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Emplacement conditions of magma(s) forming Jurassic plutonic rocks in Gümüşhane (Eastern Pontides, Turkey)

Emre AYDINÇAKIR[a*], Ramazan GÜNDÜZ[b] and Cem YÜCEL[c]

[a]*Department of Geological Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, Gümüşhane, Turkey*
[b]*Department of Geological Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, Gümüşhane, Turkey*
[c]*Department of Mining Engineering, Faculty of Engineering and Natural Sciences, Gümüşhane University, Gümüşhane, Turkey*

Research Article

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ABSTRACT

In this study, the petrography, mineral chemistry and crystallization conditions were reported for the Alemdar and Işıkdere plutons located in limited areas in the south of the Eastern Pontides. These plutons, which trend mostly in NE-SW directions, were emplaced by cutting the Early-Middle Carboniferous-aged Gümüşhane Granitoid and Early-Middle Jurassic Şenköy formation. Petrographically, the studied plutons are compositionally fine to medium grained quartz-diorite, quartz monzodiorite and tonalite. The rocks in the plutons have granular, poikilitic, monzonitic, graphic and rare porphyritic textures with consist of plagioclase, (An_{05-92}), hornblende (Mg# = 0.52-0.81), biotite (Mg# = 0.32-0.67), orthoclase, quartz and Fe-Ti oxide. According to thermobarometric calculations, plutons have crystallization temperatures, pressures and oxygen fugacity values ranging from 541°C to 938°C, 0.1 to 4.4 kbar, and -23 to-12, respectively. The estimated water content calculated from amphibole is between 4.4 to 7.8%. It can be concluded that the studied plutons were emplaced at mid to shallow crustal depths (~4-15 km).

1. Introduction

The Eastern Pontide Orogenic Belt (NE Turkey), where the study area is located, comprises volcanic and plutonic rock assemblages (Karslı et al., 2007, 2012; Kaygusuz et al., 2008, 2018; Dokuz, 2011; Temizel et al., 2012, 2018, 2019*a*, 2019*b*; Aydınçakır and Şen, 2013; Arslan et al., 2013; Aydın, 2014; Yücel et al., 2017). The region dominantly hosts plutonic and volcanic rocks formed over long periods of time from the Permo-Carboniferous to the end of the Eocene (Figure 1). Carboniferous-aged plutonic rocks (Yılmaz, 1972; Çoğulu, 1975; Topuz et al., 2010; Dokuz, 2011; Kaygusuz et al., 2012, 2016; Karslı et al., 2016; Dokuz et al., 2017*a*) were emplaced by cutting across the metamorphic rocks. The basement rocks in the region are unconformably overlain by Jurassic volcano-sedimentary sequences (Şenköy formation, Kandemir, 2004) (Kandemir, 2004; Dokuz and Tanyolu, 2006; Eyüboğlu et al., 2006; Şen, 2007; Kandemir and Yılmaz, 2009; Genç and Tüysüz, 2010; Dokuz et al., 2017*b*). Cretaceous-aged plutonic rocks known to be subduction related (Şahin et al., 2004; Kaygusuz and Aydınçakır, 2009, 2011; Karslı et al., 2010; Kaygusuz et al., 2013; Sipahi et al., 2017; Eyüboğlu et al., 2019; Temizel and Kurt, 2019; Temizel et al., 2019*a*) have contact relations with volcanic and/or volcanoclastic rocks. Eocene-aged plutons (Yılmaz and Boztuğ, 1996; Arslan and Aslan,

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* *Corresponding author: Emre AYDINÇAKIR, aydincakir61@gmail.com*

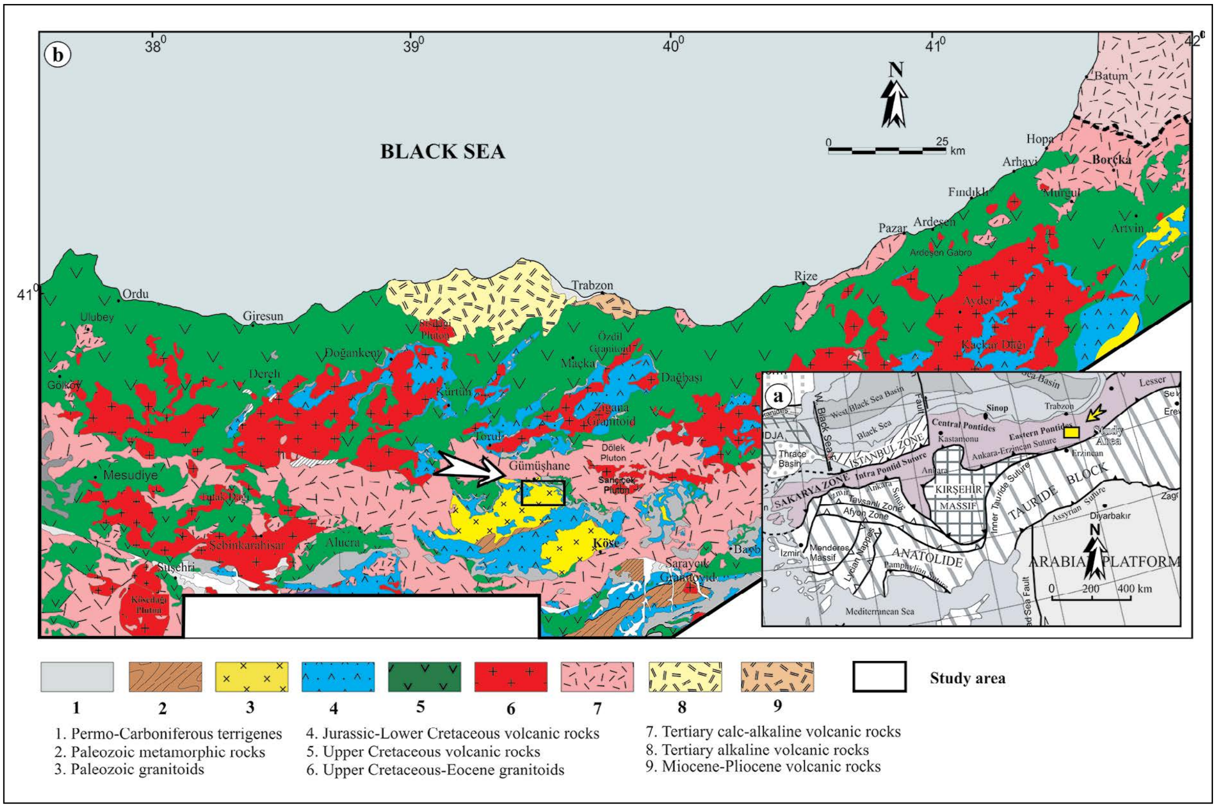

Figure 1- a) Tectonic branches of Turkey (after Okay and Tüysüz, 1999) and b) geologic map showing volcanic and magmatic rocks outcropping in the Eastern Pontides (after Güven, 1993; Aydınçakır and Şen, 2013; Yücel et al., 2017)

2006; Karslı et al., 2007, 2011; 2012; Kaygusuz and Öztürk, 2015; Eyüboğlu et al., 2017; Kaygusuz et al., 2018; Temizel et al., 2018, 2019*b*) were emplaced by cutting the whole series.

In recent years a limited number of studies were completed in the Eastern and Central Pontides about the geodynamic source of mafic and acidic rocks emplaced in the Early-Middle-Late Jurassic period (Dokuz et al., 2010; Karslı et al., 2014, 2017; Eyüboğlu et al., 2016; Çimen et al., 2017, 2018). However, the direction and the time of subduction and the geochemical features of associated magmatic activity are still controversial. Since the emplacement conditions of the plutons have not been studied previously, this is the first study to reveal the emplacement conditions of plutons.

This study focuses mainly on the petrography and mineral chemistry of the Jurassic-aged Alemdar and Işıkdere Plutons observed in a narrow area in the Gümüşhane (Eastern Pontides) region with the aim of 1) determining physicochemical properties such as temperature, pressure and oxygen fugacity effective during crystallisation of magma(s), and 2) combining physicochemical data with geologic data to determine the evolution of magma(s) in the crust.

2. Regional Geology

The oldest units in the Eastern Pontide Orogenic Belt comprise metamorphic basement of Early-Middle Carboniferous gneiss, schist, amphibolite, marble and minor metaperidotites (Topuz et al., 2004, 2007; Okay et al., 2006; Dokuz, 2011) (Figure 1). These rocks were intruded by Middle Carboniferous-Early Permian plutonic rocks (Çoğulu, 1975; Topuz et al., 2010; Dokuz, 2011; Kaygusuz et al., 2012, 2016; Karslı et al., 2016; Dokuz et al., 2017*a*). Late Carboniferous shallow marine-terrestrial sedimentary rocks, unconformably overlying the basement metamorphic rocks, are observed only in the Pulur region (Okay and Leven, 1996; Kandemir and Lerosey-Aubril, 2011). Jurassic rocks in the Eastern Pontides comprise pyroclastic and sedimentary rocks containing clastic and limestone blocks (Ağar, 1977; Saydam Eker et al., 2012). The Şenköy formation consists of andesite, basalt, agglomerate and diabase displaying lateral transitions, and different thicknesses over short distance, with volcanics, pebblestone, marl, claystone, sandstone and Ammonitico rosso-type limestones (Dokuz and Tanyolu, 2006; Şen, 2007). Recent studies have shown that plutonic equivalents of pillow basalts were formed during the time interval ranging from Middle Triassic to Early Jurassic (Dokuz and Tanyolu., 2006; Eyüboğlu et al., 2010, 2016; Ustaömer and Robertson, 2010; Karslı et al., 2014). In the region, the Late Jurassic-Early Cretaceous period is very barren in terms of tectonic movements and magmatic activity. In this period, carbonate deposition is the common rock lithology.

The Late Cretaceous period present that a lithology dominated by plutonic and volcanic rocks of the north-south direction in the Eastern Pontides (Okay and Şahintürk, 1997; Kaygusuz et al., 2008; Kaygusuz and Aydınçakır, 2009; Karslı et al., 2012; Aydın, 2014; Yücel, 2017; Demir, 2019). High potassium magmatism is also widespread in the region (Altherr et al., 2008; Eyüboğlu et al., 2010; Gülmez et al., 2016; Aydınçakır, 2016, 2017; Özdamar et al., 2017). The collision of the Eastern Pontides magmatic arc and the Anatolide-Tauride continental block occurred in the Late Paleocene-Early Eocene (Okay and Şahintürk, 1997; Dilek, 2006). The Early Eocene (54-48 Ma) adakitic and non-adakitic magmatism in the Eastern Pontides (Eyüboğlu et al., 2010, 2013; Topuz et al., 2011; Karslı et al., 2011; 2013; Dokuz et al., 2013; Aydınçakır, 2014; Temizel et al., 2019*b*) is thought to the last stage of arc to continent collision. As for the Eocene period is represented by the post-collisional calc-alkaline volcanic rocks and high-K calc-alkaline and shoshonitic plutons (Karslı et al., 2007, 2012; Aslan, 2010; Temizel et al., 2012, 2018; Aydınçakır and Şen, 2013; Arslan et al., 2013; Aslan, et al., 2014; Yücel et al., 2017; Eyüboğlu et al., 2017). The clastic rocks are widespread in the region in the post-Eocene (Okay and Şahintürk, 1997) and are generally accompanied by Neogene alkaline volcanic rocks (Aydın et al., 2008; Arslan et al., 2013; Yücel et al., 2014; 2017).

3. Material and Method

During field studies, geological maps of Güven (1993) and MTA (2002) were used to prepare 1/25.000 scale geological map and rock samples were taken from the Alemdar and Işıkdere plutons to perform petrographic and mineral chemistry studies. Thin sections were prepared in Gümüşhane University Department of Geological Engineering Thin Section Laboratory. The thin sections were investigated with polarising microscope and mineral content and textural features were determined. For modal analysis, a Swift brand point counter was used. Counts were generally completed according to grain size at 0.02 to 0.04 mm intervals and nearly 600-800 points were counted in each section.

Mineral chemistry analyses were performed at Bretagne Occidentale University Geoscience Marines (IFREMER) Electron Microprobe Laboratory located in Brest (France). Samples for mineral chemistry analysis with a CAMECA-SX-100 WDS brand device were prepared as carbon-coated polished sections. The device setting was 15 kV electron bombardment and 20 nA bombardment flow. The count time for Si, Al, Ti, Fe, Mn, Mg, Ca, Na and K elements was set to 10 s. Analyses of hornblende and Fe-Ti oxides used 1 µm point ray while feldspar and mica mineral analyses used slightly defocused (10 µm) rays to prevent losses due to sodium evaporation. Analyses used natural mineral standards of forsterite, diopside, orthoclase, albite, anorthite, biotite, apatite, wollastonite and magnetite. Analyses were carried out with analytic error less than 1% for major elements and less than 200 ppm for trace elements.

4. Results

4.1. Geological Setting of Plutons

The basement of the study area where the Alemdar and Işıkdere plutons are located comprises the Early-Middle Carboniferous Gümüşhane Granitoid (Çoğulu, 1975; Topuz et al., 2010) (Figure 2). The Gümüşhane Granitoid is unconformably overlain by the Early-Middle Jurassic pebblestone, marl, sandstone, siltstone, tuff, and Ammonitic Rosso-type limestone and acidic-basic lava, dikes and sills of the Şenköy formation (Kandemir, 2004) (Figure 2). The Şenköy formation is conformably overlain by the Upper Jurassic-Lower Cretaceous carbonate limestones of the Berdiga formation (Pelin, 1977). The youngest unit is Quaternary alluvium (Figure 2).

The Alemdar Pluton covers an area of 7-8 km^2 around Bağlarbaşı town, Alemdar locale and

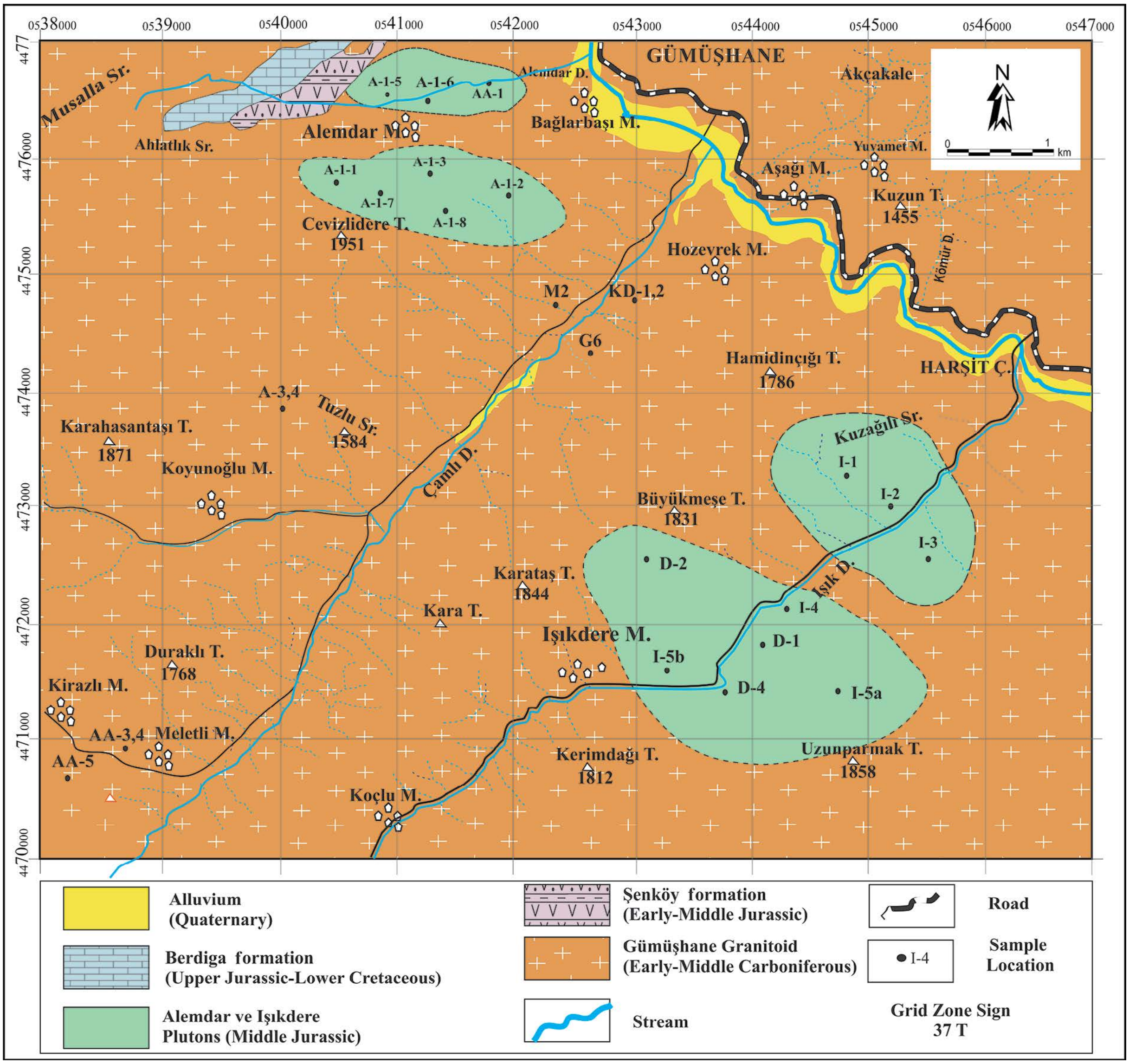

Figure 2- Geologic map of the study area.

Cevizlidere Hill in the south of Gümüşhane province (Figure 2). Alemdar Pluton was intruded into the Early-Middle Carboniferous Gümüşhane Granitoid and volcanic and volcano-sedimentary rocks of the Early-Middle Jurassic Şenköy formation (Figure 3a). According to contact and crosscutting relations of the pluton in the field, the age of the pluton was accepted as Jurassic in this study for the first time. The Alemdar Pluton has elliptical shape (Figure 2) and very hard, fractured and jointed structure. It also outcrops as small blocks (Figure 3a, b). Epidotization and silicification are observed in contact zones between the pluton and country rock (Figure 3c). Outcrops of the Alemdar pluton generally has rounded form. Due to the abundance of ferromagnesian minerals such as hornblende and biotite, it is generally gray-dark gray colored and is moderate-fine grained (Figure 3d, e). The Işıkdere Pluton forms two stocks outcropping in Işıkdere locale and surroundings toward the southwest along the Işık Dere (stream) valley. The Işıkdere Pluton has NW-SE trend with nearly elliptical shape (Figure 2). The Işıkdere Pluton intruded into the Gümüşhane Granitoid (Figure 2). The pluton is clearly distinguished from the Gümüşhane Granitoid by its dark gray and/or greenish-gray colour (Figure 3d). The rocks forming the Işıkdere Pluton appear to be very fresh and are recognized by remarkable mafic mineral content (Figure 3e).

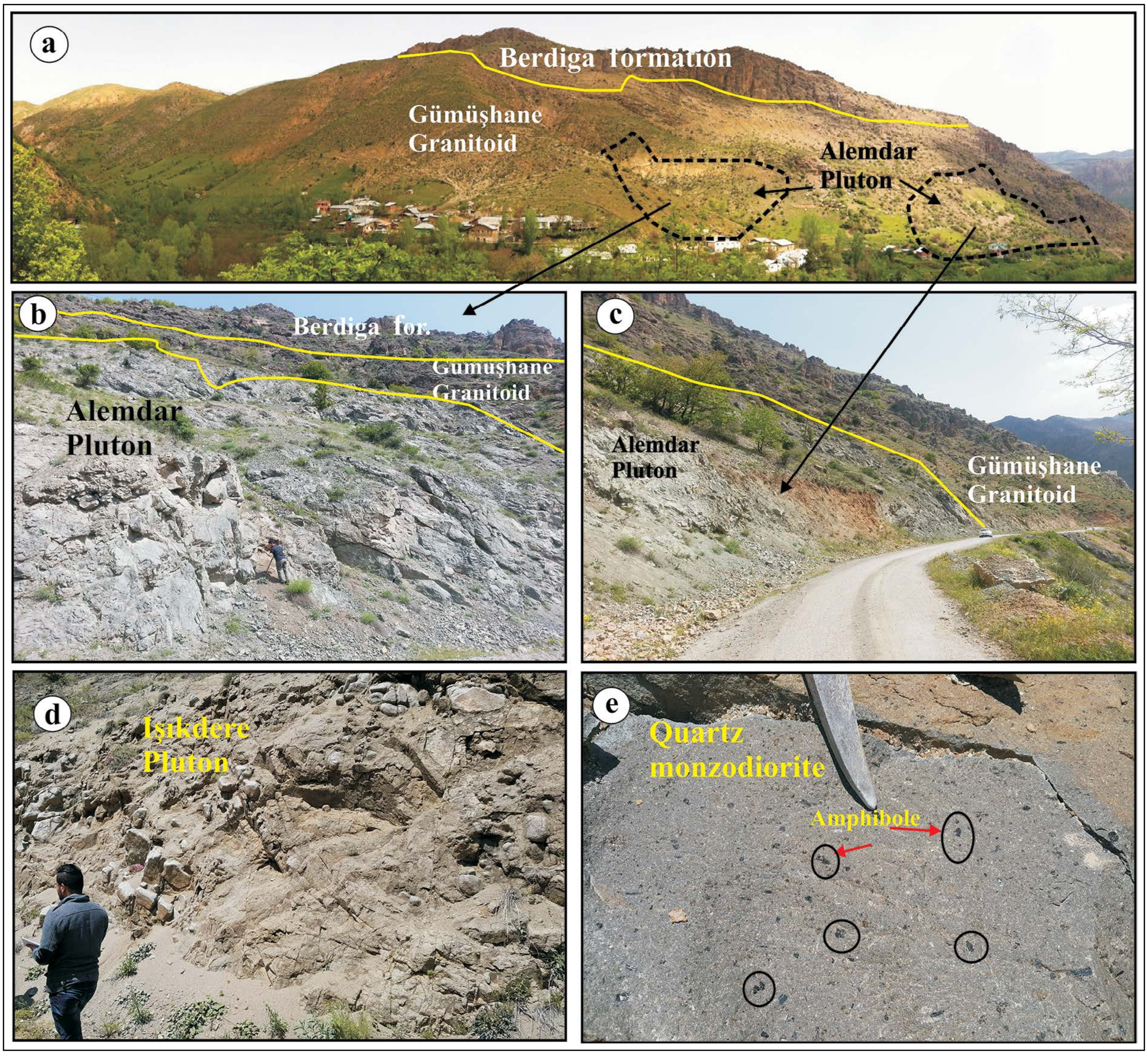

Figure 3- a) Contact relations between the Alemdar Pluton and surrounding rocks (photo taken toward the north in Alemdar locale), b, c) Contact relations between Alemdar Pluton and Gümüşhane Granitoid (Alemdar), d) Field view of Işıkdere Pluton (taken toward the north, Işıkdere neighborhood) and e) close-up view of Işıkdere Pluton.

4.2. Petrography

The petrographic charecteristics of the rocks from the Alemdar and Işıkdere Plutons were investigated and are given in table 1. On the QAP diagram (Streckeisen, 1976) based on modal mineralogical analysis (Figure 4), the Alemdar Pluton is represented by quartz-monzodiorite and quartz diorite, while the Işıkdere Pluton is characterized by tonalite (Figure 4).

Petrographic studied of the Alemdar and Işıkdere Plutons demonstrates that they have fine-medium granular, porphyritic, monzonitic and poikilitic texture (Figure 5a-h). The main minerals are dominated by plagioclase, quartz, K-feldspar, hornblende, biotite and magnetite. Apatite and zircon comprise accessory minerals.

The plagioclase from the Alemdar and Işıkdere Plutons is represented by euhedral and subhedral crystals, mostly coarser grained phenocrysts (57-69%) with finer-grained crystals in the groundmass (Figure 5). Some plagioclase crystals display albite twinning (Figure 5a, d and e), oscillatory zoning (Figure 5b, f) and occasional sieve texture (Figure 5a, b). Inverse zoning in some plagioclase minerals

Table 1- The general petrographical characteristics and modal composition of the rocks from the Alemdar and Işıkdere Plutons.

Pluton	**ALEMDAR (n= 13)**			**IŞIKDERE (n= 15)**		
Rock units	Quartz diorite, quartz monzodiorite			Tonalite		
Texture	Granular, porphyric, poikilitic, monzonitic, myrmekitic			Granular, porphyric, poikilitic, monzonitic, myrmekitic		
Grain size	Fine-medium prophryic			Fine-medium porphryic		
Modal min (%)	Max	Min	Mean	Max	Min	Mean
Plagioclase	66.5	58.0	62.4	68.7	57.1	63.1
Quartz	15.8	12.0	13.8	16.2	11.0	13.8
Orthoclase	9.0	2.0	5.8	13.2	1.6	5.9
Hornblende	17.3	5.2	11.4	11.8	2.0	7.3
Biotite	7.8	2.9	5.2	9.7	6.1	8.2
Opaque minerals	2.6	0.7	1.5	1.7	1.2	1.5
Secondary minerals	4.1	2.2	3.2	5.2	1.1	3.4
Accessory minerals	3.1	1.3	2.4	2.5	1.0	1.5

n= sample number

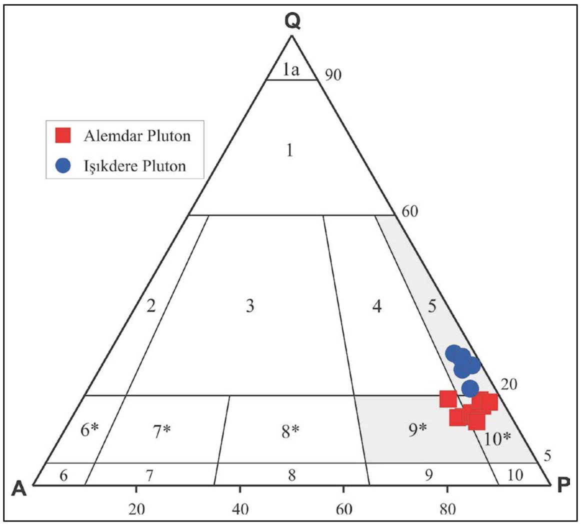

Figure 4- The QAP plot of the rock samples from Alemdar and Işıkdere Plutons (Streckeisen, 1976). The fields; (1a) quarzolite, (1a) quartz rich granitoid, (2) alkaline feldspar granite, (3) granite, (4) granodiorite, (5) tonalite, (6*) quartz alkaline feldspar granite, (7*) quartz syenite, (8*) quartz monzonite, (9*) quartz monzodiorite/quartz monzogabbro, (10*) quartz diorite/quartz gabbro/quartz anorthosite, (6) alkali feldspar syenite, (7) syenite, (8) monzonite, (9) monzodiorite/monzogabbro, (10) diorite/gabbro/anorthosite.

especially indicates disequilibrium crystallization (Figure 5a). Some plagioclases are partially sericitized and kaolinized (Figure 5). The K-feldspars (2-13%) are generally anhedral and common (Figure 5a, g and h). They have carlsbad twin and poikilitic grains tend to contain hornblende, plagioclase and opaque minerals (Figure 5a, e). The poikilitic texture shown by K-feldspar may represent disequilibrium crystallization, forming monzonitic texture surrounding plagioclase in some samples (Figure 5a). Some samples are fractured and partially kaolinized (Figure 5e). Quartz (11-16%) is anhedral, small crystals with generally undulose extinction (Figure 5d). Hornblendes (2-17%) are dark brown and dark green pleochroism, and two directional hornblende cleavage (Figure 5c, f). Poikilitic hornblendes contain inclusions of plagioclase and opaque minerals and may indicate disequilibrium crystallization (Figure 5c). Biotites (3-8%) appears rod-like or leaf-like crystals (Figure 5e, g and h). Biotites have one direction well defined cleavage (001) and light-dark brown pleochroism. Opaque minerals (1-3%) are generally located around, or as inclusions within, mafic minerals such as hornblende and biotite (Figure 5a, c, d and e).

4.3 Mineral Chemistry

4.3.1. Plagioclase

Plagioclase is found in almost all rock types from the Alemdar and Işıkdere Plutons. Plagioclases are observed as euhedral crystals with size varying from 0.1-1 mm. Plagioclases occur as both fine to moderate-large crystals (Figure 6a). The plagioclase crystals display occasional oscillatory (Figure 6a), normal and inverse zoning (Figure 6b). Plagioclases are generally phenocrysts, microlites and laths. The An content of

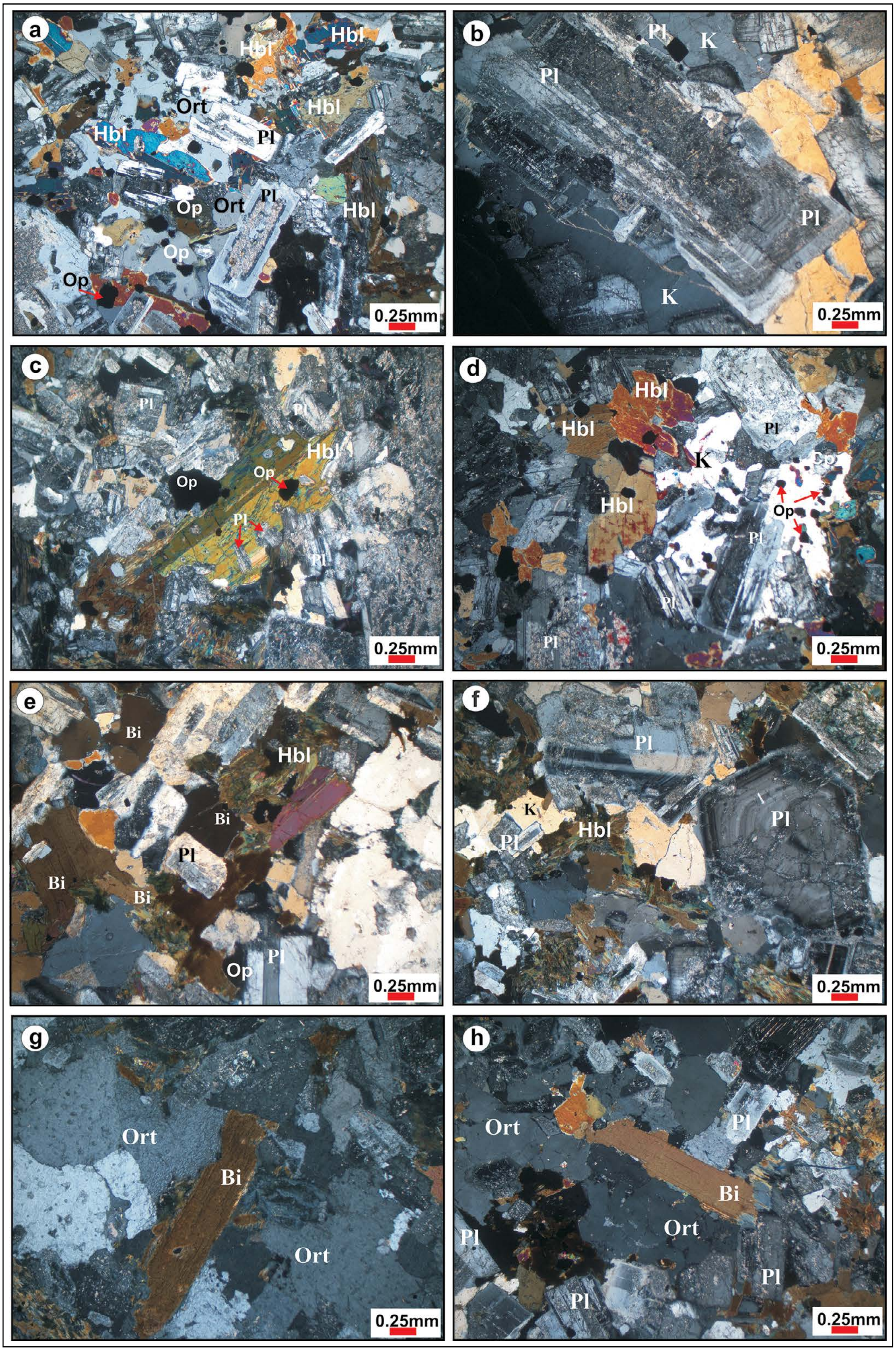

Figure 5- The Alemdar Pluton a) monzonitic texture formed of orthoclase crystal containing plagioclase, b) large-zoned plagioclase crystal surrounded by quartz and containing plagioclase inclusions, c) opaque mineral and hornblende crystal with poikilitic texture containing plagioclase inclusions, d) euhedral plagioclase crystal showing albite twinning, e) euhedral biotite and hornblende crystals. From the Işıkdere Pluton f) plagioclase crystals showing zoned texture and quartz crystal with poikilitic texture and g, h) euhedral biotite crystals (Sample No: A-1-1, I-4; Ç.N.; Pl: Plagioclase, Hbl: Hornblende, Ort: Orthoclase, Bi: Biotite, K: Quartz, Op: Opaque mineral).

plagioclases is from 92 to 05, compositions ranging andesine to anorthite (Figure 7). Andesine composition is $An_{42}Ab_{43}Or_{15}$ in the core and $An_{33-49}Ab_{49-65}Or_{1-4}$, in the rim, labradorite composition is $An_{52-68}Ab_{30-47}Or_{0-4}$ in the core and $An_{51-57}Ab_{42-49}Or_{0-2}$, at the rim, while bytownite composition is $An_{70-79}Ab_{21-30}Or_{0-1}$ in the core and $An_{71}Ab_{29}Or_{1}$ at the rim. One sample was anorthite $An_{92}Ab_{8}Or_{0}$ composition (Supplementary Table 1, Figure 7).

The plagioclase compositions in the Işıkdere Pluton are oligoclase to bytownite (An_{13-77}) (Figure 7). Oligoclase have composition of $An_{30}Ab_{71}Or_{2}$ in the core and $An_{13-29}Ab_{76-86}Or_{2-3}$ in the rim, andesine has composition of $An_{32-50}Ab_{49-61}Or_{1-2}$ in the core and $An_{36-49}Ab_{49-61}Or_{1-2}$ in the rim, labradorite composition is $An_{50-69}Ab_{29-49}Or_{1-2}$ in the core and $An_{51-58}Ab_{41-48}Or_{1-2}$ in the rim, while bytownite composition is $An_{70-77}Ab_{23-29}Or_{1-2}$ in the core and $An_{77}Ab_{23}Or_{1}$ in the rim.

4.3.2. Hornblende

Hornblendes in the Alemdar and Işıkdere Plutons are calcic (Figure 8a) and are classified as magnesiohornblende according to Leake et al. (1997) (Figure 8b). Fe^{+2} and Fe^{+3} calculations from FeO were based on stoichiometric methods. The Mg numbers (Mg/(Mg+Fe^{+2})) of hornblendes from the Alemdar and Işıkdere Plutons vary from 0.52-0.81 and 0.52-0.80, respectively (Supplementary Table 2).

4.3.3. Biotite

The dark-colored micas from the Alemdar Pluton plot on the biotite field of the $Fe^{top}/(Fe^{top}+Mg)$ versus Al^{iv}(apfu) diagram and their $Mg/(Mg+Fe^{top})$ values ranging from 0.47-0.50 (Figure 9, Supplementary Table 3). Micas from the Işıkdere Pluton plot in the biotite (Mg number 0.32-0.67) field of the same classification diagram, with only one sample plot on the Mg-enriched biotite (Figure 9, Supplementary Table 3).

4.3.4. Fe-Ti oxides

Fe-Ti oxides in the Alemdar and Işıkdere plutons are generally anhedral in groundmass and inclusions in ferromagnesian minerals (Figure 10). Fe-Ti oxides in the plutons are classified as magnetite (Supplementary Table 4, Figure 11).

5. Discussion

The variations in temperature (T), pressure (P) and fugacity (partial pressure of oxygen) of magma are the most important factors controlling minerals that will form and the equilibrium status of these minerals. Determination of these factors (T, P, *f*O, etc.) provides significant information about the crystallization process in magma. Thermodynamic features allow the possibility to estimate which minerals will

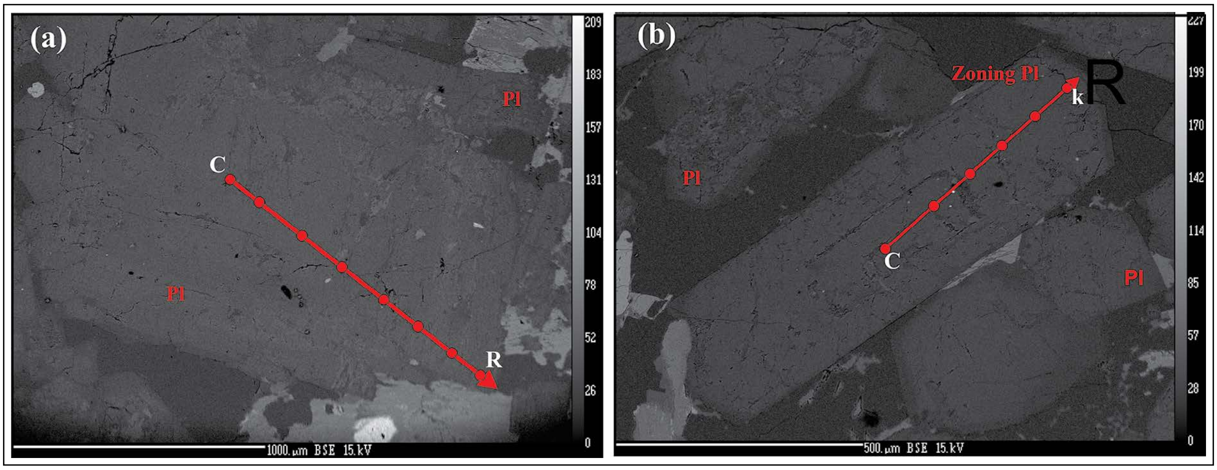

Figure 6- Back scatter electron (BSE) images for euhedral and zoned plagioclases from Alemdar and Işıkdere plutons (Pl: plagioclase, c: core, r: rim).

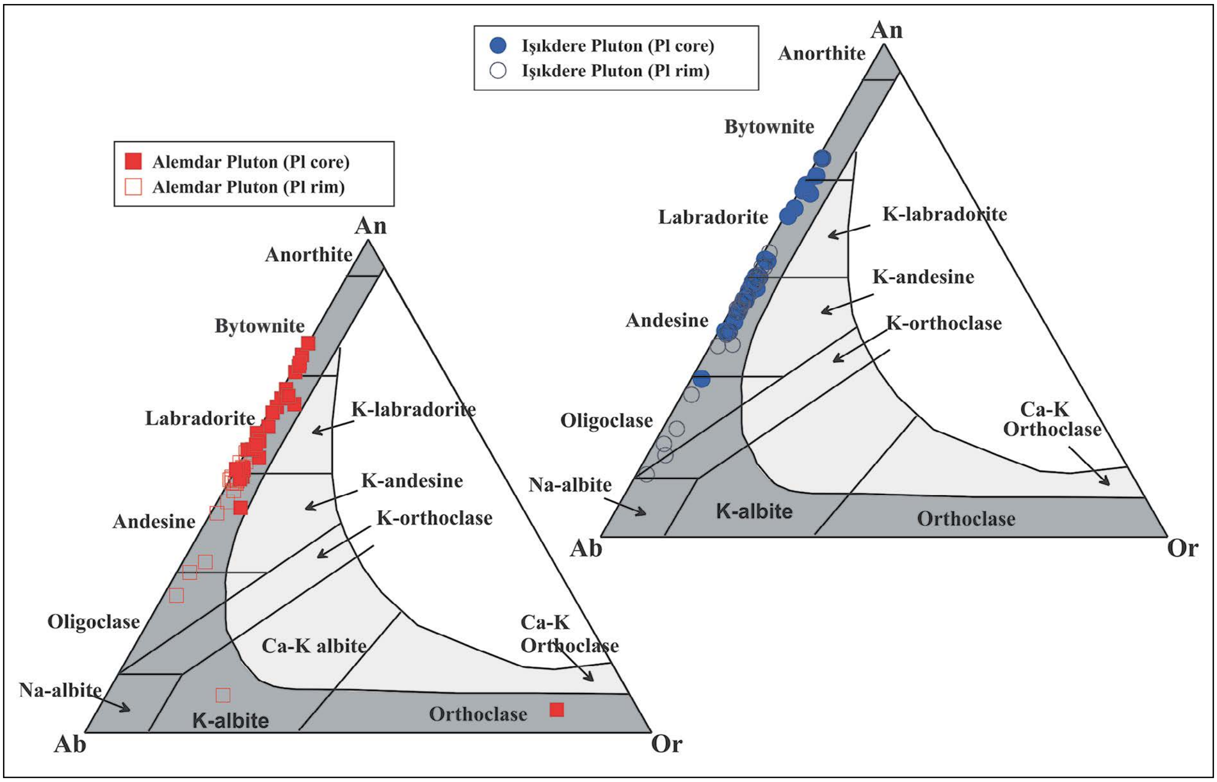

Figure 7- Ab-An-Or ternary diagram showing feldspar compositions of the Alemdar and Işıkdere plutons (Smith and Brown, 1988).

form under different conditions and simultaneously the opportunity to use mineral assemblages and compositions to determine conditions in the setting in which the rock formed (thermobarometry). The error margins in thermodynamic calculations may be determined by revealing the errors in all stages of P-T estimations; these errors may be made in the stages of analyzing mineral compositions, determining and using thermodynamic data and in selecting calibration methods. The error margins for thermodynamic calculations generally vary from ± 30-50°C for temperature and ± 1-0.5 kbar for pressure. In plutonic rocks, limited mineral assemblages that can be used for thermobarometric calculations make determination

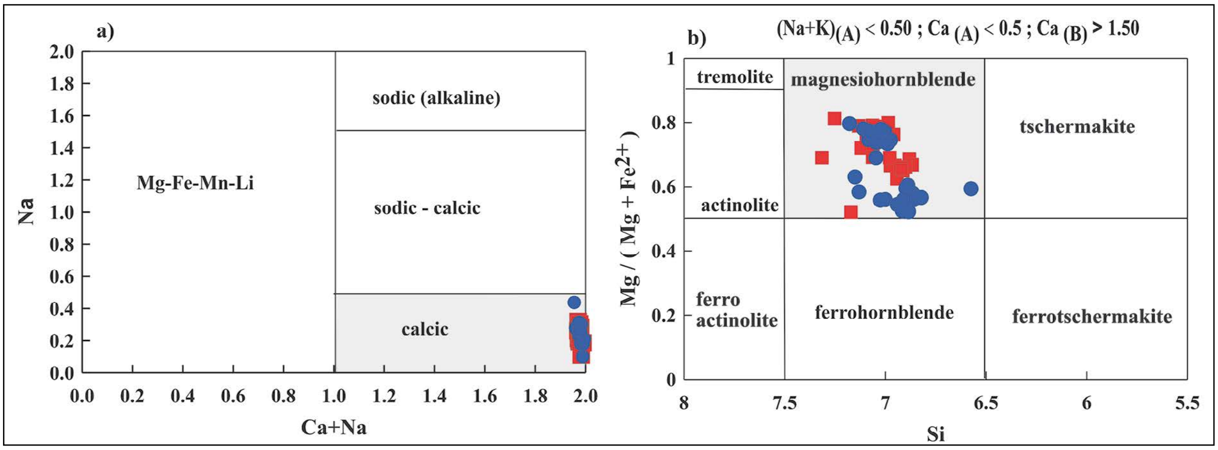

Figure 8- Hornblendes from Alemdar and Işıkdere plutons on classification diagrams (Leake et al., 1997) (symbols as in figure 7).

of pressure and temperature conditions more difficult.

A variety of thermobarometric calculations were made using the minerals and mineral assemblages (hornblende, plagioclase, biotite, K-feldspar, quartz, Fe-Ti oxides) found in these plutonic rocks. Hornblende-plagioclase (Holland and Blundy, 1994), hornblende (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012) and biotite (Luhr et al., 1984) thermometers and hornblende-$Al^{(t)}$ (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992), amphibole (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012) and biotite (Uchida et al., 2007) barometers were used for the studied rocks. The pressures obtained from the hornblende-Al barometer are compatible with the pressures obtained from geological features and coeval metamorphics (Ague, 1997; Toksoy-Köksal, 2016). The oxidation of magma may be found with these mineral assemblages and mineral chemistry (Wones, 1989; Ridolfi et al., 2010; Ridolfi and Renzulli, 2012). The original oxygen fugacity of the granitic magmas cannot be determined

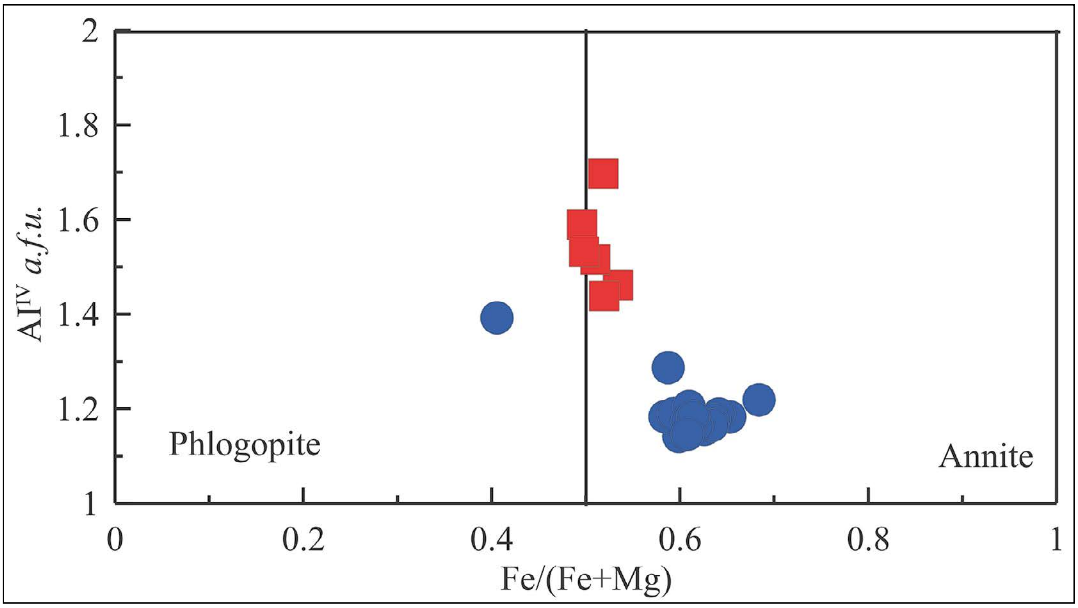

Figure 9- Biotites from the studied plutonic rocks on classification diagram (Speer, 1984) (symbols as in Figure 7).

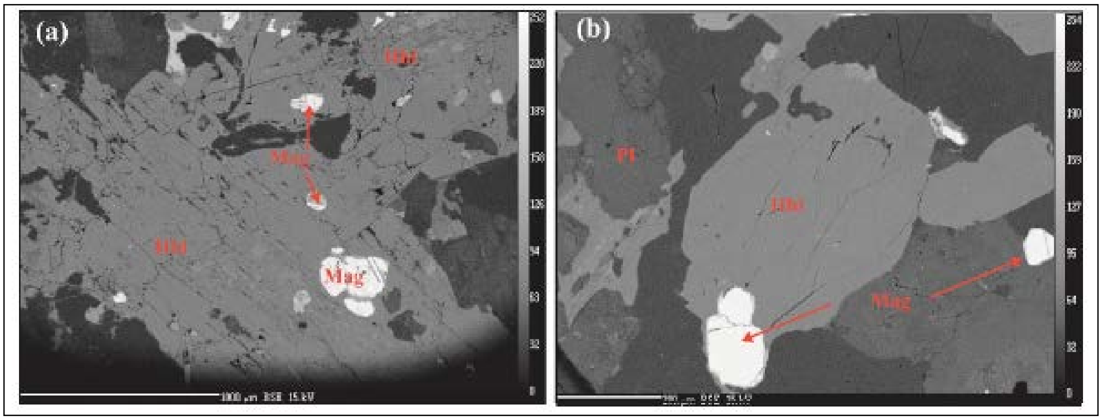

Figure 10- BSE images of Fe-Ti oxides in the Alemdar and Işıkdere plutonic rocks (a and b) euhedral and subhedral magnetite as inclusion in groundmass and hornblende (Sample no: A-1-5 and B-1; Hbl: hornblende, Pl: plagioclase, Mag: magnetite).

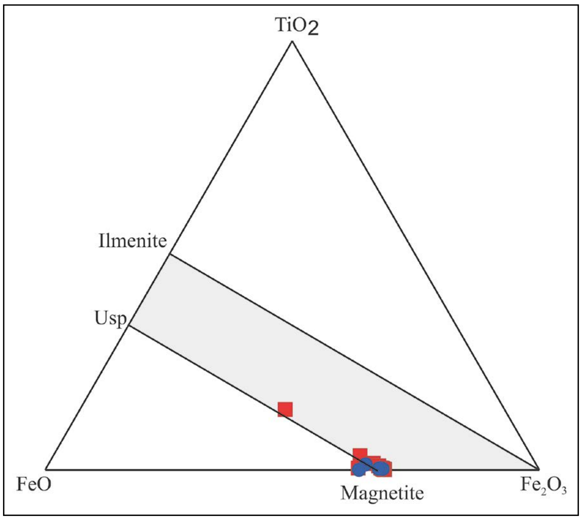

Figure 11- Fe-Ti oxides from the studied plutons on the FeO-TiO_2-Fe_2O_3 ternary diagram (Bacon and Hirschmann, 1988) (symbols as in figure 7).

due to slow cooling, so only relative approaches and calculations can be used (Kemp, 2004).

5.1. Crystallization Conditions of Magmas Forming the Plutons

5.1.1. Geothermobarometer

Since hornblende and plagioclase are mineral pairs commonly found in calcalkaline magmatic rocks, they are used for thermobarometery calculations by many researchers (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Blundy and Holland, 1990; Schmidt, 1992; Holland and Blundy, 1994). Mineral composition of the studied plutons is suitable for thermobarometry calculations since they include these two minerals. However, as transformation to actinolite in the system, chloritization, and formation of opaque minerals is common after formation of hornblende, components with alteration should be excluded from the calculations (Hammarstrom and Zen, 1986). Besides, chemical compositions of minerals such as hornblende and plagioclase display variations according to increasing temperature and pressure conditions (Laird and Albee, 1981; Hammarstrom and Zen, 1986).

With the aim of determining temperature (T) conditions, the net-transfer variation reactions (edenite–tremolite (edenite+4 quartz = tremolite+albite) and edenite–richterite (edenite+albite = richterite+anorthite)) recommended for the geothermometer developed for hornblende-plagioclase pairs in calcalkaline granitoids were used (Holland and Blundy, 1994). According to Anderson (1996), the edenite-richterite-based thermometer is more useful compared to other magmatic thermometers and should be chosen. Using the hornblende-plagioclase thermometer recommended by Holland and Blundy (1994), at <5 kbar pressure the temperature calculated for the Alemdar Pluton is between 754 and 931˚C (mean = 829˚C), and varies from 610 to 938˚C (mean = 811±16˚C) for the Işıkdere Pluton varies (Table 2). Additionally, pressures calculated according to Ridolfi et al. (2010) were between 0.6 and 1.1 kbar (mean = 0.9±0.2) for the Alemdar Pluton, 0.7-1.1 kbar (mean = 0.9±0.2) for the Işıkdere Pluton (Table 3), with the temperatures of 741-814°C (mean = 785±16) for the Alemdar Pluton and 764-816°C (mean = 785±16) for the Işıkdere Pluton (Table 2). According to Ridolfi and Renzulli (2012), the estimated crystallization pressures are 0.7-1.2 kbar (mean = 0.9±0.3) and 0.6-1.0 kbar (mean = 0.9±0.2) for the Alemdar and Işıkdere Plutons, respectively (Table 3). The temperature values calculated for the Alemdar and Işıkdere Plutons varied from 662-791°C (mean = 757±38˚C) and 690-786°C (mean = 756±28˚C), respectively (Table 2).

The temperatures and pressures estimated according to biotite minerals (Luhr et al., 1984) in the Alemdar and Işıkdere Plutons (Uchida et al., 2007) vary from 541-741°C (mean. = 645±81˚C) (Table 2) and 2.2-3.8 kbar (mean = 2.8±0.6 kbar) for the Alemdar Pluton and 619-695°C (mean = 674±18°C) and 0.4-1.9 kbar (mean = 0.8±0.4 kbar) for the Işıkdere Pluton (Table 3).

In hornblende minerals from plutonic rocks, total aluminium $Al^{(t)}$ is used as a marker of pressure in pressure calculations. The estimated pressures reflect the crystallization depths of the hornblendes. The pressure (P) estimates based on the $Al^{(t)}$ content of hornblende in the Alemdar Pluton vary between 0.4 and 2.3 kbar (mean = 1.5±0.4 kbar) according to Hammarstrom and Zen (1986), 0.1-2.2 kbar (mean = 1.4±0.5 kbar) according to Johnson and Rutherford (1989), 0.2-1.7 kbar (mean = 1.1±0.4 kbar) according to Hollister et al. (1987) and 1.1-2.9 kbar (mean = 2.2±0.4 kbar) according to Schmidt (1992) (Table 3).

The values obtained for pressure estimations for the Işıkdere Pluton varied from 0.8-3.9 kbar (mean

= 1.7±0.6 kbar) according to Hammarstrom and Zen (1986), 0.5-4.0 kbar (mean = 1.5±0.7 kbar) according to Johnson and Rutherford (1989), 0.5-3.1 kbar (mean = 1.2±0.5 kbar) according to Hollister et al. (1987) and 1.4-4.4 kbar (mean = 2.3±0.6 kbar) according to Schmidt (1992) (Table 3).

The amphibole-plagioclase and amphibole barometers used in this study similar reveals values (0.1-3.1 kbar) (Table 3), while the values obtained from the biotite barometer are slightly higher (0.4-3.8 kbar). In the literature, there are studies stating that the pressure values calculated for granitoids using the hornblende Al barometer are consistent with geological features and the emplacement depths of the plutons (Tulloch and Challis, 2000). In the light of the qualitative and quantitative data obtained in this study, the emplacement pressures for the plutons are limited to ~1-4 kbar. The hornblendes in the studied plutons are calcic hornblendes with $Al^{(t)}$ values lower than 2.0. This value ($Al^{(t)}$ <2.00) generally indicates shallow depth intrusion (Hammarstrom and Zen, 1986; Kaygusuz et al., 2018). Additionally, the textural properties like porphyritic and regrowth supporting the shallow intrusion of the plutons are noteworthy in the studied plutons (Figure 5).

The solidus temperature given by thermometers like amphibole-plagioclase is generally >700°C (Anderson, 1996). Considering the mineral associations in plutons, an attempt is made to determine a reasonable crystallization temperature interval using different thermometric approaches. As stated above, the values estimated with the hornblende-plagioclase (Holland and Blundy, 1994) thermometer are high and have a broad temperature interval (610-928°C) (Table

Table 2- The temperature estimates calculated using hornblende-plagioclase (Holland and Blundy, 1994), hornblende (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012) and biotite (Luhr et al., 1984) for the plutons.

	T°C Holland and Blundy (1994)	T°C Ridolfi et al. (2010)	T°C Ridolfi and Renzulli (2012)	T°C Luhr et al. (1984)
Alemdar Pluton (n*)	**35**	**35**	**35**	**6**
Min.	754	741	662	541
Max.	931	814	791	741
Mean	829	785±16	757±38	645
Işıkdere Pluton (n*)	**31**	**31**	**31**	**16**
Min.	610	764	690	619
Max.	938	816	786	695
Mean	811±16	786±5	756±28	674

* n: the number of analyzes

Table 3- The pressure estimates for the plutons calculated using hornblende-Al, hornblende and biotite barometers.

	P1 (kbar) Hammarstrom and Zen (1986)	P2 (kbar) Johnson and Rutherfort (1989)	P3 (kbar) Hollister et al. (1987)	P4 (kbar) Schmidt (1992)	P5(kbar) Ridolfi et al. (2010)	P6 (kbar) Ridolfi and Renzulli (2012)	P7 (kbar) Uchida et al. (2007)
Alemdar Plütonu (n*)	**35**	**35**	**35**	**35**	**35**	**35**	**6**
Min.	0.4	0.1	0.2	1.1	0.6	0.7	2.2
Max.	2.3	2.2	1.7	2.9	1.1	1.2	3.8
Mean	1.5 ± 0.4	1.4 ± 0.5	1.1 ± 0.4	2.2 ± 0.4	0.9 ± 0.2	0.9 ± 0.3	2.8
Mean Depth (km)	5.7	5.0	4.2	8.0	3.3	3.3	10.3
Işıkdere Plütonu (n*)	**31**	**31**	**31**	**31**	**31**	**31**	**16**
Min.	0.8	0.5	0.5	1.4	0.7	0.6	0.4
Max.	3.9	4.0	3.1	4.4	1.1	1.0	1.9
Mean	1.7 ± 0.6	1.5 ± 0.7	1.2 ± 0.5	2.3 ± 0.6	0.9 ± 0.3	0.9 ± 0.2	0.8
Mean Depth (km)	6.1	5.5	4.5	8.4	3.3	3.3	2.9

* n: the number of analyzes, depth was taken as 1kbar=3.7 km for the continental crust (Tulloch and Challis. 2000).

2). Additionally, thermometer estimations calculated using calcic hornblende in chemical equilibrium with calcalkaline volcanic rocks (Ridolfi et al., 2010; Ridolfi and Renzulli, 2012) gave partially lower temperatures (662-816°C). In addition to hornblende-based thermometric calculations, the biotite-Ti thermometer (Luhr et al., 1984) was used and low temperature (541-741°C) values were estimated (Table 2). The low temperature values obtained from the biotite thermometer show reequilibration with subsolidus intracrystal variation during cooling of feldspars (Toksoy-Köksal, 2016). Additionally, the hornblende-plagioclase thermometer giving a broad interval may indicate re-equilibration in slowly-cooling rocks in the late stage.

5.1.2. Oxygen Fugacity and Water Content

Another important factor in crystallization processes in magmatic rocks is oxygen fugacity (fO_2) which is defined as partial pressure of oxygen. Oxygen fugacity controls the pressure-temperature correlations in melts and affects the stability intervals for rock-forming minerals. This value changes as a function of temperature, and generally increases linked to the increase in temperature (Wones, 1989; Ridolfi et al., 2010). Additionally, the amount of oxygen contained in silicate melts is controlled by the source of temperature and mixing rates of gases.

Due to slow cooling, the original oxygen fugacity of granitic magmas cannot be determined, so there are only relative approaches and calculations available (Wones, 1989; Anderson and Smith, 1995; Kemp, 2004). The oxygen fugacity values ($\log_{10} fO_2$) calculated with the approach proposed by Wones (1989), were between -20.0 to -15.5 (mean = -18.9) for Alemdar Pluton, -19.7 to -17.0 (mean = -17.7) for Işıkdere Pluton (Table 4). The oxygen fugacity values calculated according to Ridolfi et al. (2010), using the Mg content of hornblendes in the plutons are, respectively between -14.7 to -11.8 and between -14.1 to 11.9 (Table 4). The relative oxygen fugacity (ΔNNO) varies from 0.5-2.2 and 0.6-2.1, respectively. The (ΔNNO) values calculated according to Ridolfi and Renzulli (2012) vary between -2.1 to 0.3. The mean water (H_2O) content calculated according to Ridolfi et al. (2010) is 4.4 to 7.8 wt% for Alemdar Pluton, 4.5 to 5.9% for Işıkdere Pluton, while mean water content was 4.8-7.3% for Alemdar Pluton and 4.5-5.8% for Işıkdere Pluton according to Ridolfi and Renzulli (2012) (Table 4).

The water content of magma containing amphiboles is controversial with variations between 2-3% according to Luhr et al. (1984), mean 5% according to Eggler (1972), Helz (1973) and Naney (1983), and mean 6% according to Merzbacher and Eggler (1984). The water content calculated from amphiboles in the studied samples varies from 4.4-7.8%. 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 the continental crust without full crystallization (Helmy et al., 2004).

In conclusion, according to thermobarometric calculations based on mineral chemistry data, the studied rocks have estimations for pressure values from 1 to 4 kbar and temperature values from 541 to

Table 4- Oxygen fugacity and water content for plutons calculated using hornblende and biotite minerals.

	Ridolfi et al. (2010)			**Ridolfi and Renzulli (2012)**		**Wones (1989)**
	DNNO	**fO_2**	**H_2O**	**DNNO**	**H_2O**	**fO_2**
Alemdar Pluton (n*)	**35**	**35**	**35**	**35**	**35**	**6**
Min.	0.5	-14.7	4.4	-2.1	4.8	-23.0
Max.	2.2	-11.8	7.8	0.3	7.3	-15.5
Mean	1.6	-12.6	5.0	-0.4	5.3	-18.9
Işıkdere Pluton (n*)	**35**	**35**	**35**	**35**	**35**	**16**
Min.	0.6	-14.1	4.5	-2.1	4.5	-19.7
Max	2.1	-11.9	5.9	0.3	5.8	-17.0
mean	1.3	-12.8	5.1	-0.9	5.1	-17.7

* n: the number of analyses

938°C. Considering all these features, it is proposed that the investigated plutons were emplaced at mid to shallow depths (4-15 km) from hydrous magmas.

5.2. Disequilibrium Parameters

The composition of minerals and textural features observed in rocks are related to the different types of disequilibrium during evolution of magma. Cooling, decompression and/or magma mixing are among factors triggering variations in temperature, pressure and composition of magma. As a result of these factors, the magmas may come into disequilibrium (Nixon 1988; Rutherford and Hill, 1993; Simonetti et al., 1996; Perugini et al., 2003). Petrographic or textural criteria, which involve the disequilibrium of texture as sieved plagioclase crystals (Dungan and Rhodes, 1978), presence of normal and sieved plagioclases in the same sample (Stimac and Pearce, 1992; Venezky and Rutherford, 1997), and rounded and embayed crystals (Stimac and Pearce, 1992). Compositional criteria, which involve the determination of normally and reversely zoned crystals and the presence of these two types of crystals in the same sample (Sakuyama, 1981).

The textural, petrographic and mineral compositional features of the studied magmatic rocks which indicates the presence of disequilibrium and compositional zoning in the plagioclase (Figure 5b, f, 12). In addition to oscillatory zoning in plagioclases, the observation of occasional sieve texture may be another textural feature representing disequilibrium (Figure 5b, f). The reverse zoning observed in some plagioclase minerals, especially, and presence of both reverse and normal zoned plagioclase in the same sample indicate disequilibrium crystallization (Figure 12a-f). Additionally, K-feldspars containing poikilitic hornblende, plagioclase and opaque minerals and

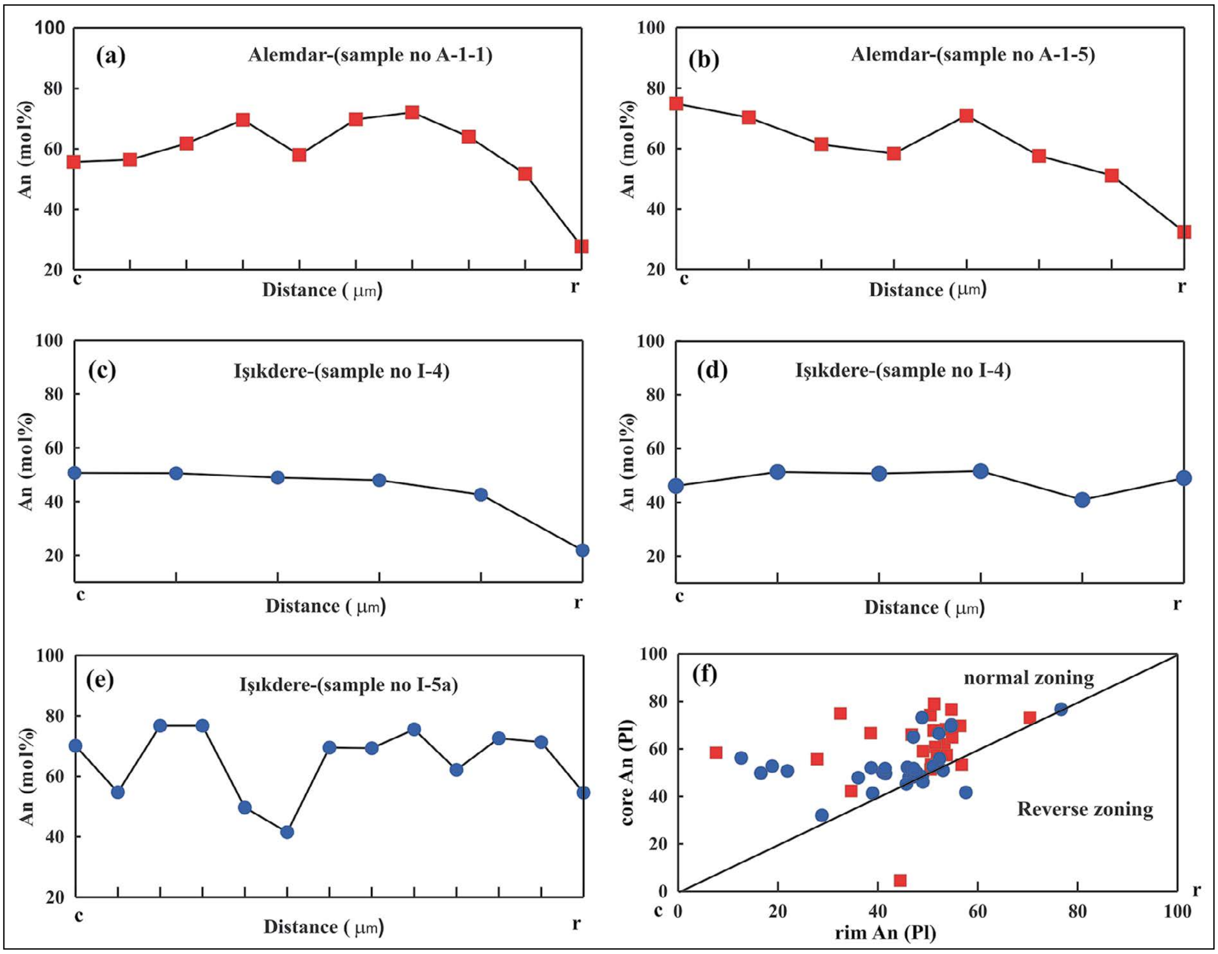

Figure 12- Core-rim An content variations in normally and reverse zoning in plagioclase of the studied plutons (c: core, r: rim).

this observed textural feature (Figure 5a) may be considered further data representing disequilibrium crystallization.

While normally zoning for plagioclases can be explained by fractional crystallization, reversely zoning there are differing views can be explained by using different views; (i) temperature and pressure increase under water-saturated conditions (Blundy and Cashman, 2001), (ii) temperature increases during ascent of water-saturated magmas (Blundy et al., 2006) and (iii) temperature increases because of back mixing (Couch et al., 2001) of magma to hotter, recharging magma (Streck, 2008). The rim of the plagioclases from studied commonly display a wide range of compositions (An_{8-77}). This wide compositional range of the plagioclase rims in a single sample indicates the complex origin of the plagioclase due to magma mixing (Wallace and Carmicheal, 1994).

5.3. Evolution of Magma within the Crust

According to pre-existing studies from the region, Lower-Middle Jurassic rocks originated in a back-arc extensional environment associated with the southward subduction of the Paleo-Tethyan oceanic lithosphere (Karslı et al., 2017). The extension occurring in the back-arc caused asthenospheric upwelling and due to this upwelling heat flow caused partial melting of the lithospheric mantle and formation of magmas leading to formation of Jurassic rocks. Again, thinning and fracture systems forming in the crust due to tectonic extension allowed movement of these melts upward within the crust. Petrographic and mineral chemical data show the presence of magma chambers at two different levels of moderate and shallow depths with evolving magma which formed Jurassic rocks under polybaric crystallization conditions. According to barometer estimations based on minerals (Table 3), the studied rocks indicate the presence of magma chambers at nearly 8-12 km (Figure 13). At these depths in addition to hornblende

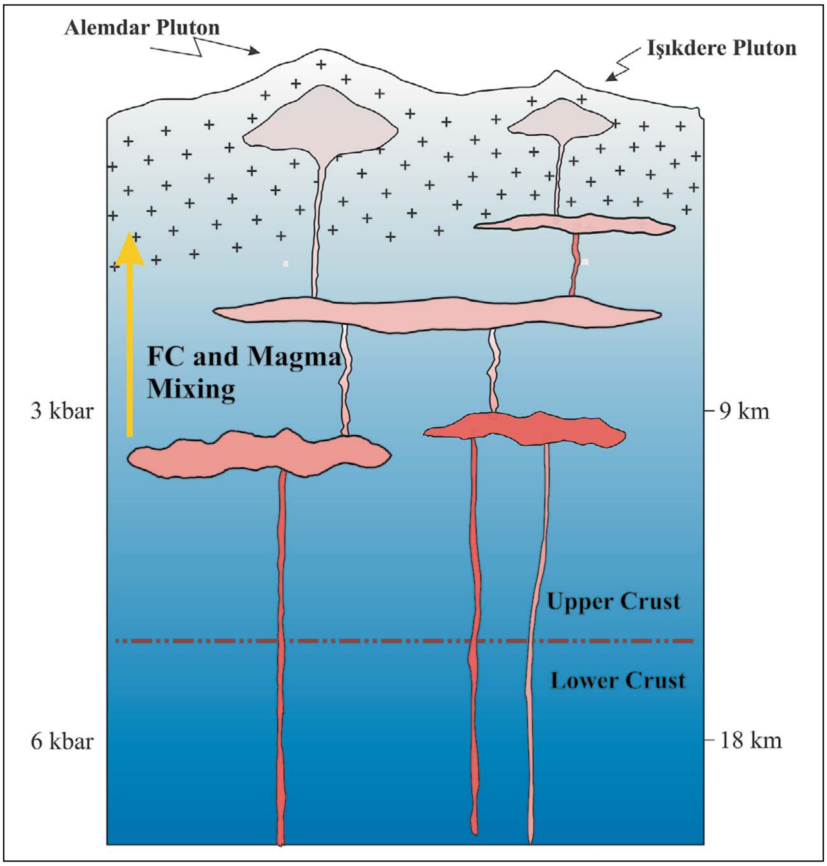

Figure 13- Schematic cross-section showing development of studied plutons within the crust.

crystallization, crystallization of plagioclase with high anorthite content and biotite is observed. Later the magma began to rise and was retained in different magma chambers at moderate levels of 4-5 km depth (Figure 13). In addition to fractional crystallization in the magma chambers, the magma mixing events occurred characterized by textural features like sieve texture and zoning. Magma rise occurred again and magma was stored in shallow magma chambers at 2-3 km depth (Figure 13). The dominant minerals in this magma chamber were biotite, plagioclase with low An content, K-feldspar and finally quartz crystalizing at relatively lower temperatures. Oxygen fugacity estimations indicate that crystallization at this level occurred under very high oxidation conditions. Finally, the fractionating magma was emplaced at shallow levels and cooled.

6. Conclusion

- The rocks of the Alemdar and Işıkdere Plutons outcropping around Gümüşhane in the south of the Eastern Pontide Orogenic belt are fine-moderate grained and quartz-diorite, quartz monzodiorite and tonalite composition.

- Petrographically, the studied plutons comprise of mainly plagioclase, hornblende, biotite, K-feldspar, quartz and Fe-Ti oxide minerals.

- There were also observed some textural features in these studied plutons indicating disequilibrium crystallization such as; sieve and oscillatory zoned plagioclase, presence of normally and reversely zoned plagioclase in the same sample, the poikilitic textures observed in K-feldspar minerals.

- According to thermobarometer estimations, the investigated plutons have pressures from 0.1 to 4.4 kbar, temperature from 541 to 938°C, oxygen fugacity values from -23 to -12 and water contents of 4.4-7.8%. Considering field, petrographic and thermobarometric data, the studied plutons were intruded at mid to shallow depts (~4-15 km) in continental crust.

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Supplementary Data

Tables 1-4; Electronic Data for Appendices are available at https://dergi.mta.gov.tr/documents/2307_162_supplementary_tables_emre_aydincakir.pdf.

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