# Mammal bearing late Miocene tuffs of the Akkaşdağı region; distribution, age, petrographical and geochemical characteristics

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Karadenizli L., Seyitoğlu G., Sen S., Arnaud N., Kazancı N., Saraç G. & Alçiçek C. 2005. — Mammal bearing late Miocene tuffs of the Akkaşdağı region; distribution, age, petrographical and geochemical characteristics, *in* Sen S. (ed.), Geology, mammals and environments at Akkaşdağı, late Miocene of Central Anatolia. *Geodiversitas* 27 (4) : 553-566.

**ABSTRACT**

The Neogene tuffs of the Akkaşdağı region, in the south eastern part of the Çankırı-Çorum Basin in Central Anatolia, yielded one of the richest mammalian faunas of Turkey. The main aim of the present study is to provide data on the distribution, age, petrographical, mineralogical and geochemical composition of these tuffs. It is shown that they are primary products of a volcanic process. The Akkaşdağı tuffs are included in a late Miocene sedimentary sequence and were deposited as pyroclastic flow deposits. The gas escape structures (gas segregation pipes) in tuffs and the abundance of pumice and lithic clasts in the lower parts should be mentioned. The age of the tuffs is determined as late Miocene (MN 12 zone) based on the rich mammalian fauna and as 7.1 ± 0.1 Ma on the basis of radiometric dating. The petrographic investigations indicated that the Akkaşdağı tuffs are vitric tuffs. Biotite and lithic clasts occur in a glassy matrix. In addition, they contain feldspar (orthoclase), quartz phenocrysts, oxyhornblende and pumice clasts. With these properties, the tuffs present all characteristics of ignimbrites. Geochemical analyses reveal the calc-alkaline nature and rhyolitic composition of these tuffs. These results show that the Akkaşdağı tuffs show similarities to those of the Nevşehir Plateau which belong to the Central Anatolian Volcanic Province. Because these tuffs are pyroclastic flow deposits, it is thought that the source area should be close to Akkaşdağı. Volcanic activity might have caused the mass death of mammals the remains of which are concentrated in several bone pockets.

**KEY WORDS**
Tuff,
geochemical analyses,
radiometric dating,
late Miocene,
Akkaşdağı,
Central Anatolia,
Turkey.

**RÉSUMÉ**

*Les tufs du Miocène supérieur des environs d'Akkaşdağı ; distribution, âge et caractères pétrographiques et géochimiques.*

Les tufs néogènes de la région d'Akkaşdağı, dans le sud-est du bassin de Çankırı-Çorum en Anatolie Centrale, ont livré l'une des plus riches faunes de mammifères de Turquie. L'objectif principal de cette étude est de présenter les données sur la distribution, l'âge et la composition pétrographique, minéralogique et géochimique de ces tufs. Il s'agit des produits primaires d'une activité volcanique. Les tufs d'Akkaşdağı sont intercalés dans une séquence sédimentaire du Miocène supérieur et sont déposés comme des coulées pyroclastiques. La présence des structures de fuite de gaz (cheminées de ségrégation de gaz) dans les tufs et l'abondance de pierres ponces et des galets dans les parties inférieures des coulées doivent être mentionnées. La riche faune de mammifères fossilisée dans les poches de ravinement de la partie supérieure du tuf est datée du Turolien moyen (zone MN 12). De même, un échantillon du tuf primaire donne un âge radiométrique de 7,1 ± 0,1 Ma. L'étude pétrographique montre que le tuf d'Akkaşdağı est un tuf vitrique. Les grains de biotites et des galets sont abondants dans la matrice. La matrice contient feldspar (orthoclase), phénocrystaux de quartz, oxyhornblende et galets de pumice. Avec ces propriétés, les tufs présentent toutes les caractéristiques d'ignimbrites. Les analyses géochimiques ont révélé la nature calc-alcaline et la composition rhyolitique de ces tufs. De par leur composition, les tufs d'Akkaşdağı présentent des ressemblances avec ceux du plateau de Nevşehir qui appartiennent à la province volcanique d'Anatolie Centrale. La nature et la composition de ces tufs suggèrent que la région source devrait être à proximité d'Akkaşdağı. L'activité volcanique pourrait être le facteur principal pour la mort massive de mammifères dont les restes sont concentrés dans de nombreuses poches.

**MOTS CLÉS**
Tuf,
analyses géochimiques,
datation radiométrique,
Miocène supérieur,
Akkaşdağı,
Anatolie Centrale,
Turquie.

## INTRODUCTION

The study area is in Central Anatolia, between the towns of Keskin and Kaman. This area is situated between the Cappadocian and Galatian volcanic complexes, both belonging to the Central Anatolian Volcanic Province (CAVP) (Fig. 1A). While the area is mainly filled with late Miocene-Pliocene fluvio-lacustrine deposits; volcanic and volcanoclastic deposits crop out only between Akkaşdağı and Değirmenözü Village (Figs 1B; 2A).

The tectonic, sedimentologic and stratigraphic characteristics of the region are described in the papers of Seyitoğlu *et al.* (2005) and Kazancı *et al.* (2005). The present study concerns the volcanic characteristics of the area, with remarks on their tectonic and sedimentologic context. For this purpose, the outcrop distribution, ages, mineralogical and geochemical characteristics of the volcanic deposits are studied, and the evolution of the volcanic activity in the region is discussed. Because this volcanic activity depends intimately on the paleogeographic evolution and tectonic regime of the region, it is important to know when and how this process occurred. Another question is the possible impact of volcanic activity on the mass death that the nearby mammalian fossil site seems to present. Data from the literature show examples that volcanic activity may play an important role in the collective annihilation of mammals leading to mass extinction. At Akkaşdağı, fossil vertebrate remains are densely accumulated in small channels immediately above the thick tuff level.

Birgili *et al.* (1975) and Bilgin *et al.* (1986) described the regional geology. They assigned the sedimentary deposits and the interfingering volcanics to the Kızılırmak Formation based on their lithological resemblance to the type area of this formation. Recent studies showed that the latter formation is of late Oligocene age, and it has no stratigraphic relation with the deposits of the Akkaşdağı area. Consequently, the studied deposits are named as the Akkaşdağı Formation (Kazancı *et al.* 2005) (Figs 1; 2). Lateral and vertical facies variation in the Akkaşdağı Formation shows that the sequence was deposited in a variety of terrestrial environments such as flood plain-terminal fan, fluvial and lacustrine (Kazancı *et al.* 2005). At the time of deposition of the Akkaşdağı Formation, an extensional tectonic regime dominated the region, and the Neogene sequences accumulated in a horst-graben system (Seyitoğlu *et al.* 2005).

Facies analyses in the sequences including the Akkaşdağı tuffs reveal that the tuffs were deposited into the shallow lake and flood plain environments as pyroclastic flows. Their sedimentary structures and the characteristic texture support this interpretation. From the petrographic studies, it appears that these are vitric tuffs or ignimbrites. Also, the geochemical analyses determined them to be calc-alkaline in nature and rhyolitic in composition.

## GEOLOGICAL SETTING

The development of Central Anatolian basins occurred in Late Cretaceous-Early Tertiary as a result of the closure of Neo-Tethyan Ocean (Görür *et al.* 1984). Since the closure of the ocean was diachronous, the evolution of the Central Anatolian basins was not parallel to each other (Şengör & Yılmaz 1981; Görür *et al.* 1984, 1998; Tüysüz & Dellaloğlu 1994; Koçyiğit *et al.* 1995; Erdoğan *et al.* 1996; Seyitoğlu *et al.* 2000). The basement units of the Çankırı-Çorum Basin are metamorphic rocks belonging to the Kırşehir Continent and ophiolitic rocks of Neo-Tethyan suture zone (Fig. 1B). In the SW part of this basin, the Deliceırmak Formation and its Ceritkale Member are the oldest sedimentary units dated to the middle-late Eocene; they accumulated in fluvial and shallow marine environments, unconformably on the basement. The plutonic rocks cutting these units are widespread (Fig. 1B). The Oligocene Güvendik Formation consists of a thick bedded gypsum. The overlying Neogene unit is the Akkaşdağı Formation; its detailed stratigraphy will be given in the following chapter.

The contribution of volcanic products to the infill of the Çankırı-Çorum Basin increased since

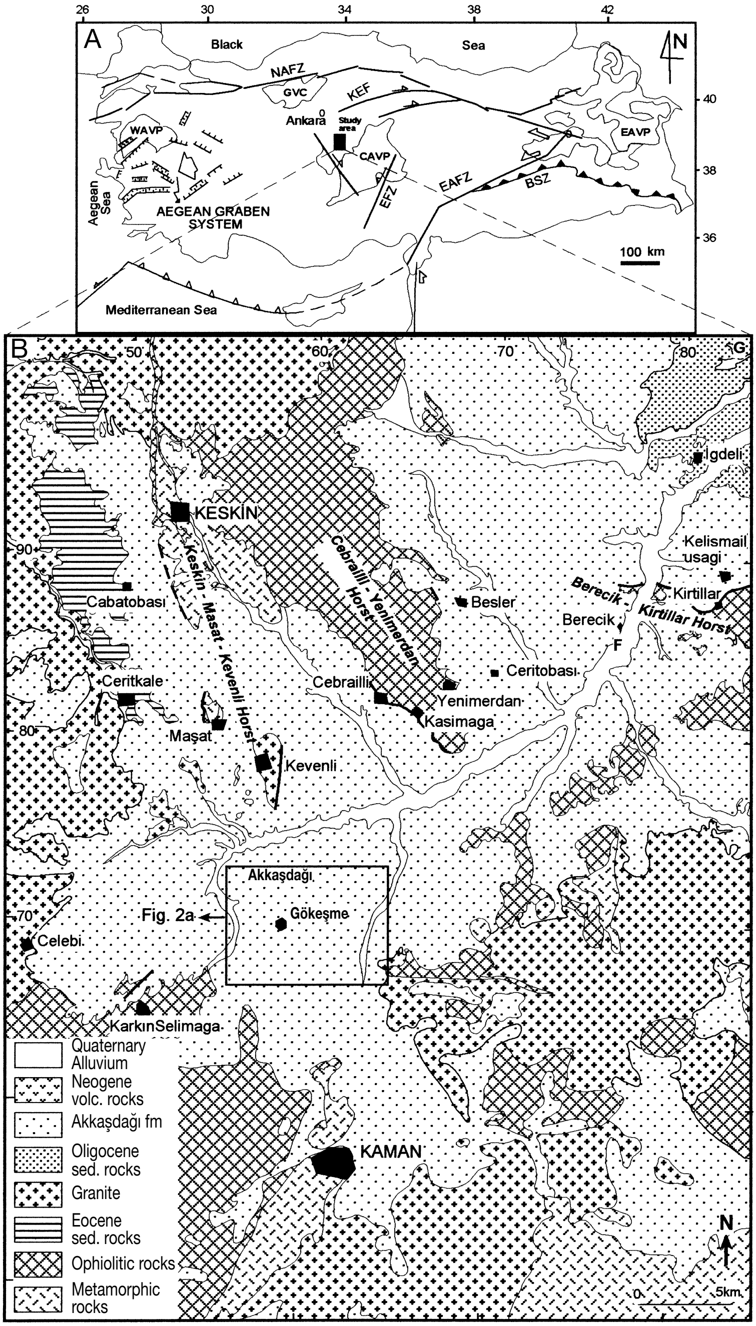


FIG. 1. — **A**, location map and major structural features of Turkey with location of Oligocene to Quarternary volcanism; **B**, map of the area SW of Çankırı-Çorum Basin (modified from Bilgin *et al.* 1986). Abbreviations: **CAVP**, Central Anatolian Volcanic Province; **WAVP**, West Anatolian Volcanic Province; **EAVP**, East Anatolian Volcanic Province; **GVC**, Galatia Volcanic Complex; **NAFZ**, North Anatolian Fault Zone; **EAFZ**, East Anatolian Fault Zone; **BSZ**, Bitlis Suture Zone; **EFZ**, Ecemis Fault Zone; **KEF**, Kırıkkale Erbaa Fault.

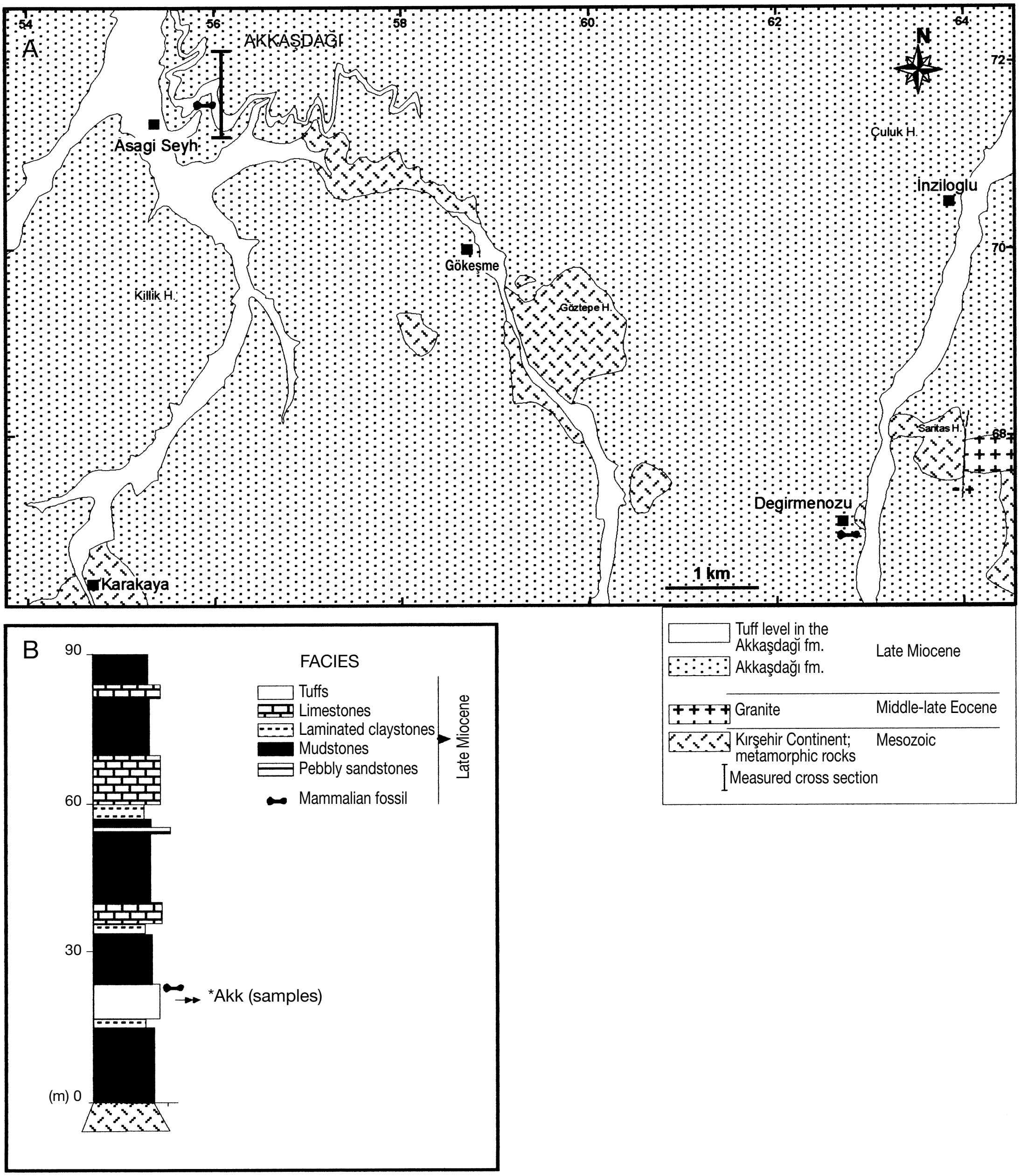


FIG. 2. — **A**, detailed geological map of the area with mammal locaties; **B**, section across the Akkaşdağı mammal locality and facies distribution in the Akkaşdağı Formation.

the Eocene, reaching its maximum in the late Miocene-Pliocene. It is not known how the volcanic activity depends on the internal dynamics of the Çankırı-Çorum Basin.

In Turkey, there are three main volcanic provinces differing in geological age (Oligocene to Quaternary) and chemical composition (Innocenti *et al.* 1982; Yılmaz 1990) (Fig. 1A): 1) Western Anatolian Volcanic Province; 2) Eastern Anatolian Volcanic Province; and 3) Central Anatolian Volcanic Province.

The studied region is within the Central Anatolian Volcanic Province and the chemical composition of the Akkaşdağı tuffs agrees with this province. The Central Anatolian Volcanic Province is composed of two distinct parts: Galatian Volcanic Province to the northwest and Cappadocian Volcanic Province to the southeast. These volcanic provinces developed throughout the Cenozoic as a consequence of the convergence between the Afro-Arabian and Eurasian plates and continental collision.

## MATERIAL AND METHODS

The team of the Akkaşdağı project prepared detailed geological maps of the area for the tectonic, stratigraphic and sedimentological investigations of Neogene deposits as well as the basement rocks; this was completed by logging five stratigraphic sections. Facies analyses were carried out to determine the main sedimentary structures and processes. Samples were collected for age determination and geochemical analyses of tuffs and sediments. Chemical analyses were done in the laboratories of MTA (Ankara) and the Centre de Recherches pétrographiques et géochimiques du CNRS (Nancy). In the X-Ray Fluorescence Spectrometer analyses, the values of the major elements are given as % in oxide and those of the trace elements as ppm. In addition, the petrographic determinations were done on the volcanoclastic rocks using thin sections. Finally, the sedimentological characteristics of volcanoclastic rocks, the texture of pumices, and the existence if any of the fallout deposits were investigated. Dating was achieved with the $^{40}Ar/^{39}Ar$ technique. The whole rock samples were crushed, sieved and 20 mg of pure biotite grains were selected under the binocular microscope then packed and irradiated at the Phoenix Memorial reactor of the University of Michigan, in the L67 position. J factor was estimated by the use of duplicates of the Fish Canyon sanidine standard with an age of 28.48 Ma (Schmitz & Bowring 2001) with 1% relative standard deviation. Interfering nuclear reactions on K and Ca were calculated by co-irradiation of pure salts. Samples were loaded in aluminium packets into a frequency furnace the temperature of which is calibrated by means of an optical pyrometer, and step heated in a classical fashion from usually 700°C to 1400°C. Each step lasted for 20 minutes. The gas was purified by the means of cold traps with liquid air and AL-Zr getters. Once cleaned the gas was introduced into a VG3600 mass spectrometer and analyzed in a fashion similar to that described by Arnaud *et al.* (2003).

## AKKAŞDAĞI TUFFS

Akkaşdağı tuffs are investigated in detail to throw light on their stratigraphic context, facies characteristics, mineralogy, geochemistry and their relation to regional tectonics. In the SW Çankırı-Çorum Basin, the volcanoclastic deposits crop out in limited areas. This is considered to result from intense erosion and an extensive Quaternary cover.

### STRATIGRAPHY

In the regional geological studies, the Neogene succession is mapped as the Kızılırmak Formation dated to late Miocene (Birgili *et al.* 1975; Seymen 1981a, b). Subsequently, Erdoğan *et al.* (1996) named these successions as "Cover sediments" and assigned them a middle Miocene age based on their "stratigraphical experiments". In the scope of the project, large areas of the Çankırı-Çorum Basin have been investigated, including the type area of the Kızılırmak Formation. Four mammal localities in this area, one being in the type section, yielded late

Oligocene fossils. Moreover, the Kızılırmak Formation in its type area has no stratigraphic relationship with other outcrops mapped elsewhere, including the Akkaşdağı area. Therefore, it is concluded that the Neogene filling in the Akkaşdağı region cannot belong to this formation, but represents a new formation named by us the Akkaşdağı Formation (Fig. 2A). The Akkaşdağı Formation mainly contains clastics deposits (conglomerates, sandstones, mudstones) but also intercalations of some limestones and pyroclastic tuffs (Fig. 2B).

### FACIES

Analyses in the Akkaşdağı Formation (Kazancı *et al.* 2005) determined, in order of abundance, the following facies: mudstones, pebbly sandstone, limestones, laminated claystones and tuffs (Fig. 2B). Their lateral and vertical relationships show that the sequence was deposited in a flood plain – terminal fan, fluvial, lacustrine environments. The tuffs were deposited onto the shallow lake claystones and the flood plain mudstones.

The tuffs crop out in limited areas. The measured sections were taken along the slopes of Akkaşdağı (white browed mountain) which is the main topographic feature in the region (Fig. 2). The tuffs form a unique horizon, approximately 5-7 m thick, in the lower levels of the sequence. Mammalian remains are concentrated inside small channels at the top of this horizon; these channels are filled with eroded tuff which is the only matrix of the fossil beds. Most of the mammalian fossils were found in the southwestern sector of Akkaşdağı, except a tooth of an elephant-like animal determined as *Choerolophodon* sp. at Değirmenözü (Fig. 2A).

The general colour of the tuffs is white to beige and locally light pink. They are fine grained with a few or no crystals. In the lower part, there are vertical gas pipes surrounded by red coloured pebbles (Tmax = 4 cm, Tave = 0.8-1 cm) and pumice pebbles (Tmax = 3 cm, Tave = 0.5-1 cm). In the upper part, scarce red lithic fragments and pumice are also observed. In addition, calcified rhyolitic lava was found at two levels inside the tuff. The thickness of the tuff horizon varies between 5 and 7 m; its upper 1 m is partially weathered and bioturbated.

The tuff level is massive and probably represents a single flow. No bedding is observed. Massive tuffs, rich in pumice and lithic components, and having hot gas escapes structures are generally due to pyroclastic flow processes (Fischer & Schmincke 1984; Cas & Wright 1988).

### PETROGRAPHICAL CHARACTERIZATION

The mineralogical and petrographical studies evidenced that the Akkaşdağı tuffs are vitric tuffs (Fig. 3A-G). Field observations showed that there are two different parts in the tuffs of the Akkaşdağı sections (Kazancı *et al.* 2005): a massive and undeformed, lower part and a deformed and partly weathered upper part. In spite of this appearance, the microscopic examinations revealed a rather homogeneous composition with biotite crystals in an abundant glassy matrix and a few lithic clasts (Fig. 3A-D). In addition, it contains feldspar (orthoclase), quartz phenocrysts, oxyhornblende (Fig. 3E, F) and pumice clasts (Fig. 3G). With these characteristics, the Akkaşdağı tuffs may be classified as an ignimbrite. Rhyolitic lava found at two levels in the tuffs are calcified (Fig. 3H).

### GEOCHEMICAL CHARACTERIZATION

Three samples were analysed and the results are presented in TAS diagram (Miyashiro 1978; Le Bas *et al.* 1986) (Fig. 4). Samples plot in the dacite and rhyolite fields and show a subalkaline character. AFM diagram of the samples indicates that they are calcalkaline in nature (Irwine & Baragar 1971) (Fig. 4). The analyses of trace elements are given in the Appendix and presented in the multi-element diagrams (Fig. 4). The higher values for Ba and Rb show the presence of potassium-rich minerals in the samples. In addition, high Sr values are indicative of Ca-rich minerals included in plagioclase compounds. Th (23.83 ppm) and U (6.78 ppm) have radioactive properties. Their possible effect on the annihilation of mammals will be explored in future studies. The high values of rare earth elements in the samples is conform to what expected for the continental crust (Fig. 4; Appendix).

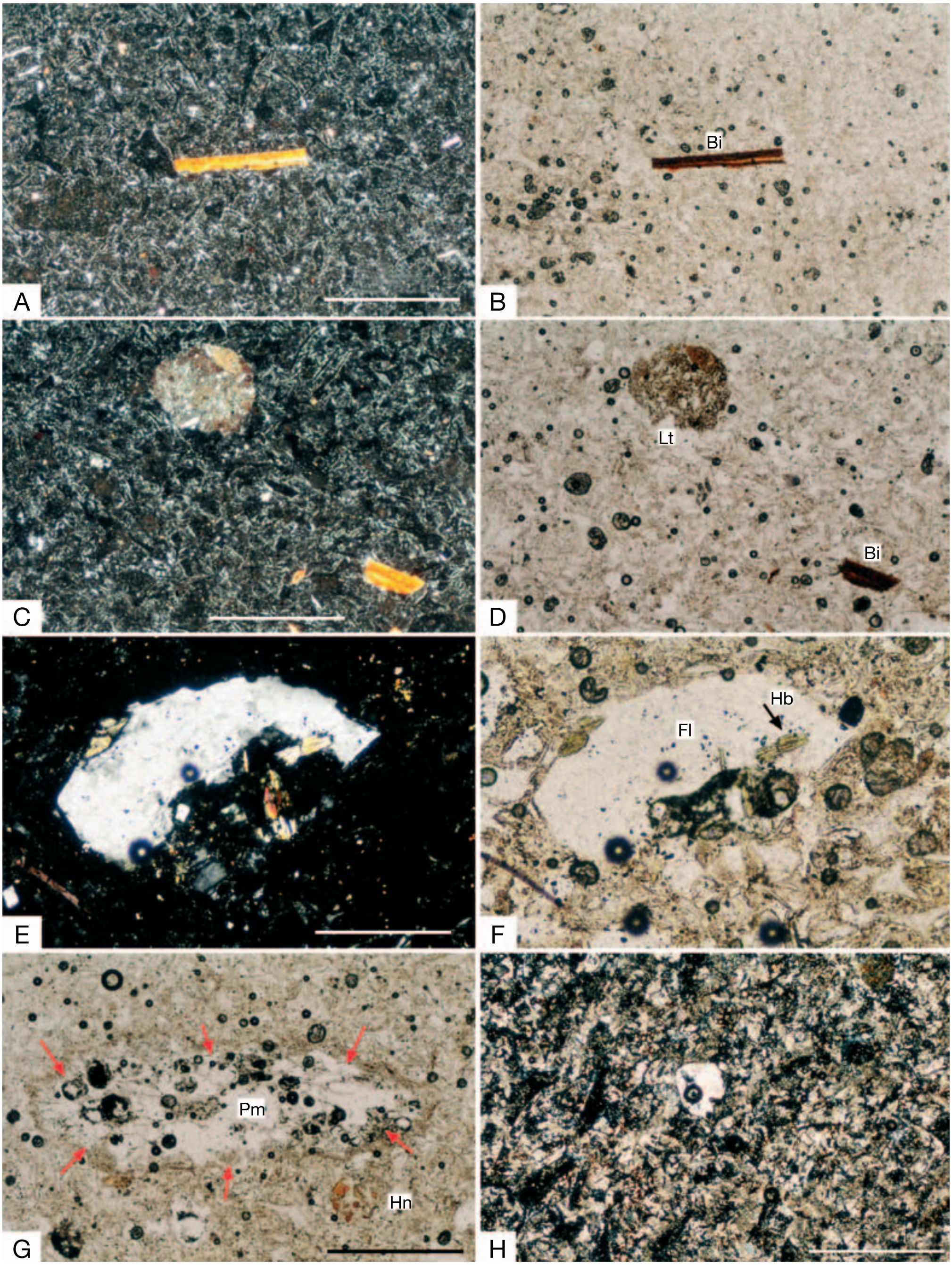


FIG. 3. — Representative photomicrographs of the studied tuffs; **A**, **B**, vitric tuff of upper level (cross-plane polarized light); **C**, **D**, vitric tuff of lower level (cross-plane polarized light); **E**, **F**, vitric tuffs consisting of an abundant glassy material, feldspar (**Fl**) and hornblend (**Hb**) (cross-plane polarized light); **G**, pumice clast (**Pm**) and oxyhornblend (**Hn**) (plane polarized light); **H**, rhyolitic lavas found at two levels in tuffs are completely calcified (cross polarized light). Abbreviations: **Bi**, biotite; **Lt**, lithic clast. Scales bars: A-D, G, H, 0.7 mm; E, F, 0.4 mm.

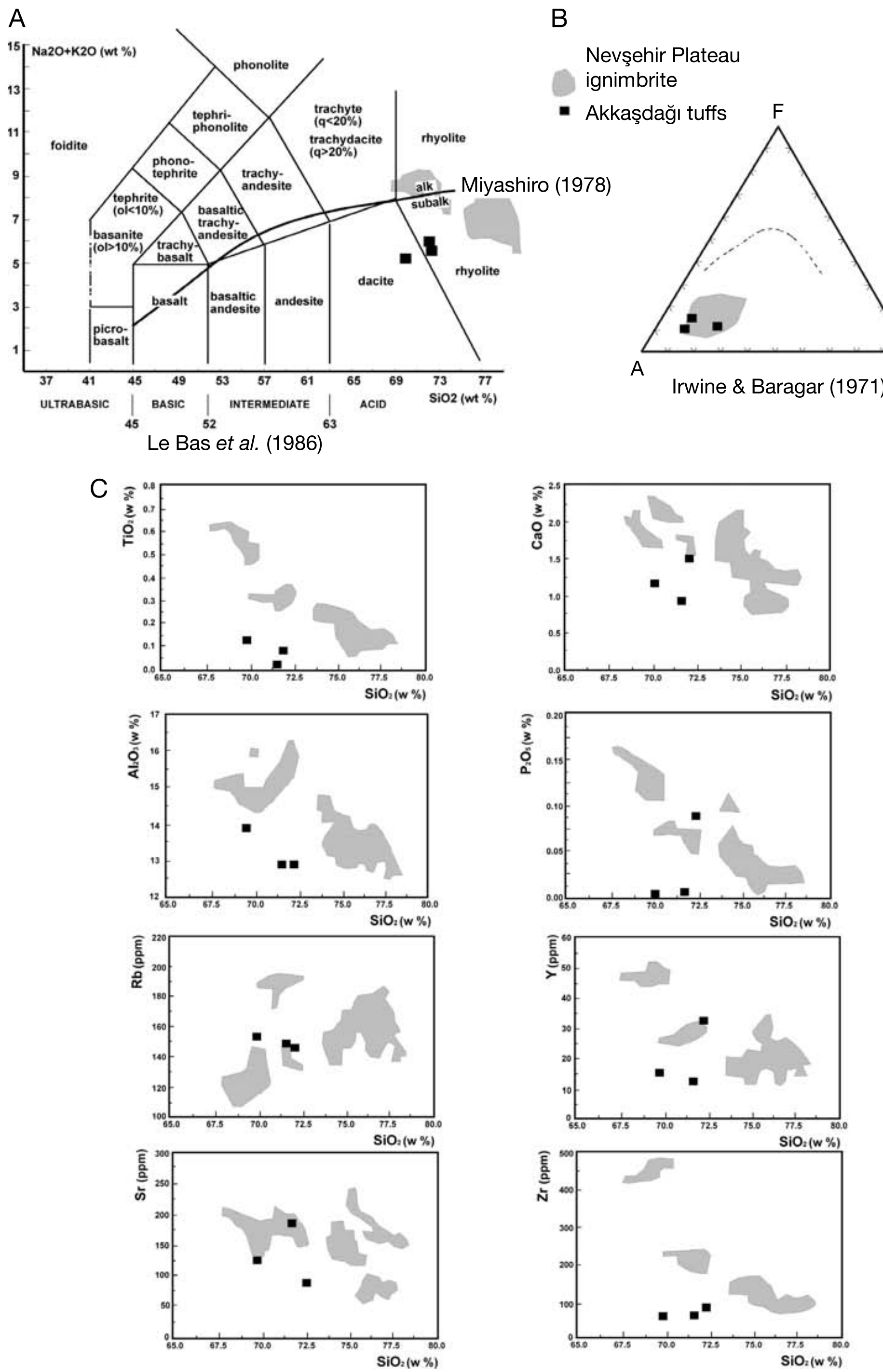


FIG. 4. — **A**, total alkali vs. $SiO_2$ diagram for the studied tuffs and Nevşehir Plateau ignimbrite. Classification scheme is from Le Bas *et al.* (1986), with the alkaline-subalkaline line by Miyashiro (1978); **B**, AFM diagram is from Irwine & Baragar (1971); **C**, Hacker variation diagrams for the studied tuffs and Nevşehir Plateau ignimbrite.

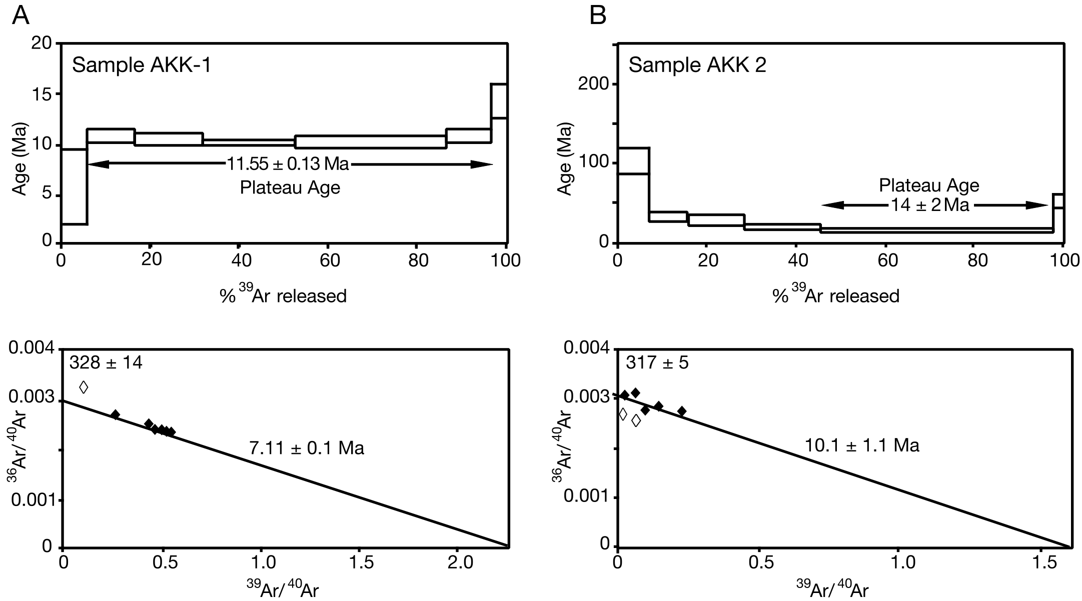


FIG. 5. — Integrated $^{39}$Ar/$^{40}$Ar ages for two samples from the Akkaşdağı tuffs; **A**, sample AKK-1 from the main tuff horizon, three meters below the bone pocket AK-5; **B**, sample AKK-2 from the reworked tuffs filling the bone pocket AK-5.

To determine the radiometric age of the Akkaşdağı tuffs, two samples were taken, the one (AKK-1) from the non-weathered lower part of the tuff level and the other (AKK-2) from the tuff filling the fossil bone pocket AK-5 at the top of the main tuff horizon. They were analysed following the methodology given in the previous section. Results are interpreted with the usual age plateau and inverse isochron diagrams. The age obtained from the analyses is a weighted mean plateau age, the error of which takes into account the error on the J factor. The isochron ages are obtained in an inverse isochron diagram of $^{36}$Ar/$^{40}$Ar versus $^{39}$Ar/$^{40}$Ar (Roddick *et al.* 1980) which allows homogeneous excess components to be individualized in many occasions. Errors in age and intercept include individual errors on each point and linear regression by York's method (1969). Its accuracy relative to individual errors is measured with the Mean Square Weighted Deviation (MSWD).

Sample AKK-1 (Fig. 5A) shows an age plateau at 11.21 ± 0.51 Ma when discarding the first and large steps. However, a subtle saddle shape suggest possible pollution by argon excess often present in volcanic rocks, which is indeed revealed by the inverse isochron diagram with an excellent MSWD (0.01) and a trapped component with a $^{40}$Ar/$^{36}$Ar ratio of 328 ± 14. The age derived from the isochron is much younger, i.e. 7.1 ± 0.1 Ma, which is taken as the age of the eruption. Sample AKK-2 (Fig. 5B) also displays a broad saddle shape, with a poorly defined plateau at 15.7 ± 2.4 which is at the limit of statistical confidence. The inverse isochron yields an age of 10.1 ± 1.1 Ma with a well expressed excess argon component with a $^{40}$Ar/$^{36}$Ar ratio of 317 ± 5. This age is considered significant. However, this age is older than the one from the first sample which is stratigraphically below and taken from the unreworked tuff. This result indicates that the sample AKK-2 from a bone pocket is formed of sediments reworked from the main tuff and consequently unreliable for radiometric dating. Moreover, such an older age is not in agreement with the biostratigraphic age of the Akkaşdağı mammalian fauna.

Most of the ignimbrite volcanism in the Central Anatolian Volcanic Province occured during the late Miocene-Pliocene interval throughout the Nevşehir Plateau (Cappadocia) (Le Pennec *et al.* 1994, 2005). In the ignimbrite sequence of the Nevşehir Plateau these authors recognized five main (Zelve, Sarımaden Tepe, Cemilköy, Gördeles, Kızılkaya) and two small (Tahar and Sofular) ignimbrite units (Appendix). The fault systems in the eastern side of the plateau caused the development of ignimbrite volcanos and caldera (Le Pennec *et al.* 1994). The Akkaşdağı tuffs have also a similar origin. The grabens resulting from extensional tectonic regime in the late Miocene were partly filled with pyroclastic deposits. Although the source area of the Akkaşdağı tuffs is not in the Nevşehir Plateau, their characteristics fit well with the general scheme of the other volcanoes in Anatolia. Late Tertiary volcanism in Central Anatolia has generally calc-alkaline characteristics, and originated in continental crust (Batum 1978; Tokel *et al.* 1988; Pearce *et al.* 1990; Ercan *et al.* 1991; Le Pennec *et al.* 1994, 2005; Dönmez *et al.* 2003).

The geological development of the volcanism during the Late Tertiary in Anatolia is explained as follows (Şengör & Yılmaz 1981; Temel 1992; Aydar *et al.* 1994; Dönmez *et al.* 2003): the volcanism developed in relation to the approach of the African continent to Eurasia in late Eocene-early Miocene, as a result of the subduction of the oceanic crust under the Anatolian Block; the lower-middle Miocene volcanism developed in a back-arc basin; and the upper Miocene volcanism seems to be related to fractional crystallization of basaltic magma which occurred with partial melting of the oceanic crust in the subduction zones. The last type of volcanism shows crustal contamination which becomes effective in the upper Pliocene-Quaternary, when it takes the characteristics of a inter-continental volcanism. Similarly, the Akkaşdağı tuffs are also thought to be developed by fractional crystallization of magma which occured with partial melting of oceanic crust in the subduction zones in the late Miocene.

## DISCUSSION AND CONCLUSION

The Akkaşdağı region in the southeastern part of the Çankırı-Çorum Basin recorded different and interesting events in late Miocene. Sedimentary and volcanoclastic deposits containing rich mammalian fossils were studied by multidisciplinary approches (tectonics, sedimentology, stratigraphy, paleontology, mineralogy, petrology, etc.), clarifying many aspects of the geology of the area. In the Akkaşdağı area, graben or half-graben type sub-basins were developed under the effect of regional extensional tectonics during the late Miocene (Seyitoğlu *et al.* 2005). To the east and southeast of this region, while aluvial fan and fluvial deposits were developing, flood plains and shallow lakes were formed in the basin center (Kazancı *et al.* 2005). Volcanic activity developed as a result of normal faults produced by the extensional tectonic regime. The products of this volcanic activity are rhyolitic pyroclastics. They are seen only between Akkaşdağı and Değirmenözü Village, and they display important thickness (Fig. 2). Pyroclastic flow deposition might be also depending on the wind prevailing at the time of eruption. The available outcrops could represent only a fraction of the initial deposits because they are easily eroded.

The pyroclastics are calc-alkaline rocks of rhyolitic type and derived from an acidic magma. Their petrographical analyses showed that they are vitric tuff and have ignimbrite characteristics. The radiometric dating of the unweathered part of these tuffs at the mammal locality gave an age of 7.1 ± 0.1 Ma which is compatible with the biostratigraphic age of this fauna. The Akkaşdağı tuffs and Nevşehir Plateau ignimbrites were compared. It appears that they are similar in lithology and geochemical composition with minor differences. Consequently, it is possible to include the Akkaşdağı tuffs in the Central Anatolian Volcanic Province. Similarly, the Akkaşdağı tuffs are thought to be developed by fractional crystallization of magma which occurred with partial melting of oceanic crust in the subduction zones.

Why did mammals of many different families and genera get killed at Akkaşdağı? Volcanic activity may have played an important role in this annihilation. Because mammalian fossils were found concentrated in pockets on the thick tuff deposits, the annihilation could have been thought as occurred during the end phases of the volcanic activity. The causes affecting mammalian annihilation might be as follows: 1) food resources of mammals could be destroyed due to the fact that the region was covered with pyroclastic deposits, or dust covered vegetation and disturbed the biomass; 2) mammals became concentrated around the rare water holes (shallow lakes), concentrating carnivorous and herbivorous mammals together in reduced habitats; and 3) poisoning could have occurred due to the outlet of the poisonous gases during the end stage of the volcanic activity. Chemical analyses indicate that radioactive trace elements (Th and U) are present in large amounts in these tuffs supporting such an hypothesis.

**Acknowledgements**

This project is supported by MTA General Directorate (Project no. 16-A3/B3), TUBITAK (Project no. 101Y108), CNRS-INSU (ECLIPSE) and Ankara University Research Fund (Project no. 20010705053). The authors thank Ali Rıza Çolakoğlu for petrographical determinations, Alaaddin Temel (Ankara) and one anonymous referee for their valuable comments, Nilgün Güleç (Ankara) for helpful critism of the manuscript and Martin Pickford (MNHN) for English improvements.

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*Submitted on 13 August 2004;*
*accepted on 24 October 2005.*

# APPENDIX

Major oxide and trace elements of the studied tuffs and Nevşehir Plateau ignimbrite.

| Location | Akkaşdaği tuffs | | | Cappadocian tuffs (after Le Pennec *et al.* 1994) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Kavak** | **Zelve** | **Sarımaden** | **Cemilköy** | **Gördeles** | **Sofular** | **Kızılkaya** | **Valibaba-Incesu** |
| Age (Ma) | 7.1 ± 0.1 | | | 8.6 ± 1.7<br>8.75 ± 0.2<br>9.17 ± 0.2<br>11.2 ± 2.5 | 7.52 ± 0.2<br>7.70 ± 0.2 | 8.0 ± 1.6<br>8.5 ± 0.2<br>8.6 ± 1.7 | 6.51 ± -0.2<br>6.78 ± 0.2 | 7.8 ± 1.6 | 6.8 ± 1.4 | 4.4 ± 0.1<br>4.9 ± 0.2<br>5.4 ± 1.1<br>5.5 ± 0.2 | 2.7 ± 0.1<br>2.8 ± 0.1<br>3.0 ± 0.1 |
| $SiO_2$ | 72.20 | 69.20 | 71.61 | 75.02 | 76.84 | 73.05 | 76.52 | 71.13 | | 74.90 | 69.96 |
| $TiO_2$ | 0.10 | 0.20 | 0.09 < | 0.17 | 0.15 | 0.30 | 0.11 | 0.31 | | 0.24 | 0.48 |
| $Al_2O_3$ | 13.00 | 14.20 | 12.87 | 14.08 | 13.25 | 14.26 | 13.02 | 14.74 | | 13.03 | 14.56 |
| $Fe_2O_3$ | 1.40 | 1.90 | 1.20 | 1.31 | 1.17 | 1.97 | 0.97 | 2.34 | | 1.51 | 3.70 |
| MnO | 0.10 | 0.10 | 0.08 | 0.07 | 0.07 | 0.09 | 0.07 | 0.08 | | 0.06 | 0.05 |
| MgO | 0.90 | 1.80 | 0.82 | 0.40 | 0.32 | 0.52 | 0.23 | 0.70 | | 0.48 | 0.61 |
| CaO | 1.50 | 1.10 | 0.92 | 1.88 | 1.25 | 1.52 | 0.87 | 2.04 | | 1.53 | 1.73 |
| $Na_2O$ | 2.90 | 3.20 | 3.66 | 2.34 | 2.04 | 3.26 | 2.56 | 2.84 | | 2.89 | 3.96 |
| $K_2O$ | 3.00 | 2.60 | 3.05 | 4.70 | 4.88 | 4.98 | 5.63 | 5.76 | | 5.31 | 4.68 |
| $P_2O_5$ | 0.10 | < L.D. | – | 0.04 | 0.03 | 0.06 | 0.02 | 0.07 | | 0.05 | 0.11 |
| Total | 100.00 | 100.00 | 99.8 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | | 100.00 | |
| Rb | 144 | 155 | 151.50 | 159 | 147 | 154 | 178 | 184 | | 166 | 144 |
| Sr | 194 | 150 | 115.80 | 213 | 163 | 144 | 80 | 174 | | 136 | 138 |
| Ba | 712 | 668 | 697.40 | 966 | 1003 | 933 | 776 | 690 | | 689 | 576 |
| Zr | 100 | 96 | 75.02 | 98 | 102 | 200 | 89 | 221 | | 138 | 474 |
| Nb | 23 | < 20 | 93 | 11 | 11 | 12 | 8 | 12 | | 10 | 19 |
| Y | 32 | 16 | 12.47 | 22 | 20 | 78 | 13.1 | 19.7 | | 10.4 | 37.70 |
| La | | | 28.86 | | | 39.00 | 33.00 | | | 33.00 | 44.20 |
| Ce | | | 51.50 | | | 68.90 | 55.10 | | | 52.30 | 86.40 |
| Pr | | | 4.57 | | | 6.91 | 5.11 | | | 4.72 | 9.96 |
| Nd | | | 13.47 < | | | 22.00 | 15.00 | | | 13.30 | 36.10 |
| Sm | | | 2.253 | | | 3.77 | 2.45 | | | 2.06 | 7.46 |
| Eu | | | 0.261 | | | 0.66 | 0.33 | | | 0.42 | 1.30 |
| Gd | | | 1.821 | | | 3.12 | 1.99 | | | 1.64 | 6.90 |
| Dy | | | 1.883 | | | 3.21 | 2.00 | | | 1.66 | 7.00 |
| Ho | | | 0.377 | | | 0.69 | 0.45 | | | 0.36 | 1.44 |
| Er | | | 1.217 | | | 2.19 | 1.42 | | | 1.15 | 4.30 |
| Th | | | 23.83 | | | | | | | | |
| U | | | 6.775 | | | | | | | | |