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The origin and emplacement dynamics of the volcaniclastic and sedimentary clastic dykes in volcanic fields: a case study from the Erenlerdağ-Alacadağ Volcanic complex (Konya-Türkiye)

Volkanik sahalarda yer alan volkaniklastik ve sedimanter klastik daykların kökeni ve yerleşim dinamikleri: Erenlerdağ-Alacadağ Volkanik kompleksinden (Konya-Türkiye) bir durum çalışması

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Abstract

Distinguishing a volcaniclastic dyke from a sedimentary clastic dyke is one of the major tasks in volcanological field studies due to its different origins. As a volcaniclastic dyke, pyroclastic dykes have great importance in locating volcanic vent facies for ignimbrite-forming eruptions. Here, our purpose is to determine the origin of clastic dykes and find the vent facies for ignimbrites from the Mio-Pliocene Erenlerdağ-Alacadağ Volcanic Complex (ErAVC), Central Anatolia. The ErAVC covers a large area in the southwest of Konya (Central Anatolia, Türkiye) and shows unimodal character. The ErAVC consists of calc-alkaline basaltic-andesite (enclaves), andesite, dacite, and rarely rhyolite. It comprises mainly lava domes/lava flows and their volcaniclastic counterparts (block and ash flows, ignimbrites). The ignimbrites (Erenkaya-1, 2, and 3) compositionally range from andesite to dacite. Clastic dykes cut the Erenkaya ignimbrites in three different locations along the northeast of the ErAVC. The first group of these dykes consists of mainly very fine-grained ash-size material and lithic-rich wall side facies, exhibiting characteristics of a pyroclastic dyke emplaced by the fluidization of volcaniclastic materials. The other one, which is fine-grained material from the edges, while the middle part contains very coarse (block-sized) and dense pumice components. Field studies show that this dyke was emplaced by post-volcanic secondary processes (e.g. sedimentary clastic dyke) as a fissure fill. These clastic dykes indicate that a caldera collapse process in the north of the ErAVC may form the Erenkaya ignimbrites.

Keywords: Volcaniclastic and Sedimentary clastic dykes, Pyroclastic rocks and Ignimbrites, Volcanostratigraphy, Erenlerdağ-Alacadağ Volcanic Complex, ErAVC.

Öz

Volkaniklastik bir daykın sedimanter klastik bir dayktan ayırt edilmesi, farklı köken ve yerleşimleri nedeniyle volkanik saha araştırmalarının ana konularından biridir. Volkaniklastik bir dayk olan piroklastik dayklar, ignimbirit oluşturan patlamalar için volkanizmanın merkezi fasiyesinin belirlenmesinde büyük öneme sahiptir. Bu çalışmadaki amaç, Orta Anadolu'daki Miyo-Pliyosen Erenlerdağ-Alacadağ Volkanik Kompleksi'ndeki (ErAVK) kırıntılı dayklarının kökenini belirlemek ve ignimbiritlerin çıkış (merkezi) fasiyesini tespit etmektir. ErAVK, Konya'nın güneybatısında (Orta Anadolu, Türkiye) geniş bir alanı kaplar ve unimodal bir jeokimyasal karakter gösterir. ErAVK kalk-alkali bazaltik-andezit (anklavlar), andezit, dasit ve nadiren riyolitten oluşur. ErAVK, domlar/lav akıntıları ve bunların volkaniklastik eşleniklerinden (blok ve kül akıntıları ve ignimbiritler) meydana gelir. İgnimbritler (Erenkaya) bileşim olarak andezitten dasite kadar değişmekte olup kırıntılı dayklar, ErAVK'nin kuzeydoğusunda Erenkaya ignimbiritlerini (Erenkaya-1, 2 ve 3) üç farklı noktada kesmektedir. Bu kırıntılı dayklardan ilk ikisi çoğunlukla ince taneli kül boyutunda malzemeden oluşmakta olup kenar fasiyeslere doğru litikçe zengindir ve volkaniklastik malzemelerin akışkanlaşmasıyla yerleşen piroklastik dayk özelliği göstermektedir. Diğer dayk ise kenarlarından itibaren ince taneli ve kül boyutundaki malzemeden oluşurken, orta kısmı oldukça iri (blok boyutunda) ve yoğun pomza bileşenleri içermektedir. Saha çalışmaları, bu ikinci daykın volkanizma sonrası ikincil süreçler (örneğin sedimanter klastik dayk) ile ilişkili çatlak dolgusu şeklinde olduğunu göstermektedir. Bu kırıntılı dayklar, Erenkaya ignimbiritlerini oluşturan volkanik faaliyetin ErAVK'nin kuzeyinde meydana gelen bir kaldera çökme süreci ile ilişkilendirilebileceğini ortaya koymaktadır.

Anahtar kelimeler: Volkaniklastik ve Sedimanter klastik dayklar, Piroklastik kayalar ve İgnimbiritler, Volkanostratigrafi, Erenlerdağ-Alacadağ volkanik kompleksi, ErAVK.

1 Introduction

Clastic dykes, including volcaniclastic and sedimentary clastic dykes develop through volcanic or sedimentary processes in various geological settings (e.g., subaqueous to subaerial, phreatomagmatic to magmatic explosions). Sedimentary clastic dykes can be simply separated into two categories such as ''neptunian dykes'' and ''injection dykes''. However, volcaniclastic dykes are more complex and diverse [1 and reference therein]: (1) Pyroclastic dykes (e.g., PD) related to ignimbrite-forming eruptions, (2) Phreatomagmatic pipes, diatremes, and kimberlite pipes, (3) Peperite dykes, and (4) Intrusive breccias (e.g. tuffisite). Of these, PDs are of prime interest in modern volcanology because they provide strong evidence for the vent location of ignimbrite-forming eruptions. Although gas-fluidization (e.g., an upward flow of gas exerts a

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drag force that partially supports clasts so that the dispersion behaves like a fluid) is thought to be one of the main mechanisms for the formation of PDs, its role is not well understood. Thus, this study aims to demonstrate the relationship between the ignimbrite-forming eruption center and clastic dykes in a volcanic field. In addition, a new practical classification scheme is proposed for the clastic dykes in volcanic fields based on the previous studies.

Despite different emplacement characteristics and their importance, studies on volcaniclastic dykes are underestimated due to their rarity in nature [1]-[6]. However, volcaniclastic dykes provide a good opportunity to examine processes and mechanisms that accompany subaerial magmatic explosions. Therefore, they are a guide in determining volcanic centers and subsequent processes. For example, Motoki et al. (2012) suggested two different stages for the relationship between eruption vent and volcaniclastic dyke emplacements in the Morro dos Gatos alkaline complex (Rio de Janeiro/Brazil): (1) Fluidization of pyroclastic material (mostly composed of lapilli-ash), (2) Collapse of the eruption vent or chimney filling (characteristically contains lithics and large blocks) [3]. On the other hand, Vezzoli and Corazzato (2016) explained the emplacement mechanism of post-volcanic/eruption downward mass flow clastic dykes, which developed as a result of lateral collapses on Stromboli volcano (Italy), by the re-mobilization of pyroclastic sediments on the volcano slopes [1].

2 Regional geology

The ErAVC covers a large area in the Beyşehir Basin (Located in the Central Taurus), characterized by a graben-like structure containing different stratigraphic, lithological, and tectonic structures (Figure 1).

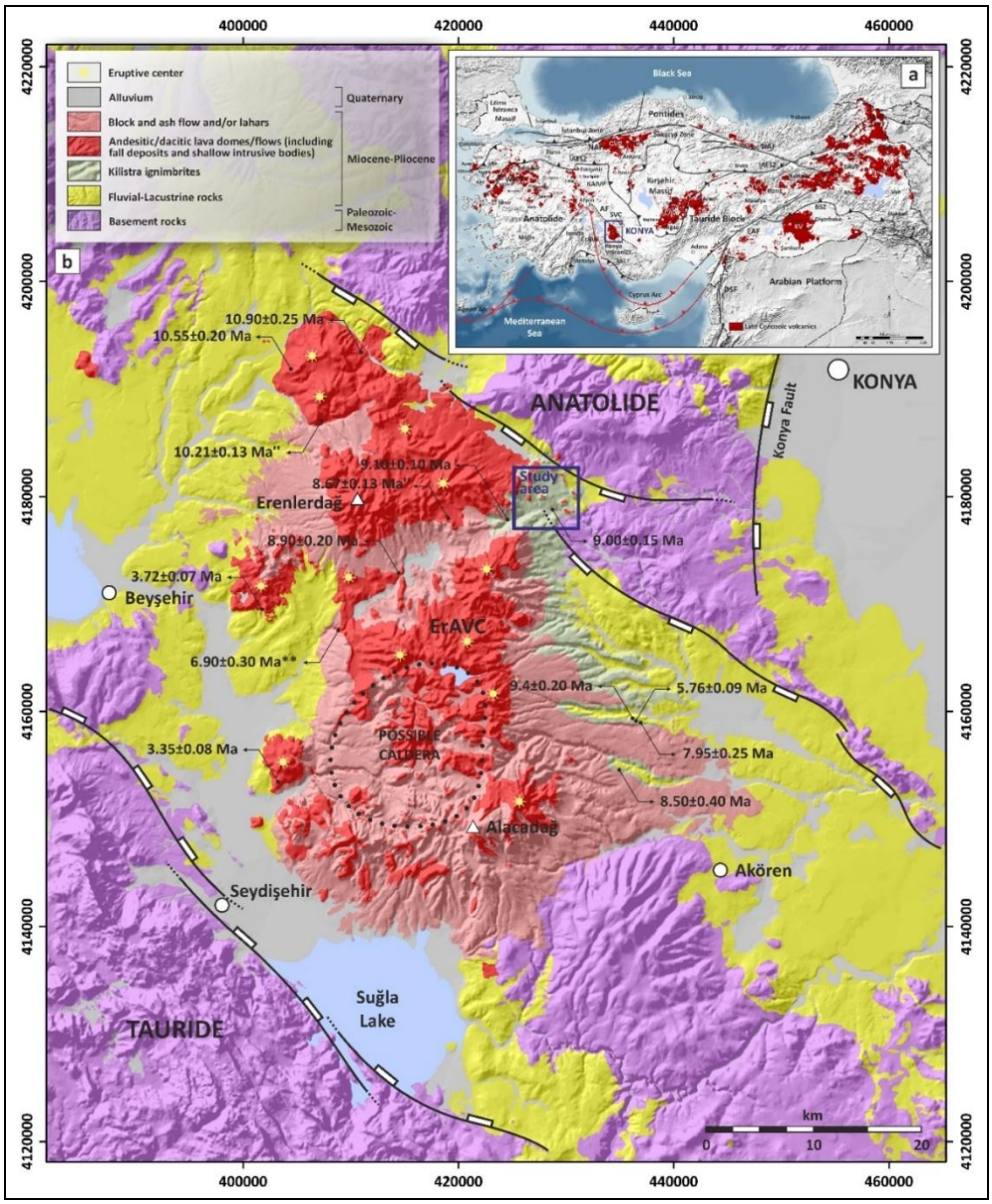


Figure 1(a): The major suture zones (solid black lines with the triangle), arc systems (red lines with the triangle), continental blocks [40], and distribution of the main Post-Collision (Late Cenozoic) volcanic fields [41]. (b): Simplified geological map of the west of Konya [31], General Directorate of Mineral Research and Exploration 1/100000 geology map. Distribution of K/Ar [33],[42]**, and U-Pb [43]'' dating results.

The ErAVC covers a large area in the Beyşehir Basin (located in the Central Taurides), characterized by a graben-like structure containing different stratigraphic, lithological, and tectonic structures (Figure 1). The Beyşehir Basin is mostly controlled by parallel and/or sub-parallel normal faults in the northwest-southeast and northeast-southwest directions. The basin-filling Mio-Pliocene fluvial-lacustrine sediments is evidence of the intermontane basin controlled by these regional faults [7]-[9]. In addition, this graben system is bordered by the Taurus Belt (Central Taurides-southwest) and the Afyon Zone (Anatolide-northeast). The Central Taurides are grouped tectonically autochthonous and allochthonous assemblages of basement rocks such as metacarbonates and metaclastics [10]-[19]. These crystalline-metamorphosed rocks consist of metaclastic rocks alternating with metacarbonates and metamarls from the Paleozoic to the end of the Mesozoic [14], [20]-[23]. These basement rocks are unconformably covered by the Neogene-Quaternary fluvial-lacustrine units such as limestone, conglomerate, sandstone, and siltstone [22], [24]-[27].

The Neogene volcanic rocks (ErAVC) have an unimodal geochemical character [28]-[30]. The ErAVC can be classified as basaltic andesite (enclaves), andesite, dacite, and rhyolite, according to the total alkali-silica diagram [30]-[32]. Keller et al. (1977) geochemically first defined these rocks as a calc-alkaline series. The authors also argued that the ErAVC was associated with the subduction-related volcanism, producing lava domes/lava flows, pyroclastic falls, and flows (i.e. block and ash flows and ignimbrites) [29]-[31], [33]. Also, Besang et al. (1977) presented the first geochronological (K/Ar radiometric age) data and stated that volcanism continued for a long period from the Miocene (10.90±0.25 Ma) to the Pliocene (3.35±0.08 Ma). Based on the trace element and Sr-Nd isotope data, Temel et al. (1998) argued to be of the subduction-related origin of the ErAVC [32]. Finally, Asan et al. (2021; 2024) suggested that the unimodal chemical character of the ErAVC was resulted from magma recharge and mixing processes in an extensional post-collision volcanic setting based on the trace element and Sr-Nd-Pb isotope data [29], [30].

3 Methodology and field observations

This study focuses mainly on the detailed field observations of volcaniclastic units, which are widely observed in the east and northeast of the ErAVC. Firstly, the detailed geological map and lithology descriptions of the study area given by Keller et al. (1977) were revised. The boundaries of volcaniclastic units and faults defined in previous studies [7]-[9], [34], [35] were re-evaluated. The characteristics of the faults are shown in the geological map (Figures 1 and 2). Secondly, a general stratigraphic section was created to represent regional geology (Figure 3). The detailed-stratigraphic sections have also been illustrated for two locations where clastic dykes are located within the discontinuities of the ignimbrites in the field. Strike and dip direction were measured to better understand the relationship between these two dykes and their host rocks.

3.1 Volcanostratigraphy

General stratigraphic section begins with re-worked volcanogenic conglomerates conformably overlying pre-volcanic fluvial-lake sediments in the study area. Then, the fine-grained ash and small-sized pumice-rich lapilli ash overlay harmoniously on these volcanogenic conglomerates, respectively. These units are conformably overlain by a limestone layer and alternations of conglomerate, sandstone, and mudstone, which occasionally contain well-rounded pumice layers (Figure 3).

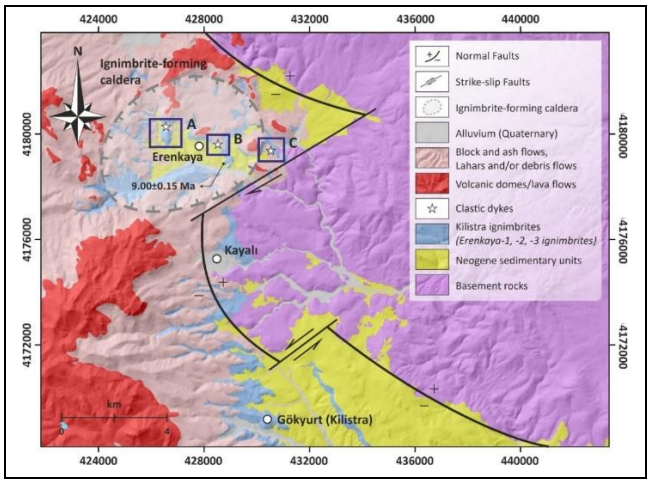


Figure 2. Map showing the detailed geology of the study area and the locations of the clastic dykes. K/Ar dating result from [33].

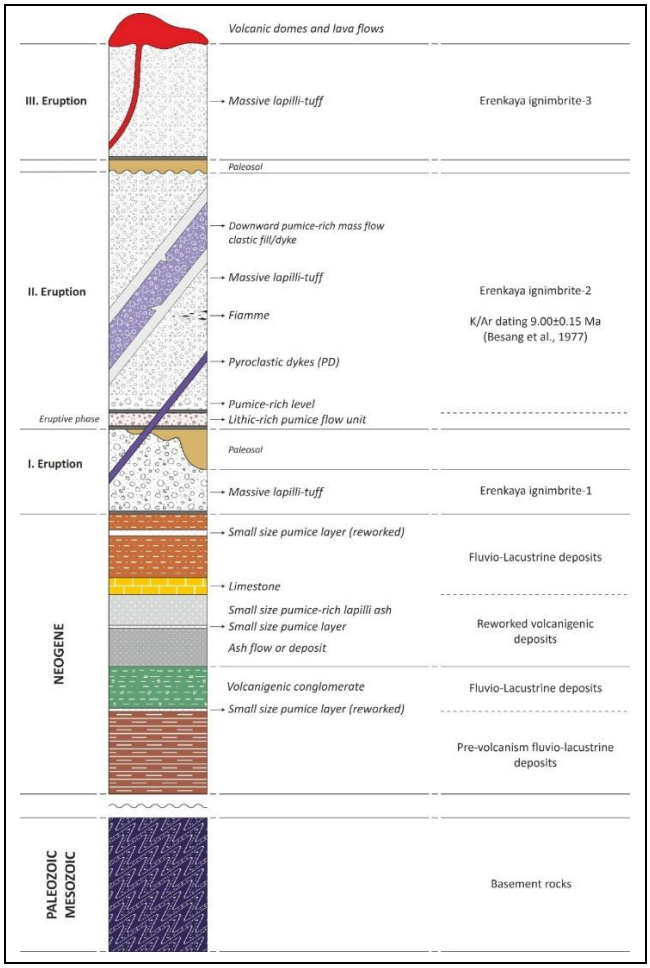


Figure 3. A generalized (unscaled) stratigraphic column section of the study area and its surroundings [38], K/Ar dating [33].

Although there are many stratigraphic studies on the crystalline basement and terrestrial sediments outcropping

around the ErAVC [19]-[21], [27], [36], all references to the detailed stratigraphy of the volcaniclastic sequences in the region are from Keller et al. (1977). The stratigraphy of volcaniclastic sequences was processed separately and defined according to the lithofacies classification scheme of ignimbrites proposed by Branney and Kokelaar (2002) (Table 1) [37].

The whole ignimbrite sequences were grouped under a single name as "Kilistra ignimbrites" [38], [39] because six different ignimbrite units (Erenkaya 1, 2, 3, Detse, Evliyatekke, and Sadıklar) cover a large area in the east of the ErAVC (Figures 1, 2, and 3). In addition, it has been determined that the Erenkaya ignimbrites consist of three different eruption stages separated by two paleosol levels (Figure 4) in the same study. Finally, these ignimbrites are mainly covered by lava flows/domes and debris flow/avalanche or lahars in the study area.

Table 1. Ignimbrite lithofacies classification scheme: Non-genetic lithofacies terms commonly used in this study [37].

mLT	Massive lapilli-tuff (or lapilli ash)
pmLT	Pumice-rich massive lapilli-tuff
pmL	Pumice-rich massive lapilli
//sT	Parallel-stratified (laminated) tuff

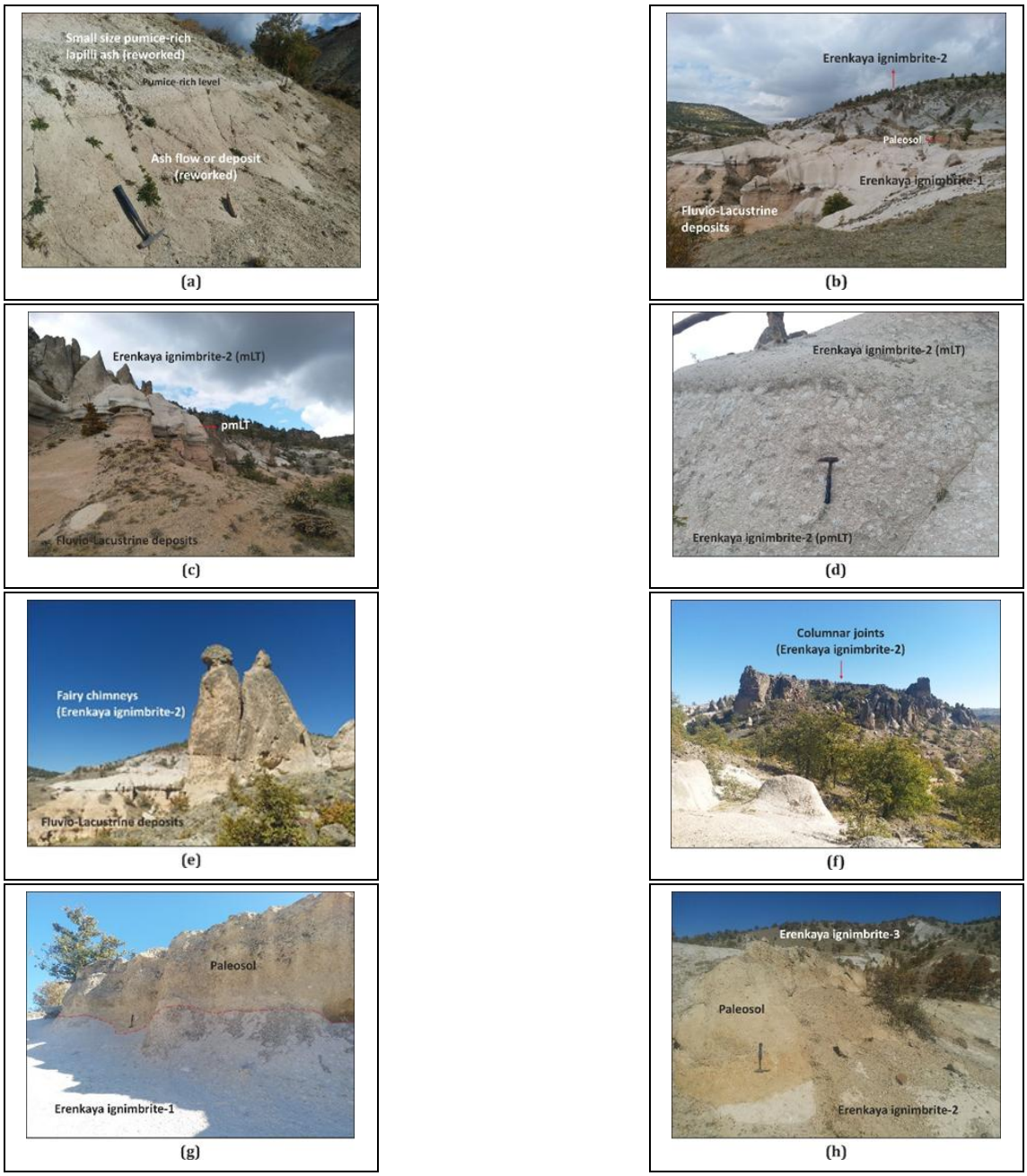


Figure 4. Field photos from the study area. Fluvio-lacustrine deposits. (a): Reworked volcanigenic deposits (Characterized by intraclasts and decomposition, transportation, and deposition structures, etc.), (b): Erenkaya ignimbrite-1 and -2, fluvio-lacustrine deposits and paleosol. (c): and (d): Erenkaya ignimbrite-2 and fluvio-lacustrine deposits. (e): and (f): Erenkaya ignimbrite-2 fairy chimneys and Columnar joints. (g): and (h): Paleosol levels between the Erenkaya-1, -2, and -3.

3.1.1 Erenkaya ignimbrites

The Erenkaya ignimbrites were first described by Keller et al. (1977) and called "Bulumya ignimbrite" [31]. The Erenkaya ignimbrites, which were emphasized to consist of three different Pyroclastic Density Current (PDC) levels, are classified in this study as Erenkaya ignimbrites-1, -2, and -3, from bottom to top, respectively (Figures 3 and 4). These ignimbrites can also be easily separated from each other due to their field characteristics, components (e.g. pumice, lithics, volcanic glass, etc.), and petrographic features [37], [44], [45].

The fluvio-lacustrine sediments are overlain horizontally by the massive Erenkaya ignimbrite-1 (pmLT), which represents the beginning of the main volcanism in the field. The Erenkaya ignimbrite-1 contains large (>10 cm) and well-rounded pumices but lesser lithics. The Erenkaya ignimbrite-1 is covered by a paleosol level with a highly variable thickness that overlays on the erosion surface and separates from the Erenkaya ignimbrite-2 (Figures 3 and 4). The Erenkaya ignimbrite-2 begins with a level consisting of small-sized and sub-rounded pumices (pmLT; 15-20 cm in thickness). The Erenkaya ignimbrite-2 consists of a PDC containing pumices of variable sizes (mLT) reaching 150 meters. The Erenkaya ignimbrite-2 is the most common PDC in the study area and shows primary/hot emplacement features, such as occasionally containing welded pumice (fiamme) and columnar joints. Bozdağ et al. (2016) argued that the Erenkaya ignimbrite-2 is characterized by a vertical zonation of welding degree (e.g. non-welded-lower part and welded-upper part) around the ancient city of Kilistra. The Erenkaya ignimbrite-3 is separated from the Erenkaya ignimbrite-2 by another paleosol level in the west of the study area (Figures 3 and 4). The Erenkaya ignimbrite-3 contains large and well-rounded pumices (mLT) with lesser lithics, similar to the Erenkaya ignimbrite-1. Each eruption is also distinguished by characteristic pyroclastic fall deposits (//sT and pmL). Lastly, these three PDCs are covered by debris flows/lahars (Figure 2).

3.1.2 Clastic dykes in the ErAVC

In this study, the clastic dykes are divided into two main groups; sedimentary clastic and volcaniclastic dykes (Table 2).

Table 2. Volcaniclastic and sedimentary clastic dyke classification scheme modified from [1].

1. Sedimentary clastic dykes
A. Fissure fills (Neptunian dykes)
B. Injection dykes
2. Volcaniclastic dykes
A. Pyroclastic dykes (PD)
B. Phreatomagmatic pipes, diatremes, and kimberlite pipes
C. Peperite dykes
D. Intrusive breccias

The Erenkaya ignimbrite-1 and -2 are cut by a volcaniclastic dyke (Appendix A). This dyke (N20E/70SE), located in the northwest of the study area (Location-A), exhibits lithological and structural features indicating a pyroclastic dyke (PD) as a result of primary emplacement (juvenile). It is ~90 m long and ~1.5 m wide. It generally consists of partially consolidated fine ash and contains lithic fragments. The lithic components are mostly angular, small-sized and some of them highly silicified. These are also concentrated mostly in the dyke edge zones Figures 5(a) and (b). The second PD (Location-B; N8W/80SW) cut Erenkaya ignimbrite-2 (Appendix B) and show similar lithology characteristics to the pyroclastic dyke in the Location-A. But, this dyke is larger than the first one (~175 m long and ~12 m wide) Figures 5(c) and (d).

Another clastic dyke located in the east of the study area (Location-C), relatively reflects the outer facies characteristics of volcanism, and consists of a thinner PDC (Erenkaya ignimbrite-2). This dyke (N5E/75NW) located here exhibits lithological and structural features indicating secondary emplacement (Appendix C). Its length could not be determined due to volcaniclastic debris flow/avalanche or lahar covers, but its width is large (>5 m). This dyke observed in Location-C exhibits two different lithological facies characteristics from its edge to center. The edge facies of this dyke have a very fine-grained lithology, and its middle (center) zone contains very coarse pumices, mostly with well-rounded block-sized. The bottom boundary of the middle zone of this clastic settlement can be observed clearly towards the south Figures 5(e) and (f).

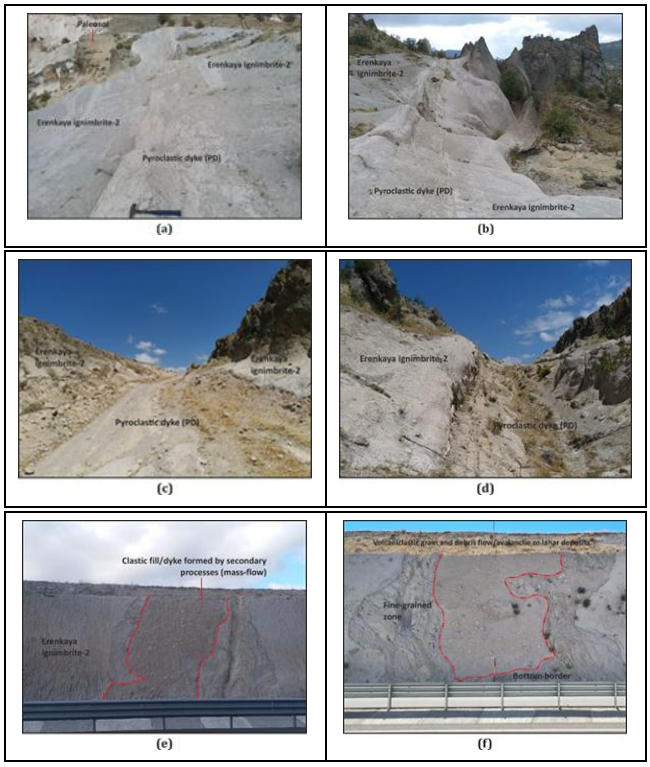


Figure 5. Landscapes of the pyroclastic dyke (PD) emplaced in the Location-A, N20E/70SE. Direction of views. (a): Northeast and (b): Southwest (UTM coordinate: 36S 426535m E; 4179983m N). Landscapes of the pyroclastic dyke (PD) emplaced in the Location-B, N8W/80SW. Direction of views. (c): northwest and (d): North (UTM coordinate: 36S 428511m E; 4179404m N). Landscapes of the sedimentary clastic dyke emplaced in the Location-C, N5E/75NW. Direction of views. (e): North and f) South (UTM coordinate: 36S 430397m E; 4179138m N).

4 Results and discussion

4.1 Conceptual model of the clastic dykes in the ErAVC

The very fine-grained ash lithology exhibited by the clastic dykes observed in Location-A and -B are pyroclastic dykes (PD)

with primary emplacement features as a result of the fluidization of volcaniclastic material [1], [3], [4] in Figure 6(a). However, clastic dykes in a volcanic complex can also emplace as channel fillings in fractures and cracks through post-eruption mass flow due to the re-mobilization of volcaniclastics on the volcano slopes [1], [47]. Depending on the composition of the clastic materials flowing into the fracture/crack systems, these can exhibit a highly complex lithology. As a result, a sedimentary clastic dyke observed in Location-C consists of two different facies, and the bottom boundary of the center (middle) zone is observed. It is also proof that the emplacement of this dyke is controlled by secondary processes from pre-existing volcaniclastic materials as a result of mass flow deposits in Figure 6(b).

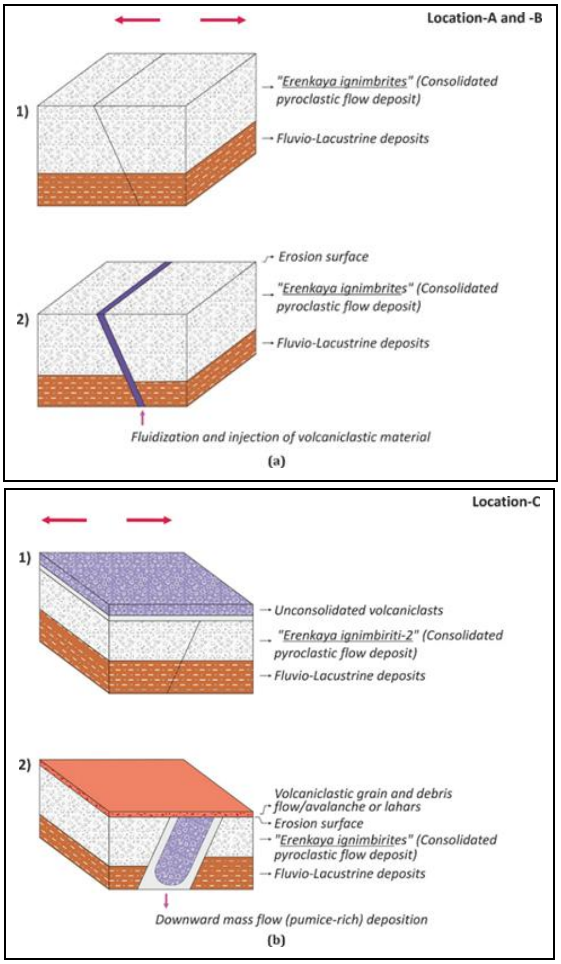


Figure 6(a): Location-A and -B: Schematic model of the pyroclastic dyke (PD) emplacement as a result of fluidization and injection forces. (1): Separating and/or faulting caused by extensional stresses. (2): Pyroclastic dyke emplacement in the cracks/fractures opened by strong injection of clastic materials. (b): Location-C: Schematic model of the sedimentary clastic dyke emplacement as a result of secondary processes (decomposition, transport, and deposition). (1) Separating and/or faulting caused by extensional stresses. (2): Emplacement of unconsolidated clastic material in the form of a dyke into the cracks/fractures as a result of mass flow.

It is known that volcaniclastic dykes are very rare in volcanic areas and are primarily associated with caldera and fissure-vent eruptions [2],[5],[6],[48]-[52]. In particular, these dykes related to the injection of volcaniclastic material into fracture/crack systems from the depths (similar to Location-A and -B) or the collapse/filling of the eruption vent are a result of primary processes located in the eruption center and/or vicinity of the eruption vent. On the other hand, it is thought that the other clastic dykes were formed as a result of the caldera collapse and settled into cracks near the caldera walls by secondary processes in a volcanic field (Location-C). In addition, the Erenkaya ignimbrite-2, widely distributed in the region and observed at a very thick level within the study area, points to a caldera eruption by its large volume [53]. In summary, it is possible to explain the presence of pyroclastic activities and clastic dyke emplacements in the study area in three different periods; 1: The large volume ignimbrite eruption (Erenkaya ignimbrite-2; 9.00±0.15Ma), 2: Upward injection of volcaniclasts in the intra-caldera fracture as a result of fluidization, 3: Downward mass flow/re-mobilization and emplacement in the fracture/crack near the caldera walls in Figure 7(a), (b), and (c).

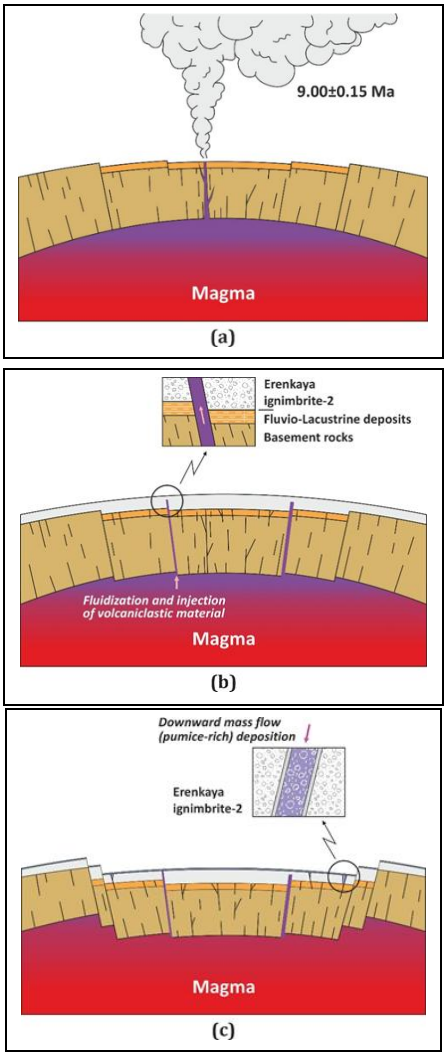


Figure 7. Conceptual models of pre-volcanism caldera collapse proposed for clastic dykes in the study area. (a): Eruption of the Erenkaya ignimbrite-2 (9.00±0.15 Ma). (b): Pyroclastic dykes (PD) emplacement as a result of fluidization and injection processes. (c): Sedimentary clastic dyke emplacement as a result of downward mass flow near the caldera wall.

4.2 The importance of clastic dykes in a volcanic field

The detailed studies on the clastic (volcaniclastic) dykes are limited, and these dykes have been observed in different volcanic fields around the world related mostly to caldera environments [1],[2],[5],[54]-[57]. Firstly, the relationship between caldera and volcaniclastic dykes was emphasized by Aguirre-Díaz and Labarthe-Hernández (2003). On the other hand, some studies focused only on the settlement dynamics, lithological and structural characteristics of the clastic dykes in the volcanic fields rather than their relationship with regional volcanism [3],[4],[6],[58],[59]. In these studies, the emplacement of these clastic dykes was explained by primary volcanic processes. However, the emplacement models of the clastic dykes from Stromboli were detailed by Vezzoli and Corazzato (2016). Therefore, we tried to explain the origin of the clastic dykes in the ErAVC, based on the models proposed by Vezzoli and Corazzato (2016). Vezzoli and Corazzato (2016) emphasized that the emplacement of clastic dykes in the Stromboli volcanic field consists of three stages (polyphases) that follow each other. These stages can be defined as Phase I: Fluidization of pyroclastics and upward injection, Phase II: Collapse of the eruption vent and downward deposition, and Phase III: Post-volcanic downward mass/debris deposition. Phase I- and II represent primary processes, but the authors emphasize that Phase III is revealed due to post-eruption secondary processes. Vezzoli and Corazzato (2016) consecutively linked all three phases in their study. However, as stated by the authors, these relations may not be seen in every volcanic environment. Therefore, we decided to describe the clastic dykes in the ErAVC without any genetic relation and improved a classification schema based on Vezzoli and Corazzato (2016) for clastic dykes fundamentally under two main groups (Table 2). In this study, the first group of these dykes (Location-A and -B; Figure 6a) from the ErAVC has been described as a result of fluidization and upward injection controlled by "extension processes" and/or "hydrofracturing" [1], [3], [4]. On the other hand, the second group (Location-C; Figure 6(b) is completely associated with post-eruption processes, as described by Vezzoli and Corazzato (2016). As a result, these two dyke groups in the study area have different lithological, structural, and emplacement features. In other words, there is no genetic relationship between these two groups due to differences in their lithology, structure, and emplacement characteristics.

5 Conclusions

Clastic dykes are rarely observed in volcanic fields, but they can form in any setting under different types (e.g. lithology, structure etc.), stages, and conditions. Some of them are emplaced by primary processes (i.e. fluidization and injection of volcaniclastics) and are characteristic structures of eruption centers. Therefore, the pyroclastic dyke outcropping in Location-A and -B is very important as it points to the source location of the Erenkaya ignimbrites. In addition, the other dyke, which was controlled by sedimentary processes (e.g. decomposition, transportation, and deposition) in Location-C, has a different emplacement model with its characteristics (two different levels from edge to center). It is also predicted to be located in the cracks near the caldera border. Thus, considering the presence of these volcaniclastic dykes and the relationship with the Erenkaya ignimbrites, it can be proof that the eruption center forming the ignimbrites is located in the north of the ErAVC.

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7 Author contribution statements

Mesut Gündüz, writing-original draft, Methodology and Data collection, Field investigation, Visualization, Conceptualization, Formal analysis. Ali Müjdat Özkan, field investigation, Stratigraphic-Sedimentological analysis. Kürşad Asan, writing-original draft, Field investigation, Formal analysis.

8 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared". "There is no conflict of interest with any person / institution in the article prepared".

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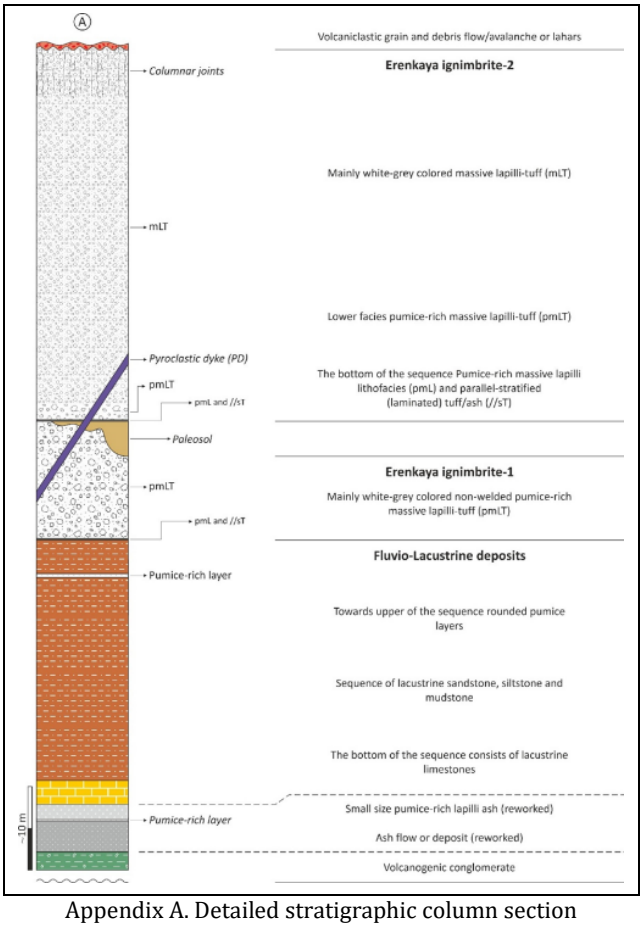
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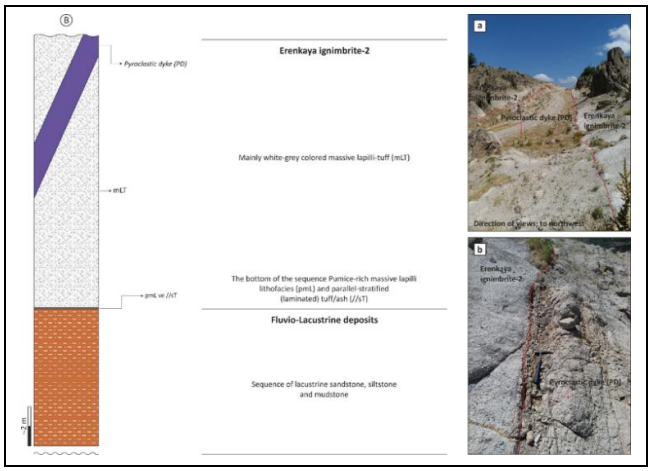
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Appendix A



Appendix A. Detailed stratigraphic column section representing Location-A and its surroundings in the study [38].

Appendix B



Appendix B. Detailed stratigraphic column section representing Location-B and its surroundings in the study area.

Appendix C



Appendix C. Detailed stratigraphic column section representing Location-C and its surroundings in the study area [38].