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article in press

Quaternary maar volcanism in the Central Anatolian Volcanic Province (Türkiye): Implications for eruption dynamics

Göksu Uslular^{*,1,2,3}, Gonca Gençalioğlu Kuşcu¹, Joël Ruch², Çağdaş Sağır^{4,5}

¹ Department of Geological Engineering, Muğla Sıtkı Koçman University, Kötekli Campus, 48000,

5 Muğla, Türkiye

² Department of Earth Sciences, University of Geneva, Rue des Maraîchers 13, 1205, Geneva, Switzerland

³ Polar Research Institute, TÜBİTAK Marmara Research Centre, Gebze Campus, 41470, Kocaeli, Türkiye

10 ⁴ Department of Geological Engineering, Middle East Technical University, 06800, Ankara, Türkiye

⁵ Ekofly Engineering, Consultancy, RandD Ltd., Middle East Technical University Technopolis ETKİM Block, 06800 Ankara, Türkiye

* goksu.uslular@tubitak.gov.tr [corresponding author]

 ORCID (GU): 0000-0001-8485-0093

15  ORCID (GGK): 0000-0001-9801-6542

 ORCID (JR): 0000-0003-1829-6762

 ORCID (ÇS): 0000-0001-5962-721X

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20 Abstract

Maars preserve sensitive records of shallow magma ascent, magma-water interaction, and substrate excavation. We present the first regional synthesis of 18 Quaternary maars in the Central Anatolian Volcanic Province (CAVP), integrating field stratigraphy, lithofacies analysis, componentry, juvenile clast petrography and SEM micromorphology, whole-rock major-element geochemistry, UAV-based mapping, and morphometry. The maars
25 range in composition from mafic to felsic and formed within hard, mixed, and soft substrates. Tephra-ring successions record deposits generated by repeated phreatomagmatic explosions through variable contributions from substrate excavation, ballistic emplacement, debris- or jet-collapse processes, pyroclastic density currents, fallout, and local remobilization. Mafic-intermediate maar deposits are commonly more lithic-rich and contain
30 rugged, thick-walled scoriaceous juvenile clasts. In contrast, felsic maars are more juvenile-rich and contain highly vesicular pumice, perlite, and obsidian. Several maars are spatially and stratigraphically associated with other monogenetic edifices: scoria cones modify or overprint some mafic-intermediate maars, whereas lava domes occupy or deform parts of several felsic maars. Where relative chronology is sufficiently constrained, these

relationships are consistent with transitions from phreatomagmatic maar formation to Strombolian activity, and to late-stage explosive or effusive rhyolitic activity. Nested, chain-like, and complex crater morphologies indicate multiple explosion loci, vent migration, structural control, and post-eruptive modification. Substrate effects are expressed most clearly in lithic assemblages and partially in crater morphology: hard to mixed type-1 substrates yield predominantly crystalline and volcanic lithics, while mixed type-2 to soft substrates are commonly associated with sedimentary lithics, gentler crater-wall slopes, soft-sediment deformation, and volcanoclastic interbeds. The CAVP maars demonstrate that maar evolution reflects the variable influence of magma composition, substrate properties, hydrogeological conditions, and vent evolution, providing a regional framework for interpreting compositionally and environmentally diverse monogenetic volcanic systems.

Second-language abstract

Maar volkanları, sıg magma yükselimi, magma-su etkileşimi ve temel kayaçların kazılması süreçlerine ilişkin önemli kayıtlar sunmaktadır. Bu çalışmada, Orta Anadolu Volkanik Bölgesi (OAVB)'ndeki 18 Kuvaterner yaşlı maarın ilk bölgesel sentezi sunulmaktadır. Çökellerin stratigrafisi, litofasiyes analizi, bileşen analizi, juvenil tane petrografisi ve SEM mikromorfolojisi, tüm kayaç ana element jeokimyası, İHA tabanlı haritalama ve morfometri verileri birlikte değerlendirilmektedir. Maarlar mafikten felsik bileşime kadar değişmekte ve sert, karma ve yumuşak temel litolojilerin içerisinde oluşmuşlardır. Tefra halkası istifleri; temel kayaçları, balistik yerleşim, debri jetleri ve jet çökmesi, piroklastik surge tabakaları, litik mercekler ve juvenilce zengin lapilli birimler, ve local olarak yeniden taşınmanın çeşitli katkılarıyla gelişen tekrarlayan freatomagmatik patlamaların ürünlerini kaydetmektedir. Mafik-ortaç maarlar genellikle litikçe zengin olup pürüzlü yüzeyli ve kalın vezikül duvarlarına sahip cüruf taneleri içerirken, felsik maarlar juvenilce daha zengindir ve yüksek veziküllü pomza, perlit ve obsidyen içermektedir. Bazı maarlar diğer monojenetik volkanlarla mekansal ve stratigrafik olarak ilişkilidir: cüruf konileri bazı mafik-ortaç maar kraterlerini değiştirir ve üzerlerken, lav domları bazı felsik maar kraterlerinin belirli bölümlerini doldurmakta veya deforme etmektedir. Jeokronolojik açıdan ilişkilendirilebilen örneklerde, bu ilişkiler freatomagmatik maar oluşumundan Stromboliyen aktiviteye ve geç ever patlamalı veya efüzif riyolitik aktiviteye geçişlerle temsil edildiği gözlemlenmiştir. İç içe geçmiş, zincir şeklinde ve karmaşık krater morfolojileri; çoklu patlama odaklarına, bacanın yer değiştirmesine, yapısal kontrole ve püskürme sonrası modifikasyona işaret etmektedir. Temel litolojisinin etkisi en belirgin olarak litik bileşenlerde ve kısmen krater morfolojisinde görülmektedir: sert ve karma tip-1 temel litolojileri çoğunlukla kristalen ve volkanik litikler barındırırken, karma tip-2 ve yumuşak temel litolojileri genellikle sedimanter litikler, daha düşük krater duvarı eğimleri yumuşak sediman deformasyonu ve

volkaniklastik ara seviyeler ile ilişkilidir. OAVB maarları, maar evriminin magma bileşimi, temel litolojisi özellikleri, hidrojeolojik koşullar ve baca evriminin değişen etkileriyle şekillendiğini göstermekte ve bileşimsel ve çevresel açıdan farklı monojenetik volkanik sistemlerin yorumlanması için bölgesel bir çerçeve sunmaktadır.

1 INTRODUCTION

Maar-diatreme volcanoes (hereafter maars) are common monogenetic volcanic landforms that occur in diverse tectonic settings and substrate lithologies (Lorenz 2003; White and Ross 2011; Graettinger 2018). A maar comprises a broad, low-rimmed crater excavated below the pre-eruptive surface, a surrounding tephra (or ejecta) ring composed of pyroclastic deposits, and a subsurface diatreme filled with juvenile and country-rock debris (Lorenz and McBirney 1970; Lorenz 1973; Lorenz and Kurszlauskis 2007; White and Ross 2011). Most maars are produced by shallow phreatomagmatic explosions involving interaction between ascending magma and external water through molten fuel-coolant interaction (MFCI), although the coolant may include groundwater, surface water, hydrothermal fluids, or water-bearing sediment (Sheridan and Wohletz 1981; White 1996; Zimanowski et al. 1997; Büttner et al. 2002). Their deposits and morphologies therefore archive shallow magma ascent, magma-water interaction, substrate excavation, and eruption dynamics in monogenetic volcanic systems (Lorenz 2007; Valentine et al. 2011; Smith and Németh 2017; Valentine et al. 2017).

Conceptual models of maar formation have changed substantially over the last two decades. Earlier models emphasized progressive downward migration of explosion loci (Lorenz 1973) or single dominant explosions controlling crater dimensions (Goto et al. 2001). Experimental, numerical, and field studies have recently shown that maars grow incrementally through many discrete explosions, with explosion loci migrating vertically and laterally within an evolving diatreme and occurring at variable depths (< 200 m). Consequently, tephra rings selectively record explosions that excavate and eject material to the surface, whereas explosions that generate limited or no surface ejecta may leave no distinct record in the tephra ring (Valentine et al. 2011; Ross et al. 2013; Taddeucci et al. 2013; Graettinger et al. 2014; Valentine et al. 2014; Graettinger et al. 2015; Valentine et al. 2017; Sweeney et al. 2018). The scaled-depth framework ($d/E^{1/3}$, where d is explosion depth and E is released energy) and the optimal scaled depth (OSD) concept provide a useful qualitative basis for evaluating how explosion depth relative to released energy influences crater excavation and the production of surface ejecta (Goto et al. 2001; Valentine et al. 2014; Graettinger and Valentine 2017). However, individual beds in natural tephra rings should not be assigned to specific scaled-depth regimes unless explosion energy, vent/diatreme geometry, and substrate properties are independently constrained. Lithofacies, grain size, and componentry are therefore useful but non-

unique process proxies because they may be affected by substrate properties, vent and crater geometry, vent migration, magma composition, and post-depositional processes. Recognizing these limitations, recent studies
95 increasingly adopt multi-proxy approaches that integrate field stratigraphy, componentry, juvenile-clast petrography and geochemistry, crater morphology and mapping (Brenna et al. 2012; Lefebvre et al. 2013; Pedrazzi et al. 2014; Chako Tchamabé et al. 2016; Graetinger and Valentine 2017; Foote et al. 2022; Nolan and Graetinger 2022).

Interactions between external environmental factors and internal magmatic processes shape the morphology and
100 architecture of maar deposits. External controls include substrate lithology and mechanical strength, aquifer architecture (i.e., fracture-controlled or pore-controlled), groundwater availability, pre-existing faults and topographic relief, crater lake and playa development, and post-eruptive erosion and sedimentation (Lorenz 2003; Auer et al. 2007; Macorps et al. 2016). Internal controls include magma composition, viscosity, volatile content, ascent rate, magma flux, and the degree of magma evolution within shallow crustal reservoirs (White and Ross
105 2011; Berghuijs and Mattsson 2013; Gurusunga et al. 2023; Planagumà et al. 2023). Both sets of factors may operate simultaneously and can reinforce or counteract one another, making interpretations based on any single proxy inherently ambiguous. Although phreatomagmatic processes occur across a wide compositional spectrum, mafic-intermediate and felsic maar systems may differ in juvenile-clast textures, associations with other monogenetic volcanoes, eruption-style evolution, and geochemical characteristics (White and Ross 2011; Jordan et al. 2015;
110 Ross et al. 2017; Kósik et al. 2020; Uslular et al. 2022; Planagumà et al. 2023). These differences, superimposed on contrasting substrate and hydrogeological settings, contribute to the broad diversity of maar morphologies, deposit architectures, and clast assemblages observed worldwide (White and Ross 2011; Graetinger 2018; Németh and Kósik 2020).

The Central Anatolian Volcanic Province (CAVP) is one of the major Neogene-Quaternary volcanic regions in
115 Türkiye (Figure 1A-B), characterized by plateau-like topography (~ 1 km a.s.l.) and a semi-arid continental climate. Extending approximately 250 km across central Anatolia, the CAVP contains numerous polygenetic volcanoes, voluminous ignimbrite units, and hundreds of monogenetic volcanoes grouped into six volcanic fields (Figure 1B; Toprak 1998; Aydar et al. 2012; Uslular et al. 2021). Monogenetic volcanism occurs throughout the province, although its distribution and geological setting vary spatially. The northern and central sectors are dominated by
120 hard crystalline and volcanic substrates and include both polygenetic and monogenetic volcanic centers, whereas extensive monogenetic volcanic fields become more prominent towards the south, where volcanism developed largely over lacustrine and volcano-sedimentary successions (Figure 1B; Keller 1974; Floyd et al. 1998; Toprak 1998; Kuzucuoğlu et al. 1999; Yalınız et al. 1999; Gevrek and Kazancı 2000; Uslular et al. 2015, 2021, 2022;

Brehme et al. 2021). Quaternary maars in the CAVP range from mafic-intermediate to felsic in composition, occur
125 within hard, mixed, and soft substrates, and are spatially associated with other monogenetic volcanic edifices, crater
lakes or playas, fault systems, and pre-existing volcanic landforms (Uslular 2023). This diversity makes the CAVP
a particularly well-suited natural laboratory for investigating how internal magmatic and external environmental
factors control the formation and evolution of maars. Despite this potential, previous studies have largely focused
on individual maars or selected volcanic fields (Keller 1974; Gevrek and Kazancı 2000; Gençalioglu-Kuşcu et al.
130 2007; Aydar et al. 2011; Gençalioglu-Kuşcu 2011; Uslular et al. 2022), or on the regional petrological evolution of
monogenetic fields that include maars among other volcanic landforms (Reid et al. 2017; Doğan-Külahçı et al.
2018; Uslular and Gençalioglu-Kuşcu 2019; Gençoglu Korkmaz et al. 2026). A region-wide synthesis integrating
current concepts in maar volcanism and multi-proxy methods has not previously been attempted. In particular, it
remains unclear how internal magmatic and external environmental factors have shaped the diversity of CAVP
135 maars and how they affect eruption dynamics and edifice evolution across contrasting volcanic and substrate
settings.

Here, we provide the first integrated regional synthesis of Quaternary maar volcanism in the CAVP. We document
18 maars, including 11 with exposed tephra-ring deposits thicker than 1 m, and combine field observations,
lithofacies and grain size analyses, componentry, juvenile-clast petrography and SEM micromorphology, whole-
140 rock major-element geochemistry, UAV-based mapping and morphometry, and available geological constraints.
We aim to: (1) characterize the distribution, morphology, composition, and substrate settings of CAVP maars; (2)
classify and interpret their main lithofacies and depositional processes; (3) compare felsic, intermediate, and mafic
maar systems in terms of deposit architecture, juvenile-clast characteristics, and whole-rock compositional
characteristics; (4) evaluate how substrate lithology, aquifer architecture, magma composition, associated
145 monogenetic edifices, and vent migration have influenced deposit architecture and crater morphology; (5) use
scaled-depth as a qualitative framework for evaluating variability in crater excavation and surface-ejecta
production; and (6) place CAVP maar volcanism within the broader context of compositionally and
environmentally diverse monogenetic volcanic systems.

The Neogene tectonic evolution of Anatolia is commonly interpreted as tectonic escape, involving the westward displacement of Anatolia accommodated primarily by major strike-slip fault systems following the Arabia-Eurasia collision (Şengör et al. 1985). In central Anatolia, which occupies a transitional region between extensional western Anatolia and compressional eastern Anatolia (Figure 1A), the NE-SW-directed strike-slip tectonism and transtensional deformation have been active since at least the late Miocene (Göncüoğlu and Toprak 1992; Dhont et al. 1998; Tatar et al. 2000; Aydemir 2009; Özsayın et al. 2013). The CAVP lies within this tectonically transitional region and has experienced widespread volcanism from the middle Miocene to the present (Göncüoğlu and Toprak 1992; Toprak 1998). The CAVP includes approximately 19 polygenetic volcanoes, voluminous ignimbrite deposits, and widespread monogenetic volcanism, with ~540 Quaternary monogenetic vents grouped into six volcanic fields (Aydar et al. 1995; Toprak 1998; Aydar et al. 2012; Uslular et al. 2021). It has been interpreted as a low-flux intraplate volcanic field, bounded and controlled by two transtensional strike-slip fault zones (Uslular et al. 2021): the Tuzgölü and Central Anatolian fault zones, which have dextral and sinistral kinematics, respectively (Toprak and Göncüoğlu 1993; Çemen et al. 1999). Quaternary monogenetic volcanism is widespread throughout the province and includes numerous scoria cones and lava domes, as well as less abundant maars and tuff rings/cones (Toprak 1998; Aydar et al. 2011; Uslular et al. 2021).

Monogenetic volcanoes in the CAVP are clustered into six distinct volcanic fields (Figures 1B and 2A-E), whose distribution reflects regional tectonic structures and variations in substrate lithology (Uslular et al. 2021). The northern and central parts of the CAVP include both polygenetic volcanic complexes (e.g., Nevşehir-Acıgöl caldera, Erciyes stratovolcano) and monogenetic volcanic centers (Druitt et al. 1995; Dhont et al. 1998; Şen et al. 2003; Aydar et al. 2011; Çubukçu et al. 2024; Figures 1B and 2A-B), and are dominated by crystalline basement rocks and volcanic units intercalated with Neogene sediments (Göncüoğlu and Toprak 1992; Yalınız et al. 1999). In contrast, extensive monogenetic fields such as Eğrikuyu and Karapınar become more prominent towards the southern sector of the province (Keller 1974; Aydar et al. 1995; Uslular et al. 2015), where they developed largely within paleolacustrine successions comprising limestone bedrock overlain by Neogene volcano-sedimentary deposits (Kuzucuoğlu et al. 1999; Bayer-Altın et al. 2015).

Phreatomagmatic activity within the CAVP is represented by maars and a few tuff rings (Toprak 1998; Aydar et al. 2011) (Figures 1 and 2A-E). Many CAVP maars are depicted in regional geological maps and briefly described in reports published by the Mineral Research and Exploration Directorate of Türkiye (MTA) (Türkecan et al. 2004), but detailed studies remain relatively scarce. Keller (1974) was the first to describe the depositional and petrological

180 characteristics of maars and other monogenetic volcanoes in the Karapınar Monogenetic Field (KMF; Figures 1
and 2E). Gevrek and Kazancı (2000) investigated the basaltic Narlıgöl maar in the Derinkuyu Volcanic Complex
(DVC; Figures 1 and 2C) and proposed a basic morphological classification of maars based on crater size. Türkecan
et al. (2004) presented field observations and eruption scenarios for maars within the Acıgöl caldera and provided
petrological and geochronological information on the Obruk scoria cone near İcik maar. The Cora maar within the
185 Erciyes Volcanic Complex (EVC; Figures 1 and 2A) is the most extensively studied in the CAVP, with previous
studies focusing on its depositional and petrological characteristics (Gençalioglu-Kuşcu et al. 2007; Gençalioglu-
Kuşcu 2011). Aydar et al. (2011) examined several maars (Acıgöl-N, Kocadağ, and İcik) in the Nevşehir-Acıgöl
Volcanic Complex (NAVC; Figure 1), and Uslular et al. (2022) subsequently investigated their depositional and
petrological characteristics in greater detail. Other maars, such as Kutören (M15; Figures 1 and 2D), have been
190 incorporated into regional petrological studies together with volcanic rocks from surrounding monogenetic
volcanoes (Reid et al. 2017; Doğan-Külahçı et al. 2018; Uslular and Gençalioglu-Kuşcu 2019; Çubukçu et al.
2024). In addition to maars, hydrovolcanism is represented by tuff rings/cones in the NAVC (Karataş and Kuzuluk;
Aydar et al. 2011; Figure 2B) and explosion craters in both the NAVC (around Kocadağ; Druitt et al. 1995) and
KMF (Yılanobruğu, Keller 1974; Figure 2E). Geochronological data for CAVP maars are also limited (Table 1).
195 Direct absolute ages are available for only a few maars, including Cora (126-353 ka, K-Ar, Gençalioglu-Kuşcu,
2011) and Acıgöl-N (20.3 ± 0.9 ka, 2σ , U-Th/He; Schmitt et al. 2011), whereas the ages of others are constrained
indirectly by ages obtained from adjacent monogenetic volcanoes (e.g., Mekeobruğu maar, $\geq 390 \pm 90$ ka, 2σ , Ar-
Ar, Reid et al., 2017). Sediments preserved in maar lakes and playas, including those of Acıgöl-N, Narlıgöl, and
Mekegölü, have additionally been investigated as archives for paleoenvironmental reconstructions of the region
200 (Kuzucuoglu et al. 1998; Roberts et al. 2001; Roberts et al. 2016; Tuncer et al. 2019).

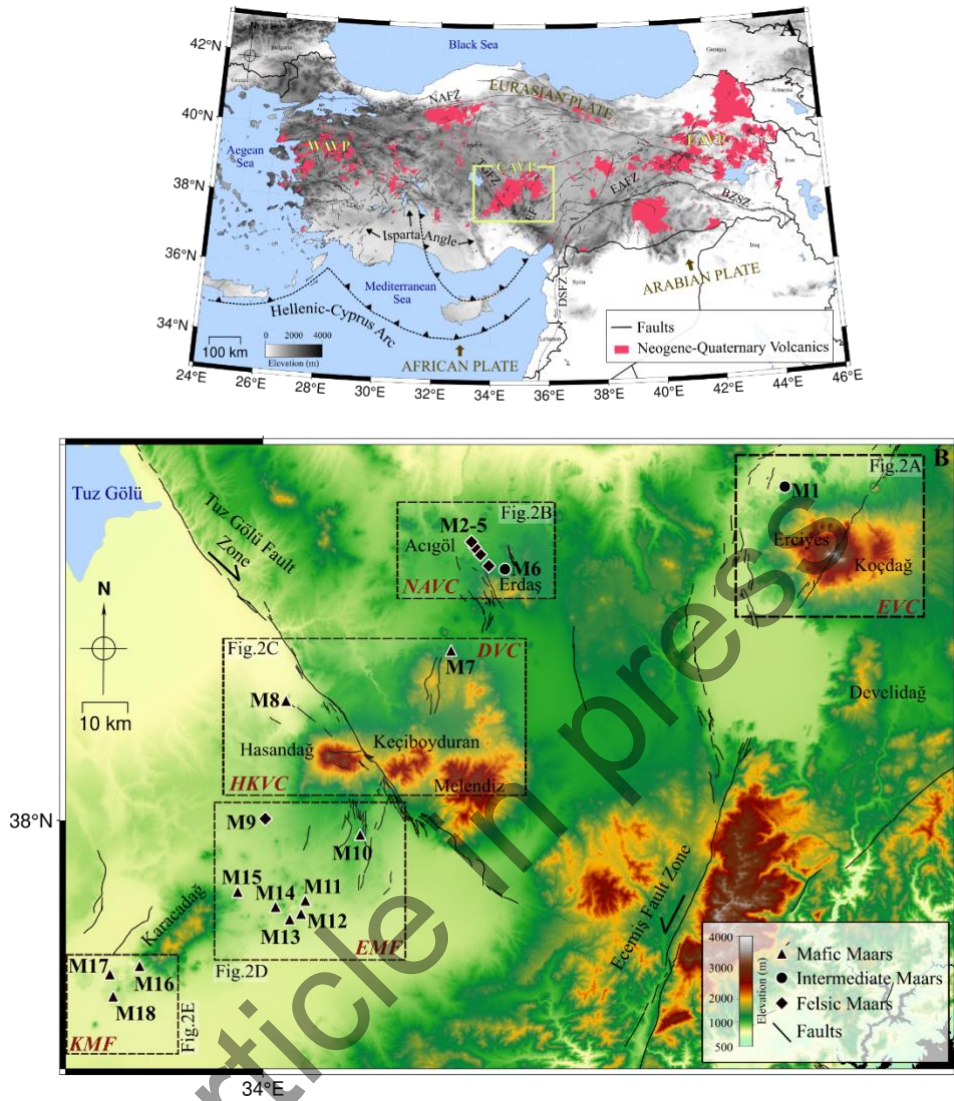


Figure 1: [A] Simplified tectonic map of Türkiye illustrating Neogene-Quaternary volcanics (compiled from Şenel 2002) and active faults (Emre et al. 2018). The shaded digital elevation model (15 arc- second global relief, SRTM15+V2.7 original) is produced using PyGMT (Tian et al. 2024) and Web-GMT tools (Salihoğlu and Uslular 2025). Abbreviations are: WAVP: Western Anatolian Volcanic Province; CAVP: Central Anatolian Volcanic Province; EAVP: Eastern Anatolian Volcanic Province; BZSZ: Bitlis-Zagros Suture Zone; DSFZ: Dead Sea Fault Zone; EAFZ: East Anatolian Fault Zone; EF: Ercemiş Fault; NAFZ: North Anatolian Fault Zone; TGFZ: Tuz Gölü Fault Zone. [B] The spatial distribution of CAVP maars and some of the polygenetic volcanoes (e.g., Hasandağ, Erciyes) is displayed on a colored relief map (3 arc-second global relief). Maar compositions are mainly from this study. The maars labelled M1 to M18 are Cora, İnallı, Kalecitepe, Acıgöl-N, Korudağ, İçik, Narlıgöl, Yıpraktepe, Obruk, Leşkeri, Karafatma, Çayankışlası, Develiini, İblizliini, Kutören, Acıgöl-K, Mekegölü, and Mekeobruğu. EVC: Erciyes Volcanic Complex; NAVC: Nevşehir-Acıgöl Volcanic Complex; DVC: Derinkuyu Volcanic Complex; HKVC: Hasandağ-Keçiboyduran Volcanic Complex; EMF: Eğrikuyu Monogenetic Field; KMF: Karapınar Monogenetic Field.

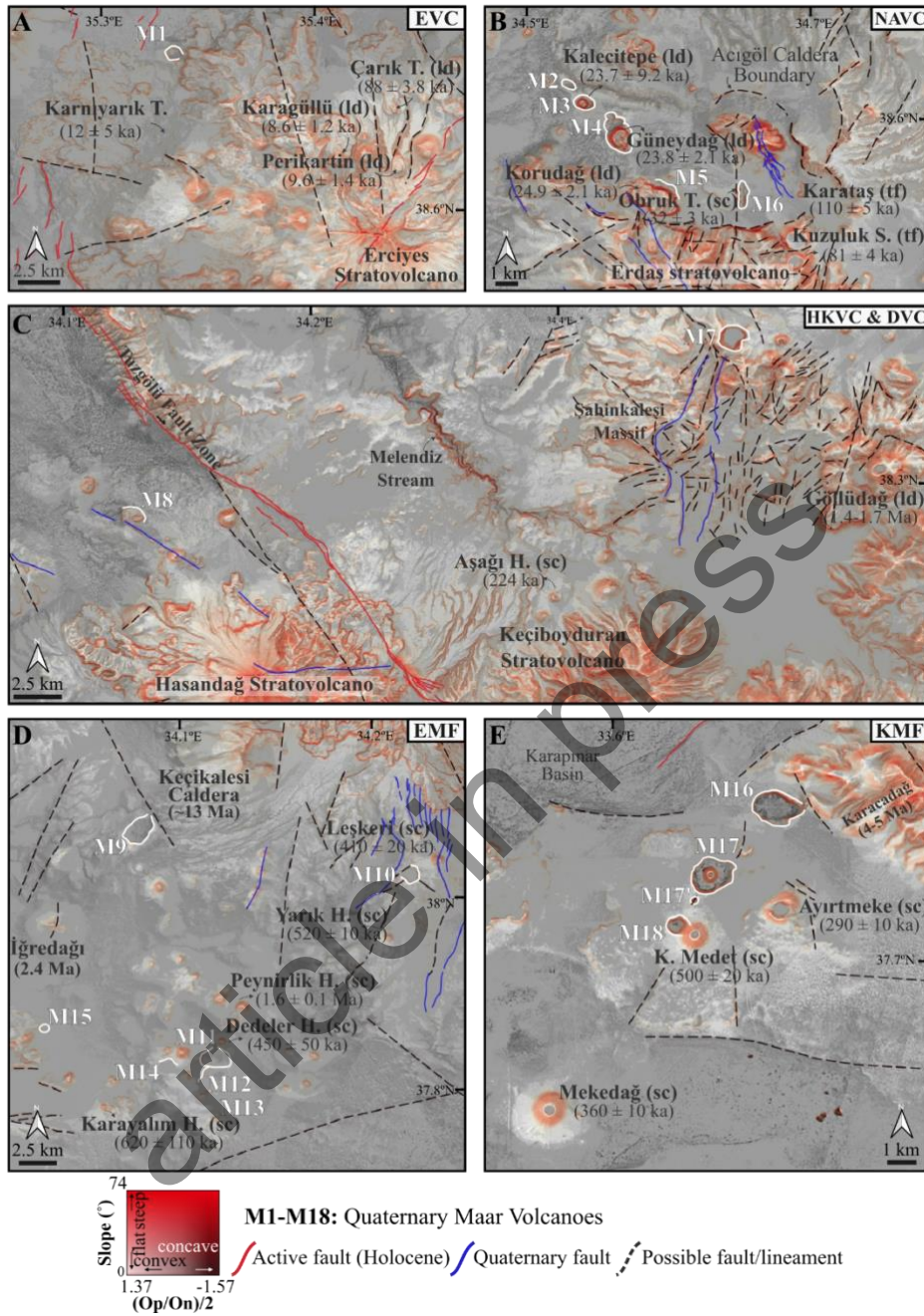


Figure 2: Red relief image maps of volcanic fields where the studied maars (M1 to M18; Table 1) are located. The maps were derived from 30 m-resolution ALOS3D DEMs. Op and On represent positive and negative openness, respectively: [A] The Erciyes volcanic complex (EVC); [B] The Nevşehir-Acıgöl caldera complex (NAVC); [C] The Hasandağ-Keçiboyduran volcanic complex (HKVC); [D] Eğrikuyu and [E] Karapınar monogenetic fields. Age data from the literature (Türkecan et al. 2004; Aydar et al. 2011; Gençalioglu-Kuşcu 2011; Schmitt et al. 2011; Aydın et al. 2014; Reid et al. 2017; Friedrichs et al. 2020, 2021). Id: lava dome; tf: tuff ring; sc: scoria cone.

3 METHODS AND MATERIALS

225 3.1 Field observations and mapping

We conducted fieldwork throughout the CAVP in 2017 and 2018 to identify representative outcrops of previously documented maars (Kazancı et al. 1995; Gevrek and Kazancı 2000; Gençalioglu-Kuşcu et al. 2007; Aydar et al. 2011) and to investigate lesser-known maars in the region. Of the 18 studied maars, 11 had accessible tephra-ring exposures thicker than 1 m and were therefore included in detailed stratigraphic and granulometric analyses.

230 Suitable exposures were not available at M3, M8, M10, M12, M13, M14, and M18 (Figure 1B). At each exposed section, we collected representative samples of the identified lithofacies from an area of $\sim 0.1 \text{ m}^2$ within the lowermost 2.5 m of the exposed stratigraphic succession for grain-size and componentry analyses. Each outcrop was also described in terms of stratigraphy, bedding characteristics (e.g., sedimentary structures, facies descriptions, thickness), and types of juvenile and lithic clasts.

235 Existing geological maps of the studied maars were revised when available, whereas new geological maps were prepared for maars that had not previously been mapped in detail (Supplementary Figure S1). To complement the field observations, 12 maars with visible topography suitable for UAV surveying and appropriate field conditions (e.g., outside settlements and military zones) were surveyed using a lightweight UAV (DJI Phantom 3 Pro). Drone images acquired with $\sim 65\text{-}70\%$ overlap ratio were processed via Agisoft Metashape Professional Edition software

240 following the Structure from Motion-Multi-View Stereo (SfM-MVS) workflow (Bemis et al. 2014). In addition to the resulting high-resolution orthomosaics and digital elevation models (DEMs), mapping incorporated WorldView 1-2 images ($\sim 50 \text{ cm}$ resolution), Google Earth images, 1/25000-scale topographic maps, and 30 m resolution ALOS (Advanced Land Observing Satellite) World 3D (ALOS3D) DEMs (Tadono et al. 2015). For regional maps of volcanic fields containing the studied maars (Figure 2), we generated red relief image maps (RRIM; Chiba et al.

245 2008) from ALOS3D DEMs using the positive (Op) and negative (On) openness calculated in SAGA GIS (Conrad et al. 2015).

We classified substrate types using lithic-clast assemblages observed in the maar deposits, together with published geological information on the underlying and surrounding lithologies. Four substrate classes were distinguished: hard, mixed type-1 (hard > soft), mixed type-2 (soft < hard), and soft.

250 3.2 Morphometric measurements

The CAVP maars with visible, complete or nearly complete ejecta rims were digitized using high-resolution UAV-derived DEMs and orthomosaics, supplemented by the satellite and topographic datasets described above. Ellipses were fitted to the ejecta rim using the “shape tools” plugin of QGIS (v. 3.6) to determine the major and minor axes, eccentricity, aspect ratio, and elongation azimuths. The fitted ellipses were visually evaluated against the mapped
255 rims to avoid imposing inappropriate elliptical geometries on strongly irregular craters. Elongation azimuths were displayed on length-weighted rose diagrams. For first-order volume estimates, each crater was assumed to be an inverted truncated cone, with the rim and crater base diameters defining the larger and smaller radii, respectively. Pre-existing topography was considered where it could be recognized from pre-maar deposits exposed along crater walls or from the inclination of preserved rim surfaces. The measured parameters included ejecta-rim diameter
260 (D_{cr}), crater-base diameter (D_b), crater depth (d_{cr}), inner crater-wall slope (S_{cr}), perimeter (P_{cr}), area (A_{cr}), and volume (crater, V_{cr} ; ejecta, V_{ejc}). The ratio-based parameters, such as aspect ratio (AR), elongation (EL), and isometric circularity (IC), were calculated following Graettinger (2018), who adopted these metrics from 2D particle-shape nomenclature (Russ 2006). Ejecta volume was estimated using the empirical relationship ($V_{ejc} = 1.24 \times V_{cr}$; Graettinger 2016; and references therein). Both crater- and ejecta-volume estimates should be regarded
265 as first-order approximations because erosion, burial, crater infill, pre-existing topography, and emplacement of later monogenetic edifices may bias the reconstructed crater geometry.

Following the crater-morphology classification of Graettinger and Bearden (2021), which considers explosion footprints and final crater planform, the studied maars were assigned to seven principal morphological types: circle, ellipse, peanut, chain, triple, teardrops, and convoluted. We also used the terms “nested” and “complex” for crater
270 geometries that were not adequately represented by these end-member classes. “Nested” was used for maars comprising superposed or closely overlapping crater depressions, whereas “complex” was used for craters displaying combinations of multiple morphological elements and/or substantial modification by associated monogenetic volcanic edifices.

3.3 Depositional terminology and granulometric analysis

275 The maar lithofacies terminology of Graettinger and Valentine (2017) was adapted to describe the CAVP maar successions. Eight recurring lithofacies were distinguished: TB_{1-3} , TB_{lens} , AT_{1-2} , AT_x , and LT, which are related to the broader categories of massive tuff breccia and lapilli tuff (TB), ash and lapilli tuff (AT), cross-bedded stratification (AT_x), and lapilli tuff (LT). The term “tuff” was used to conform to the nomenclature; however, it is

important to note that most maar deposits in the CAVP are unconsolidated. To describe the sedimentological features of the lithofacies, several key studies were followed (Fisher and Waters 1970; Schmincke et al. 1973; Wohletz and Sheridan 1979; Sohn and Chough 1989; Branney and Kokelaar 2002). Representative samples from selected lithofacies were dried and dry-sieved from -4Φ to 4Φ at 1Φ intervals, where $\Phi = -\log_{10}d$ and d is particle size in mm. Grain-size statistics, including mean, median, sorting, skewness, and kurtosis, were calculated using the GRADISTAT MS Excel Macro (Blott and Pye 2001) (Supplementary Material 1). Further methodological details are provided in Uslular (2023). Componentry was determined for the $>250\ \mu\text{m}$ ($\leq 2\Phi$) fraction of representative lithofacies samples. For each analyzed sample, 300 clasts were counted from two independent subsamples of each representative layer under a binocular microscope. The duplicate counts were used to enhance the representativeness of the componentry estimates and to reduce uncertainty in differentiating juvenile from lithic clasts. Distinguishing juvenile from recycled or accidental lithic particles was more difficult in mafic deposits containing both juvenile and pre-existing basaltic material. Therefore, the componentry results are intended to characterize the sampled lithofacies and to capture broad differences among maar successions, rather than to provide quantitative reconstructions of entire tephra-ring stratigraphies. Potential uncertainties include the limited number of sampled layers and recycling of compositionally similar volcanic clasts during successive explosions.

3.4 Juvenile clast morphology, petrography and geochemistry

The juvenile material in the mafic-intermediate and felsic maar deposits is represented predominantly by scoria and pumice clasts, respectively. For scanning electron microscope (SEM) characterization, juvenile clasts from the 4–8 mm size fraction were selected, cleaned with acetone, and dried in a stove. The clasts were then mounted on SEM stubs and coated with gold dust before imaging at the research laboratories of Muğla Sıtkı Koçman University (MSKU, Türkiye; JEOL JSM-7600F) and the University of Geneva (UNIGE, Switzerland; JEOL JSM-7001F). The SEM observations were conducted at an accelerating voltage of 15kV and a working distance of $\sim 8\ \text{mm}$. For petrographic characterization, thin sections of juvenile and lithic clasts ($n = 80$) were prepared at MSKU and UNIGE. Whole-rock major-element compositions were determined for juvenile clasts representing 12 maars (excluding M3, M8, M12–14, M18) at ACME Analytical Laboratories Ltd. (Canada) by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) after fusion. The loss on ignition (LOI) values were generally less than 5%, and LOI-free major-element compositions were used for geochemical classification. The complete major-element dataset is provided in Supplementary Material 2, and the corresponding geochemical classification is shown in Supplementary Figure S2.

4 RESULTS

310 We catalogued 18 Quaternary maars in the CAVP (M1-M18; Figures 3 and 4; Table 1), which display a wide range of compositional, morphological, and depositional characteristics. Most are mafic in composition, while M1, M6, and M17 have intermediate compositions and M2-M5 and M9 maars are felsic (Table 1; Supplementary Material 2; Supplementary Figure S2). The following sections describe their general characteristics in terms of edifice morphology, lithofacies architecture, and juvenile-clast properties.

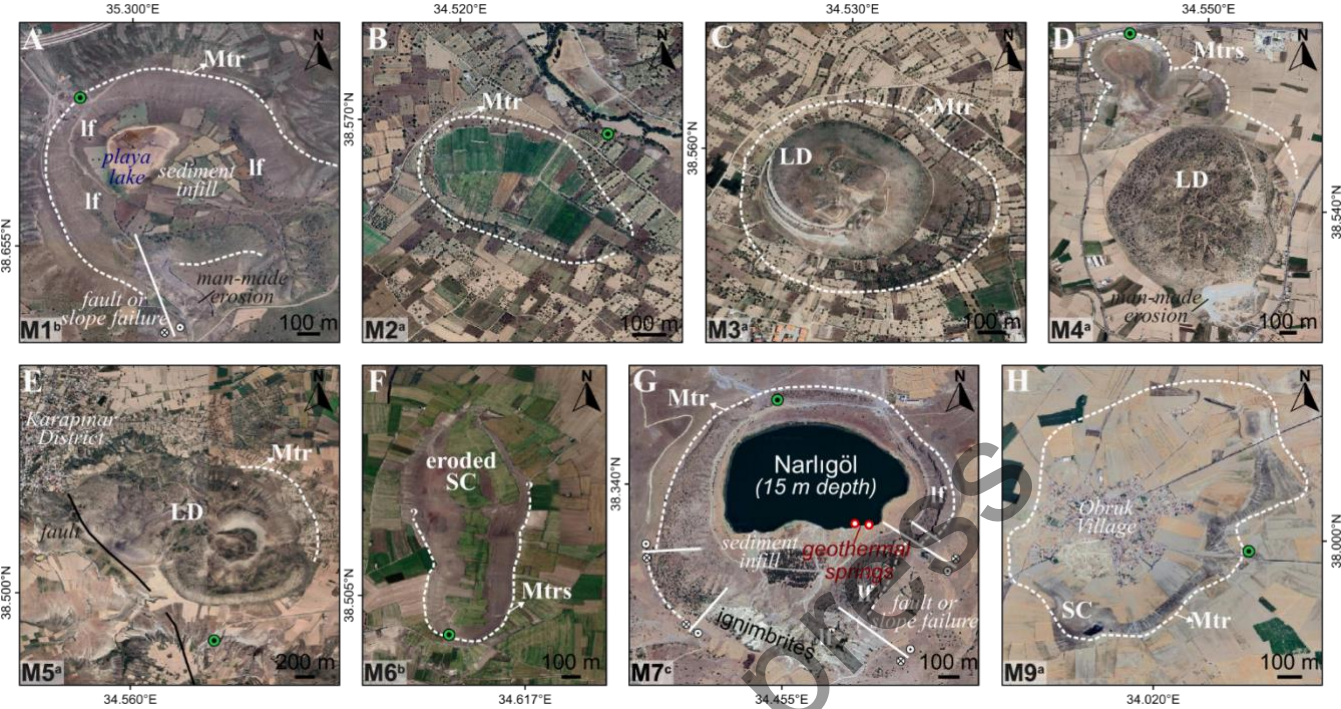
315 4.1 Edifice morphology

The CAVP maars display substantial morphological and morphometric variability (Figures 3, 4, and 5; Table 2). Their crater forms range from simple circular and elliptical depressions to nested, chain-like, convoluted, teardrop-shaped, and compound morphologies. The crater morphologies of M8 and M12-M14 are poorly preserved and cannot be reliably delineated from the available topographic data. Therefore, these maars were excluded from the
320 detailed morphometric comparison. Several maars retain well-defined, continuous tephra rings with significant inward-facing scarps (e.g., Cora, Narlıgöl, Acıgöl-K). In contrast, others display severely eroded or partially buried tephra-ring remnants (e.g., Obruk, Korudağ). Ongoing anthropogenic erosion affects the tephra rings of several maars, including Cora, Acıgöl-N, and Mekeobruğu.

Several CAVP maars are closely associated with other types of monogenetic volcanic edifices. Within the Acıgöl
325 Caldera, maars such as Kalecitepe, Acıgöl-N, and Korudağ are partly to almost completely overprinted by lava domes (Figure 3). İcik consists of coalescent craters modified by a scoria cone (Figure 3). In the southern CAVP, Kutören and Acıgöl-K are formed within or above older tuff-ring/maar structures, while Mekegölü and Mekeobruğu are spatially associated with scoria cones (Figure 4). Post-eruptive infilling is evidenced by lacustrine sediment accumulation at the crater base of several maars. Narlıgöl hosts a perennial maar lake of 15 m depth with
330 geothermal springs; Acıgöl-K contains a saline lake; and Cora, Acıgöl-N, and Obruk preserve playa lakes. Faults and slope failures affecting crater walls are identified at several sites (Cora, İcik, Narlıgöl, Leşkeri; Figures 3 and 4).

Maar (code)	Group / field	Composition	Age (ka)	Substrate	Juvenile clasts	Lithic clasts	J/L/C (%)
Cora (M1)	N / EVC	Basaltic andesite	126-353 ^b (K-Ar)	Hard	Scoria (ash-bomb); cauliflower bombs; acc.lap.	Andesite; undiff. rocks	38/60/2
İnallı (M2)	N / NAVC	Rhyolite	NA	Mixed type-1	Pumice, perlite, obsidian (ash-bomb/block)	Granite; andesite; ophiolite; ignimbrite pumice; undiff.	59/32/9
Kalecitepe (M3)	N / NAVC	Rhyolite	$\geq 23.2 \pm 9.7^c$ (U-Th/He)	Mixed type-1	NA	NA	NA
Acıgöl-N (M4)	N / NAVC	Rhyolite	20.3 ± 0.9^c (U-Th/He)	Mixed type-1	Pumice, perlite, obsidian (ash-block)	Granite; andesite; ophiolite; ignimbrite pumice; undiff.	56/28/16
Korudağ (M5)	N / NAVC	Rhyolite	$\geq 24.9 \pm 2.1^c$ (U-Th/He)	Mixed type-1	Pumice, perlite, obsidian (ash-lapilli)	Granite; andesite; ophiolite; ignimbrite pumice; undiff.	49/21/30
İcik (M6)	N / NAVC	Basaltic trachyandesite	$\geq 32 \pm 3^d$ (K-Ar)	Mixed type-1	Scoria (ash-bomb); cauliflower bombs	Rhyolite; andesite; pumice; obsidian; undiff.	35/54/11
Narlıgöl (M7)	C / DVC	Basalt	NA	Mixed type-1	Scoria (ash-lapilli)	Basalt; ignimbrite; altered rocks; undiff.	26/58/16
Yıpraktepe (M8)	C / HKVC	Basalt	$\geq 34 \pm 7^e$ (K-Ar)	NA	NA	NA	NA
Obruk (M9)	C / EMF	Rhyolite	NA	Soft	Pumice (ash-lapilli)	Lacustrine sedimentary rocks	57/33/10
Leşkeri (M10)	C / EMF	Basalt	NA	Mixed type-2	NA	NA	NA
Karafatma (M11)	C / EMF	Basalt	NA	Mixed type-2	Mostly ash-size juvenile; rare scoria lapilli	Lacustrine sedimentary rocks	22/51/27
Çayankışlası (M12)	C / EMF	NA	NA	NA	NA	NA	NA
Develiini (M13)	C / EMF	NA	NA	NA	NA	NA	NA
İblizliini (M14)	C / EMF	NA	NA	NA	NA	NA	NA
Kütören (M15)	S / EMF	Basalt	1300 ± 100^f (Ar-Ar)	Mixed type-2	Scoria (ash-bomb); acc.lap.	Tachylite-bearing tuff; ignimbrite; undiff. sedimentary rocks	18/44/38
Acıgöl-K (M16)	S / KMF	Basalt	NA	Mixed type-2	Scoria (ash-bomb); acc.lap.	Mafic lava; tuff-ring deposits; lacustrine sediments	35/61/4
Mekegölü (M17)	S / KMF	Basaltic andesite	NA	Mixed type-2	Scoria (ash-bomb); acc.lap.	Mafic lava; lacustrine sediments	NA
Mekeobruğu (M18)	S / KMF	Basaltic andesite ^a	$\geq 390 \pm 90^f$ (Ar-Ar)	Mixed type-2	Scoria (ash-lapilli)	Undiff. sediments	NA

N, C, and S = northern, central, and southern groups; J/L/C = juvenile/lithic/crystal fractions in the 0.25-16 mm size range; AL = accretionary lapilli; undiff. = undifferentiated; NA = data not available; Mixed types 1-2 are the substrate classes defined in the manuscript; ^a Keller (1974); ^b Gençalioglu-Kuşcu (2011); ^c Schmitt et al. (2011); ^d Türkecan et al. (2004); ^e Aydar et al. (1995); ^f Reid et al. (2017).



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Figure 3: Representative examples of maar morphologies in the northern and central sectors of the CAVP: [A] Cora (M1) maar with a circular crater, a well-preserved tephra-ring (Mtr) and pre-maar lava flows (If); [B] İnallı maar (M2), displaying an elliptical crater morphology; [C] Kalecitepe maar (M3), partly infilled by a central lava dome (LD); [D] Acigöl-N maar (M4), comprising coalescent craters, one of which is filled by a lava dome; [E] Korudağ maar (M5), with lava dome emplacement deforming the crater rim; [F] İcik maar (M6), comprising coalescent craters affected by a scoria cone (SC) interpreted as coeval with or younger than maar formation; [G] Narlıgöl maar (M7), hosting a crater lake and an active hydrothermal system; [H] Obruk maar (M9), excavated into lacustrine sediments. Google Earth images are preferred as the background for consistent visualization across all maars, while maar rims and other geomorphological features were delineated using UAV-based models. Detailed geological maps of maars, mainly illustrated on high-resolution hillshades, are presented in Supplementary Figure S1. Superscripts a, b, and c appended to the maar labels indicate felsic, intermediate, and mafic compositions, respectively. Green circles with black centers mark outcrops used for stratigraphic sections. White lines indicate mapped faults or slope failures, whereas circles containing dots and crosses mark the relatively elevated and collapsed sides, respectively.

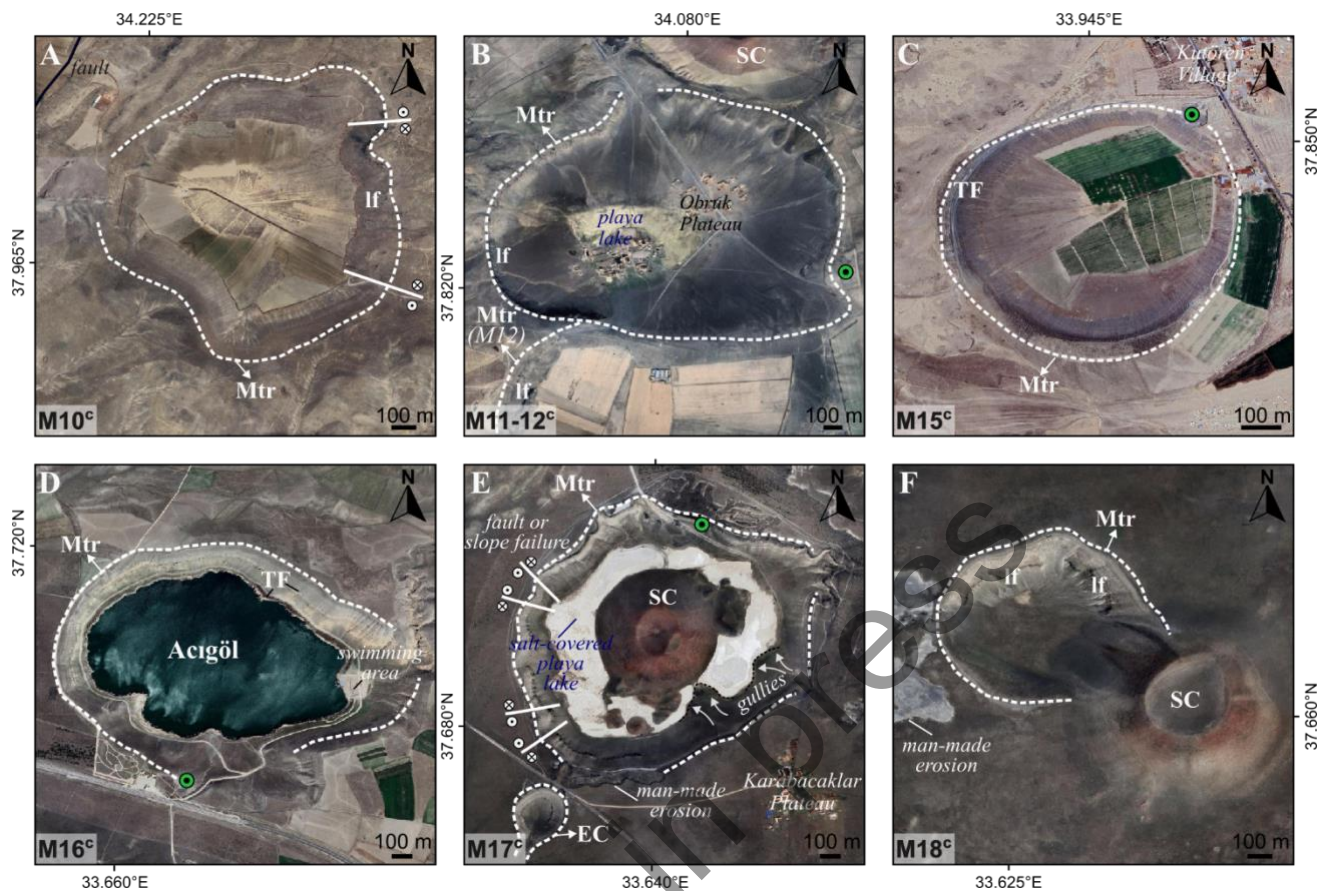


Figure 4: Representative maar morphologies from the central-southern and southern sectors of the CAVP (Karapınar and Eğrikuyu monogenetic fields): [A] Leşkeri maar (M10), where no suitable tephra-ring outcrop is exposed; [B] Karafatma maar (M11), partly filled by playa deposits and seasonal settlements, with well-exposed tephra-ring (Mtr) deposits and pre-maar lava flows (If). The western rim of Çayankışlası maar (M12), for which no suitable outcrop is available, is also visible; [C] Kutören maar (M15), emplaced within an older tuff ring (TF); [D] Acıgöl-K maar (M16), with well-exposed tephra-ring deposits and a crater lake bounded partly by older tuff ring deposits; [E] Mekegölü maar (M17), showing tephra-ring deposits along the northern rim and pre-maar lava flows, with its crater morphology deformed by a scoria cone (SC) and several satellite cones; gullies and man-made erosions are also evident. The maar lake has dried in recent decades, leaving a salt cover; [F] Mekeobruğu maar (M18) has a tilted southeastern crater rim due to the emplacement of a scoria cone. No suitable proximal tephra-ring outcrops are exposed here, except for pre-maar lava flows observed around the crater. Google Earth images were used as the background for consistent visualization of all maars, whereas the boundaries of the maar rim and other features were determined from UAV-based models. Detailed geological maps of maars, mainly illustrated on high-resolution hillshades, are available in Supplementary Figure S1. Superscripts a, b, and c appended to the maar labels indicate felsic, intermediate, and mafic compositions, respectively. Green circles with black centers mark outcrops used for stratigraphic sections. White lines indicate mapped faults or slope failures, whereas circles containing dots and crosses mark the relatively elevated and collapsed sides, respectively.

Most CAVP maars have near-circular to slightly elliptical crater outlines, with aspect ratios (AR) ranging from 0.30 (İcık) to 0.96 (Karafatma, Kutören), and isoperimetric circularity (IC) values ranging between 0.63 and 1.00 (Table 2). Kutören is the only maar with a perfect IC of 1.00, indicating a near-ideal circular form (Figure 4). In contrast, İcık has the most elongated planform (AR = 0.30) and displays a chain-type crater morphology. Similarly, Acıgöl-N is also highly elongated (AR = 0.58; IC = 0.65) and has a complex chain structure with a multi-crater footprint comprising five nested or coalescent sub-craters. Crater elongation azimuths show preferred orientations spanning N25° to N159° (Figure 5; Table 2), with clustering in NE-SW to E-W directions across different sectors of the CAVP.

Crater rim diameters (D_{cr}) vary widely across the CAVP maars. Among morphometrically well-constrained maars, D_{cr} values range from ~317 m (Yılanobruğu) to ~1970 m (Karafatma). Larger diameter estimates were obtained for the felsic Obruk (2041 ± 646 m), Acıgöl-N (2144 ± 577 m), and Korudağ (2747 ± 445 m) maars. However, their convoluted or complex crater outlines, degraded tephra rings, and large measurement uncertainties limit the representativeness of single diameter estimates. Crater base diameters (D_b) consistently represent a substantial proportion of D_{cr} , ranging from approximately 42% (İnallı, $D_b/D_{cr} = 0.42$) to 75% (Karafatma, $D_b/D_{cr} = 0.65$). Korudağ is a notable exception with $D_b/D_{cr} \sim 0.72$ due to its almost complete deformation via lava dome emplacement. Crater depths (d_{cr}) range from 20 ± 5 m (İnallı, M2) to 105 ± 41 m (Narlıgöl), with relatively large values also recorded at Cora (91 ± 13 m) and Acıgöl-K (80 ± 19 m; Figure 5A; Table 2). Inner crater-wall slopes (S°) change from $4^\circ \pm 1^\circ$ (Karafatma, Obruk) to $32^\circ \pm 4^\circ$ (Yılanobruğu), with most maars displaying slopes of 10-23°. The lowest slopes ($\leq 6^\circ$) are recorded at Karafatma, Obruk, and Kutören, all of which are located above mixed type-2 or soft substrate. The relatively steepest slopes ($\geq 19^\circ$) occur at Yılanobruğu (32°), Narlıgöl (23°), Mekegölü (20°), and Cora (19°). Rim asymmetry also varies among the maars, with significant asymmetry at Narlıgöl and a comparatively uniform rim at İnallı. The largest depth-to-diameter ratios ($d_{cr}/D_{cr} \times 10^{-3}$) occur at Mekeobruğu (~109), Yılanobruğu (~101), Cora (~78), Narlıgöl (~70), and Acıgöl-K (~48). Lower ratios are recorded in broader, shallower craters such as Obruk (~24), Karafatma (~28), Kalecitepe (~30), and İnallı (~32; Figure 5B).

Estimated crater volumes (V_{cr}) range from 0.001 km³ at Kutören to 0.139 km³ at Narlıgöl (Table 2). The four largest crater volumes occur at Narlıgöl (0.139 km³), Acıgöl-K (0.109 km³), Mekegölü (0.061 km³), and Karafatma (0.058 km³). Among the felsic maars for which volume estimates are available, Acıgöl-N has the largest crater volume (0.026 km³), followed by Obruk (0.015 km³), Kalecitepe (0.006 km³), and İnallı (0.002 km³). Ejecta volumes (V_{ejc}), estimated as $V_{cr} \times 1.24$ (Graettinger, 2016), range from ~0.001 km³ (Kutören, Yılanobruğu) to ~0.172 km³ (Narlıgöl). The largest estimated ejecta volumes correspond to Narlıgöl, Acıgöl-K (0.135 km³), Mekegölü (0.075 km³), and Karafatma (0.072 km³).

405 **Table 2: The mean values of morphometric parameters for the CAVP maars**

Maar (code)	Crater Type ^a	EL(°) ^b	AR	IC	Footprint ^a	D _{cr} (m) ^c	D _b (m)	d _{cr} (m)	S°	V _{cr} (km ³) ^d	V _{ejc} (km ³) ^e
Cora (M1)	Circle	125	0.88	0.88	1	1167±17	632±66	91±13	19±3	0.045	0.056
İnallı (M2)	Ellipse	113	0.70	0.82	2	621±85	260±52	20±5	7±1	0.002	0.002
Kalecitepe (M3)	Nested	102	0.94	0.97	2*	938±51	628±20	28±15	10±3	0.006	0.007
Acıgöl-N (M4)	Chain, Complex	159	0.58	0.65	5*	2144±577	427±218	38±14	11±4	0.026	0.032
Korudağ (M5)	Convoluted	-	-	-	na	2747±445	1970±100	29±1	-	-	-
İcik (M6)	Chain	4	0.30	0.63	3*	757±188	296±127	44±17	11±6	0.010	0.012
Narlıgöl (M7)	Ellipse (partly eroded)	95	0.82	0.90	1	1490±150	975±15	105±41	23±3	0.139	0.172
Obruk (M9)	Eroded, Convoluted	59	0.61	0.84	na	2041±646	1416±520	50±25	4±1	0.015	0.018
Leşkeri (M10)	Circle	74	0.90	0.76	1	1269±68	754±73	33±18	12±6	0.006	0.007
Karafatma (M11)	Circle	86	0.96	0.95	1	1970±40	1185±275	55±13	4±1	0.058	0.072
Kutören (M15)	Circle	77	0.96	1.00	2*	726±16	547±13	23±11	6±1	0.001	0.001
Acıgöl-K (M16)	Nested	97	0.88	0.88	2*	1662±105	1146±131	80±19	22±6	0.109	0.135
Mekegözü (M17)	Nested	56	0.87	0.90	4*	1610±110	1220±50	73±31	20±7	0.061	0.075
Yılanobruğu (M17')	Teardrop	25	0.78	0.92	1	317±39	181±29	71±5	32±4	0.002	0.002
Mekeobruğu (M18)	Nested	77	0.89	0.94	2*	906±55	569±57	99±30	19±2	0.041	0.050

^a The crater morphologies are from Graettinger and Bearden (2021); Maars with aspect ratios greater than 0.90 are considered as circular

^b The main elongation (EL) azimuth trends were measured from the ellipses fitted to the maar crater rims

410 ^c The crater diameters denote the whole length of the ejecta rim. Errors represent a 1σ standard deviation, calculated by averaging the long and short axes of each measurement.

^d The volumes were measured from crater rim to base on high-resolution UAV-based DEMs (except for Korudağ, Obruk, and Leşkeri maars)

^e The ejecta volumes were calculated using the formula of $V_{ejc} = V_{cr} \times 1.24$ (Graettinger, 2016 and references therein)

* Maars include footprints of the adjacent monogenetic volcano

AR: aspect ratio; IC: isoperimetric circularity

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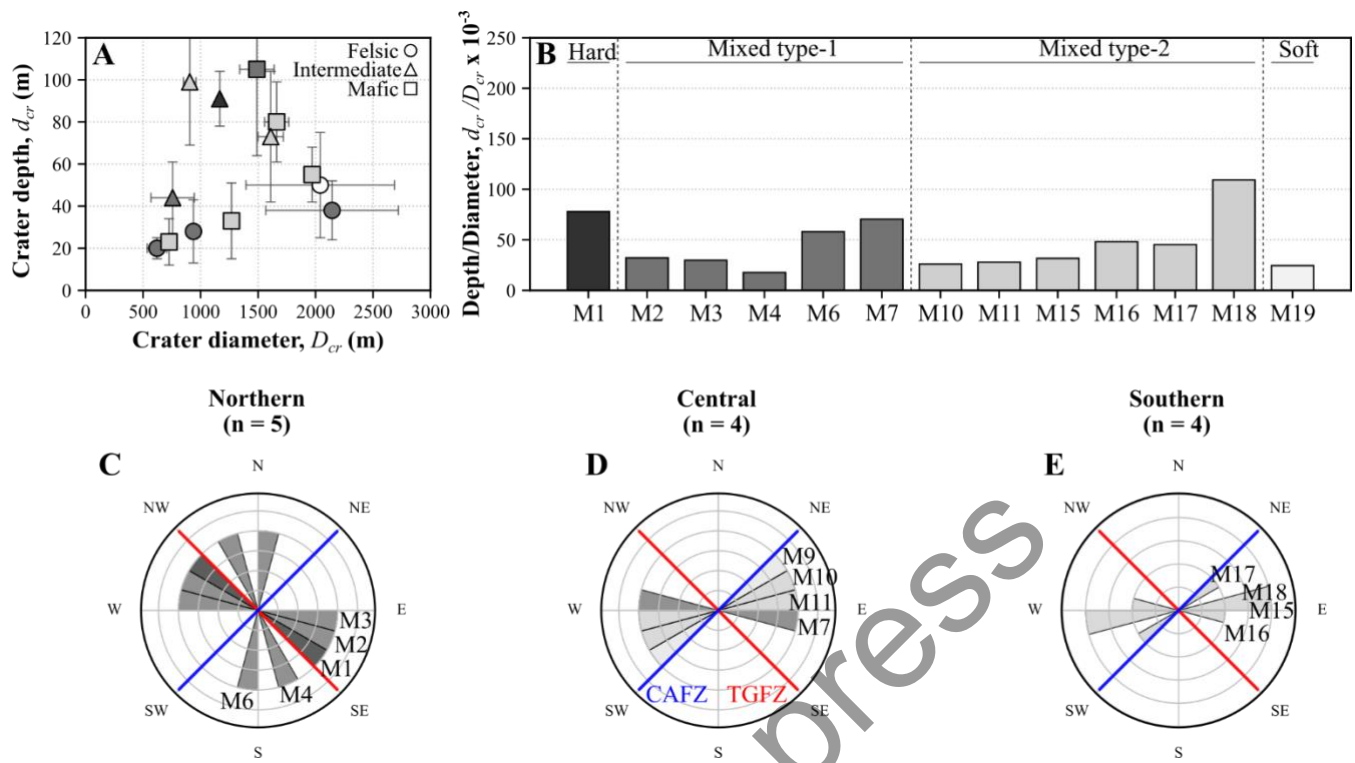


Figure 5: Morphometric characteristics and crater-elongation trends of CAVP maars; [A] Crater diameter (D_{cr}) vs crater depth (d_{cr}) for measured CAVP maars, with symbols coded by magma composition. Error bars represent measurement uncertainty derived from DEM-derived profiles. [B] Depth-to-diameter ratios ($d_{cr}/D_{cr} \times 10^{-3}$) arranged by substrata classes (hard, mixed type-1, mixed type-2, and soft). [C-E] Rose diagrams of crater elongation azimuths for maar in different sectors of the CAVP. Red and blue lines indicate the approximate orientations of Tuz Gölü Fault Zone (TGFZ) and Central Anatolian Fault Zone (CAFZ), respectively.

4.2 Lithofacies architecture

425 The tephra-ring successions of the CAVP maars display substantial variability in lithofacies and sedimentological characteristics (Figures 6A-F, 7A-M, 8A-N, and 9). Eight recurring lithofacies (TB_{1-3} , TB_{lens} , AT_{1-2} , AT_x , LT) were distinguished from the available outcrops (Figure 6A-F). These lithofacies occur in varying proportions and alternate vertically and, where exposed, laterally within the maar successions. Their general sedimentological and textural characteristics are described below:

430 **Massive Tuff Breccia (TB_1):** This facies corresponds broadly to the TB_m facies of Graettinger and Valentine (2017) and consists of thick, matrix- to clast-supported breccia beds that lack internal stratification (Figures 6A-B, 7F, and 8). TB_1 deposits are very poorly sorted and contain ash-to-lapilli-dominated matrices with abundant large lithic blocks derived from local basement or country rocks. Juvenile clasts are rare to subordinate. Clasts are generally angular to subangular, randomly oriented, and enclosed within a chaotic, structureless fabric. Beds are typically decimeters to meters thick and locally occupy depressions or channel-like geometries, as observed at Cora (M1; Figures 6A, 7A-B, and 9). Impact sags and bomb-rich intervals occur locally, including at Narlıgöl (M7; Figures 7H and 9).

Analyzed TB_1 samples from Cora, İnallı, Narlıgöl, and Acıgöl-K have median grain sizes ranging from -2.43 to 0.69ϕ and sorting values of 1.49 - 2.70ϕ (Supplementary Material 1). The grain-size distributions commonly exhibit significant coarse tails, with D_{10} values ranging from -4.34 to -2.09ϕ . Fractions between -4 and -1ϕ constitute a substantial proportion of several samples, although the relative abundance of coarse and fine material varies considerably among the analyzed TB_1 deposits.

445 **Stratified Tuff Breccia (TB_2):** TB_2 comprises crudely to moderately stratified beds characterized by alternating ash-rich and lapilli-to-block-rich layers (Figures 6B, 7D-G, 8B-C, and 9). Beds are typically centimeters to decimeters thick, with undulating contacts and moderate sorting. Internal structures include weak normal grading, low-angle cross-stratification, occasional erosional scours, and locally deformed bedding. Some successions also contain transported or embedded lithic clasts within finer-grained layers, together with soft-sediment deformation structures and locally derived clast-rich fragments (e.g., İnallı, M2; Figures 6B and 7D; Obruk, M9; Figure 7M). Similar disruption of otherwise stratified successions occurs at İcik, Karafatma, Kutören, and Acıgöl-K maars (Figures 7E, 7G, and 8B-C).

The analyzed TB_2 samples from İcik are among the coarsest samples in the dataset, with median grain sizes of -4.06 to -2.38ϕ and sorting values of 2.29 - 2.44ϕ (Supplementary Material 1). The -4ϕ fraction alone reaches 31.5-53.3 wt.%, consistent with their strongly coarse-skewed grain-size distributions.

Massive Tuff Breccia (TB₃): TB₃ consists of poorly sorted, massive, juvenile-rich breccia beds dominated by
455 blocky pumice and obsidian clasts within an ash-to-lapilli-dominated matrix (Figures 6B, 7D-F and 9). Lithic
fragments are sparse, and internal bedding or sedimentary structures are absent. These deposits are typically thick
and laterally continuous and commonly occur in the upper parts of the exposed felsic maar successions (İnallı,
Acıgöl-N, and Korudağ; Figures 6B, 7D-F and 9).

The analyzed TB₃ sample from Acıgöl-N has a median grain size of -1.07ϕ , a mean of -0.85ϕ , and a sorting value
460 of 1.67ϕ (Supplementary Material 1). The dominant grain-size classes are -2 , -1 , and 0ϕ , which together account
for most of the deposit and support the field description of TB₃ as coarse lapilli- to block-bearing, juvenile-rich
facies.

Lithic-rich Lenses (TB_{lens}): Lithic-rich lenses occur as lensoidal, clast-rich accumulations typically intercalated
within finer-grained AT deposits (Figures 6C, 7E-F, 7I, and 9). These deposits are poorly sorted, commonly clast-
465 supported, and confined to topographic lows or channel-like depressions. They have sharp basal contacts, diffuse
upper contacts, and limited lateral continuity and generally lack internal grading or lamination. Representative
examples are from Cora, Acıgöl-N, and Narlıgöl maars (Figures 6C, 7A, 7E and 7I).

Ash and Lapilli Tuff (AT₁): AT₁ corresponds broadly to the AT facies of Graettinger and Valentine (2017) and
consists of thinly bedded to finely laminated successions dominated by coarse to fine ash with minor fine lapilli
470 (Figures 6D, 7A-C, 7H-I, 7M, and 9). Beds are planar, laterally continuous, and typically millimeter- to centimeter-
thick. Lithic fragments are rare or absent. Accretionary lapilli occur in some successions (Cora and Acıgöl-K maars;
Figures 6D, 7C and 8H), while occasional impact sags locally deform lamination (e.g., Cora and İcik maars). The
deposits lack tractional features and are characterized instead by fine, parallel stratification.

Analyzed AT₁ samples from Cora, İcik, Narlıgöl, and Acıgöl-K have median grain sizes ranging from -1.34 to 1.71
475 ϕ and sorting values of 1.76 - 2.46ϕ (Supplementary Material 1). The 0 - 2ϕ fractions are commonly dominant,
although some samples contain significant coarse tails.

Ash and Lapilli Tuff (AT₂): AT₂ is defined by planar-bedded, finely stratified deposits characterized by repeated
normal grading (Figures 6E, 7D-G, 8L, and 9). Individual beds commonly show basal coarse ash to fine lapilli that
grade upward into finer ash and are separated by sharp contacts. Beds range in thickness from centimeters to
480 decimeters and commonly exhibit good lateral continuity. Ripple, dune, and cross-stratified bedforms are absent.
Representative successions are found in the İnallı, Acıgöl-N, İcik, and Korudağ maars (Figures 6E and 7).

The analyzed AT₂ samples have median grain sizes of -0.17 to 0.95ϕ and sorting values of 1.22 to 2.38ϕ
(Supplementary Material 1). The 0 - 2ϕ fractions are generally dominant, although some samples contain a
substantial coarse lapilli component.

485 **Ash and Lapilli Tuff (AT_x):** AT_x consists of laminated and stratified deposits displaying abundant tractional structures, including ripple marks, climbing ripples, cross-bedding, dune forms, and low-angle stratification (Figures 6F, 7K-M, 8A-G, and 9). Alternating ash- and lapilli-rich beds from rhythmic successions are rich in sedimentary structures. Cross-stratified and dune-bearing beds are well exposed in Obruk, Kutören, and Acıgöl-K

490 AT_x is the finest and best-sorted lithofacies among the analyzed samples. Samples from Obruk and Karafatma have median grain sizes of 0.65-2.49 ϕ , mean grain sizes of 0.48-2.35 ϕ , and sorting values of 0.64-1.51 ϕ (Supplementary Material 1). Fractions between 2 and 3 ϕ dominate many samples, with the 2 ϕ fraction often forming the modal class.

Lapilli Tuff (LT): comprises well-sorted, lapilli-supported deposits rich in juvenile clasts, with only minor ash
495 matrix and few lithics (Figures 6D, 7L, 8C, 8L-N, and 9). Beds are structureless to weakly stratified and laterally continuous over tens of meters, typically decimeters thick. LT units are frequently intercalated with AT facies, particularly AT_x and AT₂, as documented in Obruk, Kutören, and Mekegölü maars (Figures 6D, 7L, 8C, and 8L-N).

4.2.1 Other interbedded and associated deposits

500 In addition to the eight maar lithofacies described above, several successions contain volcanoclastic sedimentary interbeds and deposits associated with adjacent monogenetic volcanic edifices. These units are distinguished from the primary maar lithofacies on the basis of their sedimentological characteristics, stratigraphic position, and/or spatial relationship to the logged maar successions, and are described separately below:

Volcanoclastic sedimentary deposits (v-sed.): These deposits occur locally interbedded with the maar
505 successions, particularly at Obruk, Karafatma, and Mekegölü maars (Figures 7M, 8A-B and 8K-M). They include massive, poorly sorted volcanoclastic deposits, some of which display lahar-like characteristics. At Mekegölü, a distinctive, massive, and poorly sorted volcanoclastic unit separates the lower and upper maar deposits. It consists of a pinkish, ash-sized matrix containing lapilli-sized lithic clasts and locally scoria bombs (Figure 8K-L).

Scoria-rich deposits (sr): Scoria-rich units occur locally through the upper sections of the maar successions at
510 Karafatma, Narlıgöl, and İcik (Figures 7G and 8A). At Karafatma and Narlıgöl, these comprise well-sorted, clast-supported beds of angular to subangular scoria lapilli. At İcik, matrix-supported scoria-bearing units contain partly deformed scoria lapilli and bombs up to ~50 cm in diameter (Figure 7G) and locally display wavy to erosive contacts and soft-sediment deformation. These deposits are distinguished based on their abundance of coarse scoriaceous material, and their assignment to individual source vents is not attempted in this study.

515 **External tuff-ring deposits (tf):** Lithologically distinct tuff and hyaloclastite deposits occur locally beneath the
maar successions at Kutören and Acıgöl-K (Figure 8E and 8I-J). These deposits are exposed along the lower parts
of the crater walls and are separated from the overlying maar deposits by unconformable contacts. At Kutören,
grey, tachylyte-bearing tuffs containing lithics crop out in the northwestern part of the crater (Figure 8E). At Acıgöl-
K, palagonitized hyaloclastites intercalated with thin beige lacustrine tufa layers are exposed along the lower maar-
520 lake rim, whereas beige to brown tachylyte-bearing tuffs occur on the lower part of the northern crater wall (Figure
8I-J).

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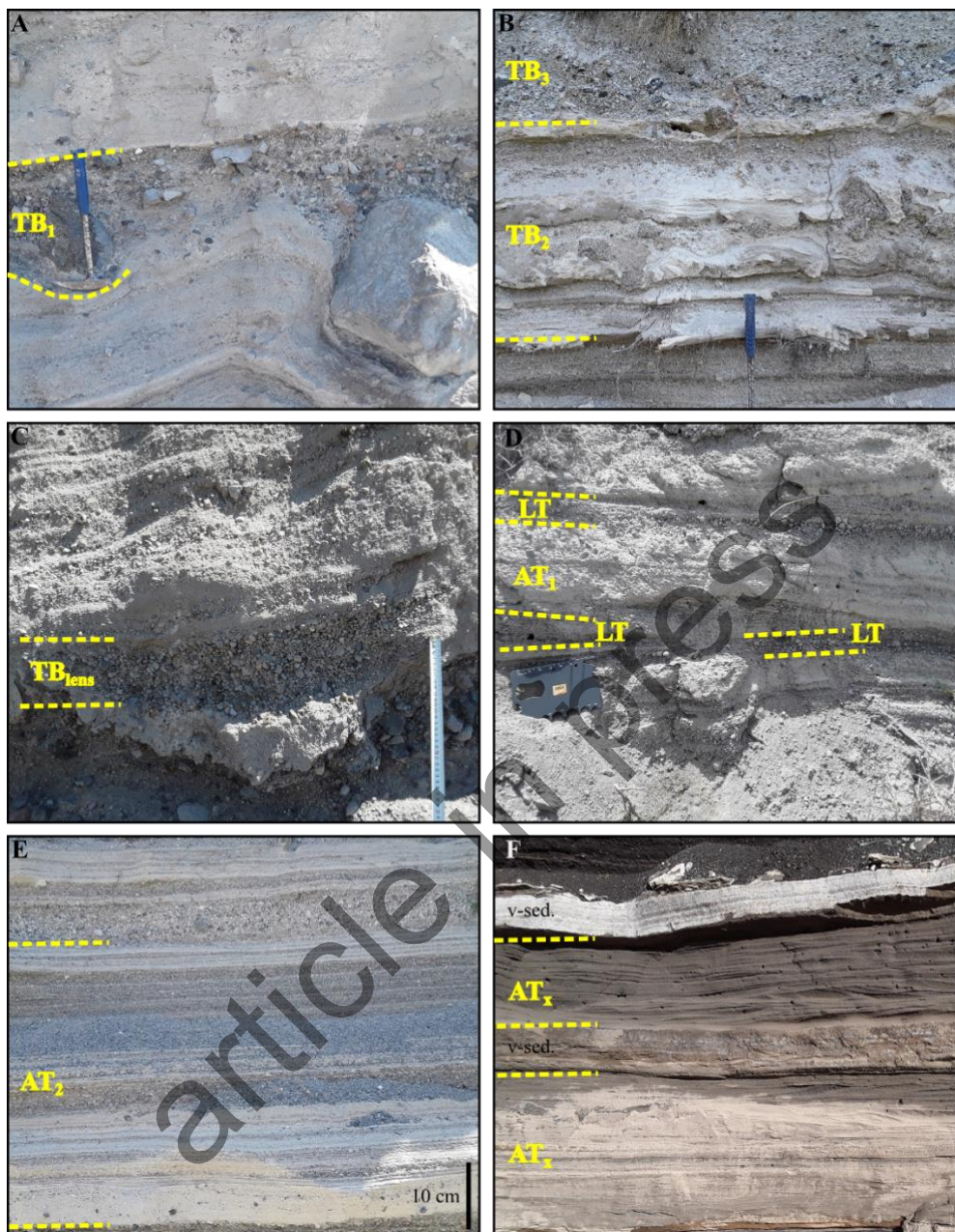


Figure 6: Representative close-up field photographs of the eight lithofacies identified in the CAVP maar tephra-ring successions. [A] Massive tuff breccia (TB₁) at Cora Maar (M1); [B] Stratified tuff breccia (TB₂) overlain by juvenile-rich massive tuff breccia (TB₃) at İnallı Maar (M2); [C] Lithic-rich lens (TB_{lens}) intercalated within finer-grained ash and lapilli tuff (AT₁) deposits at Cora Maar; [D] Lapilli tuff (LT) intercalated AT₁ deposits at Acıgöl-K maar (M16); [E] Stratified and graded ash and lapilli tuff (AT₂) at Acıgöl-N maar (M4); and [F] Cross-stratified ash and lapilli tuff (AT_x), locally separated by a volcaniclastic sedimentary interbed (v-sed.), at Karafatma maar (M11). Yellow dashed lines mark selected lithofacies boundaries. Hammer, ruler, scale card, and scale bar provide scale.

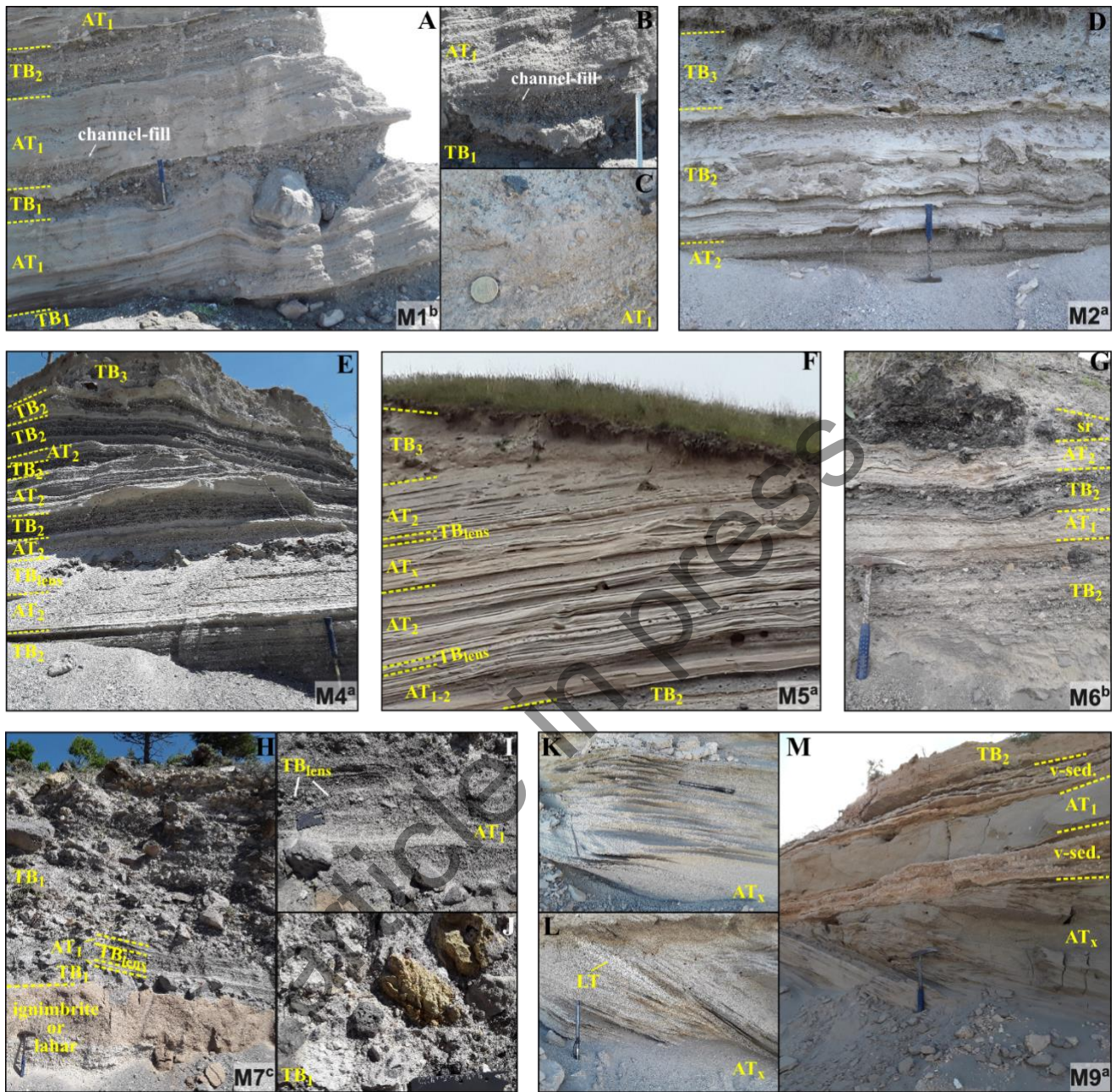


Figure 7: Field photographs of maar outcrops from the northern to central parts of the CAVP (M1, M2, M5, M6, M7, and M9), showing stratigraphic successions and lithofacies variability. Outcrops display alternations of massive and stratified tuff breccias (TB₁₋₃), ash and lapilli tuffs (AT₁₋₂, AT_x), laminated tuffs (LT), and lithic-rich lenses (TB_{lens}). Channel-fill structures (M1, M2), cross-stratification (M5, M9), lithic-rich intercalations (M7), and sedimentary features such as scour surfaces and stratified bedding highlight the complex depositional processes active during maar-forming eruptions. v-sed: volcanoclastic sedimentary deposits; sr: scoria-rich deposits. Superscripts a, b, and c appended to the maar labels indicate felsic, intermediate, and mafic compositions, respectively.

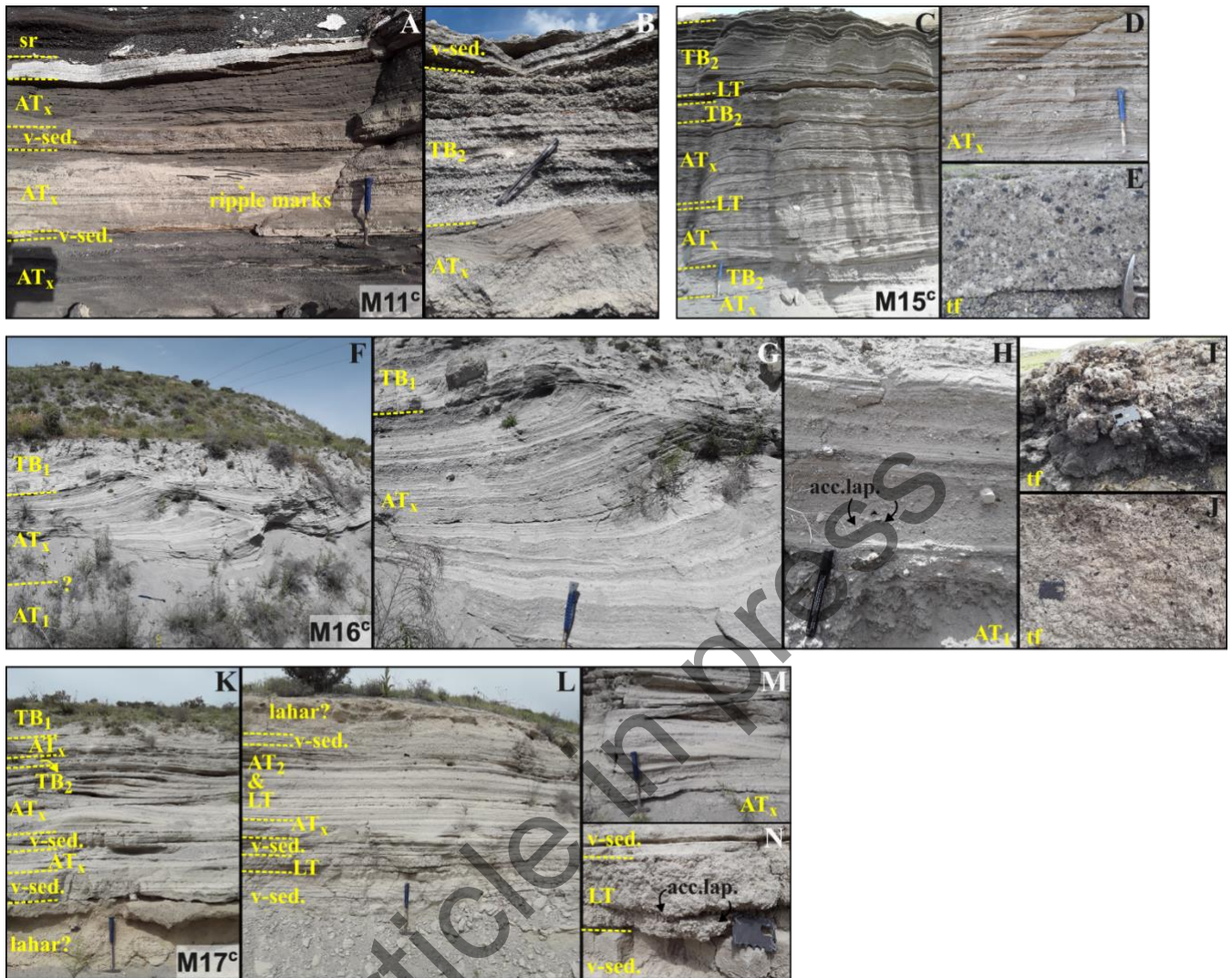


Figure 8: Field photographs of representative outcrops from the central to southern parts of the CAVP maars (M11, M15, M16, and M17), illustrating the complex stratigraphic architecture and diversity of pyroclastic facies. Outcrops display alternations of massive to stratified tuff breccias (TB₁₋₂), ash and lapilli tuffs (AT₁₋₂, AT_x), laminated tuffs (LT), scoria-rich deposits (sr), and volcaniclastic sedimentary interbeds (v-sed.). Features such as ripple marks, cross-stratification, accretionary lapilli (acc.lap.), and lahar-like units are locally present, reflecting highly variable eruptive and depositional dynamics within maar successions. Superscripts a, b, and c appended to the maar labels indicate felsic, intermediate, and mafic compositions, respectively.

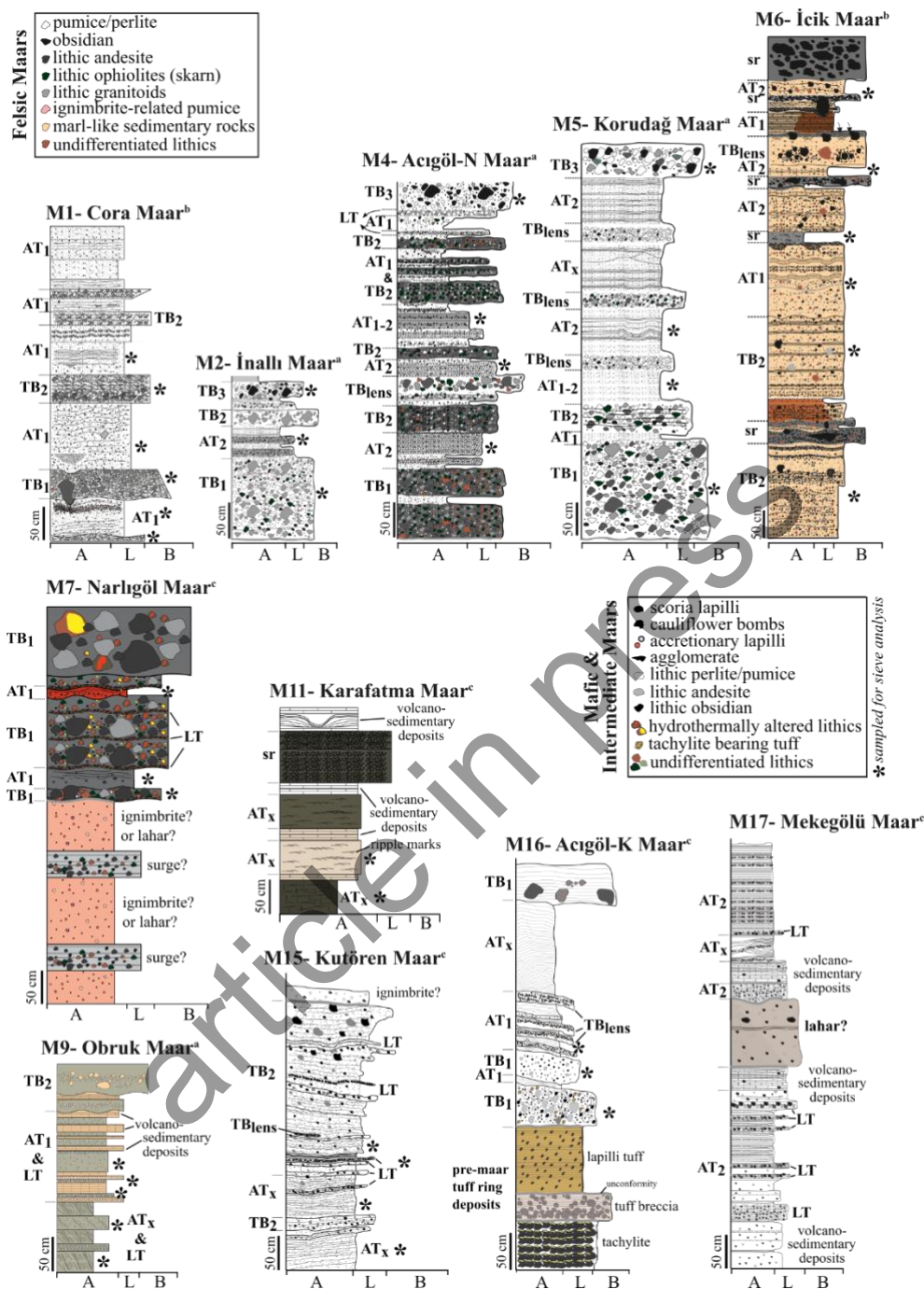


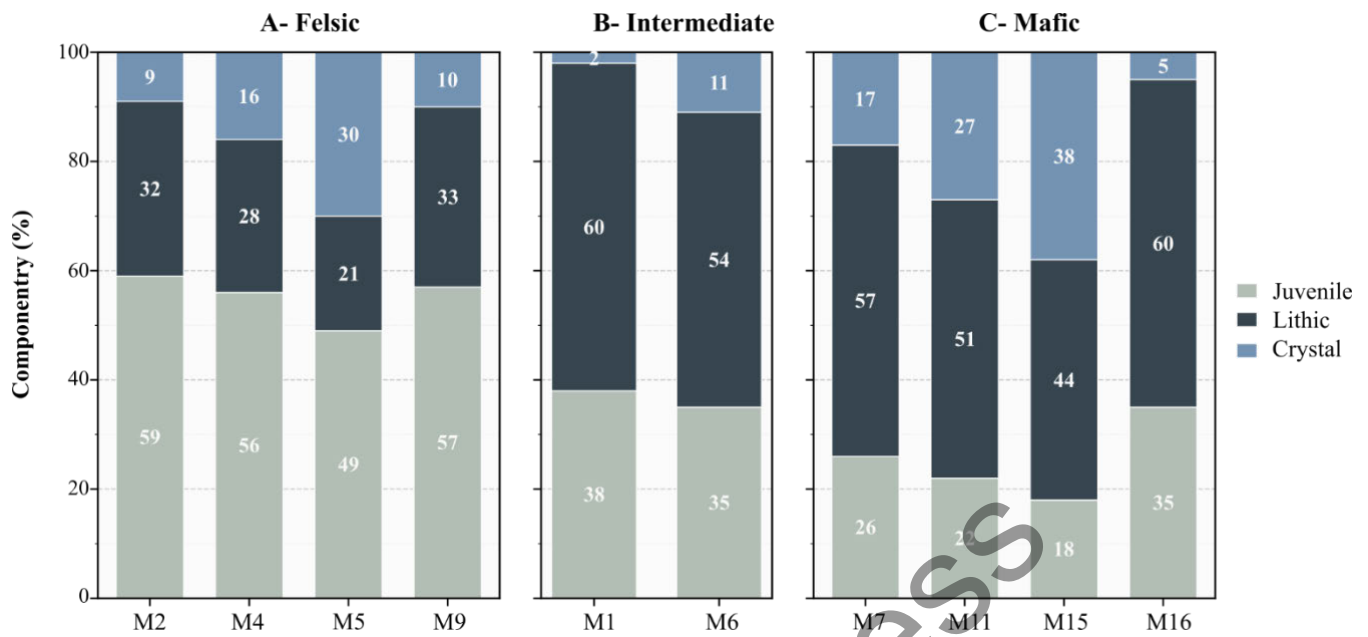
Figure 9: Stratigraphic logs of CAVP maars with available outcrops, displaying the main depositional characteristics of maar deposits and related monogenetic volcanoes (i.e., scoria cone, tuff ring). A: ash; L: lapilli; B: bomb/block.

4.3 Clast type and componentry

Juvenile and lithic clasts within the CAVP maars display a wide compositional and textural range, from fine ash and lapilli to bombs and blocks up to 50-100 cm in diameter. Mafic-intermediate maar deposits include predominantly scoriaceous juvenile clasts, commonly as lapilli and bombs, whereas felsic maars contain pumice, 555 perlite, and obsidian clasts with variable vesicularity and grain size. Accretionary lapilli are restricted to mafic-intermediate maars, including Cora, Narlıgöl, Kutören, Acıgöl-K, and Mekegölü.

Lithic assemblages vary systematically across the CAVP in accordance with the substrate classes defined in this study (hard, mixed type-1, mixed type-2, and soft substrates; Table 1). The northern maars, such as Acıgöl-N and İcik, contain abundant crystalline and volcanic lithics, including granite, ophiolite, andesite, and ignimbrite-derived 560 clasts, and are classified as hard-to-mixed type-1 substrates (Table 1). In contrast, central and southern maars include abundant lithics derived from lacustrine deposits, hydrothermally altered pyroclastic rocks, reworked volcano-sedimentary material, and lava blocks exposed around the maar craters, indicating mixed type-2 to soft substrates. In some cases, the lithic assemblages also include material from older monogenetic volcanic units. At Kutören, these include tachylyte-bearing tuff, whereas Acıgöl-K contains fragments of older mafic lava and tuff- 565 ring deposits (Figure 8).

Componentry analyses further show clear differences between the felsic and mafic-intermediate maar deposits (Figure 10). The analyzed felsic maars, including İnallı, Acıgöl-N, Korudağ, and Obruk, are juvenile-rich, with juvenile contents ranging from 49 to 59%, lithic contents from 21 to 33%, and crystal contents from 9 to 30% (Table 1). In contrast, the analyzed mafic-intermediate maars are consistently lithic-dominated, with lithic contents 570 ranging from 44 to 60%, juvenile contents from 18 to 35%, and crystal contents from 2 to 38%. Acıgöl-K and Cora show particularly higher lithic proportions (61 and 60%, respectively), followed by Narlıgöl (58%), İcik (54%), Karafatma (51%), and Kutören (44%; Table 1).



575 **Figure 10: Componentry composition (juvenile–lithic–crystal %) of CAVP maars arranged by their whole-rock (pumice or scoria) compositions.**

4.4 Juvenile petrography and micromorphology

580 Juvenile clasts from the CAVP maars display a range of petrographic and micromorphological characteristics. They can be broadly grouped into mafic-intermediate and felsic types, which differ in vesicularity, mineralogy, and textural characteristics.

Mafic-intermediate juveniles from Cora, İcık, Narlıgöl, Leşkeri, Karafatma, Kutören, Acıgöl-K, and Mekegölü maars are predominantly scoriaceous, corresponding to basaltic to trachyandesitic whole-rock compositions. Petrographic observations show vesicular fragments with olivine (Ol), plagioclase (Pl), and pyroxene (Px) phenocrysts, often subhedral to euhedral and locally skeletal or embayed (Figure 11A-D). The groundmass ranges from glassy to microcrystalline. Acıgöl-K and Mekegölü scoria also locally contain xenocrysts (Xc; e.g., quartz) and mafic microgranular enclaves (mme) (Figure 11D), which are also documented in basaltic rocks of the KMF (Gençoğlu Korkmaz et al. 2021).

590 SEM images show rugged and spongy scoria textures with relatively thick vesicle walls, irregular to interconnected vesicle networks, and locally fractured surfaces and broken vesicle walls (Figure 11E-H). Vesicles vary in shape from rounded to irregular and are often coalescent, with porous and fractured morphologies.

Felsic juveniles from İnallı, Acıgöl-N, Korudağ, and Obruk maars are dominated by highly vesicular, glass-rich pumice and perlite clasts, typical of rhyolitic composition. Petrographic observations show aphyric textures with sparse microlites (~5%). Vesicles range from rounded to elongated and are locally coalesced, with some forming tube-like shapes (Figure 12A-D). Alignment of microlites and elongated vesicles is particularly evident in İnallı and Acıgöl-N pumices, and fine spherulites occur locally within the glassy groundmass. Vesicles commonly constitute > 50% of the observed clast area.

SEM images highlight a fragile, fibrous pumiceous texture with thin, elongated vesicle walls and a sponge-like, brittle framework (Figure 12E-H). The vesicle walls are commonly collapsed or folded, producing laminar surfaces. The pumice clasts from İnallı, Korudağ, and Obruk pumices (Figure 12E-H) display sheet-like arrangements of elongated vesicles, locally associated with coalesced vesicles and thin to collapsed vesicle walls (Figure 12E-H).

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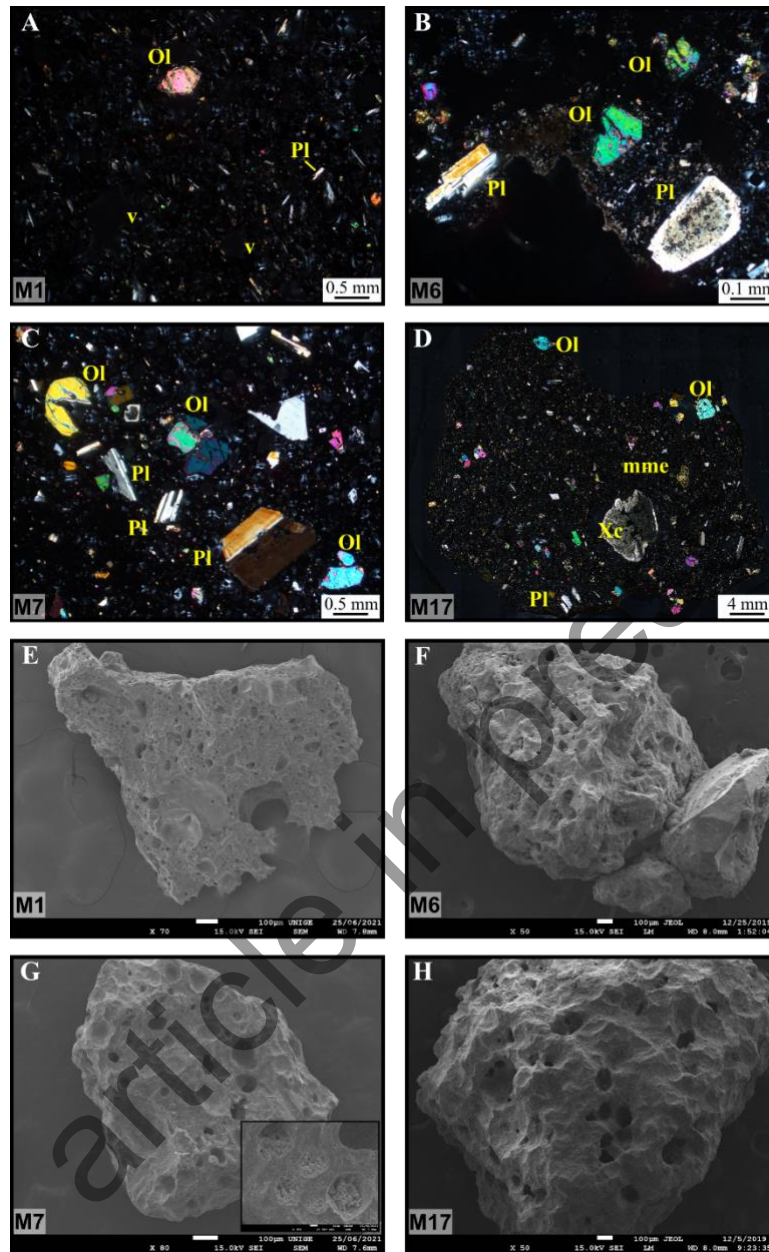


Figure 11: Representative petrographic [A-D] and SEM [E-H] images of mafic-intermediate juvenile scoria from CAVP maars. [A] Cora (M1) maar scoria displays vesicular groundmass with subhedral olivine (Ol) and plagioclase (Pl) phenocrysts; [B] İcik (M6) maar scoria includes Ol and Pl phenocrysts, including skeletal forms, within a vesicular glassy groundmass; [C] Narlıgöl (M7) maar scoria consists of abundant euhedral to skeletal Ol and Pl phenocrysts in a vesicular matrix; [D] Juvenile scoria from Mekegölü (M17) maar with Ol, Pl, xenocryst (Xc), and a mafic microgranular enclave (mme); [E-H] SEM images of the same samples (M1, M6, M7, and M17) showing rugged, spongy morphologies, relatively thick vesicle walls, irregular to interconnected vesicles, and locally fractured surfaces and broken vesicle walls.

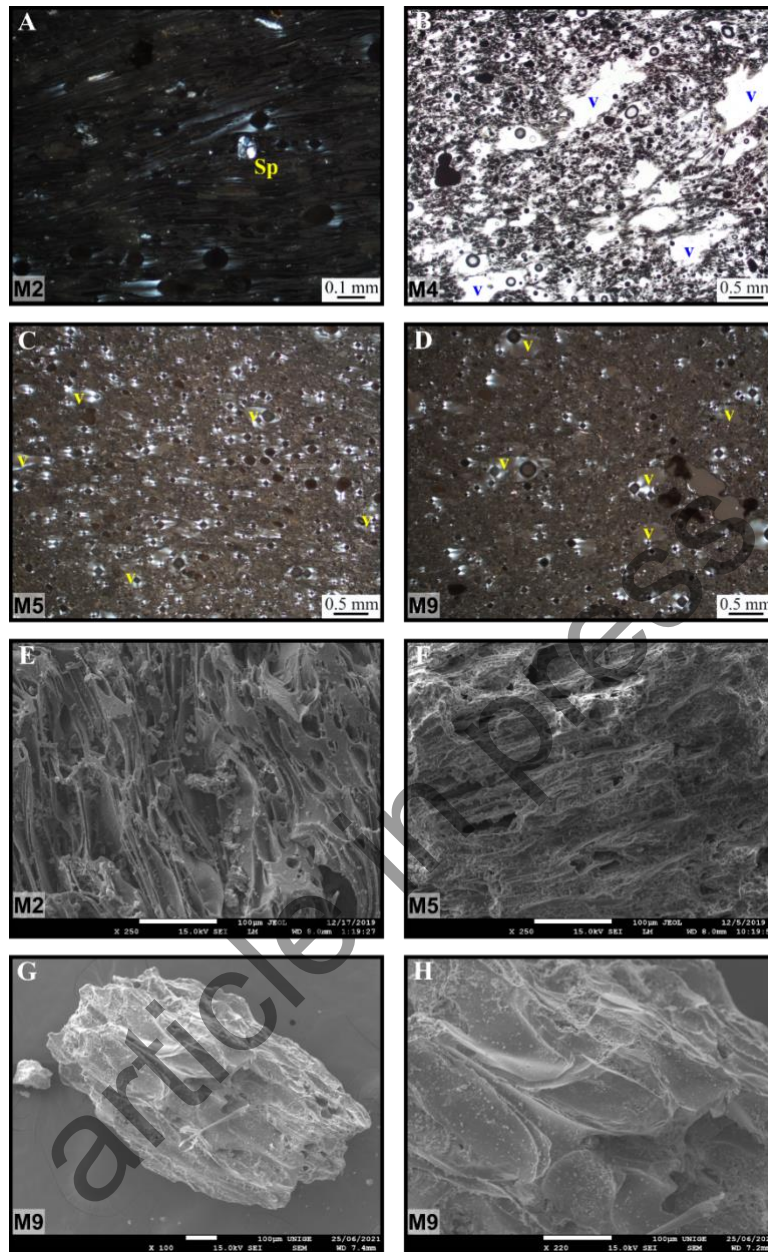


Figure 12: Representative petrographic [A-D] and SEM [E-H] images of felsic juvenile pumice and perlite from CAVP maars. [A] Highly vesicular pumice from İnallı (M2) maar with elongated vesicles and spherulites (Sp), displaying flow alignment; [B] Glass-rich pumice from Acıgöl-N (M4) maar with abundant spherical to elongate vesicles (v), reflecting strong volatile exsolution; [C] Vesicle-rich glassy pumice from Korudağ (M5) maar with interconnected and coalescent vesicles; [D] Pumice clast from Obruk (M9) maar with abundant rounded to irregular vesicles; [E-H] SEM images of the same samples (M2, M5, and M9) showing highly vesicular, locally fibrous textures characterized by thin to collapsed vesicle walls, and sheet-like arrangements of elongated vesicles.

5 DISCUSSION

5.1 Depositional processes and lithofacies significance in the CAVP maar successions

The lithofacies architecture of the CAVP maars records multiple depositional processes that may produce partly overlapping sedimentological expressions; individual facies are therefore not uniquely linked to single
625 emplacement mechanisms. Current maar models emphasize that tephra rings selectively preserve explosions that generate material reaching the surface and may contain deposits from ballistic ejecta and curtains, debris jets, concentrated and dilute PDCs, ash-cloud fallout, short-lived jet/column fallout and syn-eruptive recycling (Fisher and Waters 1970; Lorenz 1973; White 1991; Lorenz 2003; White and Ross 2011; Valentine and White 2012; Kurszlauskis and Fulop 2013; Lefebvre et al. 2013; Graettinger and Valentine 2017; Valentine et al. 2017). The
630 CAVP successions fit this framework, with vertical and lateral alternations of TB, AT, and LT facies recording repeated changes in excavation, sediment supply, PDC transport, fallout, and local remobilization during successive eruptive and depositional episodes (Graettinger et al. 2015; Németh and Kereszturi 2015; Valentine et al. 2015a; Graettinger and Valentine 2017).

TB₁ is one of the coarsest and least well-sorted proximal lithofacies. Its massive, chaotic, matrix- to clast-supported
635 fabric indicates rapid accumulation from ballistic curtains/fallout, debris jet collapse, and/or concentrated PDCs close to the vent (Sohn and Chough 1989; White 1991; Branney and Kokelaar 2002; Lorenz 2003; Graettinger and Valentine 2017; Valentine et al. 2017). The abundance of coarse lithics and blocks in many TB₁ deposits records substantial excavation of country rock and proximal accumulation. Comparable coarse, lithic-rich deposits have been described in maar tephra rings where near-vent ballistic processes and concentrated PDCs contributed
640 substantially to proximal deposition, including the Ukinrek Maars, Alaska (Self et al. 1980; Sheridan and Wohletz 1983; Ort et al. 2018), and other basaltic maar systems (Valentine et al. 2015b; Graettinger and Valentine 2017). In the CAVP, lithic-rich TB₁ in mafic-intermediate successions most clearly records substantial substrate excavation, whereas lithic-rich deposits in felsic successions may additionally contain material recycled from earlier crater-fill or tephra-ring deposits (e.g., Uslular et al. 2022). TB₁ is therefore informative about excavation
645 and proximal deposition but should not be regarded as a direct proxy for explosion energy.

TB₂ records a more distinctly stratified depositional regime than TB₁. The development of crude stratification, erosional contacts, low-angle cross-stratification, weak grading, and locally incorporated substrate-derived material indicates emplacement by unsteady, sediment-laden PDCs capable of alternating between erosion, tractional transport, and deposition (Cas and Wright 1987; Valentine 1987; Druitt 1998; Branney and Kokelaar 2002). In

650 particular, the thick TB₂ layers at İcik (M6; Figures 6 and 7G), consisting of alternating ash-rich and lapilli- to block-rich beds, undulating contacts, and local scours, record repeated fluctuations in sediment concentration, transport competence, and sediment supply. Rip-up clasts and soft-sediment deformation at Obruk (M9; Figures 7K-M and 9) further indicate interaction with weakly consolidated substrate or previously deposited tephra ring, locally under water-rich or syn-eruptively destabilized conditions (Sheridan and Wohletz 1983; Németh et al. 655 2001). Similar stratified layers are widely reported from maar and tuff-ring successions, including the Suwolbong Tuff Ring, Korea (Sohn and Chough 1989), and the Alchichica maar, Mexico (Carrasco-Núñez et al. 2007). In the CAVP, TB₂ therefore marks phases in which laterally moving currents were sufficiently energetic to transport coarse material but also organized to generate stratification.

TB₃ is best interpreted as a juvenile-rich, massive breccia facies restricted to the felsic maars in the NAVC (Figures 2B and 9). Its dominance by pumice, perlite, and obsidian clasts, together with the higher juvenile proportions recorded by componentry analysis, indicates deposition dominated by rhyolitic juvenile material. Petrographic and SEM observations further show highly vesicular, glass-rich clasts with elongated, locally coalesced vesicles and thin, locally collapsed vesicle walls (Figure 12). These textures indicate substantial vesiculation and deformation before fragmentation, but are not, by themselves, indicative of a particular fragmentation mechanism. The 665 stratigraphic position of TB₃ in the upper parts of the exposed felsic successions, together with the close association of several NAVC maars with lava domes, support a shift from substrate-rich phreatomagmatic excavation towards more juvenile-dominated jet collapse, ballistic curtains and concentrated PDCs, possibly during dome/plug disruption or late-stage shallow degassing (Carrasco-Núñez et al. 2007; White and Ross 2011; Valentine and White 2012; Ross et al. 2017; Uslular et al. 2022).

670 TB_{lens} represents localized accumulations of coarse lithic material within finer-grained deposits. Its lens-shaped geometry, sharp basal contacts, limited lateral continuity, and occurrence in channel-like depressions indicate that deposition was strongly controlled by crater-rim relief, local topographic lows, and channelized current pathways (White 1991; White and Houghton 2000; Graettinger and Valentine 2017; Valentine et al. 2017). At Cora, Acıgöl-N, and Narlıgöl (Figures 7 and 9), TB_{lens} occurs within AT-dominated successions and may record temporary 675 concentration of coarse lithics within laterally moving currents, local crater-rim collapse, or short-distance remobilization of previously deposited material (Druitt 1998; Németh and Kereszturi 2015). The available field relationships do not allow these processes to be distinguished uniquely.

AT₁ is an ash-rich, suspension-dominated facies deposited from waning dilute surges, ash clouds associated with PDCs, and short-lived fallout pulses (Fisher and Schmincke 1984; Cas and Wright 1987; Sohn and Chough 1989; 680 Druitt 1998; Branney and Kokelaar 2002). Its planar fine stratification, ash-rich character, and lack of tractional

bedforms indicate predominantly suspension-controlled deposition (Valentine 1987; Sohn and Chough 1989). Accretionary lapilli at Cora, Narlıgöl, Kutören, Acıgöl-K, and Mekegölü provide independent evidence for aggregation of fine ash within moisture-bearing eruption clouds. Because their size, internal structure, and morphology were not systematically quantified, they are not used here to infer more specific eruption conditions.

685 Their absence from other deposits should likewise not be interpreted simply in terms of water-magma ratio, because ash aggregation also depends on temperature, ash concentration, residence time, and humidity (Schumacher and Schmincke 1991; Brown et al. 2012).

AT₂ records more regularly pulsed suspension settling than AT₁. Planar bedding, repeated normal grading, sharp contacts, excellent lateral continuity, and the absence of tractional bedforms indicate fallout from short-lived explosion-fed clouds, ash-cloud fallout associated with PDCs, and/or suspension sedimentation from waning dilute PDCs (Lorenz 1973; Sohn and Chough 1989; Druitt 1998; Branney and Kokelaar 2002; White and Ross 2011). Its intercalation with TB and LT units records repeated changes in depositional regime during maar-forming activity. The available sedimentological evidence does not allow a unique distinction between direct fallout and suspension settling from dilute PDCs, although the observed bedforms do not support sustained traction-dominated deposition.

695 AT_x provides the clearest evidence for laterally moving dilute PDCs or base surges in the CAVP maars. Ripple marks, climbing ripples, cross-bedding, dune forms, and low-angle stratification record traction, saltation, and suspension fallout within dilute, turbulent PDCs (Fisher and Waters 1970; Wohletz and Sheridan 1979; Sohn and Chough 1989). AT_x is the finest and best well-sorted lithofacies in the analyzed dataset. Cross-stratified and dune-bearing beds occur at Obruk, Kutören, and Acıgöl-K (Figures 7K-M, 8C-D and 8F-G), whereas ripple-marked layers are particularly prominent at Karafatma (Figures 8A). The rhythmic alternations of ash- and lapilli-rich beds likely reflect fluctuations in sediment transport and deposition within these currents (Wohletz and Sheridan 1979; Druitt 1998; Valentine et al. 2017). Lapilli-rich beds are consistent with intervals of greater flow competence and sediment concentration, during which coarser particles were transported predominantly by traction and saltation, whereas ash-rich beds indicate increased deposition from suspension as the current became more dilute or waned

705 (Sohn and Chough, 1989; Chough and Sohn, 1990; Druitt, 1998). The transition from planar lamination to ripple- and dune-bearing beds therefore records temporal and/or spatial variations in flow regime. Accretionary lapilli at Kutören and Acıgöl-K and soft-sediment deformation observed within some of the maar successions, including Obruk, provide independent evidence that moisture-rich depositional conditions occurred during parts of these eruptions. However, these features do not define a systematic wet-to-dry surge evolution within the AT_x facies, and

710 we therefore avoid interpreting these beds in terms of a specific wet-to-dry surge evolution.

LT records relatively coarse, juvenile-rich deposition during fallout-dominated or mixed fallout-PDC intervals. Its lapilli-supported texture, relatively good sorting, minor ash matrix, limited lithic content, and intercalation with AT_x and AT_2 indicate direct fallout from short-lived explosion jets, coarse fallout from PDC-associated ash clouds, or short-lived coarse PDC pulses (Sheridan and Wohletz 1983; Fisher and Schmincke 1984; Lorenz 1986; Cas and Wright 1987; Druitt 1998; Branney and Kokelaar 2002; White and Ross 2011). In the CAVP, LT is laterally continuous over tens of meters at Obruk, Kutören, and Mekegölü. Pumice-rich LT in felsic successions reflects coarse rhyolitic juvenile dispersal, whereas scoria-bearing LT associated with mafic-intermediate successions and nearby scoria cones may record a stronger magmatic/Strombolian component, locally accompanied by phreatomagmatic pulses. LT is therefore composition-sensitive and should be interpreted together with juvenile textures and stratigraphic context.

In addition to the principal maar lithofacies, volcanoclastic sedimentary interbeds and deposits associated with adjacent monogenetic edifices provide further constraints on the stratigraphic evolution of some CAVP maar successions. Volcanoclastic sedimentary layers interbedded with primary maar deposits, particularly in the southern CAVP, indicate reworking episodes between eruptive phases. This relationship is especially evident at Mekegölü maar, where a massive, poorly sorted unit with a pinkish ash-rich matrix, juvenile and lithic lapilli, and local scoria bombs separates lower and upper maar deposits (Figure 8K-L). These characteristics are consistent with a lahar-like, sediment-laden flow that remobilized unconsolidated volcanic material, and its stratigraphic position suggests an episode of sediment redistribution between successive phases of maar-forming activity (Lorenz, 2007).

Discrete scoria-rich beds also occur within the successions of Karafatma, Narlıgöl, and İcik. Their well-sorted, commonly clast-supported character is consistent with fallout deposition. However, sedimentological characteristics alone do not allow these beds to be correlated with a specific neighboring scoria cone. At İcik, a close spatial and stratigraphic relationship exists between the maar and the adjacent Obruk scoria cone, which has previously been mapped and investigated (Türkecan et al. 2004; Aydar et al. 2011; Uslular et al. 2022). On the other hand, the tuff and hyaloclastite deposits associated with Kutören and Acıgöl-K represent a different relationship. These deposits occur beneath the maar successions and along the lower crater walls and are unconformably overlain by the maar deposits. Therefore, they are treated as older external tuff-ring units (Keller 1974).

5.2 Lithofacies variability within a scaled-depth framework

740 The optimal scaled depth (OSD) concept provides a useful qualitative framework for considering how explosion depth relative to released energy affects crater excavation and the production of surface ejecta (Goto et al. 2001). Experimental studies show that explosion depth and energy, together with substrate properties, crater geometry, and pre-existing relief, can influence crater excavation and growth, ballistic ejection, and PDC generation, or result in explosions whose effects remain largely confined to the subsurface (Graettinger et al. 2014; Valentine et al. 745 2014; Graettinger et al. 2015; Valentine et al. 2015a; Macorps et al. 2016; Sweeney et al. 2018). However, natural tephra-ring deposits do not independently constrain explosion depth or released energy, and individual facies therefore cannot be assigned to specific scaled-depth conditions.

Within this qualitative framework, coarse, lithic-rich TB₁ and parts of TB₂ are consistent with eruptive episodes involving substantial country rock excavation and abundant proximal ejecta production. In contrast, AT₁ and AT₂ 750 primarily record suspension- and fallout-dominated deposition, whereas LT represents relatively coarse fallout or mixed fallout-PDC deposition. These depositional characteristics do not necessarily imply less substantial excavation, as they may also reflect variations in sediment concentration, water availability, eruption column or PDC behavior, and the position of individual explosions within the evolving maar systems. AT_x records laterally moving dilute PDCs that persisted sufficiently to generate tractional bedforms. We therefore use the scaled-depth 755 concept only as a qualitative context for interpreting variability in country rock excavation and surface-depositional behavior.

5.3 Other potential factors controlling the maar volcanism in the CAVP

The regional CAVP dataset indicates that maar architecture results from the combined effect of substrate properties, hydrogeological conditions, magma composition, vent evolution, and post-eruptive modification. The relative 760 importance of these controls varies among individual maars. The occurrence of mafic, intermediate, and felsic maars within hard, mixed, and soft substrates in the same volcanic province provides an opportunity to compare these factors within a common regional setting.

Substrate type is most clearly recorded by the lithic assemblages and also appears to affect aspects of crater morphology and depositional architecture. Northern maars developed in hard to mixed type-1 substrates contain 765 crystalline and volcanic lithics such as granite, ophiolite, and andesite, whereas central and southern maars in mixed type-2 to soft substrates include abundant lacustrine sedimentary, volcanosedimentary, hydrothermally altered tuff, and reworked volcanic material. These assemblages show that explosive excavation occurred through substrates

with different mechanical and hydrogeological properties. The morphometric data partly support a substrate influence, with the lowest inner crater-wall slopes ($\leq 6^\circ$) occurring at maars with mixed type-2 or soft substrates (e.g., Karafatma, Obruk, and Kutören). However, relatively steep crater walls also occur in some mixed type-2 systems, such as Mekegölü ($\sim 20^\circ$), indicating that substrate strength is not the only control on crater geometry. Crater preservation is likewise affected by erosion, infilling, slope failure, and the emplacement of younger volcanic edifices, and therefore cannot be attributed solely to substrate type.

Componentry does not define a substrate-dependent pattern that is equally simple. For example, the soft-substrate rhyolitic Obruk maar remains juvenile-rich ($\sim 57\%$ juvenile, 33% lithic; Figure 10), whereas the mixed type-2 basaltic Acıgöl-K maar is strongly lithic-rich ($\sim 61\%$ lithic). This relationship indicates that relative juvenile and lithic proportions are affected by magma composition and eruptive processes in addition to substrate excavation. Similarly, the juvenile textures also described in this study show a stronger association with magma composition than the substrate class. Nevertheless, soft-sedimentary deformation, lacustrine and volcano-sedimentary lithics, and volcanoclastic interbeds provide independent field evidence for the involvement of weak, locally water-rich substrates in several central and southern maars. These characteristics are broadly compatible with experimental and field observations showing that weak, water-bearing sediment can modify magma-water interaction, although direct microtextural evidence for an “impure coolant” mechanism has not been demonstrated in the CAVP maars (Lorenz 2003; Auer et al. 2007; Macorps et al. 2016; Jubertie et al. 2026).

Hydrogeological control in the CAVP extended beyond pore water in weak or unconsolidated substrates. Narlıgöl provides a contrasting example in which fracture-controlled permeability appears to have been important. Gevrek and Kazancı (2000) interpreted the maar as having formed along a local fault zone, with magma ascending along the fault and interacting with meteoric water within the fractured zone during the phreatomagmatic eruption. The maar presently hosts geothermal springs and an active hydrothermal system, and more recent bathymetric and hydrogeochemical observations show that faults beneath Narlıgöl, particularly fault-intersection zones, act as high-permeability pathways for deep geothermal fluids and gas discharge (Brehme et al. 2021). These observations suggest that fracture-controlled groundwater circulation may have affected both vent localization and the availability of external water during maar formation. However, the present hydrothermal circulation cannot be assumed to represent the same fluid reservoir or flow configuration that existed during the Pleistocene eruption (Gevrek and Kazancı, 2000).

Magma composition is associated with systematic differences in componentry and juvenile texture. The analyzed felsic maars are generally juvenile-rich; for example, juvenile clasts comprise 59% at İnallı and 57% at Obruk (Figure 10). In contrast, several mafic-intermediate maars are lithic-rich (Figure 10). Petrographic and SEM

observations further distinguish highly vesicular, glass-rich felsic juveniles with elongated to sheet-like vesicle
800 arrangements and thin, locally collapsed vesicle walls from rugged, spongy mafic-intermediate scoria with thicker
vesicle walls and irregular to interconnected vesicle networks (Figures 11 and 12). In felsic magmas, relatively
high melt viscosity can inhibit rapid relaxation of deformed bubbles, allowing elongated vesicles, coalesced
structures, and localized strain fabrics to be preserved before fragmentation (Polacci et al. 2003; Wright and
Weinberg 2009). Although these textures are not directly characteristic of magma-water interaction, their
805 occurrence within independently identified phreatomagmatic successions suggests that external water may have
contributed to the final fragmentation of already vesiculated and deformed felsic magma (Austin-Erickson et al.
2008). The mafic-intermediate textures similarly have differences in bubble growth, coalescence, and magma
rheology, but fractured surfaces alone cannot identify a specific fragmentation mechanism (White and Ross 2011;
Ross et al. 2017; Gurusinga et al. 2023; Planagumà et al. 2023). Thus, the CAVP data show that broadly
810 phreatomagmatic maar-forming activity occurred across contrasting magma compositions, producing distinctly
different componentry and juvenile textures.

The close association of several maars with lava domes, scoria cones, older tuff rings, and crater lakes/playas
further provides a record of changes in eruptive style and vent position. In the NAVC, the relationships are
particularly clear at Kalecitepe, where a lava dome partly occupies the maar crater; at Acıgöl-N, where one of the
815 coalescent craters is filled by a lava dome; and at Korudağ, where dome emplacement overprints and deforms part
of the maar crater (Figure 3). Where their relative chronology is sufficiently constrained, these relationships are
consistent with a transition from phreatomagmatic crater excavation to juvenile-dominated explosive or effusive
rhyolitic activity (Uslular et al. 2022). Mafic maar systems show different relationships: İcik is modified by a scoria
cone, while Mekegölü and Mekeobruğu are spatially associated with scoria cones; Kutören and Acıgöl-K, in
820 contrast, developed in relation to older tuff-ring structures (Figure 4). Such spatial and stratigraphic relationships
are compatible with repeated activation of closely spaced vents and, in some cases, vent migration within a
monogenetic volcanic system (Graettinger 2018; Graettinger and Bearden 2021), rather than requiring repeated
activity through the same vent.

Water also affected the CAVP maar systems through sedimentary processes operating between, during, and after
825 eruptive phases. Crater lakes, playas, volcanoclastic sedimentary interbeds, and the lahar-like unit at Mekegölü
(Figure 8K-L) demonstrate that water also affected sediment redistribution during and after maar-forming activity.
In particular, the volcanoclastic unit separating lower and upper maar deposits at Mekegölü is consistent with an
intra-eruptive episode of water-assisted sediment remobilization. The water responsible for such reworking need
not have been derived from the same aquifer or water reservoir that participated in magma-water interaction during

830 the maar-forming explosions. Meteoric runoff, surface water, or subsequently formed crater lakes could also have driven sediment remobilization (Lorenz, 2007). Changes in the availability and source of external water can also contribute to transitions between phreatomagmatic and magmatic activity during the evolution of complex monogenetic volcanoes (Chako Tchamabé et al. 2016; Foote et al. 2023; Hencz et al. 2024). Intercalated sedimentary or reworked units may therefore record pauses or changes in depositional and eruptive conditions
835 within a complex monogenetic sequence. However, we do not interpret any studied maar succession as evidence for polycyclic or polygenetic activity without independent evidence for a significant temporal break.

Crater morphology provides additional constraints on vent evolution, structural control, and post-eruptive modification (Kereszturi et al. 2013; Graettinger 2018; Graettinger and Bearden 2021; Pedrazzi et al. 2024). Among the studied maars, İcık provides one of the clearest examples with its strongly elongated chain-like crater ($AR =$
840 0.30), consistent with multiple closely spaced explosion loci and migration along a previously mapped NNW-SSE-trending fault (Uslular et al. 2022). Similarly, Acıgöl-N has an elongated, complex footprint ($AR = 0.58$) comprising five nested or coalescent sub-craters, supporting development through multiple adjacent explosion loci. Across the CAVP, crater elongation axes show preferred NE-SW to E-W orientations broadly comparable with regional structural trends, suggesting that pre-existing structural weaknesses may have influenced vent propagation.
845 However, the morphometric data alone cannot demonstrate direct control by individual faults. Post-eruptive changes can be identified more directly by the spatial relation between maars and other nearby monogenetic volcanoes in the CAVP (e.g., maar-lava dome complexes in the NAVC; maar-scoria cone complexes in KMF, and maar-tuff-ring complexes in Acıgöl-K and Kutören). Faults and slope failures additionally affect the crater walls of Cora, İcık, Narlıgöl, and Leşkeri (Figure 3), although their timing is insufficiently constrained to classify them
850 specifically as syn-eruptive. Therefore, the complex crater morphologies record different combinations of structurally controlled vent migration, multiple explosion loci, edifice overprinting, and post-eruptive changes, which are not necessarily observed in all maars.

855 6 CONCLUSIONS

This study documents 18 Quaternary maars in the CAVP, 11 of which preserve tephra ring deposits exceeding 1 m in thickness. The regional dataset shows that maar architecture cannot be attributed to a single control. Substrate properties are most clearly expressed in lithic assemblages and, to a lesser extent, in crater geometry, whereas hydrogeological conditions affect the availability and pathways of external water. Magma composition is

860 associated with systematic differences in componentry and juvenile textures, while complex crater forms and associated monogenetic edifices record vent migration, repeated activation of closely spaced vents, and later morphological modification. The CAVP maars therefore illustrate how substrate, hydrogeology, magma properties, and vent evolution exert different but overlapping influences on maar formation.

Eight recurring lithofacies (TB₁, TB₂, TB₃, TB_{lens}, AT₁, AT₂, AT_x and LT) record deposits formed through variable
865 contributions from ballistic emplacement, debris-jet or jet-collapse processes, concentrated and dilute PDCs/base surges, fallout or suspension settling and local remobilization. Individual facies are not uniquely diagnostic of single emplacement mechanisms because similar sedimentological characteristics can result from different combinations of transport, deposition, sediment concentration, and water availability. Lithofacies interpretations therefore require integration with stratigraphic position, componentry, sedimentary structures, and field
870 relationships.

Vertical and lateral lithofacies alternations are best explained by repeated changes in excavation, sediment transport, and depositional conditions during maar-forming activity. The scaled-depth/OSD concept is useful as a qualitative framework for considering how explosion depth relative to released energy may affect crater excavation and the production of surface ejecta. However, the tephra-ring deposits in the CAVP do not independently constrain
875 explosion depth or energy, and individual beds cannot be assigned to specific scaled-depth conditions.

Componentry and juvenile textures reveal a systematic compositional contrast. The analyzed felsic maars are commonly juvenile-rich and contain pumice, perlite, and obsidian with highly vesicular textures and thin, locally collapsed vesicle walls. In contrast, the mafic-intermediate maars are generally more lithic-rich and contain scoriaceous juveniles with thicker vesicle walls and irregular to interconnected vesicle networks, together with
880 cauliflower bombs and locally accretionary lapilli. These relationships suggest that magma composition influenced the expression of phreatomagmatic fragmentation in the juvenile clasts. The higher viscosity of felsic melts favoured preservation of strongly deformed and elongated vesicle structures and abundant glassy juvenile fragments, whereas the lower-viscosity mafic-intermediate magmas produced contrasting scoriaceous vesicle texture. The greater lithic proportions in many mafic-intermediate deposits, however, also record more substantial
885 country-rock excavation and cannot be attributed to magma composition alone. The observed compositional correlation is therefore best explained by the combined effect of magma rheology, vesiculation, and substrate excavation.

Author contributions

GU: Conceptualization, Methodology, Data curation, Investigation, Visualization, Formal Analysis, Writing – original draft; GGK: Funding acquisition, Supervision, Writing – review and editing; JR: Funding acquisition, Supervision, Writing – review and editing; ÇS: Investigation, Writing – review and editing.

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Data availability

The high-resolution digital surface models and orthomosaics of maars in the CAVP are openly available through the TÜBİTAK ULAKBİM APERTA Open Data Repository at <https://doi.org/10.48623/aperta.303092>. Other datasets and figures are provided as supplementary material along with the manuscript.

Supplementary Figure S1. Geological maps of maars in the CAVP illustrated on UAV-based, high-resolution digital surface models and ALOS3D digital elevation models.

Supplementary Figure S2. Total alkali-silica (TAS) diagram showing the whole-rock compositions of juvenile clasts from the studied CAVP maars. Major-element concentrations were recalculated on an LOI-free basis. Corresponding analytical data are provided in Supplementary Table S1. ^aGençalioglu-Kuşcu 2011; Doğan-Külahçı et al. 2018; Uslular and Gençalioglu-Kuşcu 2019; Uslular et al. 2022.

Supplementary Material 1. Statistical results of sieve analysis applied to the representative layers of maars with exposed deposits

Supplementary Material 2. Major-element compositions of juvenile clasts from the CAVP maars

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