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Tephra in caves: Distal deposits of the Minoan Santorini eruption and the Campanian super-eruption

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ABSTRACT

Tephra deposits in caves are not only significant as stratigraphic markers. The comparatively sheltered position of cave environments, protected from rainfall, may preserve original distal tephra deposition features, unlikely to have survived in the open landscape. Most reported findings of tephra in caves are from the Campanian super-eruption, which originated in the area of Naples (Italy). These findings facilitate evaluation in different caves of facies variability and modes of tephra deposition, derived from the same eruption. The Campanian volcanic event, about 40,000 years ago, was the largest eruption in Europe and the Mediterranean region during the late Pleistocene. Another major volcanic event during the Quaternary was the more recent Santorini eruption in the eastern Mediterranean (Aegean Sea) during the Late Minoan cultural period, approximately 3600 years ago. This was the largest Holocene eruption in the region, but tephra deposits in caves from this event appear to be very rare. We present here the first ever finding of a visible tephra layer from the Minoan Santorini eruption in a cave. The pure tephra, situated in the Pelekita cave in eastern Crete near Kato Zakros, has a thickness of up to 9 cm. Geochemistry analyses of major elements by electron probe micro-analysis (EPMA) and trace elements by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) prove the tephra to be derived from the Minoan Santorini eruption. Radiocarbon dating also fits the time frame of this eruption. Our findings indicate that the tephra layer in the Pelekita cave is an air-fall deposit. The lower boundary of the tephra layer is sharp and wavy, draping over the underlying irregular cave surface. Particle size distribution of the tephra is bimodal and typical for suspended aeolian transport. The consistently smaller size of heavier feldspar particles adjacent to larger but lighter volcanic glass particles, in thin sections of undisturbed samples, corroborate emplacement of the tephra inside the Pelekita cave from high-altitude fallout.

1. Introduction

Explosive volcanic eruptions produce enormous amounts of fine tephra that can be transported by atmospheric winds to large distances from the volcano. It is rather difficult to assess the distribution range and volume of distal volcanic ash, because thin deposits are usually not preserved. Tephra deposits may have an original sedimentary thickness of just a few millimeters or centimeters, which usually do not survive as distinct strata in the open landscape because of rain splash, erosion and bioturbation processes. However, thin tephra layers may survive in

terrestrial environments within caves and rock shelters, and retain their original sedimentary sequence.

Besides caves, karst depressions (dolines) may also contain a record of redeposited distal tephra in sediments that were removed by erosion from the landscape surface. Though the original sedimentation sequence of tephra in karst depressions is usually lost, dolines are important as geo-archives (Sjart et al., 2010), which testify to atmospheric transport directions of the eruption cloud and perhaps may assist in volume quantification.

We report here a novel discovery of a pure volcanic tephra layer,

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derived from the Minoan Santorini eruption, found in the Pelekita cave in eastern Crete near Kato Zakros. Various characteristics are presented, including cave geomorphology, field stratigraphic observations, and laboratory data of this tephra layer. Since there are no other reported findings so far of visible Minoan tephra layers in caves, we compare our new data with tephra layers from the Campanian super-eruption. The comparative evaluation includes distance from the respective volcanic source, cave geomorphology aspects in relation to possible sedimentary pathways and emplacement of the tephra, facies characteristics and internal stratigraphy.

Most tephra layers in caves in the Mediterranean region and Europe are known from the Campanian super-eruption, which originated in the Phlegrean Fields of the Naples area (Italy). This eruption, also known as the Gray Campanian Tuff or Campanian Ignimbrite (CI), or tephra Y-5, occurred about 40,000 years ago. It was the largest volcanic event in Europe during the past 200,000 years. The Campanian Tuff/Campanian Ignimbrite is a widespread/first-order tephrochronological marker in the Central and Eastern Mediterranean deep-sea sediments known as tephra Layer Y-5 in the Upper Quaternary (Keller et al., 1978; Pyle et al., 2006; Giaccio et al., 2017). Terms as ‘Campanian eruption’ or ‘Campanian tephra’ refer in our article to this super-eruption, as we do not discuss other eruptions from the Campanian Naples area.

The Minoan Santorini eruption was the largest Holocene volcanic event in the Mediterranean region. Comparing the two explosive eruptions, the erupted volume from the Campanian super-eruption has been estimated in terms of dense-rock equivalent (DRE) at 155–235 km³ (Marti et al., 2016). The erupted volume of the Minoan Santorini eruption has been upgraded recently to 78–86 km³ DRE (Johnston et al., 2014). Therefore, the Minoan eruption may have been one-third to one-half the magnitude of the Campanian super-eruption!

The deposition of fine volcanic tephra in a cave is a rare process that probably has not been witnessed by many scientists and scholars. Therefore, a concise intro is presented below of deposition pathways of fine sediments in caves in general. Subsequently, after the regional setting (section 3) and methods (section 4), a review is given of reported Campanian tephra characteristics in caves (section 5). This gives a necessary prelude to known facies variations of tephra layers in caves and related deposition pathways in different cave settings. Such an approach enables us to compare our novel data of the visible tephra layer from the Minoan Santorini eruption, found in the Pelekita cave in Crete (section 6), directly with sedimentary facies variations of Campanian tephra in caves.

2. Deposition of fine sediments in caves

The geologist William Farrand (1979) laid the foundation of stratigraphic sedimentological research in caves and rockshelters, in which also humans may be a factor with regard to sedimentary pathways and facies formation. Thus Farrand established the field of cave geoarchaeology, as described in an obituary by his former student Paul Goldberg (2011), who himself also greatly contributed to the further development of this field (Goldberg, 2001; Goldberg and Sherwood, 2006; Karkanas and Goldberg, 2013). In a seminal article Farrand (2001) noted: “Sediment accumulation in a cave or rockshelter tends to be idiosyncratic. No two caves are exactly alike in their bedrock infrastructure, exposition, size, internal karstic relations, the influence of external geomorphological phenomena, etc.” (Farrand, 2001:538).

Indeed, the “idiosyncratic” character of sediment accumulation in caves is also reflected by the various deposition pathways of volcanic tephra from the Campanian eruption, as presented below. Caves usually develop in landscapes composed of limestone, dolomite, gypsum or even salt (Frumkin, 1998). Such types of bedrock can be dissolved by chemical weathering, resulting in karst landscapes with caves, sinkholes and underground drainage systems.

Fine sediment, including distal volcanic tephra, may enter the cave through: (a) the cave mouth, (b) cracks in the bedrock roof, or (c)

underground karst drainage channels. Sedimentary pathways may include infiltration, colluvial, aeolian, fluvial and littoral zone processes (Woodward and Goldberg, 2001). Moreover, human activities may bring sediments into caves or modify existing sediments, for example by fires for cooking or heating purposes (Goldberg and Sherwood, 2006). Layers or spots containing ash and charcoal are typical for anthropogenic sediments. Dung layers in caves from domesticated animals (Linseele et al., 2010; Karkanas and Goldberg, 2013) can also be considered anthropogenic deposits related to herding practices, as caves provide shelter for the animals.

2.1. Infiltration through bedrock fissures

Joints and bedding planes in the bedrock around the cave may be sufficiently wide for fine sands, silts and clays to be flushed in through these cracks. Such fine deposits may be derived from soils and sediments, situated on rocks directly overlying the cave (Farrand, 2001; Woodward and Goldberg, 2001).

2.2. Colluvial processes

Slope wash or runoff overland flow is capable to transport fine sediments (Woodward and Goldberg, 2001). Whether colluvial sediments can be transported to the cave entrance or into the depth of the cave depends on landscape geomorphology. Butzer (1981) presented examples from Cantabria (Spain), where runoff on hill slopes transported fine sediments to the entrance of rockshelters.

2.3. Aeolian processes

Wind activity may transport sands, silts and clays into caves and rockshelters (Woodward and Goldberg, 2001). Coarse and medium sand are usually moved by saltation, whereas fine sand, silt and clay can be transported by suspension in the air over large distances. Aeolian material can be derived from proximal or distal sources. The latter include dust storms, as well as tephra from volcanic eruptions. The Mediterranean region, including Crete, is affected by dust storms (Pye, 1992), usually derived from the Sahara desert. Campanian volcanic ash (tephra) in the Franchthi Cave in Greece is interpreted as a primary aeolian fall deposit that entered through the cave mouth (Farrand, 2000:56).

2.4. Fluvial processes

Fluvial processes and accompanying sedimentation in caves and rockshelters may be related to either internal underground karst drainage or to surface stream channels. It is important to make a clear distinction between these two genetically different fluvial origins.

2.5. Littoral zone processes

Caves and rockshelters located along the coast of seas or lakes may sometimes be inundated, due to short- and/or long-term fluctuations in water level. Thus sedimentary sequences of marine or lacustrine deposits in such caves may alternate with aeolian or colluvial sediments (Woodward and Goldberg, 2001). Also tsunamis may cause occasional sedimentation in caves, situated near the littoral zone (Butler et al., 2017).

3. Regional setting

The prime focus of our article is the first discovery of a visible tephra layer from the Minoan Santorini eruption in a cave, the Pelekita cave in eastern Crete (Greece), as presented in detail in section 6. However, this new finding is presented against the wider background of tephra deposition pathways in caves. Since no other visible tephra

Fig. 1. Map of the central and eastern Mediterranean region with adjacent areas, showing the volcanic source of the Campanian super-eruption (Naples area) and the location of caves, in which this Campanian tephra has been found. The position of the Santorini volcano is also indicated, as well as the Pelekita cave and Zominthos doline on Crete, which contain tephra from the Minoan eruption. The map has been produced with Google Earth Pro.

layers in caves are known so far from the Minoan Santorini eruption, we compared our discovery, in terms of facies and sedimentary characteristics, with tephra layers reported from the Campanian super-eruption. Both volcanic events were very powerful explosive eruptions that occurred in the Mediterranean Region (Fig. 1).

Volcanic ash from the Campanian eruption has been reported in many caves (Lowe et al., 2012; d'Errico and Banks, 2015), as shown in Fig. 1. The Campanian super-eruption arose in the Naples area (Italy) in the Phlegrean fields and possibly also from adjacent volcanic vents (De Natale et al., 2016). The most accurate date for the eruption by $^{40}\text{Ar}/^{39}\text{Ar}$ dating is 39.85 ± 0.14 ka (95% confidence level). The uncalibrated, basic, radiocarbon date is 34.29 ± 0.09 kyr BP (Giaccio et al., 2017), which requires of course further calibration into calendar years. However, the calibration curve for this time trajectory within the last Ice Age is not yet definitive.

Various estimations, modelling approaches and calculations have been conducted to assess the amount of tephra dispersed by the Campanian super-eruption. A study by Costa et al. (2012) resulted in a figure of about $250\text{--}300\text{ km}^3$ of ash, spread over an area of approximately 3.7 million km^2 . A recent investigation by Marti et al. (2016), who separately evaluated the plinian and co-ignimbrite phases of the eruption, arrived at a total bulk volume in the range of $388\text{--}588\text{ km}^3$, which corresponds to $155\text{--}235\text{ km}^3$ dense-rock equivalent (DRE).

The Santorini volcano is situated in the Aegean Sea (Greece) (Fig. 1). Its caldera is surrounded by the small islands of Thera, Therasia and Aspronisi. The huge eruption occurred during the Late Minoan IA archaeological period. However, expressed in calendar years, there are large differences of opinion between archaeological age assessment and radiocarbon dating. Concerning the former, a prominent viewpoint suggests an age around 1500 BCE (Bietak, 2015). On the other hand, ^{14}C sequence dating of an olive branch found on Thera below Minoan tephra deposits yielded a date of 1627–1600 BCE at 95% (2σ)

confidence level (Friedrich et al., 2006), assuming correct identification of tree rings. For additional data and discussions see Höflmayer (2012), Manning et al. (2014), Bruins and Van der Plicht (2014, 2017).

However, two recent developments (Pearson et al., 2018; Ehrlich et al., 2018) necessitate a reassessment of the above ^{14}C date of the Minoan Santorini eruption. Concerning olive wood, Ehrlich et al. (2018) measured radiocarbon concentrations in a modern olive tree trunk and a living olive tree branch. They obtained near-annual resolution dates using the radiocarbon “bomb peak”. Their results show that radiocarbon dates along the olive wood circumference may differ by up to a few decades. Hence, the last year of growth is not necessarily represented by ^{14}C dates of the outer tree ring, which may have implications for the ^{14}C date of the above mentioned olive tree branch found below Minoan Santorini tephra.

Concerning calibration of radiocarbon dates into calendar years, Pearson et al. (2018) published detailed ^{14}C measurements of annual tree rings from California and Ireland for the period 1700–1500 BCE, dated by dendrochronology. Their results show a distinct departure from the present calibration curve IntCal13 (Reimer et al., 2013). The implication is that the calibrated ^{14}C age of the Minoan eruption may become somewhat younger. In the meantime we have to take a step back and wait. A number of radiocarbon laboratories are currently performing many analyses to come to a consensus on revisions for the new calibration curve IntCal19, which will be released during 2019.

The volume of tephra (proximal and distal) for the Minoan Santorini eruption calculated by Sigurdsson et al. (2006) totals about 61.5 km^3 DRE, a figure which incorporated for the first time new data of an extensive underwater survey around Santorini regarding submarine pyroclastic deposits. A more recent study by Johnston et al. (2014), based on field observations and seismic reflection surveys, suggest that pyroclastic materials of the Minoan eruption were trapped within the caldera. Collapse of the caldera began during eruption phase 4, and the

voluminous phase 3 infill, estimated at 18–26 km³ DRE, was subsequently down-faulted (Johnston et al., 2014). Adding this amount to the volumetric eruption components of Sigurdsson et al. (2006) increases the total to about 78–86 km³ DRE (Johnston et al., 2014).

Tephra from the Minoan eruption has been found over a large region in both marine and terrestrial contexts, from the Black Sea to the southeastern Mediterranean region, including Turkey, Rhodes and Crete (Keller, 1980a, 1980b; McCoy and Heiken, 2000).

No visible Minoan tephra layer has been reported so far in caves. However, redeposited cryptotephra of the Minoan Santorini eruption was found by Siart et al. (2010) in the karstic Zominthos doline (Fig. 1), situated in central Crete in the Mount Ida region at an elevation of about 1185 m. This doline near the Minoan villa of Zaminthos is situated at a distance of 136 km from the Santorini volcano, in a SSW direction of 200°. Volcanogenic particles were found in sediment core Zom 5, distributed as cryptotephra from 0.20 m to 9.70 m below the surface. This was the first finding of tephra at altitudes above 1000 m in central Crete. “Evidently, great amounts of tephra were distributed in the Cretan mountains” (Siart et al., 2010:88). Hence tephra was also transported through the atmosphere in a SSW direction from Thera (Santorini).

We present in this article the first finding of a distinct visible tephra layer, derived from the Minoan Santorini eruption. The tephra is exposed in the Pelekita Cave in eastern Crete (Greece), located about 3 km north-east of Kato Zakros. Our detailed results are presented in section 6. The regional landscape setting with regard to the entrance of the cave is shown in Fig. 2. The cave mouth is located along a rather steep slope, which descends at an angle of about 30° towards the Mediterranean Sea coast.

4. Materials and methods

The visible tephra layer in the Pelekita cave in eastern Crete, derived from the Minoan Santorini eruption, constitutes the main material investigated in this research by various methods, as described below. In addition, the related review of reported tephra layers in caves from the Campanian super-eruption, forming a prelude (Section 5) to our discovery in the Pelekita cave, is based on the literature. The distance from the volcanoes to the caves with tephra layers, as well as the direction of atmospheric transport was calculated with Google Earth Pro (Fig. 1, Table 1).

Fig. 2. The landscape in the area of the Pelekita cave (eastern Crete), showing the Mediterranean Sea and the steep rocky slopes. Part of the entrance (mouth) of the Pelekita cave is visible on the left (in the shade), next to a single fig tree, about 105 m above sea level. Photo by Bruins, 28-09-2007. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Detailed field observations of the tephra layer in the Pelekita cave (eastern Crete, Greece) were made by Bruins in 2006, 2007 and 2012. The stratigraphic sections exposed in the late 1970s and early 1980s by the archaeological excavations of Davaras (1979, 1982, 1983) facilitated these field studies. A few samples were taken of the tephra, but no new excavations were conducted. In addition, the geomorphological setting of the Pelekita cave in the surrounding landscape was evaluated.

Geochemistry analysis of major elements in single volcanic glass shards of the tephra in the Pelekita cave was conducted by Keller at the University of Freiburg, using a CAMECA SX100 wavelength dispersive electron probe micro-analyzer (EPMA). Preparation of polished thin sections for analysis was done on grain mounts in epoxy. To avoid loss of alkalis, a beam diameter of 10 µm and a beam current of 10 nA were consistently applied. Calibration was undertaken against international oxide, mineral and glass standards. The results of the tephra in the Pelekita cave are compared with EPMA data of tephra from Palaikastro (Bruins et al., 2008), Santorini (Keller, 1980b; Keller et al., 2014, Druitt et al., 1999) and other locations with distal ash layers (Eastwood et al., 1999). All data are based on microprobe point measurements of single glass shards.

Trace element analysis of glass shards and pumice fragments by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was carried out by Klügel at the University of Bremen using the method described in Bruins et al. (2008). The samples were embedded in epoxy resin and analyzed with laser spot diameters between 25 and 75 µm depending on sample size; in some cases the sample was moved along the glass shards during analysis. Some epoxy was inevitably ablated together with the glass, but blank analyses of epoxy showed that this did not affect the results.

Thin sections were used for petrographic studies by Kisch at Ben-Gurion University of the Negev (Department of Geology and Environmental Sciences).

Particle size distribution of a bulk sample of the tephra was measured by Katra at Ben-Gurion University (Department of Geography and Environmental Development), using an ANALYSETTE 22 MicroTec Plus (Fritsch) laser diffractometer (Katra and Yizhaq, 2017), capable of measuring particles in the size range of 0.08–2000 µm. The sample (100 mg) was dispersed in Na-hexametaphosphate solution (0.5%) by sonication (38 kHz). The data results were calculated with the Fraunhofer diffraction model with a size resolution of 1 µm, using MasControl software.

Table 1

List of caves with tephra from the Late Pleistocene Campanian super-eruption. The respective distance of the cave from the eruption source in the Naples area, as well as the atmospheric transport direction of the tephra, were measured with Google Earth Pro. Only one main reference is usually given for each cave.

Cave Name	Country	Visible Tephra (V) or Crypto-tephra (C)	Distance from eruption (km)	Atmospheric Transport Direction	Reference
Castelcivita	Italy	V	100	ESE 113°	Giaccio, 2005
Cavallo	Italy	V	330	ESE 102°	Palma di Cesnola, 1964
Crvena Stijena	Montenegro	V	419	ENE 58°	Morley and Woodward, 2011
Golema Pesht	Macedonia	C	600	ENE 77°	Lowe et al., 2012
Magura	Bulgaria	V	765	ENE 62°	Ivanova et al., 2016
Kozarnika	Bulgaria	C	771	ENE 63°	Lowe et al., 2012
Tabula Traiana	Serbia	C	790	ENE 55°	Boric et al., 2012
Klissoura	Greece	C	830	ESE 112°	Lowe et al., 2012
Temnata	Bulgaria	V	860	ENE 69°	Giaccio et al., 2008
Franchthi	Greece	V	863	ESE 113°	Farrand, 2000; Douka et al., 2011
Haua Fteah	Libya	C	1120	SSE 139°	Douka et al., 2014

A single charcoal piece from just above the tephra layer was radiocarbon dated at the University of Groningen. Following standard chemical treatment, using the AAA protocol (Mook and Streurman, 1983), the purified charcoal was combusted by an Elemental Analyzer (Isocube) coupled to a Stable Isotope Mass Spectrometer (Isoprime). The latter provides the stable isotope ratio $\delta^{13}\text{C}$ for the CO_2 gas. A fraction of the CO_2 is trapped cryogenically and subsequently reduced to graphite using H_2 gas and Fe powder as catalyst (Aerts-Bijma et al., 2001). The $^{14}\text{C}/^{12}\text{C}$ and $^{13}\text{C}/^{12}\text{C}$ ratios in the graphite were measured by AMS, based on a 2.5 MV tandemtron system (Van der Plicht et al., 2000). The measured data are converted to conventional ^{14}C ages in BP, which by convention are normalized for isotopic fractionation using the stable isotope ratio $\delta^{13}\text{C}$ of the AMS (Mook and Van der Plicht, 1999).

5. Caves with distal tephra layers from the Campanian super-eruption: a review

The atmospheric dispersal of the Campanian volcanic ash from the vents in the Naples region settled over a wide area in the Mediterranean region, Central and Eastern Europe, as well as North Africa (Costa et al., 2012; Fitzsimmons et al., 2013; Marti et al., 2016). An overview of caves containing Campanian tephra (Fig. 1) is shown in Table 1, including atmospheric transport directions and respective distances of the distal tephra layers from their volcanic source.

We did not include all caves with Campanian tephra in our sub-sequent review, which is focussed on sedimentary pathways and modes of emplacement of the tephra. Only those caves were selected for which relevant sedimentological tephra data and geomorphological cave information were available in the respective literature reports.

5.1. Castelcivita cave in southern Italy

Located in southern Italy at a distance of ca 100 km from the eruption in an east-southeast (ESE) direction of 113° (Fig. 1, Table 1) is the Castelcivita cave (Giaccio, 2005; Giaccio et al., 2008), situated in a limestone area of central Campania. Excavations uncovered a stratigraphic sequence of about 3 m thick, exhibiting a cultural succession from base to top of Mousterian, Uluzzian and Proto-Aurignacian. A prominent tephra layer, ranging in thickness from about 20 to 50 cm, occurs at the top of the section and seals the Proto-Aurignacian. No archaeological traces exist within or above the tephra (Giaccio, 2005:10).

The tephra comprises a layer of pumices overlain by fine grey ash, which include abundant accretionary lapilli. The basal pumice layer is about 10–15 cm thick. The overlying unit, composed of fine co-ignimbrite ash fallout is usually thicker, up to several decimetres (Giaccio, 2005; Giaccio et al., 2008). The variable thickness of the tephra is interpreted to indicate redeposition. However, Giaccio (2005:10) emphasized that “in spite of being reworked, the tephra clearly shows the typical Campanian eruption sequence”.

The tephra was obviously transported to the Castelcivita cave area through the atmosphere. Concerning its emplacement in the cave, it is not clear from the description whether the tephra was first deposited as an air fall inside the cave and subsequently disturbed by water flows coming from the hillside, or was transported from the outside hillside through colluvial processes.

5.2. Crvena Stijena rockshelter in Montenegro

This large rockshelter in southwest Montenegro, situated at a distance of 419 km from the Campanian volcanic eruption in an ENE direction of 58° (Fig. 1, Table 1), is set in a prominent limestone cliff in the western foothills of the Dinaric Alps at 700 m above sea level. The rockshelter faces SSW and has a large opening, 26 m wide and 15 m high, with a horizontal depth of about 25 m (Morley and Woodward, 2011).

The Campanian tephra layer inside has a thickness of up to 10 cm and is situated within the upper two meters of a 20 m long stratigraphic section. The tephra layer drapes over a large boulder and some stones, which indicates aeolian deposition (Morley and Woodward, 2011:689). Indeed water-laid deposition of fine tephra would not be able to cause such an emplacement, like a layer of snow, on an undulating coarse surface.

Particle size analysis of the tephra shows a bimodal distribution, the main peak being in the fine sand fraction of ca. 125–250 μm , while a smaller peak occurs in the coarse silt range of 16–31 μm . The fine sand component disappears from the distal Campanian tephra at a distance of about 1500 km from the volcano and beyond (Pyle, 1989; Pyle et al., 2006).

The tephra in the Crvena Stijena rockshelter consists of a densely packed and homogeneous mass of glass shards and pumice grains, as well as some mineral grains (ca 1%). The lowermost 2 cm has the coarsest particle size distribution, as the layer shows a clear fining-upwards trend. There is no evidence for waterborne deposition such as micro-laminae. “If such reworking had taken place it might be expected that the elongate shards – a typical feature of the Campanian Ignimbrite distal tephra – would become aligned with respect to the direction of flow” (Morley and Woodward, 2011:687). Both the particle size data and the microstratigraphic observations indicate that the tephra was deposited by aeolian air-fall.

5.3. Magura cave in Bulgaria

The Magura cave in north-western Bulgaria is situated 765 km away from the Campanian volcanic eruption source in an ENE direction of 62° (Table 1, Fig. 1). A visible tephra layer from the above eruption has been found in this huge cave complex, which is famous for its pre-historic drawings (Ivanova et al., 2016). The length of this cave system is very large, exceeding 2500 m, consisting of ten large halls and numerous smaller side galleries and branches. The cave entrance lies on

Rabisha Hill at an altitude of ca 375 m, about 80 m below the hill top (Ivanova et al., 2016).

Archaeological excavations were carried out in the entrance hall, also termed the Triumphant hall, which is 120 m long, 58 m wide and its ceiling is up to 28 m high. A Campanian tephra layer was found in trench III (Ivanova et al., 2016). However, the size of the cave mouth and its distance from trench III are not mentioned. The excavations reached a depth of 4.60 m and ten lithostratigraphic layers were identified (Ivanova et al., 2016). Layer 5 is the visible tephra layer, which has a sharp and fairly planar basal contact, but its upper boundary is erosional and wavy. Hence, the thickness of the tephra layer varies laterally, ranging from about 10 to 1 cm. It has been completely eroded in some parts of the stratigraphic profile.

The internal stratigraphy of the tephra shows many finely laminated planar layers of a few mm to 1.5 cm thickness, varying in colour from cream to dark grey. The glass shards are typically up to 150 µm long and 40 µm wide, and not very vesicular. The glass chemistry is indistinguishable from the proximal units of the Campanian eruption (Tomlinson et al., 2012, 2015; Ivanova et al., 2016).

The deposition pathway of the tephra in the Magura cave is not addressed by the investigators. However, based on their description of many fine laminated layers (Ivanova et al., 2016), (re)deposition in water seems likely. The wavy upper boundary and absence of tephra in certain parts of the excavated section in trench III also indicate subsequent erosion by water in a later stage of cave history.

5.4. Franchthi cave in Greece

The most prominent visible Campanian tephra layer in a cave in Greece exists in the Franchthi cave, situated on the southwestern shore of the Argolid Peninsula in the Peloponnese region (Farrand, 2000; Douka et al., 2011). The distance from the Campanian volcano near Naples to the Franchthi cave is 863 km in an ESE direction of 113°.

This karst cave in Lower Cretaceous limestone is about 150 m long. The mouth of the cave is oriented to the northwest, presently at an altitude of 15 m above sea level (Jacobsen and Farrand, 1987), overlooking the bay of Koiladha. However, during the time of the Campanian super-eruption, some 40,000 years ago, eustatic sea level was about 75 m lower than today, while the coastline was approximately 4 km west from the Franchthi cave (van Andel et al., 1980; Perlès, 2016). The cave mouth is about 19 m wide and approximately 8–9 m high.

The Franchthi cave was excavated between 1967 and 1979. An archaeological sequence of very long duration was uncovered, ranging from the Upper Palaeolithic to the end of the Neolithic (Jacobsen and Farrand, 1987; Douka et al., 2011). The two deepest excavation trenches, termed FAS and H1B (Farrand, 2000), are situated inside the cave at a distance of about 30 m and 25 m, respectively, from the cave mouth.

The Campanian tephra layer, stratum Q, 5–9 cm thick, overlies the deepest stratum P in both trenches. However, the tephra layer is best preserved in trench FAS. Here the lower boundary of the tephra is very sharp. Farrand (2000: 56) concluded the tephra to be aeolian fallout in primary position, according to its stratigraphic and sedimentological characteristics. On the other hand, in trench H1B, the tephra appears scattered and laterally diffused, possibly due to reworking shortly after initial deposition (Farrand, 2000:86; Douka et al., 2011).

5.5. Haua Fteah cave in Libya

The most southerly finding of tephra from the Campanian super-eruption is in North Africa (Libya) in the Haua Fteah cave, situated at a distance of 1120 km from the volcanic eruption source near Naples, in a SSE direction of 139° (Table 1, Fig. 1). The cave is located in Cyrenaica (NE Libya), to the north of the Gebel Akhdar (green mountain) massif and about one km south of the Mediterranean coast. It is a very large

oval-shaped karstic doline with an entrance (mouth) of about 50 m wide and 20 m high, facing north. The area inside the cave is 80 m across (McBurney et al., 1953; Barker et al., 2010; Hunt et al., 2010; Douka et al., 2014; Barton et al., 2015).

The Haua Fteah cave was first excavated in the 1950s (McBurney et al., 1953). Excavations were renewed by the Cyrenaican Prehistory Project during the period 2007–2011 (Barker et al., 2010; Hunt et al., 2010). The potential of tephra layers and cryptotephra was utilized to refine the chronology of Late Pleistocene prehistoric archaeology in North Africa in the context of the UK project “Response of humans to abrupt environmental transitions” (RESET) (Barton et al., 2015). Cryptotephra investigations at the Haua Fteah cave were carried out jointly by RESET and the Cyrenaican Prehistory Project (Barker et al., 2010). The results were used to develop a Bayesian-based chronology for the site (Douka et al., 2014).

The methodology used by Barton et al. (2015) to find and investigate cryptotephra horizons, which are obviously not visible to the naked eye, is hereby summarized. All investigated sites were sampled contiguously at intervals of 2 or 5 cm. Samples were put in sealed bags as described by Lane et al. (2014). In the laboratory possible volcanic glass in the sediment was isolated using the methods described in Blockley et al. (2005). “If tephra shards were found during low resolution scans the corresponding individual bag samples were then processed to further identify the exact sediment depth containing the cryptotephra layer. Concentrations of volcanic glass shards were calculated after counting from grain mounts under high-powered optical microscopy and are stated as the number of shards per gram of dry sediment (s/g). Where high concentrations of glass shards were located, these samples were re-examined at 2 cm resolution to pinpoint more precisely the stratigraphic position of the tephra horizon. For each tephra layer, glass shards were concentrated and prepared for single grain compositional analysis” (Barton et al., 2015:155).

The Haua Fteah cave is considered ideal for both the capture and preservation of cryptotephra. Sediment of aeolian origin comprises a significant part of the cave fill. However, much sediment has been emplaced by colluvial in-wash and rockfall (Barton et al., 2015:161). A local informant mentioned that much surface runoff flowed into the cave mouth from the outside soil surface during severe rainfall in the 1997–1998 season. So much mud and water entered into the cave that the local informant feared he might drown (Hunt et al., 2010:1602).

The excavations in the Haua Fteah cave revealed one visible tephra and three cryptotephra layers. One of these cryptotephra horizons has been correlated with the Campanian super-eruption (Lowe et al., 2012; Douka et al., 2014; Barton et al., 2015). A distinct increase in tephra shard concentrations was detected at 18–24 cm depth in the stratigraphic context HF_T441/442. The peak concentration of about 1400 s/g is at 20–22 cm depth. Volcanic glass chemistry matches the Campanian super-eruption (Tomlinson et al., 2012). Grain sizes of volcanic glass shards are < 160 µm (Douka et al., 2014:49).

6. Distal Minoan Santorini tephra in the Pelekita cave (eastern Crete)

6.1. Cave description and discovery of the tephra layer

We report here the first finding and investigation of a visible, pure tephra layer from the Minoan Santorini eruption situated in a cave. The Pelekita cave in eastern Crete (Greece) is located at a distance of 163 km from the Santorini volcano in a SSE direction of 151° (Fig. 1). It is a karst cave formed in limestone and dolomite layers of the upper Triassic to early Tertiary Tripolitza Unit. The Pelekita cave was mapped by the Hellenic Speleological Society and has a length of 310 m (Ioannou, 1970).

Its entrance (mouth) is situated 105 m above sea level along a rather steep mountain slope descending at about 30° to the Mediterranean Sea (Fig. 2). The cave opening (mouth) is about 15 m wide and 8 m high,

Fig. 3. The entrance (mouth) of the Pelekita cave, about 15 m wide and 8 m high, as seen from within the upper level of the entrance hall. A fig tree is standing just outside the cave mouth. The tree was still alive in September 2007, but died afterwards (before 2012). Photo by Bruins, 26-07-2006.

facing east towards the sea and partly upward to the sky, as can be seen from within the cave (Figs. 3 and 4). Going inside, the cave floor descends irregularly into the entrance hall at an angle ranging from about 20° to 45° (Fig. 4). The cave continues northward from the dry entrance hall into a deeper and darker cave chamber, where stalactites and stalagmites appear. Here water drops can sometimes be heard falling from the upper roof strata. The cave then continues westwards for about 300 m (Ioannou, 1970).

The tephra layer was exposed by archaeological excavations in the Pelekita cave during the late 1970s and early 1980s (Davaras, 1979, 1982, 1983). These excavations focused on the Neolithic. The tephra layer was apparently not recognized as such but considered to be an anthropogenic ash layer. Indeed, the light grey colors of volcanic ash and anthropogenic ash may appear quite similar. Reports of the excavations in Greek do not seem to mention a tephra layer in the cave (Konstantina Aretaki, Hellenic Speleological Society, personal communication).

In 2006, Alexander MacGillivray (Co-director of the Palaikastro excavations) heard that a local shepherd had noticed a tephra layer in the Pelekita cave. He suggested to Bruins, who was that year participating in the Palaikastro excavations, doing geoarchaeological fieldwork in relation to volcanic ash and tsunami deposits (Bruins et al., 2008, 2009; Bruins and Van der Plicht, 2014), to visit the Pelekita cave in order to check this information. Indeed, during our visit to the cave on 26 July 2006 we identified a genuine volcanic ash layer, consisting of pure tephra, which was exposed in several vertical stratigraphic sections of the areas excavated by Davaras (1979, 1982, 1983), as can be seen in Figs. 4 and 5.

6.2. Field characteristics and stratigraphy of the exposed tephra layer

Bruins made detailed field observations of the tephra layer on 26 July 2006 and took a number of samples for analyses. Another one-day visit to the Pelekita cave was made on 28 September 2007 and a final visit on 13 October 2012. New excavations were not conducted. All observations in the cave and the few samples collected are based on the sections excavated by Davaras (1979, 1982, 1983).

The tephra layer is visible in the entrance hall of the Pelekita cave at a distance of about 18–21 m from the cave mouth. It is exposed in the eastern, northern and western profiles (Figs. 4 and 5) of the main area excavated by Davaras (1979, 1982, 1983). This area continues in the

south and west until it reaches the high natural rock wall that closes the entrance hall on these sides. Profile East of this excavation area has a length of 5 m. Here the tephra layer is best exposed, having a thickness of up to 9 cm.

The lower boundary of the tephra layer is very sharp and somewhat wavy (Fig. 6). It seals the surface topography of the cave as it was just prior to the Minoan Santorini eruption. Notice the two visible tiny internal layers within the tephra deposit (Fig. 6), which are composed of very small tephra particles, mostly glass shards in the range of fine to medium silt and even smaller. These two tiny layers run parallel to each other, but are not water-level. They also follow more or less the underlying pre-tephra topography in a wavy manner. These two fine layers (bands) are also visible in a polished block (Fig. 7) of an undisturbed sample, hardened by epoxy in a micromorphology lab.

It should be emphasized that Fig. 6 shows a different part of the tephra layer in the Pelekita cave than Fig. 7. The respective spatial positions are at a distance of few meters from each other along the exposed section of the tephra layer in Profile East (Figs. 4 and 5). Therefore, the internal microstratigraphy of the tephra layer remains consistent along this exposure, which is an important feature in relation to the process of tephra sedimentation in the Pelekita cave. The internal strata of the tephra layer are not water-level but slightly wavy, draping over the underlying micro-topography.

6.3. Major element analysis of the Pelekita tephra by electron microprobe (EPMA)

A Minoan Santorini origin of the tephra layer in the Pelekita cave was considered most likely, but had to be proven by geochemical analyses of volcanic glass shards. Both major elements and trace elements were investigated. Following the discovery in 2006, Bruins informed the volcanologist Jörg Keller (University of Freiburg), who has longstanding experience in the study of tephra provenance from various volcanic sources in the Mediterranean region (Keller, 1980a, 1980b; Keller et al., 1978, 1990). Subsequently Keller went to see the Pelekita cave on 18-09-2006 for further sampling and documentation of the tephra layer. Major element analysis at the University of Freiburg by electron microprobe (EPMA) of single volcanic glass shards (Table 2) proved unmistakably that the tephra is derived from the Minoan Santorini eruption.

Keller et al. (2014) presented averages for the main proximal units

Fig. 4. Descending from the cave mouth into the entrance hall, in which the Minoan Santorini tephra layer is exposed (indicated by white arrows) in Profile East. The rubble pile above Profile East is probably derived in part from the archaeological excavations by Davaras (1979, 1982, 1983), which exposed the tephra layer. The measuring stick standing against Profile East is 100 cm long. The distance from Profile East to the cave mouth is about 18 m. Photo by Bruins, 28-09-2007.

of the Minoan eruption at Santorini (Minoan A to D, according to Druitt et al., 1999), based on 190 single glass data. There are no significant differences in glass composition of all four eruption phases. All data in Table 2 show excellent agreement. Hence, the Minoan Santorini eruption is unquestionably the source of the tephra in the Pelekita cave.

6.4. Trace element analysis of the Pelekita tephra by laser ablation (LA-ICP-MS)

Besides major elements, trace element concentrations of glass shards and pumice fragments also provide vital geochemical information regarding the volcanic signature of the tephra. Following earlier cooperation concerning tephra at the nearby Minoan site of Palaikastro (NE Crete), in relation to tsunami deposits (Bruins et al., 2008), tephra from the Pelekita cave was also investigated by Klügel at the University of Bremen. The impregnated block of an undisturbed sample of the tephra layer (Fig. 7) was used for trace element analyses with laser spot diameters varying between 25 and 75 μm . Ablation of the epoxy did not affect the results. A series of LA-ICP-MS measurements was made along the stratigraphy of the tephra layer, as indicated by a vertical black line

in Fig. 7. However, the detailed results of all these stratified measurements will be published elsewhere for reasons of space. Only the average result is presented here in Table 3.

The average composition of trace elements in volcanic glass/pumice in the Pelekita tephra (Table 3), based on 43 individual measurements, shows good agreement with pumice from the Minoan eruption at Thera (phase 4 ignimbrite). The results are also compatible with those of distal Minoan tephra from Turkey (Pearce et al., 2002). The lower part of Table 3 also shows ratios of incompatible trace elements, which are more reliable chemical fingerprints than absolute concentrations, as pointed out by Pearce et al. (2002).

6.5. Petrographic studies of the Pelekita tephra layer

Thin sections of undisturbed samples of the Pelekita tephra layer, impregnated with epoxy and produced in a specialized high-quality lab, facilitated detailed microscope observations. Petrographic studies of the tephra were carried out by Kisch, while some micromorphology aspects were also evaluated by Bruins. Only a limited part of the results are reported here, particularly in relation to the important question of

Fig. 5. The entrance hall of the Pelekita cave, showing the vertical profiles of the archaeological excavations by Davaras (1979, 1982, 1983). The stratigraphic position of the Minoan tephra layer in Profiles East, North and West is indicated. The measuring stick standing against Profile East is 100 cm long. Photo by Bruins, 28-09-2007.

the pathway of tephra sedimentation into the Pelekita cave.

The thin sections show that the tephra is pure and essentially uncontaminated, except for its upper transitional part that is mixed with overlying material. The lower and middle part of the tephra layer show a good grain-size diameter sorting by gravity in relation to atmospheric settling velocity of volcanic ash particles (Wilson and Huang, 1979).

Large-size thin sections showed some pumice particles up to about 1 mm in size, having many air bubbles and thus a light mass. The mean diameter of feldspars is half or less the size of the volcanic glass particles in the Pelekita cave tephra. Concerning particle diameters of 60–80 μm , the terminal fall velocity of feldspar ($\sigma = 2.65 \text{ g/cm}^3$) is higher by a factor of ca. 2–2¼ than that of glass particles ($\sigma = 2.40 \text{ g/cm}^3$) with the same mean particle diameter (Wilson and Huang, 1979:Fig. 3d).

The range in these factors expresses their shape dependence: the factors are somewhat higher for strongly bladed (b/a ratio $\frac{1}{3}$ to $\frac{2}{3}$ and c/b ratio $< \frac{1}{3}$) than for oblate (b/a ratio $> \frac{2}{3}$ and c/b ratio $< \frac{2}{3}$), equant (b/a and c/b ratio both $> \frac{2}{3}$), or weakly bladed (b/a and c/b ratios both $\frac{1}{3}$ to $\frac{2}{3}$) feldspar shapes, where a , b , and c are the principal axial lengths. Conversely, the mean particle diameter of glass particles is larger by ca. 1½ than that of feldspars with the same terminal velocity. These factors again are somewhat larger for strongly bladed than for oblate, equant, or weakly bladed feldspar shapes.

As this sorting by gravity becomes better as the ash particles traverse higher fall altitudes, the good grain-size sorting by gravity in the

Fig. 6. Close-up of the tephra layer in the Pelekita cave. Notice the sharp lower boundary with the underlying red-brown sediment. This boundary is not horizontal, as the tephra drapes over the irregular underlying topography (indicated by white arrows). Two fine layers can be seen within the tephra stratigraphy, which are not horizontal, as would be expected in the case of deposition by water, but wavy, going along with the underlying topography. Hence the emplacement of the layer, consisting of pure tephra, seems best explained as an air-fall deposit. Photo by Bruins 26-07-2006. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 7. Large-size polished block (8 × 6 cm) of an impregnated undisturbed sample of the tephra layer in the Pelekita cave. Notice the two tiny sublayers (fine bands 1 & 2), also visible in Fig. 6 at another spatial position of the tephra layer in Profile East. The internal tephra stratigraphy is slightly wavy and *not* water-level. A post-depositional bioturbation feature (reddish-brown burrowing channel) is visible in the lower part of the tephra layer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

lower and middle part of the Pelekita cave tephra layer corroborates that these are high-altitude ash falls.

6.6. Particle size distribution of the Pelekita tephra

Another important characteristic of the tephra layer in the Pelekita

Table 3

Average trace element concentrations (in µg/g) and element ratios of Minoan Santorini tephra in the Pelekita cave and other areas, as analyzed by LA-ICP-MS.

	Pelekita tephra		Minoan Phase 4 tephra	Minoan distal tephra
	Average (N = 43)	SD	Average (N = 5)	(Pearce et al., 2002)
Rb	111	21	120	116
Sr	60.2	9.1	67.5	56.9
Y	34.3	8.2	44.0	36.3
Zr	273	63	352	287
Nb	10.6	2.0	12.3	10.1
Ba	477	118	579	461
La	25.1	5.8	31.4	32.1
Ce	53.1	11.4	63.2	50.5
Pr	5.66	1.31	6.86	6.02
Nd	21.9	4.9	26.1	24.6
Sm	5.01	1.25	5.71	5.39
Eu	0.88	0.20	0.93	0.80
Gd	5.12	1.23	6.05	5.35
Tb	0.84	0.21	0.99	1.01
Dy	5.58	1.44	6.73	6.61
Ho	1.26	0.31	1.42	1.56
Er	3.96	1.00	4.86	4.52
Tm	0.64	0.18	0.71	0.74
Yb	4.40	1.10	4.92	5.29
Lu	0.67	0.16	0.82	0.92
Hf	7.24	1.70	8.65	7.05
Ta	0.79	0.18	0.97	1.01
Pb	24.7	5.6	20.0	
Th	17.8	4.3	20.5	16.6
U	5.98	1.32	6.79	5.52
Ba/Nb	45.2	4.89	47.2	45.6
Zr/Nb	25.9	2.63	28.6	28.4
Zr/Th	15.3	0.89	17.1	17.3
Zr/Y	7.96	0.37	7.99	7.91
La/Lu	37.2	5.17	38.5	34.9
La/Nb	2.38	0.23	2.56	3.18
Th/Nb	1.69	0.18	1.67	1.64
Th/U	2.98	0.36	3.02	3.01
Th/Hf	2.47	0.19	2.37	2.35
Nb/Y	0.31	0.04	0.28	0.28
Nb/U	1.77	0.19	1.81	1.83
Hf/Ta	9.20	1.01	8.90	6.98

cave is its particle size distribution. Katra investigated a bulk tephra sample from the Pelekita cave, measured by laser diffractometer at Ben-Gurion University of the Negev. The detailed results (Table 4, Fig. 8)

Table 2

Major element analyses by EPMA of single glass shards of tephra from the Pelekita cave by Keller, and comparisons with other data of the Minoan eruption of Thera (Santorini). All analyses were carried out by electron microprobe. Results in weight percentages are normalised to 100%, volatile-free. FeOt = total Fe calculated as Fe²⁺; n = number of point analyses; SD = standard deviation. Blank: not analysed or not detected.

Tephra Layer Pelekita Cave			Palaikastro ø	Thera Plinian Phase	Thera Plinian Phase	Thera Minoan Phases A-D	Gölkisar Minoan Tephra
			Bruins et al., 2008	Keller 1980a,b	Druitt et al., 1999	Keller et al., 2014	Eastwood et al., 1999
n = 7	SD	n = 72	n = 4	n = 7	n = 190	n = 67	
SiO ₂	72.22	1.75	73.25	73.00	73.44	73.81	73.61
TiO ₂	0.28	0.04	0.29	0.32	0.31	0.29	0.29
Al ₂ O ₃	13.96	0.36	14.09	14.13	14.46	13.53	14.02
FeOt	2.12	0.11	2.11	2.13	2.05	2.07	2.04
MnO	0.07	0.04	0.07			0.10	0.07
MgO	0.31	0.02	0.31	0.34	0.25	0.29	0.28
CaO	1.43	0.04	1.43	1.48	1.56	1.39	1.40
Na ₂ O	4.89	0.47	4.83	4.79	4.81	4.83	4.76
K ₂ O	3.23	0.11	3.29	3.45	3.16	3.54	3.24
P ₂ O ₅	0.06	0.03					
Cl	0.32	0.03	0.31	0.37		0.27	0.30
Sum	100.00		100.00	100.00	100.00	100.00	100.00

Table 4

Particle size distribution of a bulk tephra sample from the Pelekita cave, measured by laser diffractometer ANALYSETTE 22 MicroTec Plus (Fritsch) at Ben-Gurion University of the Negev (Katra and Yizhaq, 2017). The results were calculated with the Fraunhofer diffraction model (size resolution of 1 μm), using MasControl software.

Particle Size Fraction	Phi	Micron (rounded)	Tephra Pelekita cave, weight (%)
Fine sand	2–3	250–125	0.00
Very fine sand	3–4	125–63	5.69
Very coarse silt	4–5	63–31	41.80
Coarse silt	5–6	31–16	20.66
Medium silt	6–7	16–8	17.64
Fine silt	7–8	8–4	7.91
Very fine silt	8–9	4–2	2.36
Very coarse clay	9–10	2–1	1.30
Coarse clay	10–11	1–0.5	0.02
Medium clay	11–12	0.5–0.24	0.00
Fine clay	12–13	0.24–0.12	0.27
Very fine clay	< 13	< 0.12	2.32

Fig. 8. Particle size distribution of a bulk tephra sample from the Pelekita cave, measured by laser diffractometer. The statistical parameters are also listed.

show a basically bimodal distribution typical for suspended aeolian transport, as known also from dust storms and dust deposition (Katra et al., 2014; Katra and Yizhaq, 2017).

The largest detected size fraction of the tephra bulk sample is very fine sand, ranging from 63 to 125 μm (3–4 Phi). The mean particle size is 32 μm . The main peak lies in the very coarse silt fraction (around 47.4 μm) and a secondary peak occurs around 16.9 μm (medium to coarse silt). The very fine clay fraction (< 0.12 μm) shows a minor third peak.

An additional comment relates to pumice particles with many air bubbles, up to 1 mm in size, as mentioned above in the petrographic study. Such particles may float in water and are perhaps not suitable for detection by laser diffractometer. Moreover, the sample measured by the diffractometer is very small, only 100 mg. Such a small sub-sample may not include the full range of particles that are visible by microscope on a large-size thin section (8 × 6 cm) of the tephra layer.

6.7. Radiocarbon dating of a charcoal piece above the Pelekita tephra layer

A small piece of charcoal was found in situ in the Pelekita cave just above the tephra layer. It is obvious that the charcoal is anthropogenic in origin, in terms of deposition. Considering its stratigraphic position, the charcoal piece probably reflects renewed usage of the cave by

Table 5

Duplo AMS measurement (University of Groningen) of the charcoal sample, situated in situ just above the tephra layer in the Pelekita cave.

Groningen AMS nr	Sample name	Age BP	$\delta^{13}\text{C}$ (‰)	C %	Material
GrA 48438a	Pelekita PC-01	3385 ± 40	−25.43	61.8	charcoal
GrA 48438b	Pelekita PC-01	3345 ± 40	−25.43	61.8	charcoal

humans after the Minoan Santorini eruption. The charcoal was dated by AMS at Groningen University (Table 5). Two AMS measurements were obtained of the same sample, in order to enhance precision and accuracy.

The weighted average of the two dates is 3365 ± 28 yr BP, which is accepted by the chi-square test ($T = 0.5$, $5\% = 3.8$). The calibrated date, using OxCal 4.2 (Bronk Ramsey, 2001, 2017) and the IntCal13 calibration curve (Reimer et al., 2013), is 1687–1627 cal BCE for the 1 σ range (68.2%) and 1743–1564 cal BCE for the 2 σ range (95.4%). The rather wide calibrated age range (2 σ range) matches the established radiocarbon age for the Minoan Santorini eruption. Nevertheless, the value of the uncalibrated date is slightly older than other results for the Minoan Santorini eruption from Thera and Crete (Bruins and Van der Plicht, 2014; Manning et al., 2014). Possibly the charcoal consists of wood that already grew before the eruption, but was used by people to make a fire in the cave after the eruption (old-wood effect). The $\delta^{13}\text{C}$ and organic Carbon content are within the normal range for charcoal.

7. Discussion and conclusions

How was the tephra deposited in the Pelekita cave? It is obvious that during the Minoan eruption, the tephra travelled from the Santorini volcano through the atmosphere to eastern Crete. The tephra settled as air-fall on the landscape surface, but how was the precise mechanism of emplacement within the Pelekita cave? There are two main theoretical options: (1) Primary air-fall deposit of the tephra through the cave mouth. (2) Redeposition of the tephra by rainwater from the surrounding landscape into the cave, either as colluvial runoff through the cave mouth or through cracks (joints) in the surrounding bedrock.

Evaluating first the second options – redeposition by water – there seem to be a number of problems. The cave entrance (Fig. 2) is situated in the lower part of a rock cliff along a rather steep slope (ca. 30°). Hence most runoff rainwater with sediment from the upper slope and cliff above the cave will probably flow towards the Mediterranean Sea, because the potential collection area in front of the cave mouth is very small in terms of areal extent. The dominant inclination of the geomorphic surface area of the landscape outside the cave mouth is downward towards the sea (Fig. 2).

Moreover, if tephra was washed from the surrounding landscape surface into the cave, either through the cave mouth or through cracks in the surrounding bedrock, it seems inevitable that redeposited tephra would have been mixed with omnipresent terra rossa soil and silt- or sand-sized rock particles. However, the tephra layer in the cave appears very pure in its lower and middle part. The upper boundary of the tephra layer is gradual and mixed with reddish-brown sediment overlying the tephra. Indeed it is to be expected that human reuse of the cave after the Santorini eruption would have caused trampling and disturbance of the upper part of the tephra layer by people and domesticated animals, concurrently with accumulation of overlying cave sediments. Spherulites from dung were observed by Bruins in thin sections of brown sediment directly overlying the tephra.

Considering the other option of deposition and emplacement of the tephra by air-fall into the cave, there appear to be a number of features in favor of that possibility. The lower contact of the tephra layer with the underlying red-brown cave sediment is both very sharp and irregular wavy (Fig. 6). If the tephra was deposited by water, the surface of

the underlying sediment would most likely have been smoothed by the water flow, while the internal layering of the tephra would probably show planar laminae that are water-level. This is not the case. The tephra layer drapes over the underlying irregular surface. Also the internal stratigraphy of the tephra layer, particularly two tiny layers composed of fine silty volcanic-glass shards (Figs. 6 and 7), is somewhat wavy, and not water-level.

Comparing the Minoan Santorini tephra layer in the Pelekita cave with tephra from the Campanian eruption in other caves, it is clear that the features of the tephra layer deposited by water in the Magura cave in Bulgaria are quite dissimilar (section 5.3). The tephra in the latter cave shows many finely laminated planar layers of a few mm to 1.5 cm thickness, varying in colour from cream to dark grey (Ivanova et al., 2016). The tephra layer in the Pelekita cave is not characterized by a sequence of many fine laminae that are planar, i.e. water-level.

On the other hand there is much similarity between the tephra layers in the Pelekita cave and the Franchthi cave (section 5.4.). The Campanian tephra layer in the latter cave also has a very sharp lower boundary with the underlying sediment. The mouth of the Franchthi cave, about 19 m wide and some 9 m high, has about the same size as the mouth of the Pelekita cave (15 m wide, 8 m high). Also the distance of the exposed tephra from the cave opening (mouth) is comparable: 25–30 m in the Franchthi cave, and 18–21 m in the Pelekita cave. The thickness of both tephra layers is also very similar, being 5–9 cm in the Franchthi cave and 5–9 cm in the Pelekita cave. It was concluded by Farrand (2000: 56) that the tephra layer in the Franchthi cave, as exposed in trench FAS, is aeolian fallout in primary position, based on its stratigraphic and sedimentological characteristics. We favor a similar interpretation concerning the tephra layer in the Pelekita cave.

The particle size distribution of the tephra in the Pelekita cave underlines the sedimentological character of its aeolian air-fall emplacement. The particle size fractions detected by this methodology are typical for grains that are transported in the air by suspension, a feature familiar from dust storms (Katra et al., 2014) and dust deposition (Katra and Yizhaq, 2017).

Finally, petrographic microscope studies of the Pelekita tephra, using thin sections of undisturbed samples, in which the stratigraphy has been preserved, yielded convincing results concerning the process of aeolian sedimentation. The tephra is pure in its lower and middle part, without contamination, showing good sorting in relation to atmospheric settling velocity of volcanic ash particles (Wilson and Huang, 1979). The excellent sorting by gravity of grain-size in relation to particles of different specific weight (volcanic glass, pumice, feldspars) in the lower and middle part of the tephra layer confirms sedimentation from high-altitude ash falls.

In conclusion, the Minoan Santorini tephra in the Pelekita cave (eastern Crete) settled directly through the air through the cave mouth opening into the entrance hall of the cave. Here the tephra was protected from rainfall and remained largely preserved as a visible layer, 6–9 cm thick. The original thickness was probably even greater. However, subsequent human usage of the cave, after the Minoan eruption, caused some disturbance of the upper part of the tephra layer and mixing with overlying material.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.quaint.2018.09.040>.

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