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Volcanism and evolution of the landscapes in Cappadocia

Attila Çiner, Erkan Aydar and M. Akif Sarıkaya

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LA CAPPADOCE MÉRIDIONALE
de la préhistoire à la période byzantine

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Olivier Pelon (1934 – 2012)

(Cliché C. Boni)

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PRÉFACE

Dominique Beyer

Il y a environ 25 ans, Olivier Pelon organisait à l'Institut Français d'Etudes Anatoliennes d'Istanbul un colloque destiné à faire l'état des recherches sur la Cappadoce méridionale jusqu'à la fin de l'époque romaine. Ce colloque avait pu être publié quelques années plus tard par les soins des Editions Recherche sur les Civilisations[1]. La publication groupait dix communications — trois des participants n'ayant pas remis leurs textes — et une annexe. Quatre grandes périodes y étaient alors représentées :

— *L'époque préhistorique*, avec une communication sur les fouilles de Köşk Höyük par son directeur d'alors, U. Silistreli, malheureusement disparu peu après ;
— *La protohistoire et le début de l'âge du Fer*, plus fournie avec quatre contributions, la première sur les trouvailles céramiques du district minier du Bolkardağı (B. Aksoy), les trois autres concernant la fouille de Porsuk, avec une communication de son directeur, O. Pelon, sur l'occupation hittite et le début de l'âge du Fer, les deux autres (S. Dupré et Fr. Blaizot) évoquant la découverte d'un squelette du Bronze Récent. Il faut y ajouter, à propos de Porsuk, le contenu de l'annexe, avec une recherche de M. Coindoz sur les voies de communication entre la Tyanitide et les Portes Ciliciennes ;
— *L'époque « phrygienne »*, avec la publication de l'important matériel funéraire du tumulus de Kaynarca (M. Akkaya) et les observations sur les inscriptions paléo-phrygiennes de Tyane (E. Varinlioglu et Cl. Brixhe) ;
— *L'époque romaine* enfin, avec une définition territoriale de la Cappadoce (D. French) et une étude sur l'activité des fonctionnaires territoriaux au Haut-Empire d'après les inscriptions (B. Rémy).

Un quart de siècle après ce premier colloque, il était intéressant de faire un nouveau point sur l'avancée des recherches dans cette Cappadoce méridionale, de la préhistoire à la période byzantine. On doit aux compétences et au

1 Brigitte Le Guen-Pollet et Olivier Pelon, éd., *La Cappadoce méridionale jusqu'à la fin de l'époque romaine, Etat des recherches, Actes du Colloque d'Istanbul, Institut Français d'Etudes Anatoliennes, 13-14 avril 1987*, Editions Recherche sur les Civilisations, Paris, 1991.

dynamisme d'Olivier Henry d'avoir conçu et organisé ce nouveau colloque, placé cette fois encore sous l'égide de l'Institut Français d'Etudes Anatoliennes — que son directeur, Jean-François Pérouse, en soit vivement remercié — et intégré à la série des Rencontres d'archéologie de l'IFEA.

Les communications ont été au nombre de vingt-trois, ce qui témoigne du développement des recherches et de leur diversification.

Si les périodes néolithique et chalcolithique ont été particulièrement bien représentées[2], ce qui témoigne bien de l'importance de cette phase de la préhistoire cappadocienne, liée aux gisements d'obsidienne des Melendiz Dağları, et du dynamisme de nos collègues turcs de l'Université d'Istanbul, on soulignera en revanche l'absence presque totale du Bronze Ancien. Cette phase est en effet peu représentée dans l'archéologie locale, et on regrettera d'autant plus d'avoir manqué une contribution consacrée aux trouvailles majeures du site de Göltepe et de la mine d'étain de Kestel[3].

La même remarque peut s'appliquer au Bronze Moyen. On pouvait espérer la participation de notre collègue Aliye Öztan (cf. note 2), responsable des fouilles du riche site d'Acemhöyük, qui aurait pu combler cette lacune, même si son site, l'un des plus représentatifs de la période des comptoirs assyriens de Cappadoce, était situé nettement plus à l'ouest que les autres.

La fin du Bronze Moyen, fort heureusement, est représentée à Porsuk, de même que le Bronze Récent qui bénéficie, depuis peu, tout comme l'Âge du Fer, du démarrage fructueux des fouilles de Kınık Höyük. L'équipe de Porsuk, bien représentée dans ce colloque (du Bronze à l'époque romaine), attend d'ailleurs beaucoup des contacts scientifiques et amicaux entre nos deux missions, de même que des liens tissés également, mais depuis plus longtemps, avec nos amis de la fouille italienne de Kemerhisar-Tyane. L'Antiquité tardive et Byzance ont pu être ainsi représentées, principalement autour de Tyane, ce qui n'avait pas pu être le cas lors du premier colloque.

En octobre 2012, quelques semaines avant la tenue de la Rencontre, on apprenait malheureusement le décès brutal et inattendu d'Olivier Pelon, ancien directeur de la mission de Porsuk (jusqu'en 2002) et organisateur de ce premier colloque cappadocien. C'est bien en hommage à sa mémoire que notre Rencontre cappadocienne de 2012 et sa publication ont été naturellement dédiées. Sa communication générale sur Porsuk a pu être malgré tout présentée à Istanbul par Françoise Laroche-Traunecker.

Il nous reste à présenter à nouveau tous nos remerciements à Olivier Henry pour son investissement, mais aussi pour son infinie patience devant nos propres manquements. Merci aussi à Aksel Tibet, responsable des publications de l'IFEA et pilier de la mission de Porsuk, pour son dévouement et sa vaste expérience en matière éditoriale.

2 Seul un texte en revanche nous a été remis pour publication. Aliye Öztan, qui avait repris la direction des fouilles du néolithique récent de Köşk Höyük, n'a malheureusement pas pu répondre favorablement à notre invitation.

3 Un problème de communication particulièrement regrettable nous a privés de la participation de notre estimée collègue Aslıhan Yener. Elle n'a pas pu, par la suite, nous fournir à temps un texte sur ces découvertes fondamentales.

VOLCANISM AND EVOLUTION OF THE LANDSCAPES IN CAPPADOCIA

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Abstract

Cappadocia, situated in the Central Anatolia Plateau in Turkey, is characterized by widespread volcanic rocks (lavas, ignimbrites and pyroclastic deposits) alternating with fluvio-lacustrine sediments of Miocene (around 10 million years) to Quaternary age. The evolution of the Cappadocian landscape starts with gently sloping plateaus, which are then dissected, usually along fractures of soft-unwelded ignimbrites, to form mushroom-like, cone-shaped structures known locally as 'fairy chimneys'. We present here a brief description of the stratigraphy of the Cappadocian volcanic succession and explain types of volcanic products. Different landforms created by the erosion of the volcanic rocks are also explained. Because of the favorable engineering properties of the ignimbrites, ancient populations have carved their houses, churches and even underground cities for centuries. Today, this unique cultural and morphological heritage site, classified under UNESCO World Heritage List since 1985, is one of the most visited regions of Turkey.

1. Introduction

Situated in the center of Anatolia, Cappadocia is famous for its rock-hewn habitations, churches and underground cities carved into soft volcanic deposits. Humans who settled in the area centuries ago were well aware of the engineering properties of this material and this is the reason why the troglodytic habitations are numbered by thousands in the region. The peculiar landforms called fairy chimneys, smooth hills and valleys, together with

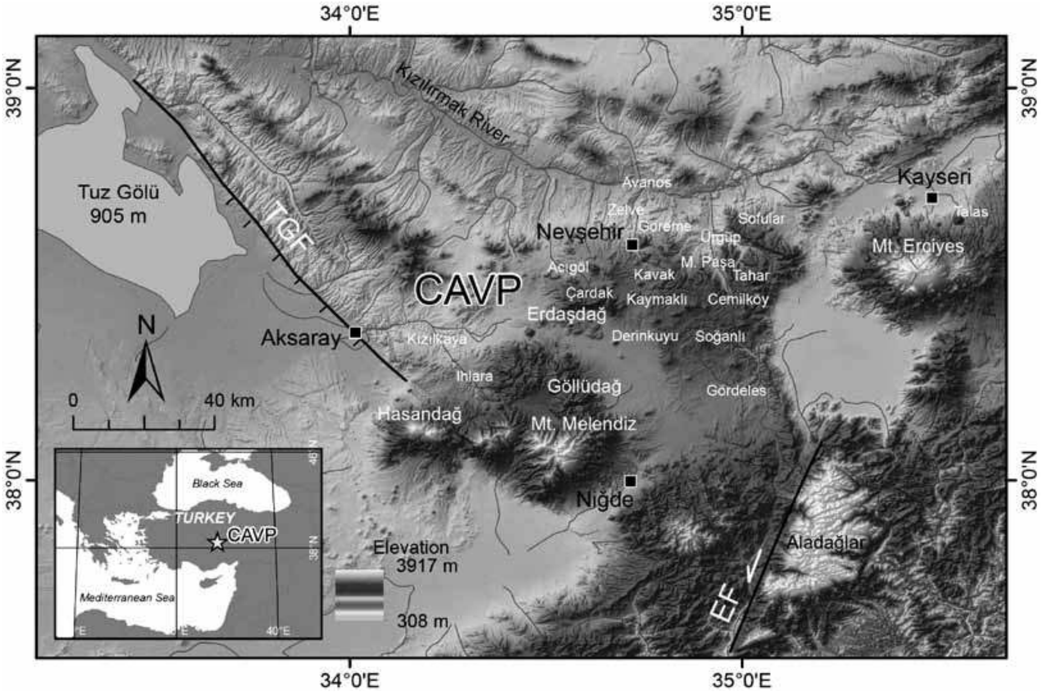


Fig. 1: Digital Elevation Model of the Central Anatolian Volcanic Province (CAVP). TGF: Tuz Gölü Fault, EF: Ecemiş Fault.

volcanoes make this region a land of fascinating geography. We present here a brief overview of the geological and geomorphological characteristics of this unique cultural and morphological heritage site that was included in the UNESCO World Heritage List in 1985.

2. Geology

Cappadocia is part of the Central Anatolia Volcanic Province (CAVP) which is comprised of Upper Miocene-Holocene ignimbrites, volcanic ash deposits and lava flows intercalated with fluvio-lacustrine sediments covering around 20.000 km^2 (fig. 1)[1]. Tuz Gölü Fault to the west and Ecemiş Fault to the east and two Quaternary stratovolcanoes, namely Hasandağ (3254 m) to the west and Erciyes (3917 m) to the east, delineate the Nevşehir plateau where the average altitude reaches 1400 m[2].

The geology of the CAVP is related to the convergence of the Afro-Arabian continent toward the Eurasian plate since Late Miocene times giving rise to widespread and intense volcanic activity[3]. The pre-volcanic basement of the CAVP is composed of plutonic rocks (granites and gabbros) of Cretaceous age[4] and metamorphic rocks of the Central Anatolian Crystalline Complex[5]. Sub-crustal detachment-delamination of lower crust that occurred around 5 Ma ago (Ma = million years) is thought to be responsible for the volcanism and plateau formation under the influence of extensional tectonic regime[6]. Different layers of voluminous ignimbrites (since 10 Ma) and various volcanic products (e.g., ignimbrites, lavas) originating from Quaternary stratovolcanoes (2.58 Ma) cover large areas in the region.

2.1. Volcanic Rocks

2.1.1. Ignimbrites

The ignimbrites and lava flows in the CAVP were first described by Pasquarè[7] and the stratigraphy was further refined by numerical ages obtained by using various dating techniques[8]. Recently, Aydar *et al.* (2012) published $^{40}Ar/^{39}Ar$ plagioclase eruption

1 Le Pennec *et al.* 1994.
2 Aydar *et al.* 2012.
3 Innocenti *et al.* 1975; Aydar *et al.* 1993; 1995; Piper *et al.* 2002

4 Aydar *et al.* 1995; 2012
5 Aydar *et al.* 1995; Dilek/Sandvol 2009.
6 Aydar *et al.* 2010.
7 Pasquarè 1968.
8 Innocenti *et al.* 1975; Pasquarè *et al.* 1988; Le Pennec *et al.* 1994; 2005; Mues-Schumacher/Schumacher 1996; Temel *et al.* 1998; Agrò *et al.* 2014.

a

b

Fig. 3: Photographs showing stratigraphic section with different ignimbrites: a. Creamy white Kavak Ignimbrite at the base overlain by white Zelve air-fall deposits and pink Zelve Ignimbrite. White fluviolacustrine sediments are on top. b. Grey Cemilköy Ignimbrite with fairy chimney developments at the base overlain by white lacustrine sediments, grey Gördeles Ignimbrite and red fluvial deposits. Thick white deposits represent fluviolacustrine sediments and the overlying welded unit is Kızılkaya Ignimbrite.

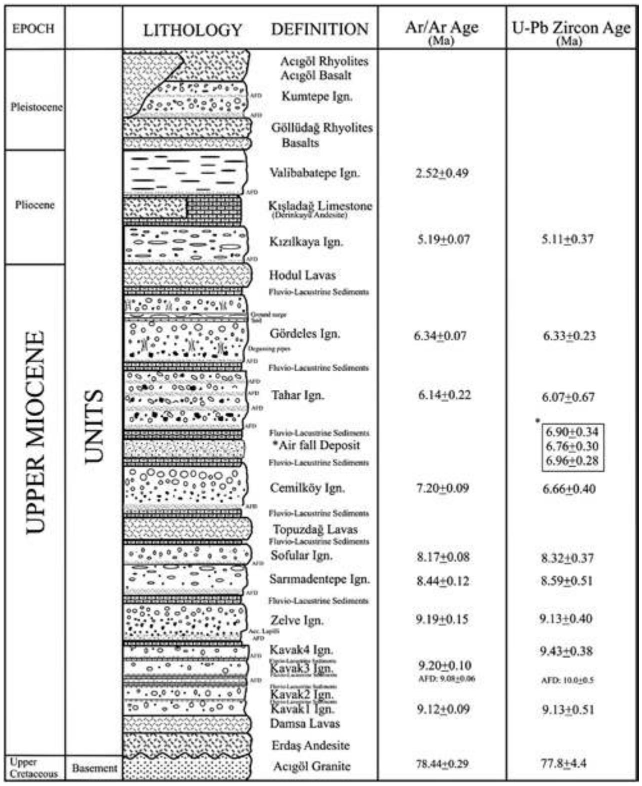


Fig. 2: Composite stratigraphic column and crystallization/ eruption ages for the CAVP. AFD = Air-fall deposit (from Aydar *et al.* 2012).

and $^{206}Pb/^{238}U$ zircon crystallization ages where they refined the stratigraphy by defining a total of ten ignimbrite sequences following the terminology outlined in Le Pennec *et al.* (1994), respecting mostly original names given by Pasquarè (1968) (fig. 2).

These ignimbrite sequences with ages ranging from 10 Ma to Quaternary are known as, in stratigraphic order from old to young, Kavak, Zelve, Sarımadentepe, Sofular, Cemilköy, Tahar, Gördeles, Kızılkaya, Valibabatepe and Kumtepe Ignimbrites, and several independent pumiceous air-fall deposits, often following the closest village names or hills in the region.

The Kavak Ignimbrites are the oldest pyroclastic deposits (<10 Ma) of the CAVP and are made up of 4 distinct units alternating with ash-rich fluvio-lacustrine sediments indicating multiple eruptions[9] (fig. 3a). The uppermost unit of Kavak (Kavak-4) is different from the white underlying sub-units (Kavak 1 to 3) with its pinkish color. A rhinoceros skull was incidentally found within this layer around Karacaşar village by the Volcanology team of Hacettepe University. Emplacement of Kavak-4 sourced from the Çardak Caldera most likely provoked the instant death of the Karacaşar rhino and the skull being separated from the remnant body and baked under a temperature approximating 400°C, then transported northward, rolled, and trapped

9 Aydar *et al.* 2012.

in disarray into that pyroclastic flow forming the pinkish Kavak-4 Ignimbrite[10].

The total volume of the ignimbrites is around 80 km^3, distributed over 2600 km^2 with a thickness ranging between 10 m and 150 m[11]. Kavak Ignimbrites are composed of crystal-rich pumice with large crystals of biotite, plagioclase and quartz. The Kavak Ignimbrites are generally unwelded and well-developed fairy chimneys and human made caves are numerous.

The overlying Zelve Ignimbrite (9.2 Ma) is composed of a white, 5-12 m thick basal Plinian air-fall deposit almost exclusively composed of glassy rhyolitic pumice[12] that in turn is overlain by a single cooling unit of pink ignimbrite with an average thickness of about 60 m (fig. 3b). This basal air-fall deposit is a consolidated pumice layer, locally known as 'Esbelli Stone', and is the most desirable building stone in the region because of its resistance to erosion. Devitrification and alteration occasionally replace pumice glass with yellowish zeolitic aggregates. Together with Zelve Ignimbrites, some parts of Kavak and Cemilköy Ignimbrites represent such kind of alteration causing re-crystallization of volcanic glass to zeolites around Sarıhıdır and Tuzköy villages. Those villages suffer mesothelioma diseases (lung cancer) due to those cancerogenius airborne minerals. Overlying the basal fallout is a series of pyroclastic units that display laminated, plane-parallel, or low-angle cross bedding indicating a hydrovolcanic episode during the emplacement of Zelve Ignimbrites. The volume and areal extent of the Zelve Ignimbrites is estimated to be 120 km^3 and 4200 km^2, respectively[13]. Zelve Ignimbrites contribute to form typical fairy chimneys with two or three hats.

Sarımadentepe Ignimbrite (8.4 Ma) is a very limited ignimbrite outcropping around Mustafapaşa and Ayvalı villages, mostly to the east and south of Çardak Caldera. It is a yellow-brown color welded unit, composed of a basal air-fall layer and an overlying ignimbritic flow. It constitutes the top of some earth-pillar located around eastern part of supposed caldera boundary. There is no observed fairy chimneys associated to Sarımaden Ignimbrites.

Sofular Ignimbrite (8.17 Ma) is a separate ignimbrite unit as constrained by radiometric dating and geochemical identity[14]. It outcrops around Sofular village and is composed of a fine-grained air-fall deposit underlain by a single flow unit 25 m thick[15]. The flow deposit is indurated/weakly welded, ash-supported lithic- and pumice-poor with maximum pumice size typically <4 cm. Phenocrysts in pumice comprise plagioclase, biotite and oxides.

The Cemilköy Ignimbrite (7 Ma) is one of the most voluminous and extensive units (300 km^3) of CAVP covering 8600 km^2 and reaching a thickness between 10-110 m[16]. This ignimbrite was sufficiently voluminous to regionally fill in the paleotopography, creating a volcanic peneplain. This pale-gray colored ignimbrite is composed of abundant white-pale pumice in prismatic-tabular shapes and forms smooth surfaces with fairy chimneys (fig. 3b).

Tahar Ignimbrite is restricted to the eastern part of the CAVP. It is distributed over 1000 km^2 with an estimated volume of 25 km^3 [17]. It is generally pale-pink to brown and mostly unwelded, but welding and columnar jointing is prominent around Sofular village. Its type locality is Tahar (Yeşilöz) village where it is 120 m thick[18]. The base of ignimbrite represents a lithic-rich layer. Pumices are glassy, beige to pinkish and occasionally represent flattened vesicles in the main flow unit. Mineralogical composition consists of the phenocrysts of plagioclase, amphibole, clinopyroxene, and orthopyroxene.

Gördeles Ignimbrite (6.34 Ma) has an estimated areal extent of around 3600 km^2 and a volume of 110 km^3 with a thickness changing between 7 and 20 m[19] (fig. 3b). In the field, Gördeles can be confused with Kızılkaya or Sarımadentepe Ignimbrites which all are similarly welded and pale gray to light brownish in color. Aydar *et al.* (2102) distinguish two different units of Gördeles (Lower and Upper), which are separated by a paleosol. A lithic rich layer with gas escape pipes is found at the base of the Lower Gördeles around Kayırlı village. The main flow unit contains pumice with textural differences (fibrous vs. sub-spherically vesiculated) and color variations ranging from pale-brown to bright-white which are,

10 Antoine *et al.* 2012.
11 Le Pennec *et al.* 1994.
12 Schumacher/Mues-Schumacher 1996.
13 Le Pennec *et al.* 1994.
14 Aydar *et al.* 2012.
15 Aydar *et al.* 2012.
16 Le Pennec *et al.* 1994.
17 Le Pennec *et al.* 1994.
18 Aydar *et al.* 2012.
19 Le Pennec *et al.* 1994.

however, compositionally identical. Phenocrysts are plagioclase, biotite, clinopyroxene and oxides[20].

Kızılkaya Ignimbrite (5.2 Ma) is the most widespread unit in the CAVP and forms a plateau over an area of 8500-10600 km^2 with a volume of 180 km^3 [21] (fig. 3b). Locally, thickness reaches >40-50 m (e.g., the Derinkuyu underground city) and peak at 80 m (Ihlara Valley) with an average thickness of 15 m. The Kızılkaya Ignimbrite generally consists of two distinct flow units that are often strongly welded with well-developed columnar jointing with cliffs and precipitous canyon walls. Texturally, Kızılkaya pumice looks like Gördeles Ignimbrite pumice, with similar phenocrysts of plagioclase, biotite, orthopyroxene and oxides[22].

Valibabatepe Ignimbrite (2.5 Ma) is a low-aspect ratio (5200 km^2, 100km^3)[23] ignimbrite as Kızılkaya. It has red and black layers in the proximal facies that become pinkish and gray at distal facies. It was first described by Pasquarè (1968), and we keep this original name rather than İncesu Ignimbrite that is also used to define this ignimbrite in the literature[24]. The strongly welded Valibabatepe Ignimbrite displays eutaxitic textures and well-developed fiamme. It outcrops at the eastern part of plateau, toward Erciyes Volcano and it reaches a maximum thickness of 40 m around Talas, at the base of Mt. Erciyes from which it originated[25]. Basal Plinian fallout deposits contain dacitic pumice with a modal mineral assemblage of plagioclase, amphibole, and clinopyroxene. The absence of biotite is one of the main field characteristics of the Valibabatepe Ignimbrite[26].

Kumtepe Ignimbrite is the youngest ignimbrite of Cappadocia, erupted during the Late Pleistocene. It erupted in two successive (Lower and Upper Acıgöl or Kumtepe) eruptions separated by paleosol, or cinder cone deposits[27]. Main outcrops are found along the Acıgöl-Nevsehir highway and cover all older ignimbrites. The lower unit is made dominantly of fallout deposits with a single flow unit, while the upper unit has a basal fallout rich in obsidian lithics underlying a pinkish-beige flow unit. We keep the name of Kumtepe defined originally by Pasquarè (1968), but it is also called the Acıgöl tuffs as it was originated from Acıgöl Caldera[28]. The zircon age of deposits is 206 ka and 163 ka (ka: 1000 years) for lower and upper units respectively[29].

2.1.2. Source areas for the ignimbrites

Cappadocian ignimbrites were mistakenly thought to be the products of dominating volcanoes, and rhyolitic massive of Göllüdağ volcanoes. In reality Late Miocene-Pliocene ignimbrites have their own eruption centers leading to caldera collapses[30]. Although the source areas are still a matter of debate, Kavak and Sarımadentepe Ignimbrites are thought to be related to Çardak Caldera and Zelve and Kumtepe Ignimbrites to Erdaş-Acıgöl area. Tahar Ignimbrite probably generated to the east of Derinkuyu. The source area of Sofular Ignimbrite was proposed to be below Topuzdağ area by Le Pennec *et al.* (1994). The source of Kızılkaya and Cemilköy Ignimbrites are still enigmatic, proposed to be Derinkuyu Basin[31].

2.1.3. Quaternary volcanoes and monogenic centers

Cappadocia hosts two Quaternary stratovolcanoes: Erciyes and Hasandağ (fig. 4a, b). Both volcanoes have their own evolutionary history.

The Hasandağ is a double peaked composite stratovolcano: Big and Small Hasandağ (3268 and 3069 m; respectively), culminating on a plateau situated at 1 km above sea level. Multiple evolutionary stages were identified as Paleo-, Meso-, and Neo-Hasandağ by extrusive dome emplacement and intermittent collapse events associated with ignimbrites[32]. Limited geochronological data indicate emplacement of the oldest lavas at 7.21±0.01 Ma (K-Ar)[33], and ignimbrite emplacement during an early caldera collapse at 6.31±0.20 Ma ($^{40}Ar/^{39}Ar$) that are contemporaneous with widespread Neogene ignimbrite volcanism in Cappadocia[34]. Dome extrusion with associated block and ash flow deposits and adventive monogenetic

20 Aydar *et al.* 2012.
21 Le Pennec *et al.* 1994; Schumacher/Mues-Schumacher 1996.
22 Aydar *et al.* 2012.
23 Le Pennec *et al.* 1994.
24 Schumacher/Mues-Schumacher 1996; Viereck-Götte *et al.* 2010.
25 Sen *et al.* 2003.
26 Aydar *et al.* 2012.
27 Druitt *et al.* 1995.
28 Druitt *et al.* 1995.
29 Schmitt *et al.* 2011.
30 Le Pennec *et al.* 1994; Froger *et al.* 1998; Aydar *et al.* 2012.
31 Le Pennec *et al.* 1994; Agrò *et al.* 2014.
32 Aydar/Gourgaud 1998; Aydar *et al.* 2014.
33 Aydar/Gourgaud 1998.
34 Deniel *et al.* 1998.

a

b

Fig. 4: Views of a. Erciyes Volcano; b. Hasandağ Volcano.

vent eruptions at the base are collectively attributed to the Neo-Hasandağ stage; actual form of volcano. The Neo-Hasandağ, comprising two summits, bears numerous collapsed andesitic to rhyodacitic lava domes on its flanks creating widespread pyroclastic deposits. The resulting soft block-and-ash flow deposits are deeply affected by erosion and intensively carved especially on Big Hasandağ flanks. Debris avalanche deposits outcrop north of the volcano, forming a typical hummocky surface.

Hasandağ is considered to be an active-subactive volcano. K/Ar ages exhibit that the volcanic activities happened during the Holocene with an andesitic lava dome extrusion at the northern flank, yielding a maximum age of 6 ka[35]. Another andesitic lava flow erupted at the western base of the volcano with zero-age $^{40}Ar/^{39}Ar$[36]. Two summit domes (Big Hasandağ) yield the ages of 29 ka and 33 ka[37]. Recently, pumices collected from the summit of Big Hasandağ were dated to constrain the eruption age with U-Th/He method measured on zircon crystals to 8.97±0.64 ka and 28.9±1.5 ka[38]. Holocene age (8.97±0.64 ka) is the most important as it was probably witnessed by humans. British archaeologist James Mellaart discovered numerous wall sketches in the Neolithic settlement of Çatalhöyük during 1960's. A mural sketching between findings of Mellaart[39] was showing an erupting volcano behind a city. This is accepted to be the first map in human history[40].

The mural sketching describes a double peaked volcano in the ground and an eruption cloud rising from the neck located between two terminal cones with the eruption cloud direction towards the tallest cone[41]. The position of Small and Big Hasandağ terminal cones might be a view of Hasandağ from the north. An eruptive column rises from the neck between two cones, drifting west and depositing its air-fall deposits on Big Hasandağ terminal cone. In the front of mural sketching, there is a bird's-eye view settlement near a creek. It is believed that this was a plan view of Çatalhöyük settlement[42]. The bird flight distance between Çatalhöyük and Hasandağ is about, 130 km. The earth's circularity does not allow viewing of the whole Hasandağ volcano as it was sketched on a wall of Çatalhöyük. A horizon line for a person with a height of 1.70 m standing on a flat area is around at 4.7 km. On a clear day, one can only see the summital part of the volcano from such a distance. Therefore there are two possibilities: either this sketch is fictive, although it contains numerous correct descriptions from a volcanological point of view (eruption column,

35 Aydar/Gourgaud 1998.
36 Kuzucuoğlu *et al.* 1998.
37 Kuzucuoğlu *et al.* 1998.
38 Schmitt *et al.* 2014.
39 Mellaart 1964.
40 Clarke 2013; Sigurdsson *et al.* 2000.
41 Schmitt *et al.* 2014.
42 Schmitt *et al.* 2014.


a


b


c

Fig. 5: a. Aligned cinder cones 'corridor'. Erdaşdağ can be seen on the background. b. Acıgöl rhyolitic maar and a rhyolitic dome on the background. c. A cinder cone. Red color indicates hot oxidation zone corresponding to volcanic conduit /chimney.

eruption cloud, wind effect drifting cloud toward west, air-falls and ejectas etc.) or, the settlement on the wall sketch represents Aşıklıhöyük which is also a Neolithic settlement, situated near Melendiz Creek to the north of Hasandağ. There is also a hill just behind this settlement, allowing a bird's-eye view and a panorama on Hasandağ. The recent U-Th/He eruption age determination proves that the volcano explosively erupted 9000 years ago (8.97±0.64 ka) and was eye witnessed by a Çatalhöyük resident at Aşıklıhöyük[43].

The other Quaternary stratovolcano, Erciyes, is a huge, voluminous stratovolcano (3300 km^2), with at least 64 monogenetic vents on its flanks[44]. Its summit reaches 3917 m above sea level (relative height around 3000 m from the Sultansazlığı basin). Erciyes was well known in the antiquity and its name probably derives from Mont Argaeos (Greek) or Argaeus (Latin) meaning 'bright' or 'white'[45]. Mt Argaeos must have deeply impressed Caeseria (present day Kayseri city) people since they usually used a sketch of Argaeos in the tails side of roman provincial coins while the heads illustrated the gods, emperors or kings.

The volcanological evolution of Erciyes is divided into two main stages: Koçdağ and Erciyes[46]. The eastern flank of Erciyes represents the remnant of Koçdağ stage. Volcanic products are basaltic, andesitic lava flows, scoriaceous ejectas and well-welded Valibabatepe Ignimbrites. After ignimbrite emplacement occurred 2.5 Ma[47], Koçdağ volcano collapsed creating a large caldera. At present, one can observe the caldera boundary around the ski center. Erciyes volcano rose within this caldera and is characterized by andesitic dacitic lava flows and domes, basaltic lava flow and cinder cones and maars. Toward the end of this stage, the volcanic activities are marked by rhyodacitic dome emplacements (Dikkartın, Perikartın and Karagüllü domes) preceding important pyroclastic activities. Those lava domes were dated to 10 ka by ^{36}Cl cosmogenic surface exposure dating methods[48]. Pyroclastics preceding the Dikkartın dome emplacement were found in the Mediterranean Sea near Israel during a marine drilling program[49]. The violent explosive character and the voluminous

43 Schmitt *et al.* 2014.
44 Sen *et al.* 2003.
45 Facaros/Pauls 2000.
46 Sen *et al.* 2003.
47 Aydar *et al.* 2012.

48 Sarıkaya *et al.* 2006.
49 Hamann *et al.* 2010.

ash fall deposits must have had a significant impact on the adjacent regions. During the Dikkartın eruption of Erciyes volcano, several Pre-Pottery Neolithic settlements were located in the proposed distribution area of Dikkartın tephra, such as in Central Anatolia (e.g., Çatalhöyük), on Cyprus (e.g., Tenta, Khirokitia), and in the Near East (e.g., Ain Ghazal), dated by archaeological artifacts[50].

Hundreds of monogenetic vents, such as cinder cones, maars and lava domes are also observed (fig. 5a-c). Miocene aged Erdaşdağ separate the rhyolitic center of Acıgöl from a basaltic lava and cinder cone field situated to the north of Ihlara Valley[51]. Two different rhyolitic systems, namely Acıgöl and Göllüdağ, are present. The Acıgöl system is younger and dated to Late Pleistocene (190-20 ka)[52]. The youngest age is related to Acıgöl maar and Güneydağ dome (20 ka and 23 ka, respectively)[53] near Acıgöl-Nevşehir highway.

3. Geomorphology

The morphology of the CAVP is dominated by plateaus cut in places by valleys where fairy chimneys and man made troglodytes exist next to each other. The Kızılırmak River to the north flows mostly within these volcanic and fluvio-lacustrine products (fig. 6). Channel deposits of this river are also often found lying unconformably on these ignimbrites creating peculiar morphological features[54].

Fig. 6: Kızılırmak River. The actual flood plain (F) and ancient terraces (T) composed of channel deposits (mainly conglomerates).

3.1. Plateaus and valleys

Strongly welded Kızılkaya Ignimbrite is the most widespread unit in the CAVP. It covers most of the underlying deposits and forms a high plateau with a flat topography (mesa) from the Soğanlı Valley to the east until the Ihlara Valley to the west (fig. 7). The plateau is cut by paleo- and recent fluvial systems forming valleys and deep gorges, in places reaching several hundreds meters in depth. Colorful sections of stratified ignimbrites often eroded to form smooth landscapes can be observed within these valleys (fig. 8a, b). Troglodytic houses, pigeonholes and fruit trees and grapevines complete this landscape.

Fig. 7: Kızılıkaya Ignimbrite incised to form Ihlara Valley.

a

b

Fig. 8: a-b. Smooth landscape formed by the erosion of Kavak Ignimbrite.

50 Hamann *et al.* 2010.
51 Yıldırım/Özgür 1981; Bigazzi *et al.* 1993; Mouralis *et al.* 2002.
52 Bigazzi *et al.* 1993; Schmitt *et al.* 2011.
53 Schmitt *et al.* 2011.
54 Çiner *et al.* 2014; Doğan 2010; 2011.

3.2. Fairy chimneys

The so-called fairy chimneys are unique mushroom-like landforms composed of differentially eroding ignimbrites (a pyroclastic flow composed of a very poorly sorted mixture of volcanic ash, or tuff when lithified, pumice and rock fragments) often alternating with fluvio-lacustrine sediments[55]. Among ten ignimbrite units defined in the CAVP, the fairy chimneys are extensively developed on Kavak, Zelve, Cemilköy and to some extent on Kızılkaya and Gördeles Ignimbrites.

3.3.1. Formation and erosion

The formation and deterioration of the fairy chimneys are controlled by spacing, aperture and strike and dip of discontinuities initially formed by thermal stress[56]. The evolution of this landscape starts with gently sloping plateaus, which later differentially erode, due to the physical characteristics of successive ignimbrite layers. Plateaus are then dissected – often starting from cooling fractures – to form fairy chimneys. Because of the occasional presence of soft layers such as lacustrine deposits and/or air-fall deposits between the ignimbrite flows, the chimney caps are formed. For a limited time the caps protect the fairy chimneys from erosion giving rise to the development of the mushroom-like morphology. However, when the hard cap is eroded away, a sharp-pointed chimney is formed, and eventually the remaining cone is quickly destroyed by ongoing erosion. Several types of fairy chimneys are formed depending on the nature of the ignimbrites (fig. 9a-h).

3.3.2. Effect of climate

The climate (amount of precipitation, freezing and thawing cycles) also plays an important role in the development of the fairy chimneys. Hot and dry summers, and cold and wet winters characterize modern climate in Cappadocia where average summer temperature at 1260 m, is 19°C and an average winter temperature is 0°C. Except within valleys the region is poorly vegetated and hence the rainfall and snowmelt accentuate the active erosion.

Several studies[57] indicate that the climate since the Last Glacial Maximum (LGM) (around 20.000 years ago) has been characterized by a general increase in temperatures and an increase of precipitation at the onset of the Holocene, and later a decrease towards the Late Holocene. Paleo-glacier modeling results on Erciyes Volcano showed that during the LGM the climate was 8-11°C colder and the precipitation values were more or less similar to modern values. During the Late Glacial time (around 14.000 years ago), climate was colder by 4°C and up to 50% wetter. The Early Holocene was 2-5°C colder and up to twice as wet as today, while the Late Holocene was 2-3°C colder with the precipitation rates similar to those of today[58].

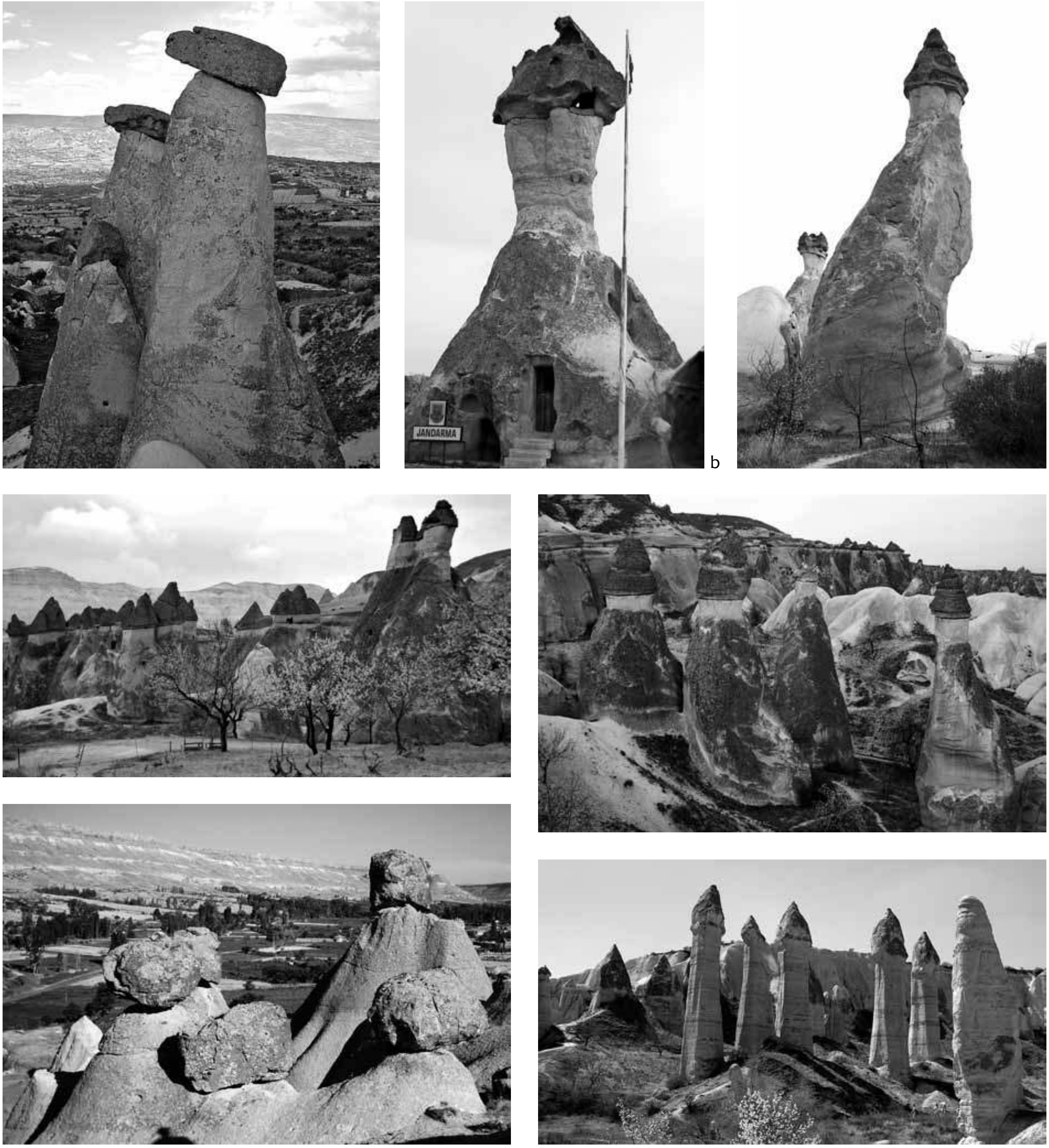
The precipitation and temperature contrasts from the LGM till today, together with contrasts in densities and types of vegetation cover most probably accentuated differential erosion in the Cappadocian fairy chimneys.

3.3.3. Erosion rates

Although erosion controls the formation of fairy chimneys, it also has a negative effect on their alteration and eventually on their-future existence[59]. In addition to natural processes, anthropogenic effects induced by increasing touristic influence also play an important role in their disappearance. To better understand the processes that create the formation of the fairy chimneys and to better appreciate their vulnerability, Sarıkaya *et al.* (2015) conducted a study in order to quantify the erosion rates. To achieve this aim, they used in-situ produced cosmogenic isotopes for the first time in the Cappadocian landscape and obtained quantifiable long-term erosion rates for fairy chimney development stages. Their results show that the apparent ages of samples vary between 148.4±8.0 ka and 26.7±2.8 ka and the plateaus erode at a low rate of 0.6 cm/ka - 0.9 cm/ka. The erosion rate increases from 2.3 cm/ka to 3.3 cm/ka when the landscape is dissected to form fairy chimneys. The caps of chimneys have erosion rates of 3.1 cm/ka and once the chimney caps disappear and expose softer rocks below, erosion rates increase

55 Le Pennec *et al.* 1994.
56 Topal 1995; Topal/Doyuran 1995; 1997; 1998; Aydan/Ulusay 2003; Aydan *et al.* 2007; Erguler 2009.

57 For Cappadocia see Roberts *et al.* 2001; Woldring/Bottema 2002; Jones *et al.* 2007; Sarıkaya *et al.* 2009; 2011; 2014a; Zreda *et al.* 2011; Ulusoy *et al.* 2014.
58 Sarıkaya *et al.* 2009.
59 Çiner *et al.* 2013.



a b c d e f g

h

Fig. 9: Different types of fairy chimneys observed in Cappadocia: a. These fairy chimneys near Ürgüp are locally known under the pseudo-name of ‘Family’ due to their resemblances to a couple and a child. They are composed of Kavak Ignimbrite overlain by Zelve Plinian fall deposits making up the harder tops. b-e. Paşabağ area fairy chimneys: Gendarmerie carved into a fairy chimney. Lower layer is Kavak Ignimbrite overlain by creamy white fluviolacustrine sediments. f. Fairy chimney in Cemilköy Ignimbrite overlain by rock falls. g-h. Fairy chimneys near Göreme.

significantly, perhaps by an order of magnitude or more. Other erosion rates obtained from the softer part of the Kavak ignimbrite indicate 0.4 mm/year and 2.5 mm/year erosion[60].

On much longer timescales Aydar *et al.* (2013) calculated the erosion/incision rates using the morphological/paleoaltimetric features of radiometrically well-constrained volcanic units in the area. They proposed that starting from 10 Ma until 5 Ma, there was no major erosion or incision. Basing on the morphology, uplift rate, and incision rates, they also proposed that the onset of plateau uplift is post 8 Ma and incision started after 5 Ma. Between 5 and 2.5 Ma, the incision rate is calculated as 0.12 mm/year, whereas, in the last 2.5 Ma, the incision rate slowed down to 0.04 mm/year.

On the other hand, Doğan[61] using basalt flows that cover Kızılırmak terraces calculated 0.08 mm/year average incision rate for the last 2 Ma. Recently, Çiner *et al.* (2015) used cosmogenic isochron-burial nuclide dating method on several terraces of Kızılırmak to propose an average incision rate of 0.06 mm/year since 1.9 Ma. Using the base of a basalt fill above the modern course of the Kızılırmak, Çiner *et al.* (2015) also calculated a similar mean incision and hence rock uplift rate (0.05-0.06 mm/year) for the last 2 Ma.

4. Conclusions

Cappadocia is famous for its volcanic rocks that date back from Miocene (10 Ma) to Quaternary age. The erosion of the ignimbrites created a unique landscape characterized by plateaus, valleys and fairy chimneys of different types. Rock hewn houses, churches and underground cities carved by humans that settled in the area makes this region one of the most popular touristic destination classified under UNESCO's World Heritage List since 1985.

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Glossary[62]

Basalt: Volcanic rock with 44-52% silica content that in conjunction with typically higher flow temperatures results in relatively fluid magmas.

Andesite: Volcanic rock with 53-63% silica content (SiO_2) having a viscosity when molten that is typically intermediate to that of basalt and rhyolite.

Rhyolite: Volcanic rock with more than 68% silica having exceptionally sluggish flow characteristics owing to its high silica content and typically lower emplacement temperatures.

Lava: Molten rock expelled at the Earth's surface by volcanic eruptions

Magma: A mantle- or crust-derived, physically and chemically complex mixture of molten rock, solids (e.g., crystalline or refractory fragments), and gases (e.g., CO_2 or H_2O).

Pyroclasts: Fragmentary material ejected during a volcanic eruption, including pumice, ash, and rock fragments.

Pumice: A light-colored, cellular, and glassy rock, typically less dense than water because of the large fraction of bubbles (vesicles) in the glass.

Pyroclastic fall (= air-fall or fallout deposits): The rain-out of pyroclasts through the atmosphere from an eruption jet or plume during an explosive eruption.

Caldera: Crater or surface depression resulting from collapse of an underlying magma chamber roof during withdrawal of magma, mostly related to ignimbritic eruptions for silicic magmas.

Ignimbrites: Pyroclastic deposits primarily formed by volcanic ash and pumice, resulting from great explosive eruptions that generate pyroclastic flows. Welded or unwelded, pumiceous, ash-rich deposit of pyroclastic density current(s). This term was formerly used for strongly welded deposits only. Ignimbrite is a pyroclastic flow composed of very poorly sorted mixture of volcanic ash, pumice and rock fragments. It is also called as 'tuff'.

60 Erguler 2009.
61 Doğan 2011.

62 Compiled from *Encyclopedia of Volcanoes*, Sigurdsson *et al*. 2000.

Block-and-ash flow deposit: Small-volume pyroclastic flow deposit characterized by a large fraction of dense to moderately vesicular juvenile blocks in a medium to coarse ash matrix of the same composition. They are mostly related to collapses of hot lava domes.

Monogenetic vents: A volcano that erupts in single eruptive period and style. e.g., Cinder cones, maars and lava domes.

Scoria cones, also called cinder or tephra cones, are relatively small but common volcanoes that form by the eruption of low-viscosity, generally basaltic magma in Strombolian or Hawaiian eruptions. They commonly occur in groups or fields, some consisting of hundreds of eruptive centers.

Maars, formed subaerially and/or in shallow water. They result from phreatomagmatic (= hydrovolcanic) eruptions due to mixing of ascending magma with groundwater or surface water.

Stratovolcano: A volcano constructed of alternating layers of lava flows and pyroclastic rocks.

Lava dome: A lava that cannot flow due to high viscosity and accumulated over the vent.

Plutonic: Magma cools in the interior of the earth, the resulting igneous rocks are referred to as intrusive or plutonic rocks.

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