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Petrography and crystallization conditions of the Pelitli Pluton in the Bayburt area, Eastern Pontides (NE Turkey)

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Abstract
In this study, the mineralogy, petrography and mineral chemistry *of* the Middle Eocene Pelitli pluton located to the north of Bayburt are determined, and the crystallisation conditions of the studied pluton were estimated by means of thermobarometer calculations. The main units in the study area are the Eocene Yazyurdu Formation, which are consists of basalt, andesite and minor dacite lavas and their pyroclastic equivalents, intercalated with siltstone, sandstone, marl and limestone. All these units were intruded by the Middle Eocene Pelitli Pluton. Quaternary alluviums form the youngest rocks of the study area. The Pelitli Pluton extend mostly in NE-SW directions and are approximately ellipsoid in shape. This pluton is diorite, tonalite, granodiorite and granite in composition and the main minerals are plagioclase, orthoclase, quartz, hornblende, biotite, pyroxene and Fe-Ti oxides. The rocks of pluton have fine to medium granular, porphyric, monzonitic, poikilitic, occasionally myrmekitic and micrographic textures. Plagioclases are labradorite to albite in composition (An_{60-02}). K-feldispare are orthoclase in composition (Or_{90-79}). Pyroxenes are diopside and augite in composition ($Wo_{46-41}En_{44-39}Fs_{16-14}$) and the Mg-number varies from 0.72 to 0.76. Hornblende displays a narrow compositional range (Mg# = 0.73-0.93) and are magnesio-hornblende in composition. Biotites are magnesium-rich (Mg# = 0.56-0.62). Crystallization temperatures calculated from amphibole-plagioclase and clinopyroxene minerals are 666 °C to 1161 °C and pressure values are 0.1 to 2.7 kbar. Based on the obtained data, it is suggested that the studied Pelitli Pluton was emplaced at shallow depths (~ 1 to 8 km).

Keywords: mineralogy-petrography, mineral chemistry, geothermobarometer, pelitli pluton, eastern pontides, bayburt.

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 [1-12]. There are various sized plutons in the region with a broad age range varying from Early Carboniferous to Middle Eocene and composition varying from mainly gabbro to granite (Figure 1). These plutons intruded mainly at three different period including Paleozoic, Cretaceous and Eocene. Of these Palaeozoic-aged plutons intruded into the metamorphic rocks [13-15], Cretaceous plutons intruded into the subduction-related volcanic and/or volcanoclastic rocks [16-19], and Eocene and later plutons are intruded in a narrow area cutting all former series [19, 20-24].

Although there are studies on whole-rock geochemistry and isotopic properties of the Pelitli pluton [19, 23, 25], no study has been detailed conducted on the crystallization conditions of the Pelitli pluton.

In this study, mineralogical, petrographical and mineral chemistry features of the Pelitli Pluton outcropped north of Bayburt are reported to provide the pressure and temperature conditions during the crystallization of the pluton. This study is a part of the master's thesis prepared by [26].

2. Regional geology and stratigraphy

The basement rocks of the Eastern Pontides are represented by early Carboniferous metamorphic rocks [27] that are intruded by Middle to Late Carboniferous plutons [15, 28-31]. These basement rocks are unconformably overlain by the Jurassic volcanics, volcaniclastic and plutonic rocks [32-34].

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The Jurassic rocks are conformably overlain by Late Jurassic-Early Cretaceous carbonate rocks [35]. The Late Cretaceous units that unconformably overlie these carbonate rocks consist of volcanic, plutonic and sedimentary rocks [36-40]. These rocks are overlain by Late Paleocene-Early Eocene adakitic rocks [41-42], Middle Eocene volcanic, sub-volcanic and sedimentary rocks [3, 5, 8, 10, 33, 43-48] and cuts by Middle Eocene plutonic rocks [12, 19, 21-22, 49-51]. These units are overlain by Neogene volcanic rocks [52] and are covered by Late Miocene and Plio–Quaternary adakitic volcanic-subvolcanic rocks [53]. Miocene and post-Miocene magmatisms are calc-alkaline to alkaline compositions in the Trabzon-Gümüşhane areas [52-53] and calc-alkaline in the Kandilli-Ilıca areas [54-55]. All units are unconformably overlain by Quaternary alluvium.

The study area, which are an area of about 50 km^2, located in the south zone of the Eastern Pontides and is generally dominated by volcanic and plutonic rocks (Figure 1). The oldest rocks in the study area are represented by the Eocene Yazyurdu Formation [56], consists of basalt, andesite and minor dacite lavas and their pyroclastic equivalents, intercalated with siltstone, sandstone, marl and limestone. All these units were intruded by the Middle Eocene Pelitli Pluton [19, 25-26]. Quaternary alluviums are the youngest rocks of the study area (Figure 1).

The Pelitli Pluton are generally ellipse in shapes with its long axis extending in a northeast-southwest direction (Figure 1). It gives an outcrop over an area of approximately 16 km^2 and the length is 5-6 km with width of 3-4 km. The pluton cuts the Yazyurdu Formation and metavolcanics developed along the contacts. The Pelitli Pluton generally has a slightly weathered appearance. The arenaization is mostly seen the west of Pelitli Village and the east of Üzengili Village. This pluton contains mafic magmatic enclaves (MME) with sizes varying from 2 to 10 cm. The enclaves are finer grained and darker than the host rock.

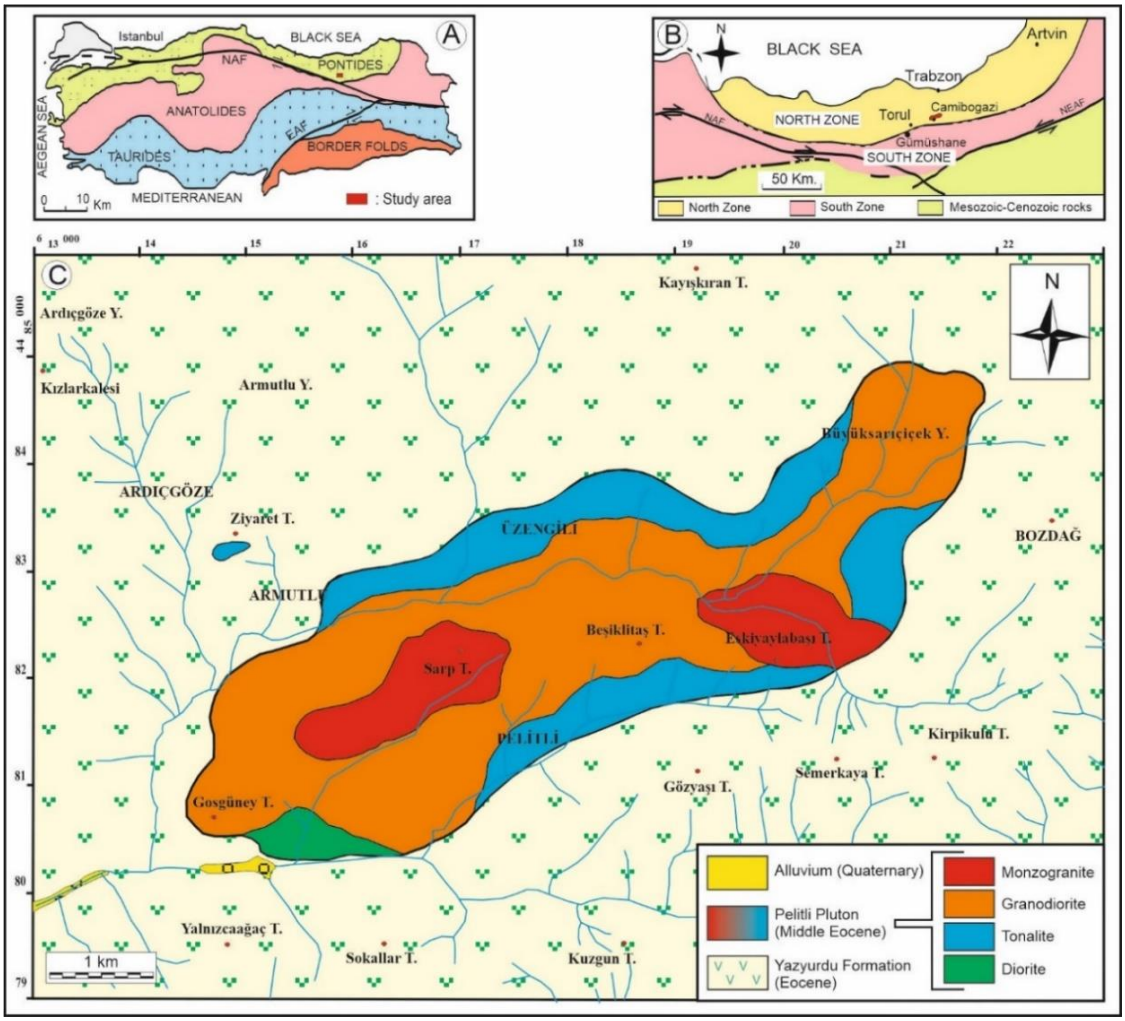

Figure 1. Geological map of the study area (modified by [25-26]).

3. Analysis methods

A total of thirty-five samples were collected from the Pelitli Pluton in the fields. Thin sections of rock samples were prepared, and detailed petrographic properties were determined under polarizing microscope. Microscopic studies resulted in three representative samples being selected for electron microprobe analyses.

Electron microprobe analyses performed on three samples from the studied Pelitli Pluton 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 and pyroxene 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, orthoclase (UCB), albite (UCB), anorthite (UCB), biotite, caersuitite (UCB), diopside (UCB) and magnetite (UCB) standards were used.

4. Petrography

Rock samples from the Pelitli Pluton are modally composed of diorite, tonalite, granodiorite and monzogranite in composition. The diorites, the oldest rocks in the pluton, form small outcrops at the southwestern margin of the pluton (Figure 1). Compared to the other granitic rocks, they can be easily distinguished from them by their higher mafic mineral content, darker color and very little quartz content. Tonalites form large outcrops after granodiorites. This unit, which forms the rim facies of the pluton, is light gray in the field. Granodiorites constitute the bulk of the elliptically shaped pluton. They are generally located core of the pluton (Figure 1). Monzogranites are usually located centre of the pluton with two outcrops (Figure 1). They are generally light gray and locally pinkish in color and partly kaolinized. The contact between granodiorite and monzogranite are sharp.

The rocks from the Pelitli Pluton have fine to medium grained, porphyritic, poikilitic, monzonitic, micrographic and granophyric textures (Figure 2a-d). The main minerals are plagioclase, quartz, orthoclase, hornblende, biotite and pyroxene; accessory minerals are apatite, zircon, opaque minerals and secondary minerals are sericite, chlorite, calcite, epidote and clay minerals (Figure 2a-d).

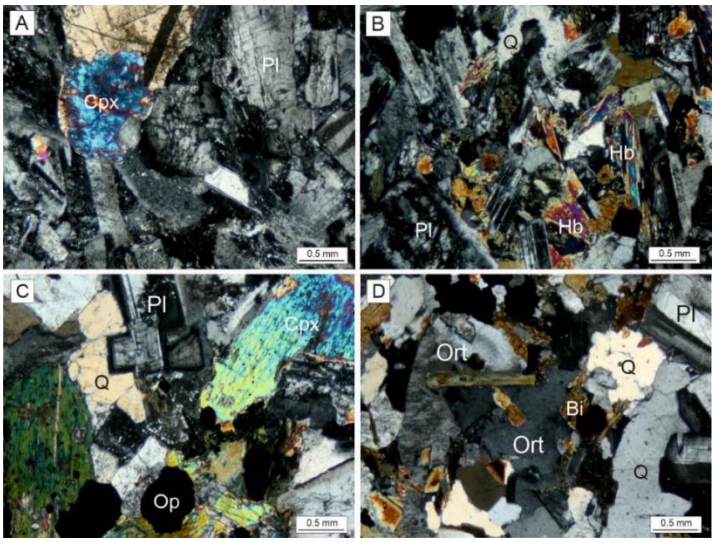

Figure 2. Texture features observed in the Pelitli Pluton, A) diorites, B) tonalites, C) granodiorites and D) monzogranites (Crossed polarized light, Pl: Plagioclase, Ort: Orthoclase, Q: Quartz, Bi: Biotite, Cpx: Clino-pyroxene, Hb: Hornblende, Op: Opaque minerals)

Plagioclases are common in all samples and found as subhedral and anhedral crystals. They commonly display normal and reverse zoned. It tends to be an early, dominant phase, and show oscillatory zoning and prismatic-cellular growth. Quartz is anhedral with irregular cracks and is interstitial to the other minerals. They generally show undulating extinction. K-feldspars form anhedral to subhedral crystals of orthoclase and fills in between the other minerals. It is generally in microperthitic structure and carlsbad twin is prominent in some minerals. Hornblendes are generally observed as euhedral crystals, and some of them also include poikilitic plagioclase and opaque minerals. In some sections, they appear to be chloritized in places along the cleavage. Biotite is euhedral to subhedral and forms prismatic crystals and lamellae. Clinopyroxene forms subhedral to anhedral crystals, is abundant in diorites, and is mainly composed of diopside and augite. Apatites are generally found as inclusions in quartz and feldspar in acicular shapes. Zircon is observed in all rocks as euhedrally small prismatic crystals.

5. Mineral chemistry

Plagioclase, K-feldspare, hornblende, biotite and clinopyroxene minerals were commonly observed in the studied Pelitli rocks. The minimum and maximum values of the microprobe compositions for plagioclase and K-feldspare are given in Table 1.

Table 1. Minimum and maximum values of microprobe analysis for plagioclase and K-feldspare

Plagioclase	**SiO_2**	**Al_2O_3**	**FeO**	**CaO**	**Na_2O**	**K_2O**	**BaO**	**SrO**	**Total**		
min	50.16	18.58	0.04	0.38	4.46	0.02	0.00	0.01	98.73		
max	69.25	29.98	0.71	12.75	11.52	0.64	0.13	0.16	101.00		
avg	61.60	23.58	0.32	5.28	8.77	0.22	0.04	0.07	99.90		
	Si	**Al**	**$Fe^{(ii)}$**	**Ca**	**Na**	**K**	**Ba**	**Sr**	**An**	**Ab**	**Or**
min	2.32	0.99	0.00	0.02	0.40	0.00	0.00	0.00	1.77	38.90	0.11
max	3.00	1.61	0.03	0.63	0.98	0.04	0.00	0.00	60.06	97.81	3.32
avg	2.74	1.24	0.01	0.26	0.76	0.01	0.00	0.00	24.57	74.20	1.23
K-feldspare	**SiO_2**	**Al_2O_3**	**FeO**	**CaO**	**Na_2O**	**K_2O**	**BaO**	**SrO**	**Total**		
min	61.98	17.89	0.01	0.02	0.47	13.54	0.01	0.01	97.00		
max	64.14	18.50	0.36	0.13	2.35	16.11	1.17	0.11	99.36		
avg	62.98	18.22	0.11	0.05	1.07	15.31	0.37	0.05	98.16		
	Si	**Al**	**$Fe^{(ii)}$**	**Ca**	**Na**	**K**	**Ba**	**Sr**	**An**	**Ab**	**Or**
min	2.96	1.00	0.00	0.00	0.04	0.81	0.00	0.00	0.09	4.21	78.92
max	2.99	1.03	0.01	0.01	0.21	0.98	0.02	0.00	0.65	20.84	95.59
avg	2.98	1.01	0.00	0.00	0.10	0.92	0.01	0.00	0.26	9.59	90.14
min: minimum values, max: maximum values, avg: average values											

A wide range in anorthite compositions (An_{60} to An_{02}) can be found in studied samples. The anorthite composition decreases from the diorites to the monzogranites (Figure 3a; Table 1). The Or contents of K-feldspar are between 96 and 79, without any chemical zoning in the crystals (Figure 3b, Table 1).

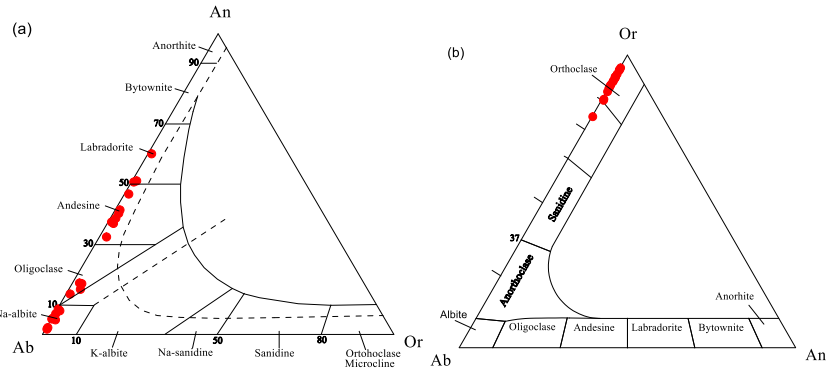

Figure 3. (a-b) Classification of plagioclase and K-feldspar on a ternary An–Ab–Or plot (after [57]) from the rocks of the Pelitli Pluton

The minimum and maximum values of the microprobe data for amphibole, biotite and clino-pyroxene are presented in Table 2, 3 and 4.

Table 2. Minimum and maximum values of microprobe analysis for amphibole

Amphibole	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	
min	50.21	0.19	1.73	11.14	0.37	15.15	10.58	0.28	0.19	96.98	
max	52.90	0.94	5.19	14.40	0.88	17.25	11.89	1.27	0.48	98.72	
avg	51.41	0.71	4.16	12.71	0.56	16.03	11.28	0.73	0.30	97.88	
	Si	**Ti**	**Al**	**$Fe^{(ii)}$**	**Mn**	**Mg**	**Ca**	**Na**	**K**	**Fe#**	**Mg#**
min	7.06	0.02	0.29	1.31	0.04	3.20	1.58	0.15	0.03	0.17	0.73
max	7.50	0.10	0.86	1.71	0.11	3.62	1.80	0.70	0.09	0.88	0.93
avg	7.28	0.08	0.69	1.50	0.07	3.38	1.71	0.40	0.05	0.52	0.82

Table 3. Minimum and maximum values of microprobe analysis for biotite

Biotite	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	
min	37.50	4.24	12.38	16.13	0.19	13.43	0.08	0.06	8.71	97.3	
max	39.35	5.36	13.92	19.46	0.27	14.96	0.29	0.27	9.37	98.9	
avg	38.44	4.74	12.88	17.33	0.23	14.21	0.21	0.19	9.04	97.9	
	Si	**Ti**	**Al**	**$Fe^{(ii)}$**	**Mn**	**Mg**	**Ca**	**Na**	**K**	**Fe#**	**Mg#**
min	5.51	0.46	2.12	1.95	0.02	2.89	0.01	0.02	1.60	0.38	0.56
max	5.68	0.59	2.37	2.38	0.03	3.26	0.04	0.08	1.75	0.44	0.62
avg	5.61	0.52	2.21	2.12	0.03	3.09	0.03	0.05	1.68	0.41	0.59

Table 4. Minimum and maximum values of microprobe analysis for clino-pyroxene

Pyroxene	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Total			
min	51.25	0.16	0.64	8.18	0.34	13.32	19.99	0.29	97.0			
max	52.87	0.62	2.51	9.02	0.42	15.32	22.32	0.37	99.2			
avg	52.21	0.28	1.21	8.63	0.40	14.13	21.45	0.33	98.6			
	Si	**Ti**	**Al**	**$Fe^{(ii)}$**	**Mn**	**Mg**	**Ca**	**Na**	**Wo**	**En**	**Fs**	**Mg#**
min	1.91	0.00	0.03	0.26	0.01	0.76	0.80	0.02	41.3	39.3	13.8	0.72
max	2.00	0.02	0.11	0.29	0.01	0.85	0.90	0.03	45.9	44.1	15.7	0.76
avg	1.97	0.01	0.05	0.27	0.01	0.79	0.87	0.02	44.6	40.8	14.6	0.74

All the amphiboles in the plutons are calcic amphiboles (Figure 4a) and are mainly magnesio-hornblende in composition on the [58] classification diagram (Figure 4b). The Mg-number (Mg#) varies between 0.73 and 0.93 (Table 2).

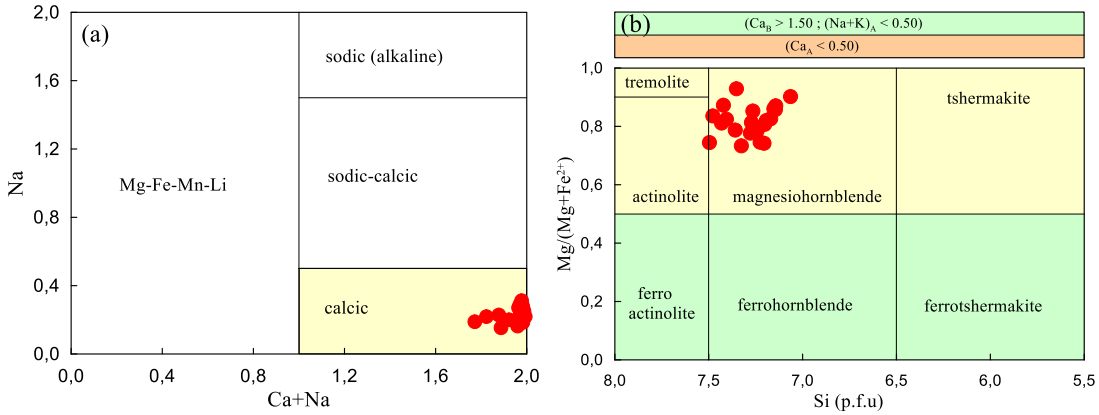

Figure 4. (a-b) Hornblende classification diagrams (after [58]) from the rocks of the Pelitli Pluton

Biotites are solid melt products between the end members of phlogopite and annite and are rich in Mg [(Fe/(Fe+Mg) = 0.38-0.44] (Figure 5a and b, Table 3).

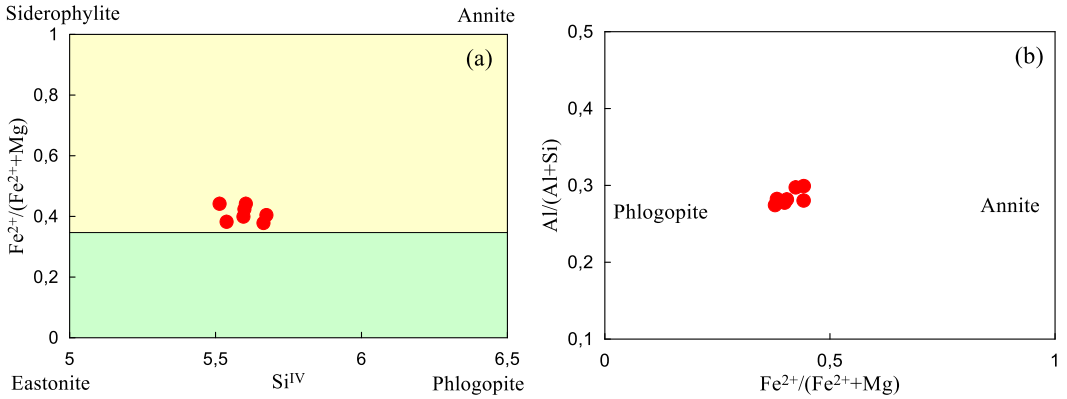

Figure 5. Biotite composition from the rocks of the Pelitli Pluton, (a) Si^{IV} vs. (Fe^{2+}/Fe^{2+}+Mg) and (b) (Fe^{2+}/Fe^{2+}+Mg) vs. Al/(Al+Si) diagrams [59]

All the pyroxenes are of calcic clino-pyroxene ($Wo_{46-41}En_{44-39}Fs_{16-14}$) and are generally augite and diopside in composition (Table 4, Figure 6a). Mg number (Mg#) of clino-pyroxenes range from 0.72 to 0.76 (Table 4). They are placed in the CATS and AC-JD-UR fields in the Ti-Na-Al^4 diagram [60] (Figure 6b).

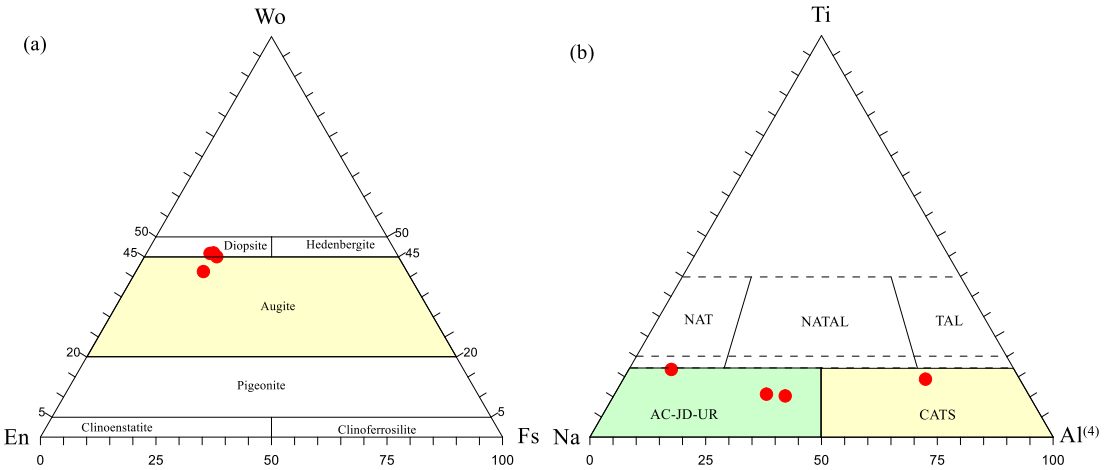

Figure 6. Classification diagrams of pyroxene from the rocks of the Pelitli Pluton, a) Wo-En-Fs [48], b) Ti-Na-$Al^{(4)}$ [60].

6. Intensive parameters

6.1. Clinopyroxene thermobarometry

Estimates of quantitative pressure and temperature on the clinopyroxene composition were re-evaluated by [61]. [61] gave an equilibrium constant using the Fe–Mg exchange and $K_D(Fe\text{-}Mg)^{cpx\text{-}melts}$ = 0.27±0.03. The calculated results of the studied rocks show pressures ranging from 0.6 to 2.7 kbar and temperatures ranging from 1121 to 1161 °C (Table 5).

Table 5. Clinopyroxene temperature and pressure calculations in the studied rocks

	Eqn 32b (P kbar)	Eqn 32d (T °C)	Eqn 35 ($K_{D(Fe\text{-}Mg)}$)
Clino-pyroxene			
min	0.6	1121	0.26
max	2.7	1161	0.27
avg	1.5	1138	0.27

6.2. Amphibole-plagioclase thermobarometer

Microprobe data for the amphibole and plagioclase phenocrysts from the studied rocks were used to calculate temperature using the equations suggested by [62]. Pressures were calculated using Al-in-amphibole method and equations proposed by [63-65] for plutonic rocks. The results obtained from the amphibole-plagioclase thermometer are given in Table 6. Calculated pressures and temperatures give

values of 0.1 to 1.1 kbar and 666 to 767 °C for the studied rocks, respectivelly (Table 6).

Table 6. Amphibole-plagioclase temperature and pressure calculations in the studied rocks

	P1 (kbar) [1]	P2 (kbar) [2]	P3 (kbar) [3]	T °C [4]
Amphibole-plagioclase				
min	0.1	0.1	0.7	666
max	0.4	0.1	1.1	767
avg	0.2	0.1	0.9	721
[1][63], [2][64], [3][65], [4][62]				

7. Discussion and conclusions

The Eastern Pontides 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 [66], with new studies in the region clarifying these correlations [1, 19]. The studied Pelitli Pluton are generally emplaced parallel to the NE-SW oriented fracture lines. The pluton generally has 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 amphibole-plagioclase barometers used in this study produced similar values (0.1 to 1.1 kbar), while the values obtained from the clinopyroxene barometer were higher (0.6 to 2.7) (Table 5 and 6). When compared with the other Eocene-aged plutonic rocks in the Eastern Pontides, the pressure values for Pelitli Pluton are similar to the values identified for the Dölek-Sarıçiçek plutons (1-3.8 kbar, [21]) and Aydıntepe and Kemerlikdağı Plutons (0.1-2.8 kbar, [19]), whereas, they have lower values compared to the Dölek, Sarıçiçek, Sorkunlu, Üzengili and Arslandede plutons (0.3-8.2 kbar, [23]). As mentioned previously, the amphiboles in the studied plutonic rocks are calcic amphiboles with $Al^{(t)}$ values lower than 2.0. According to [63], hornblendes with $Al^{(t)} \leq 2.0$ values generally indicate shallow depth intrusion. Additionally, the textural properties like graphic-growth supporting shallow intrusion of the plutons are noteworthy in the studied pluton.

Calculations made on minerals in the studied plutonic rocks indicate temperature values varied between 666 and 767 °C for amphibole-plagioclase thermometers, while the values indicate that the clinopyroxene thermometer were higher (1121 to 1161 °C) (Table 5 and 6). Compared with the other plutonic rocks with similar age in the Eastern Pontides, the studied Pelitli Pluton have similar temperature values for the Dölek-Sarıçiçek plutons (617-768 °C, [21] and Aydıntepe and Kemerlikdağı Plutons (616-1172 °C, [19]).

The biotites formed in the studied Pelitli Pluton have average values of Al^4 (2.12 to 2.37 fbb) and partly high Mg# (0.56 to 0.62). These values close to the biotites in the pluton formed by mantle-sourced magma products (Al^4 = 2.3-2.4; Mg# > 0.60) (Figure 7a). As shown in Figure 7a, the biotites of studied pluton remain near the mantle-sourced melt curve. This leads to the consideration that the source rock was derived from the mantle source.

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 666 to 1161 °C (Table 5 and 6). When field, petrographic and thermobarometric data are considered together, it is proposed that the studied Pelitli Pluton was emplaced at shallow depths (1-8 km) within Eastern Pontide continental crust thickened after collision in the Cenozoic period.

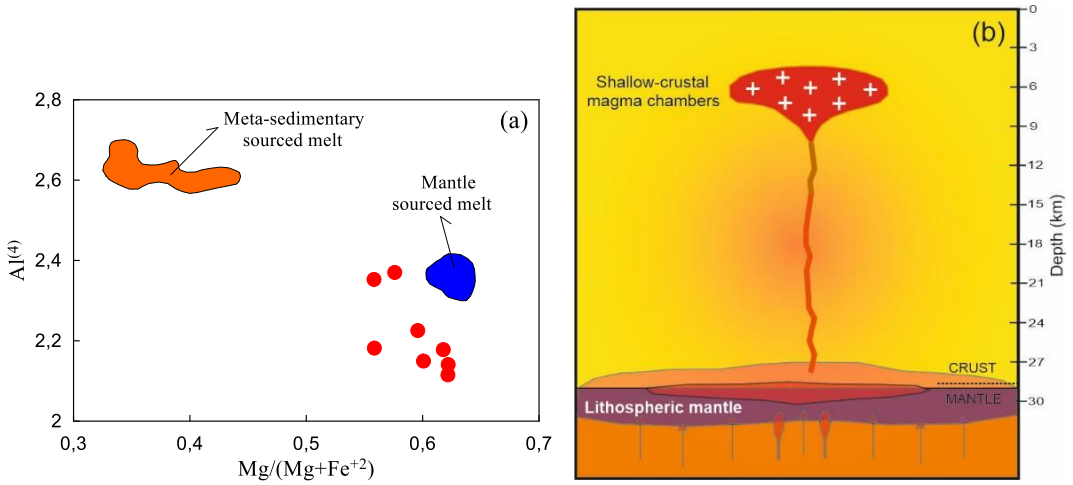

Figure 7. (a) Correlation between Al^{4}-Mg/(Mg+Fe^{+2}) in biotites from the Pelitli Pluton, and comparison with meta-sedimentary sourced melts and mantle sourced moderate-felsic melts (b) Schematic illustration of crystallization paths for the studied rocks in the Eastern Pontides (meta-sedimentary melt area from [67], mantle sourced melt area taken from [68]

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