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First evidence of a distal early Holocene ash layer in Eastern Mediterranean deep-sea sediments derived from the Anatolian volcanic province

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ABSTRACT

A hitherto unknown distal volcanic ash layer has been detected in a sediment core recovered from the southeastern Levantine Sea (Eastern Mediterranean Sea). Radiometric, stratigraphic and sedimentological data show that the tephra, here termed as S1 tephra, was deposited between 8970 and 8690 cal yr BP. The high-silica rhyolitic composition excludes an origin from any known eruptions of the Italian, Aegean or Arabian volcanic provinces but suggests a prevailing Central Anatolian provenance. We compare the S1 tephra with proximal to medial-distal tephra deposits from well-known Mediterranean ash layers and ash fall deposits from the Central Anatolian volcanic field using electron probe microanalyses on volcanic glass shards and morphological analyses on ash particles. We postulate a correlation with the Early Holocene 'Dikkartın' dome eruption of Erciyes Dağ volcano (Cappadocia, Turkey). So far, no tephra of the Central Anatolian volcanic province has been detected in marine sediment archives in the Eastern Mediterranean region. The occurrence of the S1 tephra in the south-eastern part of the Levantine Sea indicates a wide dispersal of pyroclastic material from Erciyes Dağ more than 600 km to the south and is therefore an important tephrostratigraphical marker in sediments of the easternmost Mediterranean Sea and the adjacent hinterland.

Introduction

Tephra layers produced during explosive volcanic eruptions and distributed by tropospheric and stratospheric wind regimes and water currents can be deposited in terrestrial and marine environments. They represent marker beds for tephrochronological dating of sedimentary sequences, which are often used for palaeoclimatic and palaeoenvironmental reconstructions (e.g., Mangerud et al., 1984; Brauer et al. 2000; Ehrmann et al., 2007; Hamann et al., 2008). In addition, volcanic ash layers provide a direct temporal link between the different archives in a variety of environmental settings including deep and shallow marine and lake sediments.

The Eastern Mediterranean region is characterized by a high frequency and intensity of explosive volcanic eruptions, widespread dispersal of ashes by predominantly westerly winds and a diverse chemical composition of erupted tephras. During the last six decades, the results from several deep-sea drilling projects have contributed to the development of a marine tephrostratigraphic framework for the past 300,000 yr. A detailed compilation of these studies until 1997 was published by Narcisi and Vezzoli (1999). More recently, tephrochronological investigations within palaeoclimate research programs based on terrestrial-lacustrine sedimentary environments and detailed work on absolute ages of pyroclastic units have provided further important time markers in stratigraphic sequences (e.g., Sullivan, 1988; Calanchi, 1996; Kuzucuoğlu et al., 1998; Eastwood et al., 1999; Seymour et al., 2004; Wulf et al., 2004).

Many late Quaternary tephras in the central Mediterranean can be attributed to the highly explosive volcanism in the Italian volcanic province (Fig. 1). Major eruptions of Mt. Vesuvius, the Phlegrean Fields, the Eolian Islands and the Palinuro seamount have provided numerous and thick distal tephra layers (e.g., Siani et al., 2004; Wulf et al., 2008). The Aegean volcanic province comprises one of the best known catastrophic events notably the ~1600 BC eruption of the Thera volcano (Santorini) that has been implicated in the demise of the Minoan civilization (e.g., Bruins et al., 2008). The associated marine Z-2 tephra spread over large distances (Narcisi and Vezzoli, 1999 and references therein). Multiple phase eruptions characterize the Central Anatolian volcanic province (e.g., Pastre et al., 1998; Gevrek and Kazanci, 2000; Şen at al., 2003; Tryon et al., 2009). Two major volcanic centres have been identified, the Cappadocian (including Erciyes Dağ, Göllü Dağ, Hasan Dağ) and the Konya volcanoes (including Kara Dağ). The first

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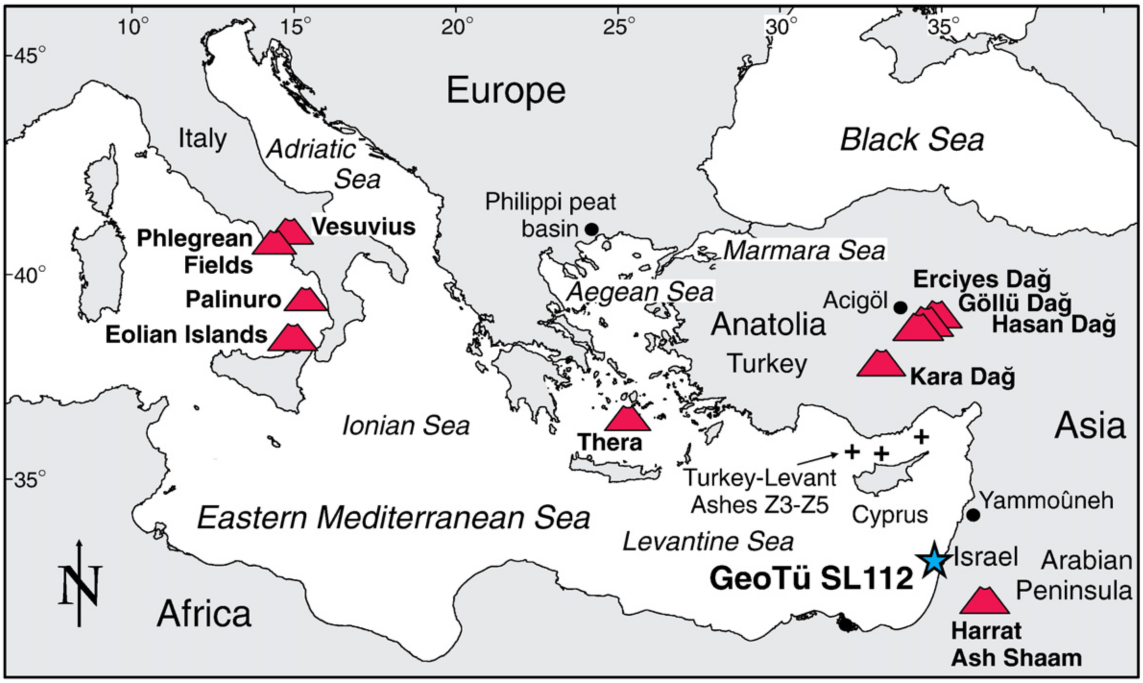

Figure 1. Map of the Eastern Mediterranean and adjacent areas with the location of coring site GeoTü SL112 and late Quaternary volcanic provinces.

tephrochronological investigations of Anatolian tephra were published recently (e.g., Druitt et al., 1995; Deniel et al., 1998; Kuzucuoğlu et al., 1998). The Arabian volcanic province is attributed to an extensive intraplate volcanism with explosive eruptions active since the Miocene (e.g., Ibrahim et al., 2003; Shaw et al., 2003). These volcanic activities continued into recent times, documented for example by Grainger (1996) from lava fields of western Saudi Arabia.

To identify the source volcano of tephra layers found in sedimentary sequences, well-established methods such as major-element analyses are commonly combined with morphological studies on tephra particles. In this paper, we present evidence for a so far unknown Holocene tephra found in a deep-sea sediment core from the Israeli continental slope in the south-eastern Levantine Sea. The possible origin of this ash will be discussed based on the major-element glass chemistry and fractal geometry of ash particles.

Regional setting

The Mediterranean Sea is an intercontinental sea, connected to the Atlantic Ocean by the shallow Strait of Gibraltar in the west and to the Marmara Sea and the Black Sea in the north by the Strait of Dardanelles and the Bosphorus Strait. The Strait of Sicily, a narrow and shallow trench, separates the Western from the Eastern Mediterranean Sea. The Levantine Sea as part of the Eastern Mediterranean Sea (Fig. 1) is situated between two major climatic regimes. The North Atlantic Oscillation controls the temperate and humid to semi-arid climate of southeastern Europe and Turkey (e.g., Hurrell et al., 2003). Semiarid to arid tropical and subtropical climate dominates northern Africa, and the Near East is influenced by the temperate and humid conditions of the north and the arid climate of the south. The general circulation pattern exhibits a counter-clockwise current of the Eastern Mediterranean Surface Water (e.g., Pickard and Emery, 1982; Pinardi and Masetti, 2000).

The Levantine Sea is situated in a suitable wind position to major volcanic provinces in the Eastern Mediterranean: the Italian and the Aegean volcanic province in the northwest, the Central Anatolian volcanoes in the north and the Arabian volcanic province in the south (Fig. 1). Thereby, two tropospheric wind systems are relevant for the distribution of ash fall deposits; the northern part of the Levantine Sea is influenced by northerly Etesian winds (Karalis, 1976; Poulos et al., 2000; Raicich et al., 2003), strong easterly Sharqiya winds develop over the Near East, which also affect the Levant (Saaroni et al., 1998).

Material and methods

Sediments

A sediment gravity core, GeoTü SL112, with a total length of 5.31 m was recovered from the south-eastern Levantine Sea (Eastern Mediterranean Sea) on the Israeli continental slope (32°44.52′N, 34°39.02′E) from 892 m water depth during the RV *Meteor* cruise M51/3 in 2001 (Fig. 1) (Hemleben, 2002). The sediments consist mainly of clay with low amounts of silt and sand. The upper 30 cm of sediment is light red to dark reddish grey in colour. The lower sediment section comprises dark grey and dark reddish brown clays with rare fragments of macroscopically visible biogenous and lithogenous components (Fig. 2). The clay-sized sediment fraction is dominated by smectite (45–77%) and low concentrations of illite (4–21%), kaolinite (12–26%) and chlorite (5–13%) (Hamann et al., 2009). Apart from a weakly laminated section at 220–275 cm, the sediments are in general moderately bioturbated with traces of pteropods and foraminifers. The laminated sequence is dark reddish brown and represents the sapropel layer S1. The laminated sequence is dark reddish brown and represents the sapropel layer S1, supported by paleontological and geochemical data. Thereby, the absence of benthic species *Uvigerina mediterranea* and *Planulina ariminensis* across S1 compared to pre-and post intervals document dysoxic conditions during time of formation (Kuhnt et al., 2008). Further, the high concentration of total organic carbon suggests elevated primary conditions and/or enhanced preservations of organic matter (Hamann, 2008).

At 260 cm depth within sapropel S1, a distal tephra (S1 tephra) occurs, which was already mentioned in Hamann (2008) and Hamann et al. (2008, 2009). This tephra is visible as an approximately 1 mm thick, discrete, light grey layer with a sharp base and top (Fig. 2). It consists of silt to sand-sized tephra components with maximum grain sizes of 125 μm.

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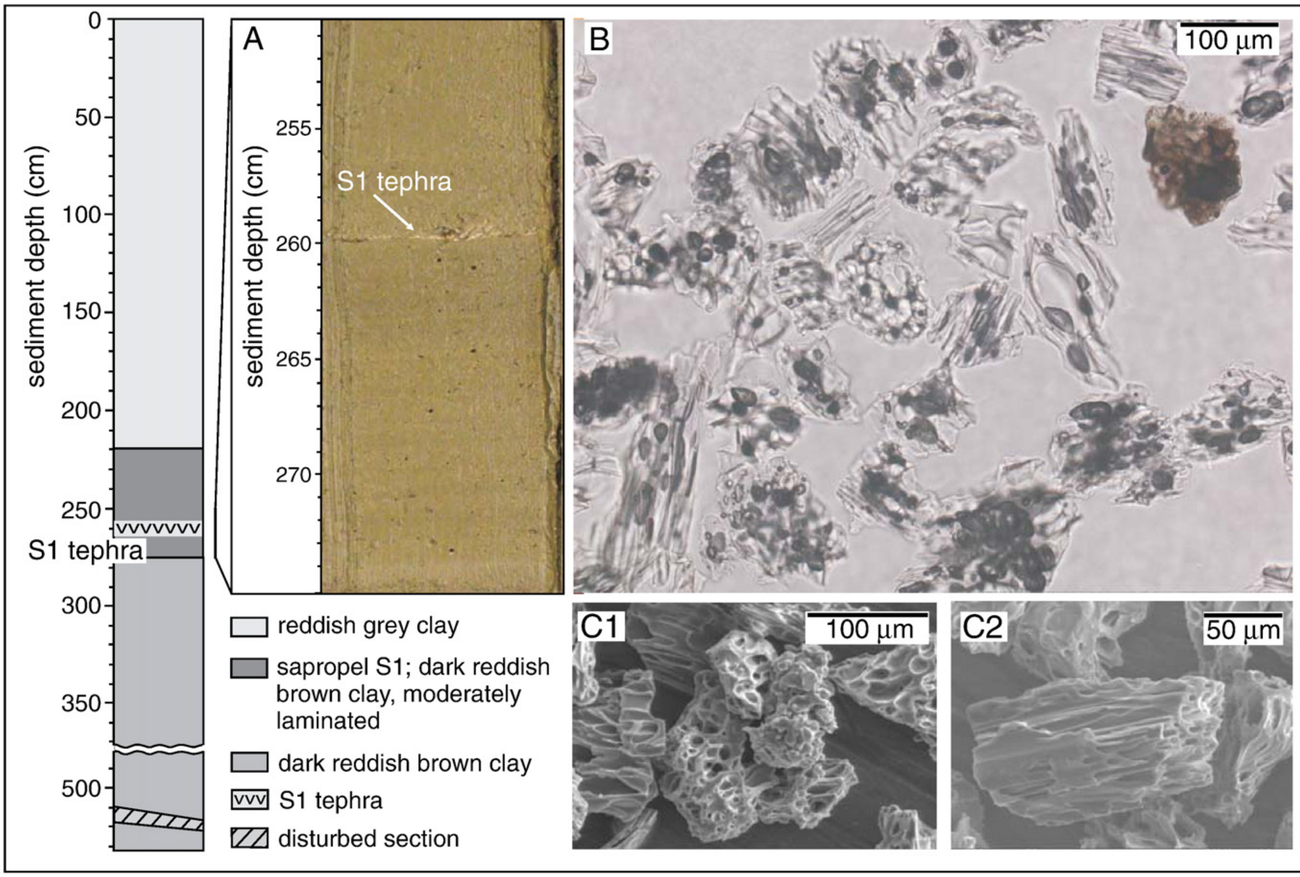

Figure 2. Lithological profile of sediment core GeoTü SL112 with position of S1 tephra. Depth in cm below sediment surface is given on the left side. (A) Core photography with S1 tephra. (B) Microscopic photo of S1 tephra showing volcanic glass shards. (C1, C2) SEM images of pumice fragments.

Samples from three dome eruptions (Dikkartın, Karagüllü and Perikartın) of Erciyes Dağ were chosen for comparison with the S1 tephra as they have similar compositions and ages to S1 tephra. The three rhyodacitic domes mentioned in this paper are exposed on the southern and the northern flanks of the volcano. The eruption of Dikkartın commenced as purely magmatic and continued as phreatomagmatic with interlayered phreatoplinian fall and surge deposits with different bed forms related to the amount of water that interacted with the vesiculating magma (Şen et al., 2002; Ersoy, 2007). These eruption phases were followed by a sub-Plinian eruption and passive lava extrusion. The phreatomagmatism created an explosion crater surrounded by a tuff ring rampart, and final extrusions filled the explosion crater with a lava dome. The extruded lava flowed down about 5 km toward the south covering an area of 11.7 km^2 and corresponds to 0.82 km^3 of erupted magma. Here, the volcanic ash particles from the thickest (15 m on the outcrop 6 km from the source), most widespread (at least 800 km^2) and the purely magmatic air-fall deposit of Dikkartın were used for microprobe and morphology analysis.

Tephra geochemical analyses

The tephra, hereafter named as S1 tephra, has been sampled and treated with 10% hydrogen peroxide to remove organic matter and 10% hydrochloric acid to dissolve carbonate. The residual sample was freeze-dried and sieved over a 63-μm mesh to separate the sand fraction. The fraction>63 μm, which consists almost exclusively of glass shards, was used for microprobe and morphology analysis. The shards were embedded in epoxy resin, polished with aluminium oxide abrasives, and carbon coated prior to electron probe micro analysis (EPMA). The major-element composition of glass shards from the S1 tephra and Erciyes Dağ dome eruptions (Dikkartın, Karagüllü and Perikartın) was determined using a JEOL JXA-8200 electron microprobe at ETH Zurich (Table 1). A 5-nA amperage with a voltage offset of 15 kV, a beam size of 5 μm and a peak counting time of 10 s were used. Glass compositions were calibrated with an internal standard. The totals of oxides were normalized to 100 wt. % in order to allow comparison with published geochemical data. The TAS diagram in Figure 3 was visualized with the software PetroGraph of Petrelli et al. (2005). The EPMA data of the S1 tephra and the radiocarbon ages for core GeoTü S112 can be retrieved from the Pangaea data base of the Alfred Wegener Institute at Bremerhaven, Germany (www.pangaea.de; doi:10.1594/PANGAEA.713713, 10.1594/PANGAEA.730369).

Morphological characterization of tephra particles

Volcanic ash components often have morphological key features which allow the characterization of fragmentation and transportation processes associated with the volcanic eruptions. However, highly complex morphologies of pyroclastic particles may complicate a quantitative characterization. This is why the analysis of volcanic clast shape remains largely qualitative (Marshall, 1987) and subjective (Sheridan and Marshall, 1983). Some shape parameters such as circularity, compactness, elongation, rectangularity (Dellino and La Volpe, 1996) have been measured on the volcanic ash particles. Simple adimensional shape parameters allowed a good discrimination between ash clasts related to different eruption processes (magmatic and phreatomagmatic) in some cases, such as the Monte-Plato-Rocche Rosse eruptions on the Eolian Islands, Italy (Dellino and La Volpe, 1996), and the Reykjanes volcanic system in Iceland (Eiriksson et al.,

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Table 1
Mean values and 1σ standard deviation of major element chemistry (wt. %) obtained by microprobe analyses on single glass shards from the S1 tephra of core GeoTü SL112 and samples from Erciyes Dağ eruptions Dikkartın, Karagüllü and Perikartın.

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cl	Total
S1 tephra											
1	70.04	0.14	11.63	0.89	0.07	0.30	1.37	2.91	3.29	0.14	90.78
2	71.56	0.14	11.95	1.02	0.07	0.28	1.34	2.73	3.52	0.10	92.71
3	72.14	0.19	12.42	1.09	0.02	0.31	1.31	1.55	3.25	0.11	92.39
4	70.01	0.17	12.07	1.03	0.07	0.30	1.35	3.23	3.08	0.13	91.44
5	69.80	0.21	11.57	1.24	0.07	0.30	1.36	3.01	3.27	0.11	90.94
6	72.39	0.21	12.04	1.14	0.08	0.25	1.25	2.39	3.39	0.12	93.27
7	9.25	0.13	12.06	1.10	0.10	0.27	1.32	2.99	3.21	0.10	90.53
8	71.19	0.17	12.42	1.30	0.00	0.25	1.39	3.00	3.22	0.09	93.03
9	71.48	0.19	12.78	1.10	0.04	0.27	1.58	1.89	3.25	0.19	92.77
10	71.20	0.15	12.32	1.04	0.00	0.25	1.24	3.26	2.86	0.16	92.48
11	70.88	0.19	11.62	1.09	0.08	0.21	1.35	2.87	3.26	0.13	91.68
Mean	70.90	0.17	12.08	1.09	0.06	0.27	1.35	2.71	3.24	0.13	92.00
σ	1.008	0.027	0.384	0.111	0.034	0.032	0.090	0.523	0.166	0.029	
Erciyes Dağ, Dikkartın eruption											
1	73.84	0.11	12.99	1.31	0.00	0.27	1.50	3.44	3.25	0.14	96.85
2	72.17	0.19	12.53	1.41	0.02	0.28	1.41	3.38	3.22	0.13	94.74
3	72.74	0.23	12.12	1.27	0.13	0.27	1.37	3.22	3.36	0.14	94.85
4	72.90	0.22	12.47	1.19	0.02	0.23	1.38	3.70	3.18	0.16	95.45
5	72.66	0.28	12.29	1.23	0.05	0.29	1.29	3.45	3.30	0.17	95.01
6	73.05	0.13	12.73	1.22	0.07	0.18	1.38	3.72	3.23	0.16	95.85
7	73.25	0.15	12.62	1.09	0.10	0.29	1.45	3.74	3.49	0.13	96.32
8	73.11	0.14	12.74	1.26	0.02	0.25	1.43	3.72	3.41	0.09	96.18
9	71.94	0.21	12.31	1.25	0.10	0.28	1.45	3.50	3.32	0.14	94.50
10	73.63	0.18	12.88	1.23	0.05	0.23	1.43	3.76	3.21	0.13	96.72
11	72.37	0.19	12.32	1.19	0.05	0.24	1.45	3.69	3.16	0.13	94.78
12	73.26	0.21	12.69	1.31	0.00	0.26	1.43	3.34	3.49	0.12	96.11
Mean	72.91	0.19	12.56	1.25	0.05	0.26	1.41	3.56	3.30	0.14	95.61
σ	0.568	0.048	0.264	0.079	0.042	0.033	0.053	0.187	0.114	0.020	
Erciyes Dağ, Karagüllü eruption											
1	74.52	0.12	11.14	0.71	0.09	0.07	0.76	2.90	3.97	0.13	94.42
2	74.08	0.11	11.77	0.94	0.10	0.17	1.02	3.24	3.75	0.10	95.28
3	74.34	0.08	11.76	0.81	0.02	0.13	0.97	3.14	3.71	0.10	95.05
4	73.98	0.04	11.82	0.80	0.04	0.15	1.05	3.04	3.38	0.08	94.38
5	74.09	0.11	11.78	0.87	0.04	0.19	0.99	3.26	3.52	0.12	94.97
6	73.92	0.11	11.70	0.89	0.07	0.14	1.11	3.41	3.53	0.16	95.04
7	73.93	0.13	11.74	0.88	0.13	0.17	0.99	3.08	3.27	0.10	94.42
8	73.52	0.15	11.83	0.90	0.01	0.15	1.06	3.28	3.70	0.10	94.69
9	73.67	0.08	11.49	0.83	0.00	0.16	1.05	2.96	3.78	0.12	94.14
10	73.75	0.19	11.67	0.85	0.07	0.16	0.99	3.07	3.73	0.11	94.60
11	73.95	0.05	11.65	0.89	0.05	0.20	0.89	3.10	3.71	0.09	94.57
12	74.52	0.09	10.91	0.82	0.09	0.18	0.82	3.05	3.83	0.12	94.44
Mean	74.02	0.11	11.61	0.85	0.06	0.16	0.97	3.13	3.66	0.11	94.67
σ	0.313	0.041	0.290	0.060	0.041	0.034	0.102	0.146	0.197	0.022	
Erciyes Dağ, Perikartın eruption											
1	73.48	0.15	11.44	0.78	0.04	0.21	1.04	3.24	3.51	0.08	93.96
2	72.26	0.15	11.04	0.68	0.00	0.13	0.99	2.80	3.35	0.08	91.48
3	72.76	0.10	11.47	0.87	0.10	0.11	1.04	3.23	3.23	0.14	93.06
4	72.73	0.16	11.41	0.92	0.00	0.21	1.06	3.27	3.36	0.13	93.24
5	72.28	0.14	11.57	0.90	0.02	0.17	1.19	3.32	3.52	0.11	93.22
6	71.90	0.09	11.28	0.86	0.04	0.20	1.12	3.08	3.58	0.16	92.31
7	72.40	0.04	11.69	0.80	0.04	0.11	1.05	3.31	3.48	0.10	93.03
9	71.94	0.12	11.19	0.76	0.03	0.17	0.89	3.04	3.36	0.13	91.61
10	72.64	0.09	11.38	0.75	0.07	0.17	0.96	3.21	3.43	0.12	92.82
11	72.66	0.15	11.51	0.82	0.02	0.20	1.02	3.21	3.60	0.07	93.25
12	73.36	0.04	11.58	0.89	0.05	0.10	0.90	3.06	3.56	0.16	93.71
Mean	72.58	0.11	11.41	0.82	0.04	0.16	1.02	3.16	3.45	0.12	92.88
σ	0.508	0.043	0.187	0.074	0.029	0.042	0.088	0.154	0.117	0.032	

n: number of samples.

1996). Fractal geometry is another popular technique with the potential to quantify fragmentation and transport mechanisms of pyroclastic particles and is believed to be more effective than classical particle shape analysis (Maria and Carey, 2007). The compatibility with the morphological complexity makes techniques based on fractal analysis good prospects for characterizing volcanic particle shapes (Maria and Carey, 2002).

Polished blocks prepared for EPMA were also used for morphological analysis using a SEM; therefore a Zeiss EVO 50 XVP SEM at Hacettepe University was used for image acquisition. The block samples were coated with carbon to counteract grain surface charging while scanning with the electron beam. On average, 70 particle micrographs (secondary electron images) were taken from each sample. The micrographs were converted to binary images and the outlines of ash particle sections were used for fractal dimension measurements. Image processing and analysis of the images were performed using the ImageJ program (Rasband, 2009) and Fraclac plugin.

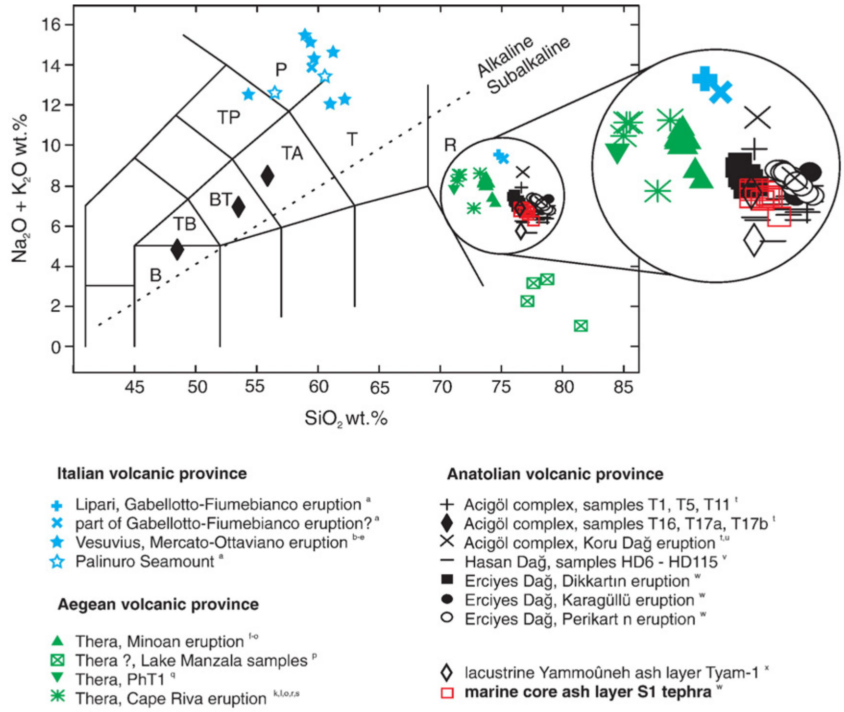

Figure 3. Total alkali-silica diagram (TAS, Le Bas et al., 1986) for chemical discrimination of S1 tephra and classical Late Quaternary ash fall deposits in the Eastern Mediterranean. Element chemistry data on single glass shards or glass concentrates using mainly EMP and minor SEM-EDS, ICP-AES, XRF techniques were taken from (a) Siani et al., 2004; (b) Wulf et al., 2004; (c) Davies et al., 2002; (d) Paterne et al., 1988; (e) Jahns and van den Bogaard, 1998; (f) Pearce et al., 2002; (g) Eastwood et al., 1999; (h) Sullivan, 1990; (i) Sullivan, 1988; (j) Watkins et al., 1978; (k) Federman and Carey, 1980; (l) Vinci, 1985; (m) Guichard et al., 1993; (n) Keller, 1980; (o) Druitt et al., 1999; (p) Stanley and Sheng, 1986; (q) Seymore et al., 2004; (r) Wulf et al., 2002; (s) Hardiman, 1999; (t) Kuzucuoğlu et al., 1998; (u) Druitt et al., 1995; (v) Pastre et al., 1998; (w) this study; (x) Develle et al., 2009; P: phonolite; TP: tephriphonolite; T: trachyte; TA: trachyandesite; BT: basaltic trachyandesite; TB: trachybasalt; B: basalt; R: rhyolite.

Tephra description

Composition of S1 tephra

The S1 tephra can be classified as a vitric ash that consists of abundant high-vesicular pumice fragments and rare plagioclase, orthopyroxene, greenish clinopyroxene and amphibole phenocrystals (Fig. 2). The chemical composition of the glass shards is homogenous rhyolitic as defined in the total alkali versus silica classification after Le Bas et al. (1986) (Fig. 3; Table 1). The normalized silica concentrations of the glass shards are high and range between 76.6 and 78.3 wt.%, with a mean of 77.2 wt.%. Sodium and potassium concentrations vary between 2.68–3.21 wt.% and 3.29–3.65 wt.%, respectively. Calcium and iron values are low and range between 0.95–1.46 wt.% and 0.92–1.41 wt.%, respectively.

Age of S1 tephra

S1 tephra was deposited during the time of formation of sapropel S1 in the Mediterranean Sea. These organic-rich sediments were dated in core SL112 between 9600 and 6500 yr cal BP (Kuhnt et al., 2008). Due to the poorly ventilated bottom water and suboxic to anoxic conditions during this time interval, the sediment was not bioturbated and the S1 tephra was deposited within faintly laminated sediments. The accumulation of glass shards is restricted to a thin layer, which has not been reworked or mixed with the sediment below or above. Hence, the layer reflects the direct deposition by air fall and settling through the water column. Sapropel S1 has been interrupted by the ‘8200 yr cooling event’, global climate event caused by a melt water outflow into the North Atlantic Ocean (e.g., Rohling and Pälike, 2005). This event separates sapropel S1 into an older S1a and a younger S1b layer. In the SL112 sediment core, this interruption of sapropel S1 cannot be seen macroscopically, but has been observed by the presence of benthic foraminifera in the interval between 248 cm and 245 cm sediment depth (Kuhnt et al., 2008). According to the position of the S1 tephra in the S1a layer, an age between 9600 and 8200 cal yr BP can be assigned for the time of tephra deposition.

In addition, a more accurate age for the sediment interval 259–261 cm, which includes the S1 tephra, has been obtained from ^{14}C-accelerator mass spectrometry (AMS) dating of planktonic foraminifera (Hamann et al., 2008). An uncalibrated radiocarbon age of 8,365 ± 65 ^{14}C yr BP (KIA 30176) was obtained which when calibrated to calendar years using the radiocarbon calibration software of Fairbanks et al. (2005) and after correction for an estimated reservoir age of 400 yr (Siani et al., 2001), produces a calibrated age of between 8970 and 8690 cal yr BP with a mean age of 8833 cal yr BP. This calibrated radiocarbon age is consistent with the stratigraphic position of the S1 tephra within sapropel S1a.

Discussion

Potential sources of S1 tephra based on chemical composition

Several volcanic fields with prominent Late Pleistocene and Holocene explosive volcanism are possible sources for the S1 tephra, given their stratigraphic position and geochemical signatures. In this context, the major element compositions of prominent ash fall deposits of explosive eruptions have been compiled in Figure 3 according to the classification of Le Bas et al. (1986).

Italian volcanic province

Siani et al. (2004) described an ash layer in marine sediments of the Adriatic Sea within sapropel S1. This tephra layer of rhyolitic composition is dated between 7610 and 7450 ^{14}C yr BP (Siani et al., 2004) and probably belongs to E-1 tephra that has been correlated to the Gabellotto-Fiumebianco eruption of Lipari (Eolian Islands; 7840–7700 ^{14}C yr BP) because of their similar composition and stratigraphical position (Paterne et al., 1988; Fontugne et al., 1989; Siani et al., 2004). These deposits are widely dispersed in the Tyrrhenian and southern Adriatic Seas. The V-1 tephra has been associated with the Mercato-Ottaviano eruption of Vesuvius (Paterne et al., 1988). The predominantly phonolitic tephra has been dated between 8045 and 7975 cal yr BP (Rolandi et al., 1993; Andronico et al., 1995; Aulinas et al., 2004). Furthermore, Siani et al. (2004) documented in Adriatic marine sediments the tephra layer 'Pal', which is tentatively correlated with an eruption of the Palinuro Seamount based on their trachyphonolitic to phonolitic composition. The eruption is dated between 10,080 and 9900 ^{14}C yr BP.

In summary, the Italian volcanic province produced a couple of late Quaternary tephra layers that have a similar age as the S1 tephra. With exception of the Gabellotto-Fiumebianco eruption of Lipari Island those tephras do not match the geochemical composition of the S1 tephra. Fallout products of the Gabellotto-Fiumebianco eruption, however, show lower silica concentrations and higher alkali contents. They are, furthermore, dispersed towards the NE and E and are restricted to the central part of the Mediterranean (e.g., Siani et al., 2004). We therefore exclude a correlation of the Lipari as well as any other Holocene tephras from the Italian province with the S1 tephra.

Aegean volcanic province

The explosive volcanism from the Hellenic Arc has produced a large number of ash fall deposits. The Minoan Ash, termed as Z-2 and first reported by Keller and Ninkovich (1972) and McCoy (1974), has been attributed to the explosive eruption of Thera (Santorini) between 3590 and 3550 cal yr BP (Betancourt and Michael, 1987). Several publications show its widespread distribution in terrestrial and marine sedimentary archives in Europe, Northern Africa and Asia (e.g., Ninkovich and Heezen, 1965; Federman and Carey, 1980; Narcisi and Vezzoli, 1999; Pearce et al., 2002). Volcanic shards of this eruption are reported even from the Nile delta (Stanley and Sheng, 1986). Another rhyolitic tephra layer termed as PhT1 has been identified in the Philippi peat basin in Greece (Fig. 1) with a radiocarbon age of 13,000 cal yr BP by Seymour et al. (2004). They suggested an origin from Thera (Santorini) based on the subalkaline character of the glass shards and the similar chemical composition to the Minoan and Cape Riva eruption (Fig. 3). The prominent rhyolitic tephra Y-2 is characterized by a wide dispersion and has been found in the Aegean, the Marmara (Wulf et al., 2002), and the Levantine Seas (Clift and Blusztajn, 1999). Terrestrial archives from Turkey (Eastwood et al., 1998, 1999) and the Philippi peat (Seymour et al., 2004) contain this tephra, which has been linked to the Cape Riva eruption of Santorini at 21,950 cal yr BP (Wulf et al., 2002).

In general, several studies of the Thera eruptions (Santorini) indicate a prevalent rhyolitic character, similar to the composition of S1 tephra, but with lower silica contents. In addition, the S1 tephra has a distinctly different age which excludes the Aegean volcanic province as a possible source.

Arabian volcanic province

The proximity of the core position to the eastern mainland and prevailing easterly winds also suggest a volcanic origin from the east of the coring locations for S1 tephra. Potential sources discussed here are the volcanic fields on the Arabian Peninsula (Fig. 1).

The massive alkaline Harrat Ash Shaam volcanic field extends from southern Syria through northwestern Jordan to Saudi Arabia. It comprises numerous provinces, which were active during the Holocene, i.e., the basaltic cinder cones of the Golan Heights near Lake Kinneret in Israel, the 'Es Safa' basaltic lava fields and the alkaline volcanic field of 'Jabal ad Druze' in its northern part of Harrat Ash Shaam (Brown et al., 1984). Large alkali basaltic volcanic fields of Miocene to Holocene age extend from the southern part of Harrat Ash Ahaam along the western part of the Arabian Peninsula (Brown et al., 1984). The only basaltic stratovolcano in the Harrats of the western part of the Arabian Peninsula, Jabal Qidr, was active until historical times (e.g., Camp et al., 1991). The Pleistocene-Holocene Al Wahbah Maar on the southwestern Arabian Peninsula produced several phreatric explosions and basaltic lava flows (Grainger, 1996). The pyroclastic deposits of these volcanic centres are poorly studied. Stratovolcanoes in the northwestern and southeastern part of Iran (i.e., Sahand, Sabalan, Damavand, Bazman, and Taftan volcanoes) are located at more than 1500 km distance and east of coring site GeoTü SL112. These volcanic centres were active during the Holocene (e.g., Karakhanian et al., 2002), but reveal a distinct basaltic, andesitic to trachyandesitic composition of erupted products (e.g., Innocenti et al., 1982).

We exclude, however, a correlation of the S1 tephra with any of the volcanic centres in Syria, Saudi Arabia and Iran based on the distinct mafic composition of volcanics and the prevailing northerly winds in the western part of the Arabian Peninsula. Though ash from Syria and Iran might be dispersed to the west into the Levantine Basin, so far no evidence is given for such a deposition in Holocene lake sediment records of the Dead Sea (e.g., Migowski et al., 2006) or Lake Kinneret (e.g., Hazan et al., 2005) in central and northern Israel. Both sites are located closer and in favourable wind position to Syrian and Iranian volcanoes.

Central Anatolian volcanic province

The Central Anatolian volcanic province has been characterized by highly explosive eruptions during the Late Pleistocene and Holocene, and represents the most likely source for the S1 tephra due both to its close proximity and favourable wind direction to coring site SL112 and also to the petrology of the erupted products. Tephras of diverse geochemical compositions were found in lacustrine deposits of the Acıgöl Maar (Fig. 1; Kuzucuoğlu et al., 1998). The colourless glasses (samples T1, T5 and T11) are of rhyolitic composition with high silica content (77–79 wt.% SiO_2). The pyroclastic products, have been dated firstly roughly to >14,000 ^{14}C yr BP and 11,000 ^{14}C yr BP, respectively; in the meantime revises by Roberts et al. (2001) at ~3000 yr to an age of around 9000 ^{14}C yr BP. Younger ash falls (samples T16 and T17a, b) are of alkaline composition, ranging from distinct basaltic to basaltic trachyandesitic and trachyandesitic. These tephra layers have an age between 8600 and 7530 ^{14}C yr BP and are related to a strombolian source, probably the basaltic series of the local Acıgöl complex (Kuzucuoğlu et al., 1998). The Koru Dağ Tuff has been interpreted as a younger product of the Acıgöl complex by Druitt et al. (1995) and detected by Kuzucuoğlu et al. (1998) in lacustrine sequences of Palaeo Lake Konya. This tephra is characterized by brown aphyric obsidian

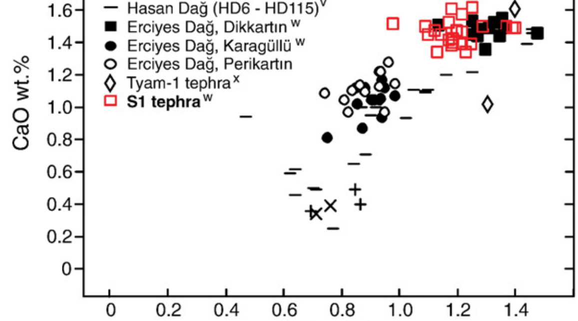

Figure 4. Harker diagram FeO versus CaO (wt.%) for discriminating ash deposits from the Anatolian volcanic province and the S1 tephra. Data sources, see figure caption Fig. 3.

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glass high-silica (78 wt. %) rhyolitic in composition. The eruption of Koru Dağ, however, has been dated at approximately 20,000 cal yr BP (Druitt et al., 1995) and, therefore, can be excluded as tephra equivalent for the S1 tephra. The Hasan Dağ stratovolcano is characterized by calc-alkaline volcanism (Deniel et al., 1998). Pastre et al. (1998) presented tephrostratigraphical investigations on volcanic sequences related to activities during the Late Pleistocene between 35,000 and 28,000 ^{14}C yr BP and during the Holocene. The chemical composition of ash fall deposits is rhyolitic with similar silica and alkali concentrations to the S1 tephra (Fig. 3). Other elements such as FeO and CaO, however, do not match the chemical composition (Fig. 4).

With an elevation of 3917 m and a basal diameter of 55–60 km, Erciyes Dağ is the largest stratovolcano in the Central Anatolia volcanic province. The volcanological evolution of Erciyes Dağ from Pliocene-Quaternary to historical times can be examined in two main parts: Koçdağ and New Erciyes Stages. Koçdağ is mainly composed of lava flows of alkaline basalt, andesite and basaltic andesites. The first explosive activity is the Valibaba ignimbrite eruption, 2.8 Ma (Innocenti et al., 1975), and this eruption was followed by caldera collapse. The new Erciyes stage represents different basaltic andesitic, andesitic, dacitic, rhyodacitic lava generations and associated pyroclastics. The emplacement of the pyroclastics prior to rhyodacitic dome and debris avalanche deposits is the best known and most recent products of the volcano (Kürkçüoglu et al., 1998; Şen et al., 2003). The ages of the pyroclastic deposits related to the emplacements (Dikkartın, Karagüllü, and Perikartın) on the flanks of Erciyes Dağ range between 10,200 and 7900 cal yr BP (Sarikaya et al., 2006) and show a high-silica rhyolitic glass composition, which matches that of the S1 tephra (Fig. 3, Table 1). The detailed geochemical comparison (Fig. 4) and using the similarity coefficient (r) calculation after Borchardt et al. (1972) suggests that the S1 tephra can be most likely allocated to the Dikkartın tephra ($r = 0.92$) rather than to the Karagüllü ($r = 0.79$) and Perikartın ($r = 0.81$) ashes.

Morphological comparison between S1 tephra and Erciyes Dağ samples

In order to manifest the geochemically based correlation of S1 tephra, an analysis of variance (ANOVA) was performed on the fractal dimension values of ash particles to verify their suitability for differentiating among the samples of the S1 tephra and the mid-to early Holocene Erciyes Dağ dome eruptions 'Dikkartın', 'Karagüllü' and 'Perikartın' (Şen, 1997; Şen et al., 2002, Ersoy, 2007). A variable has been accepted when the variance between groups (samples) is significantly larger than the variances within the groups (replicates). Fractal analysis is most suitable for the differentiation of the samples, having *p*-values well below 0.05 with a 95% confidence interval (CI) (Fig. 5).

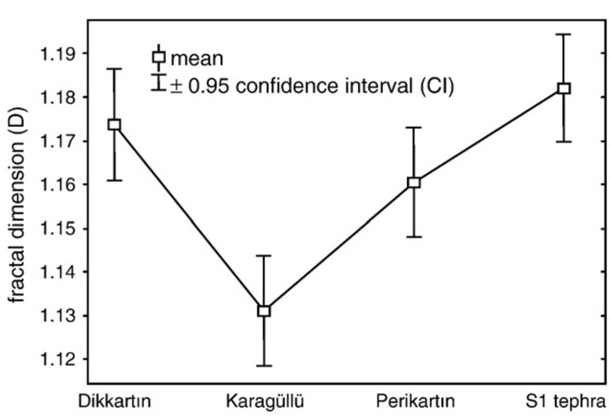

Figure 5. Analysis of variance (ANOVA) of fractal dimension (D). Samples Dikkartın, Karagüllu, Perikartın and S1 tephra are shown. Mean values are given with corresponding 95% confidence interval (CI).

The Karagüllü samples have lower fractal dimension values indicative of volcanic ash particles with smooth outlines and less irregular surfaces, often less vesicular blocky and with equant shapes. The presence of blocky shapes is considered a sufficient condition to refer these glassy particles to hydromagmatic fragmentation processes (Dellino and La Volpe, 1996). Therefore, the Karagüllü dome explosion has more phreatomagmatic components than other explosions.

Perikartın, Dikkartın and S1 tephra samples appear to be derived from drier explosions with higher plinian columns. Ersoy (2007) indicates a wider distribution for the Dikkartın sample among other dome eruption samples and estimates the climactic eruption column as high as 25 km by applying the method of Carey and Sparks (1986). Samples from drier eruptions have higher fractal dimensions indicating ash particles derived directly from a vesiculating magma that has not interacted with meteoric water. Magmatic pyroclastic rocks are formed by magma vesiculation and this process depends on composition, temperature, and volatile content of the magma. These factors control viscosity and surface tension. Shapes of vitric ash particles from magmatic eruptions are mostly dependent on vesicle shapes and densities, which are controlled by the parameters listed above (Heiken and Wohletz, 1985). Petrologic and morphologic characteristics of intermediate and acidic pyroclasts are related to higher viscosities (10^3 to 10^6 poise) and the higher volatile contents of their source magmas. Viscosities of above 10^3 poise do not allow the formation of droplets by surface tension. Pyroclast shapes are dependent upon the geometry of vesicles developed within the highly viscous magmas. Pyroclasts derived from such high viscosity magmas do not have smooth surfaces but exposed broken vesicle walls providing sharp, irregular surfaces.

The analyses of the fractal dimension values of ash particles show a clear correlation between the samples of the S1 tephra and Erciyes Dağ samples. Thereby, the Dikkartın dome eruption is proposed to be the source for S1 tephra in light of the high analogy of both their ash morphology and similar geochemical composition.

Comparison with other marine tephras

McCoy (1974, 1981) mentioned three 'Turkey-Levant Ashes', termed Z-3, Z-4, Z-5 in the Eastern Levantine Sea. These ashes are located in sediment cores north and east of Cyprus (Fig. 1) with an estimated age between 10,000 and 8000 cal yr BP (McCoy, 1981). Unfortunately, no geochemical analyses are reported for these ashes (F.W. McCoy, personal communication 2006). Based on the wide dispersal of pyroclastic material from Erciyes Dağ, the geographic position of the Z-3, Z-4 and Z-5 coring sites in between this volcano and site SL112 as well as the similar temporal framework, we suggest that the 'Turkey-Levant Ashes' may also originate from to the Central Anatolian volcanic province and correlate with one of the mid-to early Holocene Dikkartın, Karagüllü and Perikartın eruptions of Erciyes Dağ. However, further studies of these marine tephras are required to establish a more detailed and robust distribution pattern of Central Anatolian ashes. Develle et al. (2009) identified in sediments from the Yammoûneh palaeo-lake in Lebanon a colourless ash-layer (Tyam-1 tephra) of rhyolithic composition with an age between 9450 and 7750 cal yr BP (Fig. 1). The geochemical fingerprint and the stratigraphic position suggest an Anatolian volcanic province origin and, in particular, a tight correlation with the marine S1 tephra of this studies. As shown in Figures 3 and 4, microprobe data from the marine S1 tephra, the lacustrine Tyam-1 tephra and samples from the Anatolian volcanic province define a narrow cluster. The occurrence of the Tyam-1 tephra on the Near East mainland between the postulated source volcano Erciyes Dağ and the S1 tephra suggest a southerly, south-easterly dispersal of fallout products.

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Conclusions

Geochemical analyses obtained by electron probe microanalyses on volcanic glass shards, the geographical and stratigraphical position suggest that the Central Anatolian volcanic province is the most likely source for the S1 tephra. As shown in Figure 3, the major-element data of tephra deposits which originated from the Acıgöl complex, the volcanic fields of the Hasan and Erciyes Dağları, are consistent with the chemical composition of the S1 tephra. All samples of the Dikkartın, Karagüllü and Perikartın eruptions from Erciyes Dağ plot into a narrow cluster (Fig. 3). Additional ash morphological analyses of ash particles enabled us to isolate the Dikkartın eruption as the possible and highly likely source for the S1 tephra. Both samples, Dikkartın tephra and S1 tephra, show exposed broken vesicle walls with sharp and irregular surfaces, formed directly from a vesiculating magma which can be attributed to a dry volcanic explosion. With an estimated climactic eruption column height of 25 km, the Dikkartın eruption of Erciyes Dağ was more violent than the Karagüllü and Perikartın eruptions (Ersoy, 2007). The Dikkartın dome is situated on the southern flank of Erciyes Dağ. The air-fall deposits mentioned in this paper outcrop in the south, east and northeast of the dome covering an area of at least 800 km^2.

The violent explosive character and the voluminous ash fall deposits must have had a significant impact on the adjacent regions. During the Dikkartın eruption of Erciyes Dağ volcano, several Pre-Pottery Neolithic settlements were located in the proposed distribution area of the S1 tephra (Fig. 1), such as in Central Anatolia (e.g., Çatalhöyük), on Cyprus (e.g., Tenta, Khirokitia), and in the Near East (e.g., 'Ain Ghazal), dated by archaeological artefacts (see compilation by Weninger et al., 2006). Investigations of other archaeological sites have shown that prehistoric cultures significantly benefited from volcanic activities: nutrient-rich ash fall deposits caused long-term improvement of the soil fertilization over wide areas and an associated yield increase in agriculture (e.g., Williams and McBirney, 1979). The access of volcanic products, tephra and obsidian played an important role in the evolution of these early cultures. Tephra was used as an ingredient for manufacturing ceramics (e.g., Arnold, 1985; Ford and Rose, 1995). Obsidian, a recent marker artefact for network exchanges of the ancient civilizations (Shackley, 1998; Carter et al., 2006), might have been a positive effect on the social and economic situation. In contrast, obvious destructive impacts of abrupt explosive volcanic events on the Neolithic cultures of the eastern Mediterranean region may have led to crop failure and famine. Extreme events have been described as potential catalysers for the demise of cultures, similar to the collapse of the Minoan civilisation (e.g., Bruins et al., 2008).

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