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Mineral Chemistry and Petrochemistry of Post-Collisional Tertiary Mafic to Felsic Cogenetic Volcanics in the Ulubey (Ordu) Area, Eastern Pontides, NE Turkey

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Abstract: Post-collisional Tertiary volcanic rocks in the Ulubey (Ordu) area at the western edge of the eastern Pontides palaeo-arc are divided into four suites. The Yenisayaca basalt (TB) contains plagioclase ($An_{61–83}$), clinopyroxene ($Wo_{42–44}En_{39–41}Fs_{15–18}$) and olivine phenocrysts and titanomagnetite microphenocrysts, whereas the Çatal Tepe and Elekçioğlu Tepe suite (ÇES), Işık Tepe suite (ITS) and andesite/ trachyandesite suite (ATS) rocks include plagioclase ($An_{23–78}$), clinopyroxene ($Wo_{27–48}En_{37–55}Fs_{11–26}$), hornblende (Mg#= 0.63–0.76), biotite (Mg#= 0.63–0.82), sanidine phenocrysts and titanomagnetite and apatite microphenocrysts.

Petrochemically, the volcanic rocks show tholeiitic-alkaline to the calc-alkaline affinities, and have medium to high-K contents. Most samples have low Mg#, Cr, and Ni, which indicates that they have undergone significant fractional crystallization from mantle-derived melts. The geochemical variations can be explained by fractionation of common mineral phases such as clinopyroxene ± plagioclase ± magnetite in the Yenisayaca basalt, and hornblende + biotite + plagioclase ± magnetite ± apatite ± sanidine in the Çatal Tepe and Elekçioğlu Tepe suite, Işık Tepe suite and andesite/trachyandesite suite rocks. N-Type MORB-normalized trace element patterns show that Ulubey volcanic rocks are enriched in LILE and to a lesser extent in Th and Ce, but depleted in Zr, Y and TiO_2. Besides, the rocks have depletion in Nb and Ta relative to LILE, moderate LREE/HREE ratios and high Th/Yb ratios, all of which indicate that parental magma(s) probably derived from an enriched source region (probably lithospheric mantle) which was previously modified by fluids. The C1-chondrite-normalized REE patterns are concave with low to medium enrichment, indicating similar source areas for the Yenisayaca Basalt, Çatal Tepe and Elekçioğlu Tepe suite, Işık Tepe suite and andesite/trachyandesite suite. The REE patterns also imply that negative Eu anomalies are probably associated with plagioclase fractionation in the evolution of the rocks.

Key Words: calc-alkaline volcanics, crystal fractionation, mineral chemistry, Tertiary volcanism, eastern Pontides, Turkey

Ulubey (Ordu) Yöresi Çarpışma Sonrası Tersiyer Yaşlı Mafik-Felsik Kayaçların Mineral Kimyası ve Petrokimyası, Doğu Pontidler, KD Türkiye

Özet: Eski bir adayayı olan Doğu Pontidler'in batı kısmında yer alan Ulubey (Ordu) yöresindeki çarpışma sonrası Tersiyer yaşlı volkanik kayaçlar dört takıma ayrılmıştır. Yenisayaca bazaltı plajiyoklas ($An_{61–83}$), klinopiroksen ($Wo_{42–44}En_{39–41}Fs_{15–18}$) ve olivine fenokristalleri ve titanomagnetit içerirken, Çatal Tepe ve Elekçioğlu Tepe takımı (ÇES), Işık Tepe takımı ve andezit/trakiandezit takımını oluşturan kayaçlar ise plajiyoklas ($An_{23–78}$), klinopiroksen ($Wo_{27–48}En_{37–55}Fs_{11–26}$), hornblend (Mg#= 0.63–0.76), biyotit (Mg#= 0.63–0.82), sanidin fenokristalleri, titanomagnetit ve apatit içermektedir.

Petrokimyasal verilere göre, kayaçlar toleyitik-alkalenden kalk-alkalene kadar değişen karaktere sahip olup, orta-yüksek-K içerirler. Örneklerin çoğunun düşük Mg-numarası ile Cr ve Ni içeriklerine sahip olması, bu kayaçların mantodan türemiş ergiyiklerden itibaren önemli derecede ayrımlaşmaya uğradıklarını göstermektedir. Harker diyagramlarına göre, Yenisayaca bazaltı'nda klinopiroksen ± plajiyoklas ± magnetit ayrımlaşması, Çatal Tepe ve Elekçioğlu Tepe takımı (ÇES), Işık Tepe takımı ve andezit/trakiandezit takımını oluşturan kayaçlarda ise hornblend + biyotit + plajiyoklas ± magnetit ± apatit ± sanidin ayrımlaşması etkili olmuştur. Ulubey (Ordu) yöresi volkanitlerinin N-tipi Okyanus Ortası Sırtı Bazaltı (N-Type MORB)'na normalize edilmiş iz element dağılımlarına göre, Ulubey yöresi volkanik kayaçları özellikle büyük iyon yarıçaplı litofil element ve daha az oranda Th ve Ce konsantrasyonları bakımından zenginleşme, fakat Zr, Y ve TiO_2 konsantrasyonları bakımından tüketilme göstermektedirler. Buna ilaveten, kayaçların büyük iyon yarıçaplı litofil elementlere kıyasla azalan Nb ve Ta içerikleri, orta derecede HNTE (hafif nadir toprak element) /ANTE (ağır nadir toprak element) oranları ve yüksek Th/Yb oranları; volkanitlerin köken magmasının muhtemelen daha önceden akışkanlar tarafından metazomatizmaya uğratılmış zenginleşmiş bir kaynak bölgeden (muhtemelen litosferik manto) türeyebileceklerini ifade etmektedir. C1-kondrite normalize edilmiş nadir toprak element dağılımları, düşük-orta derecede zenginleşmeyle konkav şekilli olup, Yenisayaca Bazaltı ile Çatal Tepe ve Elekçioğlu Tepe takımı (ÇES), Işık Tepe takımı ve andezit/trakiandezit takımını oluşturan kayaçların benzer kaynaklardan itibaren oluştuğunu düşündürmektedir. Nadir toprak element dağılımlarında gözlenen negatif Eu anomalisi, kayaçların gelişiminde plajiyoklas ayrımlaşmasının etkili olabileceğini göstermektedir.

Anahtar Sözcükler: Kalk-alkalen volkanitler, kristal ayrımlaşması, mineral kimyası, Tersiyer volkanizması, Doğu Pontid, Türkiye

Introduction

The eastern Pontides form the northern margin of Anatolia, straddling the North Anatolian transform Fault Zone, rising steeply inland from the Black Sea region, which was shaped by the Alpine orogenesis. The eastern Pontides, as a palaeo-arc, are an example of long-term crustal evolution from pre-subduction rifting, through arc volcanism and plutonism to post-subduction alkaline volcanism (e.g., Akın 1978; Şengör & Yılmaz 1981; Akıncı 1984). The eastern Pontides are characterized by three volcanic cycles erupted in Liassic, Late Cretaceous and Eocene times (Arslan *et al*. 1997). Although many authors have disputed the evolution of the volcanic rocks in the region, the studies about geochemical and petrogenetic studies are limited (e.g., Adamia *et al*. 1977; Kazmin *et al*. 1986; Tokel 1995; Çamur *et al*. 1996; Arslan *et al*. 1997, 2000, 2002, 2007a, b; Şen *et al*. 1998; Arslan & Aliyazıcıoğlu 2001; Temizel 2002; Temizel & Arslan 2003, 2005; Şen 2007; Temizel *et al*. 2007; Temizel & Arslan 2008). Tertiary volcanic rocks in the region were derived from an enriched MORB-like mantle source, related to subduction (Çamur *et al*. 1996; Arslan *et al*. 1997). The general geochemical characteristics of these volcanic rocks within the Pontide-arc setting imply that their parental magma was derived from the upper mantle and/or lower crust (Arslan *et al*. 1997). According to the geochemical data, the volcanic rocks, mainly calc-alkaline in composition and showing moderate potassium enrichment, evolved by shallow-level fractional crystallization, magma-mixing and contamination of a parental magma derived from metasomatized upper mantle by partial melting after thickening of the Pontide-arc during the Paleocene–Eocene (Arslan & Aliyazıcıoğlu 2001; Arslan *et al.* 2001, 2002, 2007a, b; Temizel *et al.* 2007; Temizel & Arslan 2008).

In this study, focusing on the western part of the eastern Pontides, the mineral chemistry and petrochemical characteristics of Tertiary aged post-collisional volcanic rocks in the Ulubey (Ordu) area (Figure 1) were investigated; the evolution and affinity of the volcanic rocks were outlined in the light of mineral chemistry and geochemical findings.

Geological Setting

As a palaeo-island arc, the eastern Pontides are divided into northern and southern zones (Özsayar *et al.* 1981). The northern zone is dominated by Late Cretaceous and Middle Eocene volcanic and volcaniclastic rocks, whereas pre-Late Cretaceous rocks are widely exposed in the southern zone (Arslan *et al*. 1997; Şen *et al.* 1998; Arslan *et al*. 2000, 2002; Şen 2007). Volcanic rocks of the eastern Pontides lie unconformably on a Palaeozoic heterogeneous crystalline basement, the Pulur Massif, consisting of metamorphic sequences of varying metamorphic grades, and are also cross-cut by granitoids of Permian age (Yılmaz 1972; Okay & Şahintürk 1997; Topuz *et al*. 2004 a,b). The stratigraphy and age of the Upper Palaeozoic sequence has been investigated by several workers with conflicting views (e.g., Ağar 1977; Robinson *et al*. 1995; Okay & Şahintürk 1997; Yılmaz *et al*. 1997). The Permian and Triassic events are not widely known in the eastern Pontides. However, the Jurassic is characteristically represented by predominantly volcaniclastic rocks. Volcanic, volcano-sedimentary rocks, and locally developed sediments of Liassic–Dogger age (Ağar 1977; Robinson *et al*. 1995) rest unconformably on the basement. The Liassic volcanic rocks, tholeiitic in character, consist mainly of basalt and, to a lesser extent andesite, trachy-andesites and their pyroclastic equivalents. These rocks are conformably overlain by the Dogger–Malm–Cretaceous platform carbonates.

The Upper Cretaceous series, unconformably overlying carbonate rocks, is dominated by sedimentary rocks in the northern part of the eastern Pontides (e.g., Robinson *et al*. 1995). The volcanic rocks, tholeiitic to calc-alkaline, are dominantly dacite and rhyolite with lesser basalt, andesite, and their pyroclastic equivalents. Some plutonic rocks were also intruded during Jurassic to Paleocene time (Okay & Şahintürk 1997; Yılmaz *et al*. 1997). During Paleocene–Early Eocene time, there was a major break in sedimentation. The Upper Cretaceous series is unconformably overlain by Eocene mainly volcanic rocks, with rare volcaniclastics and sedimentary rocks, suggesting that the eastern Pontides were above sea level during Palaeocene–Early Eocene time, probably related to collision (Okay & Şahintürk 1997; Boztuğ *et al*. 2004).

Calc-alkaline to alkaline Tertiary volcanic rocks (Figure 1a), are dominantly basalt, tephrite, and andesite lavas, although there are lithological and chemical variations between the rocks exposed in the Trabzon and Tonya region (northern zone) and those of the Gümüşhane and Ordu region (southern zone) (Arslan *et al*. 1997, 2000,

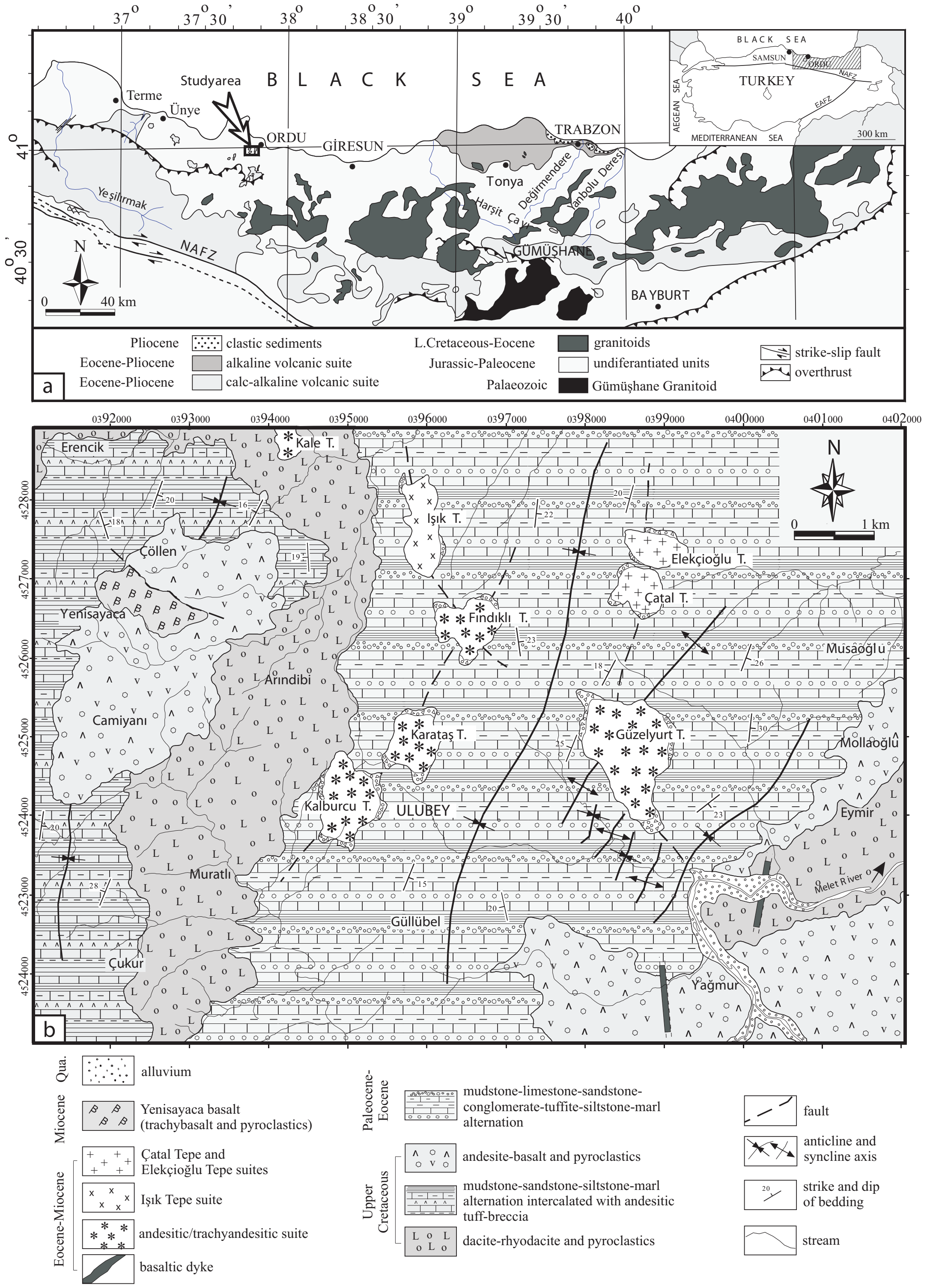

Figure 1. Simplified geological map of the eastern Pontides (after Güven 1993) showing the distribution of the Tertiary volcanics and intrusions (**a**), geological map (**b**) of the Ulubey (Ordu) area. NAFZ– North Anatolian Fault Zone. EAFZ– East Anatolian Fault Zone.

2002, 2007a, b; Şen *et al*. 1998; Temizel & Arslan 2002, 2003; Aydın 2004; Temizel & Arslan 2005; Arslan & Aslan 2006; Şen 2007; Temizel *et al.* 2007; Temizel & Arslan 2008). Several granitoids representing this magmatic episode intrude Eocene volcanic and volcaniclastic rocks (e.g., Arslan *et al*. 2004; Boztuğ *et al*. 2005a, b, 2006, 2007; Arslan & Aslan 2006; Boztuğ & Harlavan 2008).

Local Geology and Stratigraphy

The study area is located in the Ulubey (Ordu) region, in the west of the eastern Pontide palaeo-arc (Figure 1). The basement in the studied area comprises Upper Cretaceous dacite, rhyodacite and pyroclastics, containing coarse-grained quartz (0.5–1 cm in diameter), plagioclase and biotite and partly shows chloritization and silicification (Figures 1 & 2). The basement is conformably overlain by Upper Cretaceous mudstone, siltstone and a microfossil-bearing marl and sandstone alternation intercalated with greenish yellow, light brown coloured, medium- to thick-bedded (1–50 cm) tuffs and andesitic breccias (2–15 cm in diameter). This unit is conformably overlain by Upper Cretaceous grey to dark grey, greenish-grey and black andesite, basalt and pyroclastics. The unit is locally affected by hydrothermal alteration and weathering, and the fractures of the rocks are generally filled by silica and clay. The Paleocene–Eocene sedimentary unit comprises at its base microfossil-bearing mudstone which is overlain, in turn, by a ~4-m-thick conglomerate, grey-white coloured and medium–thick-bedded limestone, grey coloured and thin–medium-bedded sandstone, greyish-brownish coloured and ~1–2-m-thick tuffite, and grey-white and yellowish coloured, thin-bedded siltstone and marl alternation. The Upper Cretaceous and Paleocene–Eocene units are cross-cut by basaltic dykes. All these units are cross-cut by Middle Eocene andesite/ trachyandesite suite (ATS – Kalburcu Tepe Dome, Güzelyurt Tepe Dome, Fındıklı Tepe Dome and Karataş Tepe Dome), Işık Tepe suite (ITS – Işık Tepe Dome) and Çatal Tepe and Elekçioğlu Tepe suite (ÇES – Çatal Tepe Dome and Elekçioğlu Tepe Dome) and Miocene Yenisayaca Basalt (TB – trachybasalt) and pyroclastics. Middle Eocene volcanic rocks are grey to dark grey and commonly fractured, whereas Miocene Yenisayaca basalt is grey to black and show mainly massive and rarely prismatic jointing. The rocks contain large augite crystals (0.5–1 cm) and partly show exfoliation with chloritization and silicification. All these units are unconformably overlain by Quaternary alluvium (Figures 1 & 2). Based on the field observations, the Miocene TB and Middle Eocene ÇES, ITS and ATS outcrop are probably controlled by NW–SE-trending fault and by NE–SW-, NW–SE-trending faults, respectively (Figure 1b).

Analytical Methods

130 thin sections from the volcanic rocks of the study area were examined under the microscope. Selected samples were analyzed for mineral chemistry, whole-rock major-, trace- and rare-earth-element compositions. Mineral compositions were determined using a JEOL JXA-8900L electron microprobe on carbon-coated polished sections at the McGill University, Earth & Planetary Sciences, Canada. Counting times for individual elements and sample currents were 20s and 20 nA, respectively. Whole-rock petrochemical analyses were carried out at ACME Analytical Laboratories Ltd., Vancouver, Canada. Major and trace element compositions were determined by ICP from pulps after 0.2 g samples of rock powder were fused with 1.5 g $LiBO_2$ and then dissolved in 100 ml 5% HNO_3. Rare earth element contents were analyzed by ICP-MS from pulps after 0.25 g samples of rock powder were dissolved by four acid digestions. Loss on ignition (LOI) is by weight difference after ignition at 1000 °C. Detection limits range 0.01 to 0.1 wt % for major oxides, 0.1 to 10 ppm for trace elements and 0.01 to 0.5 ppm for the rare earth elements.

Results

Petrography and Mineral Chemistry

Petrographically, the Tertiary volcanic rocks studied are described in four groups; andesite/ trachyandesite suite (ATS), Işık Tepe suite (ITS), Çatal Tepe and Elekçioğlu Tepe suite (ÇES) and Yenisayaca basalt (TB). The textures and mineralogical compositions of the studied rocks from these suites can be summarized as follows.

The ATS rocks have microlitic porphyritic, hyalo-microlitic, hyalo-microlitic porphyritic, hyalopilitic, fluidal and sieve textures (Figure 3a–c). Typical mineral assemblages in the rocks are plagioclase, clinopyroxene, hornblende, biotite, Fe-Ti oxide and apatite. Plagioclases

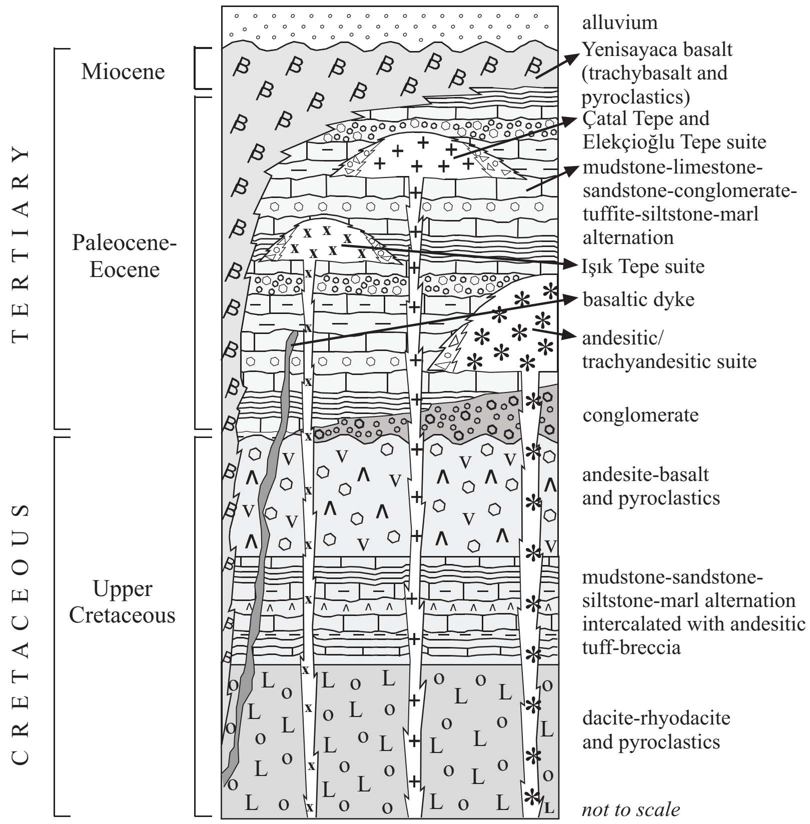

Figure 2. Simplified stratigraphic columnar section of the Ulubey (Ordu) area.

(An_{23-71}) (Figure 4, Table 1), varying in shape from euhedral to subhedral crystals, are present both as phenocrysts and microlites (some of which are albite in composition) in the glassy-fluidal groundmass (Figure 3a–c). Plagioclases exhibit also albite twinning and oscillatory zoning. Clinopyroxenes ($Wo_{27-47}En_{41-55}Fs_{13-26}$), are mainly anhedral with scarce subhedral grains, and are diopside-augite (Morimoto 1988; Figure 5, Table 2). Hornblendes occur as both subhedral and euhedral grains, and are classified (Leake *et al.* 1997) as magnesio-hastingsite (Mg#= 0.68–0.76, Figure 6, Table 3). The biotites (Mg#= 0.74–0.81, Table 3), which are anhedral-subhedral grains, occur as elongated crystals and may be rimmed by Fe-Ti oxide grains at the rim. The Fe-Ti oxides are titanomagnetite (Bacon & Hirschmann 1988; Table 4). Secondary chlorite and quartz is also present. Resorbed quartz as probably xenocryst is often surrounded by reaction rims composed of small-lath shaped clinopyroxene crystals.

The ITS rocks have a variety of volcanic rocks from trachyandesite to rhyolite. The trachyandesite and rhyolite show mainly hyalo-microlitic, hyalo-microlitic porphyritic, fluidal and perlitic textures. The trachyandesites consist of plagioclase, clinopyroxene, hornblende, Fe-Ti oxides (Figure 3d) and the rhyolites contain plagioclase, sanidine, hornblende, biotite and Fe-Ti oxides (Figure 3e). Plagioclase, showing sieve-texture and oscillatory zoning, occurs as subhedral to euhedral phenocrysts in the glassy-fluidal groundmass in trachyandesite (Figure 3d). Clinopyroxene appear opaque and glass inclusions in trachyandesite. Subhedral to euhedral sanidine, plagioclase and biotite phenocrysts in a microcrystalline to glassy groundmass show perlitic fracturing (Figure 3e).

The ÇES rocks show hyalo-microlitic, hyalo-microlitic porphyritic, fluidal and sieve textures (Figure 3f, g). The ÇES rocks consist mainly of plagioclase, clinopyroxene, hornblende and rare biotite and Fe-Ti oxide. Plagioclases

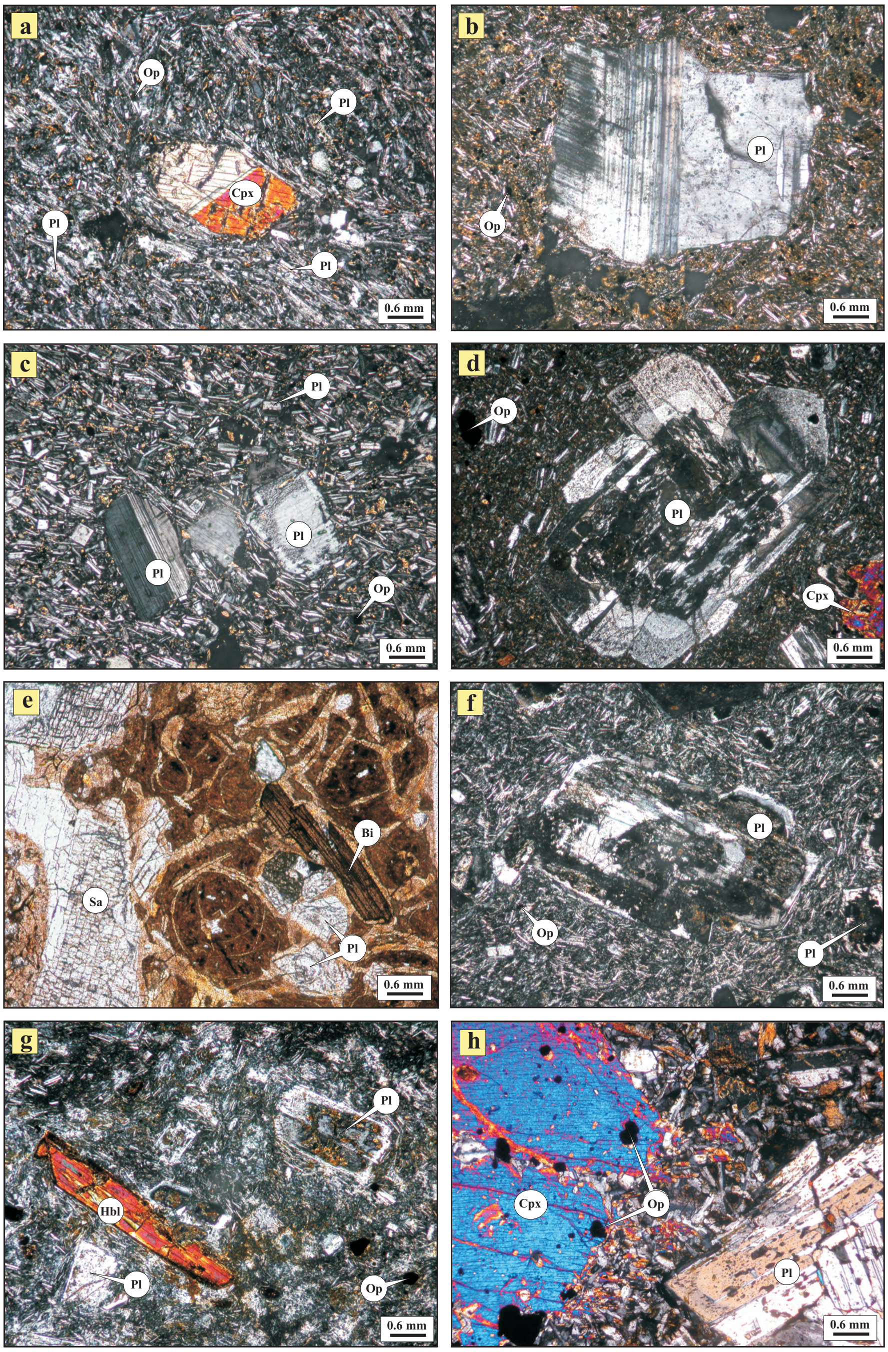

Figure 3. (a) A subparallel arrangement of microlite plagioclases in the groundmass illustrates trachytic texture with no glass (Sample No. KB-9; XPL); (b) subhedral plagioclase phenocryst showing multiple twinning in trachytic texture (Sample No. FK-9; XPL); (c) oscillatory zoned and twinned plagioclase phenocrysts and opaques set in trachytic texture (Sample No. KR-1; XPL); (d) the complex twinning in plagioclase (Sample No. IS-7; XPL); (e) sanidine, plagioclase and biotite phenocrysts in a microcrystalline to glassy groundmass showing perlitic fracturing (Sample No. IS-9; PPL); (f) sieve texture and overgrowth in plagioclase phenocryst (Sample No. CT-2; XPL); (g) hornblende with opaque rim, and oscillatory zoned plagioclase (Sample No. EC-7; XPL); (h) clinopyroxene containing opaque inclusions, and oscillatory zoned plagioclase (Sample No. YS-13; XPL). Cpx– clinopyroxene, Hbl– hornblende, Bi– biotite, Pl– plagioclase, Sa– sanidine, Op– opaque.

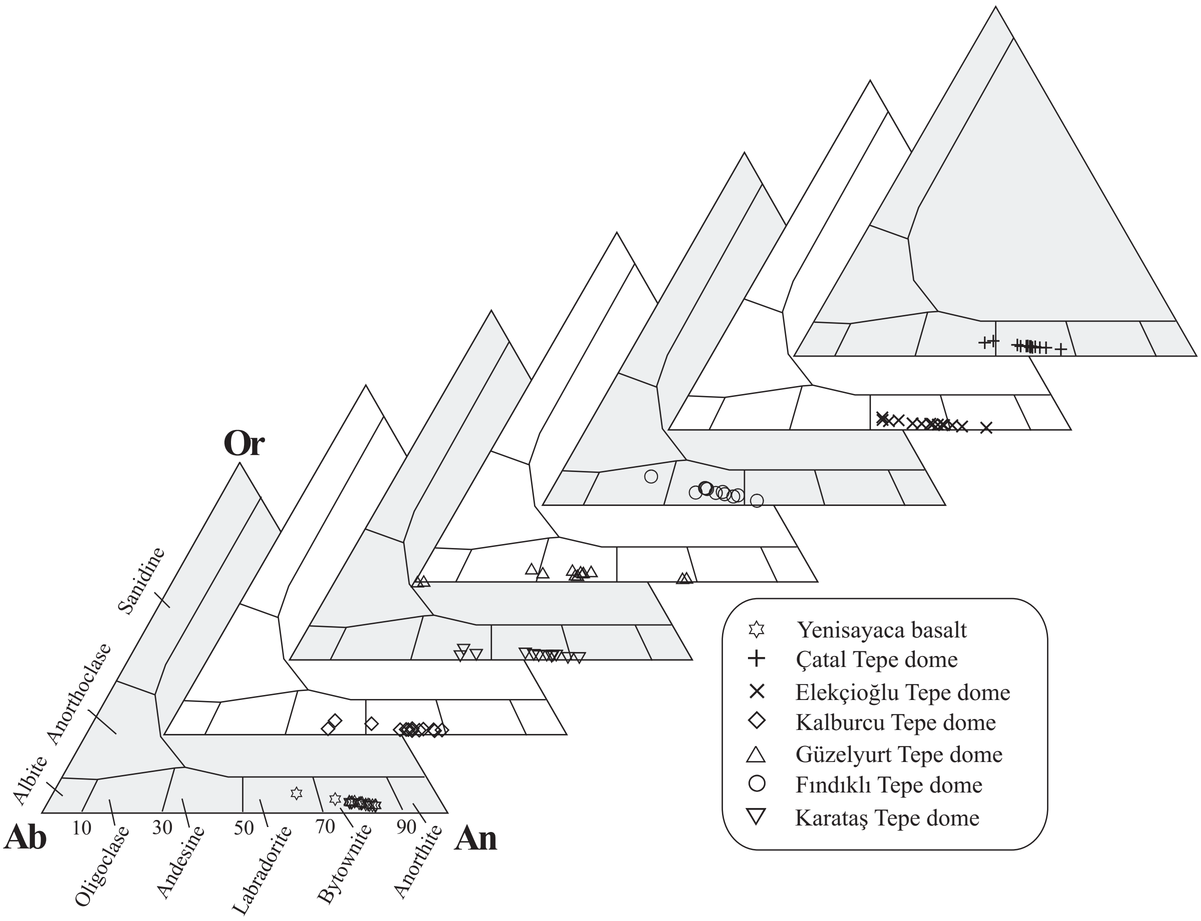

Figure 4. Classification of the feldspars in the Ulubey (Ordu) volcanics on ternary An-Ab-Or plot.

($An_{45–79}$; Figure 4, Table 1), with euhedral to subhedral crystals, are present both as phenocrysts and microlites in the glassy groundmass. Some of these show sieve-texture and oscillatory to complex zoning (Figure 3f, g). Clinopyroxene ($Wo_{28–30}En_{47–48}Fs_{22–24}$) phenocrysts are augite (Morimoto 1988; Figure 5, Table 2) and very limited in composition. Hornblendes occur as both subhedral and euhedral grains, and are classified (Leake *et al.* 1997) as magnesio-hastingsite (Mg#= 0.63–0.69; Figure 6, Table 3). Some of these are also corroded. The Fe-Ti oxides are titanomagnetite (Bacon & Hirschmann 1988; Table 4). The groundmass, composed of subhedral plagioclase microlites and glass, exhibits flow texture.

The TB is generally highly porphyritic with 40–50% of plagioclase and Ca-rich clinopyroxene phenocrysts, and also shows sieve, glomeroporphyric, hyalopilitic, intersertal and intergranular textures (Figure 3h). Clinopyroxene megacrysts, plagioclase and olivine phenocrysts are enclosed within a glassy or fine-grained groundmass that contains plagioclase microlites, Fe-Ti oxides and glass. Secondary calcite and chlorite are also present. Plagioclase is bytownite (Figure 4, Table 1) in composition ($An_{61–83}$) and occurs as mainly subhedral laths and microlites in the groundmass. Clinopyroxene megacrysts are euhedral to subhedral, rounded, broken or twinned, unzoned or weakly zoned, and are often sieve-textured (Figure 3h). The clinopyroxene crystals are fairly homogeneous in composition ($Wo_{42–44}En_{40–41}Fs_{16–17}$) and are classified as augite and diopsidic-augite (Morimoto 1988; Figure 5, Table 2). Some of them include Fe-Ti oxide and plagioclase, and show chloritization. Unzoned, subhedral and fractured olivine phenocrysts are extensively iddingsitized in the TB. The Fe-Ti oxides are titanomagnetite (Bacon & Hirschmann 1988; Table 4).

Table 1. Representative electron microprobe analyses of plagioclase of the Ulubey (Ordu) volcanics. Abbreviations: Plg– plagioclase, pheno– phenocryst, Ab– albite, An– anorthite, Or– orthoclase

				Çatal Tepe and Elekçioğlu Tepe suite						Andesite / Trachandesite suite											
	Yenisayaca Basalt			Çatal Tepe Dome			Elekçioğlu Tepe Dome			Fındıklı Tepe Andesite			Güzelyurt Tepe Andesite			Kalburcu Tepe Andesite			Karataş Tepe Andesite		
Sample No	YS-2	YS-2	YS-8	CT-2	CT-2	CT-5	EC-7	EC-8	EC-8	FK-2	FK-2	FK-3	GY-10	GY-10	GY-11	KB-2	KB-9	KB-9	KR-4	KR-5	KR-5
	Plg-3	Plg-6	Plg-5	Plg-6	Plg-7	Plg-6	Plg-3	Plg-7	Plg-9	Plg-7	Plg-12	Plg-3	Plg-7	Plg-10	Plg-5	Plg-1	Plg-8	Plg-9	Plg-11	Plg-1	Plg-3
	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno
	rim	core	rim	core	core	rim	core	rim	core	core	core	rim	core	core	core	core	core	core	core	core	core
SiO_2	49.13	47.95	52.29	53.22	53.29	55.80	54.02	52.74	50.94	59.90	56.99	58.96	51.89	58.75	51.43	51.32	51.73	57.73	58.25	51.39	52.68
Al_2O_3	31.61	32.36	28.93	29.67	29.20	27.33	29.31	30.29	31.37	25.26	27.50	25.38	30.35	25.49	30.76	29.98	30.03	26.12	26.29	30.73	28.96
FeO*	0.88	0.84	0.83	0.40	0.46	0.44	0.53	0.42	0.42	0.13	0.26	0.15	0.61	0.67	0.54	0.86	0.73	0.19	0.21	0.64	0.76
MnO	0.00	0.03	0.00	0.00	0.02	0.04	0.03	0.03	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02
MgO	0.09	0.07	0.10	0.03	0.03	0.03	0.04	0.03	0.01	0.01	0.02	0.01	0.04	0.03	0.01	0.08	0.05	0.01	0.01	0.06	0.06
CaO	15.58	16.49	12.29	12.36	12.16	9.70	12.13	12.91	14.05	7.52	9.65	7.74	13.55	7.96	13.95	13.44	13.18	8.42	8.61	13.85	12.19
Na_2O	2.11	1.85	3.77	4.05	4.26	5.49	4.33	3.81	3.22	6.94	5.95	6.40	3.75	6.72	3.73	3.57	3.94	6.76	6.45	3.39	4.35
K_2O	0.35	0.25	0.81	0.35	0.36	0.69	0.34	0.32	0.24	0.59	0.41	0.81	0.20	0.33	0.19	0.19	0.26	0.30	0.23	0.14	0.24
Total	99.75	99.84	99.02	100.08	99.78	99.52	100.73	100.55	100.27	100.35	100.78	99.46	100.39	99.95	100.61	99.44	99.93	99.53	100.06	100.20	99.26
Numbers of cations on the basis of 32 oxygens.																					
Si	9.04	8.84	9.62	9.64	9.69	10.11	9.72	9.52	9.26	10.66	10.17	10.60	9.42	10.53	9.33	9.41	9.44	10.40	10.42	9.34	9.65
Al	6.85	7.03	6.27	6.33	6.26	5.84	6.22	6.45	6.72	5.30	5.79	5.38	6.49	5.39	6.57	6.48	6.46	5.55	5.55	6.59	6.25
Fe^{2+}	0.14	0.13	0.13	0.06	0.07	0.07	0.08	0.06	0.06	0.02	0.04	0.02	0.09	0.10	0.08	0.13	0.11	0.03	0.03	0.10	0.12
Mn	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.02	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.02	0.01	0.00	0.00	0.02	0.02
Ca	3.07	3.26	2.42	2.40	2.37	1.88	2.34	2.50	2.74	1.44	1.85	1.49	2.64	1.53	2.71	2.64	2.58	1.63	1.65	2.70	2.39
Na	0.75	0.66	1.35	1.42	1.50	1.93	1.51	1.33	1.13	2.40	2.06	2.23	1.32	2.33	1.31	1.27	1.39	2.36	2.24	1.20	1.54
K	0.08	0.06	0.19	0.08	0.08	0.16	0.08	0.07	0.06	0.13	0.09	0.19	0.05	0.07	0.04	0.05	0.06	0.07	0.05	0.03	0.06
Total	19.95	20.00	19.94	19.94	19.98	20.01	19.96	19.94	19.97	19.95	20.01	19.91	20.02	19.96	20.04	20.00	20.05	20.04	19.94	19.98	20.03
Ab mol. %	19.24	16.63	33.98	36.47	37.96	48.57	38.49	34.17	28.87	60.44	51.50	57.12	32.98	59.28	32.25	32.09	34.58	58.22	56.82	30.44	38.67
An mol. %	78.66	81.92	61.19	61.47	59.94	47.42	59.54	63.97	69.71	36.21	46.15	38.14	65.86	38.82	66.67	66.75	63.90	40.09	41.87	68.73	59.91
Or mol. %	2.10	1.45	4.83	2.06	2.10	4.01	1.97	1.86	1.42	3.35	2.35	4.74	1.16	1.90	1.08	1.16	1.52	1.69	1.31	0.83	1.42

* Total iron as Fe^{2+}.

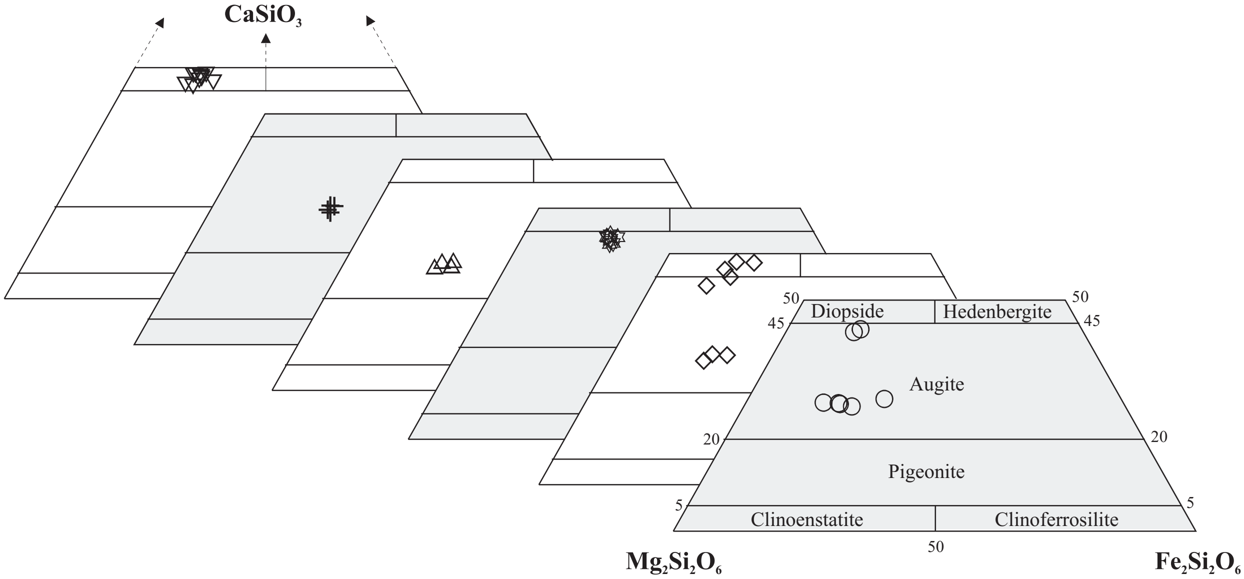

Figure 5. Clinopyroxene classification diagram (Morimoto 1988) of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 4.

The groundmass is composed of lath-shaped plagioclase microlites and augite, as well as rare magnetite, and volcanic glass.

Whole-rock Major and Trace Elements

Representative whole-rock major and trace element data for samples of the Ulubey (Ordu) volcanics are listed in Table 5. Geochemically, the volcanic rocks are also described in four groups; andesite/trachyandesite suite (ATS), Işık Tepe suite (ITS), Çatal Tepe and Elekçioğlu Tepe suite (ÇES) and Yenisayaca basalt (TB). The volcanic rocks, following the total alkali versus silica classification of Le Maitre *et al.* (2002), are mainly classified as trachy-basalt (TB); dacite, trachy-dacite (ÇES); basaltic trachy-andesite, trachy-andesite, trachy-dacite and rhyolite (ITS); andesite, trachy-andesite (ATS) (Figure 7). The TB and ITS rocks display alkaline compositions, whereas ÇES and ATS rocks are generally sub-alkaline (Figure 7). In an AFM diagram (Figure 8), the TB is tholeiitic-alkaline in character and the ÇES and ATS rocks display a typical calc-alkaline trend.

Most major and trace element variations display good positive or negative correlations with increasing SiO_2 contents (Figures 9 & 10), reflecting the significant role of fractional crystallization processes of different mineral phases during the evolution of the volcanic suites. There is a decrease for TiO_2, Al_2O_3, P_2O_5, Fe_2O_3*, K_2O, MnO, MgO, Co, and Y contents, whereas an increase for Na_2O, Rb, Sr, Ba, Zr, Ce, Hf, Nb and Th contents with increasing SiO_2 in ATS (Figures 9 & 10). TiO_2, Al_2O_3, P_2O_5, Fe_2O_3*, K_2O, CaO, MnO, MgO, Sr, Ba and Co contents decrease, whereas Na_2O, Rb, Zr, Ce, Hf, Nb, Y and Th increase with increasing SiO_2 in ITS (Figures 9 & 10). There is a decrease for TiO_2, Fe_2O_3*, Na_2O, CaO, MnO, MgO, Sr, Ce, Hf, Y and Co contents, whereas an increase for Al_2O_3, P_2O_5, K_2O, P_2O_5, Ba and Th contents with increasing SiO_2 in ÇES (Figures 9 & 10). Al_2O_3, Na_2O, CaO, MnO, Rb, Sr, Zr, Ce, Nb, Th and Co contents decrease, whereas TiO_2, P_2O_5, Fe_2O_3*, MgO, Ba, Hf and Y increase with increasing SiO_2 in TB (Figures 9 & 10). Decreasing P_2O_5, TiO_2, and Sr with increasing SiO_2 are probably related to apatite, magnetite, and plagioclase fractionation, respectively. The samples have moderate to high Al_2O_3 (10–21wt%) content with considerable scattering, probably as a result of variations in the plagioclase abundances. CaO decreases with increasing SiO_2 in TB, ÇES and ITS, reflecting the strong clinopyroxene and plagioclase fractionation. Fe_2O_3* decreases with increased differentiation; this pattern may be related to clinopyroxene fractionation. Decreasing Fe_2O_3, MgO and MnO with increasing SiO_2 are probably related to hornblende and biotite fractionation in the ÇES,

Table 2. Representative electron microprobe analyses of clinopyroxene minerals for the Ulubey (Ordu) volcanics. Abbreviations: Cpx– clinopyroxene, pheno– phenocryst, Wo– wollastonite, En– enstatite, Fs– ferrosilite.

	Çatal Tepe and Elekçioğlu Tepe suite						Andesite / Trachyandesite suite											
	Yenisayaca Basalt			Çatal Tepe Dome			Fındıklı Tepe Dome			Güzelyurt Tepe Dome			Kalburcu Tepe Dome			Karataş Tepe Dome		
Sample No	YS-8	YS-8	YS-8	CT-5	CT-5	CT-5	FK-2	FK-2	FK-2	GY-11	GY-11	GY-11	KB-9	KB-9	KB-9	KR-5	KR-5	KR-5
	Cpx-1	Cpx-3	Cpx-4	Cpx-5	Cpx-7	Cpx-12	Cpx-3	Cpx-5	Cpx-6	Cpx-8	Cpx-9	Cpx-10	Cpx-1	Cpx-2	Cpx-4	Cpx-8	Cpx-9	Cpx-10
	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno	pheno
	rim	rim	core	core	core	core	rim	core	core	core	core	core	core	core	core	rim	core	core
SiO_2	48.93	49.52	50.32	41.70	42.90	40.63	50.41	42.38	44.19	42.33	43.53	43.80	45.02	43.62	49.60	51.13	49.49	48.68
TiO_2	0.84	0.87	0.59	1.98	1.87	1.68	0.61	1.11	1.27	1.19	1.25	1.20	1.22	1.36	0.79	0.29	0.58	0.82
Al_2O_3	3.89	3.79	3.33	12.92	11.71	13.55	3.96	12.43	11.22	12.66	11.05	11.34	10.07	11.83	4.37	2.39	5.08	6.44
FeO*	10.67	10.77	9.89	12.02	12.33	11.73	8.77	13.74	9.69	10.86	10.72	9.43	9.98	10.43	8.86	7.89	7.11	8.00
MnO	0.33	0.39	0.30	0.19	0.25	0.16	0.39	0.13	0.12	0.14	0.13	0.10	0.15	0.14	0.30	0.20	0.12	0.13
MgO	13.95	13.43	14.39	13.54	14.41	13.93	14.98	13.47	16.84	15.33	14.98	16.69	16.57	15.79	14.12	14.34	13.02	12.82
CaO	20.36	20.79	21.05	11.93	11.76	12.16	21.18	11.63	11.73	11.09	11.44	11.27	11.24	11.79	21.61	22.15	22.03	21.76
Na_2O	0.37	0.31	0.31	2.03	2.02	1.96	0.34	2.06	2.20	2.16	2.17	2.14	2.12	2.04	0.38	0.25	0.54	0.67
Total	99.34	99.87	100.18	96.31	97.25	95.80	100.64	96.95	97.26	95.76	95.27	95.97	96.37	97.00	100.03	98.64	97.97	99.32
Numbers of cations on the basis of 6 oxygens.																		
Si	1.86	1.87	1.88	1.61	1.64	1.58	1.87	1.64	1.67	1.63	1.69	1.67	1.72	1.66	1.86	1.93	1.87	1.83
Ti	0.02	0.02	0.02	0.06	0.05	0.05	0.02	0.03	0.04	0.03	0.04	0.03	0.03	0.04	0.02	0.01	0.02	0.02
Al	0.17	0.17	0.15	0.59	0.53	0.62	0.17	0.57	0.50	0.58	0.50	0.51	0.45	0.53	0.19	0.11	0.23	0.28
Fe^{+2}	0.34	0.34	0.31	0.39	0.39	0.38	0.27	0.44	0.31	0.35	0.35	0.30	0.32	0.33	0.28	0.25	0.23	0.25
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Mg	0.79	0.76	0.80	0.78	0.82	0.81	0.83	0.78	0.95	0.88	0.87	0.95	0.94	0.90	0.79	0.81	0.73	0.72
Ca	0.83	0.84	0.84	0.49	0.48	0.51	0.84	0.48	0.48	0.46	0.48	0.46	0.46	0.48	0.87	0.90	0.89	0.87
Na	0.03	0.02	0.02	0.15	0.15	0.15	0.02	0.15	0.16	0.16	0.16	0.16	0.16	0.15	0.03	0.02	0.04	0.05
Total	4.05	4.03	4.03	4.08	4.07	4.11	4.03	4.09	4.11	4.09	4.09	4.08	4.08	4.09	4.05	4.04	4.01	4.02
Mg #	69.97	68.97	72.18	66.76	67.56	67.92	75.28	63.60	75.60	71.57	71.36	75.93	74.74	72.96	73.97	76.41	76.55	74.06
Wo	42.32	43.41	43.15	29.71	28.39	29.89	43.35	28.30	27.45	27.12	28.15	26.93	26.72	28.14	44.87	45.89	48.22	47.48
En	40.36	39.03	41.03	46.92	48.37	47.62	42.64	45.60	54.85	52.16	51.27	55.48	54.77	52.43	40.78	41.35	39.64	38.90
Fs	17.32	17.56	15.82	23.37	23.24	22.49	14.01	26.10	17.70	20.72	20.58	17.59	18.51	19.43	14.35	12.76	12.14	13.62

* Total iron as Fe^{2+}. Mg # (Mg-number) = Mg / (Mg + Fe^{2+}).

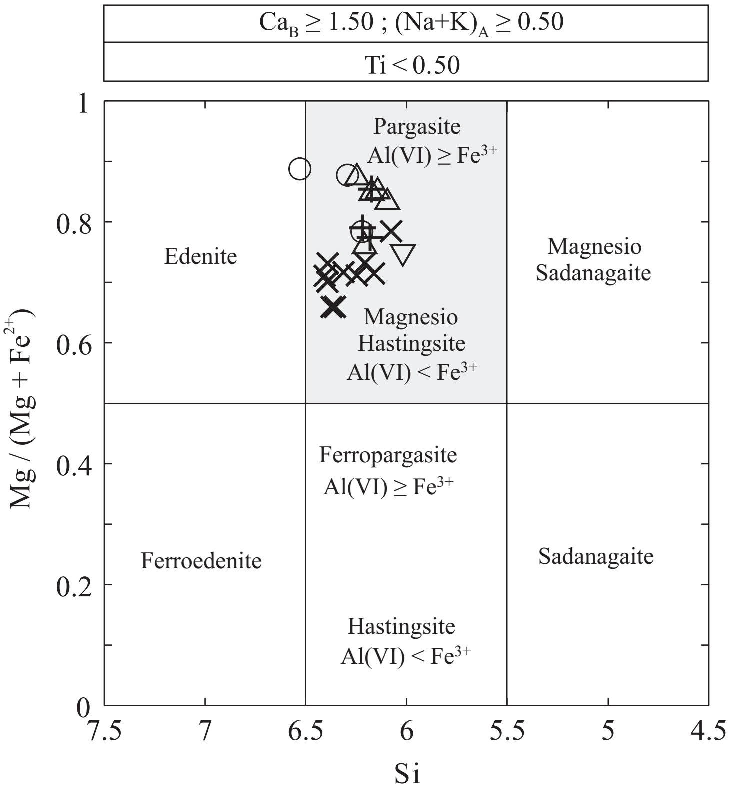

Figure 6. Hornblende classification diagram (Leake *et al.* 1997) of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 4.

ITS and ATS rocks. Na_2O and K_2O show generally non-linear positive correlations with SiO_2 in ÇES and ITS, common in a magmatic system that involves fractionation of calcic plagioclase, clinopyroxene, biotite and/or sanidine. Decreasing P_2O_5, TiO_2, and Sr with increasing SiO_2 are probably related to apatite, titanomagnetite, and plagioclase fractionation, respectively. All these variations can be explained by fractionation of common mineral phases as clinopyroxene ± plagioclase ± magnetite in TB, and hornblende + biotite + plagioclase ± magnetite ± apatite ± sanidine in ÇES, ITS and ATS rocks (Figures 9 & 10).

In N-Type MORB-normalized (Sun & McDonough 1989) spidergram (Figure 11), the studied rocks show enrichment in large ion lithophile elements (LILE; e.g., Sr, K_2O, Rb and Ba), Th and Ce, but depletion in some high field strength elements (HFSE; e.g., Zr, Y and TiO_2) relative to LILE. In general, all of these features are similar to those of subduction related volcanics (i.e. Pearce 1983; Pearce & Peate 1995).

Rare Earth Elements

C1-chondrite-normalized (Sun & McDonough 1989) REE patterns (Figure 12) are enriched in LREE relative to HREE, in a manner typical of calc-alkaline suites. All volcanic rocks (TB, ÇES, ITS and ATS) show moderately fractionated C1-chondrite-normalized REE patterns, parallel to each other with (La_N/Lu_N)= 7–28, indicating a similar origin for TB, ÇES, ITS and ATS. Additionally, the REE distributions have characteristic concave patterns, suggesting a significant role of clinopyroxene and hornblende fractionation in the evolution of the rocks (Figure 12). It is generally suggested that hornblende is characterized by REE enrichment and moderately enriched LREE contents (Thompson *et al.* 1984; Thirlwall *et al.* 1994). All the volcanic rocks have negative Eu

Table 3. Representative electron microprobe analyses of amphibole and biotite minerals for the Ulubey (Ordu) volcanics. Abbreviations: Amp– amphibole, M.Has– magnesio hastingsite, Bio– biotite, pheno– phenocryst.

	Çatal Tepe and Elekçioğlu Tepe suite				Andesite / Trachyandesite suite				
	Çatal T. Dome		Elekçioğlu T.D.		Fındıklı T. Dome		Güzelyurt T. Dome		Karataş T.D.
Sample No	CT-2 M.Has. Amp-3 core	CT-2 M.Has. Amp-3 rim	EC-7 M.Has. Amp-2 core	EC-7 M.Has. Amp-6 core	FK-3 M.Has. Amp-1 core	FK-3 M.Has. Amp-2 core	GY-10 M.Has. Amp-2 core	GY-10 M.Has. Amp-6 core	KR-4 M.Has. Amp-4 core
SiO_2	42.13	42.38	42.48	43.51	43.45	45.13	42.55	42.19	41.18
TiO_2	1.74	1.87	1.64	1.64	1.19	1.21	1.36	1.27	1.94
Al_2O_3	12.03	11.38	12.00	10.11	11.55	9.60	12.29	12.55	13.29
FeO*	12.27	11.89	13.17	14.02	10.19	9.49	10.70	11.83	13.43
MnO	0.22	0.24	0.30	0.46	0.14	0.13	0.12	0.16	0.15
MgO	14.16	14.63	13.29	13.46	16.26	17.04	15.77	14.12	13.28
CaO	11.58	11.59	11.60	11.58	10.87	11.06	11.67	11.34	11.69
Na_2O	1.92	1.95	1.99	1.84	2.21	1.87	2.31	2.30	2.29
K_2O	1.17	1.12	1.28	1.09	0.72	0.70	0.85	1.00	0.68
Total	97.22	97.05	97.75	97.71	96.58	96.23	97.62	96.76	97.93
Numbers of cations on the basis of 23 oxygens.									
Si	6.18	6.22	6.25	6.41	6.29	6.53	6.14	6.21	6.02
Ti	0.19	0.21	0.18	0.18	0.13	0.13	0.15	0.14	0.21
Al [IV]	1.82	1.78	1.75	1.59	1.71	1.47	1.86	1.79	1.98
Al [VI]	0.26	0.19	0.33	0.16	0.26	0.17	0.24	0.38	0.31
Fe^{3+}	0.60	0.61	0.44	0.52	0.74	0.68	0.72	0.51	0.65
Fe^{2+}	0.91	0.85	1.18	1.20	0.49	0.47	0.57	0.95	1.00
Mn	0.03	0.03	0.04	0.06	0.02	0.02	0.01	0.02	0.02
Mg	3.10	3.20	2.91	2.96	3.51	3.67	3.39	3.10	2.89
Ca	1.82	1.82	1.83	1.83	1.69	1.71	1.80	1.79	1.83
Na	0.55	0.55	0.57	0.53	0.62	0.52	0.65	0.66	0.65
K	0.22	0.21	0.24	0.20	0.13	0.13	0.16	0.19	0.13
Total	15.68	15.67	15.72	15.64	15.59	15.50	15.69	15.74	15.69
Mg#	67.29	68.68	64.27	63.13	73.99	76.20	72.42	68.02	63.80

Recalculations of Fe^{3+}, Fe^{2+} and mineral formulae after Leake et al. (1997).
Mg# (Mg-number) = $Mg/(Mg+Fe^{3+}+Fe^{2+})$.

	Çatal T. and Elekçioğlu T. suite			Andesite/Trachyandesite suite		
	Çatal T.D.	Elekçioğlu T.D.		Fındıklı T.D.		Güzelyurt T.D.
Sample No	CT-2 Bio-5 pheno core	EC-7 Bio-4 pheno core	EC-8 Bio-11 pheno core	FK-3 Bio-11 pheno core	FK-3 Bio-11 pheno rim	GY-10 Bio-11 pheno core
SiO_2	37.69	41.60	36.97	37.15	37.76	44.12
TiO_2	3.07	1.97	3.14	5.10	5.22	1.2
Al_2O_3	15.25	12.69	15.75	15.13	15.23	10.47
FeO*	9.54	13.76	13.28	8.21	7.83	10.15
MnO	0.15	0.27	0.18	0.13	0.12	0.15
MgO	19.60	12.98	16.85	19.55	19.37	16.52
CaO	0.05	11.61	0.05	0.05	0.10	11.01
Na_2O	0.66	2.05	0.79	0.96	0.91	2.31
K_2O	9.12	1.21	8.78	8.67	8.47	0.65
Total	95.13	98.14	95.79	94.95	95.01	96.58
Numbers of cations on the basis of 22 oxygens.						
Si	5.50	5.91	5.45	5.40	5.46	6.21
Ti	0.34	0.21	0.35	0.56	0.57	0.13
Al [IV]	2.50	2.09	2.56	2.59	2.54	1.74
Al [VI]	0.12	0.03	0.18	0.00	0.05	0.00
Fe^{2+}	1.16	1.63	1.64	1.00	0.95	1.19
Mn	0.02	0.03	0.02	0.02	0.02	0.02
Mg	4.27	2.75	3.70	4.24	4.17	3.47
Ca	0.01	1.77	0.01	0.01	0.01	1.66
Na	0.19	0.57	0.23	0.27	0.26	0.63
K	1.70	0.22	1.65	1.61	1.56	0.12
Total	15.81	15.21	15.79	15.7	15.59	15.17
Mg#	0.79	0.63	0.69	0.81	0.82	0.74
Phologopite	72	59	63	73	73	72
Annite	20	35	28	17	16	25

* Total iron as Fe^{2+}. Mg # (Mg-number) = $Mg / (Mg + Fe^{2+})$.

Table 4. Representative electron microprobe analyses of Fe-Ti oxide minerals for the Ulubey (Ordu) volcanics.

			Çatal Tepe and Elekçioğlu Tepe suite				Andesite / Trachandesite suite							
	Yenisayaca Basalt		Çatal Tepe Dome		Elekçioğlu Tepe Dome		Fındıklı Tepe Dome		Güzelyurt Tepe Dome		Kalburcu Tepe Dome		Karataş Tepe Dome	
Sample No	YS-2-5 Titano-Magnetite	YS-2-7 Titano-Magnetite	CT-2-2 Titano-Magnetite	CT-2-10 Titano-Magnetite	EC-7-1 Titano-Magnetite	EC-7-7 Titano-Magnetite	FK-2-1 Titano-Magnetite	FK-2-10 Titano-Magnetite	GY-10-3 Titano-Magnetite	GY-10-9 Titano-Magnetite	KB-2-3 Titano-Magnetite	KB-2-8 Titano-Magnetite	KR-4-3 Titano-Magnetite	KR-4-10 Titano-Magnetite
SiO_2	0.09	0.41	3.02	1.39	0.04	2.11	0.00	0.04	0.00	0.00	0.06	0.07	0.07	0.04
TiO_2	7.45	8.71	3.77	2.25	5.01	2.47	4.40	4.80	1.60	1.44	0.59	0.30	5.49	6.03
Al_2O_3	5.38	4.89	1.61	1.11	2.30	1.17	1.69	1.54	0.64	0.50	0.25	0.14	1.33	1.00
Fe_2O_3	43.60	39.80	42.00	49.90	49.50	47.60	53.10	52.10	57.90	58.50	58.30	60.20	50.90	49.90
FeO	31.20	33.60	32.70	29.10	30.70	30.30	29.40	30.40	28.80	28.70	27.40	27.70	28.90	30.20
MnO	0.42	0.52	0.41	0.47	0.98	0.55	0.54	0.56	0.31	0.36	0.12	0.09	0.86	1.01
MgO	3.27	2.42	0.40	0.58	0.91	0.42	1.77	1.34	0.33	0.24	0.08	0.08	2.39	1.68
CaO	0.01	0.03	0.30	0.16	0.01	0.22	0.03	0.05	0.02	0.02	0.14	0.18	0.03	0.07
Cr_2O_3	0.14	0.11	0.04	0.08	0.08	0.04	0.00	0.02	0.09	0.07	0.07	0.06	0.06	0.04
V_2O_3	0.70	0.80	0.31	0.47	0.52	0.34	0.35	0.35	0.57	0.58	0.44	0.45	0.38	0.35
Total	92.26	91.29	84.56	85.51	90.05	85.22	91.28	91.20	90.26	90.41	87.45	89.27	90.41	90.32
Numbers of cations on the basis of 4 oxygens.														
Si	0.00	0.02	0.13	0.06	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.22	0.26	0.12	0.07	0.16	0.08	0.14	0.15	0.05	0.05	0.02	0.01	0.17	0.19
Al	0.25	0.23	0.08	0.06	0.11	0.06	0.08	0.07	0.03	0.02	0.01	0.01	0.06	0.05
Fe^{3+}	1.28	1.19	1.39	1.65	1.55	1.58	1.64	1.61	1.84	1.86	1.93	1.95	1.58	1.56
Fe^{2+}	1.02	1.11	1.20	1.07	1.07	1.12	1.01	1.05	1.02	1.02	1.01	1.00	0.99	1.05
Mn	0.01	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.03	0.04
Mg	0.19	0.14	0.03	0.04	0.06	0.03	0.11	0.08	0.02	0.02	0.00	0.01	0.15	0.10
Ca	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V	0.02	0.03	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01
Total	2.99	3.00	2.99	3.00	3.00	3.00	3.01	2.99	2.99	3.00	3.00	3.01	2.99	3.00

Oxide equilibria based on the partitioning test of Bacon & Hirschmann (1988); Fe allocated as FeO/Fe_2O_3 on basis of stoichiometry.

Table 5. Representative whole-rock major (wt%) and trace element (ppm) data for samples of the Ulubey (Ordu) volcanics.

					Çatal Tepe and Elekçioğlu Tepe suite						Işık Tepe suite		
	Bas. Dyke	Yenisayaca Basalt			Çatal Tepe Dome Dome			Elekçioğlu Tepe Dome			Işık Tepe Dome		
Sample No.	V-6	YS-1	YS-2	YS-3	CT-2	CT-3	CT-4	EC-1	EC-2	EC-5	IS-2	IS-4	IS-7
SiO_2	54.92	50.50	50.74	49.77	68.18	68.43	63.88	67.30	67.98	66.85	53.80	74.37	61.59
TiO_2	0.65	0.65	0.63	0.63	0.28	0.27	0.35	0.26	0.26	0.25	0.67	0.19	0.31
Al_2O_3	17.55	20.91	20.75	20.66	16.50	16.05	15.64	15.59	16.01	15.52	17.00	12.78	18.98
Fe_2O_3*	6.82	7.24	7.02	6.97	1.69	2.83	3.51	2.69	2.53	2.66	6.85	1.99	3.56
MnO	0.13	0.10	0.10	0.12	0.01	0.05	0.07	0.03	0.03	0.02	0.27	0.05	0.05
MgO	2.21	2.34	2.32	2.29	0.26	0.11	1.59	0.76	0.36	0.89	2.26	0.27	0.75
CaO	5.72	9.12	9.02	9.68	2.30	1.78	4.36	2.45	2.37	2.41	7.92	0.51	1.78
Na_2O	5.77	2.58	2.60	2.54	3.36	3.13	3.44	3.22	3.26	3.18	2.63	2.55	2.72
K_2O	2.74	3.20	3.26	3.17	4.71	5.25	3.08	4.85	4.81	5.06	5.10	6.17	7.77
P_2O_5	0.45	0.30	0.31	0.31	0.14	0.15	0.17	0.12	0.13	0.11	0.27	0.06	0.13
LOI	2.90	3.00	3.20	3.80	2.30	1.70	3.70	2.50	2.00	2.80	3.60	0.90	1.90
Total	99.86	99.94	99.95	99.94	99.73	99.75	99.79	99.77	99.74	99.75	100.37	99.84	99.54
Zr	76.5	95.9	99.3	98.1	111.0	111.5	110.9	111.5	113.6	107.6	118.1	330.2	229.6
Y	21.7	19.5	20.5	21.8	19.3	18.7	18.4	16.3	15.3	14.6	31.7	33.0	24.4
Sr	745.9	779.4	799.5	797.8	567.6	471.9	708.6	555.7	551.5	508.6	575.7	68.7	404.5
Rb	74.8	110.3	111.6	105.3	136.6	143.7	138.9	142.0	136.9	141.3	165.9	334.8	227.4
Th	7.4	11.9	12.8	12.7	7.2	8.2	6.9	8.2	7.3	7.5	10.3	62.5	29.1
Ta	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.9	2.0	0.9
Hf	2.4	2.7	2.6	2.4	3.3	2.8	3.2	3.3	2.7	3.0	2.8	10.0	5.8
Ni	2.4	4.4	3.7	4.1	2.4	3.7	4.8	1.9	1.8	2.2	9.3	1.0	1.2
Co	14.8	21.3	16.6	19.5	2.8	3.7	10.0	4.2	3.6	4.2	14.1	1.2	6.8
Ba	601.6	516.3	535.2	488.7	856.8	914.8	850.3	893.8	888.1	874.0	670.6	75.4	635.4
Nb	3.9	5.0	5.1	5.3	5.4	5.6	5.6	5.5	5.5	5.3	8.9	23.8	14.2
La	26.6	23.1	24.2	25.2	38.7	28.5	31.1	27.9	27.2	25.1	41.5	64.5	49.5
Ce	55.7	46.8	48.0	48.3	45.1	48.0	50.6	46.4	47.3	45.1	81.5	122.9	83.4
Pr	6.63	5.27	5.40	5.36	6.73	5.34	5.79	5.26	5.13	4.74	10.06	13.22	9.75
Nd	25.8	23.0	24.1	24.3	24.2	18.7	21.8	18.5	18.6	17.1	33.5	42.0	33.2
Sm	5.8	4.8	4.8	4.8	4.3	3.3	3.9	3.4	3.4	3.1	7.6	7.9	6.0
Eu	1.29	1.37	1.39	1.38	0.96	0.88	1.00	0.87	0.78	0.79	1.51	0.48	1.35
Gd	4.48	3.92	4.00	4.06	3.90	3.12	3.24	3.04	2.81	2.51	6.99	5.98	4.72
Tb	0.70	0.63	0.63	0.69	0.54	0.48	0.53	0.45	0.38	0.41	1.05	0.92	0.82
Dy	3.73	3.46	3.20	3.63	2.92	2.80	2.84	2.30	2.42	2.25	5.64	5.38	3.71
Ho	0.81	0.66	0.65	0.70	0.59	0.55	0.58	0.50	0.48	0.46	1.13	1.12	0.82
Er	2.05	1.67	1.72	1.90	1.59	1.58	1.62	1.46	1.28	1.26	3.08	3.04	2.14
Tm	0.33	0.28	0.30	0.32	0.24	0.23	0.26	0.22	0.22	0.19	0.5	0.55	0.34
Yb	1.97	1.75	1.86	1.85	1.64	1.73	1.83	1.69	1.44	1.54	3.37	3.99	2.62
Lu	0.31	0.27	0.29	0.29	0.28	0.26	0.29	0.25	0.25	0.25	0.55	0.63	0.42
Mg#	24	24	25	25	13	4	31	22	12	25	25	12	17

Fe_2O_3*, total iron as Fe_2O_3; LOI: loss on ignition.

Mg# (Mg-number) =100 x MgO / (MgO+Fe_2O_3*).

Table 5. (Continued)

	Andesite / Trachandesite suite											
	Kalburcu Tepe Dome			Güzelyurt Tepe Dome			Fındıklı Tepe Dome			Karataş Tepe Dome		
Sample No.	KB-1	KB-2	KB-4	GY-1	GY-2	GY-4	FK-1	FK-2	FK-3	KR-2	KR-4	KR-7
SiO_2	58.48	59.21	79.29	56.77	57.46	57.65	55.61	57.19	58.60	59.71	60.25	61.88
TiO_2	0.60	0.58	0.14	0.57	0.56	0.56	0.58	0.57	0.58	0.48	0.49	0.47
Al_2O_3	18.46	17.86	10.69	16.61	16.65	16.72	16.98	16.59	16.96	18.22	18.34	17.78
Fe_2O_3*	5.47	5.45	1.79	6.85	6.72	6.66	6.25	6.12	6.00	4.84	4.98	4.61
MnO	0.11	0.09	0.01	0.12	0.11	0.12	0.06	0.05	0.07	0.07	0.07	0.06
MgO	1.78	1.75	0.26	3.65	3.54	3.57	4.18	3.86	2.95	1.74	1.36	1.27
CaO	5.56	6.44	0.92	5.67	5.63	5.57	5.43	5.12	6.46	6.60	6.56	6.44
Na_2O	4.38	4.19	3.01	3.97	3.85	4.26	3.24	3.12	3.40	3.97	3.85	3.84
K_2O	2.20	2.16	2.93	2.55	2.53	2.32	3.31	3.23	2.70	2.17	2.28	2.07
P_2O_5	0.38	0.37	0.01	0.23	0.23	0.23	0.24	0.23	0.24	0.31	0.31	0.29
LOI	2.30	1.60	0.80	2.80	2.50	2.10	3.90	3.70	1.80	1.60	1.20	1.00
Total	99.72	99.70	99.85	99.79	99.78	99.76	99.78	99.78	99.76	99.71	99.69	99.71
Zr	72.1	74.0	68.7	64.1	61.9	59.1	64.9	62.0	62.7	78.8	72.2	70.0
Y	11.2	11.5	15.0	14.8	13.7	13.8	13.0	12.4	12.5	11.7	12.0	11.0
Sr	1428.5	1565.5	104.3	920.7	990.7	1018.5	1006.1	1004.5	1236.8	1575.2	1580.0	1573.7
Rb	58.1	52.9	93.6	66.0	66.0	63.9	57.8	56.0	49.9	54.4	49.7	46.2
Th	5.5	5.6	12.0	3.7	2.5	3.0	2.8	2.8	3.1	6.9	6	5.8
Ta	0.2	0.4	0.6	0.3	0.2	0.1	0.2	0.1	0.1	0.3	0.2	0.2
Hf	2.5	2.4	2.2	2.4	2.1	2.0	2.2	2.3	2.2	2.6	2.6	2.4
Ni	6.1	4.2	6.1	23.7	21.8	23.9	19.5	15.9	21.0	3.9	3.7	3.8
Co	13.9	13.1	3.1	23.4	23.4	23.2	19.6	16.9	21.2	10.8	11.1	9.8
Ba	834.9	900.7	865.3	743.9	777.6	738.4	694.5	687.4	711.1	891.4	828.9	831.9
Nb	5.0	7.1	9.3	3.1	3.1	2.9	3.2	3.0	2.8	4.8	4.8	4.3
La	29.9	30.0	24.6	17.6	16.9	16.1	17.4	16.7	16.4	29.3	29.3	27.4
Ce	64.7	65.5	48.3	36.5	35.9	34.9	35.7	33.8	34.8	62.0	61.4	57.1
Pr	7.37	7.73	4.93	4.42	4.26	4.11	4.27	4.23	4.24	6.84	7.02	6.62
Nd	29.0	30.7	16.8	18.7	17.6	16.8	18	17.5	17.9	27.1	27.3	27.0
Sm	5.2	5.1	3.0	3.7	3.8	3.6	3.5	3.5	3.6	4.6	4.7	4.0
Eu	1.30	1.41	0.47	1.00	1.02	1.01	1.04	1.02	1.00	1.20	1.18	1.17
Gd	3.37	3.45	2.41	3.22	2.93	3.09	3.02	2.94	3.19	3.08	3.18	2.94
Tb	0.44	0.41	0.38	0.49	0.43	0.42	0.40	0.41	0.43	0.42	0.44	0.40
Dy	2.08	2.14	2.15	2.51	2.43	2.41	2.26	2.13	2.19	2.06	2.03	1.96
Ho	0.39	0.39	0.44	0.5	0.45	0.47	0.41	0.39	0.41	0.38	0.41	0.36
Er	0.93	0.88	1.39	1.31	1.21	1.19	1.10	1.07	1.08	0.96	0.99	0.97
Tm	0.12	0.14	0.23	0.18	0.17	0.16	0.17	0.14	0.15	0.15	0.13	0.12
Yb	0.96	0.87	1.59	1.33	1.05	1.17	1.07	1.05	1.05	1.03	1.05	0.86
Lu	0.11	0.14	0.26	0.17	0.17	0.17	0.17	0.14	0.15	0.16	0.16	0.13
Mg#	25	24	13	35	35	35	40	39	33	26	21	22

Fe_2O_3*, total iron as Fe_2O_3 ; LOI: loss on ignition.

Mg# (Mg-number) =100 x MgO / (MgO+Fe_2O_3*).

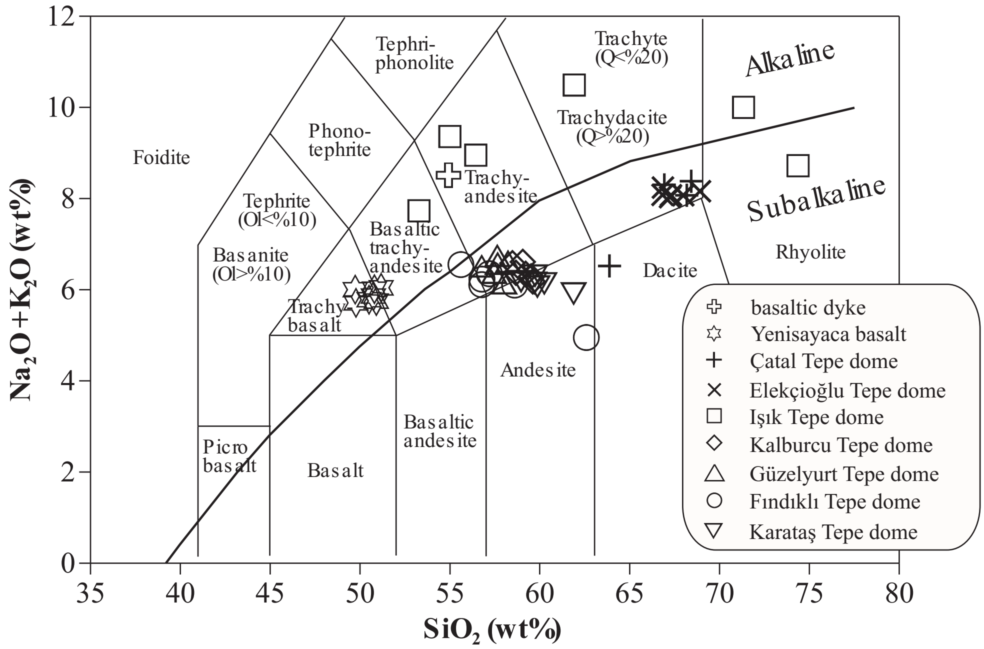

Figure 7. SiO_2 (wt%) versus Na_2O+K_2O (wt%) chemical nomenclature diagram (Le Maitre *et al.* 2002) of the Ulubey (Ordu) volcanic rocks (alkaline-subalkaline dividing line is from Irvine & Baragar 1971. Symbols are the same as for Figure 7.

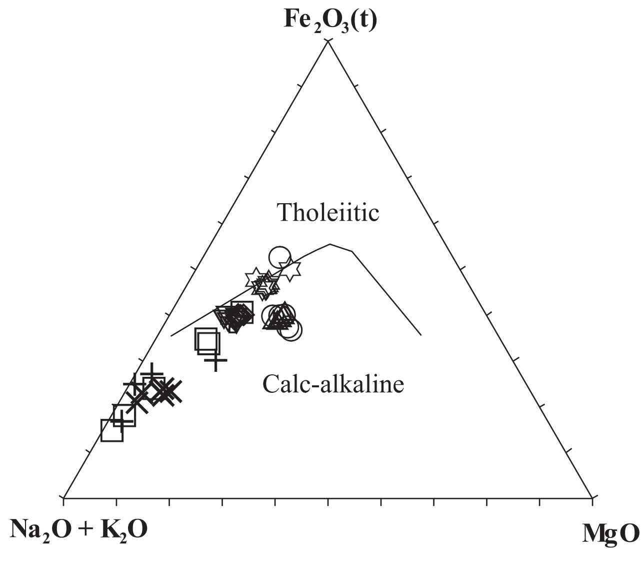

Figure 8. AFM ternary plot (Tholeiitic-Calcalkaline dividing curve is from Irvine & Baragar 1971) of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 7.

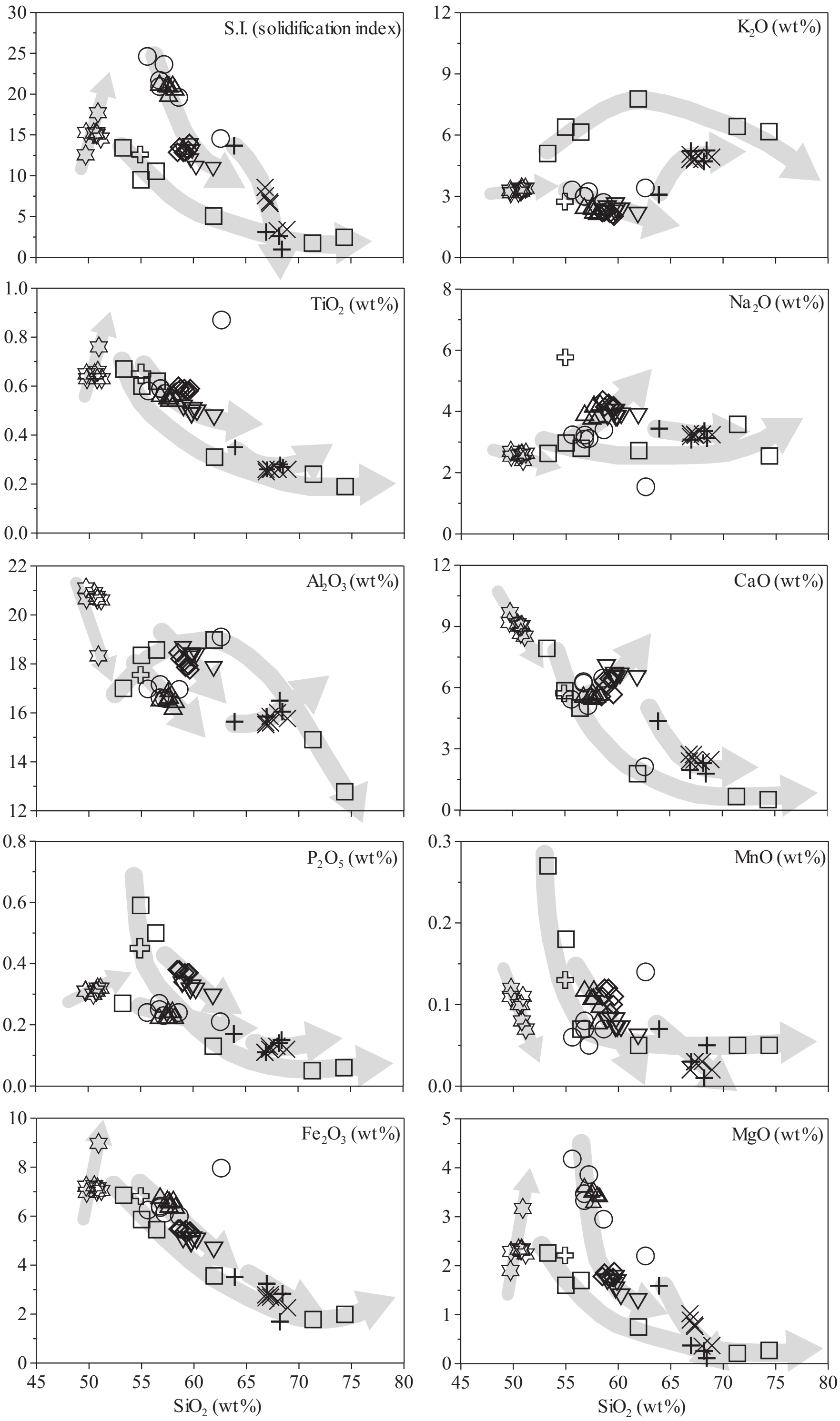

Figure 9. SiO_2 (wt%) versus major oxide (wt%) variation plots of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 7.

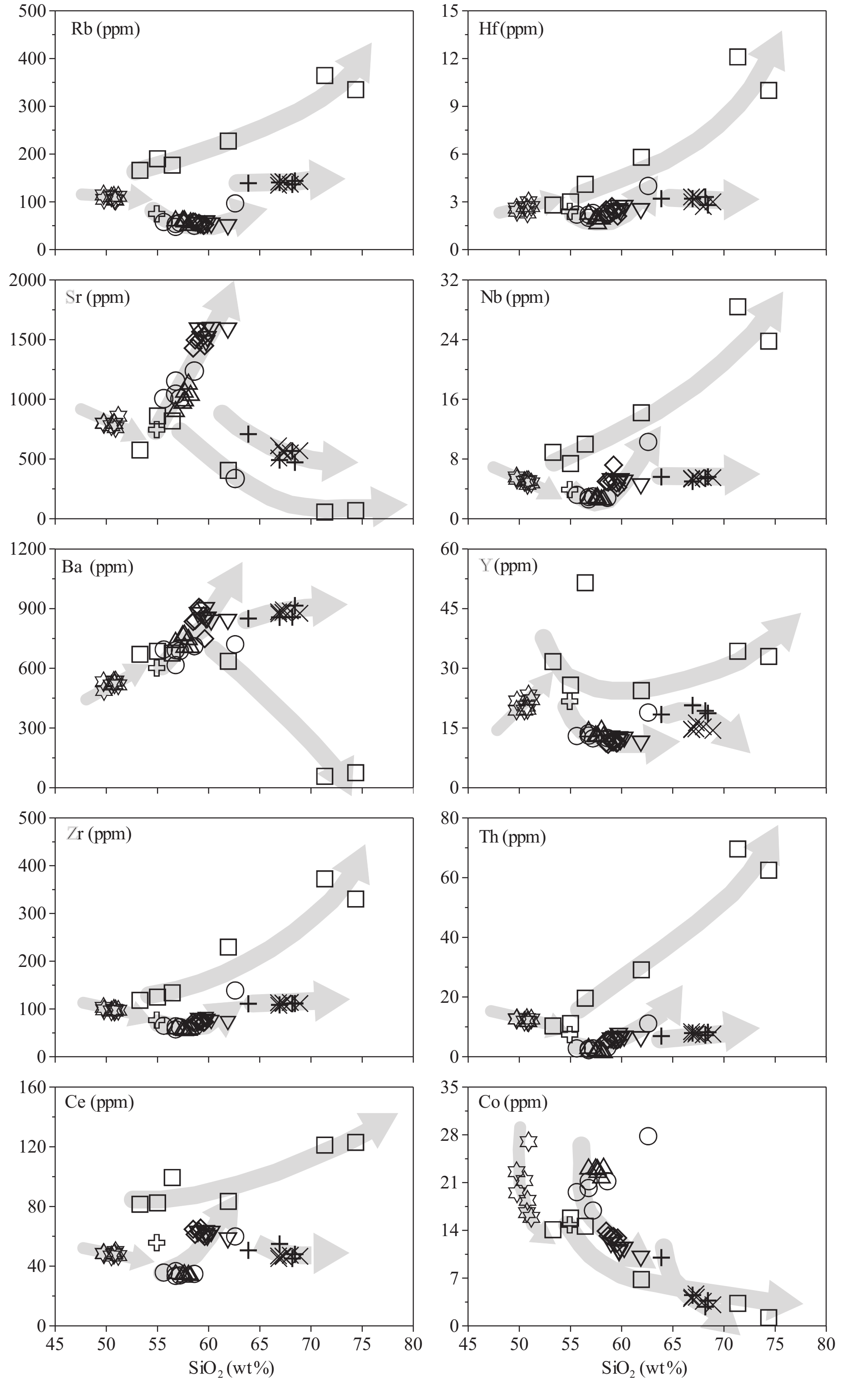

Figure 10. SiO_2 (wt%) versus trace element (ppm) variation plots of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 7.

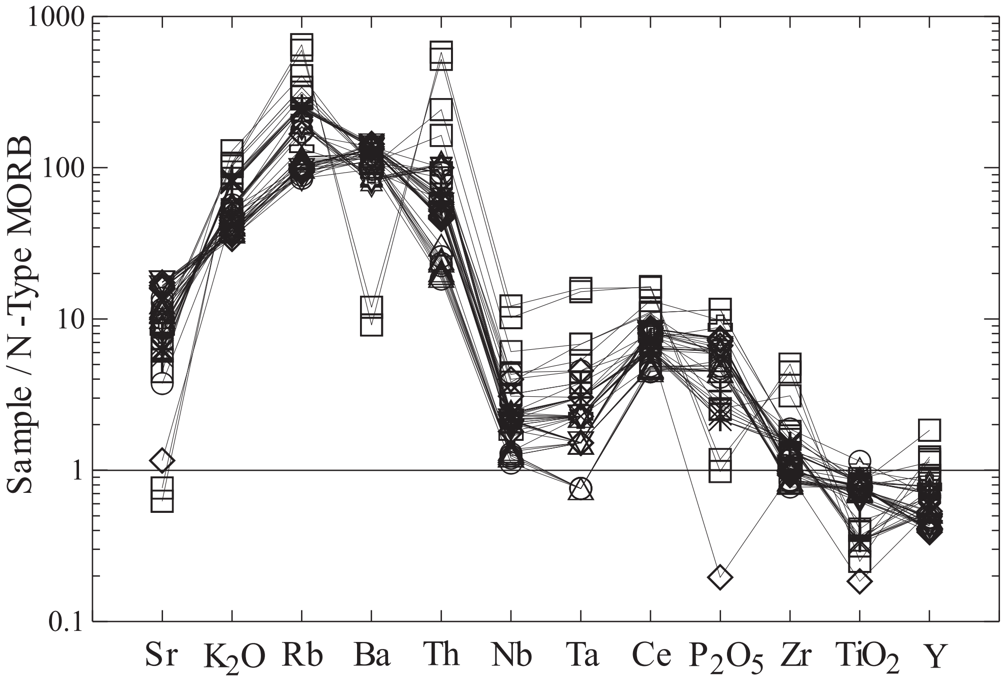

Figure 11. N-type MORB (Sun & McDonough 1989) normalised trace element plot of the volcanic rocks. Symbols are the same as for Figure 7.

anomalies (Figure 12), probably associated with plagioclase fractionation. The most basic samples have Yb_N< 10, which indicates the presence of garnet as a residual phase in the mantle source.

Discussion and Conclusions

The Ulubey (Ordu) area at the western edge of the eastern Pontides palaeo-arc is represented by Yenisayaca basalt (TB), Çatal Tepe and Elekçioğlu Tepe suite (ÇES), Işık Tepe suite (ITS) and andesite/ trachyandesite suite (ATS) associated with sediments deposited in a shallow basin environment.

The Ulubey volcanic rocks indicate a magma evolution from calc-alkaline to tholeiitic-alkaline in character. The calc-alkaline affinity is confirmed by the LILE enrichment and low Nb, Ta, Zr, and TiO_2 contents. Mineral chemistry data also are compatible with the calc-alkaline series (e.g., Ewart 1982; Machado *et al.* 2001). Variation diagrams of major and trace elements with SiO_2 indicate trends resulting from fractional crystallization. The fractionating phases are clinopyroxene ± plagioclase ± magnetite in TB, and hornblende + biotite + plagioclase ± magnetite ± apatite ± sanidine in ÇES, ITS and ATS rocks. Additionally, the variation diagrams such as Zr vs MgO, SiO_2, Y, Ce, La and Ni vs Rb show that fractional crystallization (FC) ± assimilation-fractional crystallization (AFC) ± magma mixing (MM) played a significant role in the evolution of the ÇES, ITS, ATS and TB (Figure 13). The trace element geochemical characteristics of the Ulubey volcanics signify a subduction zone-related magmatic signature with depletion in Zr, TiO_2 and Y, enrichment in LILE (e.g., Sr, K_2O, Rb, Ba), Th and Ce, and high Ba/Zr ratios (cf. Thrilwall *et al.* 1994, 1996; Pearce & Peate 1995; Borg *et al.* 1997; Churikova *et al.* 2001; Elburg *et al.* 2002; Turner 2002, 2005; George *et al.* 2004; Bindeman *et al.* 2005; McDermott *et al.* 2005; Zellmer *et al.* 2005). The studied rocks also have much higher La/Nb (2.7–8.9) and Ba/Nb (45–261) ratios compared to MORB, OIB, and intra-plate volcanics (Sun & Mc Donough 1989; Figure 14a). Additionally, all the samples plot either in or next to the arc volcanic subfield in the Nb/Th vs Nb diagram (Figure 14b). Such an arc-like geochemical signature for the Ulubey volcanics seems to be sourced either from subduction zone enrichment and/or crustal contamination. The fractionations of LILE/LREE,

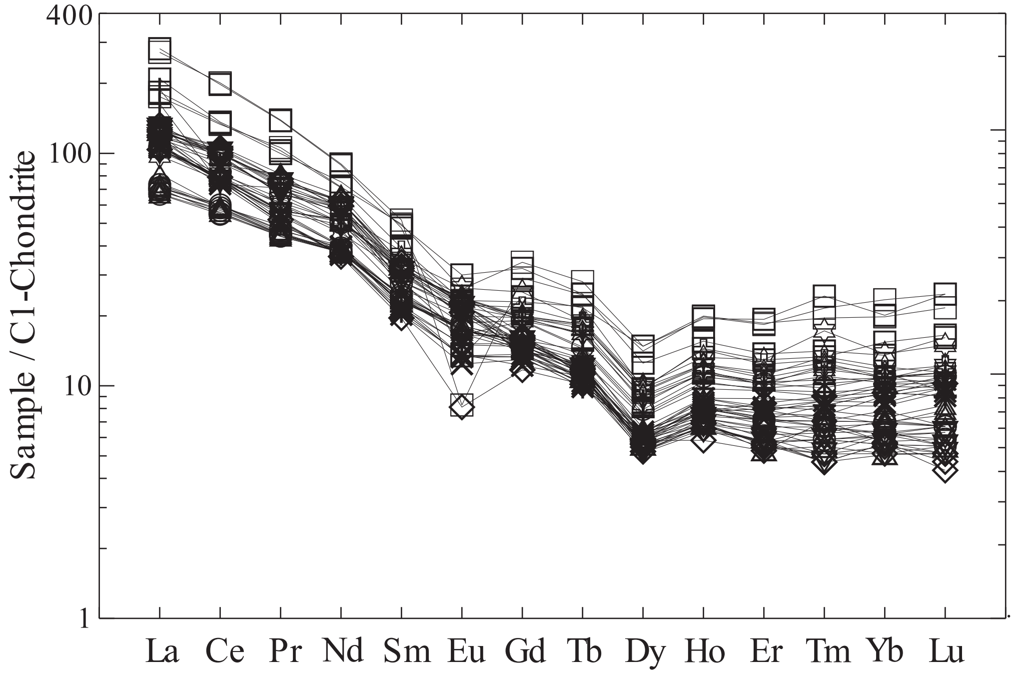

Figure 12. C1-Chondrite (Sun & McDonough 1989) normalised rare earth element patterns of the volcanic rocks. Symbols are the same as for Figure 7.

LILE/HFSE and REE/HFSE (Figure 14a, b) have been mostly attributed to subduction-related metasomatism (Schiano *et al.* 1995; Bindeman *et al.* 2005), possibly due to HFSE being retained in the subduction slab during progressive dehydration, whereas the LILE and LREE are transported upward by slab-derived fluid or melts fertilizing the overlying mantle wedge (McDonough 1991; Churikova *et al.* 2001; Elburg *et al.* 2002). Therefore, significant LILE and LREE enrichment observed in the volcanic rocks seem to favour an enriched mantle rather than depleted mantle reservoirs in their origin (Rogers *et al.* 1995; Hochstaedter *et al.* 2000; Condie *et al.* 2002; Leat *et al.* 2002; Zhu *et al.* 2006). In addition, an enrichment in Th and slightly Nb-Ta relative to N-type MORB (Figure 11) may be attributed to crustal contamination during magma ascent in the evolution of the Ulubey volcanics.

The Eocene rocks, comprising mainly of volcanics and rarely volcaniclastics and sediments, and unconformably overlying the Upper Cretaceous rocks, imply that the eastern Pontides was above sea-level during Paleocene–Early Eocene time (Okay & Şahintürk 1997). Different researchers argued for different timing and mechanism of the collision in light of the structural considerations and the composition and timing of igneous activity. Şengör & Yılmaz (1981), Yılmaz *et al.* (1997), Okay & Şahintürk (1997) and Boztuğ *et al.* (2004) propose a Paleocene–Early Eocene (ca. 55 Ma) collision, resulting in crustal thickening and regional uplift of the eastern Pontides, characterized by telescoping of the continental margin into a stack of north-vergent thrust slices. According to Tokel (1977), Akın (1978) and Robinson *et al.* (1995), the Middle Eocene volcanic rocks were related to northward subduction of the eastern Pontides and collision occurred in the Oligocene (ca. 30 Ma). The contrasting interpretations for the timing and the mechanism of collision in the eastern Pontides largely result from considerations of Tertiary magmatism in this region. However, lineaments (faults or structural boundaries) trending E–W, NE–SW and NW–SE directions in the region point to the major structural zones of Pontide crust that indicates an extensional tectonic regime (Maden *et al.* 2009).

All of these facts suggest that the primitive melts for the Ulubey volcanics were derived from decompression melting of an enriched continental lithospheric mantle,

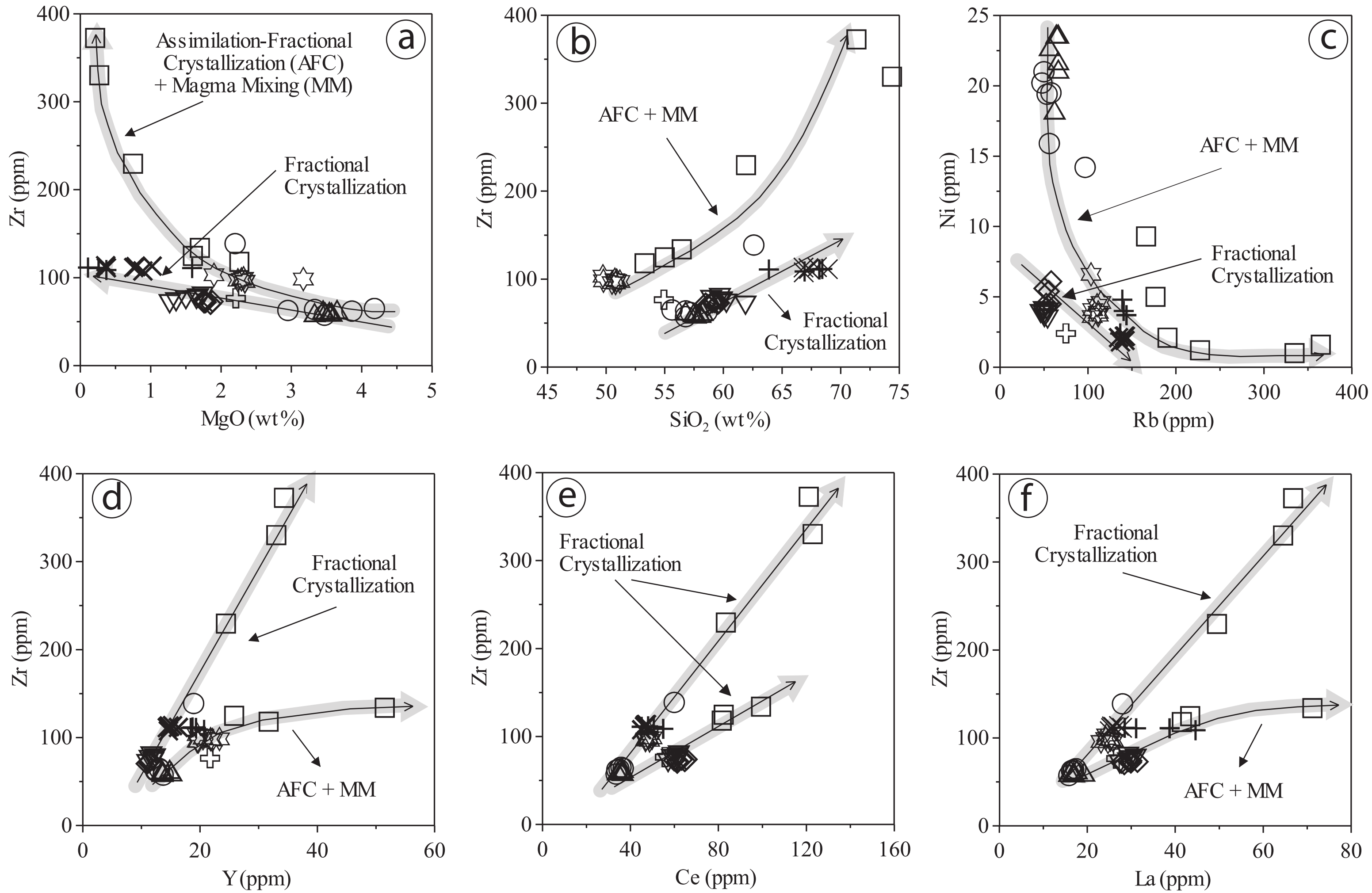

Figure 13. Zr (ppm) vs MgO (wt%), SiO_2 (wt%), Y (ppm), Ce (ppm), La (ppm) and Ni (ppm) vs. Rb (ppm) diagrams representing the fractional crystallization (FC), assimilation-fractional crystallization (AFC) and magma mixing (MM) of the Ulubey (Ordu) volcanic rocks. Symbols are the same as for Figure 7.

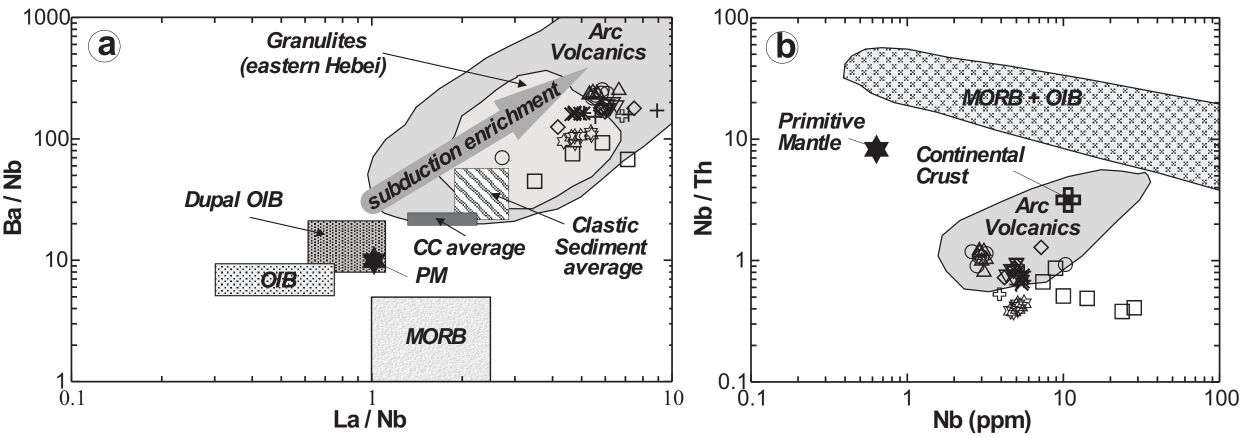

Figure 14. (a) Ba/Nb vs La/Nb (Jahn *et al*. 1999), (b) Nb/Th vs Nb (ppm) plots of the Ulubey (Ordu) volcanic rocks. Data sources for fields: Arc Volcanics and Archean granulites from eastern Hebei (data from Jahn & Zhang 1984); PM (Primitive Mantle; Sun & McDonough 1989); CC average (Continental Crust average; Taylor & Mclennan 1985; Condie 1993), Clastic Sediment average (Condie 1993); MORB (Mid-Ocean Ridge Basalts), OIB (Ocean-Island Basalt) and Dupal-OIB (Le Roux 1986) in (a) and Primitive Mantle (Hoffman 1988); Continental Crust, MORB (Mid-Ocean Ridge Basalts), OIB (Ocean-Island Basalt) and Arc Volcanics (Schmidberger & Hegner 1999) in (b). Symbols are the same as for Figure 7.

which had been previously metasomatized by fluids derived from an earlier subduction zone during Palaeocene–Eocene time (e.g., Temizel & Arslan 2008) similar to that of Eocene Kösedağ pluton in the Suşehri-Sivas area (Boztuğ 2008). Furthermore, the Ulubey volcanic rocks developed by high to shallow-level fractional crystallization of the parental magma(s). This occurred after thickening of the Pontide palaeo-magmatic arc crust during Paleocene–Eocene time, possibly within a transtentional environment. In the Ulubey area, post-collisional Tertiary mafic to felsic volcanism started with pyroclastic products in a shallow marine environment in Middle Eocene time, and was followed by extensive sub-aerial andesitic to rhyolitic and rare basaltic volcanism during late Eocene and Miocene time, respectively.

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