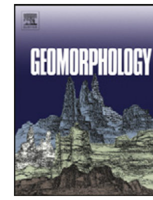
Geomorphology 234 (2015) 182–191

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Fairy chimney erosion rates on Cappadocia ignimbrites, Turkey: Insights from cosmogenic nuclides

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ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form 31 October 2014
Accepted 14 December 2014
Available online 4 February 2015

Keywords:
Cappadocia
Volcanism
Bedrock erosion rates
Ignimbrites
Cosmogenic ^{36}Cl
Turkey

ABSTRACT

Cappadocia, in the Central Anatolian Plateau of Turkey, is famous for its unique landscape and unusual rock formations. The development of this landscape dates back to Late Miocene epoch (c. 10 million years) when volcanoes spread pyroclastic deposits over an area of about 20,000 km^2. The volcanism continued for several millions of years and laid down thick and colorful ignimbrite layers. The evolution of the Cappadocian landscape starts with nearly-horizontal plateaus, which are then dissected, usually along cooling fractures, to form mushroom-like structures (hoodoos) locally known as "fairy chimneys". Different layers of ignimbrites have different resistance to erosion: softer layers (necks) are easier to erode compared to the harder ignimbrites (caps). When the chimneys are isolated, the caps play an important role in slowing further erosion of softer layers. When the caps finally drop or completely erode away, the soft necks of the chimneys are quickly destroyed. Here, for the first time, we have determined the bedrock erosion rates at the three evolution stages of fairy chimneys using the cosmogenic chlorine-36 (^{36}Cl): the pre-chimney (plateaus) stage, the chimney stage and the post-chimney stage. The data show that the plateaus erode at a very low rate between 0.58 ± 0.02 cm/ky and 0.93 ± 0.05 cm/ky. When dissection of a plateau starts, the erosion rate increases to about 4.5 ± 0.6 cm/ky. The caps of chimneys have erosion rates between 3.21 ± 0.36 cm/ky and 3.39 ± 0.36 cm/ky. Once the chimneys disappear, erosion rates increase significantly to 28.0 ± 9.9 cm/ky.

1. Introduction

Cappadocia, situated in the Central Anatolian Volcanic Province (CAVP) (Fig. 1), is one of the most important touristic sites of Turkey; it has beautiful landscape, man-made troglodyte settlements, old churches and underground cities. Cappadocia was included in the UNESCO World Heritage List in 1985 and since then increasing numbers of tourists have visited the area to appreciate this unique cultural heritage and natural beauty.

In this landscape, mushroom-like structures made up of harder volcanic rocks underlined by softer rocks, locally known as hoodoos or "fairy chimneys", are probably the most peculiar features (Fig. 2). Fairy chimneys are unique landforms composed of differentially eroding ignimbrites (a pyroclastic flow deposit composed of very poorly sorted mixture of volcanic ash, or tuff when lithified, pumice and rock fragments) often alternating with fluvio-lacustrine sediments (Le Pennec et al., 1994). Outside of Cappadocia, hoodoos are also found in the Colorado Plateau and in the Badlands, and are best known in the northern section of Bryce Canyon National Park, in the USA (Davis and Pollock, 2003). They are called *demoiselles coiffées* ("ladies with hairdos") in the French Alps (René, 1940). While hoodoos are encountered in several other areas under different names such as tent rock, earth pyramid or Devil's towers, nowhere in the world are they as abundant as in Cappadocia.

The evolution of this landscape starts with gently sloping plateaus, which later differentially erode due to the variable physical characteristics of different ignimbrite layers. Plateaus are 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 harder ignimbrite flows, the chimney caps are formed in the overlying resistant ignimbrites. For 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.

The formation and deterioration of the fairy chimneys are controlled by spacing, aperture and strike and dip of discontinuities initially formed by thermal stress (Emre and Güner, 1985; Topal, 1995; Topal and Doyuran, 1995; Aydan et al., 2007; Erguler, 2009; Çiner et al., 2013). Topal and Doyuran (1997, 1998) used material and mass properties, such as average pore diameter, saturation coefficient, wet-to-dry strength ratio and static rock durability index of Cappadocian tuffs in order to show that they have low to very low durability. The fairy

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http://dx.doi.org/10.1016/j.geomorph.2014.12.039
0169-555X/

chimney formation is less obvious on horizontal flanks, but accentuated in areas when slope angle increases. In areas where freezing and thawing are more pronounced because of minimum exposure to the sun and/or type of surface drainage pattern, fairy chimney erosion increases.

On much smaller scales, water seems to be the main weathering mechanism controlling the erosion of the fairy chimneys. Garcia-Vallès et al. (2003) have shown that the hydrolysis of volcanic glass and feldspar that forms zeolites and clay minerals is an effective agent that facilitates erosion. On the other hand, the presence of a lichen biofilm on the surface of the fairy chimneys substantially reduces water accessibility to the ignimbrite and, thus, decreases the erosion rate (Garcia-Vallès et al., 2003).

Although erosion is the driving force in the initial formation of fairy chimneys, it has also a negative effect on their alteration and eventually on their future existence. In addition to natural processes, anthropogenic effects induced by increasing tourist influence also play an important role in their disappearance. Quantifying erosion rates is of great importance across a wide range of environmental science disciplines. However, this has been difficult at the millennial timescales until the advent of cosmogenic dating methods that allow quantifying of long-term erosion rates (Matsushi et al., 2006; Bourlès et al., 2011). To quantify the fairy chimney erosion rates we used in-situ produced cosmogenic ^{36}Cl for the first time in the Cappadocian landscape, and obtained long-term erosion rates for their three development stages: the pre-chimney (plateau) stage, the chimney stage and the post-chimney stage.

2. Geology and geomorphology

The CAVP is made up of Upper Miocene–Holocene ignimbrites, volcanic ash deposits and lava flows intercalated with fluvio-lacustrine sediments that cover around 20,000 km^2 (Le Pennec et al., 1994) (Fig. 1A). Tuz Gölü Fault to the west and Ecemiş Fault to the east, and two Quaternary stratovolcanoes, namely Hasandağ to the west and Erciyes to the east, delineate the Nevşehir plateau where the average elevation reaches 1400 m above sea level (asl) (Aydar et al., 2012). The topographic relief is high. Kızılırmak River defines the base level of the region at around 950 m asl. The drainage network is well established and shows a dendritic character (Fig. 1B).

The convergence of the Afro-Arabian continent with the Eurasian plate since Late Miocene times is responsible for the creation of the widespread and intense volcanic activity observed in Cappadocia (Innocenti et al., 1975; Piper et al., 2002; Aydar et al., 2010). The prevolcanic basement of CAVP is composed of plutonic rocks (mainly granites and gabbros) of Cretaceous age (Aydar et al., 2012) and metamorphic rocks of the Central Anatolian Crystalline Complex (Dilek and Sandvol, 2009). As a result of numerous large-volume ignimbrite deposits, Quaternary stratovolcanoes and monogenic centers exist in CAVP.

Cappadocia hosts two Quaternary stratovolcanoes: Hasandağ and Erciyes. The Hasandağ is a stratovolcano (3268 m asl) with multiple evolutionary stages characterized by extrusive dome emplacement and intermittent collapse events associated with ignimbrites (Aydar and Gourgaud, 1998; Aydar et al., 2012). Hasandağ is considered to be an active–subactive volcano; K/Ar ages on an andesitic lava dome yielded a maximum age of 6 ky (Aydar and Gourgaud, 1998), and an andesitic lava flow at the western base of the volcano gave a zero age (Kuzucuoğlu et al., 1998).

The other Quaternary volcano, Erciyes (3917 m asl), is a very large stratovolcano (3300 km^2), with at least 64 monogenetic vents on its flanks (Şen et al., 2003). Volcanic products are basaltic and andesitic lava flows, scoriaceous ejecta and ignimbrites. After ignimbrite emplacement that occurred c. 2.5 Ma (Aydar et al., 2012), the volcano collapsed creating a large caldera. The following stage is characterized by andesitic dacitic lava flows and domes, basaltic lava flow and cinder cones and maars (Şen et al., 2003). Rhyodacitic dome emplacements preceding important pyroclastic activities mark the end of this stage. The lava domes were dated to c. 10 ky by ^{36}Cl cosmogenic surface exposure dating method (Sarıkaya et al., 2006).

Hundreds of monogenetic vents, such as cinder cones, maars and lava domes are also present in Cappadocia. A basaltic lava and cinder cone field is situated to the north of Ihlara Valley (Bigazzi et al., 1993; Mouralis et al., 2002). Two different rhyolitic systems, namely Acıgöl and Göllüdağ, are present. The Acıgöl system is younger and dated to Late Pleistocene (190–20 ky; Bigazzi et al., 1993; Schmitt et al., 2011).

The ignimbrites and intercalated lava flows were first described by Pasquarè (1968) followed by many others, and the stratigraphy was further refined by numerical ages obtained by using various dating techniques (Innocenti et al., 1975; Pasquarè et al., 1988; Le Pennec et al. 1994, 2005; Mues-Schumacher and Schumacher, 1996; Temel et al., 1998; Aydar et al., 2012). Because it incorporates complementary geochronological data (eruption age based on ^{40}Ar/^{39}Ar in plagioclase and crystallization ages based on ^{206}Pb/^{238}U in zircon), we used recently updated stratigraphy where Aydar et al. (2012) define ten ignimbrite sequences, following the terminology outlined in Le Pennec et al. (1994) (Fig. 3). These ignimbrite sequences with ages ranging from Miocene to Quaternary are known as, in stratigraphic order from old to young, Kavak, Zelve, Sarımadentepe, Sofular, Cemilköy, Tahar, Gördeles, Kızılkaya, Valibabatepe and Kumtepe ignimbrites, often following the closest village names in the region. These data show that the formation age of the ignimbrite deposits is sufficiently old to assume infinite exposure ages to calculate the erosion rate of their surfaces.

Among ten ignimbrite units defined in CAVP, the fairy chimneys are extensively developed on Kavak, Zelve, Cemilköy and to some extent on Kızılkaya and Gördeles ignimbrites. Besides, strongly welded Kızılkaya ignimbrite covers most of the underlying deposits and forms a high plateau (mesa) between Soğanlı Valley in the east and Ihlara Valley in the west (Figs. 1, 2A). Because we sampled from plateau- and fairy chimney-forming ignimbrites, a brief description of these units is given below.

The Kavak ignimbrites (Fig. 2B, D) are the oldest pyroclastic deposits (9.20 Ma) of the CAVP and are made up of 4 distinct units alternating with ash-rich fluvio-lacustrine sediments indicating multiple eruptions (Aydar et al., 2012). The total volume of the ignimbrites is around 80 km^3 that is distributed over 2600 km^2 with a thickness varying between 10 m and 150 m (Le Pennec et al., 1994).

Immediately overlying Zelve ignimbrite (9.19 Ma) is composed of a white, 5–12 m-thick basal Plinian air-fall deposit (Fig. 2E) composed almost exclusively of glassy rhyolitic pumice (Schumacher and Mues-Schumacher, 1996), which in turn is overlain by a single cooling unit of pink ignimbrite with an average thickness of about 60 m (Le Pennec et al., 1994). This basal air-fall deposit is a strongly welded pumice, locally known as "Esbelli Stone", and is the most desirable building stone in the region because of its resistance to erosion.

The Cemilköy ignimbrite (7.2 Ma) is one of the most voluminous units (300 km^3) of CAVP covering 8600 km^2 and reaching a thickness of 10–110 m (Le Pennec et al., 1994). This pale-gray ignimbrite is composed of pumice in prismatic shapes and forms smooth surfaces with fairy chimneys due to its unwelded nature, especially abundant along the Damsa Valley (Fig. 1B).

Gördeles ignimbrite (6.34 Ma) has an estimated areal extent of ~3600 km^2 and a volume of 110 km^3 with a thickness changing between 7 m and 20 m (Le Pennec et al., 1994). Gördeles ignimbrite can be confused with Kızılkaya ignimbrite, which is moderately welded and has pale gray to light brownish color (Aydar et al., 2012).

Kızılkaya ignimbrite (5.2 Ma) is the most widespread unit in the CAVP and forms a plateau over an area of ~8500–10,600 km^2 with a volume of 180 km^3 (Le Pennec et al., 1994; Schumacher and Mues-Schumacher, 1996). The average thickness is 15 m, but locally it exceeds 40–50 m (e.g., the Derinkuyu underground city) and peaks at ~80 m (Ihlara Valley) (Fig. 2A). The Kızılkaya ignimbrite generally consists of two distinct flow units that are often strongly welded with well-