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Classification and generation of the enclaves in Karapınar-Karacadağ volcanic rocks (Central Anatolia)

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Keywords
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ABSTRACT

Karapınar-Karacadağ Volcanic Rocks (KKVR) have very complex magmatic history and outcropped the southwestern part of the Cappadocia Volcanic Province (Central Anatolia). Here we present the petrography and whole-rock chemistry of the enclave-bearing rocks to constrain their source and evolution history. These petrographic observation and geochemical data reveal that the enclaves in the Karapınar-Karacadağ volcanic rocks are magma mixing/mingling enclaves (MME), magma segregation enclaves (MSE), and xenoliths. Here we discriminated these enclaves into eight different types according to their mineral composition and textural features. The magma mixing/mingling enclaves (Type 1, 7, 8) are the mixing products of coeval more felsic and mafic magmas. They show hypocrystalline porphyritic, holocrystalline granular, and intergranular textures, and rich in mafic minerals, and have characteristic petrographic features such as quenched amphibole, bladed biotite, ocelli-quartz, sieved and cellular plagioclases. In andesites they range from basalt to andesite in composition. However, in basalts, they are in basaltic composition. The magma segregation enclaves (Type 2, 4, 5, 6), which are observed in almost all the KKVRs, are cognate xenolith because of plucking from the different parts of the magma chamber. They are holocrystalline and granular in texture. The magma segregation enclaves contained in the andesitic host rocks are hornblende gabbro and pyroxene gabbro in composition, whereas in the basaltic host rocks they are dunite, lherzolite, and basalt in composition. The xenolithic enclaves (Type 3) are observed in the basalts as quartz, plagioclase, biotite, and amphibole xenocrysts. Major oxides and trace element data of the studied rocks indicate that the MSEs are more primitive than their host rocks, and all of the enclaves (MME-MSE) are in accordance with their hosts. According to petrographic observations and geochemical data we propose that fractional crystallization, magma mixing and assimilation processes have a key role in the evolution of the KKVRs and their enclaves.

1. INTRODUCTION

Generally, enclave means crystal clots (clusters) in the rock and they differ from the host rock in which it is located, disrupting the homogeneous appearance of the host-rock (Barbarin and Didier, 1992). Enclaves may be distinguished from the host-rock in terms of color, shape, size, texture, and mineralogical composition macroscopically and/or microscopically. The sizes of enclaves can vary from microscopic scale to several hundred meters. They can be composed of several different minerals or only one mineral (Cantagrel et al., 1984). Enclaves contain important information about the genesis and evolution of magma and magma chamber processes. Based on formation, origins, and relationships with felsic host rocks, the enclaves in granitoid rocks have been classified as (1) Xenolite, (2) Restite, (3) Cognate enclave (4) Microgranular enclave (Barbarin and Didier, 1991; Best, 2003; Cantagrel et al., 1984; Dahlquist, 2002; Didier, 1991; Ilbeyli and Pearce, 2005; Kadioglu and Gülec, 1996; Kadıoğlu and Güleç, 1999; Kocak et al., 2011; Kumar, 2010; Kumar et al., 2004; Kumar and Singh, 2014; Noyes et al., 1983; Özdamar et al., 2021; Winter, 2014; Zhang and Zhao, 2017). Xenoliths are known as foreign rock fragments assimilated from the wall-rock during ascending (Maury and Didier, 1991; Tindle and

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Pearce, 1983), and generally seem like a metamorphic rock. Due to their metamorphic textures and the sharp contacts with their hosts, they could be easily separated from the cognate enclaves (Cantagrel et al., 1984; Didier, 1991; Shelley, 1993). Restites are known as the residual material after partial melting (Chappell et al., 1987; Chen et al., 1991). Cognate enclaves are early-crystallized mineral clots or segregation of mafic phases, or products of earlier solidified phases which were wall and border rock in the magma chamber (Dahlquist, 2002; Kadıoğlu and Güleç, 1999; Kocak et al., 2011; Noyes et al., 1983). They have cogenetic affiliation with their hosts, and have a coarse-grained appearance. If early-formed minerals assemblages seemed as cumulate textures, such as adcumulate, intercumulate, orthocumulate etc. they are called cumulate enclaves. Cumulates are generally present mafic magmas rather than the felsic magmas because of the different viscosity of the residual melts (Kumar and Singh, 2014). Magma segregation enclaves (MSE) as a kind of cognate enclave are formed by segregation and accumulation of the early-crystallized minerals, are also known monomineralic or polimineralic crystal clots displaying glomeroporphyritic textures. Phenocrysts are liable to aggregate into clusters as glomerocrysts, showing glomeroporphyritic texture in basalts (Gill, 2010). Microgranular enclaves are common in granitoids and they are rarely divided into subgroups as mafic and felsic microgranular enclaves. They are formed as a result of the reaction of coeval mafic and felsic magmas and are actually the products of the magma mingling process (Barbarin and Didier, 1991; Best, 2003; Cantagrel et al., 1984; Dahlquist, 2002; Didier, 1991; Ilbeyli and Pearce, 2005; Kadioglu and Gülec, 1996; Kadıoğlu and Güleç, 1999; Kocak et al., 2011; Kumar, 2010; Kumar et al., 2004; Kumar and Singh, 2014; Noyes et al., 1983; Winter, 2014). They are the products of hybridization process. While a homogeneous mixing takes place in the magma mixing process, the mingling process generates partial mixing. MMEs are liable to be cogenetic with their host rocks. They generally have a fine-grained appearance, and are equigranular to porphyritic in nature (Kumar, 2010). Some researchers (Winter, 2014) suggest that schlieren and chilled margins might be accepted as microgranular enclaves. Since volcanic rocks show textures ranging from holocrystalline granular to vitrophyric porphyritic, and they may have a groundmass composed of volcanic glass and/or microlite, and their minerals are generally small in size and acicular in shape, the definition of magma mixing/mingling enclaves (MME) is more convenient for volcanic units rather than the definition microgranular enclave. Therefore, considering their formation, origins and transportation of the host rock, enclaves can generally be divided into four groups: (1) Xenolite, (2) Restite, (3) Magma segregation enclave (4) Magma mixing/mingling enclave (Kadıoğlu and Güleç, 1999). In addition, MME may also contain another enclaves termed as double enclaves (Didier, 1973), or composite enclaves (Kumar, 2010).

Here, we present for the first time, field and petrographic features (textural, mineralogical) and whole-rock major oxide-trace element characteristics of the enclaves and their host rocks from the Neogene-Ouaternary aged Karapınar-Karacadağ Volcanic Rocks. With this scope, we aim to determine the enclaves' occurrence, origins, relationships, and their importance in the Cenozoic Central Anatolian Volcanism.

2. GEOLOGICAL SETTING

The Karapınar-Karacadağ Volcanic Units are the southwestern extension of the Cappadocia Volcanic Province (CVP), and these post-collisional products commonly outcrop in the Kırşehir and Anatolide blocks in Central Anatolia (Gençoğlu Korkmaz et al., 2022) (Figure 1). Neogene aged calc-alkaline volcanites are mostly represented by lava flows/domes and pyroclastics, which are called “Karacadağ Volcanics”. However Quaternary aged calc-alkaline-mildly alkaline volcanics outcropping as lava flows, maar pyroclastics and cinder cones, are called “Karapınar volcanics” (Gençoğlu Korkmaz et al., 2022). Keller (1974) argues that the geological and genetic understanding of Karacadağ was hindered by the arrival of much younger basaltic scoria cones (Karapınar volcanics) that do not have a direct genetic relationship to the northeast of Karacadağ. In recent studies, the age of Karapınar volcanics is <2.5 Ma (Dogan-Kulahci et al., 2018; Reid et al., 2017) as a result of ^{40}Ar-^{39}Ar geochronology, while Platzman et al. (1998), (K-Ar; 4.7-5.98 Ma) and Gençoğlu Korkmaz et al. (2022), (^{40}Ar-^{39}Ar; 5.65-5.45 Ma) suggest that Karacadağ volcanics are Mio-Pliocene. The Karacadağ volcanics consist of lava flows and pyroclastics with in calcalkaline character, they are rarely basaltic and trachytic and mainly andesitic-dacitic in composition. Moreover, andesitic and dacitic rocks contain two types of enclaves as magma segregation enclaves and magma mixing enclaves. Karapınar volcanics, on the other hand, have mildly alkaline-calcalkaline (transitional) character, and are mostly basaltic and rarely andesitic products, and include three types of enclaves: magma segregation enclaves, magma mixing enclaves and xenoliths (Gençoğlu Korkmaz et al., 2018). The calc-alkaline rocks of the CVP are characterized by LILE/HFSE enrichments showing negative Nb, Ta and Ti anomalies. However, Na-alkaline volcanics from CVP are quite similar to calc-alkaline rocks in terms of LILE and REE patterns, although they have some OIB-like basaltic rock features (Aydar et al., 1994; Dogan-Kulahci et al., 2018; Ercan, 1987; Ercan et al., 1990; Güllü and Kadıoğlu, 2019; Notsu et al., 1995; Reid et al., 2017; Uslular and Gençalioğlu-Kuşcu, 2019). Di Giuseppe et al. (2018) suggest that a mixing process between calc-alkaline and intraplate magmas during magma uplift resulted in the formation of Ne normative basalts in Central Anatolia. Gençoğlu Korkmaz et al. (2022) report that not only temporally but also spatially crustal contamination has a critical role in the evolution of the rocks. Furthermore, from Neogene to Quaternary the effect of the crustal contamination process has decreased, but it has increased again spatially in Quaternary. Moreover, they report that all geochemical data and petrological models reveal that Karapınar mildly alkaline basalts obtained an orogenic character via contamination with Karacadağ volcanites. In addition, Gençoğlu Korkmaz and Kurt (2021) suggested that magma recharging processes and convection in the magma chamber are effective in the formation of the rocks and their enclaves. Also they stated that these (multiple) recharging processes gave rise to the triggering of the Karapınar-Karacadağ volcanism.

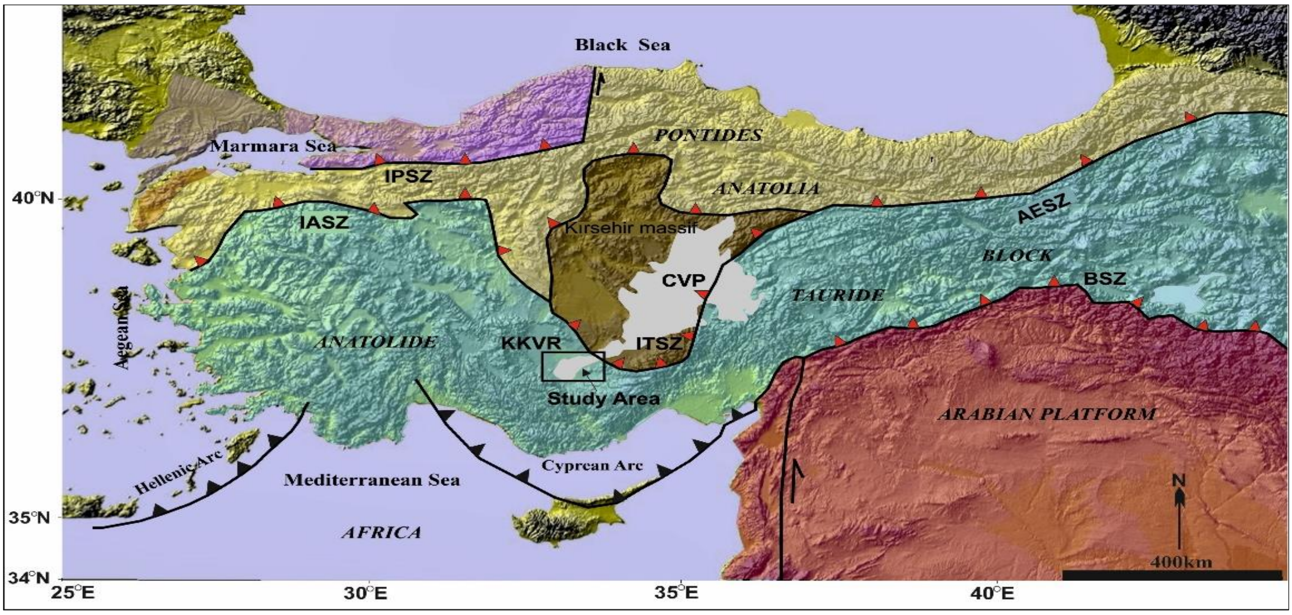

Figure 1. Location of the investigated area in the map showing the main tectonic units of Turkey (Okay and Tüysüz, 1999). The map shows also the position of the, Hellenic arc, and Cyprus arc. CVP: Cappadocian Volcanic Province, IASZ: İzmir-Ankara-Suture Zone, AESZ: Ankara-Erzincan Suture Zone, IPSZ: Intra-Pontide Suture Zone, ITSZ: Inner Tauride Suture Zone, BSZ: Bitlis Suture Zone. Solid lines stand for major suture zones (black lines with red triangles) separating continental blocks and arc systems (black lines with black triangles) The map is taken from Gençoğlu Korkmaz et al. (2022)

3. METHOD

Within the scope of this study, 180 thin sections were made from the most representative 700 samples collected from the Karapınar-Karacadağ area. Some of the basaltic and andesitic rocks from the KKVR contain enclaves with different textures and compositions varying in size from µm-dm. Approximately fifty of the collected samples contain enclaves in mm-dm size. Among them, twenty most representative and freshest enclaves and their hosts were used for this study.

In this study, some enclaves were carefully separated from the host-rock thus facilitating chemical analyses. Detailed petrographic examinations (modal mineralogical composition, texture, classification, alteration) of the samples, whose thin sections were obtained at the Thin Section Laboratory of Ankara University Earth Sciences Application and Research Center (YEBİM), were carried out with the help of polarizing microscopy in Konya Technical University Geological Engineering Department. Besides, microphotographs were taken to highlight important mineralogical and petrographic features.

Among these samples, the most representative and determinant host-rock (eight) and enclave (nine) samples were analyzed in Spectro X-Lab 2000 model PED-XRF (Polarized Energy Dispersive XRF) device at YEBİM. The samples were first crushed in Retsch brand automatic stone crusher, then they were ground in a Tungsten Carbide mill in Fritsch brand automatic grinder. 4 grams of sample was mixed with 0.9 grams of binding material (wax-polyvinyl alcohol) and made ready for analysis in pellet form by compressing under a hydraulic press. Results of whole-rock analyses of the samples are available from Supplementary Material 1.

4. RESULTS

4.1. Types of Enclaves: Petrography and classification of the enclaves

KKVRs were classified as Basalt-1 (B1), Andesite-1(A1), Andesite-2(A2), Andesite-3(A3), Andesite-4(A4), Dacite(D), Trachyte (T) (Karacadağ volcanic units) and Basalt-2(B2) and Basalt-3(B3) (Karapınar volcanic units) based on their petrographical and chemical properties as reported in Gençoğlu Korkmaz et al. (2022). Karacadağ volcanites are calc-alkaline, however Karapınar volcanites are mildly alkaline (B2) to calc-alkaline (B3) (Gençoğlu Korkmaz et al., 2022).

Karacadağ stratovolcano is dominantly composed of andesitic lava units contained both macroscale (Figure 2 a-d and g-m) and microscale enclaves (Figure 4 a-s). They are generally ellipsoidal in shape (Figure 2 c, d) and rarely contain chilled margins (Figure 2 i) In the investigated area they rarely exhibit banding texture (Figure 2 a, b, l, and m). However, Karapınar Quaternary volcanism has produced dominantly basaltic scoria cones and lava flows, having mainly microscopic enclaves (Figure 2 e, f, n, o and Figure 3 a-o). Investigated enclave types, their main mineralogical contents, and their textural characteristics are summarized in Table 1 and 2. Eight types of enclaves were distinguished on the basis of petrographic characteristics, mineral composition, and textural–structural features.

Karapınar basaltic host rocks generally exhibit a texture varying from holocrystalline porphyritic to hypocrystalline porphyritic texture. They rarely display also vesicular and amygdaloidal textures. Some of the basaltic host rocks (B2) are olivine-dominated, whereas others (B3) are pyroxene-dominated. Investigated basaltic hosts have Type-1 (MMEs; Figure 3 a-c, and Figure 3 k, l), Type-2 (MSEs; Figure 3 d, h-l, n, o) and Type-3 (Xenoliths; Figure 3 m) enclaves. Along with that, they include composite enclaves (enclave in enclave; Figure 3 i-l).

Type-1 enclaves (Figure 3 a-c, k, l) are observed both in macroscale and in microscale in the Karapınar basalts (generally B2) as magma mixing enclaves (MME). They are angular to semi-rounded shaped enclaves in the field (Figure 2 e, f, n, o). The groundmass of the Type-1 enclaves is rich in microlites. The appearance of the enclaves is formed by elongated plagioclase crystals, short prismatic micro-phenocrysts of pyroxene, and rarely fructured olivine phenocrysts with minor Fe-Ti oxides.

The magma segregation enclaves (MSE) in the basalts (B2-B3) called Type-2 enclaves are holocrystalline and granular in texture and are monomineralic to polimineralic in composition. They occur as independent aggregates and rarely within Type-1 enclaves (enclave in enclave-composite enclave), and they are in microscale. They don't display any cumulate or metamorphic rock texture as cumulate enclaves. They seem like typical igneous rocks and they are coarse-grained rocks showing glomeroporphyritic textures. They are often observed as crystal clots formed by segregation of the early solidified phases (olivine, pyroxene, plagioclase crystals).

Figure 2. Macro-scale enclaves and their structural and textural properties (a)-(b) enclave swarms showing relative magmatic flow structure with host magma, (c)-(d) ellipsoidal-rounded enclaves in Karacadağ volcanic rocks (e)-(f) semi- rounded-angular enclaves in Karapınar volcanic rocks

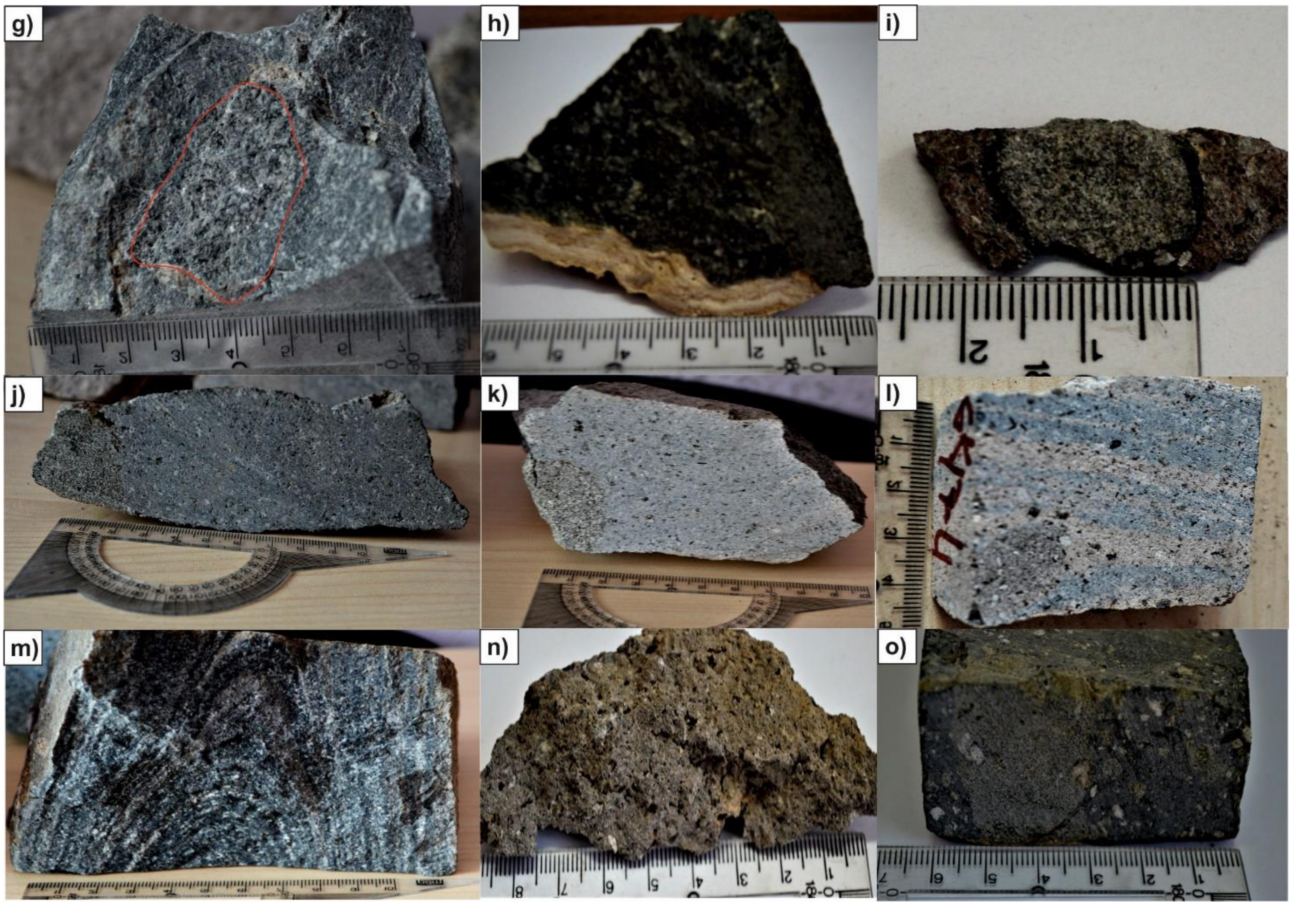

Figure 2. (continued) Macro-scale enclaves and their structural and textural properties (g)-(m) ellipsoidal-rounded enclaves in the Karacadağ volcanic rocks, (n)-(o) semi- rounded-angular enclaves in the Karapınar volcanic rocks

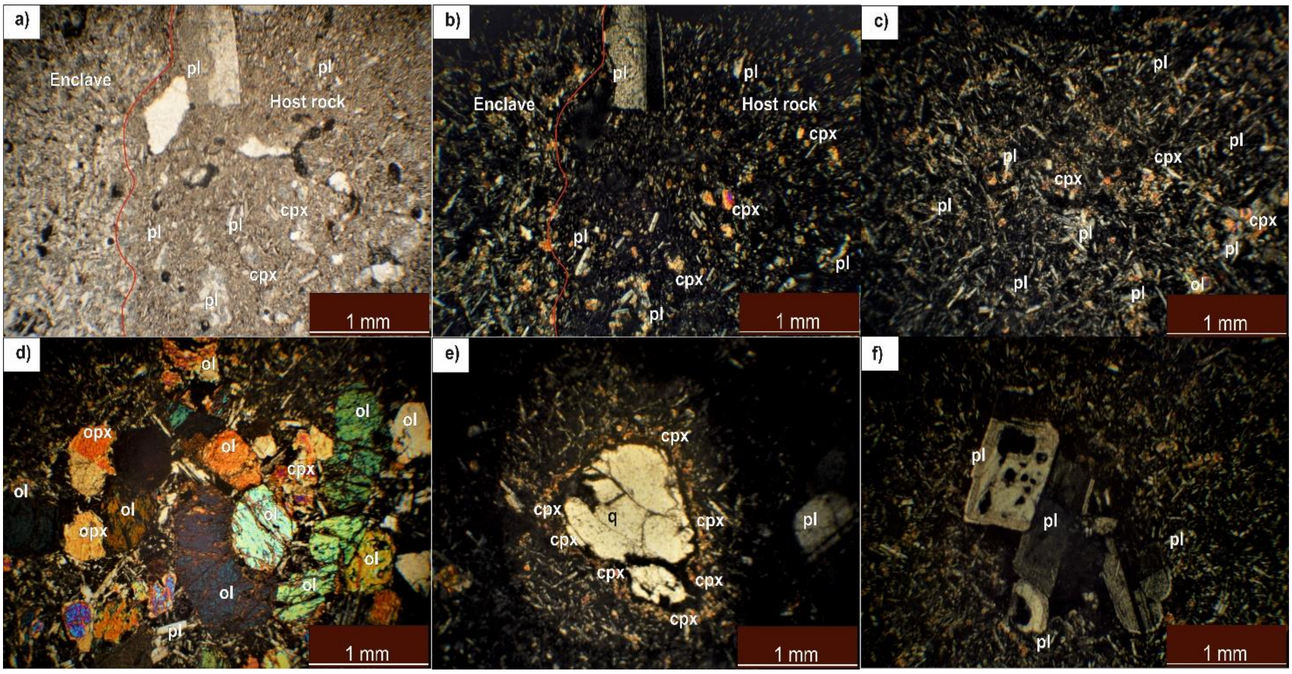

Figure 3. (a)-(b) Boundary of the Basalt-2 and Type-1 enclave (MME), (c) Type-1 enclave (MME in basaltic composition) in Basalt-2, (d) Type-2 enclave (MSE-in lherzolite composition) in Basalt-3, (e) ocelli quartz xenocryst in Basalt-3, (f) sieved plagioclase glomerocrysts (composite enclave) in Type-1 enclave. cpx: Clinopyroxene; ol:Olivine; opx: Orthopyroxene; ox: Fe-Ti oxides; pl: Plagioclase; q: Quartz (Kretz, (1983)

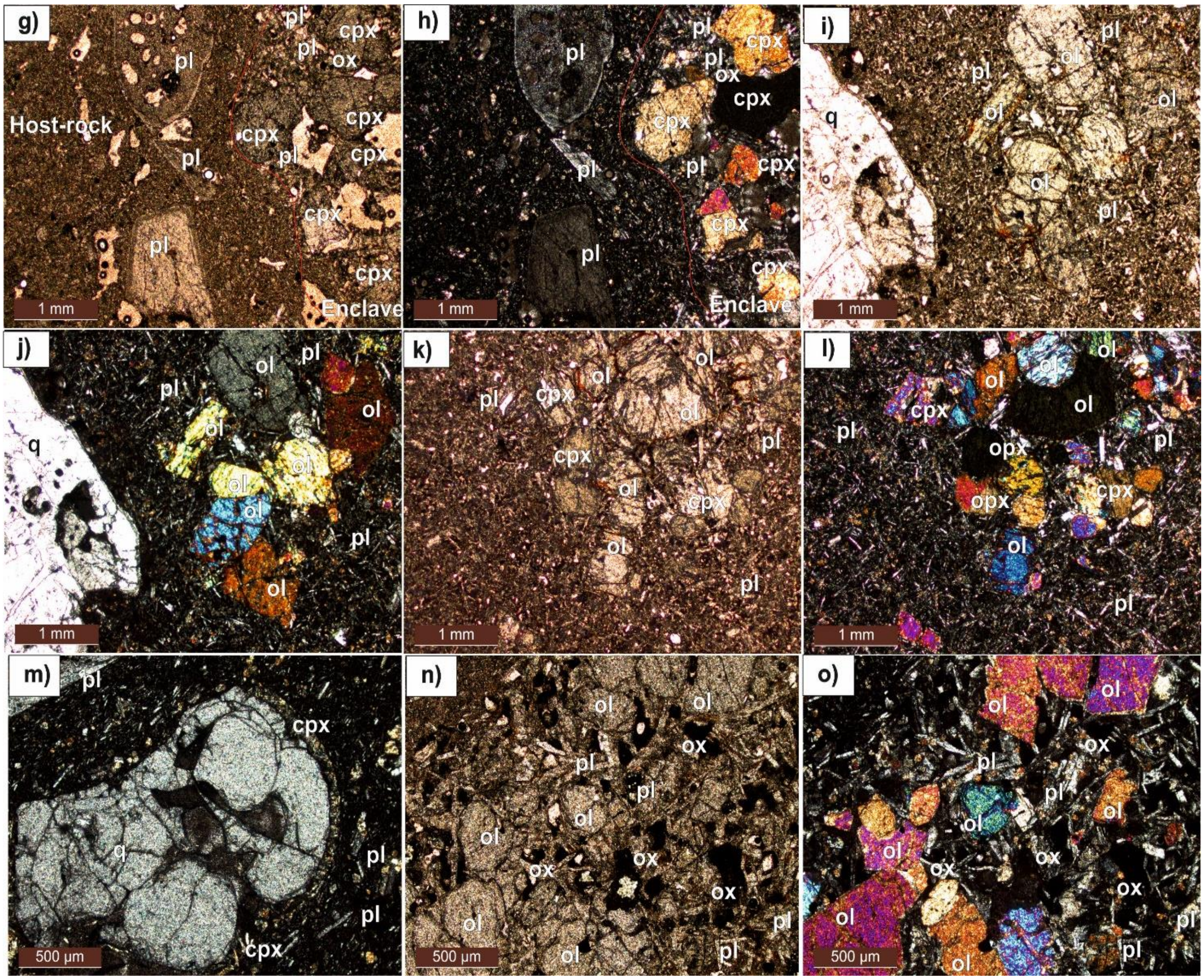

Figure 3. (continued) (g)-(h) Boundary of the in Basalt-2 and Type-1 enclave (MME), (i)-(j) Type-2 enclave (MSE-in dunite composition) and (k)-(l) Type-2 enclave (MSE-in lherzolite composition) in Basalt-2, (j)-(l) composite enclaves, (m) embayed and ocelli quartz xenocryst and (n)-(o) Type-1 enclave (MME in basaltic composition) in Basalt-3

The xenolithic enclaves (Figure 3 e, f, g, j, m) classified as Type-3 enclaves are observed in the basalts (generally in the B3) and rarely Type-1 enclaves (composite enclave) as quartz, plagioclase, biotite, and amphibole xenocrysts and also seemed a piece of quartzite rock. A composite enclave formed when one enclave is enclosed in another enclave are detected in some of the investigated rocks as demonstrated in Figure 3 e, f, j-l. Embayed and ocelli-quartz minerals and spongy cellular, coarse and/or fine sieved-plagioclase minerals are observed in both enclaves and their hosts as xenocrysts.

Karacadağ andesitic-dacitic host rocks have generally hypocrystalline porphyritic rarely vesicular textures. Some of the andesitic host rocks include amphibole and pyroxene as major mafic mineral phases. Investigated intermediate host rocks generally contain pl+ cpx± amph± bi± opx+ Fe-Ti oxides plus volcanic glass. They have Type-4 (MSEs; Figure 4b), Type-5 (MSEs; Figure 4d) Type-6 (MSEs; Figure 4f), Type-7 (MMEs; Figure 4 n, p) and Type-8 (MMEs; Figure 4 l, s) enclaves.

The magma segregation enclaves (MSE), which are observed in almost all of the Karapınar-Karacadağ Volcanic Rocks, are cognate xenolith due to their textural properties, and are best observed under the microscope because of their small sizes. MSEs in the andesitic host rocks are in amphibole gabbro, pyroxene gabbro and micro-gabbro composition with holocrystalline granular texture. Plagioclases generally exhibit dusty sieve, fine sieve and spongy sieve textures, and pyroxenes and amphiboles are rarely fractured and anhedral in host rocks relative to in MSEs. In addition, some of the plagioclases, pyroxenes, and amphiboles exhibit both textural and chemical zoning (Gençoğlu Korkmaz and Kurt, 2021). MMEs in andesites range from basalt to andesite in composition. They show hypocrystalline porphyritic, holocrystalline granular, and intergranular textures, and rich in mafic minerals, and have characteristic petrographic features such as quenched amphibole, bladed biotite, sieved and cellular plagioclases. Along with that, some of the plagioclases display both textural and chemical zoning in both enclaves and their hosts as in MSEs. Composite enclaves that appeared like basaltic/gabbroic rocks are also detected in the andesitic host rocks. Figure 4.s demonstrates that the basaltic MME from the andesitic host rock includes gabbroic MSE.

Type-4 enclaves (Figure 4b) are in the andesitic host rocks (A1) as MSEs in amphibole-gabbro composition and they are holocrystalline and equigranular in texture. They contain mainly prismatic amphibole and plagioclases and rarely clinopyroxene and opaque minerals. Amphibole and clinopyroxenes are often zoned, and plagioclases show generally sieve textures. The enclave mineralogy is the same as in the host, however, the host rock contains biotite and amphibole as major mafic phases rather than clinopyroxene (Figure 4 a). Accessory minerals contain zircon and Fe-Ti oxides.

Type-5 enclaves (Figure 4 d, h, i, k) are MSE in the andesitic (A1-A2-A3) and dacitic host rocks containing cpx+ pl +Fe-Ti ox, and rare biotite. The mineralogy of the enclaves is similar to that of their host rocks, but the enclaves contain abundant dusty sieved-plagioclases, and also have abundant clinopyroxenes as mafic phases. Some of the Type-5 enclaves are observed in two-pyroxene andesites as cpx+opx+pl+Fe-Ti oxide crystal cargoes (Figure 4 h).

Although having the same mineral composition as their enclaves (Type-6), some of the andesitic host rocks (A1) are porous and have a glassy groundmass (Figure 4 e). Type-6 enclaves (Figure 4 f) are classified as MSE and they have chilled margin through the host rock-enclave boundary. Type 6 enclaves are in the micro-gabbro composition and contain cpx+pl+ox±amph minerals. They show holocrystalline and equigranular texture. However, the chilled margins (Figure 4 g) seem as magma mixing enclave and are composed of quenched and elongated amphiboles, sieved plagioclases, rarely fructured and short prismatic clinopyroxenes and Fe-Ti oxides. Also, the grains in the chilled margins are larger than those in the enclave.

Type-7 enclaves (Figure 4n, p) are andesitic MMEs in the andesitic host (A1). They are rounded shaped and have no chilled margins. The mineralogy of the enclaves is similar to that of the andesitic host rocks. They show hypocrystalline porphyritic and intergranular textures, and rich in mafic minerals. They are composed of mainly amphibole and plagioclase, rarely clinopyroxene, biotite, Fe-Ti oxide, and volcanic glass. Along with that, they have characteristic petrographic features such as quenched amphibole, bladed biotite, sieved and cellular plagioclases. Also, some of the plagioclases display both textural and chemical zoning both in enclaves and their hosts as in MSEs (Gençoğlu Korkmaz and Kurt, 2021).

Type-8 enclaves (Figure 4 l, r, s) are basaltic MMEs in the andesitic host rocks (A2). They have flow banding structure and show marble cake textures in the field (Figure 2 a, b, m). Along with that, they are rounded shaped. They show holocrystalline and intergranular textures, and rich in mafic minerals, and have characteristic petrographic features such as sieved, cellular and zoned plagioclases, acicular plagioclases, fructured olivines. However, host rock show hypocrystalline porphyritic texture and include clinopyroxene, amphibole, biotite, plagioclase, and Fe-Ti oxide minerals. Some of the plagioclase micro-phenocrysts in both enclaves and their hosts exhibit textural and chemical zoning (Gençoğlu Korkmaz and Kurt, 2021). Type-8 enclaves also contain crystal clots including cpx+pl+ol+ox as composite enclaves in which basaltic MME have enclosed gabbroic magma segregation enclaves (Figure 4 s).

4.2 Whole-Rock Composition of the Host Rocks and Their Enclaves

Here, only enclaves, which could be separated from their hosts due to their large size and whose geochemistry could be examined, and their hosts are classified and discriminated from each other, based on total alkali-silica diagram TAS (Le Bas et al., 1986; Middlemost, 1994). While the Karapınar basalts containing enclaves fall into the basaltic andesite-andesite areas, the enclave-bearing Karacadağ volcanic rocks include compositions varying from andesite to dacite (Figure 5 a). Type-1 enclaves are basaltic-andesite, Type-4 enclave plots in the basalt field (mineralogically, they are amphibole gabbro), Type-5 enclaves plot in the basaltic-andesite, andesite area (mineralogically, they are pyroxene gabbro), Type-7 enclave is andesite and Type-8 enclave is basaltic andesite (Figure 5 a). Since MSEs (Type 4-6) exhibit holocrystalline texture as in the plutonic rocks, the TAS classification diagram generated by Middlemost (1994) was utilized to discriminate the MSEs. Accordingly, MSE enclaves have a composition ranging from gabbro to diorite (Figure 5 b). Moreover, studied rocks include calc-alkaline and high-K calc-alkaline series in the K_20-$Si0_2$ diagram. According to TAS diagrams, and SiO_2 versus K_2O classification diagram (Figure 5 d), magma segregation enclaves appear more primitive than their host rocks.

Investigated rocks and their enclaves exhibit different trends in MgO versus major oxide and trace element diagrams (Figures 6a-f, 7a-f). Karapınar enclave bearing basalts contain MgO 3-9 wt.%, SiO_2 53-62 wt.%, CaO 5-9 wt.%, TiO_2 0.68-0.94 wt.%. However, their enclaves include MgO 6-8 wt.%, SiO_2 53-56 wt.%, CaO 8.16-8.85 wt.%, TiO_2 0.85-1wt.%. Karacadağ enclave bearing andesites and dacites have MgO 1.9-4 wt.%, SiO_2 58-64 wt.%, CaO 6-8 wt.%, TiO_2 0.53-0.65 wt.%. In their enclaves, MgO contents range between 4-9 wt.%, SiO_2 values range between 51-59 wt.%, CaO contents are 9-14 wt.%, and TiO_2 values range between 0.56-0.83%wt.%.

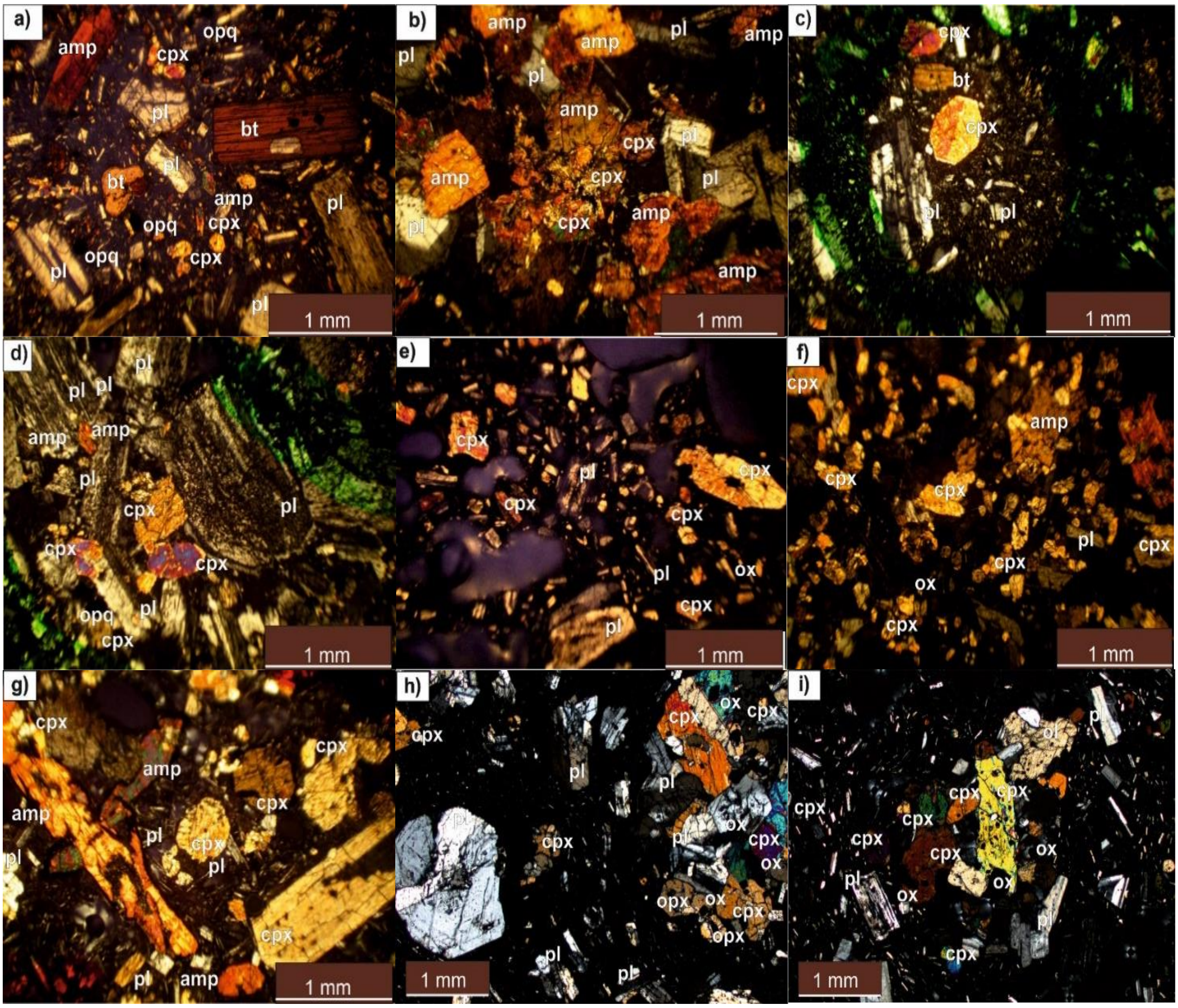

Figure 4. (a) Andesite-1 host rock and (b)its hornblende-gabbro magma segregation enclave with holocrystalline granular texture (Coarse-grained), (c) Andesite-1 host rock and (d) its pyroxene-gabbro magma segregation enclave with holocrystalline granular texture (Coarse-grained), (e) Andesite-1 host rock (vesicular) and (f) its micro-gabbro magma segregation enclave with holocrystalline equigranular texture, and (g) its chilled margins with intersertial texture (fine-grained, also porphyritic), (h) Andesite-3 host rock and (i) its pyroxene-gabbro magma segregation enclave. amph: Amphibole; bi: Biotite; cpx: Clinopyroxene; opx: Orthopyroxene; ox: Fe-Ti oxides; pl: Plagioclase; q: Quartz (Kretz, 1983)

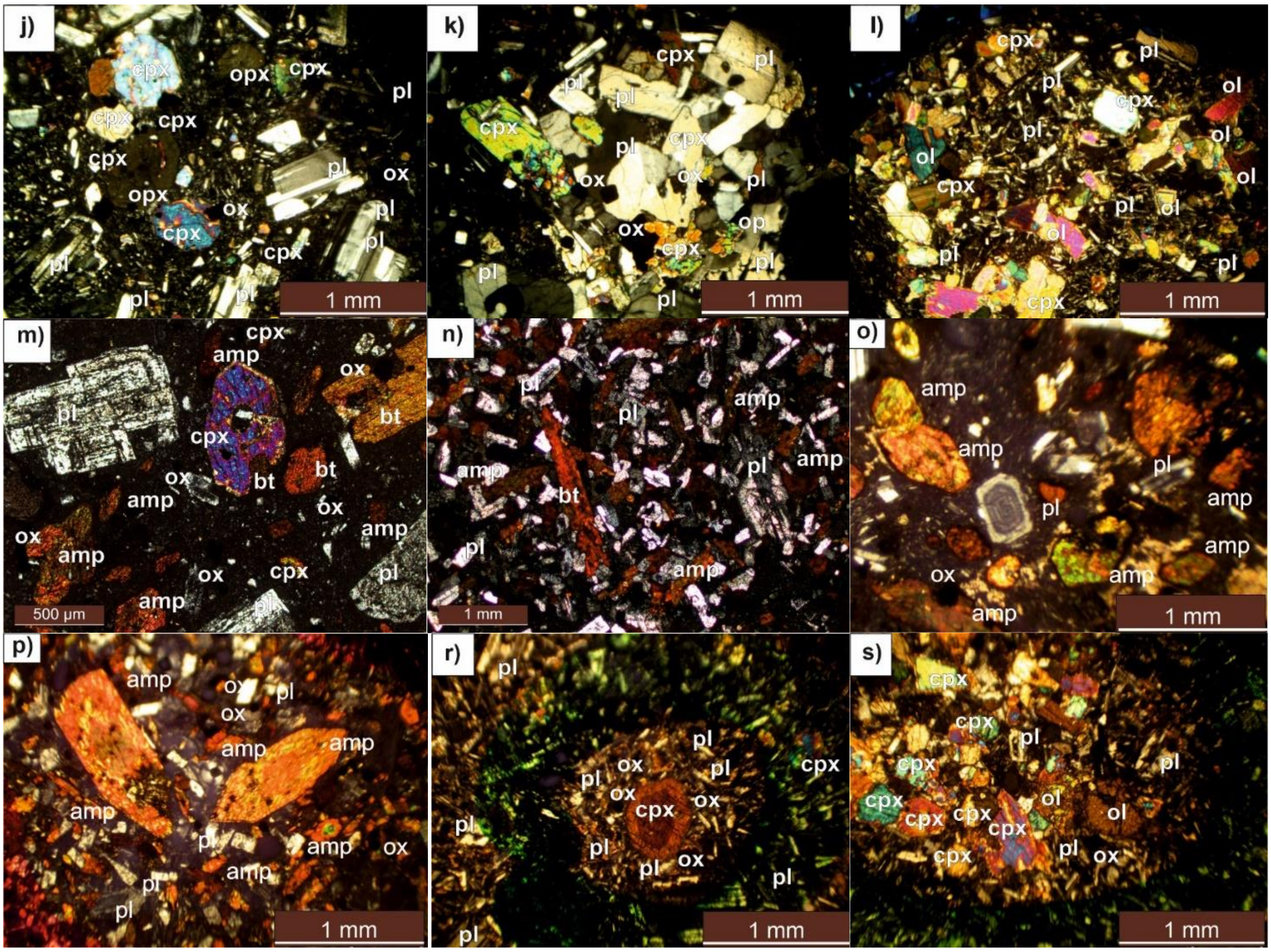

Figure 4.(continued) (j) Andesite-3 host rock (k) pyroxene-gabbro MSE (in Andesite- 3), (l) basaltic MME in the Andesite- 2, (m),(o) Andesite-1 host rock (n), (p) magma mixing enclave with elongated minerals (bladed biotites, quenched amphiboles) in the Andesit-1, (n) magma mixing enclave with elongated minerals and intersertal texture with basaltic composition, (r) basaltic magma mixing enclave in Andesite-2, (s) pyroxene gabbro magma segregation enclave/composite enclave: basaltic MME have enclosed gabbroic magma segregation enclaves

Table 1. Enclaves from the Karapınar-Karacadağ Volcanic Rocks, their main mineralogical contents, and their abundance

KKVR	Enclave Type	Classification	Rock Type (Petrographically	Composition (Enclave)	Abundance
Karapınar Volcanic Rocks	Type-1	MME	Basalt	ol+cpx+pl+ox	%30
	Type-2	MSE	Basalt, Dunite, Clinopyroxenite, Lherzolite	ol+cpx+pl+ox ol+ox cpx+(rare)ol+pl ol+opx+cpx+ox	%60
	Type-3	Xenolith / Xenocrysts	Xenocrysts of Quartz, Plagioclase, Biotite, Amphibole	q/pl/bi/amph	%10
Karacadağ Volcanic Rocks	Type-4	MSE	Amphibole Gabbro	amph+(rare)cpx+pl+ox	%10
	Type-5	MSE	Pyroxene Gabbro	cpx+pl+ox ±amph±ol	%40
	Type-6	MSE	Micro Gabbro	cpx+pl+ox±amph	%10
	Type-7	MME	Andesite	amph+bi+pl+ox	%25
	Type-8	MME	Basalt	ol+cpx+pl+ox	%15

Table 2. The compositional and textural characteristics of the enclaves and their host rocks from the Karapınar-Karacadağ Volcanic Rocks

Host rock/ Symbole	Mineral composition (Host rock)	Texture	Enclave Type/Symbole	Rock type (Enclave)	Enclave Texture	Boundary/Shape
Dacite/ D	Pl+amph+ox+bi+q ±cpx	Hypocrystalline porphyric, glomeroporphyritic texture, cellular and sieve texture (pl)	1. Magma Segregation Enclaves /MSE	1. Pyroxene Gabbro	1. Holocrystalline granular texture-Coarse grained	1. Sharp contact/ elliptical
Andesite-1/ A1	Pl+cpx+amph+ox±bi ±q±ap±zr	Hypocrystalline porphyric, glomeroporphyritic texture, cellular and sieve texture (pl)	1. Magma Segregation Enclaves /MSE 2.Magma Mixing Enclaves /MME	1.a. Amphibole Gabbro 1.b. Pyroxene Gabbro 1.c. Micro Gabbro 2.Andesite	1. Holocrystalline granular texture-Coarse grained 2. Hypocrystalline porphyric, sieve (pl), quenching (amph)-Fine grained	1.a.b. Sharp contact/ elliptical 1.c. Chilled margin/ elliptical 2. Sharp contact/ elliptical
Andesite-2/ A2	Pl+cpx+opx+amph+ bi+olxe+ox±ap±zr	Hypocrystalline porphyric, spongy cellular and sieve texture (pl)	1. Magma Segregation Enclaves /MSE 2.Magma Mixing Enclaves /MME 3. Composite Enclave /C (in 2)	1.Pyroxene Gabbro 2.Basalt 3. Pyroxene Gabbro	1. Holocrystalline granular texture-Coarse grained 2. Holocrystalline porphyric, intersertal, sieve-cellular texture (plg), quenching (amph)-Fine grained 3. Holocrystalline granular texture	1. Sharp contact /elliptical 2. Sharp contact /elliptical 3. Micro-size enclave
Andesite-3/ A3	Pl+cpx+opx+ox±ap ±zr	Hypocrystalline porphyric, glomeroporphyritic texture, cellular and sieve texture (pl)	1. Magma Segregation Enclaves /MSE	1.Pyroxene Gabbro	1. Holocrystalline granular and Holocrystalline porphyitic texture-Coarse grained	1. Micro-size enclave
Basalt-2/ B2	Ol +cpx +pl +ox (±q xe)	Holocrystalline porphyric, texture- hypocrystalline porphyric, glomeroporphyritic, vesicular, cellular and sieve (pl),ocellar (Q)	1. Magma Segregation Enclaves /MSE 2. Xenocrysts and Xenolith /Xe	1.a. Basalt 2.a. q Xenocrysts 2.b. Quartzite Xenolith fragments	1. Holocrystalline granular texture-Coarse grained 2. Ocellar and embayed (q), sieve-cellular (pl)	1a. Sharp contact/ elliptical 1b. Micro-size enclave 2a. Sharp contact 2b. Micro-size enclave
Basalt-3/ B3	cpx+pl+ol+ox (amp±bi±q±plxe)	Hypocrystalline porphyric, glomeroporphyritic, vesicular, amygdaloidal, cellular and sieve (pl), ocellar (Q)	1. Magma Segregation Enclaves 2.Magma Mixing Enclaves /MME 3.Xenocrysts/Xe 4.Composite Enclave/C (in 2)	1.a. Dunite, lherzolite 1.b. Basalt 2.Basalt 3. Q, pl, bi, amph Xenocrysts 4.a. Dunite 4.b. Q, pl, bi, amph Xenocrysts	1.a Holocrystalline granular texture -Coarse grained 1.b. Holocrystalline granular texture-Coarse grained 2. Hypocrystalline porphyric, intersertal -Fine grained 3. Ocellar and embayed (q), sieve-cellular (pl) 4.a Holocrystalline granular texture 4.b Ocellar and embayed (q), sieve-cellular (pl)	1-3-4. Micro-size enclave 2. Sharp contact/ semi-rounded-angular

amph: Amphibole; ap:Apatite; bi: Biotite; cpx: Clinopyroxene; ol:Olivine; opx: Orthopyroxene; ox: Fe-Ti oxides; pl: Plagioclase; q: Quartz; zr: Zircon (Kretz, 1983)

While, some of the Type-1 (MME) enclaves in the Karapınar basalts appear to be primitive with MgO, CaO, Al_2O_3, TiO_2, Hf, V, Ce, others are more evolved than their hosts. It may be elucidated by the effect of crustal contamination on the evolution of the host rocks. MSE enclaves (Type 4-6) from the Karacadağ andesite and dacites generally contain higher Fe_2O_3, MgO, CaO, Cr, Ni, and lower SiO_2, Al_2O_3, TiO_2, Na_2O, K_2O, Ba, Sr, Pb compared to their host rocks (Supplementary Material 1). Some MMEs (Type-7) from the A1 type rocks include higher SiO_2, Al_2O_3, Fe_2O_3, CaO, TiO2, La, Ce, Pb, Zr, Y and lower MgO Ni Th, Cr, Nb compared to their hosts. Furthermore, Type-8 enclaves from the marble cake textured A2 type host rocks contain higher Fe_2O_3, MgO, CaO, TiO_2, Cr, Ni, Sr, V lower Ba, La, Ce, Th, Pb, Zr, Y, Nb than their hosts, and so they are more primitive than their hosts (Supplementary Material 1).

Generally, investigated rocks show enrichment in large ion lithophile elements-LILE (K, Rb and Th) relative to high field strength elements-HFSE (Ta, Nb, Zr, and Hf). Moreover, the Karapınar basalts and the Type-1 enclaves (MME) are in accordance with each other in terms of trace element contents. Although MSEs display much more primitive chemical characteristics than their host rocks, the investigated Karacadağ dacite-andesites and their MSE (Type 4-6) enclaves are in a harmony with each other in MORB normalized (Pearce, 1983) trace element diagrams (Figure 8a, b).

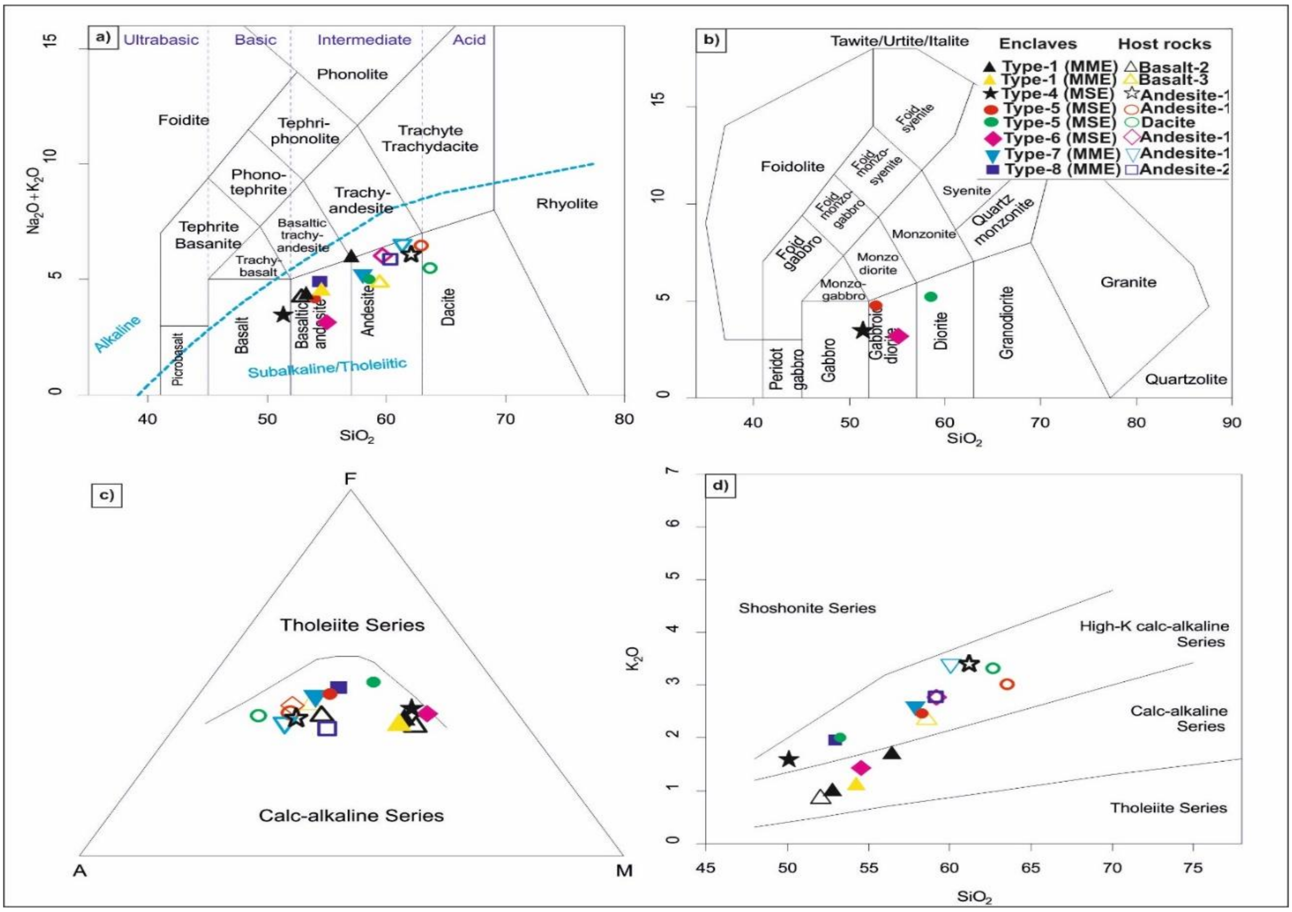

Figure 5. (a) Total alkali-silica (TAS) diagram (Le Bas et al., 1986) of the investigated enclaves and their host rocks, (b) classification of the plutonic rocks (magma segregation enclaves) using the total alkali versus silica (TAS) diagram (Middlemost, 1994), (c) AFM diagram (Irvine and Baragar, 1971) and (d) SiO_2 versus K_2O diagram of the investigated rocks

5. DISCUSSION AND CONCLUSION

Enclaves in the Karapınar volcanites are semi-rounded and angular in shape. However, in the Karacadağ volcanites they are generally ellipsoidal to rounded in shape and rarely display chilled margins, revealing that they were incorporated into their host magmas when they were still in a molten state (Pecerillo, 2005; Poli, 1992).

Bladed biotites, quenched amphiboles, acicular apatites, reverse zoned and sieved plagioclases are widely accepted as evidence of magma mixing processes (Browne et al., 2006; Chappell, 1996; Hibbard, 1991; Kadioglu and Gülec, 1996). Furthermore, a superheating phenomenon (magma mixing/self-mixing/magma replenishment) may bring about the occurrence of the embayed and ocelli-quartz minerals (Kadioğlu and Zoroğlu, 2008; Kumar and Singh, 2014). Investigated Type-1, 7, and

8 enclaves are fine-grained, and contain elongated, bladed, acicular microphenocrysts of mostly plagioclase, biotite and hornblende crystals like porphyritic enclaves in Unzen (Japan) lavas (Browne et al., 2006). Also some of the Karapınar enclave-bearing basalts include embayed-ocelli quartz minerals. They may be probably the product of rapid cooling due to the temperature differences between the more mafic magma intrusions and more evolved host magma (Browne et al., 2006; Kadioglu and Gülec, 1996; Kumar et al., 2004). Combined with similar mineral contents and mineral chemistry data between the MMEs and their host rocks, we report that the MMEs from the Karapınar Karacadağ Volcanic Rocks were formed by mixing of coeval mafic and more evolved magmas (Zhang et al., 2020). However, Type 2, 4, 5, and 6 enclaves are MSEs and equigranular textured enclaves that stemmed from the more prolonged intrusion of the mafic magma within the host magma (Browne et al., 2006). Some of MSEs have chilled margins at the host rock boundary, and contain some vesicles between microphenocrysts, implying rapid quenching as in Type-6 enclave (Figure 4 g) (Browne et al., 2006). The MSEs, which are observed in almost all of the KKVR, are cognate xenolith due to their textural, mineralogical, and chemical properties. Generally investigated MSEs from the Karacadağ andesites are more primitive than their host rock based on their major oxides and minor- trace elements (Figures 5, 6, 7, 8). It supports that MSEs formed by more primitive magma relative to their hosts, and/or were early crystallized phases of the same magmatic system. Similar mineralogical and chemical composition between the MSEs and their host rocks indicate that the host rocks and MSEs were derived from a cognate magma related to earlier phases of the volcanism (Özdamar et al., 2020). Hence, they were probably generated by accumulation and segregation of the early crystallized minerals, and then they were transported by plucking from the different parts of the magma chamber. In recent studies, based on the mineral chemistry data of the plagioclase phenocrysts, it was stated that Karapınar basalts contain a significant amount of plagioclase xenocrysts (Gençoğlu Korkmaz and Kurt, 2021).

In addition, petrographical observations reveal that especially Karapınar calc-alkaline basalts include quartz, plagioclase, amphibole, and biotite xenocrysts (Gençoğlu Korkmaz et al., 2022). Therefore, Type-3 enclaves represented by the sieved-plagioclase, ocelli-embayed quartz, biotite and amphibole xenocrysts in the Karapınar basalts are the xenoliths that were plucked from the wall rock during magma arising.

The coexistence of different types and compositions of enclaves in the same host rock may be probably an evidence of repeated/multiple replenishment processes in the magma chamber. Petrographic observations and major-trace element composition of the rocks suggests that the evolution of the Karapınar and Karacadağ volcanic rocks was dominated by fractional crystallization, with magma mixing and assimilation of the wall rocks.

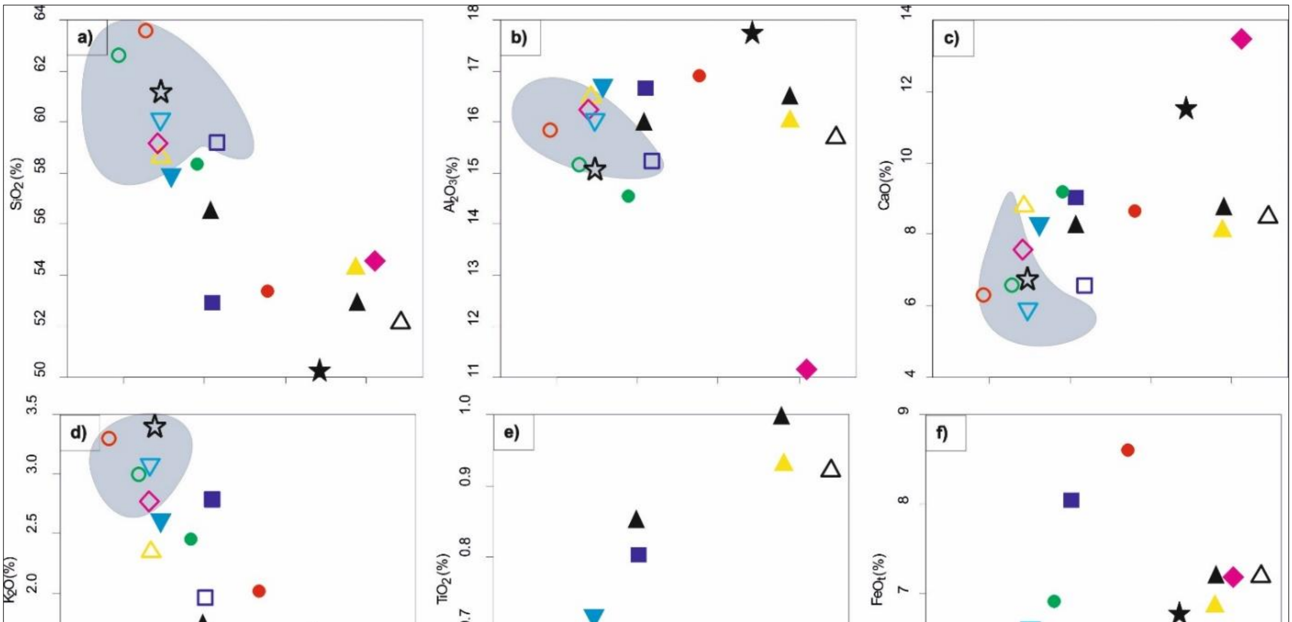

Figure 6. MgO (%wt.) vs. the selected major oxide (%wt.) distribution diagrams of the investigated rocks and their enclaves. The symbols are the same as in Figure 5. Grey-shaded areas represent the general trend of the host rocks

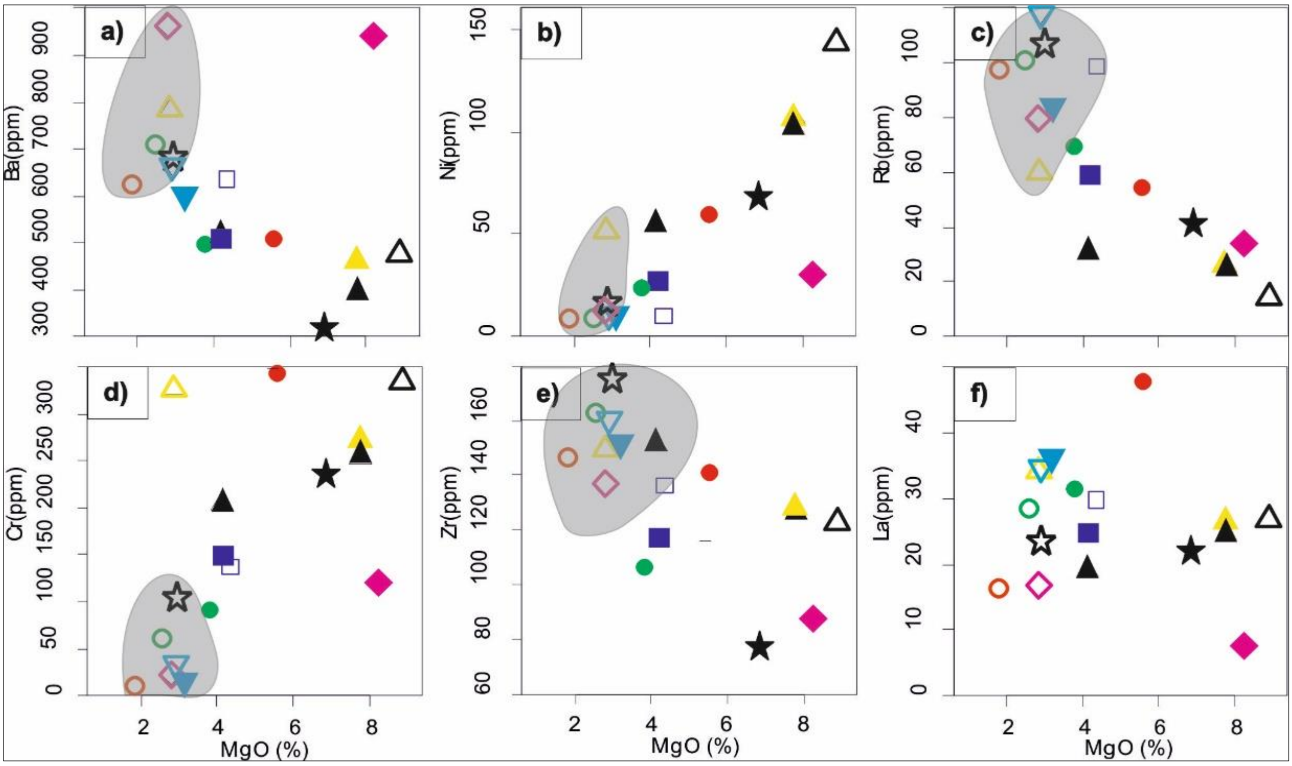

Figure 7. MgO (%wt.) vs. the selected trace element (ppm) distribution diagrams of the investigated rocks and their enclaves. The symbols are the same as in Figure 5. Grey-shaded areas represent the general trend of the host rocks

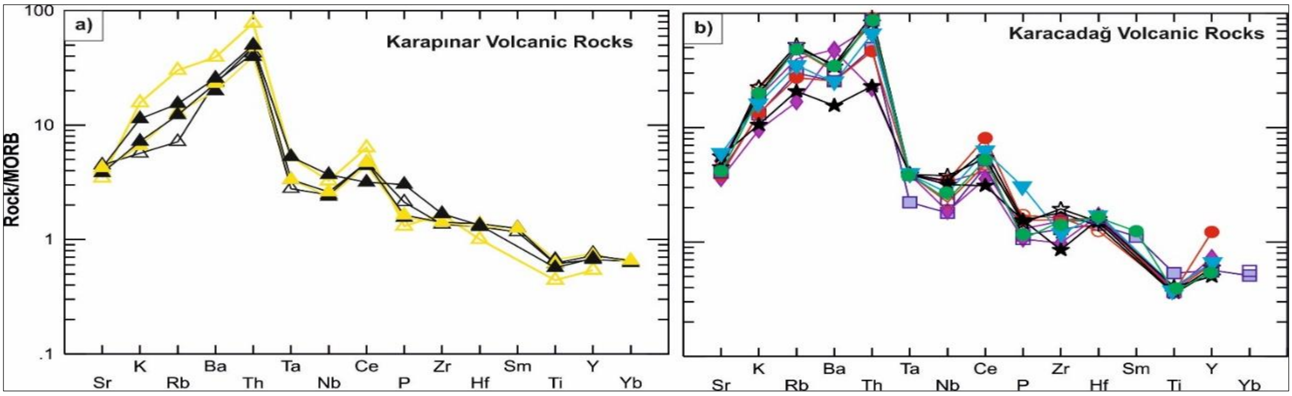

Figure 8. (a)-(b) MORB-normalized (Pearce, 1983) and diagrams of the studied rocks and their enclaves from Karapınar-Karacadağ Volcanic Rocks

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Author Contributions

The authors conceived all parts of the article together. **Gülin Gençoğlu Korkmaz** and **Kürşad Asan** realized the field study and petrographic observation, and Gülin **Gençoğlu Korkmaz**, **Hüseyin Kurt** and **Kürşad Asan** evaluated the geochemical analyses results together.

Conflicts of Interest

The authors declare no conflict of interest.

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Supplementary Material 1. Major and trace element contents of the some of the enclaves and their hosts from KKVR

Sample	Karapınar Volcanics					Karacadağ Volcanics											
	KR28H.	KR28E.	KR21H.	KR21E.	KR21E.2	GK139H.	GK139E.	GK144H.	GK144E.	GK161H.	GK161E.	GK35H.	GK35E.	GK15H.	GK15E.	GK108H.	GK108E.
Major oxides (%wt.)																	
SiO2	58.58	54.24	52.06	52.85	56.49	59.19	54.55	62.65	53.36	63.58	58.33	61.18	50.04	59.15	52.96	60.08	57.9
Al2O3	16.48	16.01	15.66	16.49	15.97	16.23	11.07	15.84	16.88	15.16	14.56	15.02	17.73	15.24	16.68	16.07	16.77
Fe2O3	5.86	7.49	7.79	7.84	6.8	6.51	7.84	5.63	9.39	5.64	7.59	5.77	7.3	6	8.63	5.69	7.29
MgO	2.86	7.77	8.89	7.78	4.14	2.82	8.23	1.87	5.59	2.55	3.84	2.93	6.85	4.36	4.2	2.91	3.15
CaO	8.75	8.09	8.46	8.72	8.15	7.57	13.48	6.29	8.58	6.55	9.16	6.78	11.59	6.56	9.03	5.89	8.36
Na2O	2.45	3.4	3.34	3.26	4.2	3.21	1.69	3.15	2.06	2.49	2.57	2.62	1.75	2.94	2.86	3.04	2.55
K2O	2.35	1.08	0.85	0.99	1.7	2.77	1.43	3.3	2	2.99	2.45	3.38	1.59	2.78	1.96	3.4	2.62
TiO2	0.66	0.93	0.92	1	0.85	0.59	0.57	0.56	0.55	0.53	0.61	0.54	0.61	0.55	0.8	0.6	0.72
P2O5	0.16	0.2	0.26	0.19	0.37	0.16	0.13	0.21	0.19	0.19	0.37	0.18	0.19	0.13	0.14	0.17	0.24
MnO	0.1	0.13	0.13	0.13	0.11	0.12	0.17	0.11	0.22	0.11	0.14	0.1	0.11	0.11	0.14	0.11	0.12
Cr2O3	0.05	0.04	0.05	0.04	0.03	0	0.02	0	0.05	0.01	0.01	0.02	0.03	0.02	0.02	0.01	0
FeOt	5.39	6.83	7.17	7.16	6.23	5.94	7.16	5.11	8.62	5.11	6.9	5.3	6.76	5.55	8.04	5.25	6.62
V2O5	0.02				0.02	0.03	0.04	0.02	0.02	0.02	0.03	0.03	0.03				
SO3	0.27				1.41	0.21	0.16	0.08	0.06	0.07	0.07	0.82	0.33				
Cl	0.03				0.29	0.03	0.02	0.01	0.01	0.04	0.06	0.05	0.06				
Total	98.62	99.38	98.41	99.29	100.52	99.43	99.39	99.73	98.96	99.93	99.8	99.41	98.21	97.84	97.42	97.97	99.71
LOI	1.73	0.3	1.2	0.4	0.33	0.73	0.33	0.32	0.83	0.52	0.42	0.72	0.93	1.9	2.3	1.8	0.63
Trace elements (ppm)																	
Ba	784.7	462	475	397	511.9	964.3	939	620.6	510	707.7	496.9	682.5	311.5	636	508	669	604.6
Ni	51.4	107	143	102	54.5	12.2	30.1	7.1	58	8.4	22.2	16.7	67.9	<20	27	<20	11.6
Co	46.8	33.4	37.8	34.9	72.5	38.4	117	49.4	46.4	56.8	54.1	51.4	46.4	19.5	29	14.7	72.9
Cs	3.9	0.9	0.5	0.7	3.7	3.7	3.8	3.5	5.5	3.8	3.6	3.8	3.5	5.2	2	5.7	
Ga	16	15.9	14.6	15.2	16.3	17.2	15.4	19.8	17.1	19.2	17.1	20.1	19.5	16.6	16.9	16.6	19
Hf	2.4	3.3	3.1	3.1	3.2	3.7	4.1	3	3.9	3.3	4.2	3.6	3.8	3.9	3.4	4.5	5.4
Nb	11.4	9.1	8.6	8.3	12.9	11.7	6.5	7.8	12.1	12	9.4	13.3	11.1	8.2	6.3	9.5	6.5
Rb	60.3	24.5	14.3	25.7	30.7	79.8	33.6	96.6	54.7	100	70.1	105.2	41.6	98.7	60	118.4	84.7
Sn	1.3	<1	<1	<1	1	1.7	1	0.9	1.8	2	3.9	1.8	3.2	<1	<1	<1	1.6
Sr	413.5	457.7	536.6	478.6	508.9	613.3	429.8	532.3	459.9	548.4	707.2	542.4	672.1	485.8	484.1	490.3	641.3
Ta	0.95	0.6	0.5	0.6	0.95	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.4	0.9	1
Th	15.6	9.6	8.5	7.9	10	15.6	4.4	18.2	9.3	19.1	13.2	16.6	4.6	17.3	9.9	20.1	14
U	10.8	2.5	2.3	2	23.2	21.3	15.1	18.3	18	9	20.8	9	13.2	5	3.1	6.3	26.5
V	104.97	125	135	153	10.58	14.05	20.43	13.72	11.87	10.36	19.03	14.39	16.07	152	245	159	17.41
W	31.1	<0.5	<0.5	<0.5	321.8	417.7	672.4	119.2	123.7	235.2	206.6	372	144.3	2.1	1.2	1.9	282.1
Zr	149.6	127.3	122.2	126.3	151	136.9	88.1	145.9	141	162.3	105.4	175.3	76.9	136.3	117.2	160.4	152
Y	16.2	21.7	20	22.6	20.5	19.8	21.9	19.2	36.7	16.7	19.7	17.9	15	16.6	17	18.8	20
La	34.2	26.6	26.8	24.7	19.1	16.8	7.5	16.5	47.8	28.4	31.4	23.1	22	29.8	24.8	34.5	36.5
Ce	63.3	47	47.1	44.1	31.6	41.7	35.6	47.6	81	62.9	62.1	54	31.1	52.1	45.4	62.4	76
Mo	3.1	0.2	1.2	0.3	5.4	12.1	4.3	3.1	6.6	4.2	4	4.2	2.9	0.2	0.7	0.2	6.4
Cu	14.8	24.9	34.3	35.4	35.2	52.2	59.9	30.6	51.7	41.1	69.7	53.6	54.5	44.9	58.4	31.3	127.9
Pb	14.6	2.1	5.9	2.9	9.9	23	12.3	18.4	13.4	23.7	20.6	25.1	12.2	3.1	4	2.5	18.6
Zn	45.2	15	22	23	53.1	56	50.8	44.9	82.3	50.9	56.5	55.3	45.1	26	30	26	60.9
As	0.6	<0.5	1.9	0.8	0.7	2.1	1.3	1.2	0.7	2.6	2.3	3.3	1.9	<0.5	1.4	<0.5	3.6
Cd	0.9	<0.1	<0.1	<0.1	1.7	0.7	0.9	0.8	1.4	0.9	2.8	0.9	0.9	<0.1	<0.1	<0.1	3.3
Sb	0.8	1.1	3.1	2.3	1	0.9	0.9	0.9	1.5	0.9	1	0.9	0.8	1.1	1.4	0.9	1.5
Cr	326.94	253.15	335.25	273.67	205.25	24.29	122.47	7.53	341.41	61.58	90.24	105.36	236.73	136.84	150.52	34.21	8.21