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Field, mineralogical and petrographic features of the micro-vesiculated mafic enclaves in the Miocene lava around Sağlik and Yatağan area, western Konya/Türkiye

Konya'nın (Türkiye) batısında, Sağlık ve Yatağan bölgesinde Miyosen lavları içindeki gazboşlukları içeren mafik anklavların saha, mineralojik ve petrografik özellikleri

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Abstract

Various Mafic Microcrystalline Enclaves (MMEs) occur in variable sizes (from a few cm to a few meters) and shapes (ellipse/rounded-angular) with well-developed chilled margin in lava dome complex as part of the subduction-related Neogene Erenlerdagi volcanic activity at the west of Konya. In/around MME, some angular-rounded space developed, possibly due to shrinking after magma degassing, and sometimes filled by calcite. Petrographical and modal image analysis shows that the micro-vesiculated MME contains plagioclase (10-84 %, 0.09-3.1 mm), amphibole (10-25%, 0.16-1.64 mm), clinopyroxene (7-20%, 0.37-0.77 mm), quartz (0-10%, 0.2-0.6 mm), biotite (0-5%, 0.81-1.63 mm), epidote (0-10%, 0.1-0.7 mm), piemontite (0-9%, 0.17-0.55mm), allanite (0-9%, 0.17-0.55 mm) and opaque iron ore (4-54%, 0.03-0.67 mm) as major constituents with accessory apatite and zircon in a diktytaxitic-like and hypidiomorph granular texture. The MME also contain older and smaller enclaves (MMEs), which are composed of plagioclase (20-82%), brownish amphibole (9-25%), clinopyroxene (5%), quartz (3-10%), epidote (10-25%), and opaque iron ore (10-35%) in a diktytaxitic-like texture. MMEs are suggested to be formed by syn-eruptive mafic (basaltic?) magma underplating of a dacitic magma reservoir at the lower crust, possibly triggering the eruptions of silicic domes by an overpressure build-up.

Keywords: Enclave, Image analyse, Konya, Mingling, Miocene, Volcanism

Öz

Konya'nın batısında, dalma-batma ile ilişkili Neojen Erenlerdağı volkanik aktivitesinin bir parçası olarak lav dom kompleksinde, iyi gelişmiş soğuma zonları içeren, değişken boyutlarda (birkaç cm'den birkaç metreye kadar) ve şekillerde (elips/yuvarlak-açılı) çeşitli Mafik Mikrokristalli Anklavlar (MMEs) oluşurlar. Magmadan muhtemelen gazın ayrılmasından sonraki büzülme nedeniyle, bazen kalsit ile doldurulmuş olan MME'nin içinde/etrafında bir kısım köşeli-yuvarlak boşluklar gelişmiştir. Petroğrafik ve modal görüntü analizi, mikro-boşluklu MME'nin diktitaksitik benzeri ve yarıözşekilli tanesel doku içinde plajiyoklaz (%10-84, 0.09-3.1 mm), amfibol (%10-25, 0.16-1.64 mm), klinopiroksen (%7-20, 0.37-0.77 mm), kuvars (%0-10, 0.2-0.6 mm), biyotit (%0-5, 0.81-16 mm), epidot (%0-10, 0.1-0.7 mm), piemontit (%0-9, 0.17-0.55 mm), allanit (%0-9, 0.17-0.55 mm) ve opak demir cevheri (%4-54, 0.03-0.67 mm) ile tali apatit ve zirkon içerdiğini göstermektedir. MME ayrıca, diktitaksitik benzeri bir dokuda plajiyoklaz (%20-82), kahverengi amfibol (%9-25), klinopiroksen (%5), kuvars (%3-10), epidot (%10-25) ve opak demir cevherinden (%10-35) oluşan daha yaşlı ve daha küçük anklav (MME) da içerir. MME' ların, muhtemelen aşırı basınç birikimiyle silisik domların püskürmelerini tetikleyen, püskürme eş zamanlı mafik (bazaltik?) magmanın alt kabukta dasitik bir magma rezervuarının altına girmesi ile oluştuğu ileri sürülmüştür.

Anahtar kelimeler: *Anklav, görüntü analizi, Konya, mingling, Miyosen, volkanizma*

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1. Introduction

A collision between Eurasia and Arap plates marks the Neotectonic stage in Anatolia, which resulted in the development of East and North Anatolian faults (Dewey et al., 1986; Şengör et al., 1985) and widespread volcanic activity such as cover 85.000 km^2 in central and west Anatolia (Ketin, 1983). Consequently, various volcanic and volcaniclastics were formed with predominant calk alkaline affinity in a region between Konya, Beyşehir and Seydişehir (Figure 1). Blumenthal (1944), Brennich (1955), Niehoff (1961) and Üstündağ (1987) have made significant contributions to understanding the area's geological features. Their work has led to notable findings, including the identification of Tertiary rocks, the proposal of an Ordovician metamorphic basement on a geological map, and the suggestion of a tectonic phase occurring between the Palaeozoic and Mesozoic in the Konya and Akşehir regions. Further investigations performed by Özcan et al. (1988), Eren (1993), and Hekimbaşı (1996) have shown the presence of the "Bozdağ formation," a Pre-Triassic region, and have provided detailed information on the stratigraphic units in the Karadag area. Keller et al. (1977) carried out dating of volcanic rocks, while Temel et al. (1998) suggested a connection between calc-alkaline volcanism in Konya and the subduction of the African plate during the Middle-Late Miocene. Karakaş & Kadir (2000) determined crystallisation patterns, and Kurt et al. (2003) suggested that subduction is substantial in the petrogenesis of volcanic rocks. Karakaya (2009) documented the effects of hydrothermal alteration, emphasising significant enrichment in altered rocks exhibiting kaolinitic and alunitic alteration. Kocak & Zedef (2016a) analysed the geochemical characteristics of lava and its enclaves in the region, suggesting that Mafic Microcrystalline Enclaves (MMEs) might have originated through the hybridisation of mafic magma physically mixed with partially crystallised felsic magma. Uyanık & Koçak (2016) studied Neogene Erenlerdağı volcanism, proposing that the volcanic formations likely formed through Assimilation-Fractional Crystallization (AFC) and/or magma mixing processes. Koçak (2023a) describes the primary petrographical characteristics of the enclaves, as observed in the limited thin sections.

Volcanic activity in the region spanned from 16.11 to 3.35 million years ago, as documented by Keller et al. (1977) and Asan & Erturk (2013) while the lava domes are dated to between 10.9 and 3.35 million years (Keller et al., 1977). Korkmaz et al. (2017) investigate the genesis of bimodal basalt-dacite volcanism in the Yükselen area, NW Konya, Central Anatolia, using $^{40}Ar/^{39}Ar$ geochronology, mineral chemistry, elemental, and Sr-Nd-Pb isotope geochemistry, revealing that the basalts originated from an enriched asthenospheric mantle source, while dacites formed by partial melting of the lower crust, both influenced by slab roll-back and break-off processes during the convergence of the African and Anatolian plates. Koçak (2023b) outlines only the petrographical characteristics of the samples without providing detailed information about them.

Situated east of Sağlık town and west of Yatağan in western Konya, the study area includes two rock quarries excellent for examining the interactions between Neogene lava and its MMEs. This study aims to determine the field, geological, and petrographical characteristics of the mafic enclaves forming within the Neogene lava (Figure 1).

The MME form as large bodies within the lava, which vary in size (from a few centimetres to several meters) and shape (ellipse/rounded-angular). The contact between MMEs and host rocks varies from sharp to transitional. The MME has a well-defined chilled margin, suggesting that it quenched quickly in contact with its host (Figure 2). Some enclaves have smaller enclaves (less than 15 cm in diameter), “enclave in enclave”. The smaller MMEs tend to be finer-grained and more uniform. Angular-rounded space developed in and around MME (Figure 3), possibly because of shrinking after magma degassing, and sometimes filled by calcite. The study aims to characterize the field, geological, and petrographical attributes of the MMEs, while also determining mineral sizes and modal mineralogical composition using the "Kameram" software.

2. Material and methods

Around 100 samples were collected, and thin sections were prepared from 70 of them. Thin sections were studied to determine their mineralogical and petrographical characteristics under a polarizing microscope at the Department of Geological Engineering, Konya Technical University. An image processing software called Kameram determined the samples' modal mineralogical composition and the size of their constituents.

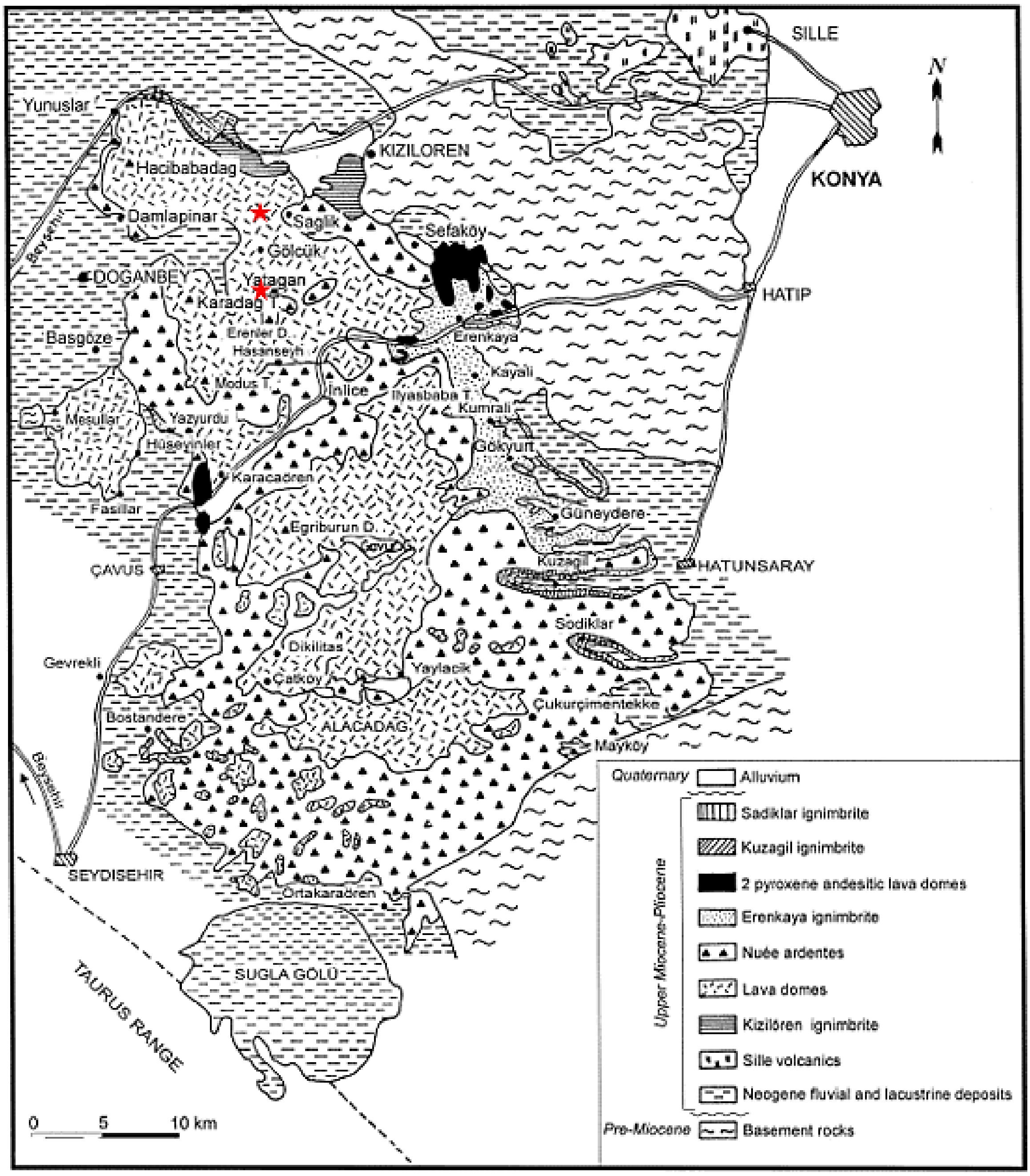

Figure 1. Location and geological maps of the study area (Keller et al., 1977). ★ : Rock quarries studied.

Figure 2. a) Enclaves formed as dyke in the volcanics to the west of Sağlık. b) A dark-coloured chilly zone (c) developed between enclaves (e) and their host (h). The long axis of the enclave is about 45 cm in length.

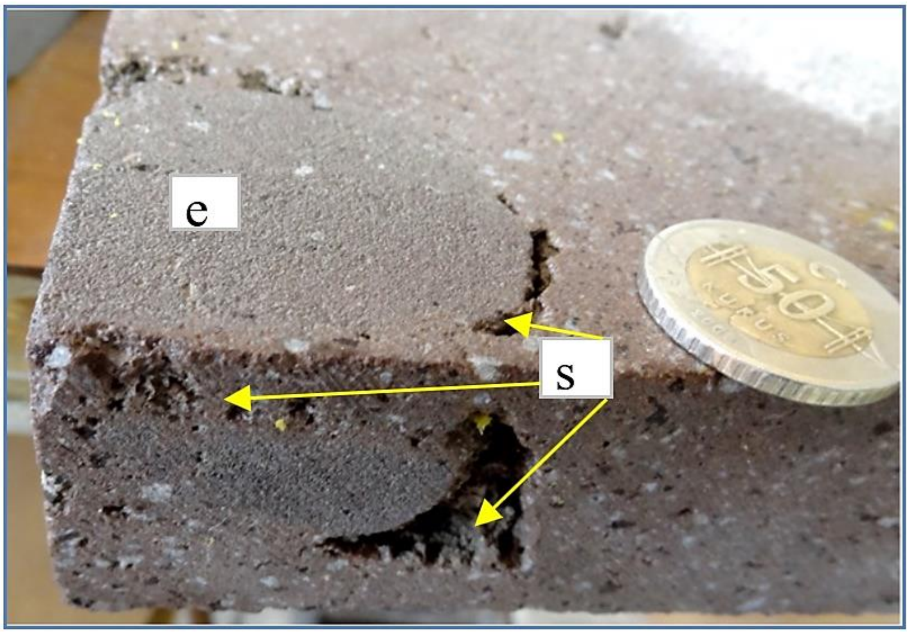

Figure 3. **S**pace (s) formed between MME and its host**.**

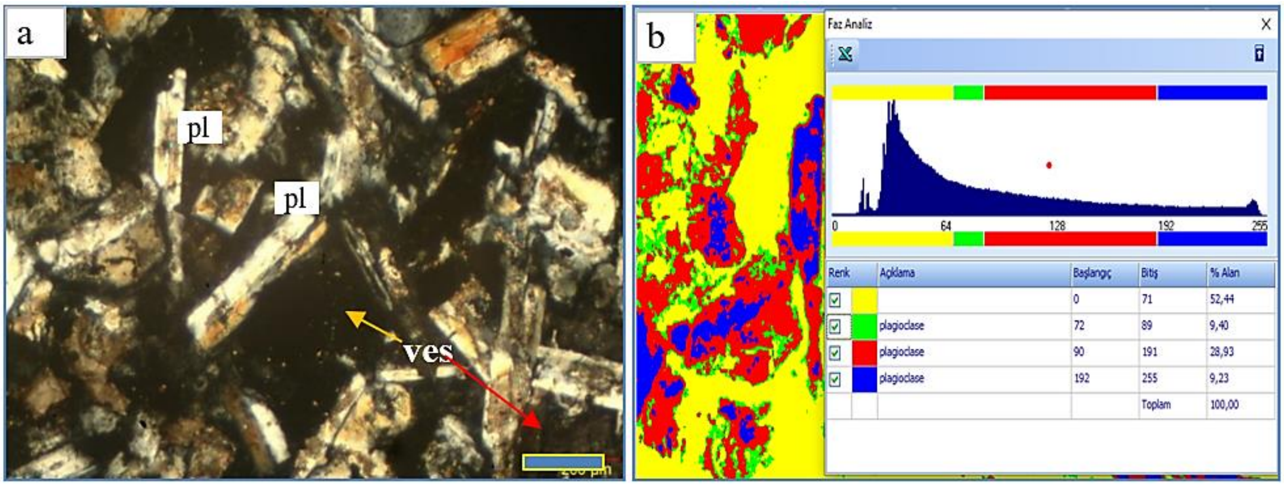

Figure 4. a) MME (XN) and its modal composition (b) determined by Kameram. pl: plagioclase (abbrevations are from Warr (2021), ves: vesicule. The scale bar is 0.1 mm.

3. Petrography

The MME contains plagioclase (10-84%, 0.09-3.1 mm), amphibole (10-25%, 0.16-1.64 mm), clinopyroxene (7-20%, 0.37-0.77 mm), quartz (0-10%, 0.2-0.6 mm), biotite (0-5%, 0.81-1.63 mm), epidote (0-10%, 0.1-0.7 mm), piemontite (0-9%, 0.17-0.55mm), allanite (0-9%, 0.17-0.55 mm) and opaque iron ore (4-51%, 0.03-0.67 mm) as major constituents with accessory apatite and zircon (Figure 4) in a diktytaxitic-like texture (Figure 4-5) constituted by common angular interstitial gas cavities between the plagioclase laths and rare hypidimorphic granular texture. On a microscale, some space has developed between MME and its host as a line, partially filled with calcite. Alteration processes also cause the crystallisation of chlorite (up to 40%) and epidote crystals. The MMEs are suggested to have a basalt-andesite chemical composition (Kocak & Zedef, 2016a).

The plagioclase crystal is mostly subhedral displaying tabular to acicular and rare skeletal texture. It shows various twinnings, e.g. polysynthetic, Albite-Carlsbad, patchy and rare flame (Figure 5). It also indicates sieved and oscillatory-zoned textures. The rim zones usually have clear resorption surfaces. Sericitization and saussuritization are common alteration processes in the plagioclase. The plagioclase phenocrysts appear to be concentrated at the contact between MME and its host.

The subhedral amphibole crystals are typified by strong pleochroism in the shades of green colour. The alteration process results in the development of an opacitic rim, a Fe-enrichment (opacification) with a typical brownish colour and the crystallisation of the epidote along its cleavage.

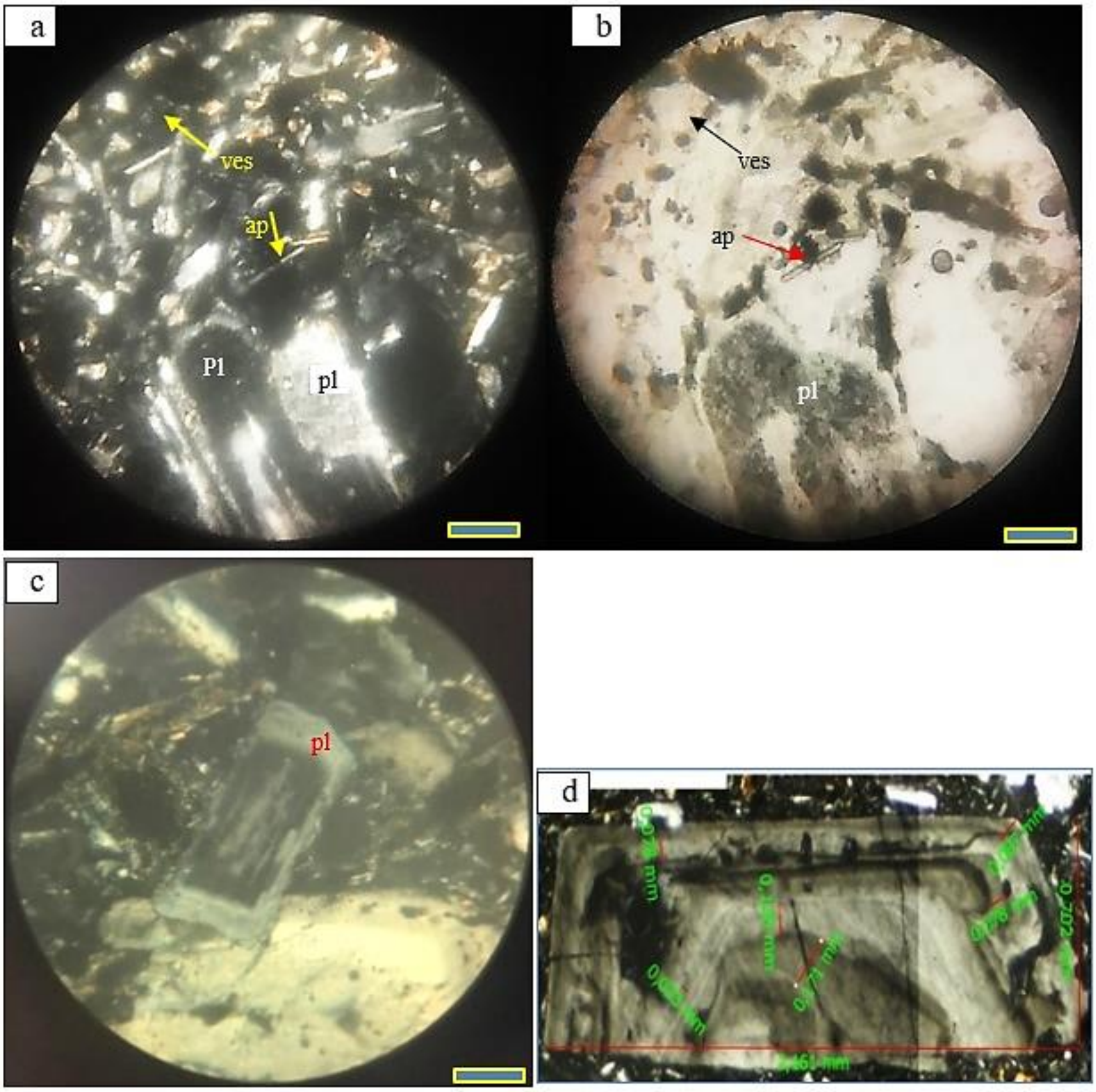

Figure 5. Plagioclase crystals in the mafic enclaves; a-b) Subhedral plagioclase with dusty-sieved rim, and apatite needle. c) Patchy twinning in plagioclase with irregular resorption surface. d) large plagioclase phenocryst with oscillatory zoning. The scale bar is 0.2 mm. a,c,d: polarised light, b: ordinary light. pl: plagioclase, ap: apatite.

The clinopyroxene (0.26 mm) is mostly subhedral and contains opaque iron ores at its core.

The biotite and epidote are infrequent in the samples. The biotite is mostly subhedral with a brownish colour and pleochroism. It has reaction rims and includes plagioclase as inclusion (0.25-0.44 mm).

The reddish piemontite (0-9%, 0.17-0.55mm) and brownish allanite (0-9%, 0.17-0.55 mm) crystals also form in the samples (Figure 6).

Some enclaves are angular in shape and contain plagioclase (0.08-0.5 mm, Figure 7), opacified brownish biotite (0.22-0.32 mm), amphibole (0.71 mm) and opaque iron ore (0.23 mm). A modal analysis by Kameram image processing software shows that plagioclase is about ~46%, and the others (biotite, amphibole and opaque iron ore) are about 54%.

The plagioclase is fresh, without sieve texture. The large one is subhedral to anhedral while the smaller ones appear to be euhedral. Some epidote and clinopyroxene crystallisations exist in opaque and plagioclase crystals, respectively.

Petrographic examinations reveal that an older enclave (*MME*) also exists, "enclave in enclave" (Figure 8) between the MME and its host. The *MME* is finer-grained and composed of plagioclase (20-82%), brownish amphibole (9-25%), clinopyroxene (5%), quartz (3-10%), epidote (10-25%) and opaque iron ore (10-35%) in a diktytaxitic-like texture. The plagioclase shows both polysynthetic twinning and a zoned texture, while the pyroxene ranges from colourless to slightly pleochroic, displaying shades of light green.

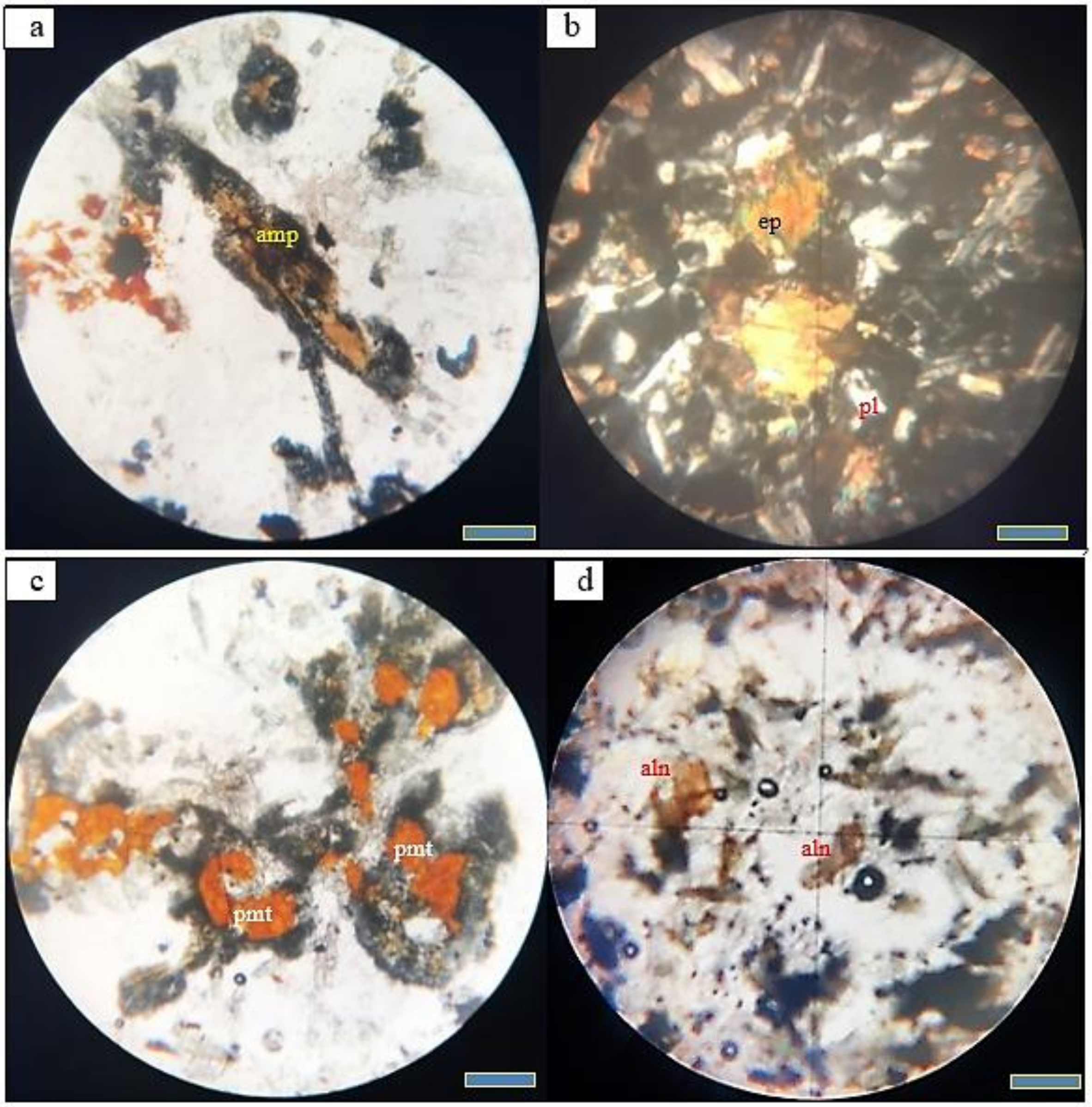

Figure 6. a) the altered amphibole (amp), b) epidote (ep), c) piemontite (pmt) , d) allanite (aln). b: polarised light, a,c-d: ordinary light, Scale bar is 0.2 mm

4. Discussion

Petrographical and modal image analysis reveal that the micro-vesiculated MME is composed of plagioclase (10-84 %, 0.09-3.1 mm), amphibole (10-25%, 0.16-1.64 mm), clinopyroxene (7-20%, 0.37-0.77 mm), quartz (0-10%, 0.2-0.6 mm), biotite (0-5%, 0.81-1.63 mm), epidote (0-10%, 0.1-0.7 mm), piemontite (0-9%, 0.17-0.55mm), allanite (0-9%, 0.17-0.55 mm) and opaque iron ore (4-54%, 0.03-0.67 mm) as major constituents, and accessory apatite and zircon in a diktytaxitic-like and hypidiomorph granular texture.

The samples exhibit various disequilibrium textures, such as opacitic rims around amphibole and biotite, resorption surface in plagioclase and patchy zoning. Opacitic rims are common in hydrated minerals such as biotite or amphiboles in volcanic rocks. Amphibole breakdown can occur due to several factors, including (1) rising temperatures, (2) gradual magma ascent and decompression, and (3) reduced water content and oxygen fugacity in the melt (Ridolfi, 2008).

In an experimental work, (Feeley, 1996) suggest that the transformation of biotite phenocrysts into anhydrous minerals (e.g. plagioclase, magnetite) as a rim implies a rise in thermal conditions or a renewal of the magma chambers. The breakdown of biotite crystals and the development of reaction rims are suggested to be determined by the bulk composition and temperature of the surrounding lava, as well as the water content within the biotite crystals.

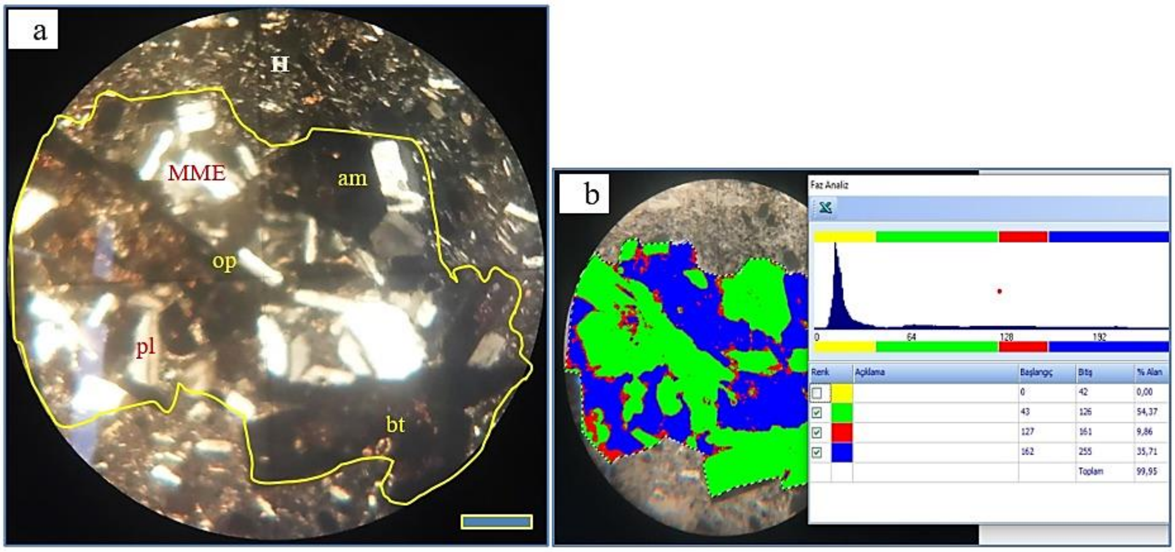

Figure 7. a) MME and host lava (h) a-b: polarised light, pl: plagioclase, bt: biotite, am: amphibole Scale bar is 0.2 mm. b) its modal analysis by kameram software. Green : opaque iron ore, biotite and amphibole. Blue: plagioclase.

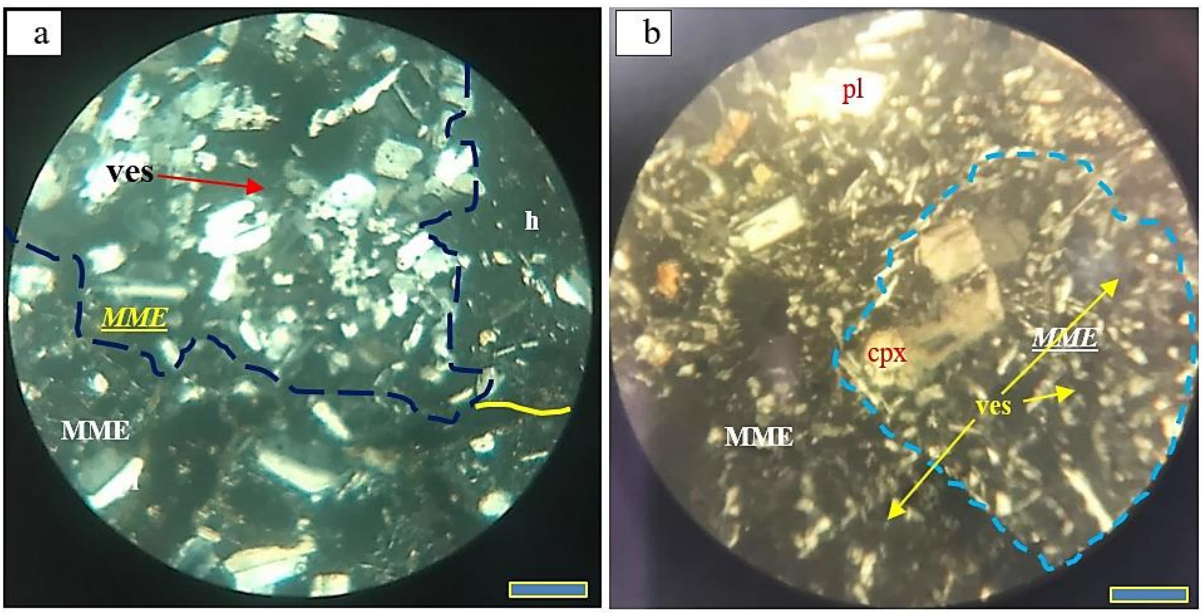

Figure 8. a) Contact between MME, host (h) and *MME*. b) Contact between MME and *MME*. cpx: clinopyroxene, pl: plagioclase. ves: vesicule. a-b: XN., The scale bar is 0.2 mm**.**

Resorption surfaces in plagioclase are widespread in volcanic and plutonic rocks, often followed by the crystallization of plagioclase with higher anorthite content. Major resorption surfaces and the subsequent increase in An content result from changes in crystallization conditions, such as increased temperature, higher water concentration in the melt, decreased pressure, or changes in magma composition. These changes are often induced by the intrusion of more mafic magma into the magma chamber where plagioclase crystallizes (Kocak, 2011; Shcherbakov, 2011).

The plagioclase exhibits patchy zoning which is believed to have developed through the dissolution of the crystal centre due to decompression, then subsequent feldspar crystallization adjusting to the new conditions (Vernon, 2004) or due to the interaction between two compositionally distinct systems, such as felsic and mafic magmas (L'Heureux, 1994), as well as due to elevated H_2O levels during the crystallization process of plagioclase (Cao, 2019). The plagioclase also shows euhedral to rounded sieved textures which are interpreted to be formed by magma mixing and mingling processes (Nakamura, 1998).

The samples contain epidote group minerals like epidote, orthite, and piemontite. Epidote is common in the Earth's crust, especially in metamorphic settings (Liou, 1993). It also occurs in skarns, altered volcanic rocks, and late-stage veins linked to silicic intrusions under lower-pressure hydrothermal conditions (Lindgren, 1933; Nakovnik, 1963). The composition of epidote, particularly its Fe^{3+} content, is significantly influenced by oxygen fugacity. Higher oxygen fugacity levels stabilize Fe-rich variants of epidote, whereas under reducing conditions approaching the quartz-fayalite-magnetite equilibrium, Al-rich epidote forms. Piemontite is rarely found in intermediate and acidic volcanic formations (Deer, 1986; Guild, 1935), and within active geothermal systems. Experimental studies and field observations highlight that high oxygen fugacity is crucial for stabilizing piemontite. Factors such as hydrothermal buffering and pre-existing minerals that maintain high oxygen levels influence this stability (Keskinen, 1987). Mineralogy of the samples suggests that the epidote group minerals in the samples are more likely to be formed by hydrothermal activities in high oxygen fugacity after the primary magmatic processes, rather than being a direct product of magma crystallization.

The extensive fine grain size in the enclaves and the lack of cumulate texture suggest they are not cumulate (Barbarin, 1992). These enclaves cannot be classified as restite due to the absence of minerals like sillimanite, andalusite, cordierite, garnet, or residual minerals formed through mica dehydration melting. Additionally, their distinct characteristics, such as subspherical in shape, existence of enclave in enclave (*MME*), contact morphologies (like phenocrysts of host lava partially enclosed in MMEs and the host lava magma), and igneous micro textures featuring abundant, strongly zoned, euhedral crystals and acicular apatite, may indicate that the MMEs may be fragments of a mafic component added continously to intermediate or felsic magma chambers (Didier, 1991). The acicular apatite is frequently observed in dark-melt droplets that enter silica-rich magmas and are often regarded as indicators of cooling (Wyllie, 1962).

The enclaves tend to form when there are substantial variations in temperature and viscosity between the host and injected magmas, a higher ratio of silicic magma compared to mafic magma, and the injection of smaller volumes (Andrews, 2014). The existence of clear quenched margins on the enclaves indicates a substantial temperature contrast between mafic and host magma. The presence of chilled margins and numerous interstitial voids within the enclaves indicates that these enclaves were likely emplaced into the dacite as liquid masses (Clynne, 1999; Saito, 2003). These textures, however, also imply relatively rapid heat transfer and quenching. The high vesicularity observed suggests that they may be permeable to gas flow and melt percolation.

Enclave shapes suggest valuable information regarding the distance between the mixing site and the observation point. Angular enclaves are typically seen as solid blocks that have fragmented and been transported with minimal alteration in shape. In contrast, rounded enclaves are generally thought to originate from angular enclaves that have been rounded by the host magma, similar to how erosion works in sedimentary processes, and/or transported over considerable distances (Didier, 1987). Accordingly, (Chen, 1990) interpreted the roundness of enclaves as evidence of abrasion. However, a rounded enclave shape doesn't always come about just from mixing, rubbing, or altering the surrounding magma. It can also be an inherent characteristic of an enclave (Bedard, 1993). Coexistence of angular to rounded anclave may support this suggestion.

In summary MMEs suggest mingling processes perhaps during replenishment by a mafic magma into a felsic magma, possibly triggering a volcanic eruption. This is resulted by development of sieve texture, amphibole and biotite reaction rims and acicular apatite. The intrusion of denser basalt into a lighter reservoir probably generated viscous gravity currents along the floor. Forcible mafic intrusion into a felsic magma chamber can induce fountaining, correlating with increased local shear rates (Campbell, 1986). Recent experimental findings (Laumonier, 2014) indicate that under moderate-to-low shear rates, the presence of bubbles indicated by diktytaxitic-like texture in the samples, can significantly reduce the shear viscosity of magmas, with a 10% bubble volume fraction potentially lowering viscosity by up to four orders of magnitude.

Fluid dynamical analyses and observational data (Sparks, 1977; Bacon, 1986) suggest that in calc-alkaline reservoirs, mixing and mingling are most likely initiated by boundary layer instabilities (Eichelberger, 1980) at centimeter to decimeter wavelength scales (Bacon, 1986) or by the disintegration of injected magma dykes (Hodge, 2012), which is observed in the study area. The quenching process, characterized by skeletal and acicular microphenocrysts of plagioclase (Lofgren, 1974) and acicular apatite (Wyllie, 1962), which suggest rapid crystallisation under undercooled conditions (Coombs, 2003).

Orogenic settings are regions where mafic magmas from the mantle interact with the continental crust, allowing them to mix with felsic magmas from the crust (Donaldson, 2003). When these magmas interact and create a uniform blend, an intermediate hybrid magma is produced, a process known as mixing (Sklyarov, 2006; Kocak, 2016). Conversely, if the interaction leads to an uneven mixture, mafic magma bubbles, or microgranular enclaves, develop within the felsic magma, a process referred to as mingling (Kocak, 2006, 2011, 2016). The mafic enclaves come from earlier magmatic stages, such as intrusive bodies or cumulates in the magma chamber or reservoir and mix with the subsequent magma (Sellés, 2004; Buriánek, 2019; Sen, 2023) in subduction-related volcanic rocks.

5. Conclusions

Consequently, the injection of hotter mafic magmas (possibly basaltic) at the bottom of the dacitic-andesitic magma chamber in the lower crust may have triggered the eruptions of silicic domes scattered throughout the volcanic province, as evidenced by the widespread presence of mafic enclaves within these extrusive products with various disequilibriom textures. The eruption is initiated by an overpressure build-up, which is not solely caused by the expansion due to magma injection and felsic magma vesiculation in the chamber, but also by the release of volatile gases from the mafic layer, as evidenced by space developed in/around the MMEs.

Declaration of Ethical Standards

Author follows all ethical guidelines including authorship, citation, data reporting, and publishing original research.

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