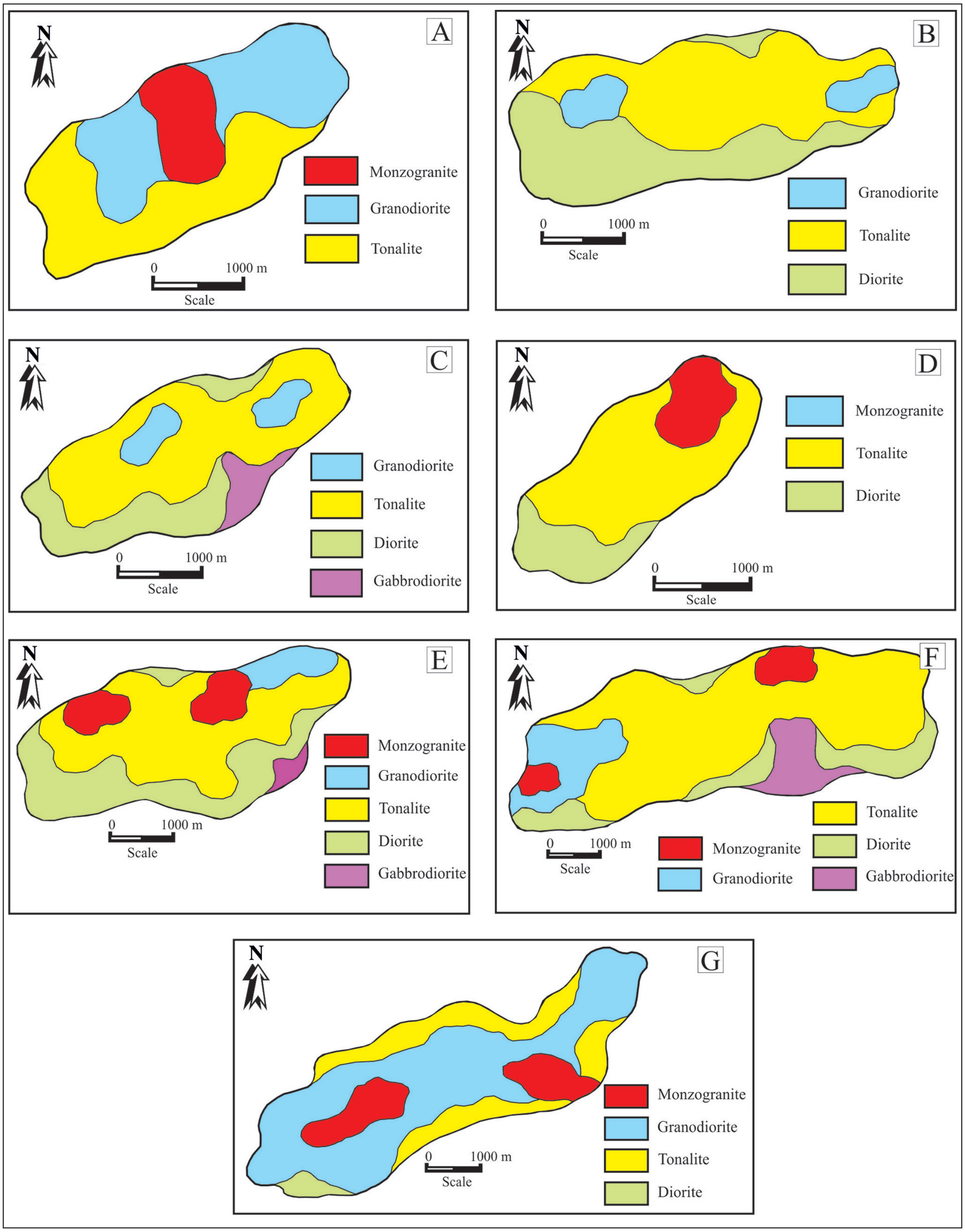

Figure 5- Maps showing locations of rocks forming the plutons a) Çiçekli, b) Somarova, c) Sorkunlu, d) Şaşurluk, e) Aydıntepe, f) Kemerlikdağı, g) Pelitli.

have less distribution (Figure 5b). The rocks of the Sorkunlu Pluton are modally granodiorite, tonalite, diorite and gabbrodiorite in composition (Figure 4). The granodiorites are generally in central sections, while gabbro diorite and diorites are located in the edge sections. The distribution of gabbro diorite and granodiorites are less (Figure 5c). The Şaşurluk Pluton is modally composed of monzogranite, tonalite and diorite (Figure 4). The monzogranites are generally in central sections with diorites around the edges. Tonalites have highest distribution of all rocks within the pluton (Figure 5d). The Aydıntepe Pluton comprises monzogranite, granodiorite, tonalite, diorite and gabbro diorite composition rocks (Figure 4). Monzogranites concentrate close to the centre of the pluton with diorite and gabbro diorites around the edges and in a surrounding zone (Figure 5e). Tonalites are the most common rock in the pluton. Samples from the Kemerlikdağı Pluton modally comprise monzogranite, granodiorite, tonalite, diorite and gabbro diorite composition rocks (Figure 4). The monzogranites are located in areas close to the centre of the pluton with diorite and gabbro diorites located near the edges (Figure 5f). Tonalites have highest distribution in the pluton. The Pelitli Pluton comprises monzogranite, granodiorite, tonalite and diorite (Figure 4). Monzogranites are located close to the centre of the pluton while diorites and tonalites are located near the edges (Figure 5g). Diorites have the lowest distribution with tonalites having the highest distribution.

Microscopic studies of plutons show fine-medium granular, porphyric, monzonitic, poikilitic, occasionally myrmekitic, micrographic and graphic textures (Figure 6a-f). In samples with monzonitic textures, euhedral and subhedral large and small plagioclase crystals were found surrounded by anhedral orthoclase crystals. Granular, monzonitic and poikilitic textures were commonly observed. Porphyric texture was rarely observed.

The main minerals comprise plagioclase, quartz, K-feldspar, biotite, amphibole, pyroxene and opaque minerals. Apatite, zircon and sphene comprise accessory minerals. Secondary mineral phases include sericite, calcite, chlorite, epidote and clay minerals.

Plagioclases form euhedral and subhedral laminated prismatic crystals and are seen in all samples. Sizes are from 0.2 to 2.5 mm. Large plagioclase crystals contain small amphibole and opaque mineral inclusions. In terms of importance, they show albite and albite-carlsbad twins. Zoned crystals generally have oscillatory zoning, with occasional sieve texture (Figure 6a). In some of the large crystals, the margins have been lost and replaced by other plagioclase crystals with different appearance, twinning and zoning. In some samples there are myrmekites similar to small bullets with potassium feldspar around the margins. Some plagioclases are less fractured and partially sericitised. The overall ratio within the studied intrusives is 23-81% with the highest proportion in the Somarova Pluton (mean 57%) and the lowest in the Çiçekli Pluton (mean 46%) (Table 1).

K-feldispar is generally anhedral with sizes both large (2.5-3 mm) and small crystals (Figure 6b). Generally fibrous perthitic texture is observed and, in some sections, carlsbad twins were clear. In those with poikilitic texture, small plagioclase, biotite and opaque mineral inclusions are present (Figure 6c-d). In some sections, myrmekites are observed at boundaries with plagioclase. Some are fractured and partly argillised. The ratio of the feldspar within the studied intrusive rocks is 1-32%, with the highest rates in the Aydıntepe Pluton (mean 13%) and the lowest rates in the Sorkunlu Pluton (mean 7%) (Table 1).

Quartz comprises large and small anhedral crystals, filling in the gaps between other minerals. On some sections wavy extinction is observed. Generally, they have fractured and broken structures. They comprise 1-46% of the studied intrusive rocks, with the highest rates in Pelitili Pluton (mean 29%) and the lowest rates in the Sorkunlu Pluton (mean 19%) (Table 1). Amphiboles are euhedral and subhedral large laminated and small crystals. They comprise 0-17% of the studied intrusive rocks, with highest rates in the Sorkunlu Pluton (mean 9%) and lowest rates in the Çiçekli Pluton (mean 3%) (Table 1).

Biotite appears as euhedral and subhedral rod-like prismatic crystals. Poikilitic texture minerals contain smaller plagioclase and opaque minerals (Figure 6e). In some sections, they observed to be partially altered and transformed to chlorite. The iron, released due to alteration, forms opaque oxide clusters along cleavages. In the studied granitoid rocks, they comprise 0-10%, with highest rates in the Çiçekli Pluton (mean 7%) and lowest rates in the Pelitli Pluton (mean 2%) (Table 1).

Pyroxenes are subhedral and anhedral laminated crystals. They are found in some sections and occasionally. In some sections they have been altered to chlorite and calcite. They comprise 1-10% of the granitoid rocks, with highest rates in the Sorkunlu Pluton (mean 5%) (Table 1).

Apatites are generally needle-like and found as inclusions in quartz and feldspar (Figure 6g). Zircon is observed in nearly all rocks as small euhedral prismatic crystals (Figure 6g). Opaque minerals are found as euhedral and subhedral both large and small

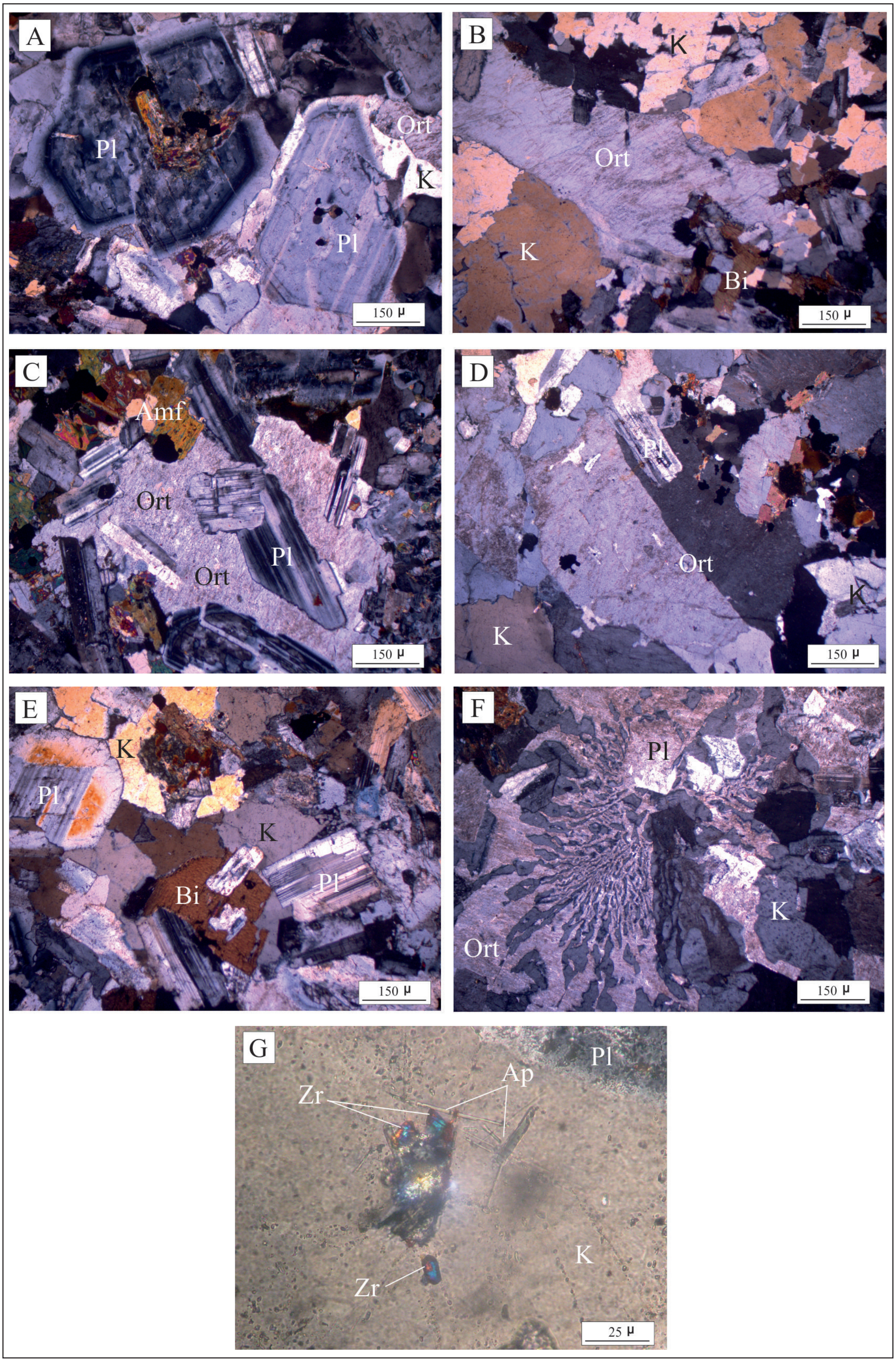

Figure 6- Microscopic characteristics of rocks from the plutons (a) zoned plagioclase minerals, (b) granular texture and large orthoclase minerals, (c-d) poikilitic orthoclase, (e) poikilitic biotite (f) micrographic texture (crossed polars, Pl: plagioclase, K: quartz, Ort: orthoclase, Bi: biotite, Amf: amphibole, Zr: zircon, Ap: apatite).

crystals. Generally, they are observed more densely in sections containing biotite and amphibole crystals. They are found at rates of 0-6% of the granitoid rocks studied (Table 1).

4.2. Mineral Chemistry of Plutons

4.2.1. Plagioclase

The minimum, maximum and mean values for plagioclase minerals found in the plutons according to microprobe analysis are given in table 2.

The An content of plagioclase in the pluton is varying from 68 to 02 (Table 2) with these values varying from An_{68-19} in the Çiçekli Pluton; An_{57-13} in the Somarova Pluton; An_{66-13} in the Sorkunlu Pluton: An_{63-03} in the Şaşurluk Pluton; An_{59-13} in the Aydıntepe Pluton; An_{64-04} in the Kemerlikdağı Pluton and An_{60-02} in the Pelitli Pluton (Table 2; Figure 7). The plagioclase of the Kemerlikdağı Pluton has the lowest An content (mean 32), while the Çiçekli Pluton has the highest An content (mean 44) (Table 2; Figure 7).

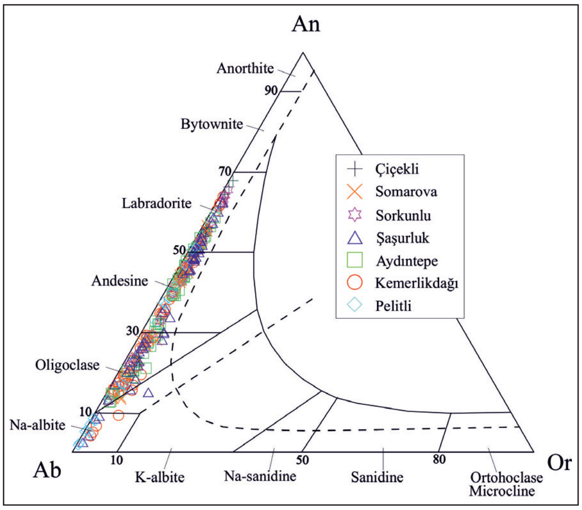

Figure 7- An-Ab-Or ternary diagram (Smith and Brown, 1988) showing plagioclase composition of studied plutons (Symbols as in figure 4).

Occasional oscillatory zoning is observed in plagioclase, with the An content of zoned crystals observed to be variable (Figure 8).

Table 2- Minimum, maximum and mean values for microprobe analyses of plagioclase.

Pluton	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	BaO	SrO	Total	Si	Al	Fe(ii)	Ca	Na	K	Ba	Sr	An	Ab	Or
Kemerlikdağı (n=57)																				
min	51.22	20.14	0.03	0.92	4.10	0.13	0.00	0.01	98.98	2.34	1.03	0.00	0.04	0.36	0.01	0.00	0.00	4.05	35.37	0.74
max	67.63	30.40	0.80	13.40	11.79	0.98	0.15	0.23	101.83	2.95	1.63	0.03	0.65	1.00	0.06	0.00	0.01	63.89	94.01	5.42
mean	59.91	25.03	0.36	6.77	7.76	0.37	0.05	0.09	100.34	2.67	1.32	0.01	0.33	0.67	0.02	0.00	0.00	32.14	65.80	2.06
Aydıntepe (n=54)																				
min	52.57	18.12	0.09	2.62	4.40	0.14	0.00	0.00	98.39	2.41	0.92	0.00	0.12	0.39	0.01	0.00	0.00	12.48	39.78	0.77
max	71.42	29.14	0.61	11.73	10.74	1.00	0.09	0.19	101.95	3.07	1.58	0.02	0.58	0.91	0.06	0.00	0.00	58.61	85.69	5.47
mean	58.70	25.81	0.31	7.60	7.18	0.38	0.03	0.09	100.10	2.63	1.36	0.01	0.37	0.62	0.02	0.00	0.00	36.36	61.49	2.15
Sorkunlu (n=34)																				
min	50.96	20.57	0.08	2.61	3.76	0.14	0.00	0.01	98.82	2.34	1.07	0.00	0.12	0.34	0.01	0.00	0.00	12.51	33.44	0.81
max	66.44	30.67	0.62	13.33	9.92	0.55	0.08	0.17	100.53	2.92	1.65	0.02	0.66	0.85	0.03	0.00	0.00	65.51	86.06	3.04
mean	56.54	26.80	0.36	8.97	6.37	0.32	0.04	0.10	99.50	2.56	1.43	0.01	0.44	0.56	0.02	0.00	0.00	43.16	55.04	1.80
Çiçekli (n=18)																				
min	50.23	22.56	0.22	4.06	3.46	0.13	0.00	0.02	99.07	2.31	1.17	0.01	0.19	0.31	0.01	0.00	0.00	19.06	31.26	0.76
max	63.69	30.96	0.63	13.59	9.10	0.65	0.09	0.17	100.39	2.81	1.68	0.02	0.67	0.78	0.04	0.00	0.00	67.85	77.31	3.63
mean	56.55	26.89	0.42	9.09	6.21	0.33	0.03	0.09	99.61	2.55	1.43	0.02	0.44	0.54	0.02	0.00	0.00	44.15	53.97	1.88
Somarova (n=29)																				
min	52.97	21.63	0.09	2.91	4.92	0.15	0.00	0.00	98.75	2.41	1.13	0.00	0.14	0.43	0.01	0.00	0.00	13.20	42.43	0.85
max	64.94	29.42	0.54	11.90	10.28	0.78	0.08	0.15	101.39	2.86	1.57	0.02	0.58	0.88	0.04	0.00	0.00	56.72	84.41	4.31
mean	58.24	25.88	0.33	7.82	7.25	0.39	0.04	0.09	100.04	2.61	1.37	0.01	0.38	0.63	0.02	0.00	0.00	36.78	61.05	2.17
Şaşurluk (n=53)																				
min	51.71	19.37	0.00	0.51	3.93	0.12	0.00	0.00	97.62	2.39	1.00	0.00	0.02	0.35	0.01	0.00	0.00	2.49	36.08	0.78
max	68.68	29.42	0.56	12.34	10.94	1.45	0.08	0.16	101.05	3.01	1.60	0.02	0.61	0.92	0.08	0.00	0.00	62.60	96.47	8.98
mean	59.02	25.31	0.26	7.24	6.84	0.40	0.03	0.08	99.18	2.65	1.35	0.01	0.35	0.59	0.02	0.00	0.00	36.04	61.56	2.40
Pelitli (n=21)																				
min	50.16	18.58	0.04	0.38	4.46	0.02	0.00	0.01	98.73	2.32	0.99	0.00	0.02	0.40	0.00	0.00	0.00	1.77	38.90	0.11
max	69.25	29.98	0.71	12.75	11.52	0.64	0.13	0.16	101.00	3.00	1.61	0.03	0.63	0.98	0.04	0.00	0.00	60.06	97.81	3.32
mean	61.60	23.58	0.32	5.28	8.77	0.22	0.04	0.07	99.90	2.74	1.24	0.01	0.26	0.76	0.01	0.00	0.00	24.57	74.20	1.23

min: minimum values, max: maximum values, mean: average values

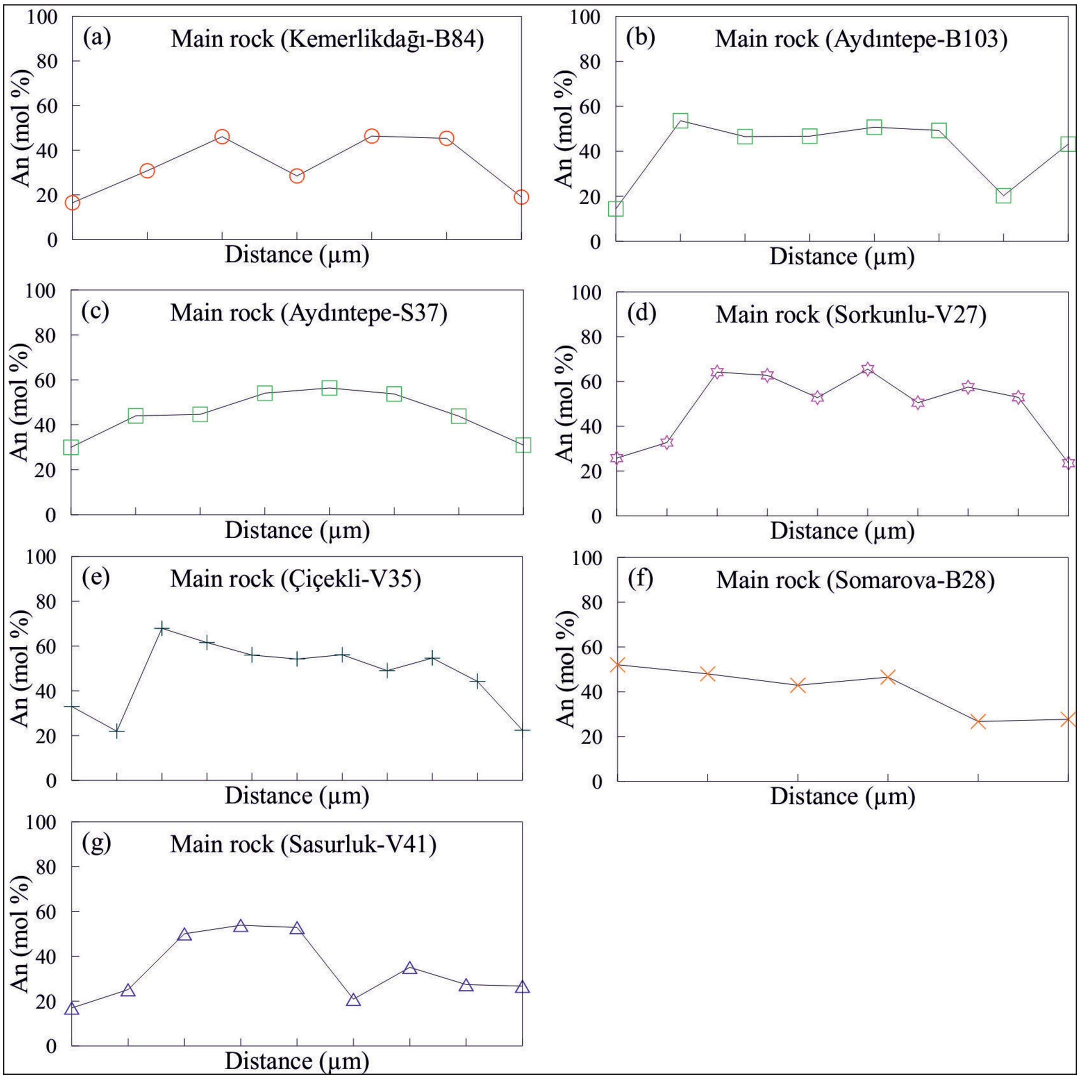

Figure 8- An (%) variations in the zoned plagioclase from the studied plutons (Symbols as in figure 4).

4.2.2. K-Feldspar

The minimum, maximum and mean values for the microprobe analyses of K-feldspar in the studied plutons are given in table 3. The Or content of K-feldspar is between 1 and 96, without any chemical zoning in the crystals. The Çiçekli Pluton has Or_{87-58}, Somarova Pluton has $Or_{93-02;}$ Sorkunlu Pluton has Or_{94-01}; Şaşurluk Pluton has Or_{96-01}; Aydıntepe Pluton has Or_{93-70}; Kemerlikdağı Pluton has Or_{96-01} and the Pelitli Pluton has Or_{96-79} (Figure 9). When the Or content of the K-feldspar is examined, the Somarova Pluton has lowest content (mean 76), while the Pelitli Pluton has highest Or content (mean 90) (Table 3; Figure 9).

Table 3- Minimum, maximum and mean values of microprobe analyses of K-feldspar

	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	BaO	SrO	Total	Si	Al	$Fe^{(ii)}$	Ca	Na	K	Ba	Sr	An	Ab	Or
Kemerlikdağı (n=22)																				
min	63.64	18.81	0.01	0.01	0.49	0.21	0.00	0.01	100.10	2.92	0.99	0.00	0.00	0.04	0.01	0.00	0.00	0.05	4.40	1.24
max	70.04	20.69	0.24	0.96	11.30	16.18	1.60	0.10	101.97	3.01	1.08	0.01	0.04	0.94	0.95	0.03	0.00	4.77	95.75	95.55
mean 65.21		19.25	0.12	0.15	2.02	13.92	0.21	0.04	100.92	2.97	1.03	0.00	0.01	0.17	0.81	0.00	0.00	0.73	17.85	81.42
Aydıntepe (n=25)																				
min	64.06	18.86	0.02	0.00	0.74	12.06	0.02	0.01	99.93	2.95	1.02	0.00	0.00	0.07	0.70	0.00	0.00	0.00	6.60	69.71
max	65.71	19.56	0.38	0.25	3.36	15.98	1.06	0.10	101.60	2.98	1.06	0.01	0.01	0.30	0.94	0.02	0.00	1.26	29.52	93.18
mean	64.89	19.19	0.12	0.09	1.80	14.26	0.26	0.04	100.64	2.97	1.03	0.00	0.00	0.16	0.83	0.00	0.00	0.44	15.99	83.58
Sorkunlu (n=17)																				
min	63.23	8.15	0.03	0.02	0.64	0.17	0.00	0.01	98.93	2.88	0.40	0.00	0.00	0.06	0.01	0.00	0.00	0.10	5.69	1.03
max	85.91	21.74	0.30	1.75	10.48	16.12	1.36	0.09	101.20	3.59	1.12	0.01	0.08	0.89	0.95	0.02	0.00	8.02	93.00	94.22
mean	65.70	18.53	0.11	0.24	2.17	13.08	0.29	0.05	100.17	3.00	1.00	0.00	0.01	0.19	0.77	0.01	0.00	1.24	20.27	78.48
Çiçekli (n=11)																				
min	63.04	18.72	0.10	0.03	1.28	9.70	0.01	0.01	99.94	2.92	1.02	0.00	0.00	0.12	0.57	0.00	0.00	0.15	11.59	58.17
max	65.33	19.70	0.20	0.29	4.43	14.66	2.82	0.10	100.72	2.98	1.08	0.01	0.01	0.39	0.87	0.05	0.00	1.46	40.37	87.31
mean	64.61	19.11	0.14	0.16	2.38	13.25	0.68	0.06	100.37	2.96	1.03	0.01	0.01	0.21	0.78	0.01	0.00	0.77	21.27	77.96
Somarova (n=17)																				
min	64.21	18.98	0.03	0.03	0.79	0.32	0.00	0.00	99.92	2.90	1.03	0.00	0.00	0.07	0.02	0.00	0.00	0.15	7.03	1.77
max	68.11	21.46	0.41	1.35	11.25	15.85	0.40	0.12	101.71	2.98	1.11	0.02	0.06	0.94	0.92	0.01	0.00	6.38	94.34	92.82
mean	65.04	19.42	0.12	0.19	2.67	12.98	0.22	0.05	100.69	2.96	1.04	0.00	0.01	0.23	0.76	0.00	0.00	0.91	23.20	75.88
Şaşurluk (n=24)																				
min	63.09	18.16	0.00	0.00	0.35	0.18	0.00	0.01	99.19	2.93	1.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	3.15	1.04
max	68.57	20.50	0.32	0.51	10.94	16.28	1.92	0.12	100.92	3.00	1.08	0.01	0.02	0.92	0.97	0.03	0.00	2.49	96.47	96.26
mean	64.47	19.09	0.10	0.12	1.55	14.40	0.37	0.06	100.16	2.97	1.04	0.00	0.01	0.14	0.85	0.01	0.00	0.58	13.94	85.48
Pelitli (n=17)																				
min	61.98	17.89	0.01	0.02	0.47	13.54	0.01	0.01	97.00	2.96	1.00	0.00	0.00	0.04	0.81	0.00	0.00	0.09	4.21	78.92
max	64.14	18.50	0.36	0.13	2.35	16.11	1.17	0.11	99.36	2.99	1.03	0.01	0.01	0.21	0.98	0.02	0.00	0.65	20.84	95.59
mean	62.98	18.22	0.11	0.05	1.07	15.31	0.37	0.05	98.16	2.98	1.01	0.00	0.00	0.10	0.92	0.01	0.00	0.26	9.59	90.14

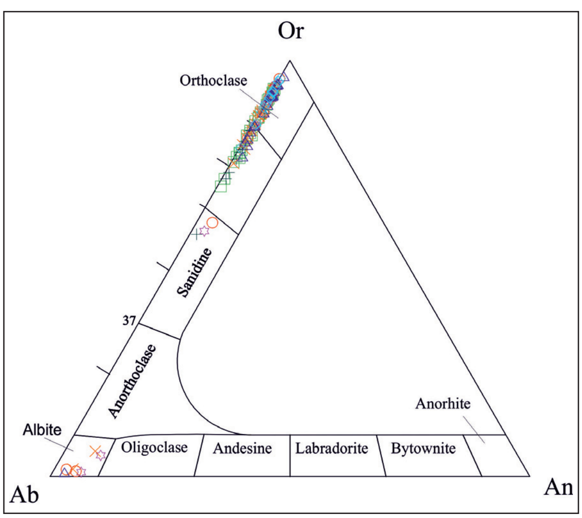

Figure 9- An-Ab-Or ternary diagram (Smith and Brown, 1988) for K-feldspars of the studied plutons (Symbols as in figure 4)

4.2.3. Biotite

The minimum, maximum and mean values of the microprobe analyses of biotite observed in plutonic rocks is given in table 4.

Biotites are solid melt products between the end members of phlogopite and annite and are close to the magnesium-rich phlogopite end (Figure 10).

Table 4- Minimum, maximum and mean values of microprobe analyses of biotite.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	F	Total	Si	Ti	Al	Fe(ii)	Mn	Mg	Ca	Na	K	Cl	F
Kemerlikdağı (n=15)																							
min	36.51	4.18	12.12	16.19	0.18	11.46	0.04	0.08	8.87	0.22	0.31	93.83	5.59	0.47	2.13	2.03	0.02	2.56	0.01	0.02	1.72	0.06	0.15
max	38.81	5.26	12.82	20.30	0.30	14.31	0.52	0.18	9.64	0.56	0.60	97.59	5.69	0.59	2.27	2.54	0.04	3.15	0.09	0.05	1.84	0.14	0.28
mean	37.55	4.58	12.50	18.26	0.23	12.83	0.14	0.12	9.23	0.39	0.42	96.24	5.63	0.52	2.21	2.29	0.03	2.87	0.02	0.03	1.76	0.10	0.20
Aydıntepe (n=23)																							
min	36.18	3.39	12.81	16.14	0.28	12.34	0.01	0.07	8.96	0.15	0.39	94.44	5.46	0.38	2.28	1.99	0.04	2.79	0.00	0.02	1.72	0.04	0.19
max	38.02	5.05	13.57	18.44	0.46	14.66	0.20	0.21	9.67	0.33	0.78	97.20	5.61	0.57	2.39	2.29	0.06	3.23	0.03	0.06	1.83	0.08	0.37
mean	36.97	4.35	13.20	17.36	0.38	13.40	0.10	0.14	9.31	0.25	0.57	96.02	5.53	0.49	2.33	2.17	0.05	2.99	0.02	0.04	1.78	0.06	0.27
Sorkunlu (n=23)																							
min	35.67	4.06	11.78	17.57	0.17	11.12	0.03	0.11	8.67	0.19	0.14	93.26	5.49	0.47	2.14	2.17	0.02	2.55	0.00	0.03	1.69	0.05	0.07
max	37.91	5.23	13.04	20.30	0.33	13.84	2.47	0.18	9.54	0.48	0.44	97.30	5.73	0.61	2.36	2.58	0.04	3.05	0.41	0.05	1.84	0.12	0.21
mean	37.01	4.47	12.51	18.85	0.25	12.28	0.22	0.14	9.18	0.32	0.29	95.52	5.62	0.51	2.24	2.40	0.03	2.78	0.04	0.04	1.78	0.08	0.14
Çiçekli (n=9)																							
min	37.23	4.41	12.13	16.06	0.10	13.46	0.02	0.14	9.15	0.45	0.71	95.17	5.53	0.49	2.14	2.00	0.01	2.95	0.00	0.04	1.73	0.11	0.33
max	37.56	4.99	12.91	17.05	0.14	14.13	0.13	0.23	9.60	0.54	0.86	96.98	5.58	0.55	2.24	2.12	0.02	3.14	0.02	0.07	1.81	0.14	0.40
mean	37.44	4.64	12.55	16.55	0.12	13.78	0.06	0.20	9.40	0.48	0.81	96.03	5.56	0.52	2.20	2.05	0.01	3.05	0.01	0.06	1.78	0.12	0.38
Somarova (n=19)																							
min	36.44	3.41	12.01	17.42	0.20	12.10	0.03	0.11	7.24	0.23	0.39	94.12	5.55	0.39	2.11	2.17	0.03	2.74	0.00	0.03	1.41	0.06	0.19
max	38.32	4.65	13.05	19.23	0.39	14.01	0.75	0.24	9.59	0.53	0.53	97.79	5.70	0.53	2.31	2.42	0.05	3.13	0.12	0.07	1.82	0.13	0.25
mean	37.45	4.22	12.53	18.33	0.27	12.93	0.14	0.18	9.21	0.31	0.46	96.02	5.63	0.48	2.22	2.30	0.03	2.90	0.02	0.05	1.76	0.08	0.22
Şaşurluk (n=14)																							
min	36.34	3.18	11.98	17.63	0.17	10.92	0.01	0.09	7.48	0.30	0.23	94.11	5.60	0.37	2.15	2.20	0.02	2.50	0.00	0.03	1.48	0.08	0.11
max	37.87	4.53	12.94	21.65	0.30	13.64	0.24	0.20	9.63	0.73	0.40	96.60	5.67	0.52	2.33	2.81	0.04	3.04	0.04	0.06	1.85	0.19	0.19
mean	37.03	4.24	12.50	19.40	0.22	12.05	0.08	0.14	9.15	0.43	0.30	95.55	5.63	0.48	2.24	2.47	0.03	2.73	0.01	0.04	1.77	0.11	0.15
Pelitli (n=8)																							
min	37.50	4.24	12.38	16.13	0.19	13.43	0.08	0.06	8.71	0.06	0.35	97.31	5.51	0.46	2.12	1.95	0.02	2.89	0.01	0.02	1.60	0.02	0.16
max	39.35	5.36	13.92	19.46	0.27	14.96	0.29	0.27	9.37	0.40	0.81	98.92	5.68	0.59	2.37	2.38	0.03	3.26	0.04	0.08	1.75	0.10	0.38
mean	38.44	4.74	12.88	17.33	0.23	14.21	0.21	0.19	9.04	0.18	0.53	97.96	5.61	0.52	2.21	2.12	0.03	3.09	0.03	0.05	1.68	0.04	0.24

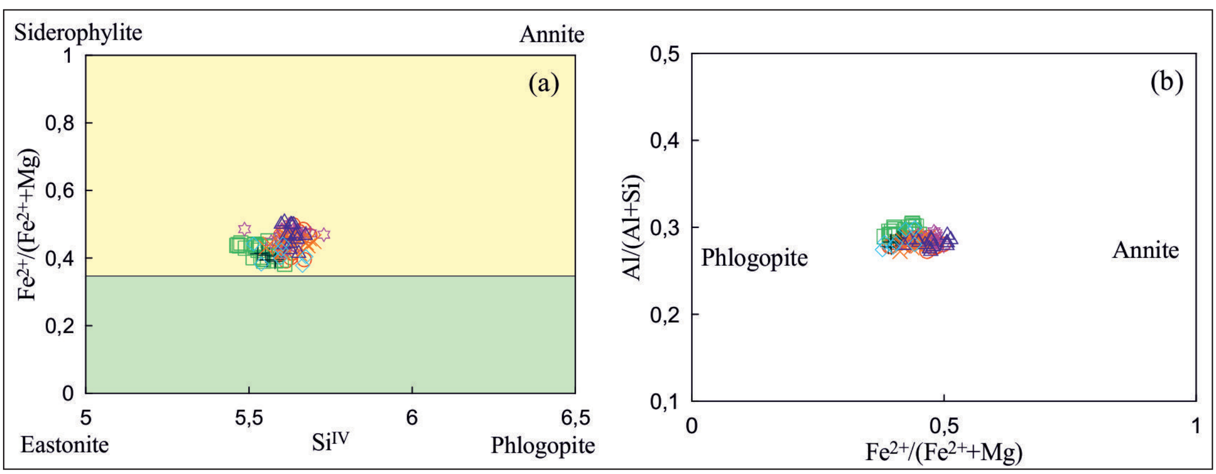

Figure 10- Biotite composition of the studied plutonic rocks on (a) Si^{IV}-(Fe^{2+}/Fe^{2+}+Mg) diagrams, (b) (Fe^{2+}/Fe^{2+}+Mg)-Al/(Al+Si) diagrams (Parsons et al., 1991) (Symbols as in figure 4).

4.2.4. Amphibole

The minimum, maximum and mean values of microprobe analyses for amphiboles in the studied plutons are given in table 5.

All of the amphiboles in the plutons are calcic amphiboles (Figure 11a) and are mainly magnesium hornblende with a small amount with actinolite composition on the Leake et al. (1997) classification diagram (Figure 11b).

Table 5- Minimum, maximum and mean values of microprobe analyses of amphiboles.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Si	Ti	Al	$Fe^{(ii)}$	Mn	Mg	Ca	Na	K
Kemerlikdağı (n=32)																			
min	47.97	0.17	1.51	10.11	0.27	12.47	10.70	0.31	0.09	96.86	6.99	0.02	0.25	1.18	0.03	2.70	1.67	0.17	0.02
max	55.42	1.37	5.46	15.44	0.91	18.31	12.89	1.54	0.60	98.55	7.73	0.15	0.94	1.88	0.11	3.86	1.98	0.87	0.11
mean	50.58	0.89	4.31	13.51	0.53	15.00	11.55	1.00	0.39	97.78	7.27	0.10	0.73	1.63	0.06	3.21	1.78	0.56	0.07
Aydıntepe (n=21)																			
min	48.35	0.11	1.50	10.15	0.50	14.33	11.13	0.23	0.08	97.26	6.95	0.01	0.25	1.21	0.06	3.10	1.67	0.13	0.01
max	54.07	1.74	6.50	13.33	0.89	18.12	12.77	1.56	0.67	98.65	7.70	0.19	1.10	1.60	0.11	3.82	1.95	0.87	0.12
mean	51.37	0.65	4.43	11.77	0.64	16.19	11.84	0.87	0.34	98.09	7.29	0.07	0.74	1.40	0.08	3.42	1.80	0.48	0.06
Sorkunlu (n=21)																			
min	47.14	0.12	3.16	14.03	0.37	12.97	10.90	0.63	0.24	96.97	6.88	0.01	0.54	1.69	0.05	2.83	1.68	0.35	0.04
max	50.97	1.30	6.20	16.59	0.57	15.01	11.73	1.50	0.66	98.35	7.38	0.14	1.07	2.01	0.07	3.22	1.83	0.85	0.12
mean	49.11	0.88	4.96	15.42	0.49	13.89	11.21	1.17	0.48	97.62	7.12	0.10	0.85	1.87	0.06	3.00	1.74	0.66	0.09
Çiçekli (n=13)																			
min	47.92	0.40	2.01	10.28	0.30	13.10	10.77	0.22	0.09	96.53	7.00	0.04	0.34	1.23	0.04	2.87	1.68	0.12	0.02
max	53.81	1.13	5.64	15.82	0.88	16.89	12.30	1.47	0.63	97.44	7.64	0.12	0.98	1.94	0.11	3.61	1.90	0.83	0.12
mean	50.87	0.78	4.32	12.73	0.55	15.19	11.35	1.03	0.37	97.17	7.32	0.08	0.73	1.53	0.07	3.26	1.75	0.58	0.07
Somarova (n=16)																			
min	47.34	0.17	1.00	12.18	0.46	12.81	11.00	0.22	0.11	96.67	6.92	0.02	0.17	1.43	0.06	2.79	1.66	0.12	0.02
max	54.58	1.24	6.34	16.35	0.76	17.05	12.15	1.56	0.76	98.82	7.78	0.14	1.09	2.00	0.09	3.57	1.86	0.88	0.14
mean	50.90	0.67	4.09	14.56	0.58	14.37	11.50	0.84	0.35	97.87	7.33	0.07	0.69	1.75	0.07	3.08	1.77	0.47	0.06
Şaşurluk (n=18)																			
min	47.80	0.23	2.06	13.09	0.43	12.77	10.45	0.62	0.19	96.70	7.00	0.02	0.34	1.54	0.05	2.81	1.57	0.34	0.03
max	53.47	1.27	5.86	16.59	0.60	16.77	12.27	1.35	0.65	98.51	7.56	0.14	1.01	2.03	0.07	3.51	1.91	0.77	0.12
mean	49.41	0.90	4.84	15.25	0.53	13.83	11.28	1.08	0.48	97.59	7.17	0.10	0.83	1.85	0.07	2.99	1.75	0.61	0.09
Pelitli (n=21)																			
min	50.21	0.19	1.73	11.14	0.37	15.15	10.58	0.28	0.19	96.98	7.06	0.02	0.29	1.31	0.04	3.20	1.58	0.15	0.03
max	52.90	0.94	5.19	14.40	0.88	17.25	11.89	1.27	0.48	98.72	7.50	0.10	0.86	1.71	0.11	3.62	1.80	0.70	0.09
mean	51.41	0.71	4.16	12.71	0.56	16.03	11.28	0.73	0.30	97.88	7.28	0.08	0.69	1.50	0.07	3.38	1.71	0.40	0.05

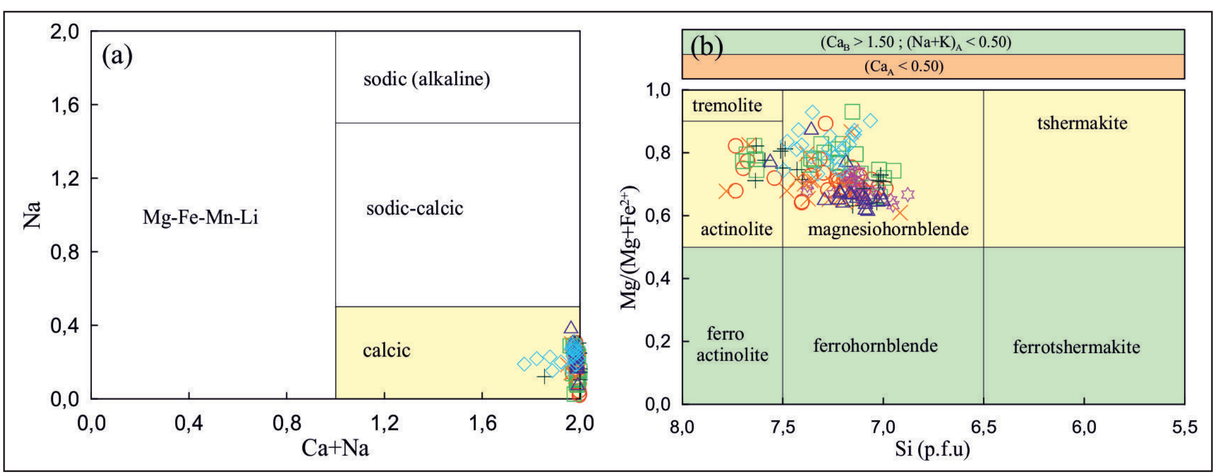

Figure 11- Composition of amphiboles (Leake et al., 1997) (Symbols as in figure 4).

4.2.5. Pyroxene

Pyroxene has been observed in some plutons and the microprobe analyses of pyroxenes are given in table 6 as minimum, maximum and mean values. All pyroxenes are calcic (Wo_{44-46}) in composition except clinoenstatite (En_{53-57}) orthorhombic pyroxenes observed in some thin-sections of Aydıntepe (Figure 12a). Calcic pyroxenes are generally augite, with lesser amounts of diopside composition (Figure 12a). Clinoenstatite and diopside composition is rare, while augite compositions are abundantly observed. On the

Table 6- Minimum, maximum and mean values of microprobe analyses of pyroxene.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Total	Si	Ti	Al	$Fe^{(ii)}$	Mn	Mg	Ca	Na	Wo	En	Fs
Kemerlikdağı (n=12)																				
min	51.00	0.11	0.38	8.07	0.26	13.04	19.97	0.30	98.28	1.87	0.00	0.02	0.25	0.01	0.73	0.79	0.02	40.34	37.06	13.40
max	53.49	0.71	3.15	12.13	0.38	15.69	22.44	0.39	100.93	1.99	0.02	0.14	0.38	0.01	0.86	0.89	0.03	45.39	44.44	19.82
mean	51.85	0.51	1.96	9.14	0.33	14.91	20.92	0.35	99.97	1.92	0.01	0.09	0.28	0.01	0.82	0.83	0.03	42.68	42.31	15.01
Aydıntepe (n=19)																				
min	51.13	0.07	0.19	8.75	0.39	13.23	0.93	0.00	97.02	1.96	0.00	0.01	0.28	0.01	0.74	0.04	0.00	1.88	37.58	15.31
max	52.58	0.29	0.66	27.17	1.07	20.23	21.89	0.28	100.08	2.00	0.01	0.03	0.87	0.03	1.15	0.89	0.02	45.75	56.99	44.78
mean	51.86	0.14	0.45	16.96	0.68	15.75	12.97	0.16	98.98	1.98	0.00	0.02	0.54	0.02	0.89	0.53	0.01	26.85	45.01	28.14
Sorkunlu (n=9)																				
min	51.04	0.34	1.22	8.15	0.24	14.62	20.52	0.22	98.68	1.89	0.01	0.05	0.26	0.01	0.81	0.81	0.02	41.46	41.49	13.58
max	52.61	0.67	2.59	10.01	0.48	15.59	20.79	0.56	100.48	1.98	0.02	0.11	0.31	0.02	0.86	0.83	0.04	43.19	44.31	16.60
mean	52.04	0.51	1.76	8.84	0.38	15.08	20.63	0.36	99.60	1.94	0.01	0.08	0.28	0.01	0.84	0.82	0.03	42.29	43.01	14.69
Çiçekli (n=11)																				
min	51.27	0.10	0.42	8.42	0.38	12.77	21.01	0.21	97.55	1.97	0.00	0.02	0.27	0.01	0.73	0.85	0.02	43.27	36.80	14.57
max	52.79	0.20	0.86	11.30	0.54	13.85	22.21	0.35	99.61	2.00	0.01	0.04	0.36	0.02	0.78	0.91	0.03	45.96	40.03	18.70
mean	52.19	0.15	0.60	9.80	0.45	13.44	21.68	0.28	98.59	1.98	0.00	0.03	0.31	0.01	0.76	0.88	0.02	44.83	38.67	16.50
Şaşurluk (n=13)																				
min	51.00	0.03	0.12	7.12	0.24	12.77	0.93	0.00	97.02	1.87	0.00	0.01	0.22	0.01	0.73	0.04	0.00	1.88	36.80	11.87
max	53.06	0.19	0.88	8.92	0.56	14.86	23.88	0.45	99.38	1.99	0.01	0.04	0.28	0.02	0.83	0.96	0.03	47.88	41.93	15.35
mean	52.79	0.15	0.67	8.26	0.45	14.19	22.18	0.27	98.95	1.98	0.00	0.03	0.26	0.01	0.80	0.89	0.02	45.53	40.52	13.95
Pelitli (n=4)																				
min	51.25	0.16	0.64	8.18	0.34	13.32	19.99	0.29	97.01	1.91	0.00	0.03	0.26	0.01	0.76	0.80	0.02	41.32	39.33	13.78
max	52.87	0.62	2.51	9.02	0.42	15.32	22.32	0.37	99.22	2.00	0.02	0.11	0.29	0.01	0.85	0.90	0.03	45.98	44.07	15.65
mean	52.21	0.28	1.21	8.63	0.40	14.13	21.45	0.33	98.64	1.97	0.01	0.05	0.27	0.01	0.79	0.87	0.02	44.55	40.82	14.63

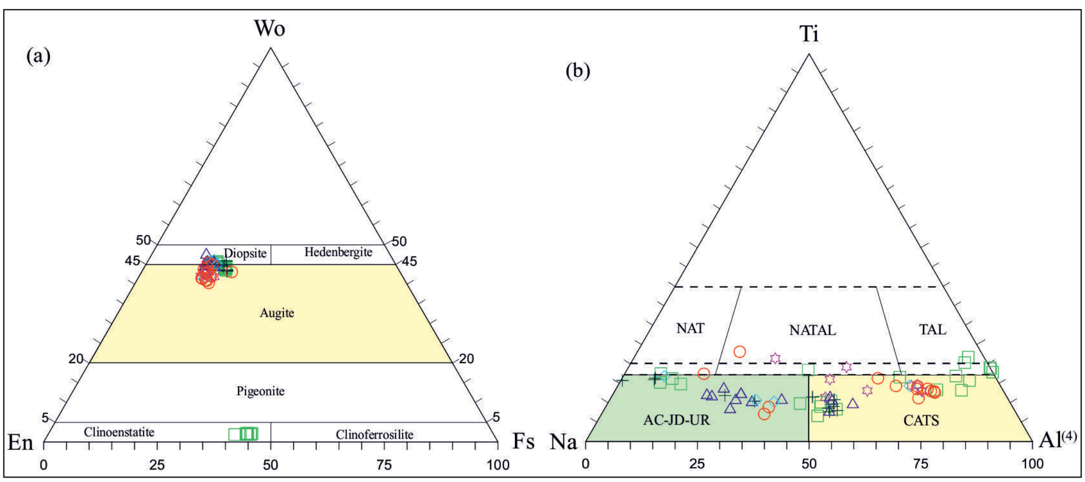

Figure 12- Pyroxenes on a) Wo-En-Fs (Morimoto, 1988), b) Ti-Na-$Al^{(4)}$ (Papike et al., 1974) diagrams (Symbols as in figure 4).

Ti-Na-Al^4 diagram for the studied rocks (Papike et al., 1974), they vary between the poor in Ti and rich in Na and $Al^{(4)}$ end members (Figure 12b).

4.2.6. Fe-Ti Oxides

The Fe-Ti oxides in the studied plutons are mainly magnetite with lower amounts of ilmenite. Microprobe analysis results for magnetite and ilmenite are given in tables 7 and 8 as minimum, maximum and mean values.

The studied magnetites are ulvospinel-magnetite solid melt products and have compositions close to the magnetite end (Figure 13a). Ilmenites are generally located at the ilmenite end of the ilmenite-hematite solid melt (Figure 13b).

Table 7- Minimum, maximum and mean values of microprobe analyses of magnetites.

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Total	Si	Ti	Al	Cr	$Fe^{(ii)}$	Mn	Mg	Ca
Kemerlikdağı (n=12)																		
min	0.03	0.06	0.06	0.01	60.27	30.62	0.02	0.00	0.02	96.97	0.01	0.02	0.03	0.00	28.62	0.01	0.00	0.01
max	0.71	3.39	1.23	0.12	67.92	33.07	1.14	0.10	0.15	100.37	0.29	1.00	0.57	0.04	31.76	0.38	0.06	0.06
mean	0.11	1.27	0.38	0.08	65.02	31.66	0.34	0.02	0.06	98.95	0.05	0.38	0.18	0.03	30.68	0.12	0.01	0.02
Aydıntepe (n=10)																		
min	0.01	0.05	0.06	0.05	67.52	31.05	0.05	0.00	0.02	99.68	0.00	0.02	0.03	0.02	31.37	0.02	0.00	0.01
max	0.07	0.42	0.40	0.07	69.54	31.50	0.15	0.03	0.14	101.51	0.03	0.13	0.19	0.02	31.82	0.05	0.02	0.06
mean	0.04	0.18	0.19	0.06	68.73	31.33	0.08	0.01	0.05	100.67	0.02	0.05	0.09	0.02	31.64	0.03	0.01	0.02
Sorkunlu (n=10)																		
min	0.03	0.09	0.15	0.08	48.72	29.93	0.03	0.00	0.02	95.36	0.01	0.03	0.07	0.03	26.22	0.01	0.00	0.01
max	2.34	8.51	1.28	0.15	69.01	36.31	2.38	0.42	0.47	101.13	0.93	2.50	0.60	0.05	31.68	0.78	0.25	0.20
mean	0.30	1.98	0.36	0.10	63.11	32.31	0.44	0.06	0.09	98.74	0.12	0.58	0.17	0.03	30.07	0.14	0.04	0.04
Çiçekli (n=5)																		
min	0.02	0.31	0.63	0.06	60.44	30.31	0.08	0.05	0.03	96.52	0.01	0.10	0.31	0.02	29.40	0.03	0.03	0.01
max	0.06	2.36	1.27	0.08	65.40	31.95	0.30	0.13	0.05	97.94	0.02	0.72	0.61	0.03	31.18	0.10	0.08	0.02
mean	0.04	1.17	0.93	0.07	63.49	31.06	0.18	0.09	0.04	97.07	0.02	0.36	0.45	0.02	30.40	0.06	0.06	0.02
Somarova (n=8)																		
min	0.01	0.43	0.18	0.07	37.23	30.96	0.06	0.00	0.02	96.09	0.00	0.13	0.09	0.02	22.52	0.02	0.00	0.01
max	0.14	13.58	2.24	0.10	68.43	41.08	1.67	0.11	0.12	101.42	0.06	3.69	0.95	0.03	31.44	0.51	0.06	0.05
mean	0.07	2.16	0.56	0.08	63.33	32.59	0.28	0.02	0.05	99.14	0.03	0.60	0.25	0.03	30.20	0.09	0.01	0.02
Şaşurluk (n=15)																		
min	0.04	0.25	0.08	0.05	57.86	30.81	0.04	0.00	0.01	97.28	0.02	0.08	0.04	0.02	28.04	0.01	0.01	0.00
max	0.50	4.49	2.42	0.17	67.01	34.16	0.63	0.19	0.32	99.15	0.20	1.34	1.12	0.05	31.58	0.21	0.11	0.14
mean	0.12	1.80	0.68	0.10	63.07	32.05	0.21	0.05	0.08	98.16	0.05	0.54	0.32	0.03	30.15	0.07	0.03	0.03
Pelitli (n=14)																		
min	0.08	0.19	0.08	0.04	56.31	29.92	0.04	0.01	0.01	96.00	0.03	0.06	0.04	0.01	28.18	0.01	0.01	0.00
max	0.72	4.98	0.63	0.55	66.03	34.26	0.69	0.18	1.02	100.05	0.29	1.49	0.30	0.18	31.48	0.23	0.12	0.44
mean	0.17	2.37	0.36	0.14	61.70	32.24	0.28	0.04	0.12	97.42	0.07	0.72	0.17	0.05	29.92	0.10	0.02	0.05

Table 8- Minimum, maximum and mean values of microprobe analyses of ilmenite.

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Total	Si	Ti	Al	Cr	$Fe^{(ii)}$	Mn	Mg	Ca
Kemerlikdağı (n=8)																	
min	0.00	44.85	0.00	0.01	41.78	2.97	0.02	0.02	97.09	0.00	9.62	0.00	0.00	9.97	0.71	0.01	0.01
max	0.09	47.25	0.04	0.02	47.50	11.16	0.11	0.16	98.42	0.03	10.03	0.01	0.00	11.22	2.69	0.05	0.05
mean	0.04	46.31	0.02	0.02	45.36	5.74	0.08	0.07	97.64	0.01	9.88	0.01	0.00	10.76	1.38	0.03	0.02
Aydıntepe (n=3)																	
min	0.04	46.57	0.04	0.02	47.15	1.64	0.27	0.03	96.51	0.01	10.00	0.01	0.00	11.19	0.40	0.11	0.01
max	0.05	47.27	0.05	0.02	47.89	1.70	0.28	0.12	96.63	0.01	10.09	0.02	0.00	11.43	0.41	0.12	0.04
mean	0.05	46.92	0.05	0.02	47.52	1.67	0.28	0.08	96.57	0.01	10.05	0.02	0.00	11.31	0.40	0.12	0.02
Çiçekli (n=4)																	
min	0.01	44.38	0.03	0.02	48.09	2.18	0.39	0.02	95.52	0.00	9.70	0.01	0.00	11.69	0.54	0.17	0.01
max	0.03	44.66	0.04	0.03	48.67	2.29	0.45	0.03	95.80	0.01	9.77	0.01	0.01	11.82	0.56	0.19	0.01
mean	0.02	44.52	0.04	0.03	48.38	2.24	0.42	0.03	95.66	0.01	9.73	0.01	0.01	11.76	0.55	0.18	0.01
Somarova (n=3)																	
min	0.03	46.36	0.02	0.02	43.98	4.85	0.07	0.04	96.86	0.01	9.90	0.01	0.00	10.32	1.16	0.03	0.01
max	0.19	47.97	0.05	0.03	44.36	6.63	0.14	0.06	97.51	0.05	10.13	0.02	0.01	10.52	1.59	0.06	0.02
mean	0.09	47.26	0.04	0.03	44.15	5.54	0.10	0.05	97.27	0.03	10.05	0.01	0.01	10.44	1.33	0.04	0.01
Şaşurluk (n=4)																	
min	0.01	47.02	0.00	0.01	43.06	3.75	0.06	0.02	95.43	0.00	10.04	0.00	0.00	10.30	0.90	0.03	0.01
max	0.06	48.38	0.04	0.03	46.12	5.06	0.10	0.09	97.50	0.02	10.28	0.01	0.01	10.95	1.21	0.04	0.03
mean	0.03	47.70	0.02	0.02	44.49	4.44	0.09	0.06	96.83	0.01	10.16	0.01	0.00	10.53	1.06	0.04	0.02
Pelitli (n=3)																	
min	0.04	47.66	0.02	0.01	44.01	4.48	0.06	0.05	96.83	0.01	10.14	0.01	0.00	10.41	1.07	0.03	0.02
max	0.04	47.84	0.04	0.05	44.51	4.73	0.10	0.10	96.91	0.01	10.18	0.01	0.01	10.53	1.13	0.04	0.03
mean	0.04	47.75	0.03	0.03	44.26	4.61	0.08	0.08	96.87	0.01	10.16	0.01	0.01	10.47	1.10	0.03	0.02

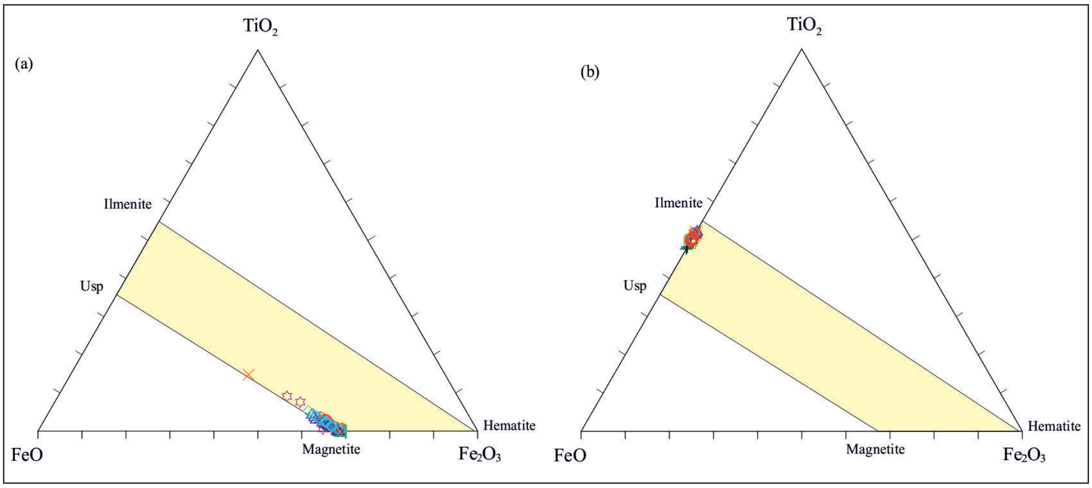

Figure 13- TiO_2-FeO-Fe_2O_3 discrimination diagrams for Fe-Ti oxides from the plutons (Bacon and Hirschmann, 1988), a) Magnetite, b) Ilmenite (Symbols as in figure 4).

4.3. Thermobarometer Calculations for the Plutons

4.3.1. Amphibole-Plagioclase thermometer

The amphibole-plagioclase thermometer recommended by Blundy and Holland (1990) was used to estimate the crystallisation temperature of the magmas. This thermometer calculates temperature with the formula T= 0.667 P - 48.98 + Y/- 0.0429 - 0.008314 LnK. The pressure (P) is calculated from amphibole minerals that developed in contact with plagioclases at equilibrium crystallisation. For $X_{ab} > 0.5$, Y=0. If $X_{ab} < 0.5$, then Y= -8.06 + 25.5(1- X_{ab})^2 is used. The K value is a special number, with (Si-4/ 8-Si) X_{ab} used. For the use of this thermometer, firstly amphibole–plagioclase equilibrium crystallisation should be accompanied by biotite, quartz, K-feldspar, pyroxene, Fe-Ti oxides ± sphene minerals. The thermometer reactions are chosen as edenite + 4 quartz = tremolite + albite and pargasite + 4 quartz = amphibole + albite. Plagioclase should have less calcic character than An_{92} and the cationic Si content of the amphibole developing in contact with plagioclase should be lower than 7.8. Additionally, this type of thermometer is sensitive for temperatures between 500 and 1100°C.

The temperatures calculated for the plutons were between 625 and 824°C (Table 9) and varied from 625 to 789ºC for Çiçekli Pluton, 659-768ºC for Somarova Pluton, 713-824ºC for Sorkunlu Pluton, 652-797ºC for Şaşurluk Pluton, 625-815ºC for Aydıntepe Pluton, 642-802ºC for Kemerlikdağı Pluton and 666-767ºC for Pelitli Pluton (Table 9). When mean values are examined, Sorkunlu Pluton has the highest (mean 761ºC), and the Çiçekli Pluton has the lowest values (mean 710ºC) (Table 9).

4.3.2. Amphibole Thermometer

Amphibole thermometer calculations were done by using the formula proposed by Ridolfi et al. (2010) and Ridolfi and Renzulli (2012) and the results are given in table 10. According to Ridolfi et al. (2010), the mean temperature values are; 681-802ºC for Aydıntepe Pluton, 693-788ºC for Çiçekli Pluton, 719-796ºC for Kemerlikdağı Pluton, 723-778ºC for Pelitli Pluton, 672-770ºC for Samarova Pluton, 696-767ºC for Şaşurluk Pluton and 710-797ºC for Sorkunlu Pluton (Table 10).

The amphibole temperatures calculated using the equations recommended by Ridolfi and Renzulli (2012) were between 645 and 842ºC for Aydıntepe Pluton, 627-792ºC for Çiçekli Pluton, 674-816ºC for Kemerlikdağı Pluton, 707-766ºC for Pelitli Pluton, 668-753ºC for Samarova Pluton, 727-774ºC for Şaşurluk Pluton and 724-804ºC for Sorkunlu Pluton (Table 10).

Table 9- Minimum, maximum and mean values for temperature and pressure calculated from amphiboles.

	P1 (kbar) (Hammarstrom and Zen, 1986)	P2 (kbar) (Hollister et al., 1987)	P3 (kbar) (Schmidt, 1992)	T°C Blundy and Holland (1990)
Çiçekli (n=13)				
min	0.2	0.2	0.9	625
max	1.0	0.7	1.6	789
mean	0.7	0.5	1.3	710
std (±)	0.2	0.2	0.2	51
Somarova (n=17)				
min	0.1	0.1	0.4	659
max	1.6	1.4	2.2	768
mean	0.5	0.5	1.0	722
std (±)	0.5	0.6	0.5	34
Sorkunlu (n=22)				
min	0.1	0.1	0.1	713
max	1.4	1.3	2.1	824
mean	0.5	0.5	1.1	761
std (±)	0.4	0.4	0.5	28
Şaşurluk (n=18)				
min	0.1	0.1	0.7	652
max	1.2	0.9	1.8	797
mean	0.5	0.5	1.2	759
std (±)	0.4	0.3	0.3	38
Aydıntepe (n=22)				
min	0.1	0.2	0.7	625
max	1.6	1.4	2.2	815
mean	0.5	0.6	1.1	727
std (±)	0.5	0.5	0.5	57
Kemerlikdağı (n=25)				
min	0.1	0.1	0.1	642
max	0.8	0.5	1.5	802
mean	0.3	0.3	0.9	746
std (±)	0.2	0.1	0.3	40
Pelitli (n=21)				
min	0.1	0.1	0.7	666
max	0.4	0.1	1.1	767
mean	0.2	0.1	0.9	721
std (±)	0.1	0.1	0.1	31
min: minimum, max: maksimum, mean: average, std: standard deviation				

4.3.3. Clinopyroxene Thermometer

Putirka et al. (1996, 2003) and Putirka (1999, 2005, 2008) were studied the equilibrium between clinopyroxene and the melt, in order to calculate the temperature and pressure of rock crystallisation. Putirka (2008) calculated the Fe-Mg variability constant as $K_D(Fe–Mg)^{cpyr-melt}$ = 0.27 ± 0.03 based on experimental observations to test the necessary equilibrium state between clinopyroxene and the melt. To calculate the clinopyroxene crystallisation temperature, it is necessary to know the melt

Table 10- Temperature, pressure, hydrometer and oxygen fugacity values obtained from amphiboles.

	Ridolfi et al. (2010)						Ridolfi and Renzulli (2012)			
	T°C	P (kbar)	ΔNNO	fO_2	H_2O		T°C	P (kbar)	ΔNNO	H_2O
Çiçekli (n=8)										
min	693	0.3	1.3	-14.4	3.1		627	0.4	-0.2	4.2
max	788	0.8	2.4	-12.3	5.5		792	0.9	1.7	5.6
mean	736	0.6	2.0	-13.4	4.0		719	0.6	0.9	4.7
std (±)	37	0.2	0.4	0.7	0.7		66	0.2	0.6	0.5
Somarova (n=8)										
min	672	0.3	1.5	-14.7	3.5		668	0.4	-0.3	4.5
max	770	0.7	2.7	-12.3	5.8		753	0.8	0.8	5.9
mean	723	0.5	1.9	-13.7	4.4		708	0.6	0.1	5.0
std (±)	32	0.2	0.4	0.7	0.7		33	0.1	0.4	0.5
Sorkunlu (n=10)										
min	710	0.4	1.3	-14.2	3.8		724	0.7	-0.1	4.5
max	797	0.9	2.1	-12.5	4.5		804	1.0	1.0	5.6
mean	753	0.7	1.7	-13.2	4.2		748	0.8	0.5	4.9
std (±)	23	0.1	0.3	0.5	0.2		24	0.1	0.3	0.4
Şaşurluk (n=11)										
min	696	0.3	1.2	-14.1	3.8		727	0.7	0.0	4.6
max	767	0.8	2.3	-13.3	4.5		774	0.9	0.8	5.4
mean	748	0.7	1.5	-13.6	4.2		749	0.8	0.3	4.8
std (±)	20	0.1	0.3	0.2	0.2		15	0.1	0.3	0.2
Aydıntepe (n=9)										
min	681	0.3	1.7	-14.3	3.2		645	0.3	-0.1	4.1
max	802	0.9	3.0	-12.0	5.7		842	1.3	2.4	6.6
mean	745	0.6	2.1	-13.0	4.0		762	0.8	1.5	4.6
std (±)	39	0.2	0.4	0.6	0.8		77	0.3	0.8	0.8
Kemerlikdağı (n=11)										
min	719	0.6	1.2	-14.6	3.4		674	0.5	-1.7	3.7
max	796	0.7	2.1	-12.2	6.8		816	0.9	1.2	5.4
mean	749	0.6	1.7	-13.3	4.3		747	0.7	0.5	4.6
std (±)	25	0.0	0.2	0.7	1.0		42	0.1	0.8	0.5
Pelitli (n=13)										
min	723	0.3	1.9	-13.6	2.9		707	0.6	0.4	4.6
max	778	0.6	2.7	-11.6	5.1		766	0.9	1.7	5.1
mean	749	0.6	2.3	-12.7	4.1		740	0.7	1.0	4.8
std (±)	18	0.1	0.3	0.6	0.7		21	0.1	0.6	0.2

composition in equilibrium with clinopyroxene. While electron microprobe analysis results are used for the clinopyroxene composition, the microprobe analyses of glass or data obtained from whole rock analyses may be used for the melt composition. In this study, the thermobarometer which calibrated based on clinopyroxene and melt composition and proposed by Putirka (2008) was used and the results are given in table 11.

The crystallisation temperatures calculated according to Putirka (2008) are between 1118 and 1127ºC for Aydıntepe Pluton, 1118 and 1122ºC for Çiçekli Pluton, 1104 and 1137ºC for Kemerlikdağı Pluton, 1121 and 1161ºC for Pelitli Pluton, 1129 and 1142ºC for Şaşurluk Pluton, and 1139 and 1158ºC for Sorkunlu Pluton (Table 11).

4.3.4. Biotite Thermometer

Using biotites from the studied plutonic rocks, biotite thermometer were calculated based on the formula proposed by Luhr et al. (1984) (Table 12). The crystallisation temperatures calculated according to Luhr et al. (1984) were between 726 and 793ºC for Kemerlikdağı Pluton, 709 and 795ºC for Aydıntepe

Table 11- Temperature and pressure values obtained from clinopyroxene (Putirka, 2008).

Clinopyroxene-liquid thermobarometer (Putirka, 2008)	P (32b. kbar)	T (ºC)	K_D (Ab-An)
Çiçekli (n=5)			
min	0.4	1118	0.26
max	0.9	1122	0.26
mean	0.6	1120	0.26
std (±)	0.2	2	0.00
Sorkunlu (n=5)			
min	0.8	1139	0.26
max	2.5	1158	0.27
mean	1.8	1151	0.27
std (±)	0.7	7	0.00
Şaşurluk (n=5)			
min	0.7	1129	0.26
max	1.4	1142	0.26
mean	1.0	1136	0.26
std (±)	0.3	5	0.00
Aydıntepe (n=3)			
min	0.2	1118	0.26
max	1.1	1127	0.26
mean	0.7	1123	0.26
std (±)	0.4	4	0.00
Kemerlikdağı (n=9)			
min	0.4	1104	0.25
max	2.6	1137	0.26
mean	1.6	1127	0.26
std (±)	0.7	16	0.00
Pelitli (n=4)			
min	0.6	1121	0.26
max	2.7	1161	0.27
mean	1.5	1138	0.27
std (±)	1.0	17	0.00

Table 12- Temperature, pressure and oxygen fugacity values obtained from biotite.

	P (kbar) Uchida et al. (2007)	T (°C) Luhr et al. (1984)	(fO_2) Wones (1989)
Çiçekli (n=7)			
min	0.2	780	-14.4
max	0.3	800	-13.8
mean	0.2	789	-14.2
std (±)	0.1	8	0.2
Somarova (n=17)			
min	0.1	698	-16.9
max	0.4	777	-14.5
mean	0.2	745	-15.4
std (±)	0.1	22	0.7
Sorkunlu (n=20)			
min	0.1	719	-16.2
max	0.4	783	-14.3
mean	0.2	750	-15.3
std (±)	0.1	22	0.6
Şaşurluk (n=11)			
min	0.1	708	-16.6
max	0.4	768	-14.7
mean	0.2	741	-15.5
std (±)	0.1	20	0.6
Aydıntepe (n=13)			
min	0.4	709	-16.5
max	0.7	794	-14.0
mean	0.5	758	-15.0
std (±)	0.1	27	0.8
Kemerlikdağı (n=13)			
min	0.1	726	-16.0
max	0.3	793	-14.0
mean	0.2	763	-14.9
std (±)	0.1	24	0.7
Pelitli (n=8)			
min	0.1	754	-15.1
max	0.7	801	-13.8
mean	0.3	778	-14.5
std (±)	0.2	19	0.5

Pluton, 719 and 783ºC for Sorkunlu Pluton, 780 and 800ºC for Çiçekli Pluton, 698 and 777ºC for Samarova Pluton, 708 and 768ºC for Şaşurluk Pluton and 754 and 801ºC for Pelitli Pluton (Table 12).

4.3.5. Ilmenite-Magnetite Thermometer

The ILMAT program prepared by Lepage (2003) linked to the chemical composition of magnetite and ilmenite minerals in plutonic rocks was used to calculate temperature and oxygen fugacity values for the studied plutonic rocks. When calculating the temperature values, the approaches recommended by Powell and Powell (1977), Spencer and Lindsley (1981) and Andersen and Lindsley (1985) were used.

The mean crystallisation temperatures calculated according to Powell and Powell (1977) were as follows: 406-661ºC for Kemerlikdağı Pluton, 496-582ºC for Çiçekli Pluton, 409-592ºC for Şaşurluk Pluton, 463-497ºC for Somarova Pluton and 595-628ºC for Pelitli Pluton (Table 13).

According to Spencer and Lindsley (1981), the temperatures were as follows; 550-719ºC for Kemerlikdağı Pluton, 618-668ºC for Çiçekli Pluton, 540-661ºC for Şaşurluk Pluton, 583-615ºC for Somarova Pluton and 648-668ºC for Pelitli Pluton (Table 13).

The temperatures according to Andersen and Lindsley (1985) were 556-734ºC for Kemerlikdağı

Table 13- Temperature and oxygen fugacity values obtained from magnetite and ilmenite pairs.

	Powell and Powell (1977)	Spencer and Lindsley (1981)		Andersen and Lindsley (1985)	
	T (°C)	T (ºC)	$\log_{10} fO_2$	T (ºC)	$\log_{10} fO_2$
Çiçekli (n=3)					
min	496	618	-15.6	629	-15.4
max	582	668	-15.1	684	-14.9
mean	541	645	-15.4	658	-15.1
std (±)	43	25	0.3	28	0.3
Somarova (n=4)					
min	463	583	-18.1	592	-17.7
max	497	615	-16.3	626	-15.9
mean	477	599	-17.0	609	-16.6
std (±)	18	16	1.0	17	1.0
Şaşurluk (n=6)					
min	409	540	-19.7	545	-19.3
max	592	661	-16.3	680	-15.9
mean	508	603	-18.2	616	-17.7
std (±)	83	51	1.5	57	1.5
Kemerlikdağı (n=6)					
min	406	550	-17.8	556	-17.5
max	661	719	-13.6	734	-13.5
mean	521	627	-16.0	638	-15.8
std (±)	118	79	2.0	84	1.9
Pelitli (n=3)					
min	595	648	-17.5	668	-17.1
max	628	668	-16.9	689	-16.4
mean	612	658	-17.2	679	-16.7
std (±)	24	14	0.4	15	0.4

Pluton, 629-684ºC for Çiçekli Pluton, 545-680ºC for Şaşurluk Pluton, 592-626ºC for Somarova Pluton and 668-689ºC for Pelitli Pluton (Table 13).

4.3.6. Amphibole-plagioclase Barometer

The total aluminium content of amphiboles increases linearly with increasing pressure and temperature (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992). Especially the $Al^{(T)}$ content of amphiboles crystallising from granitoid magmas is known to be an indicator of pressure and used in pressure calculations with various calibrations. In granitoid rocks, the $Al^{(T)}$ content of amphiboles are used with the calibrations used for pressure estimation given below:

P (kbar)= 4.76 $Al^{(T)}$ - 3.01 (Schmidt, 1992); P (kbar)= 5.03 $Al^{(T)}$ - 3.92 (Hammarstrom and Zen, 1986)

P (kbar)= 5.64 $Al^{(T)}$ - 4.76 (Hollister et al., 1987); P (kbar)= 4.28 $Al^{(T)}$ - 3.54 (Johnson and Rutherford, **1**989)

Of these, the calibration of Johnson and Rutherford (1989) was produced especially for the volcanic rocks and is used for rocks formed at very high pressures. The other three calibrations may be used for granitoid rocks. However, the calibrations of Hammarstrom and Zen (1986) and Hollister et al. (1987) provide best results for granitoid rocks crystallising under high pressure conditions, while the Schmidt (1992) calibration provides better results for rocks formed at low pressures. For pressure estimations, the amphibole crystals with $Al^{(T)}$ variations used should have formed in plagioclase, amphibole, biotite, pyroxene, K-feldspar, magnetite, ilmenite ± sphene equilibrium crystallisation.

The pressures calculated based on the aluminium-hornblende barometer in amphiboles are given in Table 9. The lowest pressures were obtained with the Hammarstrom and Zen (1986) calibration, while the highest pressures were obtained with the Schmidt (1992) calibration (Table 9).

The crystallisation pressures calculated for the studied plutons have very close values to each other

(Table 9). While the crystallisation pressures for the studied plutonic rocks vary from 0.1 to 2.2 kbar, these values are as follows for the individual plutons; 0.2-1.6 kbar for Çiçekli Pluton, 0.1-2.2 kbar for Somarova Pluton, 0.1-2.1 kbar for Sorkunlu Pluton, 0.1-1.8 kbar for Şaşurluk Pluton, 0.1-2.2 kbar for Aydıntepe Pluton, 0.1-1.5 kbar for Kemerlikdağı Pluton and 0.1-1.1 kbar for Pelitli Pluton (Table 9).

4.3.7. Amphibole Barometer

Using amphiboles in the studied plutonic rocks, amphibole barometer calculations were done based on the formula proposed by Ridolfi et al. (2010) and Ridolfi and Renzulli (2012) and the values are given in table 10.

The crystallisation pressures calculated according to Ridolfi et al. (2010) are between 0.3 and 0.9 kbar for Aydıntepe Pluton, 0.3-0.8 kbar for Çiçekli Pluton, 0.6-0.7 kbar for Kemerlikdağı Pluton, 0.3-0.6 kbar for Pelitli Pluton, 0.3-0.7 kbar for Samarova Pluton, 0.3-0.8 kbar for Şaşurluk Pluton and 0.4-0.9 kbar for Sorkunlu Pluton (Table 10).

According to Ridolfi and Renzulli (2012), the calculated crystallisation pressures are as follows; 0.3-1.3 kbar for Aydıntepe Pluton, 0.4-0.9 kbar for Çiçekli Pluton, 0.5-0.9 kbar for Kemerlikdağı Pluton, 0.6-0.9 kbar for Pelitli Pluton, 0.4-0.8 kbar for Samarova Pluton, 0.7-0.9 kbar for Şaşurluk Pluton and 0.7-1 kbar for Sorkunlu Pluton (Table 10).

4.3.8. Clinopyroxene Barometer

Pyroxene barometer formula proposed by Thompson (1977) was used to determine under which pressure the magma of the plutonic rocks were uprise. (Figure 14). Thompson (1977) stated the high crystallisation pressure in magmas was linked to high Al^T content. Thus, based on the Al^T and Ti contents of clinopyroxene, the crystallisation pressure of clinopyroxene can be estimated.

The low Al^T and Ti content of clinopyroxene in the studied plutonic rocks indicates that these minerals crystallised at a lower temperature according to Thompson (1977), with the values for these plutonic rocks below 5 kbar (Figure 14).

Thermobarometer calculations proposed by Putirka (2008) for hydrous melts and calibrated based on clinopyroxene and melt composition are given in table 11. Accordingly, the crystallisation pressures were as follows; 0.2-1.1 kbar for Aydıntepe Pluton, 0.4-0.9 kbar for Çiçekli Pluton, 0.4-2.6 kbar for Kemerlikdağı Pluton, 0.6-2.7 kbar for Pelitli Pluton, 0.7-1.4 kbar for Şaşurluk Pluton and 0.8-2.5 kbar for Sorkunlu Pluton (Table 11).

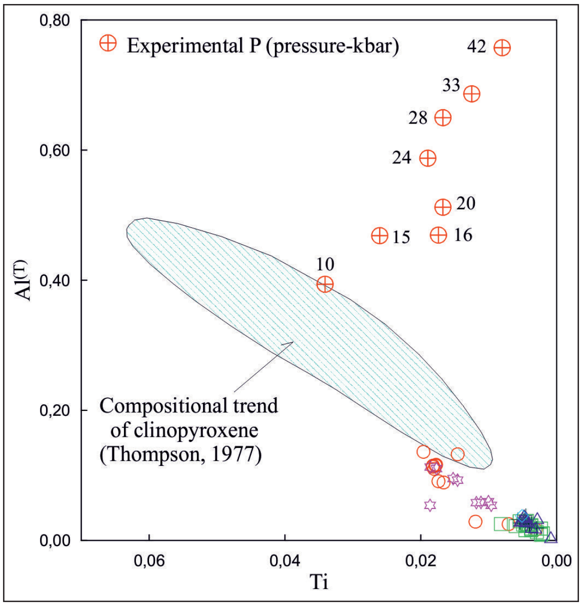

Figure 14- Correlation between Ti-Al^T related to clinopyroxenes from the plutons (For symbols see figure 4).

4.3.9. Biotite Barometer

The empirical equation for determination of the crystallisation pressures for biotites proposed by Uchida et al. (2007) was calibrated according to the calculated $Al^{(T)}$ amount according to 11 oxygen using microprobe analysis results obtained from biotites.

Using this formula recommended by Uchida et al. (2007), the pressures were between 0.1 and 0.3 kbar for Kemerlikdağı Pluton, 0.4 and 0.7 kbar for Aydıntepe Pluton, 0.1 and 0.4 kbar for Sorkunlu Pluton, 0.2 and 0.3 kbar for Çiçekli Pluton, 0.1 and 0.4 kbar for Somarova Pluton, 0.1 and 0.4 kbar for Şaşurluk Pluton and 0.1and 0.7 kbar for Pelitli Pluton (Table 12).

4.3.10. Amphibole Oxygen Fugacity

Using amphiboles from the studied plutonic rocks, oxygen fugacity calculations were performed with the formulae proposed by Ridolfi et al. (2010) and Ridolfi and Renzulli (2012) and the results obtained are given in table 10.

The amphibole oxygen fugacity (ΔNNO) calculated according to Ridolfi et al. (2010) vary as follows; 1.7 to 3 for Aydıntepe Pluton, 1.3 to 2.4 for Çiçekli Pluton, 1.2 to 2.1 for Kemerlikdağı Pluton, 1.9 to 2.7 for Pelitli Pluton, 1.5 to 2.7 for Samarova Pluton, 1.2 to 2.3 for Şaşurluk Pluton and 1.3 to 2.1 for Sorkunlu Pluton (Table 10).

Using the temperature and pressure values obtained by Ridolfi et al. (2010), the oxygen fugacity (fO_2) values calculated with the approach proposed by Wones (1989) were as follows; -14.3 to -12 for Aydıntepe Pluton, -14.4 to -12.3 for Çiçekli Pluton, 14.6 to -12.2 for Kemerlikdağı Pluton, -13.6 to -11.6 for Pelitli Pluton, -14.7 to -12.3 for Samarova Pluton, -14.1 to -13.3 for Şaşurluk Pluton and -14.2 to -12.5 for Sorkunlu Pluton (Table 10).

The oxygen fugacity values (ΔNNO) calculated using the equations of Ridolfi and Renzulli (2012) were between -0.1 to 2.4 for Aydıntepe Pluton, -0.2 to 1.7 for Çiçekli Pluton, -1.7 to 1.2 for Kemerlikdağı Pluton, 0.4 to 1.7 for Pelitli Pluton, -0.3 to 0.8 for Samarova Pluton, 0 to 0.8 for Şaşurluk Pluton and -0.1 to 1 for Sorkunlu Pluton (Table 10).

4.3.11. Biotite Oxygen Fugacity

The oxygen fugacity values (fO_2) calculated by using the pressure values recommended by Wones (1989) and calculated by Luhr et al. (1984) (Table 12) and using the temperature values by Uchida (2007) (Table 12) are given in table 12 and are as follows: -16 to -14 for Kemerlikdağı Pluton, -16.5 to -14 for Aydıntepe Pluton, -16.2 to -14.3 for Sorkunlu Pluton, -14.4 to -13.8 for Çiçekli Pluton, -16.9 to -14.5 for Samarova Pluton, 16.6 to -14.7 for Şaşurluk Pluton and -15.1 to -13.8 for Pelitli Pluton.

4.3.12. Ilmenite-magnetite Oxygen Fugacity

The oxygen fugacity values were calculated using the ILMAT program prepared by Lepage (2003) linked to the chemical composition of magnetite and ilmenite minerals in studied plutonic rocks.

The oxygen fugacity values calculated according to Spencer and Lindsley (1981) and Andersen and Lindsley (1985) were as follows; -17.8 to -13.6 for Kemerlikdağı Pluton, -15.6 to -15.1 for Çiçekli Pluton, -19.7 to -16.3 for Şaşurluk Pluton, -18.1 to -16.3 for Samarova Pluton and -17.5 to -16.9 for Pelitli Pluton (Table 13).

The oxygen fugacity values calculated according to Andersen and Lindsley (1985) are given in Table 13 and were as follows; -17.5 to -13.5 for Kemerlikdağı Pluton, -15.4 to -14.9 for Çiçekli Pluton, -19.3 to -15.9 for Şaşurluk Pluton, -17.7 to -15.9 for Samarova Pluton and -17.1 to -16.4 for Pelitli Pluton (Table 13).

4.3.13. Amphibole Hydrometer

Using amphiboles in the studied plutonic rocks, hydrometer calculations were performed using formulae recommended by Ridolfi et al. (2010) and Ridolfi and Renzulli (2012) and the results are given in table 10.

The mean water content calculated according to Ridolfi et al. (2010) is 3.2-5.7% for Aydıntepe Pluton, 3.1-5.5% for Çiçekli Pluton, 3.4-6.8% for Kemerlikdağı Pluton, 2.9-5.1% for Pelitli Pluton, 3.5-5.8% for Samarova Pluton, 3.8-4.5% for Şaşurluk Pluton and 3.8-4.5% for Sorkunlu Pluton (Table 10).

According to Ridolfi and Renzulli (2012), the calculated mean water contents were as follows; 4.1-6.6% for Aydıntepe Pluton, 4.2-5.6% for Çiçekli Pluton, 3.7-5.4% for Kemerlikdağı Pluton, 4.6-5.1% for Pelitli Pluton, 4.5-5.9% for Samarova Pluton, 4.6-5.4% for Şaşurluk Pluton and 4.5-5.6% for Sorkunlu Pluton (Table 10).

5. Discussion

The Eastern Pontides, forming from the Palaeozoic to the present day, have been under a compressional regime dominated by nearly N-S orientation especially since the beginning of the Mesozoic, with NE-SW and NW-SE oriented fracture systems developed related to this regime. Generally, the long axes of plutons in the Eastern Pontides align with these main fracture orientations. The correlation of pluton emplacement with main fracture lines was first determined by Gedikoğlu (1978), with new studies in the region clarifying these correlations (Kaygusuz et al., 2008, 2012). The studied plutonic rocks are generally emplaced parallel to the NE-SW oriented fracture lines. The plutons generally have ellipsoidal shape, with sharp and unconformable contacts with wall rocks and fine-grained contact facies with these rocks. At contacts with wall rocks, porphyritic and granophyritic textures are observed and a small number of xenoliths from the wall rocks are observed. All these characteristics indicate the studied plutonic rocks were emplaced at shallow depths of the crust.

The mineral content of the studied plutonic rocks allowed the chance to use amphibole-plagioclase (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992), amphibole (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012), biotite (Uchida et al., 2007) and clinopyroxene (Putirka, 2008) geobarometers; amphibole-plagioclase (Blundy and Holland, 1990), amphibole (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012), ilmenite-magnetite (Powell and Powell, 1977, Spencer and Lindsley, 1981; Andersen and Lindsley, 1985), biotite (Luhr et al., 1984) and clinopyroxene (Putirka, 2008) geothermometers; amphibole (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012), biotite (Wones, 1989) and ilmenite-magnetite (Spencer and Lindsley, 1981; Andersen and Lindsley, 1985) oxygen fugacity calculations and amphibole hydrometry (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012).

The amphibole-plagioclase and amphibole barometers used in this study reveals similar values (0.1-2.2 kbar), while the values obtained from the biotite barometer are lower (0.1-0.7) and the values obtained from the clinopyroxene barometer are higher (0.2-2.7). When compared with other Eocene-aged plutonic rocks in the Eastern Pontides, the pressure values for these plutonic rocks are similar to values identified for the Dölek-Sarıçiçek plutons (1-3.8 kbar, Karslı et al., 2007), whereas, they have lower values compared to the Dölek, Sarıçiçek, Sorkunlu, Üzengili and Arslandede plutons (0.3-8.2 kbar, Eyüboğlu et al., 2017). As mentioned previously, the amphiboles in the studied plutonic rocks are calcic amphiboles with $Al^{(t)}$ values lower than 2.0. According to Hammarstrom and Zen (1986), hornblendes having $Al^{(t)} \leq 2.0$ values generally indicate shallow depth intrusion. Additionally, the textural properties like graphic-growth supporting shallow intrusion of the plutons are noteworthy in the studied plutons. The solidus temperature given by thermometers like amphibole-plagioclase is generally >700°C (Anderson, 1996). If the solidus temperature obtained from amphibole--plagioclase thermometers is lower than this temperature (~700°C), subsolidus re-equilibration occurs (Moazzen and Droop, 2004).

Calculations made on minerals in the studied plutonic rocks indicate temperature values ranging between 625 and 842°C for amphibole-plagioclase, amphibole and biotite thermometers, while the values indicate that the clinopyroxene thermometer are higher (1104-1161°C) and values for the magnetite-ilmenite thermometer are lower (406-719°C). Compared with other plutonic rocks with similar age in the Eastern Pontides, the studied plutons have similar temperature values to those calculated for the Dölek-Sarıçiçek plutons (617-768°C, Karslı et al., 2007) and are lower than those of the Dölek, Sarıçiçek, Sorkunlu, Üzengili and Arslandede plutons (388-1196°C, Eyüboğlu et al., 2017).

The biotites from the studied plutons have average values of Al^4 (2.42-2.54 fbb) and partly high Mg# (0.43-0.55), posses close values to the biotites in the plutons formed by mantle-sourced magma products (Al^4 = 2.3-2.4; Mg# > 0.60) and partly different values (Figure 15). As shown in figure 15, the biotites of studied plutons remain separate from mantle-derived melt and meta-sedimentary melt mixing curve. This leads to the consideration that the source rock was not purely mantle. Additionally, the observation of textural data indicating disequilibrated crystallisation in the studied samples and the common mafic magmatic enclaves observed in most of the plutons indicates magma mixing.

As the original oxygen fugacity of granitic magmas cannot be determined due to slow cooling, only relative approaches and calculations may be made (Wones, 1989; Anderson and Smith, 1995; Kemp, 2004). In the studied samples, the oxygen fugacity values ($\log_{10} fO_2$) are between -20 and -12, similar to the values identified for the Eocene-aged Dölek-Sarıçiçek plutons (-15 to -21, Karslı et al., 2007)

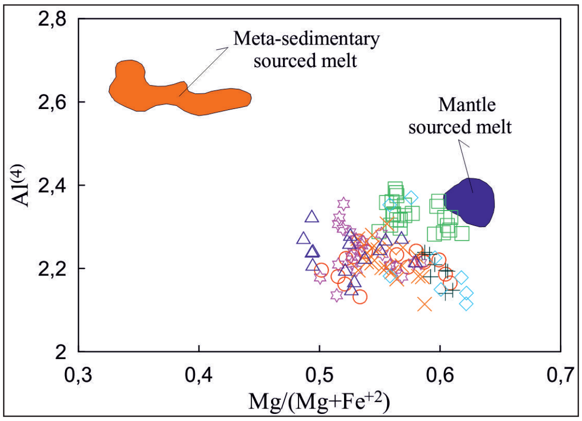

Figure 15- Correlation between Al^4-$Mg/(Mg+Fe^{+2})$ in biotites from the plutons and comparison with meta-sedimentary sourced melts and mantle sourced moderate-felsic melts [meta-sedimentary melt area from Kemp (2001), mantle sourced melt area taken from Kemp (2004)] (For symbols see figure 4).

The water content of magmas containing amphiboles is controversial, with variation between 2-3% according to Luhr et al. (1992), mean 5% according to Eggler (1972), Helz (1973) and Naney (1983) and mean 6% according to Merzbacher and Eggler (1984). In the studied samples, the water content calculated from the amphiboles was 2.9 to 6.8. The presence of hydrous mafic minerals (amphibole, biotite), titanite and apatite in the samples indicates high water and volatile contents in magma. The high temperature magmas in this content may rise to shallow depths in continental crust without completely crystallising (Helmy et al., 2004).

Finally, according to thermobarometric calculations based on mineral chemistry data, the studied rocks have pressure values between 0.1 and 2.7 kbar and temperature values from 406 to 1161°C. When all these characteristics are noted, it is proposed that the studied plutons were emplaced at shallow depths (1-8 km) within Eastern Pontide continental crust thickened after collision in the Cenozoic period.

6. Conclusions

The investigated Cenozoic plutons generally have NE-SW orientation and nearly ellipsoid shapes. The sizes of the plutons vary from 3 to 22 km^2 with the smallest Çiçekli Pluton (3 km^2) and the largest Kemerlikdağı pluton (22 km^2). The Çiçekli and Şaşurluk plutons are slightly more altered compared to the other plutons. The composition of the studied plutons ranges from gabbroic diorite to monzogranite. The main minerals in the rocks are plagioclase, K-feldspar, quartz, amphibole, biotite, pyroxene and Fe-Ti oxides. The rocks have fine-moderate granular, porphyric, monzonitic, poikilitic, occasionally myrmekitic, micrographic and graphic textures. Additionally, there are some special mixing textures observed indicating magma mixing. The An content of plagioclase in the studied plutonic rocks varies from 2 to 69, with the highest in the Sorkunlu Pluton and the lowest in the Şaşurluk Pluton. The Or content of K-feldspar varies from 1 to 96, with the lowest content in the Somarova Pluton and highest in the Şaşurluk Pluton. The biotite in the rocks is a solid melt product between the phlogopite-annite end members and is rich in magnesium. Amphiboles are calcic amphiboles, with magnesium-rich hornblende and actinolite in composition. Pyroxenes are calcic clinopyroxenes, apart from Aydıntepe Pluton containing clinoenstatite orthorhombic pyroxenes. Calcic pyroxenes are generally augite, with low rates of diopside in composition. Fe-Ti oxides comprise magnetite and ilmenite. According the thermobarometer calculations, the studied plutons have pressures from 0.1 to 2.7 kbar, temperature from 406 to 1161°C, oxygen fugacity values between -20 and -12 and water content of 2.9-6.8%. When field, petrographic and thermobarometric data are considered together, it may be concluded that the studied plutons were intruded at shallow depths (~1-8 km) in continental crust.

Acknowledgements

This study was supported by TÜBİTAK project number 115Y154. We thank Emre Topçu and Damla Selvi for their help during field studies. We gratefully acknowledge Pınar Şen, Fatih Karaoğlan, Şenel Özdamar and two anonymous reviewers for their contributions during the review and assessment stages of this manuscript.

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