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Black carbon traces of human activities in stalagmites from Turkey

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ABSTRACT

Speleothems are recognized as sensitive recorders of climatic fluctuations in the past and provide precisely dated and highly resolved environmental records. However, their potential as an archaeological archive is not fully acknowledged yet. Here we present several stalagmites containing soot and charcoal layers from various caves in Turkey and provide evidence that these black carbon layers are directly related to human activity. The archaeological artefacts found in Tabak and Kocain caves in SW Turkey support the linkage between soot and charcoal layers existence and human activity in the caves. For this study, we focus on stalagmites from Tabak and Kocain cave. To explore the age and nature of the soot and charcoal layers within stalagmites Ta-9, Ta-10 and Ko-1, Uranium series dating, scanning electron microscope (SEM) and thin section analyses were performed. The episodic soot and charcoal deposition in stalagmites Ta-9 and Ta-10 occurred between 7424 ± 225 yr BP and 6670 ± 218 yr BP while the soot and charcoal layers in stalagmite Ko-1 formed between 2830 ± 189 yr BP and 470 ± 56 yr BP. In combination with the archaeological inventory in Tabak Cave, the soot and charcoal layers within stalagmites Ta-9 and Ta-10 show that the cave was used repeatedly as a burial site during Chalcolithic period. In Kocain Cave was also used repeatedly between the Iron Age and Medieval Period, most likely for ritual activities and for providing animals with water from a small spring in the entrance to the cave. The soot and charcoal layers within stalagmites from Turkey prove that speleothems are also important as archaeological archives.

1. Introduction

The importance of speleothems for paleoclimate studies has increased over the last decade because of their ability to provide precisely-dated and highly-resolved climatic and environmental records (Badertscher et al., 2011; Bar-Matthews and Ayalon, 2011; Cheng et al., 2009, 2015; Duan et al., 2019; Finné et al., 2017; Fleitmann et al., 2003, 2009; Railsback et al., 2018). More recently, speleothems gained importance for archaeological studies by using them for dating sediment sequences containing hominin artefacts and cave paintings (Liu et al., 2015; Pike et al., 2012, 2017). In addition, soot and charcoal particles, the products if incomplete combustion of plant material and vaporized organic matter (Chylek et al., 2015), incorporated into speleothem calcite can be also used to trace human activities within caves and in rock shelters (Gradziński et al., 2003, 2007; Šebela et al., 2017; Vandevelde et al., 2017, 2018; Verheyden et al., 2006). For instance, Vandevelde et al. (2017) defined "Minimum Numbers of Occupations (MNO)" by using soot traces within carbonate concretions and investigated phases of human occupation in cave entrances and rock shelters.

Moreover, wildfires above caves can be an additional source for soot and charcoal particles in speleothems as they can be flushed into the cave through larger fissures (Desmarchelier et al., 2004; Lauritzen et al., 1990). Archaeological artefacts and other traces of human activity in caves are thus required to fully understand the origin of soot and charcoal layers within speleothems. The full potential of soot and charcoal layers in speleothems for archaeology and palaeoanthropology studies is still not fully explored yet, although they could become a rich source of information for that studies. Because speleothems can be dated back to at least 700.000 years before present using Uranium–Thorium series (U–Th hereinafter) and several million years using Uranium–Lead.

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The ability of speleothems to provide absolute and precise chronologies highlights the great potential of speleothems to contribute to the research fields of palaeoanthropology and archaeology in order to refine current models on the use of fire and human activities in caves (Hosfield et al., 2016).

Numerous caves around the world have been used by humans throughout their history and contain traces of human activity such as ceramics, tools, paintings and bones (e.g. Bourgeon et al., 2017; Ledoux et al., 2017). Caves were commonly used by humans as a shelter, burial and/or ritual site since the Palaeolithic period. The first Neanderthal grave was found in 1908 in a cave in France and revealing that they were aware of life and death (Mouret and Gunn, 2004). Caves were also considered to be sacred places and a gate to other worlds (Rowan and Ilan, 2012). Caves were therefore used as burial sites (Mouret and Gunn, 2004; Rowan and Ilan, 2012). However, in the eastern Mediterranean, in particular the Levant region, caves have been widely used for funerary and ritual activity during the Chalcolithic period (Carter et al., 2011; Rowan and Ilan, 2012). Moreover, the caves in the eastern Mediterranean region also contain substantial speleothems (i.e. stalagmites, stalactites and flowstone), therefore this region provide opportunity for speleothem-based archaeology studies.

Turkey has a long cultural history and numerous caves can be found in almost all parts of the country. For instance, caves in SW Turkey are a rich repository of archaeological remains, many of them contain speleothems (Albrecht, 1988; Albrecht et al., 1992; Eslick, 1980; Otte et al., 2003; Thissen, 2010; Umurtak, 2005). However, the majority of studies related to speleothems from Turkey focused primarily on climatic and environmental changes in the past (Badertscher et al., 2011, 2014; Baykara, 2014; Fleitmann et al., 2009; Göktürk et al., 2011; Jex et al., 2010, 2011; Rowe et al., 2012; Ünal-İmer et al., 2015, 2016; Wickens, 2013). Whereas caves in Turkey contain a considerable number of archaeological artefacts and speleothems, the lack of studies focusing on the archaeological potential of speleothems is a great discrepancy.

In this study, we highlight the importance of speleothems as archaeological records by presenting the first results of a survey of several caves in Turkey, whereas stalagmites containing soot and charcoal layers from Tabak and Kocain caves in SW Turkey (Fig. 1a and b) are the main focus of this study. The ages of the soot and charcoal layers within stalagmites collected from Tabak and Kocain caves were determined based on U–Th dating measurements of the stalagmites. Finally, we discuss whether the origin of soot and charcoal layers within stalagmites is natural or anthropogenic. Though, we did not investigate any of the caves archaeologically rather we used archaeological data that were already produced from the region. Additional stalagmites from Geyikbayırı Cave, Hacı Abbas Cave, Yelini Cave and Direkthi Cave contain soot and charcoal layers (Fig. 1a) and show that such layers are a common feature in many stalagmites. This highlight the potential of caves in Turkey to trace regional and local human activities in the past.

1.1. Geological, geographic and archaeological settings

The Taurus Mountain range along the southern part of Turkey is a major karstic region and the study area is located in SW Turkey, in the western part of this mountain range. Stalagmites presented in this study were collected from Tabak Cave, Kocain Cave, Geyikbayırı Cave, Hacı Abbas Cave, Yelini Cave, and Direkthi Cave. As mentioned above, we focus on three stalagmites from Tabak and Kocain Caves and, thus, describe the geologic and environmental settings for both caves in closer detail.

Tabak Cave (37° 5′N, 30° 34′E, 330 m asl; Fig. 1b) is located on the eastern slope of the Katran Mountain approximately 25 km north of Antalya. The cave was formed within Jurassic-Cretaceous neritic limestones (Koç, 2019) of the Beydağları Formation (Gunay et al., 1995). It is about 300 m long and has only a single narrow vertical entrance opens SSE. Tabak Cave consists of four galleries and six chambers containing numerous stalagmites (Fig. 2a). The thickness of overlying bedrock is fairly thin and varies between 20 and 25 m. According to the database of archaeological settlements and caves in Turkey, Tabak Cave is also known as Harunini Cave (TAY Project, 2019).

Kocain Cave (37° 13′N, 30° 42′E, 730 m asl) is located to the northeast of Tabak Cave (Figs. 1b), 30 km north of Antalya. Kocain Cave is widely known in Turkey because of its large entrance (~70 m) and there are up to 60 m tall columns (TAY Project, 2019). Its name arises from the size of cave (Koca-in means Huge-cave). Kocain Cave was formed within Jurassic-Cretaceous neritic limestones. The length of the cave is up to 650 m and the cave consists of two large galleries (Fig. 2b).

The vegetation above both caves is a typical C3 type vegetation in the Mediterranean region and consists of evergreen shrubs and maquis (Roberts et al., 2011). As a result of the enhanced karstification of the area, there are freshwater springs and streams in the vicinity of Tabak Cave and the area is also called as "Kırkgöz Springs". There are modern settlements close to Tabak Cave while Kocain Cave is far from any current settlements. However, Kocain Cave is frequently visited by people for recreational activities because of the spectacular and easily accessible entrance. The climate of the study area is a typical Mediterranean climate with hot/dry summers and mild/rainy winters. The mean annual precipitation and temperature in the study area is 1058.8 mm and 18.8 °C, respectively, based on local meteorological station of Turkish State Meteorological Service. The current cave air temperature of Tabak Cave is 18 °C and constant due to low ventilation in the cave, while Kocain Cave temperatures slightly variable near to entrance but in the deeper part it is constant and around 18 °C.

Mound settlements (e.g. Bademağacı Höyük) can be found north of the study area, and archaeologically important caves (e.g. Karain Cave, Öküzini Cave, Suluin Cave and Boynuzluin Cave) are very close to Tabak Cave (Fig. 3a). Archaeological excavations in Karain Cave (Taşkıran, 2018Yalçınkaya, 1994, 1991; Yalçınkaya et al., 1999b) reported finds of

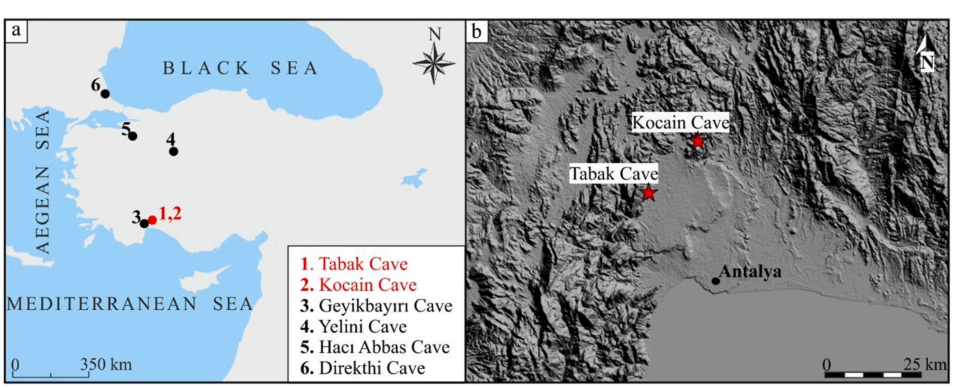

Fig. 1. Location map of studied caves. a) The caves are denoted by numbers. Stalagmites collected from all caves shown in a) contain soot and charcoal layers. b) Detailed map showing the locations of Tabak and Kocain caves.

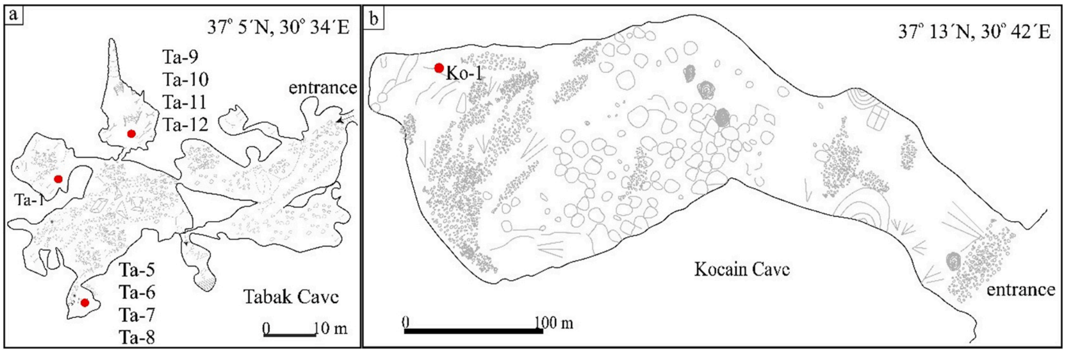

Fig. 2. Maps of Tabak and Kocain caves. Red dots denote sampling locations. a) The Tabak Cave map (from this study). A total of 9 stalagmites containing charcoal and soot layers were collected from Tabak Cave. Stalagmites Ta-9 and Ta-10, which are used in this study, were collected from the same chamber. b) Map of Kocain Cave (modified from TAY Project, 2019) with sampling location of stalagmite Ko-1 at the end of the cave. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

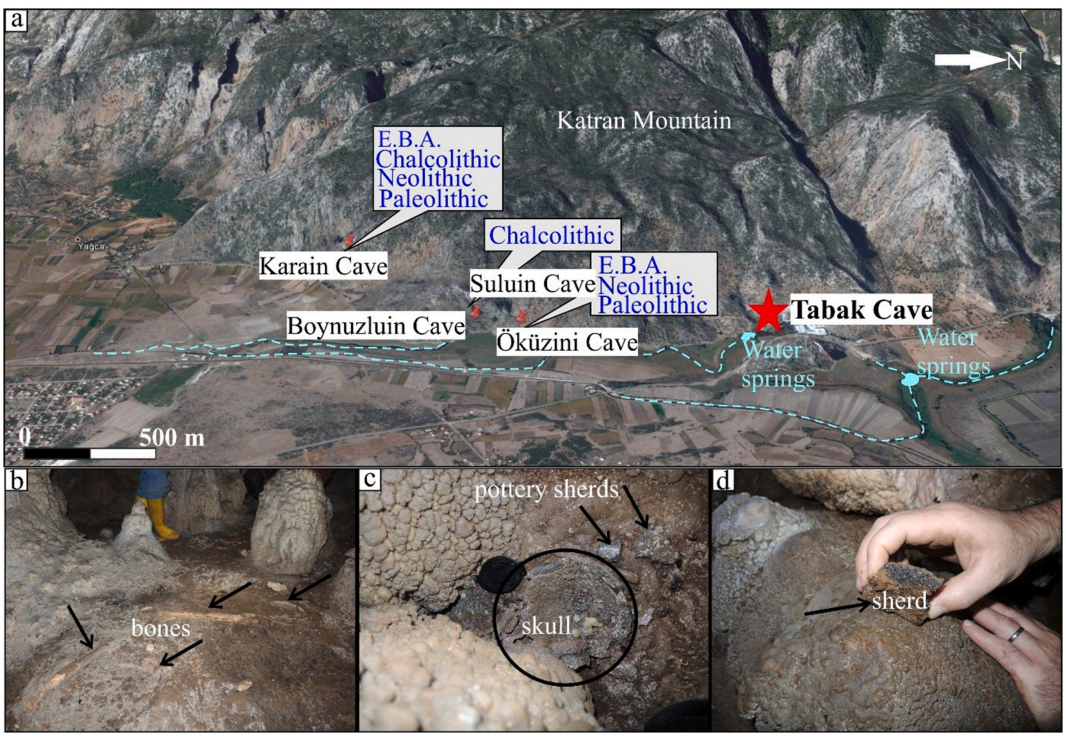

Fig. 3. a) Oblique Google Earth view. Red star marks the location of Tabak Cave and red pinpoints indicate the location of other caves, which have been investigated archaeologically. The ages of archaeological artefacts in the caves are shown above the pinpoints (The location and age information retrieved from www.tayproject.org, EBA: Early Bronze Age). The dashed line shows streams and the small blue polygons show water springs around the caves b) Human and animal bones found in Tabak Cave are indicated with arrows c-d) Pottery sherds and a part of human skull indicated by a circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Neanderthal remains in the cave and the cave has great importance to illuminate the Palaeolithic history of the eastern Mediterranean. Suluin and Öküzini caves also provide information about the archaeological history of the region as they were occupied during Neolithic, Chalcolithic and Bronze Age periods (Taşkıran et al., 2011, 2015; Yalçınkaya, 1994, 1991; Yalçınkaya et al., 1999a, 1999b) (Fig. 3a). Studies suggest a close relationship between the mound settlements and caves as pastoralists visited the caves seasonally (Taşkıran et al., 2015). Furthermore, graves, bones and charcoal remains in Öküzini Cave indicate that this cave was used as a burial site during Chalcolithic (Carter et al., 2011). Overall, there is clear evidence that the study region has been used continuously by humans since Palaeolithic.

2. Samples and method

A total of nine stalagmites containing soot and charcoal layers were collected from Tabak Cave (Fig. 4a). One stalagmite containing five soot and charcoal layers was collected from Kocain Cave (Ko-1; Fig. 4b). Almost all stalagmites from Tabak Cave contain more than one soot and charcoal layer (Fig. 4a). In this study, we focused on stalagmite Ta-9 and Ta-10 from Tabak and Ko-1 from Kocain Cave as they consist of clean and denser calcite.

A total of eight U–Th dating analyses were performed on stalagmite Ta-9 and Ta-10 (Table 1). The sampling points were selected close to soot and charcoal layers (Fig. 5a) in order to determine the absolute age. U–Th dating measurements were performed on a Thermo-Finnigan Neptune multicollector inductively coupled plasma mass spectrometer

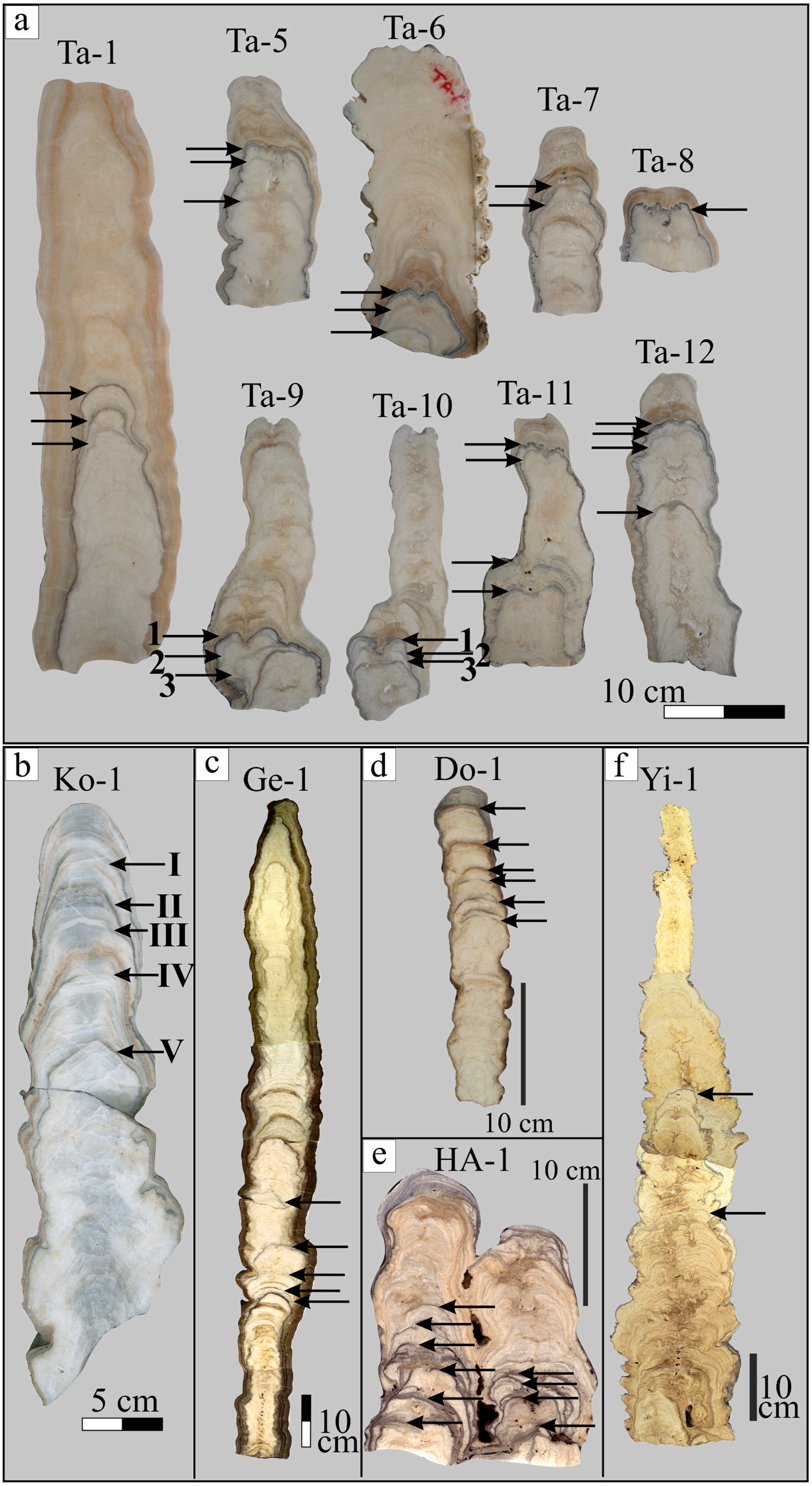

Fig. 4. a) Stalagmites containing soot and charcoal layers that were collected from the Tabak Cave. Arrows show the charcoal and soot layers. Numbers indicate soot and charcoal layers in Ta-9 and Ta-10 b) Stalagmite Ko-1 collected from the Kocain Cave. Arrows and Roman numbers show the soot and charcoal layers. c) Stalagmite Ge-1 collected from the Geyikbayırı Cave. d) Stalagmite Do-1 collected from the Direkthi Cave. e) Stalagmite HA-1 collected from Hacı Abbas Cave. f) Stalagmite Yi-1 collected from Yelini Cave. The larger version of this image can be found in supplementary files as Fig. 4S.

Table 1
U–Th dating results of stalagmite Ta-9 and Ta-10. The error is 2σ.

Sample Number	^{238}U (ppb)		^{232}Th (ppt)		^{230}Th/^{232}Th (atomic ×10^{-6})		d^{234}U* (measured)		^{230}Th/^{238}U (activity)		^{230}Th Age (yr) (uncorrected)		^{230}Th Age (yr) (corrected)		d^{234}U$_{Initial}$** (corrected)		^{230}Th Age (yr BP)*** (corrected)	
Ta-9-1	268.3	±0.3	3930	±79	30	±1	28.8	±1.2	0.0268	±0.0002	2881	±18	2466	±294	29	±1	2400	±294
Ta-9-2	473.8	±0.6	196	±4	1636	±33	16.0	±1.4	0.0411	±0.0001	4497	±14	4485	±16	16	±1	4419	±16
Ta-9-3	127.0	±0.2	1672	±34	85	±2	30.0	±2.3	0.0679	±0.0003	7431	±40	7059	±266	31	±2	6993	±266
Ta-9-4	124.1	±0.1	414	±8	692	±14	55.7	±1.3	0.1402	±0.0003	15,522	±41	15,430	±77	58	±1	15,364	±77
Ta-10-4	404.3	±0.5	516	±10	546	±11	15.2	±1.3	0.0423	±0.0001	4638	±16	4602	±30	15	±1	4536	±30
Ta-10-3	130.5	±0.1	1409	±28	99	±2	32.6	±1.2	0.0646	±0.0003	7041	±32	6736	±218	33	±1	6670	±218
Ta-10-2	103.7	±0.2	1141	±23	107	±2	32.0	±2.8	0.0713	±0.0004	7801	±51	7490	±225	33	±3	7424	±225
Ta-10-1	108.9	±0.1	948	±19	137	±3	34.6	±1.3	0.0722	±0.0003	7889	±39	7645	±177	35	±1	7579	±177

U decay constants: l238 = 1.55125 × 10^{-10} (Jaffey et al., 1971) and l234 = 2.82206 × 10^{-6} (Cheng et al., 2013). Th decay constant: l230 = 9.1705 × 10^{-6} (Cheng et al., 2013).
*δ^{234}U = ([^{234}U/^{238}U]activity − 1)×1000.
** δ^{234}Uinitial was calculated based on ^{230}Th age (T), i.e., δ^{234}Uinitial = δ^{234}Umeasured x el234xT.
Corrected ^{230}Th ages assume the initial ^{230}Th/^{232}Th atomic ratio of 4.4 ± 2.2 × 10^{-6}. Those are the values for a material at secular equilibrium, with the bulk earth ^{232}Th/^{238}U value of 3.8. The errors are arbitrarily assumed to be 50%.
***B.P. stands for "Before Present" where the "Present" is defined as the year 1950 C.E.

(MC-ICP-MS) at the Xi'an Jiaotong University. To calculate dates of the Tabak Cave stalagmites, the decay constant of Cheng et al. (2013) were used. A correction for the presence of initial ^{230}Th was applied and corrected ^{230}Th ages assume the initial ^{230}Th/^{232}Th atomic ratio of 4.4 ± 2.2 × 10^{-6}. Detailed information on analytical procedures is as described in Cheng et al. (2013). Thirty-one U–Th ages were determined for stalagmite Ko-1 (Table 2; Göktürk, 2011) and its age model is based on the StalAge algorithm (Scholz and Hoffmann, 2011).

To observe the soot and charcoal layers in close detail, thin sections were prepared from stalagmite Ta-9 and Ta-10 and examined under a cross-polarized microscope to characterize the calcite fabrics. Furthermore, to provide a closer view of soot and charcoal particles in stalagmites Ta-9, Ta-10 and Ko-1 were studied by scanning electron microscope (SEM). The SEM examination of stalagmites Ta-9 and Ta-10 was done in Faculty of Medicine SEM Analysis Unit (TEMGA), Akdeniz University. The SEM analysis of stalagmite Ko-1 was done at the Geological Institute at the University of Bern.

3. Results

3.1. Chronology

U–Th dates determined for stalagmites Ta-9 and Ta-10 from Tabak Cave are shown in Fig. 5a (see also Table 1). The U–Th ages allow us to date prominent soot and charcoal layers directly and to correlate them between samples from within the cave.

In combination with macroscopic and petrographic evidences, U–Th ages indicate that growth of Ta-9 and Ta-10 was intermittent in both stalagmites. Discontinuities were detected in both stalagmites, lasting between 4419 ± 16 yr BP and 6993 ± 266 yr BP in stalagmite Ta-9 and 4536 ± 30 yr BP and 6670 ± 218 yr BP in stalagmite Ta-10 (Fig. 5a). If the age uncertainties of the dates before the hiatus are taken into consideration, the growth of the two stalagmites had ceased contemporaneously.

The low ^{230}Th/^{232}Th ratios in stalagmites Ta-9 and Ta-10 (Table 1) indicate lower detrital contamination and related low age uncertainties (Table 1). Because of the similar growth habit of two stalagmites and close age and uncertainty before the hiatus, we were able to calculate the deposition time of the soot and charcoal layers within stalagmites Ta-9 and Ta-10 using linear interpolation between the U–Th ages of those stalagmites. Based on the current age model, charcoal and soot layers within stalagmites Ta-9 and Ta-10 were deposited simultaneously at around 6718 ± 221 yr BP (1), 7099 ± 220 yr BP (2), 7375 ± 221 yr BP (3). Using distinct soot and charcoal layers as stratigraphic marker horizons, we used the precisely-dated dark layer in stalagmite Ta-10 (Fig. 5b) to assign a relative age of 7424 ± 225 for the corresponding layer in stalagmite Ta-9 (Fig. 5b).

The chronology of the actively growing stalagmite Ko-1 is based on a total of 31 U–Th ages (Table 2; Fig. 5b). For the development of the Ko-1 age model, only U–Th ages with low detrital contamination (^{230}Th/^{232}Th ratios higher than 40) were used. Stalagmite Ko-1 was deposited continuously between 5522 ± 150 yr BP and 2005 CE (Table 2). A total of five charcoal and soot layers (Roman numbers in Fig. 4b) were identified in stalagmite Ko-1. Based on the age model, soot layers were deposited at around 470 ± 56 yr BP (I), 810 ± 67 yr BP (II), 1500 ± 133 yr BP (III), 1730 ± 38 yr BP (IV) and 2830 ± 189 yr BP (V).

3.2. Characterization of soot and charcoal layers and calcite textures

Stalagmites from Tabak Cave (Fig. 4a) exhibit very similar macroscopic features such as soot and charcoal layers, major colour changes and displacements in the growth axis. When combined with U–Th ages, these features allow cross correlation between samples from Tabak Cave. In particular the distinct soot and charcoal layer 1 (Fig. 4a) represents a distinct marker horizon which separates compact and denser from more porous and lighter calcite layers (Fig. 6a and b). In

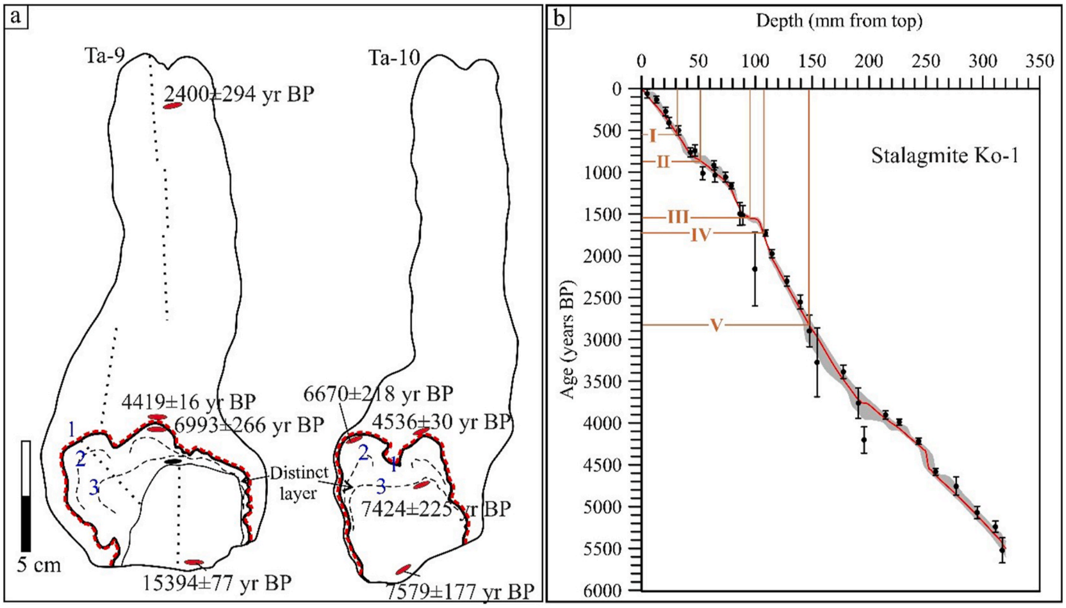

Fig. 5. a) U–Th dating points (red circles) can be seen on the sketches of stalagmites Ta-9 and Ta-10. Thick black lines represent the darkest and thickest charcoal and soot layer. The dashed lines before the darkest charcoal and soot layer indicate additional soot layers and potential discontinuities. The red and dashed lines above the thick black line indicate the hiatus. The soot and charcoal layers are denoted blue 1, 2, 3, and the age of these layers is 1–6718 ± 221 yr BP, 2–7099 ± 220 yr BP, 3–7375 ± 221 yr BP. b) Age-Depth model for stalagmite Ko-1. Roman numbers indicate the charcoal and soot layers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

stalagmites Ta-9 and Ta-10, there is a sharp contact (Fig. 6b) and cavities indicate a longer hiatus in both stalagmites. An important observation is that the charcoal and soot accumulated before the hiatuses in stalagmites Ta-9 and Ta-10, indicating that they were deposited at around 6718 ± 221 yr BP based on linear interpolation age model.

Microcrystalline calcite is observed through the darkest charcoal and soot layer 1 (Fig. 6c and d) in stalagmites Ta-9 and Ta-10. Calcite fabric turns into columnar shaped calcite from equant shaped calcite through the upper part of these two stalagmites. In thin sections (Fig. 6c and d), there are additional slightly visible soot layers below the distinct charcoal and soot layer 1 within stalagmites Ta-9 and Ta-10. The microcrystalline calcite is also seen in SEM images (Fig. 6e and f). The presence of non-calcite particles causes crystal defects and therefore promotes development of microcrystalline calcite (Frisia, 2014). The presence of microcrystalline calcite within stalagmites Ta- 9 and Ta-10 (Fig. 6c and d) is an indicator for the existence of soot and charcoal particles. Finally, SEM images of dark layers within stalagmites Ta-9 and Ta-10 show that they consist mostly of soot particles and no charcoal particles (Fig. 6e and f).

Stalagmite Ko-1 consists of compact and fairly dense calcite, whereas the upper part contains more abundant soot and charcoal layers (labelled IV in Fig. 4b) and also distinct dusty layers. The SEM image of soot layer IV shows some larger charcoal fragments of around 300 μm (Fig. 6g and h) with intact cell structures.

4. Discussion

An interesting feature of all soot and charcoal layers in stalagmites from Tabak and Kocain caves is the fact that they appear episodically, which could be related to episodic fire activity within or above both caves. Several observations indicate an anthropogenic source for the soot and charcoal layers in both caves. Firstly, all stalagmites from Tabak Cave were collected from the deeper and poorly-ventilated part of the cave. It is therefore rather unlikely that the soot and charcoal particles were transported by strong airflows from the surface or cave entrance into the deeper parts of Tabak Cave, also because the narrower entrance of Tabak Cave minimizes airflow origin soot and charcoal deposition. Because of the large entrance and volume of Kocain Cave, cave air ventilation is stronger in and thus soot and charcoal particles most likely originated from the entrance where fires for barbecues are even made today. Secondly, the very low concentration of dust or soil particles in the soot and charcoal layers (Fig. 6e, f, 6g and 6h) reduces the possibility, that soot and charcoal particles were transported by percolating water through larger fissures (Gradziński et al., 2007). Thirdly, Tabak and Kocain caves contain clear archaeological evidences for human activity. For instance, human and animal bones and Chalcolithic ceramics in Tabak Cave were reported by Yalçınkaya (1991). Some of these finds are also displayed in photos taken during one of our visits (Fig. 7e and f) and dated to Chalcolithic based on their shape and fabrics (personal communication with Prof. B. Erdoğu). Additionally, in Kocain Cave a large cistern from Roman Period (TAY Project, 2019) indicates that the cave was frequently visited by humans.

The lines of evidence reveal human activity inside both caves. There are additional indirect evidences around the cave which support possibility of human activity in close proximity to both caves. Firstly, many caves in the area and close to Tabak and Kocain caves contain archaeological artefacts. For instance, Karain Cave, Suluin Cave, Boynuzluin Cave and Öküzini Cave (Fig. 3a) have clear evidences for human occupation and presence from the Palaeolithic to Roman period (e.g. Taşkıran et al., 2015, 2011, Taşkıran, 1993; Yalçınkaya et al., 1999a, Yalçınkaya, 1994, 1991). For instance, numerous Chalcolithic, Early Bronze Age and Roman ceramics were found in Karain Cave (e.g. Yalçınkaya et al., 1999a). The archaeological finds from Öküzini Cave comprise the Epi-Palaeolithic, Neolithic and Chalcolithic periods (Carter et al., 2011). Furthermore, Öküzini Cave is characterized by grave finds (Carter et al., 2011) and defined as the first necropolis in Anatolia (Yalçınkaya et al., 1998). In addition, there are mound settlements approximately 35 km north of the study area. Bademağacı mound is one of that mounds and supply numerous archaeological artefacts which are of dated from early Neolithic to early Christianity period (Duru, 2008). Taşkıran et al. (2011) compared ceramics from Suluin Cave and Bademağacı and Höyücek mounds and suggested that there was human existence in Suluin Cave during Neolithic, Chalcolithic and Early Bronze Age. Consequently, it is not surprising to find traces for human activity

Table 2
U–Th dating results of stalagmite Ko-1. The error is 2σ.

Sample Number	Depth (mm from top)	^{238}U (ppb)		^{232}Th (ppt)		$^{230}Th/^{232}Th$ (atomic $\times 10^{-6}$)		$d^{234}U$* (measured)		$^{230}Th/^{238}U$ (activity)		^{230}Th Age (yr) (uncorrected)		^{230}Th Age (yr) (corrected)		$d^{234}U_{initial}$** (corrected)		^{230}Th Age (yr BP)*** (corrected)	
Ko-1-20	5	109.3	±0.1	321	±6	14	±2	514.7	±2.1	0.0025	±0.0004	177	±32	120	±51	515	±2	61	±51
Ko-1-21	13.2	99.0	±0.1	153	±3	32	±5	518.4	±2.3	0.0031	±0.0005	219	±34	190	±40	519	±2	131	±40
Ko1-40	21.2	81.0	±0.1	137	±3	49	±6	508.3	±1.6	0.0051	±0.0006	366	±46	333	±51	509	±2	273	±51
Ko-1-14	24.1	87.2	±0.1	348	±7	31	±2	510.2	±1.7	0.0075	±0.0005	545	±37	468	±66	511	±2	409	±66
Ko-1-22	32.5	86.5	±0.1	247	±5	49	±3	508.6	±3.1	0.0085	±0.0006	613	±40	558	±56	509	±3	499	±56
Ko-1-15	43	94.2	±0.1	334	±7	57	±2	516.9	±2.0	0.0123	±0.0004	889	±29	821	±56	518	±2	762	±56
Ko-1-23	47	102.3	±0.1	433	±9	48	±2	514.2	±2.5	0.0122	±0.0005	882	±34	801	±67	515	±3	742	±67
Ko-1-41	53.9	70.4	±0.1	283	±6	64	±3	487.4	±2.3	0.0156	±0.0008	1150	±56	1071	±79	489	±2	1011	±79
Ko-1-42	63.7	98.5	±0.1	222	±5	102	±5	500.3	±1.8	0.0140	±0.0006	1019	±47	975	±56	502	±2	915	±56
Ko-1-24	64.7	104.3	±0.1	597	±12	48	±2	506.5	±2.2	0.0165	±0.0005	1203	±35	1092	±86	508	±2	1033	±86
Ko1-43	73.9	84.5	±0.1	235	±5	95	±4	498.4	±2.0	0.0160	±0.0006	1173	±43	1119	±57	500	±2	1059	±57
Ko-1-16	79	99.0	±0.1	169	±3	166	±5	508.0	±1.5	0.0172	±0.0004	1254	±30	1221	±38	510	±2	1162	±38
Ko-1-25	86.4	98.3	±0.1	921	±18	42	±1	506.3	±2.6	0.0238	±0.0005	1738	±38	1558	±133	508	±3	1499	±133
Ko-1-44	88.9	90.5	±0.1	727	±15	49	±2	506.6	±2.8	0.0237	±0.0006	1729	±41	1574	±117	509	±3	1514	±117
Ko-1-45	99.7	95.3	±0.2	3077	±62	20	±1	507.1	±2.7	0.0388	±0.0005	2841	±41	2217	±443	510	±3	2157	±443
Ko-1-46	109	132.8	±0.3	247	±5	223	±6	516.1	±3.0	0.0252	±0.0004	1825	±28	1789	±38	519	±3	1729	±38
Ko-1-26	114.6	131.3	±0.2	374	±8	166	±4	514.5	±2.7	0.0287	±0.0004	2088	±29	2033	±48	517	±3	1974	±48
Ko-1-27	127.8	118.5	±0.1	453	±9	145	±3	518.0	±2.6	0.0336	±0.0004	2437	±32	2363	±61	521	±3	2304	±61
Ko-1-28	139.5	94.1	±0.1	513	±10	114	±3	525.7	±3.3	0.0376	±0.0006	2715	±41	2611	±84	530	±3	2552	±84
Ko-1-17	147.5	102.0	±0.1	1403	±28	53	±1	530.1	±1.6	0.0446	±0.0006	3219	±41	2958	±189	535	±2	2899	±189
Ko-1-29	154.3	93.1	±0.1	2860	±57	29	±1	543.4	±2.3	0.0545	±0.0006	3911	±46	3332	±412	549	±2	3273	±412
Ko-1-31	177.4	92.0	±0.1	482	±10	157.2	±3.6	558.3	±2.1	0.0499	±0.0006	3543	±40	3446	±80	564	±2	3387	±80
Ko-1-32	190.6	84.7	±0.1	1126	±23	71	±2	561.5	±2.1	0.0573	±0.0006	4067	±43	3819	±180	568	±2	3760	±180
Ko-1-47	195.6	80.9	±0.1	924	±19	91	±2	562.1	±2.7	0.0629	±0.0007	4474	±50	4262	±158	569	±3	4202	±158
Ko-1-33	214.6	90.9	±0.1	238	±5	358	±8	571.3	±2.1	0.0569	±0.0005	4011	±40	3963	±52	578	±2	3904	±52
Ko-1-34	226.6	117.5	±0.1	153	±3	744	±16	595.6	±2.1	0.0586	±0.0004	4071	±32	4047	±36	602	±2	3988	±36
Ko-1-35	243.6	101.1	±0.1	97	±2	1059	±24	591.2	±2.4	0.0616	±0.0005	4294	±36	4276	±38	598	±2	4217	±38
Ko-1-36	258.6	109.8	±0.1	182	±4	660	±14	575.1	±2.4	0.0662	±0.0005	4671	±35	4640	±41	583	±2	4581	±41
Ko-1-37	276.6	89.1	±0.1	731	±15	147	±3	638.1	±2.4	0.0730	±0.0005	4960	±38	4815	±109	647	±2	4756	±109
Ko-1-38	295	86.8	±0.1	409	±8	259	±6	585.1	±2.6	0.0742	±0.0006	5214	±43	5128	±75	594	±3	5069	±75
Ko-1-48	311	125.1	±0.2	541	±11	291	±6	579.6	±2.8	0.0762	±0.0005	5379	±39	5300	±68	588	±3	5240	±68
Ko-1-39	317	92.0	±0.1	1019	±20	121	±3	573.0	±2.2	0.0815	±0.0006	5785	±42	5581	±150	582	±2	5522	±150

*$\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1)\times 1000$.
**$\delta^{234}U_{initial}$ was calculated based on ^{230}Th age (T), i.e., $\delta\ ^{234}U_{initial} = \delta\ ^{234}U_{measured}$ x el234xT.
Corrected ^{230}Th ages assume the initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values or a material at secular equilibrium, with the bulk earth $^{232}Th/^{238}U$ value of 3.8. The errors are arbitrarily assumed to be 50%.
***B.P. stands for "Before Present" where the "Present" is defined as the year 1950 C.E.

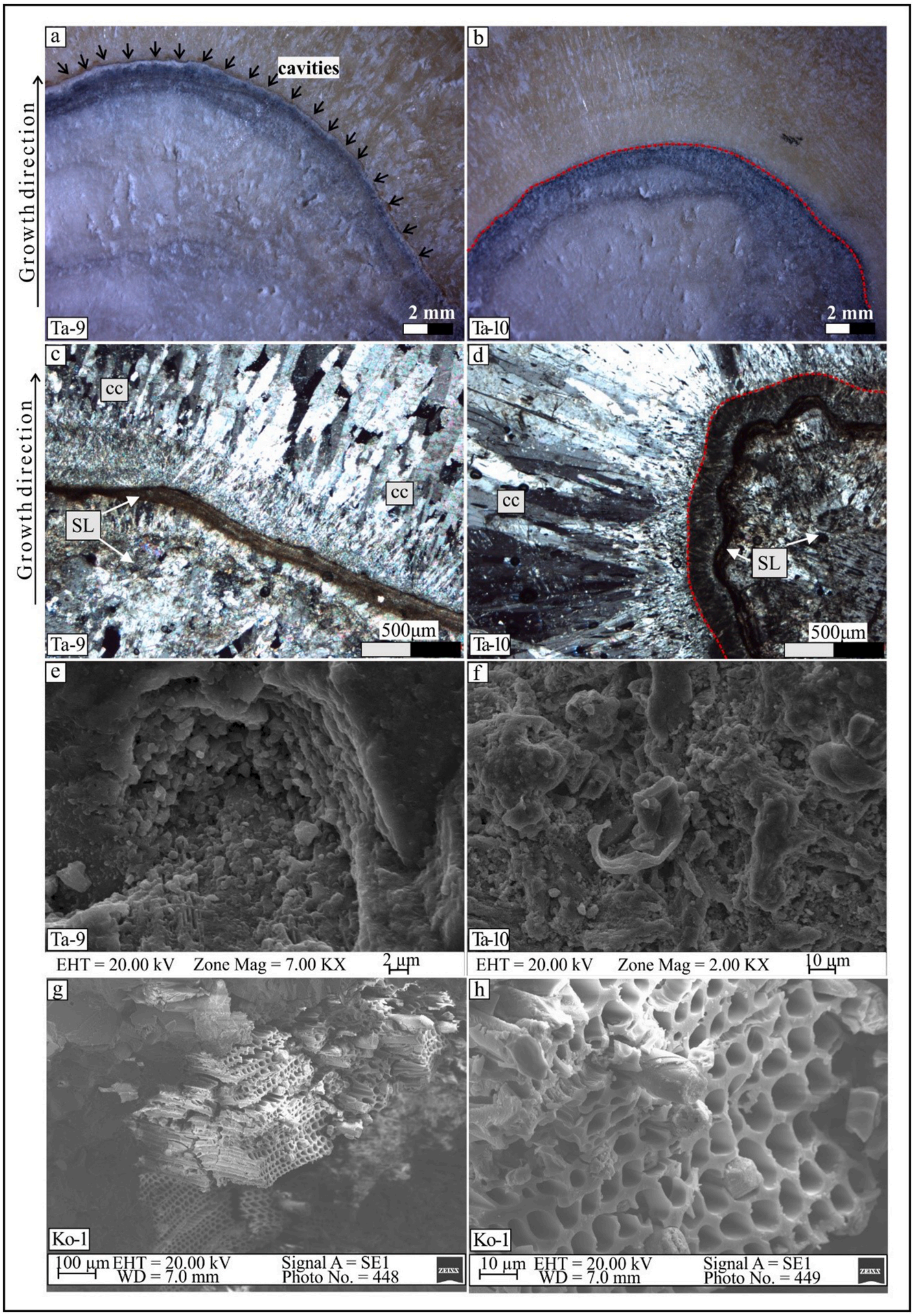

Fig. 6. a, b) Microscope view (10× magnification) of the soot layers in the stalagmites Ta-9 and Ta-10 Discontinuities are shown with arrows and red dashed line. c, d) Thin section images of the darkest soot layers within the stalagmites Ta-9 and Ta-10 under cross polarized light. There are micritic accretions after soot layers. In both stalagmites, calcite textures are changing above soot layers and become columnar shape calcite. These calcite crystals after the soot layers show clear evidence for competitive growth, as also described by Gradziński et al. (2007). e, f) SEM images of the darkest layers in stalagmites Ta-9 and Ta-10. The microcrystalline calcite and soot particles can be seen easily g) SEM image of dark layer IV within stalagmite Ko-1. The large charred wood particle is seen under 100 µm magnify h) A more detailed view of the charcoal particle in Fig. 6g under 10 µm magnification. S.L. soot layer, cc: columnar calcite. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in Tabak and Kocain caves in such a frequently occupied area.

4.1. Human activity within Tabak and Kocain Caves

Based on the artefacts, Tabak Cave was most likely used as a burial site and for ritual aspects. Pre-historic humans believed that caves were spiritual places and used caves for ritual activities (Grosman et al., 2008; Rowan and Ilan, 2012). The setting of Tabak Cave could be favourable for ritual activities, like funerary feasts based on the co-existence of human and animal bones. Stalagmites Ta-9 and Ta-10 collected from a chamber which is connected to the main gallery through a very narrow passage (Fig. 7c) and has a flat surface (Fig. 7d). The human and animal bones (personal communication with A. Uslu, MD) found in and around the chamber were overgrown by calcite and very close to ceramics (Fig. 7d, e and 7f). During the Chalcolithic period, humans were often buried with their belongings and the proximity of many ceramics and bones indicate a burial site. The episodic deposition of soot and charcoal layers within stalagmites Ta-9 and Ta-10 between 6670 ± 218 and 7400 ± 245 yr BP matches the proposed human activity during the Chalcolithic period. Moreover, the archaeological finds from other caves around Tabak Cave, i.e. Öküzini Cave (Yalçınkaya et al., 1999b; Carter et al., 2011) show that burials within caves were common during Chalcolithic period. It is rather unlikely that Tabak Cave was used as a shelter as the entrance area is too narrow and steep and it would be simply unbearable due to the poor cave air ventilation, high humidity and low cave-air temperatures of less than 18 °C.

In Kocain Cave, there is a large cistern from the Roman Period (TAY Project, 2019), and 28 inscriptions (Öztürk, 2015) testify the presence of

Fig. 7. a) Image of the steep and narrow entrance of Tabak Cave covered with shrubs. The picture was taken from upwards to entrance b) View from the entrance of Tabak Cave to SW. There is a lake in front of the cave indicated by arrow. c) The entrance of the chamber from which stalagmites Ta-9 and Ta-10 were collected. Dashed line shows the width of the gate. d) The ground of the chamber from which stalagmites Ta-9 and Ta-10 were collected. The arrows and circle show ceramics on the ground. e) Arrows show bones overgrown by calcite close to the location of stalagmites Ta-9 and Ta-10. f) A pottery sherd and a human bone very close to gate in Fig. 7c.

humans in the cave. The inscriptions indicate that Kocain Cave was used by law enforcement officers during the Roman Period for their consecration rituals (Öztürk, 2015). The age of the soot and charcoal layer IV stalagmite Ko-1 (Fig. 8) is concurrent with the inscriptions. There might be other reasons for using Tabak and Kocain caves in addition to ritual purposes. These two caves have common advantages for human. They are located very close to the coast of Mediterranean Sea in the south (Fig. 1). In the north Western Taurus Mountain with height up to 3000 m and acts as a barrier between the southern Turkey and the Central Anatolia. Because of this orographic barrier, there is more rainfall in the cave location than the inner part of Anatolia. Therefore, regional climate is favourable because of more abundant orographic rainfall. The freshwater sources (Kırkgöz springs and small lakes) around Tabak Cave and within Kocain Cave (Fig. 7b) is another advantage and explains why they were frequently used by humans. Beside the apparent necessity of freshwater for living, it attracts the animals and makes hunting easier for hunters in the vicinity of studied caves. Moreover, abundant freshwater cause abundant life and more nutrient, thus more food sources to humans. This is also required for funerary actions likewise funerary feasts (Rowan and Ilan, 2012).

The Roman Period cistern in Kocain Cave is an important evidence indicating a relationship between human and water resources around the cave. The existence of the cistern implies that there were substantial investments to harvest and store water. To have water storage is important for this region because of the dry and hot summer months. The very large entrance of Kocain Cave and the natural spring provides the ideal conditions to build a cistern, therefore, pastoralists could supply their animal herd with water. During the summer seasons, they could protect their herds and themselves against extreme heat and aridity, attacks from wild animals and other humans by taking shelter in Kocain Cave. It has not to be just during summers, it could be even in winter season for protection against extreme weather conditions.

Consequently, humans might have numerous reasons to use Tabak and Kocain caves through different time periods. The ritual aspects are the most likely reason for using Tabak Cave during Chalcolithic period. For Kocain Cave, the reasons such as water storage and protection against extreme weather conditions and attacks, in addition to ritual purposes are likely, especially, during Roman Period. The archaeological artefacts both in Tabak and Kocain caves support the proposed usage of caves.

4.2. *Speleothems as archaeological log of human occupation*

Traces of human activity within a specific landscape are sometimes difficult to find, particularly if the sites date back to the Palaeolithic and Neolithic periods. Stalagmites from Tabak Cave and Kocain Cave and other speleothems from various cave in Turkey which containing soot and charcoal particles provide a unique opportunity to trace human activities within a region. Because the stalagmites from those caves record the human activity and can provide additional information about

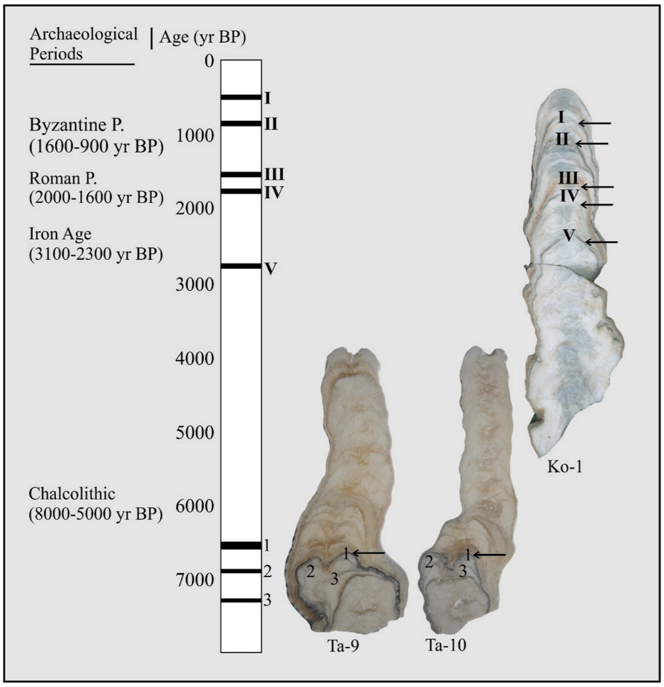

Fig. 8. Summary of securely dated soot and charcoal layers occurrence time within stalagmites Ta-9, Ta-10 and Ko-1. The deposition occurred in Tabak Cave stalagmites during Chalcolithic, while deposition in Kocain Cave from Iron Age to Byzantine Period episodically. The black bands in column on the left represent charcoal and soot layers within stalagmites and the thickness of band also represents the thickness of soot and charcoal layers. The archaeological periods are based on Allcock (2017).

the type, frequency and, more important, precisely timing of activity.

Firstly, in Tabak Cave stalagmites Ta-9 and Ta-10 exhibit at least three soot and charcoal layers deposited between 7424 ± 245 yr BP and 6670 ± 218. In combination with the archaeological finds, this means that Tabak Cave was used for ritual aspects at least three times during Chalcolithic period, episodically. We use the term “at least” based on the “MNO” definition suggested by Vandevelde et al. (2017). They showed that a single soot and charcoal layer can be consisted more than one layers. The closer view of the soot and charcoal layer number 1 in stalagmites Ta-9 and Ta-10 (Fig. 6a and b) support the MNO definition. Additionally, the thickness of soot and charcoal layers can provide information about the frequency of visits. The thicker layer means more frequent visits (Verheyden et al., 2006). In this case, Tabak Cave was visited more frequently around 6718 ± 221 yr BP indicated by thicker layer 1 (Fig. 6a and b, also see Fig. 8).

Secondly, there are five soot and charcoal layers within stalagmite Ko-1 occurred between 2830 ± 189 yr BP and 470 ± 56 yr BP. Therefore, Kocain Cave was visited at least five times during the Iron Age, Roman, Byzantine and Ottoman periods. The strong evidence of this inference is retrieved from speleothem formation. The drip water existence is ultimate condition for speleothem growth. However, to keep soot and charcoal particles on the surface of a speleothem, the drip water rate must be lower, otherwise higher drip rates can wash the particles away. Therefore, the existence of soot and charcoal layers in stalagmite Ko-1 could indicate lower drip rate and drier conditions.

Finally, stalagmites containing soot and charcoal layers from Tabak and Kocain caves from SW Turkey show that speleothems have great potential to produce archaeological data. Moreover, there are several stalagmites from caves in other regions in Turkey. If we consider the importance of this region for archaeological investigations (Allcock, 2017), speleothems can make an additional and important contribution to illuminate the archaeological past and identify potential climate-human relationships.

5. Conclusions

There are several stalagmites containing soot and charcoal layer within various caves in Turkey. Stalagmites from Tabak and Kocain caves reveal that speleothems are sensitive recorders of human activity in caves. Humans visited to Tabak Cave for their burial ceremonies during Chalcolithic period based on age data of soot and charcoal layers within stalagmites Ta-9 and Ta-10 with combination of archaeological artefacts. The visitors of Kocain Cave had different purposes, such as law enforcements for their rituals according to the inscriptions, the people who were looking for safe place with water and food resources. The common traces of them were soot and charcoal particles within stalagmite Ko-1. Speleothems provide robust data to investigate all activities in detail. Finally, we recognize that further geological and archaeological studies are required to improve understanding of archaeological history of the region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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