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40Ar–39 Ar dating, whole-rock and Sr-Nd isotope geochemistry of the Middle Eocene calc-alkaline volcanic rocks in the Bayburt area, Eastern Pontides (NE Turkey): Implications for magma evolution in an extension-related setting

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► **To cite this version:**

Abdullah Kaygusuz, Cem Yücel, Emre Aydınçakır, Mehmet Ali Gücer, Gilles Ruffet. 40Ar–39 Ar dating, whole-rock and Sr-Nd isotope geochemistry of the Middle Eocene calc-alkaline volcanic rocks in the Bayburt area, Eastern Pontides (NE Turkey): Implications for magma evolution in an extension-related setting. *Mineralogy and Petrology*, 2022, 116, pp.379-399. 10.1007/s00710-022-00788-w. insu-03752052

HAL Id: insu-03752052

<https://insu.hal.science/insu-03752052v1>

Submitted on 6 Sep 2022

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1 **^{40}Ar – ^{39}Ar dating, whole-rock and Sr-Nd isotope geochemistry of**
2 **the Middle Eocene calc-alkaline volcanic rocks in the Bayburt**
3 **area, Eastern Pontides (NE Turkey): Implications for magma**
4 **evolution in an extension-related setting**

5

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19

20 **Abstract**

21 Discussions continue about whether Middle Eocene magmatism in the Eastern Pontides is

22 associated with collision or subduction. This paper presents new whole-rock geochemistry,

23 Sr-Nd isotopic and ^{40}Ar - ^{39}Ar age data for Middle Eocene volcanic rocks from the Bayburt

24 area of the Eastern Pontides (NE Turkey) to investigate their sources and evolutionary history.

25 The new $^{40}\text{Ar}-^{39}\text{Ar}$ ages reveal that these volcanic rocks erupted between 44.6 ± 0.1 Ma and
26 43.5 ± 0.1 Ma, within the Lutetian (Middle Eocene). The studied volcanic rocks are composed
27 of basalt, andesite, basaltic andesite and minor dacite lava and pyroclastic rocks. These rocks
28 consist of plagioclase, amphibole, pyroxene, olivine, biotite, sanidine and minor quartz
29 phenocrysts with Fe-Ti oxides. They have microlithic, hyalo-microlithic, porphyritic and
30 rarely glomeroporphyritic textures. The volcanic rocks have low to high-K calc-alkaline
31 affinities. They display enrichment in large-ion lithophile elements and depletion in high-field
32 strength elements with high Th/Yb ratios, which indicate that the magmas forming the
33 volcanic rocks were derived from lithospheric mantle sources enriched by mostly slab-derived
34 fluids in the spinel stability field. $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ values vary between 0.70485 and 0.70551 and
35 $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$ values vary between 0.51255 and 0.51267. These data correspond to the mantle
36 array on the isotope ratio diagram. The main solidification processes consist of fractional
37 crystallization with minor assimilation. In light of the data obtained in this study together with
38 data from previous studies, petrogenetic character of the Middle Eocene magmas from the
39 southern parts of the Eastern Pontides may be explained by melting of an enriched
40 lithospheric mantle source initially metasomatized by subduction fluids in a post-collisional
41 extensional-related tectonic setting.

42

43 **Keywords:** $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology • Post-collisional volcanism • Sr-Nd isotopes • NE
44 Turkey • Eastern Pontides

45

46

47 **Introduction**

48

49 In orogenic belts, extensional tectonics usually develop during the post-orogenic phase after
50 the completion of continent-continent collision. This occurs due to a combination of factors
51 including the readjustment of the thickened lithosphere, lithospheric thinning by mantle
52 convection, lithospheric collapse, slab break-off or detachment (Davies and von
53 Blanckenburg 1995; Platt and England 1994; Ruppel 1995). The delamination of the mafic
54 lower crust is usually associated with regions undergoing extension, showing thinning of the
55 continental crust (Wang et al., 2008; Zhai et al., 2007).

56 The Eastern Pontides (NE Turkey, Fig. 1a), or the Eastern Sakarya Zone (ESZ), is a
57 key area for understanding the geodynamic processes during the transition from pre- to post-
58 orogenic stages and the temporal evolution of compositions of syn- to post-collisional
59 magmas. In the ESZ, the subduction and collision-related magmatic processes formed various
60 types of igneous rocks. The subduction of the Neo-Tethyan Ocean beneath the Eurasian plate
61 resulted in the development of the Pontide magmatic arc during the closure of the northern
62 branch of the Neo-Tethyan, leading to the eventual collision of the Pontides and the
63 Anatolide-Tauride block (ATB) in Late Palaeocene-Early Eocene (Yılmaz et al., 1997;
64 Şengör and Yılmaz, 1981; Okay and Şahintürk 1997). The Middle Eocene volcanic activity in
65 this region is related to a post-collisional geodynamic setting (Adamia et al., 1977; Kazmin et
66 al., 1986; Şengör and Yılmaz, 1981; Robinson et al., 1995; Arslan et al., 1997; Okay and
67 Şahintürk 1997; Altherr et al., 2008; Kaygusuz et al., 2011; Aydınçakır, 2014; Temizel et al.,
68 2012).

69 The volcanism in the ESZ continued during Mesozoic and Cenozoic (Aydın et al.,
70 2008; Eyuboğlu et al., 2011; Karlı et al., 2011; Dokuz et al., 2013; Arslan et al., 2013;
71 Özdamar, 2016; Yücel et al., 2017). The Cenozoic volcanism is characterized by four
72 magmatic cycles developed during the (1) Early Eocene, (2) Middle Eocene, (3) Late Eocene
73 to Oligocene, and (4) Miocene to Pliocene (Topuz et al., 2005; Aydın et al., 2008; Karlı et

74 al., 2020; Temizel et al., 2012; Dokuz et al., 2013; Eyuboğlu et al., 2013a; Arslan et al., 2013;
75 Aydınçakır and Şen, 2013; Aslan et al., 2014; Kaygusuz et al., 2011, 2019; Yücel et al.,
76 2014). Volcanic rocks formed during the second cycle cover extensive areas within the ESZ,
77 whereas rocks from the other three cycles are more localised (Fig. 1b). The third cycle associated
78 with an extensional setting accompanied by the growth of extensional basins due to far-field
79 extensional forces (Karlı et al., 2020), whereas the fourth cycle occurred in an extensional
80 tectonic setting, combined with strike-slip movement at regional scale related to ongoing
81 delamination (Yücel et al., 2017).

82 The second cycle magmatism in the ESZ developed during a compressional regime
83 contemporaneous with the extensional regime associated with the opening of the Black Sea
84 basin (Robinson et al., 1995; Okay et al., 1994; Ustaömer and Robertson, 1997; Görür and
85 Tüysüz, 1997). However, the style and timing of Black Sea basin opening remain
86 controversial (Shillington et al., 2008).

87 The detailed understanding of the evolution of the ESZ remains poorly constrained
88 due to the scarcity of systematic geochronological, geochemical and isotopic data. In the
89 southern zone of the ESZ, the geochemical, geochronological and isotopic properties of the
90 Middle Eocene volcanic rocks (the second cycle) were studied around Torul-Gümüşhane
91 (Kaygusuz et al., 2011), Gümüşhane (Aslan, 2010; Aslan et al., 2014) and Gümüşhane-
92 Bayburt (Arslan et al., 2013). These rocks consist of mafic to felsic lava flows, dykes and
93 associated pyroclastic deposits. They have clear subduction-related chemical signatures. The
94 Bayburt area of the southern subzone within the ESZ is much less studied, with only general
95 geology (Keskin et al., 1989), mineralogy and petrography (Kaygusuz et al., 2019), and
96 whole-rock geochemistry (Eyuboğlu et al., 2017) described in the literature.

97 In this paper we present new ^{40}Ar – ^{39}Ar dating, Sr–Nd isotope, and whole-rock
98 geochemical data from the Middle Eocene volcanic rocks (the second cycle) in the Bayburt

99 area of the ESZ (Figs. 1b and c). The results will be used to constrain the genesis of calc-
100 alkaline volcanism.

101

102

103 **Geological background**

104

105 **Regional and local geology**

106

107 The Pontides, which are one of the five main tectonic units forming the Anatolian Plate, are
108 bounded by the Black Sea and the İstanbul zone to the north, and by the east-west trending
109 İzmir-Ankara-Erzincan suture zone (IAES) to the south (Okay and Tüysüz, 1999) (Fig. 1a).
110 The Pontide belt consists of three subunits: the eastern, central and western Pontides (Ketin
111 and Canitez, 1972). The Eastern Pontides, also called the Eastern Sakarya Zone (ESZ), is part
112 of the Sakarya Zone situated in the north of Turkey that extends from the Biga Peninsula to
113 Lesser Caucasus. The ESZ is lithologically divided into two sub-zones; the northern subzone
114 and the southern subzone (Özsayar et al., 1981). Most studies agree that the ESZ is a well-
115 preserved continental magmatic arc. Magmatism in the ESZ covers a span from
116 Carboniferous to the present.

117 The pre-Late Cretaceous rock units in the ESZ are represented by Early Carboniferous
118 metamorphic rocks (Topuz et al., 2007), Middle to Late Carboniferous plutonic rocks
119 (Kaygusuz et al., 2012, 2016; Dokuz., 2011; Topuz et al., 2010; Karlı et al., 2016), Late
120 Carboniferous to Permian sedimentary rocks, Middle to Late Triassic plutonic rocks (Dokuz
121 et al., 2010), Jurassic volcanic, volcanoclastic and plutonic rocks (Kandemir and Yılmaz,
122 2009; Saydam Eker et al., 2012; Dokuz et al., 2017; Aydınçakır et al., 2020) and Late Jurassic
123 to Early Cretaceous carbonates (Pelin, 1977). All these rocks are conformably overlain by

124 Late Cretaceous volcanic rocks (Özdamar, 2016; Eyuboğlu, 2010; Aydın, 2014), and crosscut
125 by plutonic rocks of late Cretaceous age (Şipahi et al., 2018; Karşlı et al., 2010; Temizel et
126 al., 2019; Kaygusuz et al., 2021). The Cenozoic rocks are represented by the first cycle
127 adakitic rocks (Karşlı et al., 2011; Topuz et al., 2005; Dokuz et al., 2013), the second cycle
128 volcanic-subvolcanic (Aslan et al., 2014; Eyuboğlu et al., 2013b; Arslan et al., 2013;
129 Aydınçakır, 2014; Yücel et al., 2017; Kaygusuz et al., 2011, 2019; Aydınçakır et al., 2022)
130 and plutonic rocks (Karşlı et al., 2007; Boztuğ et al., 2004; Özdamar et al., 2017; Eyuboğlu et
131 al., 2017; Kaygusuz and Öztürk, 2015; Kaygusuz et al., 2018, 2020, 2021; Temizel et al.,
132 2018, 2020; Vural and Kaygusuz, 2021), the third cycle volcanic rocks (Aydın et al., 2008;
133 Arslan et al., 2013; Karşlı et al., 2020) and the fourth cycle volcanic-subvolcanic and adakitic
134 rocks (Temizel et al., 2012; Aydın et al., 2008; Dokuz et al., 2013; Yücel et al., 2017).
135 Quaternary units comprise alluvium and terraces.

136 The study area is situated in the southern part of the ESZ (Fig. 1). The oldest rocks in
137 the study area are represented by Late Cretaceous volcanic and volcanoclastic rocks, which are
138 mainly composed of andesite, basalt and pyroclastic rocks (Fig. 2). The Early Eocene
139 sedimentary rocks representing the first cycle lie conformably on this unit and consist mainly
140 of nummulite-bearing limestones, sandstone, marl and sandy limestone. The Middle Eocene
141 volcanic-volcanoclastic rocks, which represent the first cycle, conformably overlie these Early
142 Eocene sedimentary units (Figs. 3a and b) and consist of basalt, andesite and minor dacite
143 lavas and their pyroclastic equivalents, intercalated with siltstone, sandstone, marl and
144 limestone. All these units were intruded by the second cycle plutonic rocks (43 to 45 Ma;
145 Kaygusuz et al., 2020). Quaternary alluvium forms the youngest rocks in the study area.

146

147 **Volcanic sequence**

148

149 The Bayburt volcanic sequences extend in an east-west direction from Bayburt to Gümüşhane
150 areas in the southern part of the ESZ (Figs. 1b and 2). This sequence cover an area of 200 km²
151 in the study area and contain limestones interbedded with sandstone and siltstone at the base
152 and pass upward into volcanoclastic rocks (tuff and agglomerate), lava flows and dykes.
153 Sedimentary and volcanoclastic rocks are widespread at the base, they become rarer upwards
154 and are replaced by lava flows.

155 The studied second cycle volcanic rocks consist of basalt, basaltic andesite, andesite
156 and minor dacite. Basalt and basaltic andesites are the dominant lithologies within the
157 sequence. Basalt contains subhedral to euhedral olivine, pyroxene and plagioclase
158 phenocrysts. Basaltic andesites have subhedral to euhedral plagioclase, pyroxene and
159 amphibole phenocrysts. Andesitic rocks are characterized by the presence of subhedral to
160 euhedral plagioclase, pyroxene and amphibole phenocrysts. Dacitic rocks comprise a minor
161 part of the sequence, and have large quartz phenocrystals. Dacites also contain subhedral to
162 euhedral plagioclase, amphibole and biotite phenocrysts.

163 The pyroclastic deposits are mainly composed of basaltic/andesitic breccias succeeded
164 by medium- to thick-bedded tuffs. Angular breccia gravels, 5 to 40 cm in diameter, are
165 cemented by a fine-grained, altered volcanic matrix. Basaltic, andesitic and minor dacitic tuffs
166 and tuffites have less volume than the other members in the sequence. Their cavities are filled
167 with secondary calcite, epidote and quartz minerals. In places where the unit is altered,
168 exfoliation structures are observed. The total thickness of the studied volcanic sequence in the
169 study area is more than 1300 m.

170 Basaltic lavas, which form the oldest lava in the succession, yield an ⁴⁰Ar/³⁹Ar age of
171 44.6 ± 0.1 Ma (this study, Table 1). They are overlain by basaltic andesitic lava flows with an
172 ⁴⁰Ar/³⁹Ar age of 44.0 ± 0.1 Ma (this study, Table 1). Andesitic lava flows crop out above

173 these rocks. Dacitic lavas, which are the youngest lava in the succession, conformably overlie
174 these rocks and yield an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 43.5 ± 0.1 Ma (this study, Table 1).

175

176

177 **Material and methods**

178

179 Rock samples were crushed in steel crushers and ground in an agate mill to a grain size of less
180 than 200 mesh. Major elements were analyzed by inductively coupled plasma-emission
181 spectrometry (ICP-ES) from pulps after 0.2 g samples of rock powder were fused with 1.5 g
182 LiBO_2 and then dissolved in 100 ml 5% HNO_3 . Trace and rare earth elements were
183 determined by inductively coupled plasma-mass spectrometry (ICP-MS) from pulps after 0.2
184 g samples of rock powder were dissolved by four acid digestions. Sample solutions were
185 aspirated into an ICP mass spectrometer (Perkin-Elmer Elan 6000) or an ICP emission
186 spectrometer (Jarrel Ash Atomcomp Model 975) for element analyses. Loss on ignition (LOI)
187 was determined according to the weight difference at 1000°C . Analytical precision, as
188 calculated from replicate analyses, lies in the ranges of 0.01-0.04 wt% for the major elements
189 and 0.01–8.0 ppm for trace elements including rare earth elements (REEs).

190 Three single groundmass fragments from the studied volcanic rocks were analysed by
191 the continuous laser probe (CO_2 Synrad) stepwise heating ^{39}Ar - ^{40}Ar technique. The samples
192 were wrapped in Al foil to form small packets (11 mm \times 11 mm) that were stacked up to form
193 columns within which packets of fluence monitors were inserted every 10 samples. Irradiation
194 was performed at the McMaster reactor (Hamilton, Canada) and used ^{5}C high flux location
195 without Cd-shielding. It lasted 13.42 h ($\text{J/h} \approx 3.71 \times 10^{-4} \text{ h}^{-1}$). The irradiation reference was
196 sanidine TCRs (28.608 ± 0.033 Ma; according to Renne et al., 1998, 2010 and 2011). The
197 sample arrangement in the irradiation allowed us to monitor the flux gradient with a precision

198 of ± 0.2 %. Heating steps were performed with a CO₂ laser probe. All experiments concerned
199 single grains. The experimental procedure was described by Ruffet et al. (1991, 1995). The
200 five argon isotopes and the background baselines were measured in 11 cycles, in peak-
201 jumping mode. Blanks were performed routinely every first or third/fourth run and subtracted
202 from subsequent sample gas fractions. All isotopic measurements are corrected for K, Ca and
203 Cl isotopic interferences, mass discrimination and atmospheric argon contamination.
204 Apparent age errors are plotted at the 2σ level and do not include the errors on the
205 $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio and age of the monitor and decay constant. The errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$
206 ratio and age of the monitor and decay constant are included in the final calculation of the
207 (pseudo-) plateau age error margins or for apparent ages individually cited. The analyses were
208 performed on a Map215 mass spectrometer.

209 Sr and Nd isotopes from the studied volcanic rocks were conducted using thermal
210 ionisation mass spectrometry (TIMS) on a Finnigan MAT-262 mass spectrometer. For Sr and
211 Nd isotope analyses, approximately 50 mg of whole-rock powder was first dissolved in 52%
212 HF for four days at 140 °C on a hot plate, then dried, dissolved in 6 N HCl, dried again and
213 finally dissolved in 2.5 N HCl. Sr and Nd were separated using conventional ion exchange
214 techniques. Isotopic compositions were measured on a double Re filament configuration.
215 Total blanks were Sr-Nd-Sm < 0.05 ng; uncertainties were 2% for $^{87}\text{Rb}/^{86}\text{Sr}$ ratio and 0.2%
216 for $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. Sr and Nd isotope ratios were normalized to NBS987 ($^{87}\text{Sr}/^{86}\text{Sr} =$
217 0.710179 ± 0.00001) and JNd_(i) ($^{143}\text{Nd}/^{144}\text{Nd} = 0.511958 \pm 0.000006$; after Tanaka et al.
218 (2000) standard. The values measured for these standards were 0.710246 ± 0.000010 and
219 0.512076 ± 0.000006 , respectively.

220

221

222 **Results**

223

224 **Petrography**

225

226 Basalts have microlithic and microlithic–porphyritic textures (Fig. 3c). They consist of
227 plagioclase, pyroxene, olivine phenocrysts and Fe-Ti oxides with a fine-grained groundmass.

228 Basaltic andesites have generally microlithic to microlithic-porphyritic textures with
229 phenocrysts of plagioclase, clinopyroxene and minor amphibole (Fig. 3d). The groundmass is
230 composed of plagioclase microlites, small pyroxene grains and minor interstitial glass.

231 Andesites exhibit hypo-crystalline porphyritic and glomeroporphyritic textures with
232 phenocrysts of plagioclase, clinopyroxene, amphibole and minor biotite (Figs. 3e and f). The
233 groundmass has a hyalopilitic texture and contains microliths of the main mineral constituents
234 along with volcanic glass. Dacites exhibit microgranular, glomeroporphyritic and porphyritic
235 textures characterized by plagioclase, amphibole, quartz and biotite phenocrysts set in a
236 groundmass including microlites of the same minerals, Fe–Ti oxide and glass.

237 Plagioclase is the most abundant phenocryst and groundmass phase, and is found in all
238 rock types. They exhibit albite twinning, oscillatory zoning, and prismatic-cellular growth.
239 Phenocrysts are common in basaltic andesites, andesites and dacites. Anorthite content range
240 between An₈₈₋₄₉ in basalts, An₈₃₋₄₆ in basaltic andesites, An₆₀₋₃₅ in andesites, and An₅₄₋₃₁ in
241 dacites (Kaygusuz et al., 2019). Pyroxene forms subhedral to euhedral crystals and is found in
242 glomeroporphyritic aggregates together with Fe-Ti oxides and plagioclase. The pyroxene
243 phenocrysts consist of both ortho and clinopyroxene. Clinopyroxene phenocrystals (up to 2
244 mm) are the most common mafic mineral in the basaltic andesites. Pyroxenes are augite and
245 diopside (Wo₄₈₋₃₈ En₄₆₋₃₈ Fo₂₃₋₉, Kaygusuz et al., 2019). Diopside and augite are found in
246 basalts and basaltic andesites and augite in andesites (Kaygusuz et al., 2019). Inclusions of
247 opaque minerals and plagioclase occur in large pyroxene crystals (2.5 mm) showing poikilitic

248 texture. Some minerals are partially altered to calcite and uraltite. Amphibole occurs as both
249 euhedral and subhedral phenocrystals and microlites in groundmass. They are found in
250 basaltic andesite, andesite and dacite. Phenocrystals (2-2.5 mm) are common in basaltic
251 andesites, andesites and dacites. Amphiboles are calcic magnesio-hornblende in composition
252 (Kaygusuz et al., 2019). Some crystals show partial chloritization. Olivine is found as
253 euhedral to subhedral crystals in basalt and basaltic andesite. Biotite, which is anhedral–
254 subhedral, occurs in dacitic rocks and is rimmed by Fe–Ti oxide. Quartz is found in dacitic
255 rocks, and embayed quartz crystals are common. Fe–Ti oxides occur mainly together with
256 mafic minerals and are disseminated in the groundmass. They are magnetite–titanomagnetite
257 in composition (Kaygusuz et al., 2019). Kaygusuz et al. (2019) indicated that the
258 clinopyroxene pressure values of basalt, basaltic andesite and andesite range from 0.53 to 4.66
259 kbar and temperature values change from 1121 to 1182 °C. The clinopyroxene-liquid
260 thermobarometer of Putirka (2008) and the only clinopyroxene core compositions were used
261 to calculate the crystallisation temperature and pressure. Amphibole pressures and
262 temperatures give values of 1.86 to 2.54 kbar and 788 to 872 °C for the andesitic and dacitic
263 rocks (Kaygusuz et al., 2019). Al-in hornblende pressure calculations were made according to
264 Johnson and Rutherford (1989) and amphibole-plagioclase temperature calculations according
265 to Blundy and Holland (1990). Considering the thermobarometric calculations mentioned
266 above, it is concluded that the calc-alkaline magma forming the Bayburt volcanic rocks
267 equilibrated at shallow crustal depth.

268

269 **$^{40}\text{Ar} / ^{39}\text{Ar}$ geochronology**

270

271 To determine the age of volcanic rocks, we separated groundmass fractions from one basalt,
272 one basaltic andesite and dacite. The results are presented in Table 1, Table S1 and Fig 4. The

273 $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the groundmass of basalt M-36 was performed in 14 heating steps and the
274 age spectrum was defined by steps 9-14 with a plateau age 44.6 ± 0.1 Ma with 81.8% of the
275 released ^{39}Ar (Fig. 4a, Table S1 in the electronic supplementary material, ESM). The isochron
276 age for this sample is 44.5 ± 0.4 Ma with mean square of weighted deviates (MSWD)=1.76
277 (Fig. 4b, Table S1). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of groundmass of basaltic andesite K-2 was performed in
278 14 heating steps. Steps 4-14 produced a plateau age of 44.0 ± 0.1 Ma with 92.8% of the
279 released ^{39}Ar (Fig. 4c, Table S1). The isochron age of this sample is 43.9 ± 0.2 Ma with
280 MSWD = 0.57 (Fig. 4d). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of groundmass of dacite K-22 was performed in 15
281 steps (Table S1). The results suggest that the sample was affected by minor alteration or post-
282 crystallization heating. However, steps 6-13 yielded a plateau age of 43.5 ± 0.1 Ma (Figs. 4e
283 and f, Table S1). Obtained $^{40}\text{Ar}/^{39}\text{Ar}$ ages vary between 44.6 ± 0.1 and 43.5 ± 0.1 Ma,
284 indicating that the studied volcanic rocks erupted in the Middle Eocene (Lutetian).

285

286 **Geochemistry**

287

288 Field and petrographic observations indicate that the studied volcanic samples in the Bayburt
289 area suffered from minor alteration and partial chloritization and argillization. Most samples
290 have loss on ignition (LOI) values <2.9 wt%, except for samples Y7 and Y35 that have LOI
291 values of 3.5 and 3.1 wt%, respectively (Table 2).

292 Whole-rock compositions of the samples from the Bayburt volcanic rocks are given in
293 Table 2. These volcanic rocks have a large range of SiO_2 contents (48 to 68 wt%) and Mg
294 numbers [$\text{Mg\#} = 100 \times \text{MgO} / (\text{MgO} + \text{Fe}_2\text{O}_3^{\text{T}})$] (41 to 57; Table 2). The MgO and $\text{Fe}_2\text{O}_3^{\text{T}}$
295 contents range from 1.2% to 5.6% and from 3.5% to 10.6%, respectively (Table 2).

296 The samples plot in the sub-alkaline field on the TAS diagram (Fig. 5a). The samples
297 show calc-alkaline affinity on the Th versus Co diagram (Fig. 5b). Most samples are located

298 in the calc-alkaline field in the AFM diagram, but a few samples plotted on the tholeiitic and
299 calc-alkaline division line (Fig. 5c). Andesitic rocks have medium-K composition, whereas
300 basaltic andesitic and andesitic rocks have high-K composition. Basalts have low to medium-
301 K composition (Fig. 5d).

302 Contents of CaO, Al₂O₃, Fe₂O₃, MgO, P₂O₅ and TiO₂ correlate negatively with SiO₂
303 (Fig. 6), whereas K₂O shows a positive correlation and Na₂O shows a weak positive
304 correlation. Positive correlations are seen for Ba, Th, Nb, Rb, Zr, Pb and La versus SiO₂, and
305 weak negative correlations are seen for Sr, Ni and Y (Fig. 6). Basaltic rocks have higher
306 MgO, CaO, Fe₂O₃^T, Al₂O₃, TiO₂ and Ni, whereas dacitic rocks have higher K₂O, Ba, Zr, Rb
307 and Nb contents than basaltic andesitic and andesitic rocks (Fig. 6).

308 On primitive mantle-normalized diagrams all samples exhibit significant enrichment
309 in large ion lithophile elements (LILEs) (K, Th, Rb) relative to high field strength elements
310 (HFSEs) and also negative Nb, Ti and Ta anomalies relative rare earth element (REE) of
311 similar incompatibility (Figs. 7a-d). All samples have similar LREE enriched patterns
312 revealed by enrichment in light rare earth elements (LREE) and nearly flat heavy rare earth
313 elements (HREE) (La_n/Sm_n=1.85 to 5.62, Gd_N/Lu_N= 1.14 to 2.16, Table 2, Figs. 7e-h).
314 Dacites are characterised by negative Eu (Eu_n/Eu*) anomalies.

315

316 **Sr-Nd isotope geochemistry**

317

318 The studied samples have more radiogenic ⁸⁷Sr/⁸⁶Sr and less radiogenic ¹⁴³Nd/¹⁴⁴Nd isotopic
319 ratios than the bulk silica earth (BSE; Fig. 8a). The Bayburt volcanic rocks display relatively
320 homogeneous Sr-Nd isotopic compositions (Table 3; Fig. 8a). The values for ⁸⁷Sr/⁸⁶Sr_(i) range
321 from 0.70485 to 0.70551 and the values for ¹⁴³Nd/¹⁴⁴Nd_(i) range from 0.51255 to 0.51267
322 (εNd = -0.71 to +1.76), plotting within the mantle array (Fig. 8a; Table 3). Basalts and

323 basaltic andesites have lower $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ values than andesites and dacites. A single-stage
324 depleted mantle Nd model ages of the studied Bayburt samples are in the range of 0.71-1.01
325 Ga (Table 3).

326 The Bayburt volcanic rocks partly overlap with the other second cycle volcanic rocks
327 from the ESZ (Kaygusuz et al., 2011; Aydınçakır and Şen, 2013; Arslan et al., 2013; Yücel et
328 al., 2017; Aslan et al., 2014) and the second cycle plutonic rocks (Karlı et al., 2007;
329 Eyuboğlu et al., 2017; Kaygusuz and Öztürk, 2015; Kaygusuz et al., 2020). However, they
330 have higher Sr isotopic ratios than the first cycle volcanic rocks (Aydınçakır, 2014; Temizel
331 et al., 2012, 2016), Early Eocene Kop adakitic rocks (Eyuboğlu et al., 2013a), the third cycle
332 adakitic rocks (Karlı et al., 2020), the fourth cycle adakitic rocks (Eyuboğlu et al., 2012;
333 Dokuz et al., 2013; Karlı et al., 2019) and the fourth cycle volcanic rocks (Temizel et al.,
334 2012; Aydın et al., 2008; Yücel et al., 2017; Aslan et al. 2014). They have lower Sr isotopic
335 ratios than the other first cycle adakitic rocks (Eyuboğlu et al., 2011, 2018; Karlı et al., 2010)
336 (Fig. 8b).

337

338

339 **Discussion**

340

341 **Age constraints**

342

343 In previous studies, the age of the studied Bayburt volcanic rocks was estimated based on
344 contact relationships, volcano-stratigraphic criteria and biostratigraphic data. Volcanic
345 activity started in the Early Palaeocene and continued to Eocene time (Keskin et al., 1989).
346 The new $^{40}\text{Ar}-^{39}\text{Ar}$ ages in this study place Bayburt volcanic rocks between 44.6 ± 0.1 Ma
347 and 43.5 ± 0.1 Ma, within the Lutetian (the first cycle).

348 When compared with other Middle Eocene volcanic rocks in the ESZ, the new ^{40}Ar –
349 ^{39}Ar ages (44 to 43 Ma) of the studied Bayburt volcanic rocks are coeval with the Torul
350 (Gümüşhane) volcanic rocks (43 Ma; Kaygusuz et al., 2011), Alucra-Bayburt volcanic rocks
351 (44-43 Ma; Arslan et al., 2013) and Trabzon-Giresun volcanic rocks (44-43 Ma; Yücel et al.,
352 2017). The Bayburt volcanic rocks are younger than the Gümüşhane tuffs (45 Ma; Aslan,
353 2010), Trabzon-Giresun basaltic-andesitic lava flows (45 Ma; Yücel et al., 2017) and Borçka
354 volcanic rocks (46 Ma; Aydınçakır and Şen, 2013), but older than Trabzon-Giresun andesitic-
355 trachytic dikes (42-41 Ma; Yücel et al., 2017) and Gümüşhane volcanic rocks (37 Ma; Aslan
356 et al., 2014).

357

358 **Fractional crystallization**

359

360 The samples from the Bayburt volcanic rocks have low Mg#, MgO, Co, Ni and higher
361 $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ ratios demonstrating that the samples distinctively differ from primary magma
362 composition and the magma has undergone significant fractional crystallization (FC; Tables 2
363 and 4).

364 Increasing K_2O , Zr, Rb, Ba, Th, Nb and Pb versus SiO_2 and the decreasing in CaO,
365 $\text{Fe}_2\text{O}_3^{\text{T}}$, MgO, Al_2O_3 , P_2O_5 , TiO_2 , Ni, Y and Sr content with increasing silica seen in basaltic
366 to dacitic rocks indicate that they evolved via FC processes (Fig. 6). Decreasing TiO_2 , P_2O_5
367 and Sr with increasing silica suggest fractionation of magnetite, apatite, and plagioclase,
368 respectively (Fig. 6). Decreasing CaO suggests clinopyroxene fractionation. Increasing K_2O
369 and Rb with increasing SiO_2 suggest that biotite and K-feldspar were not the early
370 fractionation phases. Increasing silica with decreasing Sr and the negative Eu anomalies
371 indicate plagioclase fractionation in the dacitic rocks (Figs. 6 and 7). The downward-concave

372 REE patterns of the rocks indicate clinopyroxene or hornblende fractionation (Thirlwall et al.,
373 1994).

374 The effectiveness of the FC process was tested by a Rb versus Y plot (Fig. 9a). Since
375 Rb has a positive correlation with the increase in SiO₂ (Fig. 6) content during fractionation,
376 Rb is used as the fractionation index. The Y content of the studied samples has a negative
377 correlation with the increasing Rb content (low-Y series), indicating plagioclase, clino-
378 pyroxene and hornblende fractionation (Fig. 9a).

379 On the MgO versus Sr diagram, all samples have negative correlation (Fig. 9b). This
380 correlation indicates fractionation of ferro-magnesian minerals occurred in basalt, basaltic
381 andesite and andesites, while feldspar fractionation occurred in dacitic rocks (Fig. 9b).

382

383 **Assimilation - fractional crystallizations**

384

385 The ⁸⁷Sr/⁸⁶Sr_(i) ratios correlate positively with SiO₂ and Th and negatively with MgO (Figs.
386 10a, c and e). The ¹⁴³Nd/¹⁴⁴Nd_(i) ratios correlate negatively with SiO₂, and positively with
387 MgO and Sm/Nd (Figs. 10b, d and f). Such trends suggest that the magmas were affected by
388 assimilation - fractional crystallization processes. Assimilation of the crustal material was
389 accompanied fractional crystallization.

390 The roles of crustal assimilation and fractional crystallization processes were
391 evaluated using the equation described by DePaolo (1981). In our model, upper continental
392 crust values of Taylor and McLennan (1985) are used as crustal end-members, and the upper
393 mantle composition of Klein (2004) is used as parental magma composition. To estimate the
394 assimilation rate of the crust material by ascending magmas, different theoretical curves were
395 produced for the value of $r = 0.2$ (the ratio of the rate of assimilation to the rate of fractional
396 crystallisation) and the bulk distribution coefficients (D_{Sr} , D_{Nd}) (Fig. 11a, Table S2 in the

397 ESM). The studied Bayburt samples matched the $r = 0.2$ curves indicating that the parental
398 magma was not significantly contaminated by continental crust (Fig. 11a). However, the
399 above model can be considered as indicative only, as the modelled curve rely on appropriate
400 values for the end-member compositions and D_s .

401

402 **Mantle source**

403

404 Among subduction-related magmas, those formed via addition of water-rich fluids to the
405 mantle wedge generally have higher Ba/La ratios (Sheppard and Taylor, 1992; Elburg et al.,
406 2002), Ba/Th (>170 ; Hawkesworth et al., 1997) and Pb/Ce (>0.1 ; Elburg et al., 2002),
407 whereas magmas formed with the involvement of slab-derived melts and/or sediments are
408 generally characterised by high Th/Ce ratios (>0.15 ; Hawkesworth et al., 1997). The mean
409 values for Pb/Ce, Th/Ce and Ba/La ratios of the studied Bayburt volcanic rocks are 0.25, 0.09
410 and 20 (Table 2), respectively, indicating that water-rich fluids played an important role. This
411 is also consistent with a range of Pb/Nd values at a constant $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$ (Fig. 11b) and with
412 a wide range of Ba/Th ratios of the least fractionated samples ($\text{SiO}_2 < 52$ wt%) at similar
413 La/Sm (Fig. 11c). A typical subduction-related incompatible-element pattern on mantle-
414 normalised diagrams, characterised by prominent negative Nb and Ta anomalies (Fig 7), is
415 also consistent with the important role of slab-derived fluids. Additionally, on the Ce/Pb
416 versus Ce diagram (Fig. 11d), most of the samples correspond to the field of arc volcanics.
417 The higher Th/Yb values at a given Ta/Yb compared to the mantle array (Fig. 11e; Pearce et
418 al., 1990) is another evidence for addition of subduction related components. The trend
419 displayed by the samples parallel to the mantle array can indicate either a range of variable
420 enriched mantle source, or involvement of crustal assimilation.

421 Given that the least fractionated rocks ($\text{SiO}_2 < 52 \text{ wt}\%$) have low Mg# (54 to 44),
422 MgO (5.55 to 3.14 wt%) and compatible trace element contents (Ni = 14.4 to 3.9 ppm and Co
423 = 28.9 to 20.1 ppm; Table 2) are substantially evolved (cf. 500 to 600 ppm Cr, 250 to 300
424 ppm Ni, and 27 to 80 ppm Co in primary magmas; Wilkinson and Le Maitre, 1987; Perfit et
425 al., 1980), no inferences on the mantle source composition or conditions of melting can be
426 made.

427

428

429 **Conclusions**

430

431 Comprehensive whole-rock major, trace and rare earth elements, geochronological and Sr-
432 Nd-Pb isotope data for the studied volcanic rocks from the southern part of the Eastern
433 Pontides allow new insights into the petrogenetic evolution of the Middle Eocene magmas
434 and enable us to reach the following conclusions. (i) The studied Bayburt volcanic rocks vary
435 from basalt to dacite in composition, and define a calc-alkaline series showed enrichment of
436 LILEs and LREEs, and depletion of HFSEs, suggesting similar sources and petrogenetic
437 processes. (ii) ^{40}Ar - ^{39}Ar ages of the rocks reveals that the studied volcanic rocks were
438 emplaced in the Lutetian (44 to 43 Ma, Middle Eocene) and coincide with the time period of
439 the post-collisional extensional regime in the Eastern Pontides. (iii) The Bayburt volcanic
440 rocks have narrow initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying between 0.70485 and 0.70551 and initial
441 $^{143}\text{Nd}/^{144}\text{Nd}$ values between 0.51255 and 0.51267 indicating enriched source composition.
442 These data correspond to the mantle array on the isotope ratio diagram. (iv) The Bayburt
443 volcanic rocks were mostly affected by fractional crystallization processes rather than the
444 other magmatic processes, such as AFC, according to trace element chemistry, mineral
445 chemistry and isotope data. (v) The studied volcanic rocks were generated from an enriched

446 lithospheric mantle source initially metasomatized by subduction fluids in a post-collisional
447 extensional-related geodynamic setting.

448

449 **Acknowledgements** Thanks are due to Ferkan Sipahi, H. Enes Atay and Damla Selvi for their
450 assistances in the fieldwork. The authors thanks David Vilbert for providing Sr-Nd isotopic
451 analyses at the Géosciences Rennes, France. We thank an anonymous reviewer and journal
452 editor Leonid V. Danyushevsky for their critical and constructive comments to improve our
453 paper. This study has been funded by the Gümüşhane University Research Fund (grant
454 17.F5114.01.03).

455

456

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773 **FIGURE CAPTIONS**

774

775 **Fig. 1 (a)** Tectonic map of Turkey and its surroundings (modified from Okay and Tüysüz,
776 1999), **(b)** Simplified geological map of the Eastern Pontides showing the distribution of
777 Eocene and Miocene volcanic rocks and Eocene plutonic rocks (modified from Arslan et al.,
778 2013; Güven, 1993; Temizel et al., 2016). NAFZ – North Anatolian Fault Zone

779

780 **Fig. 2** Geological map of the study area

781

782 **Fig. 3** Field view and cross-polarised transmitted-light photomicrographs of textural features
783 of the studied Bayburt volcanic rocks **(a)** Field view of the contact between Eocene
784 sedimentary and volcanic rocks, **(b)** field view of Eocene volcanic rocks, **(c)** microlithic
785 textures in basalts, and **(d-f)** microlithic-porphyritic and glomeroporphyritic textures in
786 basaltic andesites and andesites (Pl: plagioclase, Cpx: clinopyroxene, Amp: amphibole)

787

788 **Fig. 4** ^{40}Ar - ^{39}Ar ages of the Bayburt volcanic rocks, **(a-b)** basalt (M-36), **(c-d)** basaltic
789 andesite (K-2) and **(e-f)** dacite (K-22)

790

791 **Fig. 5 (a)** Silica versus total alkalis diagram (after Middlemost, 1994), **(b)** Th versus Co
792 diagram (after Hastie et al., 2007), **(c)** AFM diagram of Irvine and Baragar (1971), and **(d)**
793 K_2O versus SiO_2 diagram for Bayburt volcanic rocks

794

795 **Fig. 6 (a-r)** SiO_2 versus major oxides, trace elements and rare earth elements variation plots
796 for Bayburt volcanic rocks

797

798 **Fig. 7 (a-d)** Primitive mantle-normalized (Sun and McDonough, 1989) trace element patterns,
799 **(e-h)** chondrite-normalized (Taylor and McLennan, 1985) rare earth element patterns for
800 Bayburt volcanic rocks

801

802 **Fig. 8 (a-b)** $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$ versus $(^{87}\text{Sr}/^{86}\text{Sr})_{(i)}$ diagrams for Bayburt volcanic rocks

803

804 **Fig. 9 (a)** Y versus Rb, and **(b)** MgO versus Sr diagrams for Bayburt volcanic rocks

805

806 **Fig. 10 (a-b)** SiO_2 versus $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ and $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$, **(c-d)** MgO (wt%) versus $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$

807 and $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$, **(e)** $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ versus Th, and **(f)** $^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$ versus Sm/Nd diagrams for

808 Bayburt volcanic rocks

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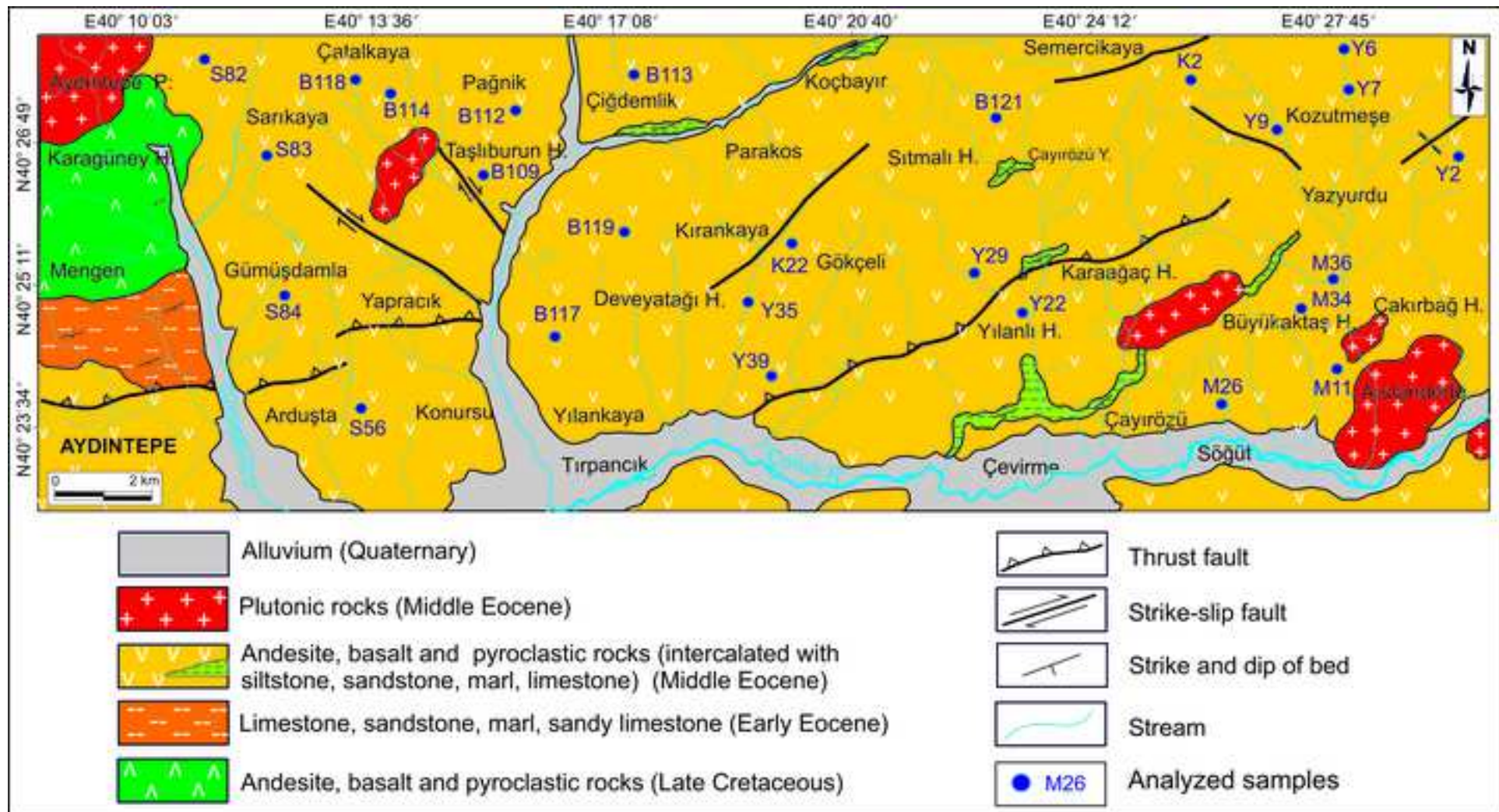
810 **Fig. 11 (a)** $(^{87}\text{Sr}/^{86}\text{Sr})_{(i)}$ versus $(^{143}\text{Nd}/^{144}\text{Nd})_{(i)}$ diagram showing two-component mixing

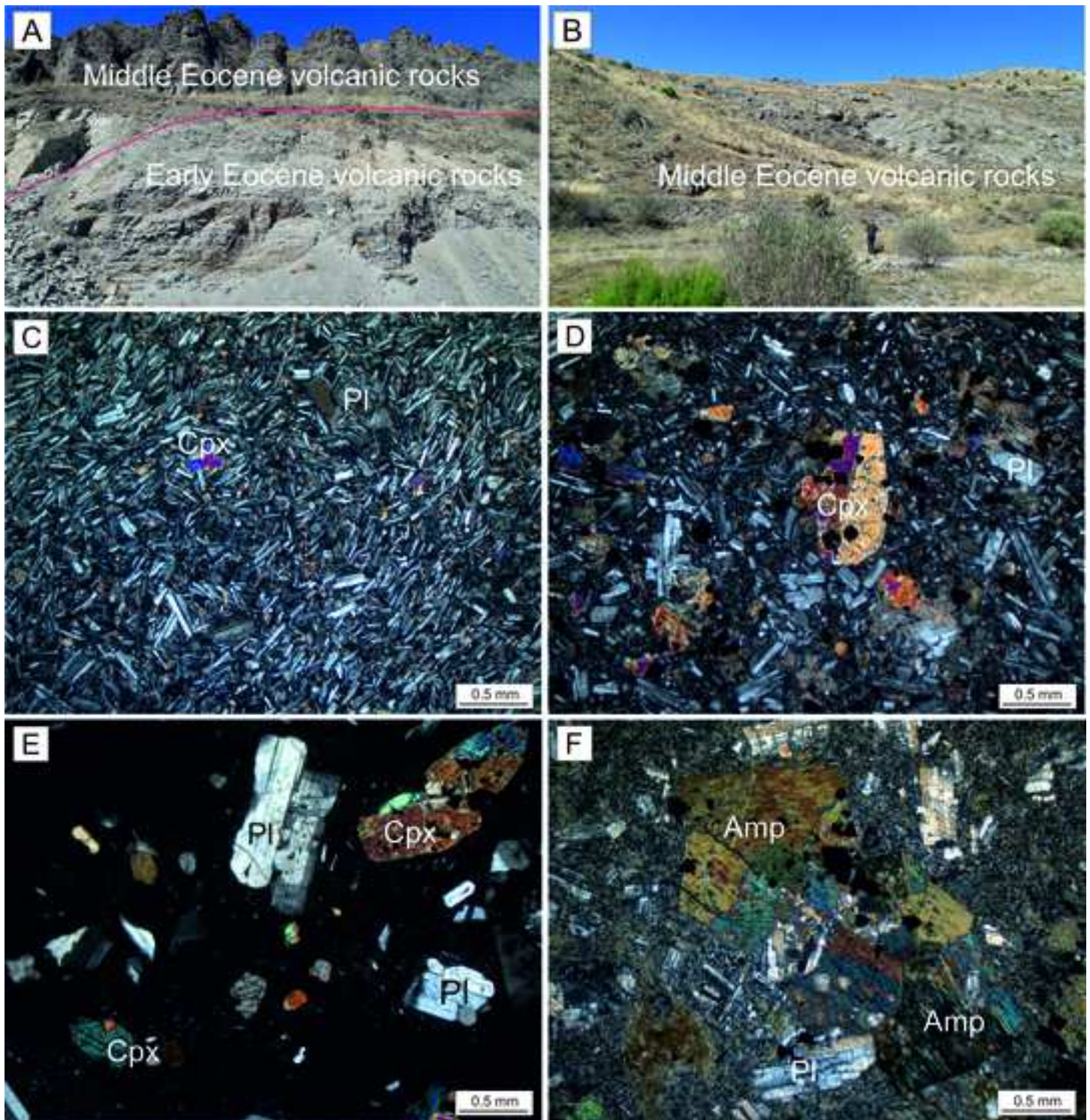
811 model, **(b)** Pb/Nd versus $(^{143}\text{Nd}/^{144}\text{Nd})_{(i)}$, **(c)** Ba/Th versus La/Sm, **(d)** Ce/Pb versus Ce (ppm),

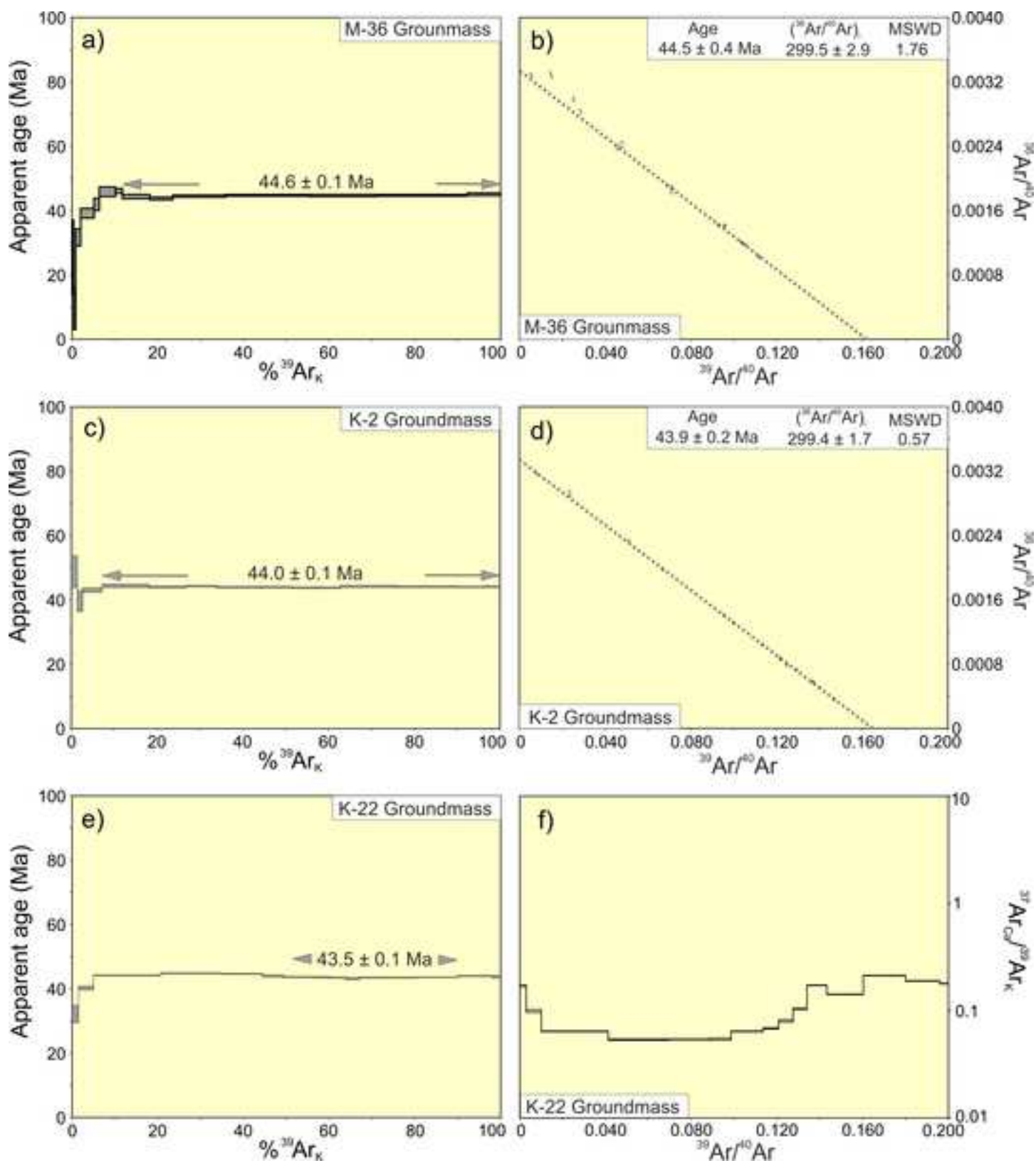
812 and **(e)** Th/Yb versus Ta/Yb (after Pearce et al., 1990) diagrams for Bayburt volcanic rocks.

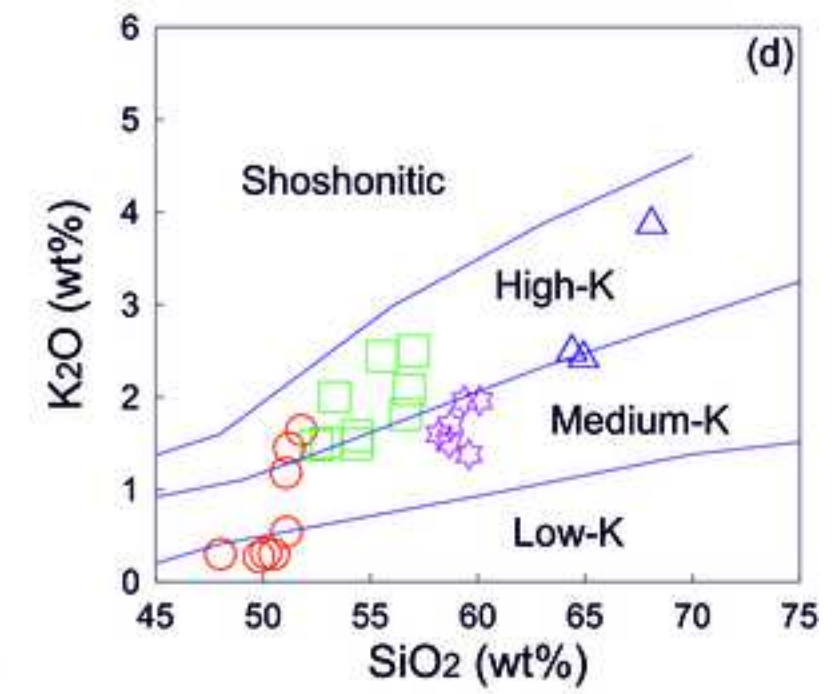
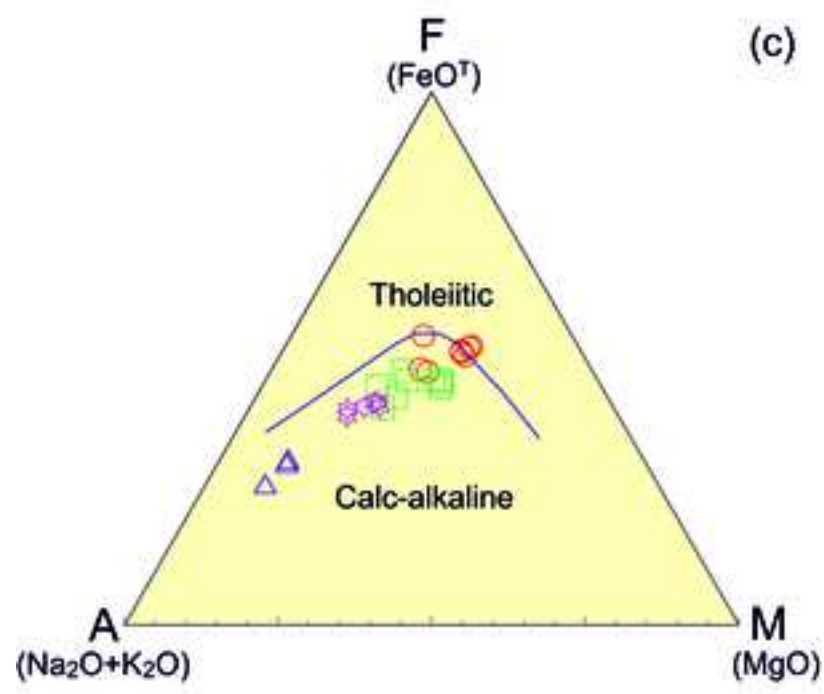
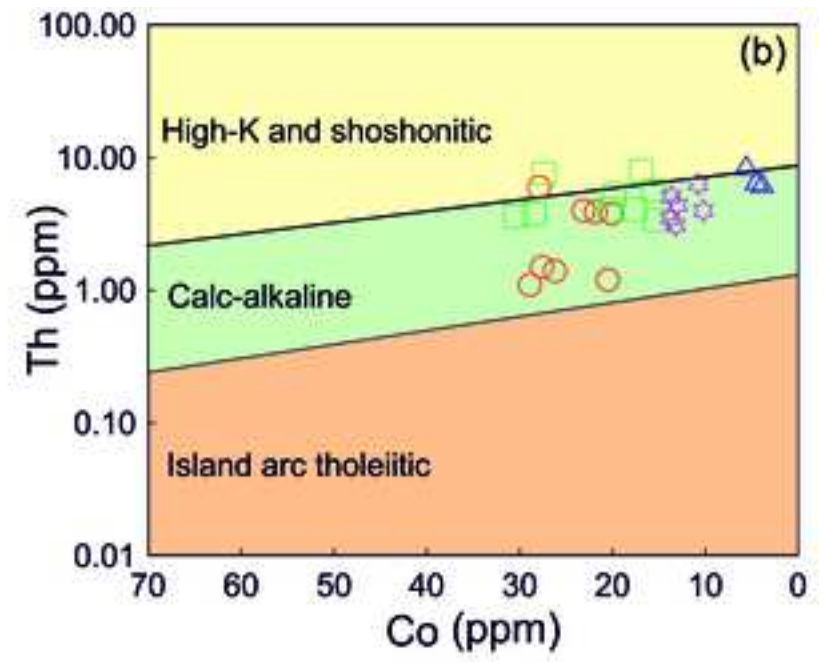
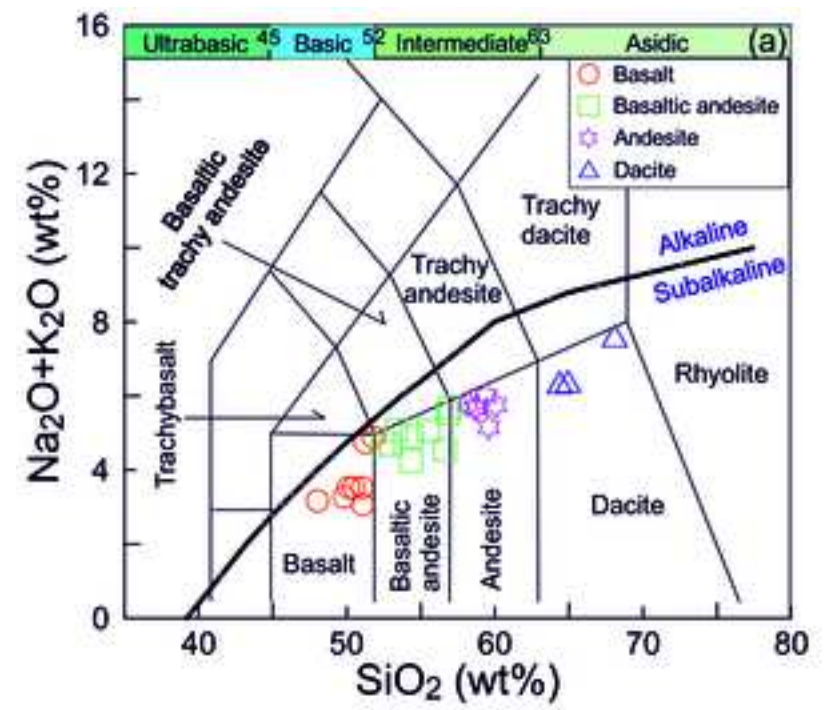
813 **(d):** Data fields after Taylor and McLennan (1985), Hofmann (1988), Harms et al. (1997),

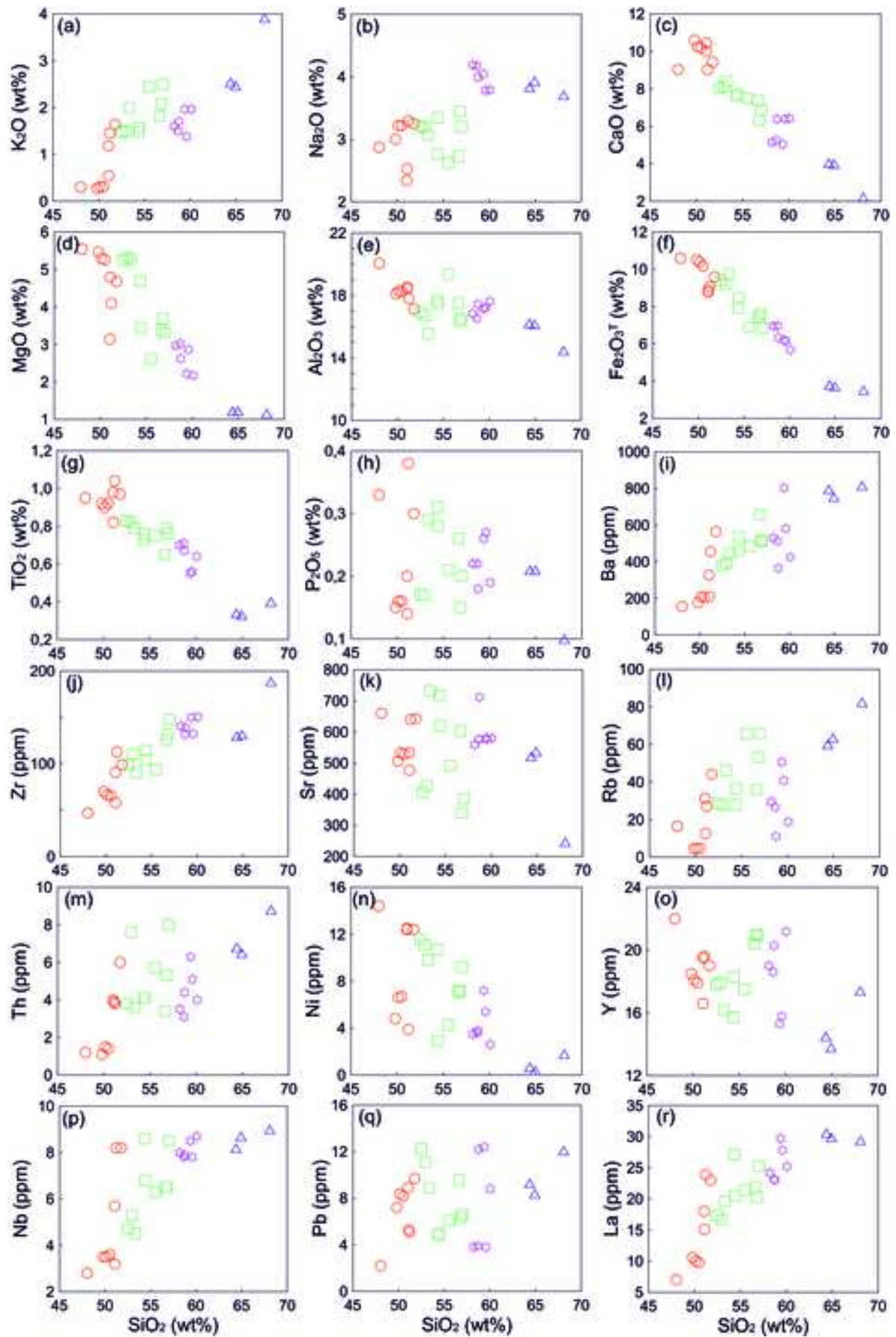
814 Schmidberger and Hegner (1999), Pearce et al. (1990), Fitton et al., (1991)

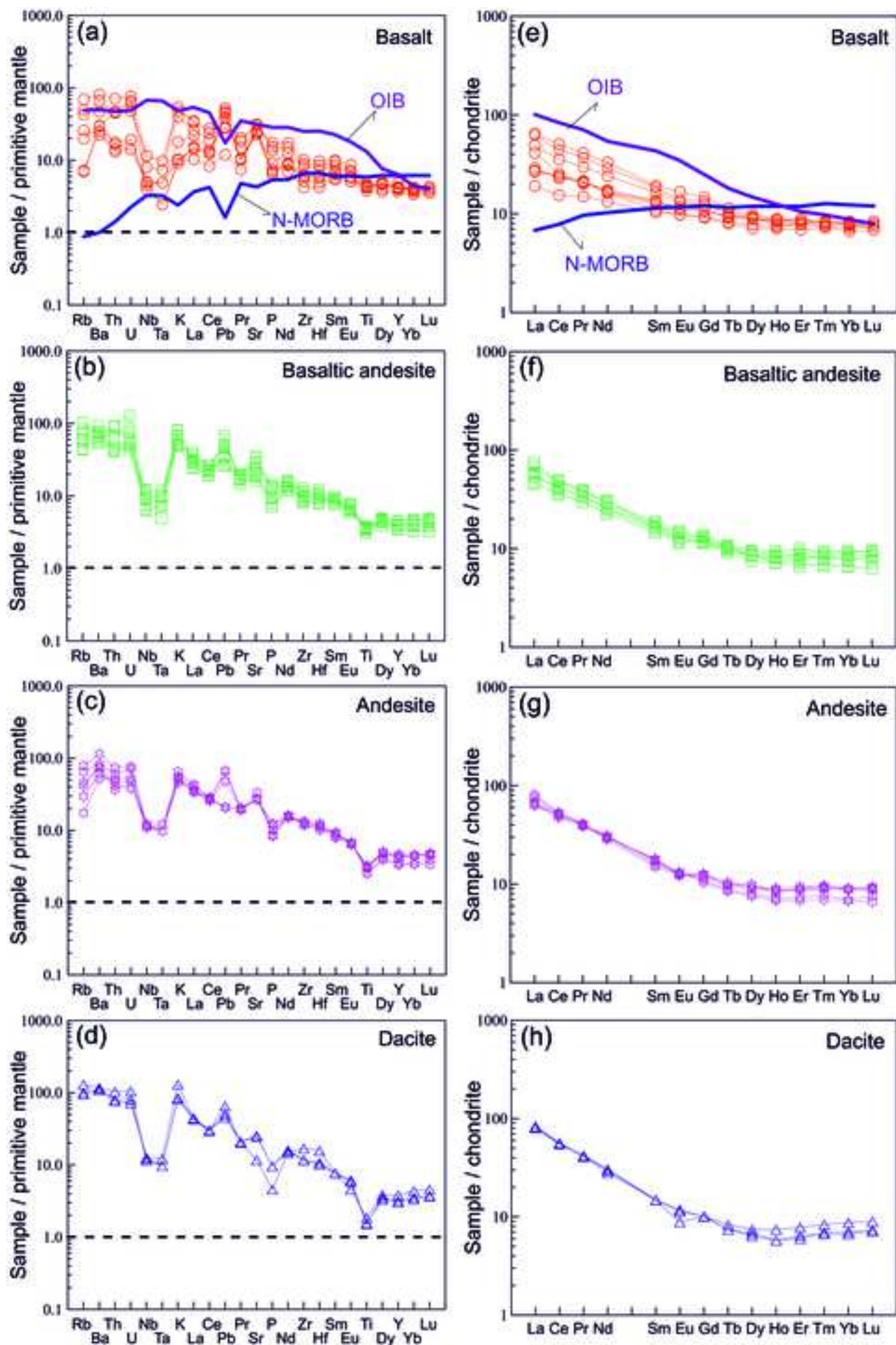


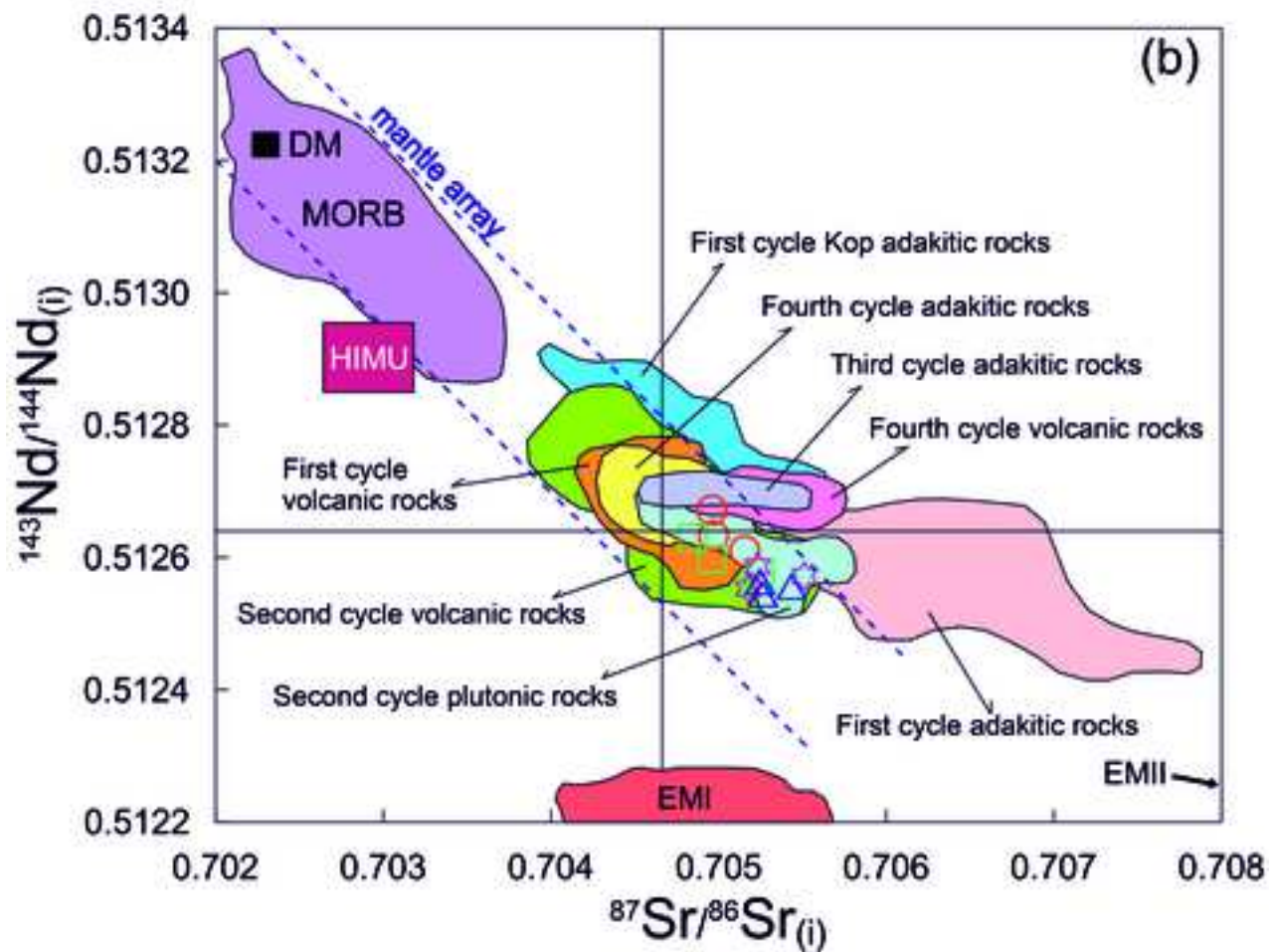
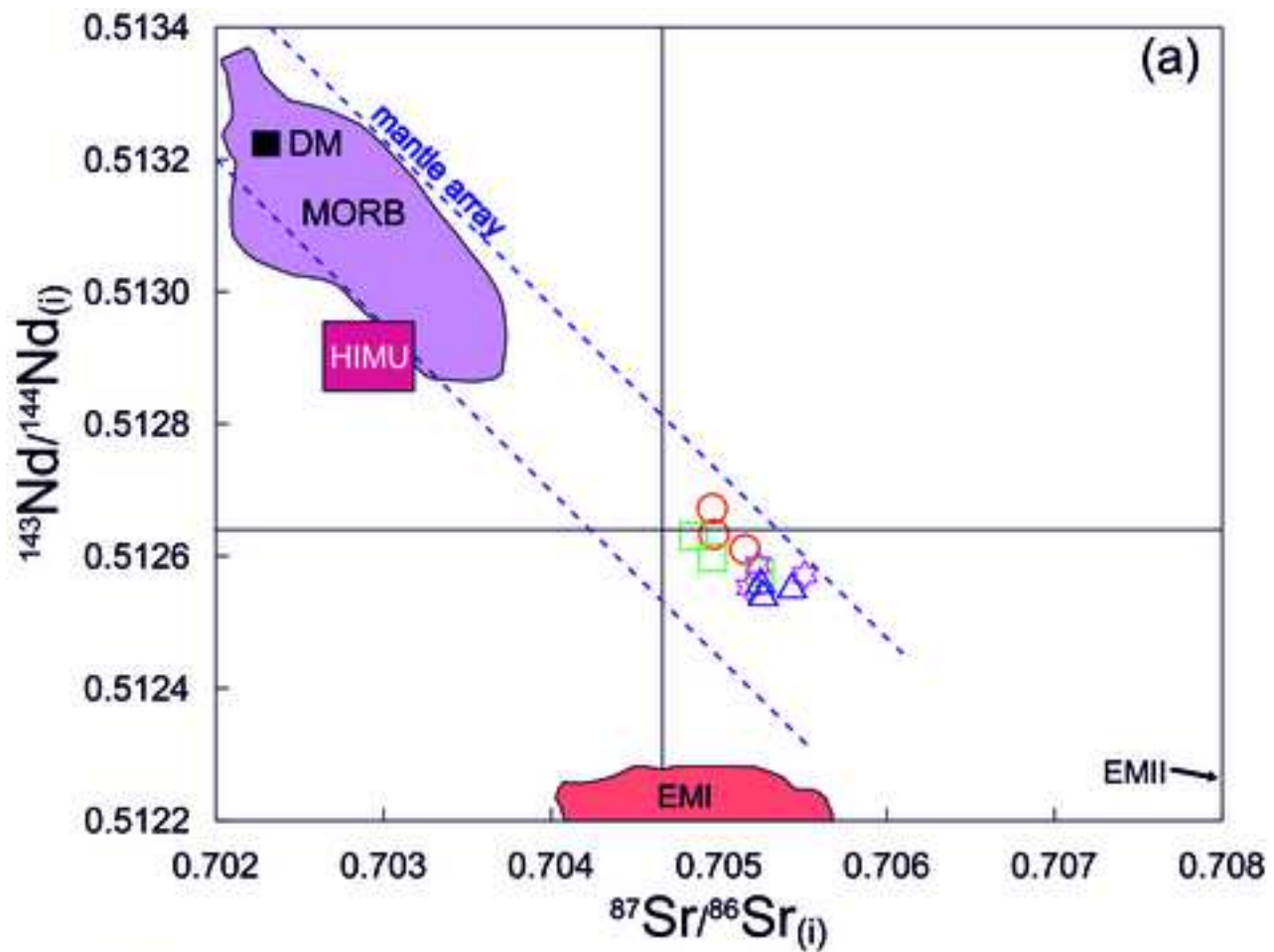


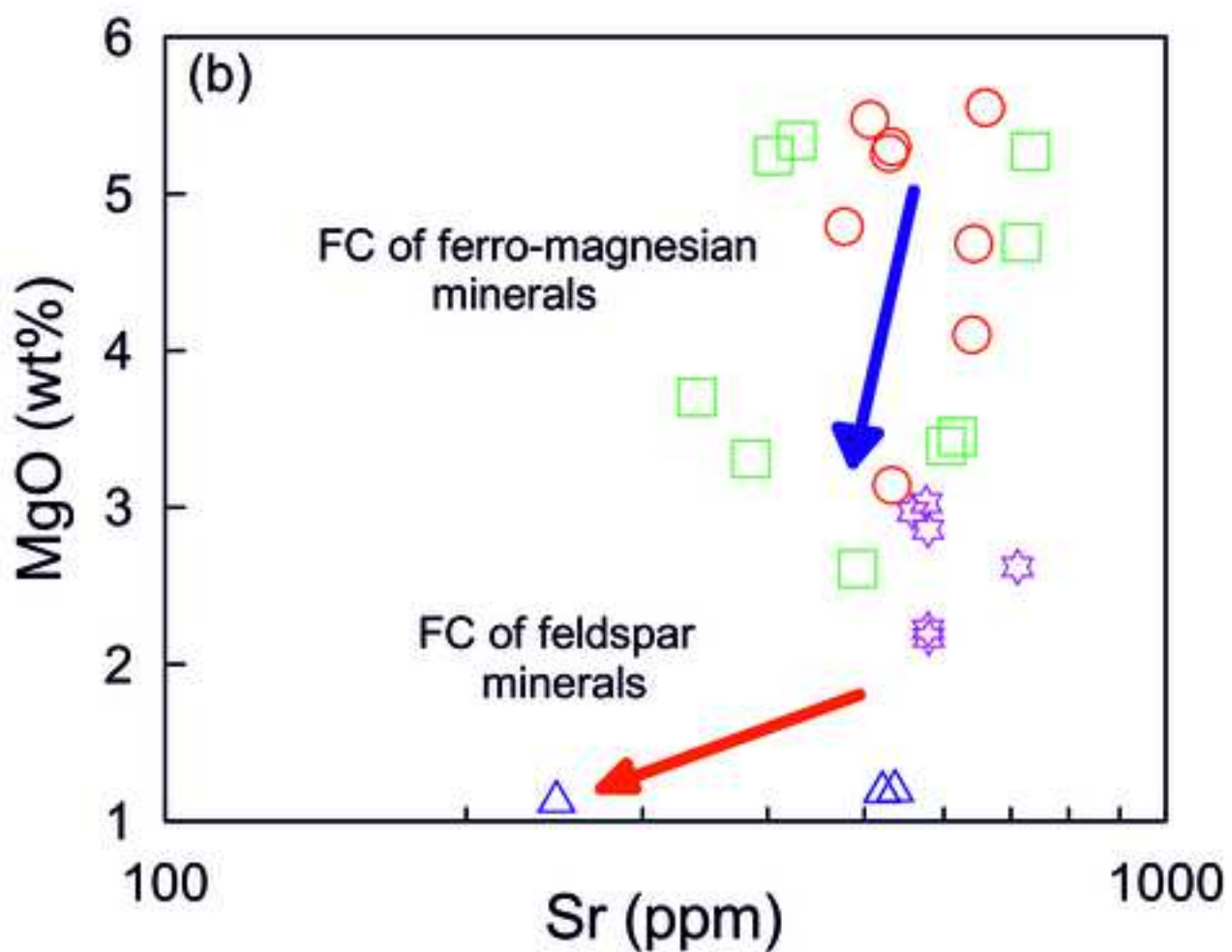
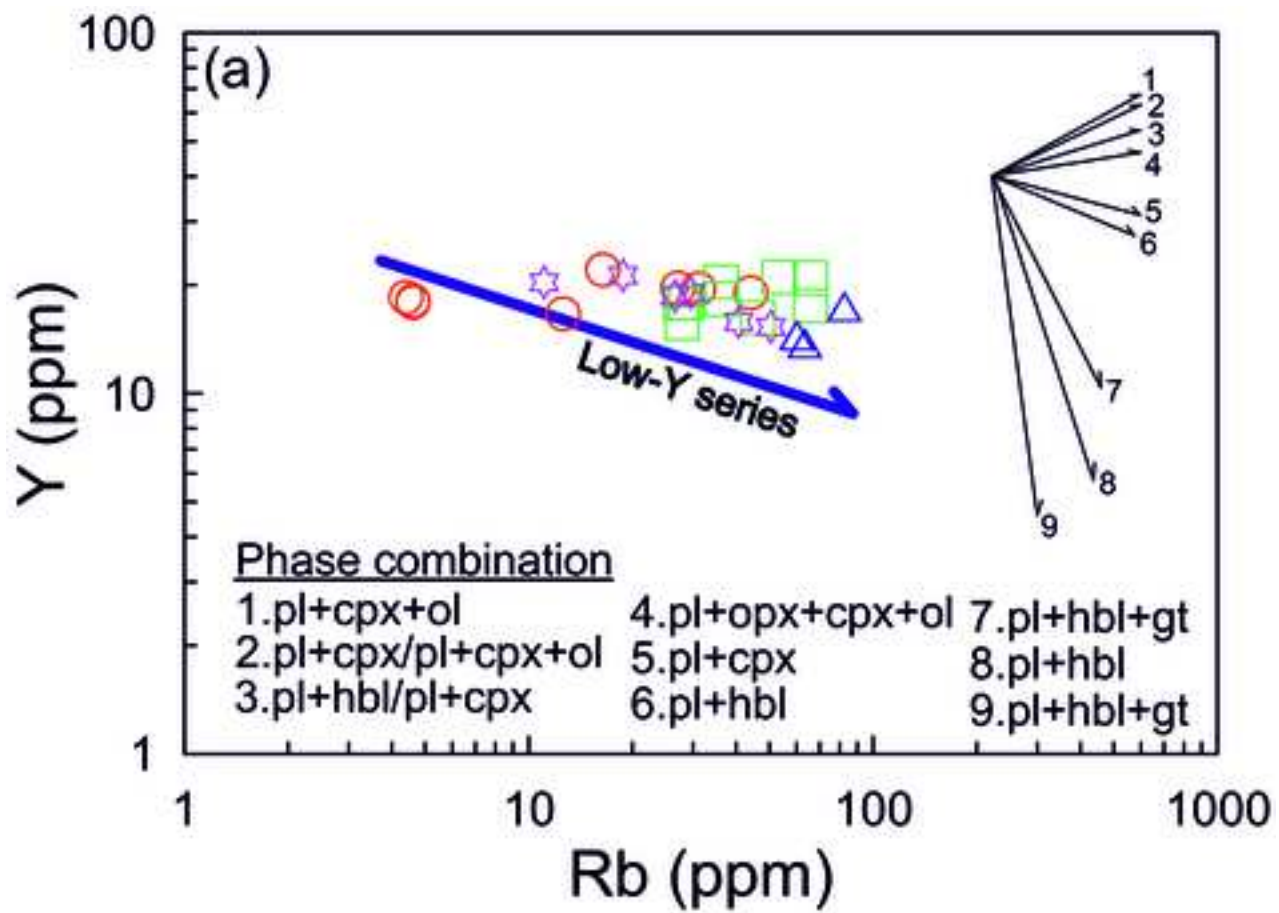


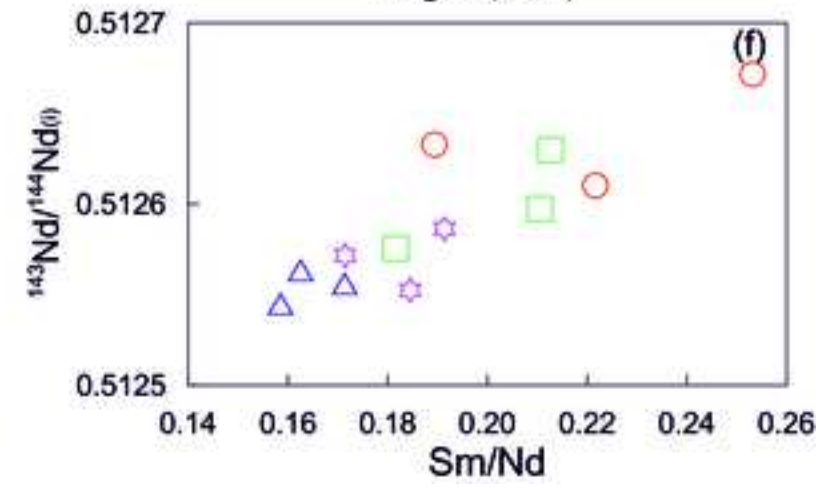
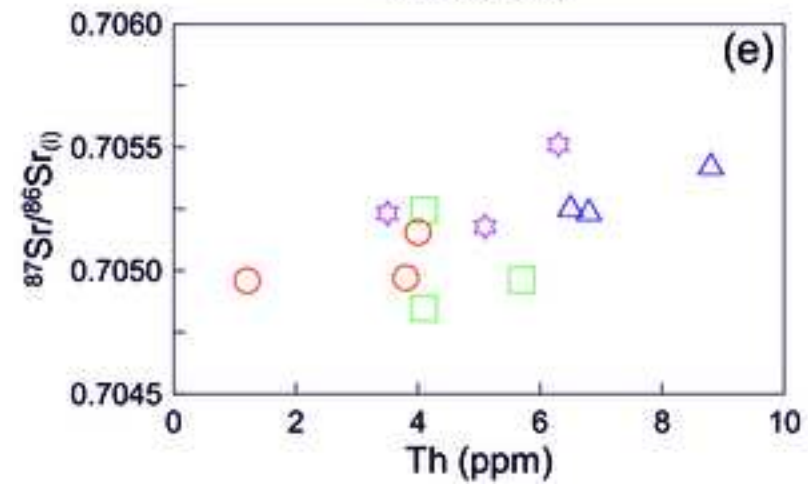
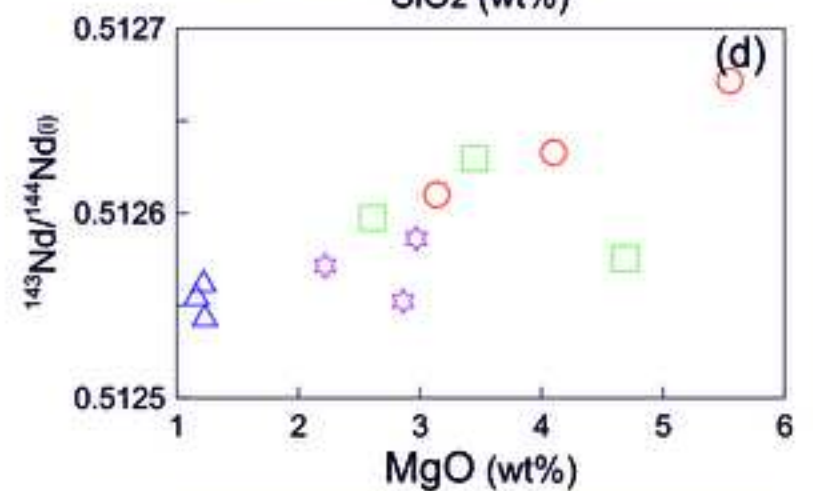
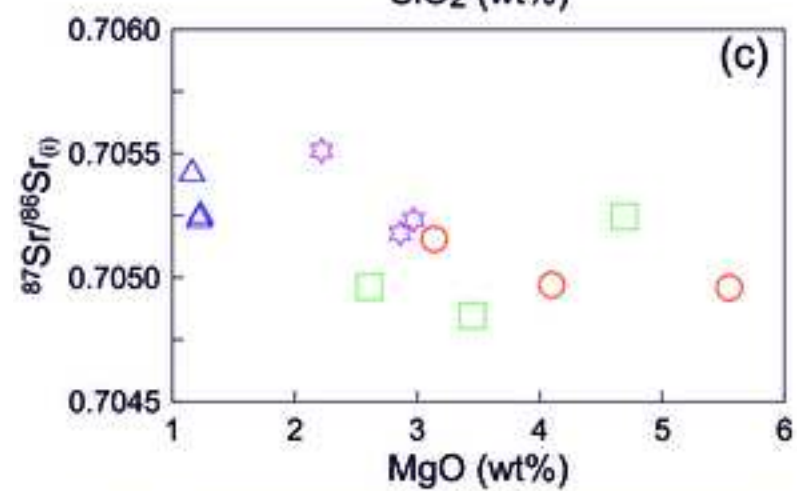
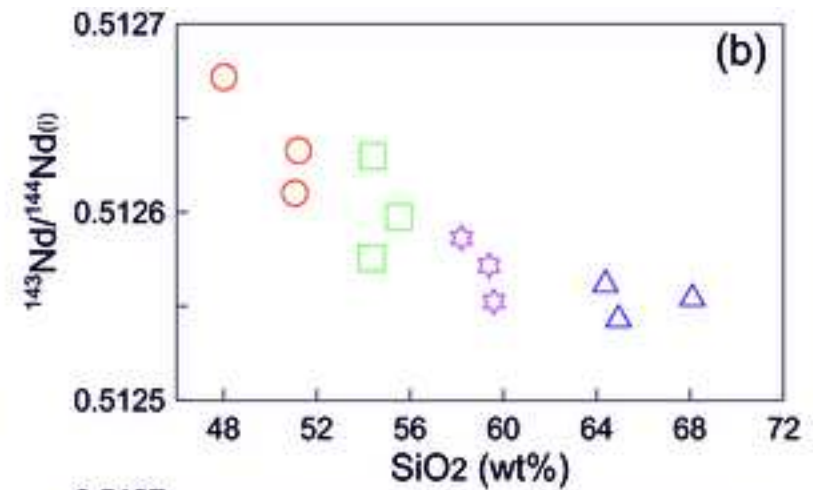
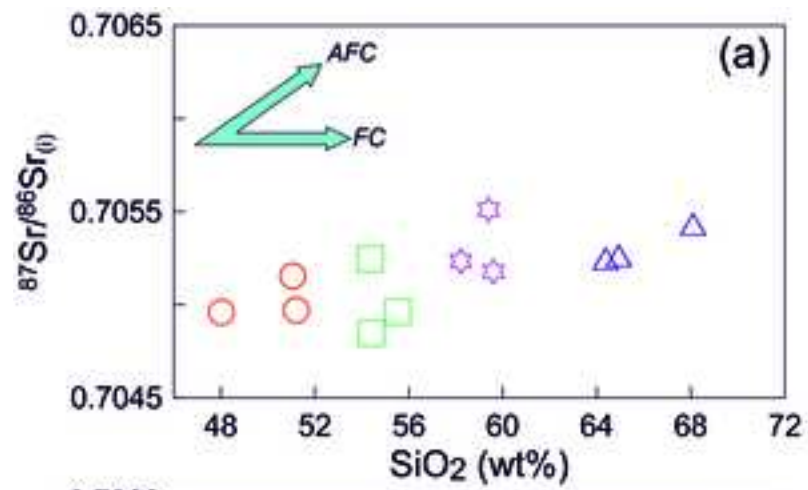


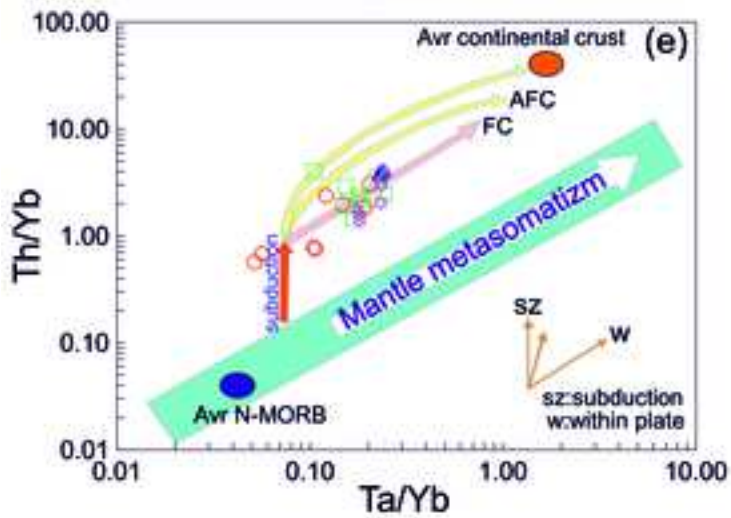
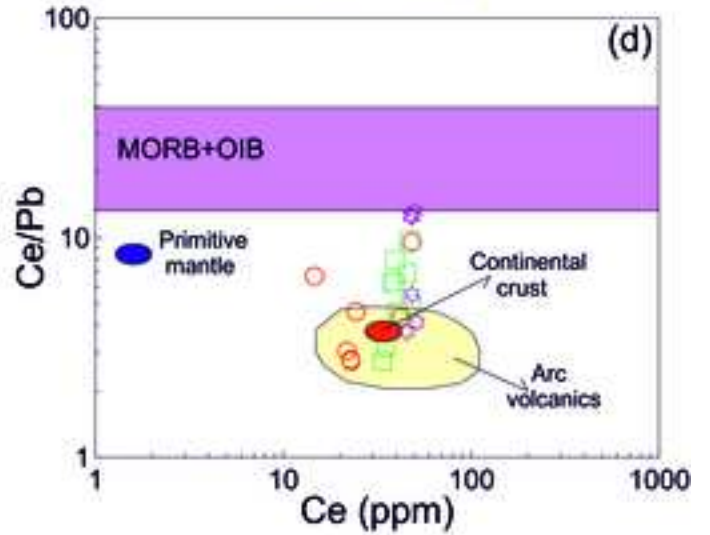
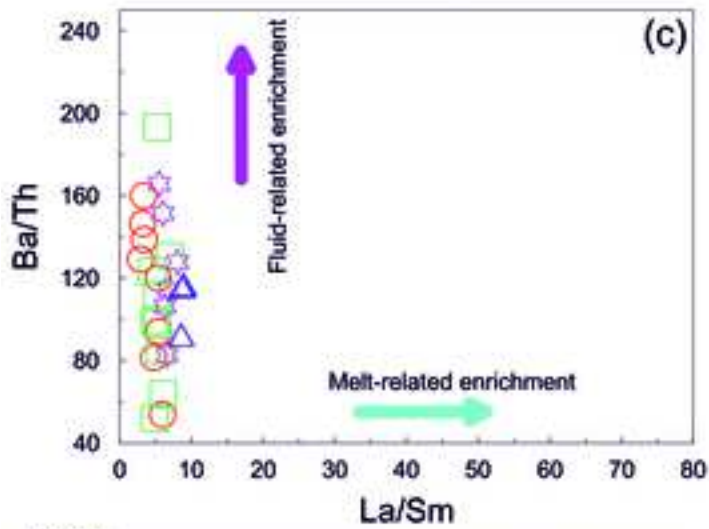
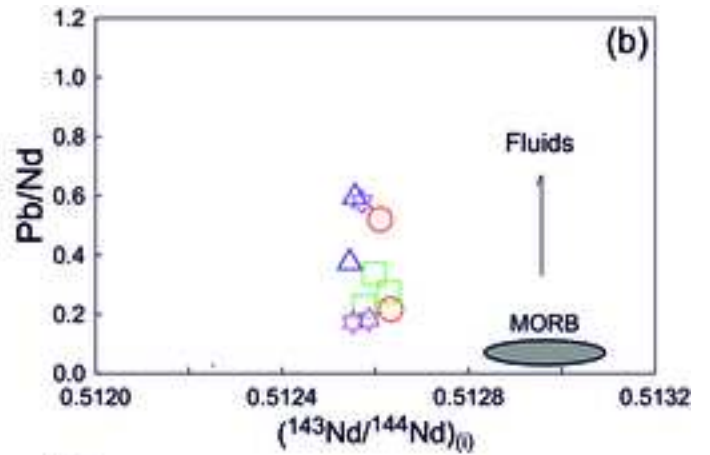
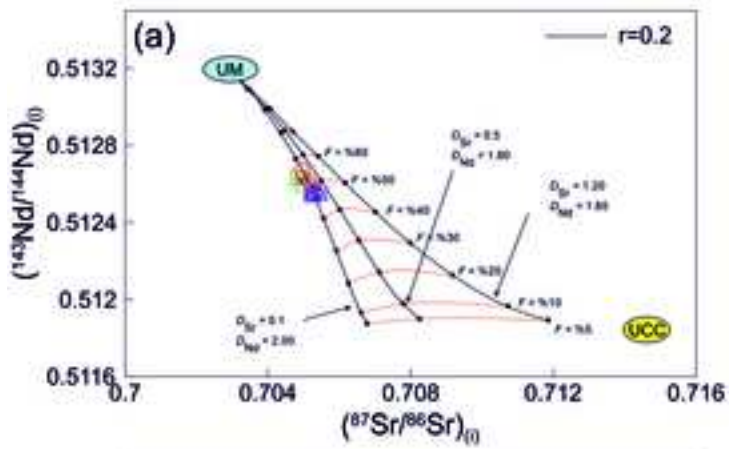












Tables and Captions

Table 1 ^{40}Ar - ^{39}Ar dating results and locations of three samples for Bayburt volcanic rocks

Sample number	Material	Locality	Rock name	Plateau age (Ma)	$\pm \sigma$	Method
M-36	groundmass	Güvenli hill	basalt	44.6	0.1	$^{40}\text{Ar}/^{39}\text{Ar}$
K-2	groundmass	Yazyurdu hill	basaltic andesite	44.0	0.1	$^{40}\text{Ar}/^{39}\text{Ar}$
K-22	groundmass	Buğdaykabarı hill	dacite	43.5	0.1	$^{40}\text{Ar}/^{39}\text{Ar}$

Table 2 Major and trace elements compositions for Bayburt volcanic rocks

Sample	Basalt				Basaltic andesite								
	Y2	S82	S83	S84	Y7	S56	M36	M11	B117	B118	M26	M34	Y9
<i>Major oxides (wt%)</i>													
SiO ₂	48.02	49.82	50.14	50.50	51.06	51.08	51.22	51.78	52.50	52.96	53.33	54.36	54.40
TiO ₂	0.95	0.92	0.90	0.92	0.98	0.82	1.04	0.97	0.83	0.82	0.79	0.73	0.76
Al ₂ O ₃	20.06	18.11	18.29	18.25	18.43	18.54	17.81	17.13	16.92	16.72	15.55	17.69	17.45
Fe ₂ O _{3T}	10.59	10.51	10.39	10.17	8.76	8.88	9.06	9.60	9.40	9.19	9.72	7.93	8.47
MnO	0.14	0.21	0.21	0.21	0.14	0.15	0.24	0.15	0.17	0.17	0.21	0.16	0.17
MgO	5.55	5.47	5.30	5.26	3.14	4.79	4.10	4.68	5.24	5.34	5.27	4.69	3.45
CaO	9.03	10.61	10.25	10.20	10.02	10.44	9.03	9.44	8.05	8.14	8.41	7.73	7.62
Na ₂ O	2.87	3.00	3.22	3.22	2.34	2.53	3.29	3.25	3.21	3.19	3.07	2.76	3.34
K ₂ O	0.30	0.27	0.31	0.30	1.18	0.54	1.45	1.64	1.48	1.50	2.00	1.49	1.58
P ₂ O ₅	0.33	0.15	0.16	0.16	0.20	0.14	0.38	0.30	0.17	0.17	0.29	0.31	0.28
LOI	2.10	0.70	0.50	0.50	3.50	1.80	2.10	0.70	1.80	1.50	1.00	1.90	2.20
Total	99.94	99.77	99.67	99.69	99.75	99.71	99.72	99.64	99.77	99.70	99.64	99.75	99.72
<i>Trace elements (ppm)</i>													
Co	20.50	28.90	27.60	26.20	23.10	21.80	20.10	27.90	28.40	27.40	30.40	20.30	17.60
Ni	14.40	4.80	6.60	6.70	12.40	12.50	3.90	12.40	11.60	11.10	9.80	10.70	2.90
V	314.00	292.00	302.00	301.00	257.00	264.00	226.00	260.00	235.00	234.00	260.00	165.00	160.00
Cu	183.30	49.70	45.30	45.10	78.00	458.20	35.20	51.90	76.10	72.30	30.40	33.70	52.30
Pb	2.20	7.20	8.40	8.20	8.90	5.30	5.10	9.70	12.30	11.10	8.90	4.80	5.00
Zn	41.00	22.00	31.00	30.00	61.00	12.00	26.00	44.00	43.00	37.00	17.00	46.00	50.00
W	0.90	0.50	0.50	0.50	0.70	1.40	0.50	0.70	0.50	0.50	0.50	0.50	0.50
Rb	16.40	4.40	4.60	4.60	31.20	12.60	27.10	44.10	28.60	27.60	46.20	27.90	36.30
Ba	155.00	176.00	208.00	205.00	326.00	210.00	456.00	565.00	378.00	395.00	444.00	536.00	461.00
Sr	660.20	506.20	532.90	529.10	532.90	477.10	640.30	643.20	405.60	427.50	732.00	717.50	618.90
Ta	0.10	0.10	0.20	0.20	0.30	0.20	0.40	0.40	0.30	0.20	0.30	0.40	0.40
Nb	2.80	3.50	3.50	3.60	5.70	3.20	8.20	8.20	4.70	5.30	4.50	8.60	6.80
Hf	1.30	1.90	1.80	1.80	2.30	1.50	3.00	2.60	2.80	3.20	2.50	2.80	2.50
Zr	47.00	70.00	66.40	65.70	90.50	57.70	113.10	99.20	98.90	110.60	90.60	114.80	104.40
Y	22.00	18.50	18.10	17.90	19.50	16.60	19.60	19.00	17.80	17.90	16.20	15.70	18.30
Th	1.20	1.10	1.50	1.40	4.00	3.90	3.80	6.00	3.80	7.60	3.60	4.10	4.10
U	0.40	0.30	0.40	0.30	1.40	1.30	1.00	1.60	0.90	1.10	1.10	1.10	1.20
Ga	17.90	15.80	15.90	15.10	17.90	16.50	18.40	16.60	14.70	15.00	14.10	16.60	16.70
La	7.00	10.60	10.00	9.80	18.00	15.10	23.90	23.00	17.40	16.70	19.60	27.10	20.50
Ce	14.70	21.90	23.00	22.90	33.80	24.40	48.50	42.30	33.70	35.20	41.00	46.90	39.40
Pr	2.04	2.89	2.94	2.78	4.08	2.84	5.62	5.08	4.09	4.09	5.07	5.39	4.72
Nd	9.40	12.40	11.60	12.00	17.10	11.50	23.50	20.50	17.10	15.90	21.90	21.20	18.20
Sm	2.38	3.14	2.89	3.06	3.79	2.51	4.45	4.25	3.56	3.38	4.34	3.85	3.87
Eu	0.86	0.95	1.01	1.00	1.14	0.85	1.45	1.21	1.01	1.00	1.33	1.14	1.26
Gd	2.86	3.30	3.34	3.35	3.79	2.79	4.49	4.12	3.59	3.61	4.17	3.49	3.74
Tb	0.48	0.55	0.53	0.54	0.58	0.46	0.66	0.61	0.58	0.56	0.58	0.53	0.59
Dy	2.94	3.38	3.48	3.47	3.40	2.70	3.72	3.56	3.29	3.25	3.24	2.85	3.41
Ho	0.63	0.72	0.64	0.68	0.73	0.60	0.76	0.74	0.70	0.62	0.61	0.61	0.71
Er	1.94	2.09	1.99	1.99	2.09	1.71	2.21	2.13	2.15	1.92	1.62	1.79	2.09
Tm	0.27	0.30	0.30	0.28	0.30	0.26	0.29	0.30	0.28	0.31	0.25	0.24	0.30
Yb	1.77	1.94	1.92	1.87	2.03	1.65	2.07	1.96	2.02	1.90	1.63	1.65	2.14
Lu	0.28	0.30	0.28	0.28	0.32	0.26	0.30	0.30	0.30	0.32	0.24	0.24	0.33
(Eu/Eu*) _n	1.01	0.90	0.99	0.95	0.91	0.98	0.98	0.87	0.86	0.87	0.94	0.93	1.00
(La/Lu) _n	2.59	3.66	3.70	3.62	5.82	6.01	8.25	7.94	6.01	5.40	8.46	11.69	6.43
(La/Sm) _n	1.85	2.12	2.18	2.02	2.99	3.79	3.38	3.41	3.08	3.11	2.84	4.43	3.33
(Gd/Lu) _n	1.27	1.37	1.48	1.49	1.47	1.33	1.86	1.71	1.49	1.40	2.16	1.81	1.41
(La/Yb) _n	2.67	3.69	3.52	3.54	5.99	6.18	7.80	7.93	5.82	5.94	8.13	11.10	6.47
Mg#	53.57	53.40	52.90	53.24	44.11	54.29	49.91	51.77	55.10	56.13	54.41	56.56	47.28
Ce/Pb	6.68	3.04	2.74	2.79	3.80	4.60	9.51	4.36	2.74	3.17	4.61	9.77	7.88
Nb/La	0.40	0.33	0.35	0.37	0.32	0.21	0.34	0.36	0.27	0.32	0.23	0.32	0.33
Ba/La	22.14	16.60	20.80	20.92	18.11	13.91	19.08	24.57	21.72	23.65	22.65	19.78	22.49
Dy/Yb	1.66	1.74	1.81	1.86	1.67	1.64	1.80	1.82	1.63	1.71	1.99	1.73	1.59
Pb/Ce	0.15	0.33	0.37	0.36	0.26	0.22	0.11	0.23	0.36	0.32	0.22	0.10	0.13
Th/Ce	0.08	0.05	0.07	0.06	0.12	0.16	0.08	0.14	0.11	0.22	0.09	0.09	0.10

Table 2' continued

Sample	Basaltic andesite				Andesite				Dacite				
	Y6	B119	B109	K2	B113	B114	B112	Y29	Y22	B121	Y35	Y39	K22
<i>Major oxides (wt%)</i>													
SiO ₂	55.54	56.63	56.82	57.00	58.21	58.67	58.75	59.39	59.59	60.07	64.38	64.93	68.10
TiO ₂	0.75	0.65	0.79	0.76	0.70	0.71	0.67	0.55	0.56	0.64	0.34	0.33	0.40
Al ₂ O ₃	19.35	17.51	16.36	16.53	16.84	16.53	17.44	17.14	17.23	17.63	16.22	16.16	14.48
Fe ₂ O _{3T}	6.90	7.44	7.61	6.84	6.94	6.97	6.35	6.19	6.16	5.67	3.81	3.71	3.52
MnO	0.12	0.17	0.13	0.10	0.14	0.14	0.13	0.11	0.16	0.12	0.14	0.14	0.06
MgO	2.61	3.39	3.70	3.31	2.97	3.03	2.62	2.22	2.86	2.17	1.22	1.23	1.16
CaO	7.50	7.40	6.32	6.86	5.15	5.25	6.39	5.04	6.39	6.43	4.05	3.99	2.22
Na ₂ O	2.62	2.73	3.45	3.20	4.19	4.17	3.99	4.04	3.78	3.79	3.83	3.93	3.71
K ₂ O	2.44	1.81	2.08	2.50	1.60	1.50	1.70	1.96	1.38	1.96	2.54	2.47	3.92
P ₂ O ₅	0.21	0.26	0.15	0.20	0.22	0.22	0.18	0.26	0.27	0.19	0.21	0.21	0.10
LOI	1.70	1.70	2.30	2.50	2.80	2.50	1.50	2.90	1.40	1.10	3.10	2.70	2.10
Total	99.74	99.69	99.71	99.80	99.76	99.69	99.72	99.80	99.78	99.77	99.84	99.80	99.77
<i>Trace elements (ppm)</i>													
Co	15.60	15.40	19.80	16.90	13.80	13.20	13.00	10.80	13.70	10.20	4.50	3.90	5.60
Ni	4.30	7.10	7.20	9.20	3.50	3.60	3.80	7.20	5.40	2.60	0.70	0.40	1.80
V	156.00	143.00	185.00	163.00	140.00	150.00	145.00	87.00	111.00	117.00	40.00	40.00	50.00
Cu	72.10	42.20	63.40	39.60	25.60	24.00	46.30	32.60	30.90	29.20	3.50	2.50	9.40
Pb	6.10	9.60	6.30	6.60	3.80	3.90	12.20	12.40	3.80	8.80	9.30	8.40	12.10
Zn	37.00	44.00	49.00	33.00	32.00	36.00	48.00	56.00	45.00	48.00	63.00	60.00	23.00
W	0.90	0.50	0.50	1.10	0.50	0.50	0.50	0.70	0.70	0.50	5.30	0.80	0.50
Rb	65.80	36.10	53.20	65.90	29.50	26.60	11.10	50.60	40.80	18.80	60.10	63.40	82.50
Ba	484.00	657.00	518.00	511.00	530.00	514.00	364.00	805.00	583.00	425.00	796.00	753.00	816.00
Sr	492.20	603.10	339.80	385.20	559.00	576.30	711.70	578.90	578.60	579.60	521.20	536.80	246.10
Ta	0.30	0.40	0.40	0.50	0.40	0.40	0.50	0.40	0.40	0.40	0.40	0.40	0.50
Nb	6.30	6.50	6.50	8.50	8.00	7.80	7.90	8.50	7.80	8.70	8.20	8.70	9.00
Hf	2.40	3.10	3.50	3.80	3.50	3.40	3.60	3.40	3.10	3.90	3.10	3.30	4.90
Zr	93.60	125.50	132.30	147.90	141.00	131.70	139.00	150.00	132.20	150.80	130.00	131.70	188.70
Y	17.50	20.40	21.00	20.90	19.00	18.60	20.30	15.30	15.80	21.20	14.50	13.80	17.40
Th	5.70	3.40	5.30	8.00	3.50	3.10	4.40	6.30	5.10	4.00	6.80	6.50	8.80
U	1.60	1.00	1.80	2.70	0.80	1.00	1.10	1.60	1.50	1.00	1.70	1.50	2.20
Ga	16.90	14.40	15.00	13.80	13.30	12.70	14.50	15.90	16.60	15.10	15.00	14.70	13.00
La	21.40	21.90	20.20	25.30	24.20	23.10	23.10	29.70	27.80	25.20	30.60	29.90	29.40
Ce	38.10	47.90	39.50	45.50	47.60	48.70	45.40	51.20	50.20	48.40	54.10	53.30	52.50
Pr	4.52	5.36	4.71	5.33	5.51	5.38	5.27	5.65	5.57	5.42	5.73	5.78	5.57
Nd	18.10	21.00	18.60	19.80	20.90	21.60	20.20	21.40	22.00	21.10	21.10	21.70	19.90
Sm	3.81	4.13	3.80	4.15	4.00	4.18	3.48	3.67	4.06	3.97	3.43	3.44	3.41
Eu	1.09	1.24	0.99	1.07	1.06	1.11	1.08	1.15	1.12	1.09	1.03	0.98	0.77
Gd	3.61	4.02	3.93	4.21	3.90	3.85	3.63	3.19	3.41	3.79	3.07	3.11	3.11
Tb	0.53	0.60	0.62	0.63	0.60	0.60	0.57	0.49	0.51	0.55	0.43	0.43	0.48
Dy	3.23	3.55	3.68	3.64	3.42	3.75	3.77	2.86	3.05	3.51	2.43	2.60	2.84
Ho	0.68	0.74	0.78	0.81	0.77	0.75	0.70	0.58	0.61	0.72	0.49	0.49	0.63
Er	1.96	2.18	2.53	2.36	2.36	2.16	2.17	1.69	1.82	2.25	1.61	1.49	1.95
Tm	0.29	0.33	0.33	0.34	0.34	0.32	0.33	0.25	0.28	0.35	0.24	0.25	0.30
Yb	1.95	2.38	2.24	2.27	2.22	2.22	2.15	1.68	1.71	2.27	1.65	1.75	2.16
Lu	0.28	0.35	0.36	0.37	0.34	0.33	0.35	0.25	0.29	0.36	0.28	0.27	0.34
(Eu/Eu*) _n	0.89	0.92	0.78	0.78	0.81	0.83	0.92	1.00	0.90	0.85	0.95	0.90	0.71
(La/Lu) _n	7.91	6.48	5.81	7.08	7.37	7.25	6.83	12.30	9.93	7.25	11.32	11.47	8.95
(La/Sm) _n	3.54	3.34	3.35	3.84	3.81	3.48	4.18	5.09	4.31	4.00	5.62	5.47	5.43
(Gd/Lu) _n	1.60	1.43	1.36	1.41	1.42	1.45	1.29	1.58	1.46	1.31	1.36	1.43	1.14
(La/Yb) _n	7.42	6.22	6.09	7.53	7.37	7.03	7.26	11.95	10.99	7.50	12.53	11.55	9.20
Mg#	45.44	50.08	51.70	51.58	48.51	48.90	47.60	44.12	50.55	45.73	41.35	42.19	42.05
Ce/Pb	6.25	4.99	6.27	6.89	12.53	12.49	3.72	4.13	13.21	5.50	5.82	6.35	4.34
Nb/La	0.29	0.30	0.32	0.34	0.33	0.34	0.34	0.29	0.28	0.35	0.27	0.29	0.31
Ba/La	22.62	30.00	25.64	20.20	21.90	22.25	15.76	27.10	20.97	16.87	26.01	25.18	27.76
Dy/Yb	1.66	1.49	1.64	1.60	1.54	1.69	1.75	1.70	1.78	1.55	1.47	1.49	1.31
Pb/Ce	0.16	0.20	0.16	0.15	0.08	0.08	0.27	0.24	0.08	0.18	0.17	0.16	0.23
Th/Ce	0.15	0.07	0.13	0.18	0.07	0.06	0.10	0.12	0.10	0.08	0.13	0.12	0.17

Fe₂O_{3T} is total iron as Fe₂O₃, LOI is loss on ignition, Mg# (Mg number) = molar 100×MgO/(MgO + Fe₂O_{3T}), Eu* = (Sm + Gd)/n/2

Table 3 Sr-Nd isotope compositions for Bayburt volcanic rocks

Sample	Rb (ppm)	Sr (ppm)	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	(2σ)	⁸⁷ Sr/ ⁸⁶ Sr _(i)	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ / ¹⁴⁴ Nd	(2σ)	¹⁴³ Nd/ ¹⁴⁴ Nd _(i)	εNd _(i) ^a	T _{DM} ^b	T _{DM} ^c
<u>Basalt</u>															
Y2	16.40	660.20	0.0720	0.705004	10	0.704959	2.38	9.40	0.153069	0.512716	5	0.512672	1.76	1.01	0.71
Y7	31.20	532.90	0.1698	0.705261	10	0.705154	3.79	17.10	0.133993	0.512649	4	0.512610	0.56	0.90	0.81
M36	27.10	640.30	0.1227	0.705047	9	0.704971	4.45	23.50	0.114481	0.512666	5	0.512633	1.00	0.71	0.77
<u>Basaltic andesite</u>															
M34	27.90	717.50	0.1128	0.705316	9	0.705245	3.85	21.20	0.109790	0.512607	5	0.512575	-0.11	0.76	0.86
Y9	36.30	618.90	0.1701	0.704953	11	0.704847	3.87	18.20	0.128552	0.512667	5	0.512630	0.94	0.82	0.78
Y6	65.80	492.20	0.3877	0.705205	10	0.704963	3.81	18.10	0.127258	0.512634	4	0.512597	0.31	0.86	0.83
<u>Andesite</u>															
B113	29.50	559.00	0.1530	0.705328	9	0.705233	4.00	20.90	0.115705	0.512620	5	0.512586	0.10	0.78	0.85
Y29	50.60	578.90	0.2535	0.705669	10	0.705511	3.67	21.40	0.103679	0.512601	5	0.512572	-0.19	0.73	0.87
Y22	40.80	578.60	0.2045	0.705305	10	0.705177	4.06	22.00	0.111569	0.512584	5	0.512552	-0.57	0.80	0.90
<u>Dacite</u>															
Y35	60.10	521.20	0.3344	0.705457	10	0.705248	3.43	21.10	0.098277	0.512592	5	0.512564	-0.35	0.71	0.88
Y39	63.40	536.80	0.3425	0.705478	10	0.705264	3.44	21.70	0.095838	0.512573	5	0.512545	-0.71	0.72	0.91
K22	82.50	246.10	0.9722	0.706042	10	0.705434	3.41	19.90	0.103595	0.512586	5	0.512556	-0.49	0.75	0.90

^a εNd_(i) values are calculated based on present-day ¹⁴⁷Sm/¹⁴⁴Nd=0.1967 and ¹⁴³Nd/¹⁴⁴Nd=0.512638

^b Single stage model age (T_{DM}^b) calculated with depleted mantle present-day parameters ¹⁴³Nd/¹⁴⁴Nd=0.513151 and ¹⁴⁷Sm/¹⁴⁴Nd=0.219

^c Two-stage model age (T_{DM}^c) according to Liew and Hofman (1988)

The Initial ¹⁴³Nd/¹⁴⁴Nd and ⁸⁷Sr/⁸⁶Sr ratios were calculated based on the ⁴⁰Ar–³⁹Ar ages reported in Table 1

Supplementary Tables

Table S1 ^{40}Ar - ^{39}Ar dating results for Bayburt volcanic rocks

Step / Sample	^{40}Ar	Error ^{40}Ar	^{39}Ar	Error ^{39}Ar	^{38}Ar	Error ^{38}Ar	^{37}Ar	Error ^{37}Ar	^{36}Ar	Error ^{36}Ar	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	Error $^{40}\text{Ar}^*/^{39}\text{Ar}_K$	Apparent age (Ma)	Error Age (Ma)	Delay to irradiation (day)
M36															
1	2030.403	5.886	11.426	0.042	0.0000010	0.0064	2.079	0.017	6.939	0.048	3.510	1.611	25.46	11.60	129.65
2	881.187	6.138	13.221	0.058	0.0000010	0.0074	2.046	0.028	3.017	0.030	1.299	0.879	9.46	6.39	129.67
3	1051.965	6.103	26.718	0.247	0.0000010	0.0102	4.484	0.025	3.278	0.020	4.377	0.371	31.69	2.66	129.69
4	2889.516	2.059	83.278	0.056	0.0000010	0.0110	17.527	0.110	8.580	0.039	5.414	0.213	39.12	1.53	129.71
5	706.199	4.839	34.045	0.321	0.0049210	0.0061	6.567	0.041	1.805	0.023	5.805	0.266	41.91	1.90	129.74
6	2196.906	5.599	100.862	0.322	0.0033680	0.0099	22.049	0.179	5.537	0.062	6.346	0.210	45.77	1.51	129.76
7	603.659	2.648	43.366	0.211	0.0095050	0.0094	12.975	0.114	1.203	0.008	6.388	0.102	46.07	0.75	129.85
8	2343.211	6.501	168.348	0.540	0.0000010	0.0094	36.213	0.171	4.746	0.043	6.149	0.100	44.36	0.74	129.87
9	1482.264	4.540	143.219	0.393	0.0077470	0.0071	21.077	0.059	2.261	0.017	6.055	0.059	43.70	0.46	129.89
10	3030.587	6.597	321.735	1.520	0.0000010	0.0054	33.432	0.062	3.847	0.015	6.171	0.046	44.52	0.38	129.92
11	4648.137	3.449	523.792	0.689	0.0000010	0.0117	44.500	0.148	5.154	0.037	6.209	0.033	44.80	0.30	129.96
12	3924.866	4.590	410.088	0.364	0.0000010	0.0104	38.320	0.145	5.071	0.044	6.191	0.043	44.67	0.36	129.98
13	6025.583	2.051	565.058	0.299	0.0000010	0.0149	95.344	0.153	9.304	0.058	6.203	0.044	44.75	0.37	130.00
Fusion	2957.472	0.792	206.176	0.109	0.0000010	0.0108	147.213	0.304	6.508	0.021	6.249	0.061	45.08	0.47	130.04
K-2															
1	10460.122	12.052	83.333	0.304	0.0092800	0.0127	3.946	0.018	34.496	0.062	6.734	0.690	48.71	4.93	130.67
2	3350.155	27.254	79.059	0.183	0.0000010	0.0116	2.972	0.010	10.187	0.053	5.458	0.448	39.59	3.22	130.68
3	5369.345	10.428	277.963	0.538	0.0000010	0.0136	10.047	0.036	13.046	0.047	5.932	0.101	42.99	0.75	130.70
4	10039.744	8.584	676.698	1.278	0.0000010	0.0086	16.395	0.015	20.740	0.078	6.116	0.066	44.30	0.51	130.74
5	5164.137	2.877	521.205	0.287	0.0000010	0.0114	12.007	0.066	7.102	0.059	6.076	0.044	44.01	0.36	130.76
6	3546.499	1.944	446.407	0.199	0.0000010	0.0081	11.036	0.035	2.977	0.043	6.113	0.034	44.28	0.30	130.78
7	6607.987	6.834	636.049	0.539	0.0000010	0.0054	18.708	0.072	9.778	0.024	6.063	0.035	43.92	0.31	130.80
8	4472.112	2.230	451.542	0.277	0.0000010	0.0094	18.735	0.055	6.206	0.020	6.062	0.032	43.91	0.29	130.84
9	2622.349	7.775	362.682	0.619	0.0000010	0.0111	16.240	0.089	1.653	0.031	6.030	0.037	43.69	0.32	130.87
10	2473.340	10.229	322.387	0.396	0.0018670	0.0100	15.000	0.080	1.950	0.014	6.047	0.039	43.80	0.33	130.89
11	6613.922	2.012	813.253	0.307	0.0000010	0.0104	39.010	0.074	6.105	0.109	6.091	0.044	44.12	0.36	130.91
12	5779.997	2.362	856.311	0.590	0.0000010	0.0109	50.769	0.135	2.361	0.092	6.087	0.034	44.09	0.30	130.95
13	2848.018	0.911	402.828	0.312	0.0000010	0.0091	69.587	0.169	1.801	0.025	6.063	0.023	43.92	0.25	130.97
Fusion	1906.303	0.971	220.643	0.181	0.0000010	0.0089	278.297	0.393	3.272	0.026	6.083	0.043	44.06	0.36	130.99
K-22															
1	6403.636	11.672	124.412	0.135	0.0014840	0.0146	1.537	0.023	20.404	0.101	4.416	0.360	32.16	2.60	133.67
2	3600.474	4.133	304.375	0.426	0.0000010	0.0168	2.200	0.059	6.723	0.074	5.541	0.083	40.26	0.62	133.68
3	10727.783	14.037	1351.797	1.633	0.0000010	0.0130	6.311	0.030	8.944	0.052	6.093	0.025	44.22	0.26	133.70

4	8349.706	5.804	1226.863	0.936	0.0000010	0.0120	4.757	0.054	2.912	0.028	6.182	0.015	44.86	0.21	133.73
5	5358.799	2.870	823.127	0.609	0.0000010	0.0092	3.214	0.033	1.178	0.021	6.157	0.014	44.68	0.21	133.77
6	2696.424	16.509	426.616	1.890	0.0000010	0.0118	1.681	0.033	0.465	0.012	6.064	0.049	44.01	0.40	133.79
7	4075.756	8.328	642.395	1.553	0.0000010	0.0119	2.969	0.019	0.877	0.013	6.010	0.023	43.62	0.24	133.82
8	1989.140	7.010	314.668	1.043	0.0000010	0.0121	1.557	0.023	0.413	0.018	6.002	0.035	43.57	0.31	133.86
9	1848.695	3.812	289.605	0.833	0.0000010	0.0151	1.684	0.033	0.458	0.012	5.988	0.027	43.47	0.26	133.88
10	1844.046	12.395	281.148	0.872	0.0000010	0.0148	2.109	0.040	0.657	0.014	5.948	0.051	43.18	0.41	133.90
11	2753.741	1.347	398.477	0.223	0.0000010	0.0141	4.940	0.031	1.382	0.024	5.982	0.023	43.43	0.24	133.95
12	5518.200	3.830	736.469	0.564	0.0000010	0.0105	7.535	0.043	4.012	0.016	5.993	0.019	43.50	0.22	133.98
13	6717.569	2.406	849.114	0.338	0.0000010	0.0095	13.005	0.065	5.846	0.029	6.005	0.021	43.59	0.24	134.00
14	5411.710	2.309	694.503	0.277	0.0000010	0.0097	9.466	0.022	4.358	0.023	6.060	0.020	43.98	0.23	134.02
Fusion	1537.283	0.676	172.713	0.173	0.0000010	0.0136	2.233	0.015	1.770	0.025	6.025	0.049	43.74	0.39	134.04

⁴⁰Ar_{atm}: atmospheric ⁴⁰Ar, ⁴⁰Ar*: radiogenic ⁴⁰Ar, Ca: produced by Ca-neutron interferences, K: produced by K-neutron interferences, Age (Ma): the date is calculated using the decay constants recommended by Steiger and Jäger (1977). The errors are at the 1σ level and do not include the error in the value of the J parameter.

Table S2 ($^{143}\text{Nd}/^{144}\text{Nd}$)_(i) and ($^{87}\text{Sr}/^{86}\text{Sr}$)_(i) compositions assumed for the end-member components in the assimilation-fractional crystallizations calculation

End member	IC ₀ (Parental magma)	IC _A (Upper continental crust)	Total Partition coefficient ($\sum D$)			
			D1	D2	D3	
Sr (ppm)	188	350	Sr	1.20	0.50	1.20
Nd (ppm)	9.62	26	Nd	1.85	1.80	1.85
$^{87}\text{Sr}/^{86}\text{Sr}$	0.7029	0.71463	For all continental crust modelling			
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51319	0.511843				
	Klein (2004)	Taylor and McLennan (1985)				