

Mediterranean tephra stratigraphy revisited: Results from a long terrestrial sequence on Lesvos Island, Greece

V. Margari ^{a,*}, D.M. Pyle ^{b,1}, C. Bryant ^c, P.L. Gibbard ^a

^a Quaternary Palaeoenvironments Group, Department of Geography, University of Cambridge, Downing Place, CB2 3EN, UK

^b Department of Earth Sciences, University of Cambridge, Downing Street, CB2 3EQ, UK

^c NERC Radiocarbon Laboratory, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride, G75 0QF, UK

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Abstract

A composite 40.2 m sediment sequence from Megali Limni, Lesvos Island, Greece, spanning the interval from 22 to 62 ka BP, contains six Pleistocene tephra layers, which can be identified on the basis of their major and trace elemental compositions. The youngest tephra deposit correlates with the 22 ka Y-2 marker, erupted during the Cape Riva eruption of Santorini. The second tephra originates from the Campanian area in Italy and corresponds to the Campanian Ignimbrite eruption (the 39 ka Y-5 marker). The next two layers are compositionally identical, and originate from Eastern islands of the Hellenic Arc; they could potentially correspond to the Upper and Lower Pumice eruptions of Nisyros or some other previously unidentified eruption from Yali. The fifth stratum corresponds to the Y-6 marker, which erupted during the Green Tuff eruption of the Pantelleria Island. The source of the last tephra layer is either the Yali–Nisyros complex or Central Anatolia; no specific corresponding eruption has yet been found. Long distal tephra sequences within terrestrial settings are rare in the eastern Mediterranean and the Megali Limni record contains the most complete sequence to date. Moreover, its age model, based on independent chronologies such as AMS and conventional radiocarbon dates and high-resolution pollen stratigraphy, provides new ages for these eruptions and places them within the context of the millennial-scale palaeoenvironmental variability of the last glacial period. Finally, the recognition of the Pantelleria tephra in this locality considerably extends the confirmed Northerly and Easterly distribution of this widespread and distinctive unit, while the existence of the Nisyros–Yali tephra on Lesvos refutes the current belief of limited tephra dispersal and small magnitude of these eruptions.

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1. Introduction

Explosive volcanic eruptions may disperse chemically distinctive tephra particles across areas of $>10^4$ – 10^6 km² (Pyle, 1999), providing important time-parallel markers indispensable for the correlation of geographically distant records. The Quaternary period of the eastern Mediterranean has been punctuated by the activity of a plethora of volcanoes. These are mainly

* Corresponding author. Present address: Earth and Biosphere Institute, School of Geography, University of Leeds, LS2 9JT, UK. Tel.: +44 1133433314; fax: +44 1133433308.

E-mail address: V.Margari@leeds.ac.uk (V. Margari).

¹ Present address: Department of Earth Sciences, University of Oxford, Parks Road, Oxford, OX1 3PR, UK.

located in three areas: the Italian Peninsula (Roman and Campanian Provinces, Aeolian Islands, Etna and Pantelleria), the Hellenic Arc (Aegina, Methana, Poros, Milos, Santorini, Nisyros, Kos and Yali) and Central Anatolia (e.g. Hasan Dagi, Mt Erciyes and Acigol) (Fig. 1). Studies of volcanic ash layers in Mediterranean deep-sea sediments were first undertaken as early as the 1950s (Mellis, 1954; Olausson, 1961). Since that time, a detailed tephrostratigraphy has been developed with about thirty tephra markers spanning

the last 200 ka (Keller et al., 1978; Narcisi and Vezzoli, 1999).

We report the results of tephra analysis of six distinct layers as identified in two sediment cores obtained from a terrestrial site on Lesbos Island, Greece. The stratigraphic position of the observed horizons is assessed and suggestions are made towards the timing and scale of their corresponding eruptions. All radiocarbon dates mentioned in the text have been calibrated and are indicated by the cal-prefix.

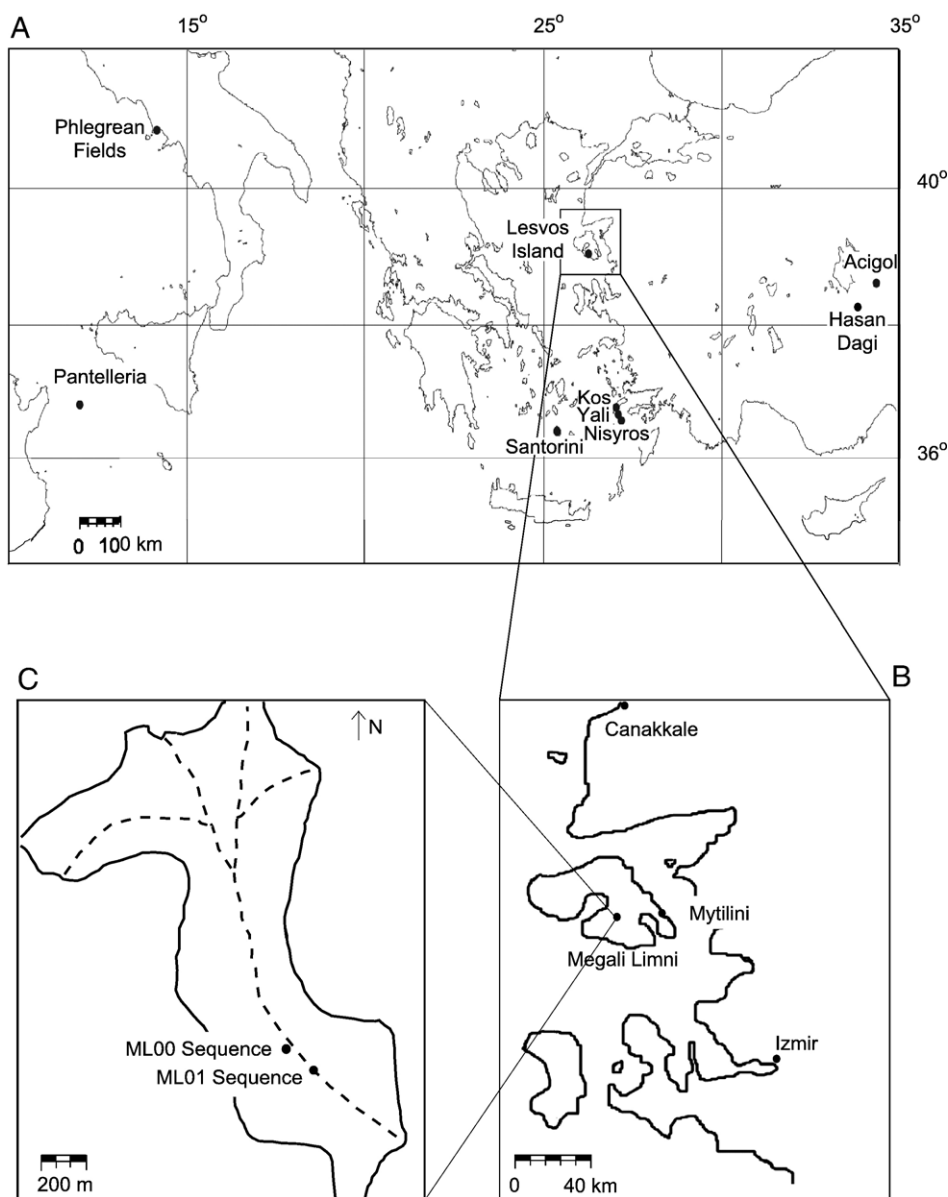


Fig. 1. Maps showing A: the location of the sites mentioned in the text; B: Megali Limni; C: Layout of the basin and the location of the ML00 and ML01 sediment sequences.

Lesvos Island is located in the northeast Aegean Sea, Greece (Fig. 1). The lake basin of Megali Limni occurs at 323 m a.s.l. at the southeastern part of the island. It covers an area of 1.48 km² and its substrate consists exclusively of peridotites. The lake basin is thought to have been initially a river valley, which was blocked at its southern end by a landslide [the four ephemeral streams, at the north of the basin nowadays (Fig. 1), were probably tributaries of the main river, which approximately followed the path of the stream that occupies the centre of the basin today]. Based on a geophysical survey the maximum sediment thickness is 40.2 m towards the southern end of the basin, at the location of the ML01 sequence (Margari, 2004). The lake was artificially drained in 1925 and has since been used for agricultural purposes.

2. Methods

2.1. Core collection

Although four cores were collected from the basin, this paper will focus on the results of the two cores for which radiocarbon dates and pollen data are available. These are: the ML01 (40.2 m long) and ML00 (8.15 m long, from 2 to 10.15 m) sequences (sediment depths are reported from ground surface). The former was obtained using a mechanical corer from the deepest point of the basin (39° 06' 08.9" N, 26° 19' 51.1" E), while the latter was obtained using a Livingstone corer from an adjacent location 145 m away.

2.2. Lithostratigraphy

The main lithostratigraphic units of the two sequences are described using the Troels-Smith (1955) system of sediment classification.

2.3. Major element geochemistry

For the glass shard extraction, 2 g of pure tephra were collected throughout the entire length of each tephra stratum identified. The tephra was sieved through a 63 µm sieve with deionised water and dried naturally overnight. In the cases where the shards did not form pure strata but were rather incorporated into the surrounding sediment, separation was achieved through treatment with hydrogen peroxide (H₂O₂), sodium pyrophosphate (NaP₂O₇) and hydrochloric acid (HCl), followed by the same sieving and drying steps. The collected shards were embedded in epoxy-resin blocks and coated with carbon.

Major element geochemical compositions were determined by Electron Microprobe Analysis (EMPA) technique. Analyses were undertaken using a Cameca SX50 electron microprobe, equipped with a Wavelength Dispersive Spectrometer (WDS), in the Department of Earth Sciences, University of Cambridge. Measuring conditions were 15 kV accelerating voltage, 10.00 nA beam current and 10 µm beam size. In order to obtain maximum recovery and avoid Na⁺ loss, due to diffusion and evaporation effects, peak counting times were 10 s for Na, 20 s for Si, Al and Cl, 40 s for Mg and 30 s for the remaining elements. Standards used were jadeite (Na), diopside (Si, Ca), corundum (Al), orthoclase (K), periclase (Mg), halite (Cl), apatite (P) and Ti, Fe, and Mn metals. Typical precision is 1–2% relative.

2.4. Trace and rare earth element geochemistry

The trace and rare earth element geochemistry of three tephra horizons was determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) on solution bulk samples, at the Department of Earth Sciences, at the University of Cambridge. For the analysis 0.1 g of pure glass shards was used, obtained by sieving with a 63 µm sieve and deionised water approximately 0.5 g of tephra. The cleaned glass separate was left overnight to dry and then was taken into solution using repeated HNO₃/HF acid attack. The resulting solutions were made up to 50 ml in 2% HNO₃. Typical precision is 0.5–5% relative based on repeat analysis of standard reference materials.

2.5. Particle size

The particle size of three tephra layers was analysed using the Malvern Mastersizer-X laser granulometer in the Department of Geography, at the University of Cambridge. Two lenses, 45 and 1000 µm, were used in order to get the full range of particle sizes. For the preparation of the samples, 1 g of tephra was taken in 1 cm intervals. In order to remove any other sediment components samples were treated with hydrogen peroxide (H₂O₂), sodium pyrophosphate (NaP₂O₇) and hydrochloric acid (HCl).

2.6. Radiocarbon dating and calibration

Accelerator Mass Spectrometry (AMS) radiocarbon dating was performed on samples composed either by bulk organic sediment or plant cuticles and macro-fossils, whenever available. The absence of limestone

substrate in the wider area of Megali Limni allowed the analyses of these samples, avoiding hard water error problems. The majority of the AMS dates were produced at the Natural Environment Research Council (NERC) Radiocarbon Laboratory in Scotland, while one date was analysed by Beta Analytic Inc. in Miami. Radiocarbon dates have been converted to calendrical ages using the calibration of Fairbanks et al. (2005), which despite recent criticism by the IntCal Working Group (Reimer et al., 2006), comprises the most updated calibration curve available at present.

3. Results and interpretation

3.1. Core lithostratigraphy

The lithostratigraphy of the ML00 and ML01 sequences is presented in Fig. 2. In total, eight tephra

layers have been identified in both cores. Their nomenclature consists of the combination of the ML-prefix followed by a number, which is based on their sequence of appearance, starting from the sediment surface. In order to facilitate their description, the layers that are present in both sequences and are correlated on the basis of their chemical fingerprint (Section 3.2) have been assigned to the same horizon.

Sediments in the longer ML01 sequence are divided into four units: (1) the lower 10 m where the main component is silt with additional parts of clay and sand, (2) the middle 15 m with primarily clay and limited organic material including some bands of either clay-silt or clay-organic material, (3) the overlying 12.69 m where the organic component of the sediment increases, leading to oscillations between half-clay and half-organic material to mainly organic material with little clay, and (4) the upper 2.51 m where the sediment is

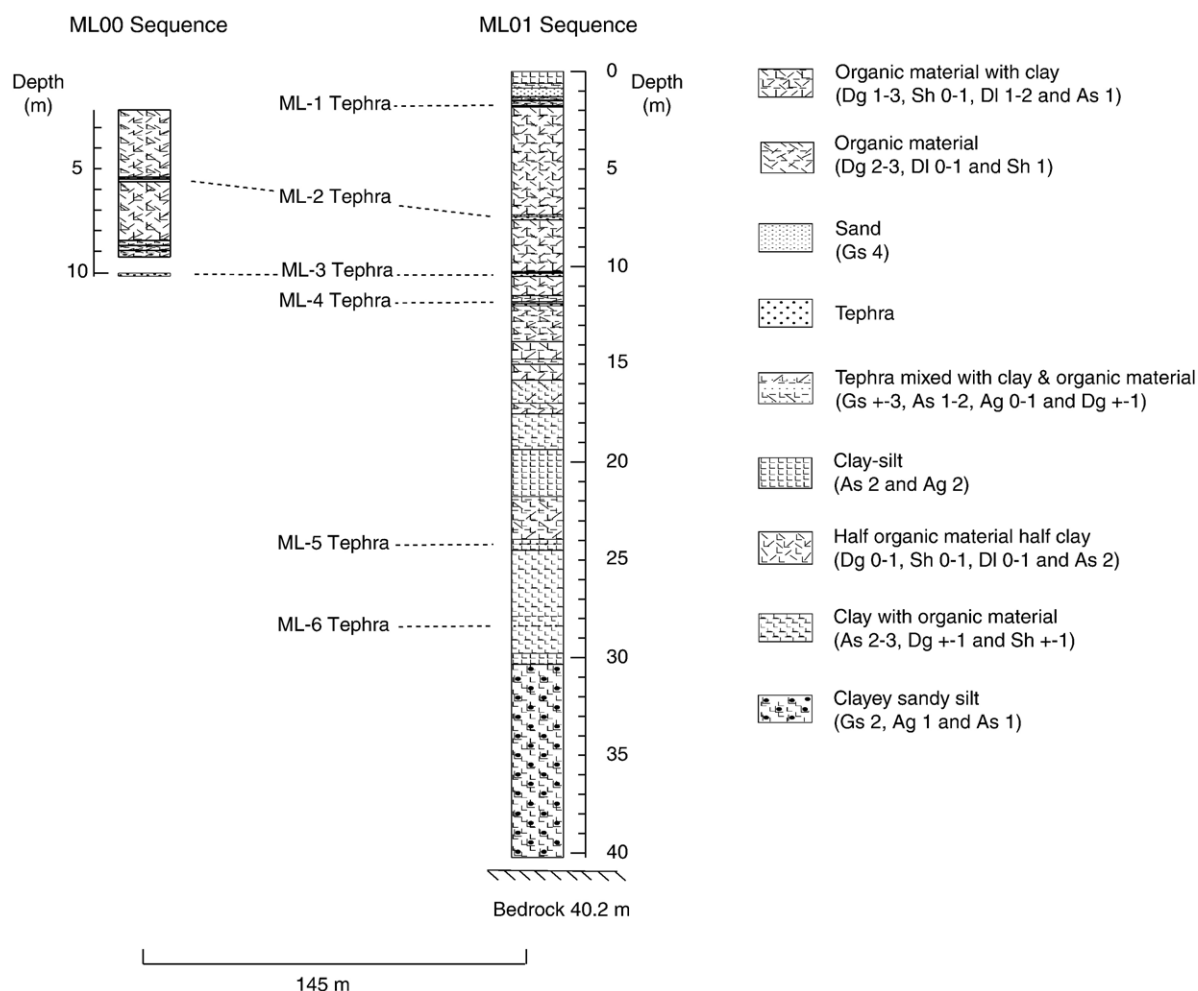


Fig. 2. Lithostratigraphy of the ML00 and ML01 sequences and position of the ML tephra layers.

mainly clayey silt, with an oxidised sandy layer from 1.29 to 0.97 m. Six tephra layers have been identified in the ML01 sequence. Three of them (ML-1 tephra, 1.80–1.82 m; ML-5 tephra from 24.215–24.25 m; ML-6 tephra from 28.41–28.42 m sediment depth) do not form discrete layers, but comprised mixed horizons with sporadic glass shards incorporated into the surrounding sediment. The other three formed pure tephra layers from 7.44 to 7.6 m (ML-2), 10.335 to 10.5 m (ML-3), and 11.89 to 12 m (ML-4). In addition, three layers, ranging in thickness from 44 to 4.5 cm, composed of glass shards and clayey organic material were identified at the depths of 11.89, 10.335 and 7.44 m and are referred to as the ‘reworked’ tephra layers henceforth.

The lithology of the ML00 sequence is characterised by predominantly organic sediments with a varying component of clay, reaching up to half of the total. Two clear tephra layers, ML-2 and ML-3, were identified from 5.5 to 5.63 m and from approximately 10 to 10.15 m (due to coring problems the exact thickness of this stratum is not known), respectively. In addition, two ‘reworked’ tephra layers were found from 5.4 to 5.5 m and from 8.96 to 9.24 m.

With the exception of the base of the clear tephra layers, which are sharply defined, all lithological changes are gradational in character and there is no

evidence of any obvious breaks or erosional surfaces, suggesting that neither the ML01 or ML00 records contain any major hiatuses or non-sequences.

3.2. Major oxide geochemistry

The initial results from the EMPA were obtained as percentage weight (wt.%) of the following oxides: SiO_2 , Al_2O_3 , FeO , CaO , K_2O , Na_2O , MnO , MgO , P_2O_5 and Cl . Volcanic glass may also contain dissolved water, which cannot be determined by EPMA. As a result individual analyses of the major oxides rarely add up to 100%. Total sums of oxides less than 92% were excluded from the analysis along with points corresponding to feldspar and quartz. Values were then normalised 100% total sum on an anhydrous basis, in order to classify tephras [Total Alkali-Silica (TAS) diagram after [Le Bas et al., 1986, Fig. 3](#)] and to facilitate comparison with previous studies (original data points are reported in the Appendix). The total number of glass shards used in the final major oxide determination was: 40 for ML-1, 105 for ML-2, 126 for ML-3, 52 for ML-4, 56 for ML-5 and 38 for ML-6. The results of the mean data including 1 sigma standard deviation for all the ML layers along with potential tephra matches from the literature are presented in [Table 1](#).

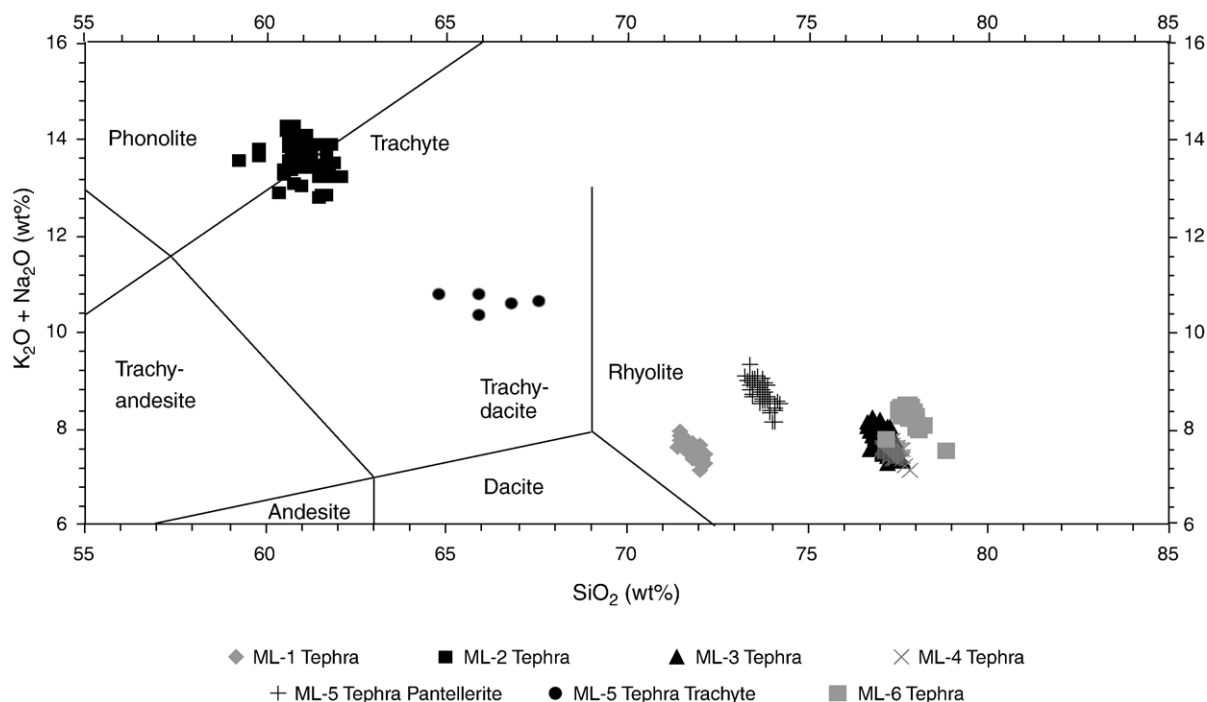


Fig. 3. TAS diagram (Total Alkali vs. SiO_2 weight percentages) after [Le Bas et al. \(1986\)](#) for classification of the ML tephra layers.

3.2.1. ML-1 tephra

The homogeneity of the glass shards in addition to the small standard deviations from the mean values indicates that the source of the ML-1 tephra is a single eruption. Its calcalkaline rhyolite composition suggests an origin from the Aegean Volcanic Arc and especially from Santorini. Of the known marine Santorini tephtras [e.g. Z-2, Y-2, Y-4, X-1, W-2, V-1, V-3 (Keller et al., 1978)], the Y-2 marker is the closest match to ML-1 (Table 1). Although the V-3 marker is the second closest match to the ML-1 tephra, it is rejected because of its stratigraphical position in the marine cores [estimated age at 180 ka BP (Narcisi and Vezzoli, 1999)].

The Y-2 tephra marker correlates with the Cape Riva eruption of Santorini (Druitt, 1985; Druitt et al., 1999), which was a distinctively chemically-zoned eruption of predominantly rhyodacite tephra with subordinate andesite tephra. Based on the recent discovery of the Y-2 tephra in marine cores from the Sea of Marmara (Wulf et al., 2002) as well as in eastern Mediterranean (e.g. Keller et al., 1978; Federman and Carey, 1980; Vinci, 1985; Hardiman, 1999; Seymour et al., 2004), it is suggested that the magnitude of the eruption was similar to that of the Minoan eruption and its fallout products had a northeasterly dispersal, also being confirmed by its presence on Lesvos Island.

The age of the Y-2 tephra has been determined by radiocarbon dating of plant macrofossils from Santorini. Three samples of charred trees, that occur sporadically in the pumice flow deposits forming the lower part of the Akrotiri Ignimbrite series, were dated using conventional radiocarbon methods and gave a range of ages from cal. 21.554 ± 0.484 ka BP to cal. 22.48 ± 0.219 ka BP (Pichler and Friedrich, 1976). Using AMS dating for one charcoal sample from a layer covered by the ignimbrites a date of cal. 21.705 ± 0.311 ka BP was obtained (Eriksen et al., 1990). Based on marine isotope stratigraphy, the age of the Y-2 tephra is estimated at ca. 18.5 ka BP by Keller et al. (1978).

3.2.2. ML-2 tephra layer

ML-2 is a trachyte whose composition suggests an origin from the Campanian area of Italy. It is apparent from Table 1 that all the Campanian tephtras have very similar chemical fingerprints making their distinction problematic (Keller et al., 1978), although the K/Na ratio has proved to be a useful discriminant. Using this ratio, 1.43 for the ML-2 layer, it appears that the closest match is the Y-5 marker with a value of 1.21, while the Y-3 and the Y-7, with 2.17 and 0.94 respectively are excluded as possibilities [these values were calculated using the data from Wulf et al. (2004)].

The Y-5 marker is the most widely dispersed Late Pleistocene tephra in the Mediterranean region. Apart from its recovery from the Eastern and Central Mediterranean deep-sea sediments, evidence of this tephra has been found on the mainland of Central Italy and in Eastern Europe as far as south-western Russia, as well as Greece (e.g. Narcisi, 1996; Seymour et al., 2004; Pyle et al., 2006). The Y-5 tephra shows a bimodal composition (Vezzoli, 1991; Civetta et al., 1997; Pappalardo et al., 2002) at source, but the full range of erupted tephra compositions is not always found at any single location, since different components were ejected during different eruptive phases (Pyle et al., 2006).

The Y-5 tephra is currently correlated with the Campanian Ignimbrite eruption of the Phlegrean Fields. Probably as a result of the inadequacies of early geochemical studies, it has only recently been shown that the Y-5 tephra is composed by a continuum of melts ranging from trachyte to phonotrachyte (Vezzoli, 1991; Civetta et al., 1997; Signorelli et al., 2001; Pappalardo et al., 2002). During the co-Ignimbrite phase of the eruption, the earlier extruded magma was chemically evolved with 1.0 to 1.9 wt.% CaO and 0.9 wt.% Cl, while the later magma was less evolved and had 1.5 to 3.1 wt.% CaO and 0.3–0.4 wt.% Cl (Signorelli et al., 2001; Pappalardo et al., 2002). These compositions are also observed in the present analysis, where two clusters of 1.9 wt.% CaO/0.85 wt.% Cl and 2.6 wt.% CaO/0.37 wt.% Cl can be identified (Fig. 4) within the ML-2 glass shards, reinforcing the correlation with the Y-5 marker.

The most accurate age of the Campanian Ignimbrite eruption of 39.3 ± 0.1 ka BP is based on single crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating of *in situ* deposits (De Vivo et al., 2001). Additional $^{40}\text{Ar}/^{39}\text{Ar}$ dates of sanidine crystals are available both from proximal sources, e.g. the Campanian Ignimbrite deposit (37.1 ± 0.4 ka BP) (Deino et al., 1994), and distal sedimentary sequences, e.g. the Tyrrhenian Sea of 41.2 ± 2.1 ka BP (Ton-That et al., 2001) and Lago di Monticchio (37.1 ± 0.3 ka BP) (Wulf et al., 2004).

3.2.3. ML-3 and ML-4 tephra layers

These tephra layers are of essentially identical chemical composition and therefore the results are discussed together. The glass shards of each layer form a homogenous group characterised by small standard deviation from the mean value, suggesting that they originated from the same volcano or even the same volcanic event. Their rhyolitic composition suggests an origin from the Aegean Volcanic Arc. The low Al_2O_3 (<13.0 wt.%) and the generally similar Na_2O and K_2O content are characteristics of rhyolitic tephra from

Table 1
Major oxide content (wt.%) on an anhydrous base of the ML tephra layers and their possible matches from the literature

	Analysis	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cl	Total
ML-1 (standard deviation)	EPMA	71.80 (0.22)	0.51 (0.01)	14.22 (0.09)	3.16 (0.12)	0.13 (0.02)	0.44 (0.01)	1.81 (0.05)	4.56 (0.17)	3.00 (0.06)	0.08 (0.01)	0.27 (0.01)	99.98
Santorini Minoan Z-2 ^a	EPMA	73.62	0.28	14.04	1.99	0.06	0.27	1.4	4.78	3.27	–	–	98.19
Santorini Y-2 ^b	EPMA	72.29	0.46	14.43	3.06	0.11	0.43	1.76	3.99	2.88	–	–	100.00
Santorini Y-4 ^c	EPMA	69.76	0.65	14.79	3.95	0.13	0.64	2.18	4.9	3.01	–	–	100.01
Santorini V-3 ^c	EPMA	69.84	0.45	15.2	3.51	0.09	0.5	1.8	5.28	3.33	–	–	100.00
ML-2 (standard deviation)	EPMA	61.01 (0.42)	0.48 (0.04)	18.18 (0.19)	3.02 (0.21)	0.21 (0.06)	0.44 (0.15)	2.12 (0.32)	5.64 (1.21)	8.05 (1.02)	0.07 (0.04)	0.71 (0.20)	99.94
Campanian Y-3 ^d	XRF	59.20	0.41	17.49	3.41	0.10	0.88	2.56	3.93	7.10	–	–	99.65
Campanian Y-3 ^e	EPMA	62.29	0.38	18.39	3.27	0.13	0.61	2.19	3.85	8.37	0.12	0.52	100.00
Campanian Y-5 ^d	XRF	59.39	0.41	18.23	3.46	0.16	0.57	1.90	5.35	7.00	–	–	99.28
Campanian Y-5 ^e	EPMA	61.44	0.42	18.68	3.05	0.23	0.35	1.70	6.39	7.73	–	–	99.99
Campanian Y-5 ^e	EPMA	61.85	0.42	19.16	2.94	0.24	0.35	1.74	5.67	6.85	0.05	0.78	100.00
Campanian Y-7 ^d	XRF	59.82	0.53	18.11	2.93	0.19	0.42	1.11	6.70	6.00	–	–	99.49
Campanian Y-7 ^e	EPMA	62.40	0.57	19.00	2.76	0.24	0.38	1.21	6.64	6.24	0.06	0.64	100.00
ML-3 (standard deviation)	EPMA	77.09 (0.20)	0.12 (0.10)	12.18 (0.09)	1.28 (0.07)	0.15 (0.10)	0.17 (0.01)	0.98 (0.03)	3.42 (0.26)	4.31 (0.09)	0.02 (0.01)	0.26 (0.01)	99.98
ML-4 (standard deviation)	EPMA	77.39 (0.16)	0.23 (0.01)	12.14 (0.1)	1.26 (0.09)	0.04 (0.02)	0.17 (0.01)	0.97 (0.02)	3.18 (0.09)	4.30 (0.06)	0.02 (0.01)	0.27 (0.01)	99.98
Nisyros Upper Pumice ^f	EPMA	75.75	0.20	12.68	1.35	0.03	0.02	1.06	3.72	4.09	–	–	98.90
Nisyros Lower Pumice ^f	EPMA	75.50	0.20	13.16	1.49	0.10	0.12	0.93	4.40	4.08	–	–	99.98
Nisyros Panaghia Kyra ^f	EPMA	64.94	0.78	16.66	3.47	–	1.02	0.42	6.12	2.60	–	–	96.01
Nisyros Upper Pumice ^g	XRF	72.79	0.30	14.07	2.29	0.50	0.82	2.15	4.08	3.38	–	–	100.00
Nisyros Lower Pumice ^g	XRF	73.24	0.33	13.99	2.32	0.07	0.62	1.59	4.17	3.61	–	–	99.47
Nisyros Ash ^h	EPMA	77.18	0.19	12.30	1.13	0.10	0.14	0.85	3.45	4.66	–	–	100.00
Nisyros A ⁱ	EPMA	78.34	0.20	13.69	1.48	–	0.17	0.91	1.73	3.50	–	–	100.00
Nisyros G ⁱ	EPMA	79.06	0.21	12.61	1.09	–	0.14	0.95	2.01	3.93	–	–	100.00
Yali-C ⁱ	EPMA	79.74	0.12	12.69	0.68	–	0.05	0.64	2.03	4.05	–	–	100.00
Yali-C ^c	EPMA	73.62	0.33	13.94	1.89	0.06	0.47	1.95	3.88	3.88	–	–	100.00
Yali-1 ^f	EPMA	76.37	0.20	12.60	1.16	0.07	0.12	0.95	3.91	4.40	–	–	99.78

Yali Pumice Breccia ^j	XRF	76.78	0.11	12.46	1.09	0.04	0.23	0.85	3.81	4.59	0.02	–	99.98
Kos Plateau Tuff ⁱ	EPMA	77.45	0.05	12.64	0.44	–	0.03	0.58	4.43	4.43	–	–	100.00
ML-5 Pantellerite	EPMA	73.73	0.43	8.31	7.14	0.32	0.08	0.31	4.30	4.44	0.01	0.84	99.93
(standard deviation)		(0.24)	(0.01)	(0.10)	(0.16)	(0.02)	(0.01)	(0.01)	(0.25)	(0.09)	(0.01)	(0.03)	
ML-5 Trachyte	EPMA	66.23	0.75	14.32	6.06	0.30	0.27	1.16	5.59	4.99	0.10	0.17	99.93
(standard deviation)		(1.04)	(0.06)	(1.10)	(0.48)	(0.02)	(0.10)	(0.27)	(0.28)	(0.14)	(0.04)	(0.06)	
Y-6 Pantellerite ^d	XRF	70.87	0.44	8.15	9.21	0.30	0.17	0.42	6.14	4.30	–	–	100.00
Y-6 Pantellerite ^k	EPMA	70.59	0.42	12.78	5.10	–	0.01	0.36	5.73	4.96	–	–	99.95
Pantelleria Pantellerite ^l	XRF	72.53	0.40	8.42	8.26	0.37	0.01	0.38	4.97	4.66	–	–	100.00
Pantelleria Trachyte ^l	XRF	66.47	0.66	12.68	7.59	0.27	0.32	1.28	5.56	4.56	0.05	0.19	99.88
ML-6 (standard deviation)	EPMA	77.81	0.09	12.37	0.56	0.06	0.06	0.63	3.68	4.60	0.01	0.11	99.98
		(0.24)	(0.01)	(0.12)	(0.08)	(0.02)	(0.02)	(0.10)	(0.20)	(0.13)	(0.02)	(0.01)	
Upper Acigöl Tuff ^m	XRF	75.53	0.09	13.66	1.13	0.06	0.13	0.80	4.02	4.56	–	–	99.98
Hasan Dagi ⁿ	ICP-AES	76.41	0.12	13.30	0.93	0.06	0.22	0.84	4.45	3.71	0.09	–	100.13

^a (Eastwood et al., 1999).

^b (Wulf et al., 2002).

^c (Vinci, 1985).

^d (Keller et al., 1978).

^e (Wulf et al., 2004).

^f (Hardiman, 1999).

^g (Francalanci et al., 1995).

^h (Vinci, 1983).

ⁱ (Federman and Carey, 1980).

^j (Allen and McPhie, 2000).

^k (Paterne et al., 1988).

^l (Civetta et al., 1988).

^m (Druitt et al., 1995).

ⁿ (Deniel et al., 1998).

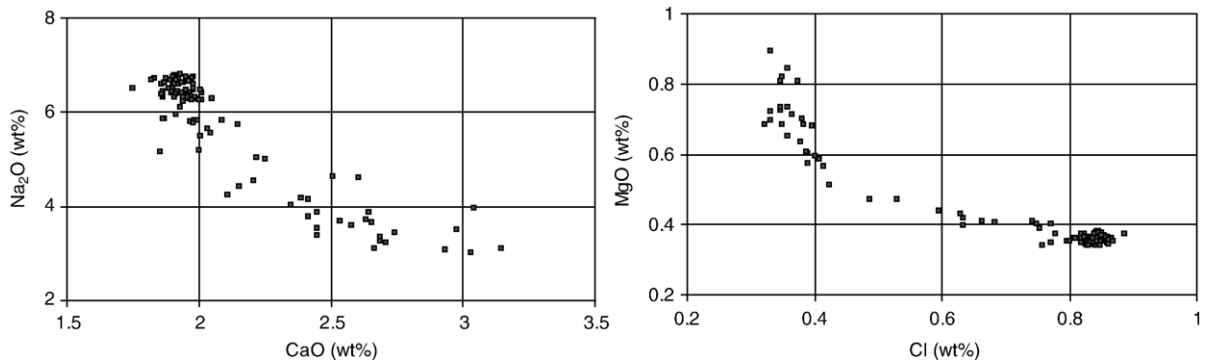


Fig. 4. Na_2O vs. CaO and MgO vs. Cl weight percentages for the ML-2 tephra layer.

Nisyros, Yali or Kos compared with other Aegean sources (Hardiman, 1999).

The last 200 ka activity of the Kos–Yali–Nisyros volcanic system in the eastern Aegean Arc is characterised by a number of eruptions. On Nisyros, three major volcanic phases can be identified: (a) the pre-caldera stratocone complex including the Panaghia Kyra sequence (b) the caldera-forming explosive eruptions of the Lower and Upper Pumice and (c) the post caldera phases (Di Paola, 1974; Wyers and Barton, 1989; Keller et al., 1990; Limburg and Varekamp, 1991; Francalanci et al., 1995; Hardiman, 1996). The young volcanic islet of Yali, is composed by a pumice succession to the south [including the Yali pumiceous breccia and the Yali fallout which correlates with the Yali-C tephra layer (Bond, 1976; Federman and Carey, 1980; Allen and McPhie, 2000)] and a lava to the North. However, the most significant eruption of this period was centred between Kos and Nisyros and is called the Kos Plateau Tuff (KPT) (Keller et al., 1990; Allen and Gas, 1998; Allen et al., 1999; Pe-Piper et al., 2005). Evidence of the KPT has been found on both Nisyros and Yali (Keller et al., 1990; Allen and McPhie, 2000).

It is apparent from Table 1 that the ML-3 and ML-4 layers have strong similarities with most of the rhyolitic layers from Nisyros, Yali and Kos, with the closest matches being the Nisyros Ash of Vinci (1983), Yali-1 of Hardiman (1999), Nisyros Lower Pumice of Hardiman (1999) and Nisyros A of Federman and Carey (1980). In detail, using the similarity coefficients following the method of Borchardt et al. (1972) the ML-3 tephra resembles in decreasing order the Nisyros Upper Pumice (Francalanci et al., 1995), Nisyros Lower Pumice (Hardiman, 1999), Nisyros Ash (Vinci (1983) and Nisyros A (Federman and Carey (1980) with values of 1.02, 1.02, 1.06 and 1.07 respectively. The ML-4 tephra is closer to Yali-1 (Hardiman, 1999) and Nisyros Ash (Vinci, 1983) with values of 1.0 and 0.99 res-

pectively. The difference in the FeO content of KPT (Federman and Carey, 1980) makes it a less probable match, while the significant dissimilarities with almost all of the oxides of the Panaghia Kyra eruption exclude it as a possibility. Given the fact that the Yali-C eruption has an age of 31 ka and has been identified in marine cores prior to the Y-5 marker (Federman and Carey, 1980) it seems implausible that either of the ML layers correspond to this eruption. The Yali pumice breccia (Allen and McPhie, 2000) could be another option, although similarity coefficients of 1.47 and 1.24 for the ML-3 and ML-4 layers respectively make it less possible. Therefore, it appears that the most plausible case is that both layers originate from Nisyros. Based on the stratigraphy of the ML01 sequence, one suggestion is that the ML-3 and ML-4 tephra correlate with the Upper and Lower Pumice eruptions, respectively.

It is worth mentioning that due to the similarities between the Upper and Lower Pumice eruptions some authors describe them together as the caldera-forming units (Di Paola, 1974; Wyers and Barton, 1989; Seymour and Vlassopoulos, 1992), thus limiting the potential of correlation of the ML-3 and ML-4 tephra layers with individual events. According to the analysis of samples from the Island of Nisyros itself the Lower Pumice always has $\text{Na}_2\text{O} < \text{K}_2\text{O}$, while the Upper Pumice has the opposite (Hardiman, 1999). However, Francalanci et al. (1995) reported $\text{Na}_2\text{O} > \text{K}_2\text{O}$ for both the Upper and the Lower Pumice eruptions. In the present analysis both horizons contain more K_2O than Na_2O , which is also supported by Vinci (1983) (although in her study only a single layer was identified thus not permitting further compositional comparisons) and Federman and Carey (1980) (who do not report any information on the location of the Nisyros A and G samples). One possible explanation for these discrepancies in the Na_2O content, is that some Na^+ loss could have occurred in the present analysis, although it is not

clear why this would apply only to the Upper Pumice layer. Another possibility is that one or even both of the ML layers correspond to previously unidentified eruptions from Nisyros, Yali or Kos. Given the fact that large parts of the area are currently below sea-level, the evidence of such submarine volcanic deposits has yet to be found. Finally it is possible that only a single eruption is represented in the sequence and that ML-3 and ML-4 correspond to only one tephra stratum. This could have arisen either through sediment slumping into the basin, inwash from the catchment or coring problems. However, visual inspection of the cores, as well as x-rays, high-resolution grain-size analysis of the tephra layers and pollen analysis, do not support this hypothesis. Moreover, the inwashed tephra particles form easily identifiable units (called ‘reworked’ tephra layers in Section 3.1) of 4.5 and 13 cm thickness, overlying both the ML-3 and ML-4 pure tephra layers, respectively. These are composed of reducing portions of glass shards towards the top and increasing portions of clayey organic material and are clearly separated from the pure tephra strata. Their deposition is believed to have resulted from inwashed tephra particles from the catchment due to wind and rain erosion shortly after the deposition of the pure tephra layers and not after one

thousand years, which is the time interval between the ML-3 and ML-4 layers (Section 3.5).

The problem of distinguishing rhyolitic tephra on the basis of their major elemental compositions is well known, and is compounded both by the fact that silica-rich ‘minimum melt’ compositions will inevitably have closely similar compositions; as well as by the fact that repeated eruptions from the same volcanic centre may produce essentially identical products. This is illustrated in Fig. 5, where the compositions of ML-3, ML-4 and ML-6 (next section) have been plotted onto the water-saturated orthoclase–quartz–albite (Or–Q–Ab) ternary diagram. These melt compositions cluster closely, overlap with the compositions of rhyolites from Yali, and have compositions consistent with melts that have equilibrated under water-saturated conditions shallow in the crust. The compositions are, however, distinguished on such a plot from the compositions of common magmatic series that has been suggested for Nisyros and Yali (Di Paola, 1974; Seymour, 1996). Bearing in mind that the distal record of the Nisyros eruptions in particular is under-represented with only single layers being identified in deep-sea cores (Vinci, 1983), as well as the possibility of chemical alteration of the tephra both pre- and post-deposition compared with the source

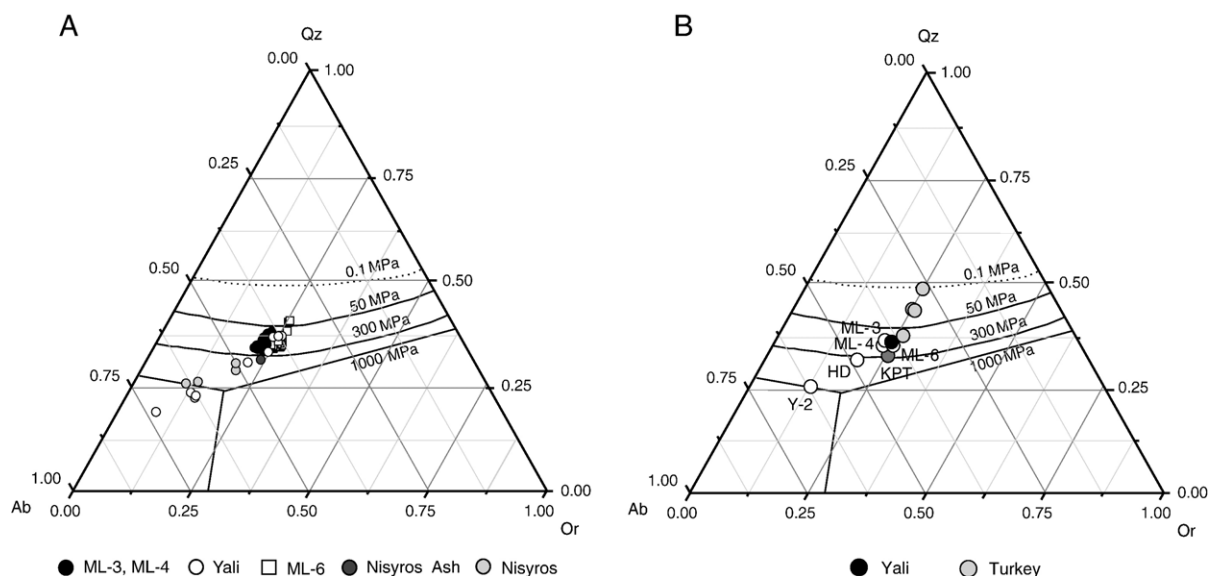


Fig. 5. Normative (Quartz, Qz; Albite, Ab; Orthoclase, Or) compositions of glass and pumice samples from the eastern Mediterranean projected from anorthite onto the water-saturated Qz–Ab–Or ternary diagram, with the locations of water-saturated cotectics and minima shown for reference (labelled curves) for 4 values of P_{H_2O} (modified after Blundy and Cashman, 2001). (A) shows that the compositions of ML-3, ML-4 and ML-6 cluster closely, and overlap with the whole-rock compositions of phenocryst-poor Yali rhyolites (Seymour, 1996; Allen and McPhie, 2000; Buettner et al., 2005), consistent with them all having last equilibrated in a shallow (50–300 MPa), water-saturated magma chamber. (B) Compositions of many high silica rhyolites are closely similar: the Kos Plateau Tuff (KPT) and Hasan Dagi (HD, Deniel et al., 1998) tephra for example; while the compositions of high silica rhyolites from other settings (e.g. other Pleistocene examples from Turkey; Kuzucuoglu et al., 1998) may be distinguished by their higher Qz contents, reflecting crystallisation at even lower pressures. The dacites and rhyodacites of Santorini (Y-2, for example; Wulf et al., 2002) are also clearly distinguished from the high-silica rhyolites of the eastern Aegean on this plot.

volcano (Pollard et al., 2003), it is suggested that the two tephra layers ML-3 and ML-4 do represent separate events, with at least one of them corresponding to the Nisyros Upper/Lower Pumice eruptions.

The recent (<200 ka) volcanic evolution of the Nisyros–Yali–Kos volcanic system was initiated at 161.3 ± 1.1 ka BP with the KPT eruption (Smith et al., 1996). KPT products have been identified on Nisyros where they underlie the pre-caldera cone (Keller et al., 1990) and on Yali where they are present within the Yali pumice breccia (Allen and McPhie, 2000). With regard to Yali, the Yali-C eruption has an age of 31 ka BP (Federman and Carey, 1980) while the Yali lava has been dated by fission-track at 24 ka BP (Wagner et al., 1976). The chronology of the Nisyros eruptions is poorly constrained by a few numerical dates and the existing evidence is contradictory. In detail, there are two radiocarbon dates, one from the palaeosol that underlies the Lower Pumice, which yielded an age of cal. 29.416 ± 0.82 ka BP (Keller et al., 1989), and a second from charcoal in the surge deposit of Upper Pumice at cal. 47.452 ka BP (Limburg and Varekamp, 1991). Applying the fission-track method to the Upper Pumice deposits, Barberi et al. (1988) obtained an age of 110 ka BP. In addition, there is a $^{40}\text{K}/^{40}\text{Ar}$ date from a dacite lava at the base of the Panaghia Kyra sequence of 38 ± 2 ka BP (Keller et al., 1990). The Yali-C pumice fall has been identified in the caldera walls of Nisyros, but not on the dome surfaces, and therefore it is believed that the formation of the caldera occurred earlier, between 31 and 35 ka BP (Hardiman, 1999). In the Mediterranean Sea marine record, the chronological position of the ‘Nisyros Ash’ has been calculated by linear extrapolation of the sedimentation rate in the stratigraphy of the Y zone, between 21 and 30 ka BP (Vinci, 1985; Narcisi and Vezzoli, 1999). Finally, a tephra, that is believed to correspond to the Lower Pumice eruption has been identified in core TR172-26 (75 km SW of Nisyros), where also by linear extrapolation, based on the position of the Y-2 and a uniform sedimentation rate it has been given an age of 35 ka BP (Hardiman, 1996).

It is important to note that the Y-5 tephra marker and the ‘Nisyros Ash’ have not previously been found in the same core. The recovery of these tephras at the same sequence is highly valuable in terms of establishing a chronology for the Nisyros eruptions in relation to the Y-5, the most widespread tephra marker in the Mediterranean.

3.2.4. ML-5 tephra layer

The ML-5 stratum represents a zoned eruption, and its chemical composition changes from a very distinctive melt, called pantellerite (with 75 wt.% SiO_2 , 8 wt.%

Al_2O_3 and 7 wt.% FeO), to trachyte. Thus, in Table 1 the composition of both these glasses are presented separately. Based on the small standard deviation from the mean values, especially for pantellerite, and the homogeneity of the glass shards in Fig. 2, it is suggested that the ML-5 tephra was formed during a single eruption. The only source in the Mediterranean Sea known to have produced this type of ash during the Pleistocene is the peralkaline volcano of Pantelleria, a small island located in the Pantelleria Rift between Sicily and Africa (Keller et al., 1978; Cornette et al., 1983).

On the island of Pantelleria, this particular eruption correlates with the formation of the ‘Green Ignimbrite’, otherwise called the ‘Green Tuff’ (Cornette et al., 1983). This pyroclastic formation is the most widespread on the island, where it is a major marker horizon (Mahood and Hildreth, 1983; Civetta et al., 1984; Civetta et al., 1988; Orsi et al., 1991). It has been suggested by Orsi and Sheridan (1984) that the ‘Green Tuff’ can be divided into eight members, with member ‘a’ corresponding to the Y-6 tephra identified in the deep-sea record. Of particular note is the fact that the ‘Green Tuff’ eruption was strongly chemically-zoned, erupting pantellerite magma in its early stages, and trachyte magma in its later stages. Both these compositions are reported in the bulk analysis of the proximal deposits and are recognised in the ML-5 tephra horizon. Because of the unique chemical composition of pantellerite, the ML-5 stratum is attributed with confidence to the Y-6 tephra (cf. Table 1).

The eruption of the ‘Green Tuff’ has been dated to 48.5 ± 3.35 and 50.8 ± 3.6 ka BP by $^{40}\text{K}/^{40}\text{Ar}$ (Cornette et al., 1983). Using the same method, Civetta et al. (1988), reported dates of 50.8 ± 2.2 , 49.9 ± 2.1 and 46.9 ± 2 ka BP for this deposit. An older age of 55 ka BP was reported by Mahood and Hildreth (1983). However neither the location of the dated samples nor the analytical data on $^{40}\text{K}/^{40}\text{Ar}$ determination were presented. Overall, these dates are in good agreement with the interpolated stratigraphical age of the Y-6 tephra in marine cores from the Ionian Sea at ca. 45 ka BP (Keller et al., 1978).

The ML-5 tephra layer represents the most easterly discovery of the Y-6 horizon; previously it had only been reported from deep-sea cores between Italy and Greece (Fig. 6). The minimum dispersal area for the Y6 tephra is estimated at 7×10^5 km², consistent with the expected magnitude of this caldera-forming eruption (Mahood and Hildreth, 1983; Civetta et al., 1988). Given the cm-scale thickness of ML-5 on Lesbos island, the minimum bulk ash volume of the Y-6 ash layer is of order 25 km³ [10 km³ dense rock equivalent (Pyle,

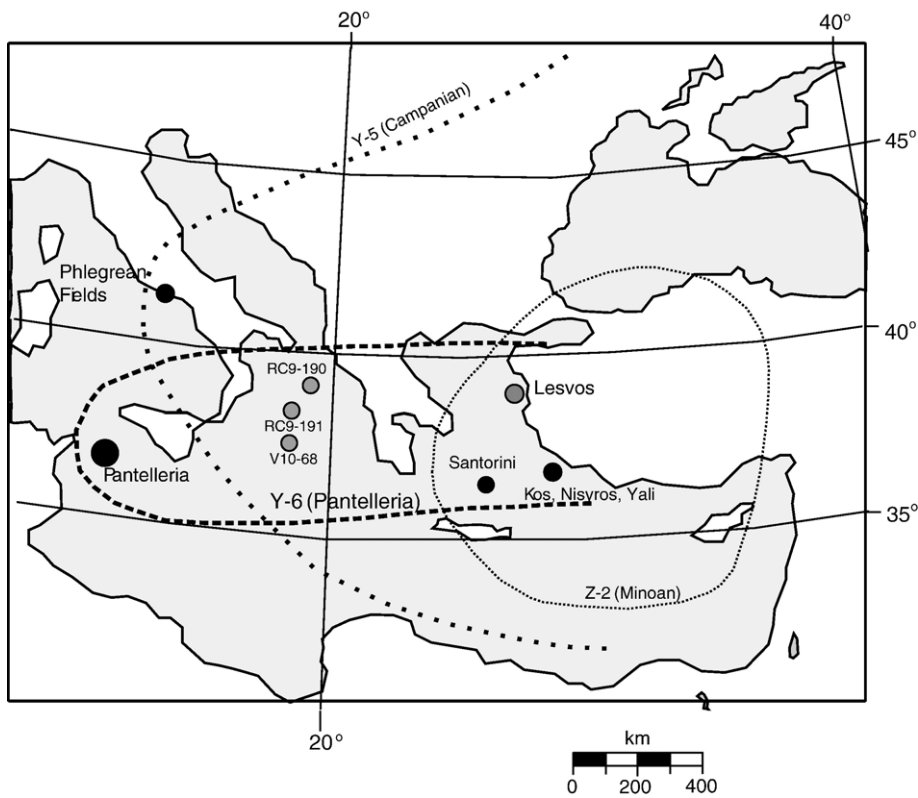


Fig. 6. Distribution of three of the major tephra horizons from the eastern Mediterranean, adapted from Pyle et al. (2006): Z-2 (Minoan eruption of Santorini); Y-5 (Campanian ignimbrite eruption of the Phlegrean Fields) and Y-6 (Green Tuff of Pantelleria, this study). Y-6 had previously only been reported from several deep-sea cores (Keller et al., 1978), but the easterly dispersal implied from the recognition of Y-6 on Lesvos is consistent with expected paleo-wind patterns.

1999)], comparable in scale to the Z-2 (Minoan) and Y-2 (Cape Riva) eruptions of Santorini (Table 2).

3.2.5. ML-6 tephra layer

The glass shards of the ML-6 layer appear to form a single homogenous group, with a composition similar to ML-3 and ML-4. The rhyolitic composition of the glass suggests an origin from the Aegean Volcanic Arc. As already mentioned the low Al_2O_3

(<13.0 wt.%) and the generally similar Na_2O and K_2O content are characteristic of ash originating from the islands of the eastern Aegean Volcanic Arc. However, none of the known younger eruptions of Nisyros resembles the chemical fingerprint of the ML-6 layer (Table 1), while the KPT can be ruled out by its age [161.3 ± 1.1 ka BP; (Smith et al., 1996)] since the ML01 sequence shows no evidence of an hiatus (according to the chronology of the ML01 sequence

Table 2
Widely dispersed tephra layers from Mediterranean volcanic eruptions over the past 75 ka

Approximate eruption age (ka)	Eruption name	Ash layer	Source volcano	Composition	Minimum tephra area km ²	Reference
3.6	Minoan	Z-2	Santorini	Rhyodacite	3×10^5	1
22.0	Cape Riva	Y-2	Santorini	Rhyodacite	3×10^5	2,3
39.3	Campanian Ignimbrite	Y-5	Phlegrean fields, Italy	Trachyte	$2-4 \times 10^6$	4
53	Green Tuff	Y-6	Pantelleria	Peralkaline rhyolite	7×10^5	5

Compiled from data in (Keller et al., 1978) (Narcisi and Vezzoli, 1999) (Druitt et al., 1999) (Pyle, 1990)¹ (Druitt, 1985)² (Wulf et al., 2002)³ (Pyle et al., 2006)⁴ (Civetta et al., 1988)⁵.

the depth of 28.41 m corresponds to ca. 57.584 ka BP, Section 3.5).

Other possible sources for the ML-6 tephra could be the Upper Acigöl Tuff and Hasan Dagi volcano from Central Turkey, whose volcanic activity ranges in age from 150 to 70 ka BP (Druitt et al., 1995) and older than 65 to 120 ka BP (Deniel et al., 1998), respectively. However, the products of both these sources are SiO₂ poor and Al₂O₃ rich compared with the ML-6 tephra. Moreover, based on the pattern of the prevailing winds in the Eastern Mediterranean where only minor easterlies occur in Central Anatolia, it seems unlikely (but still possible) that this ash reached Lesvos Island. The only remaining possibility therefore, is that the ML-6 tephra represents a previously unidentified eruption from the Aegean Arc. Until further data becomes available from both Turkey and the Hellenic Arc no firm conclusion can be drawn for the origin of the ML-6 tephra.

3.3. Trace and rare earth elements

The main purpose of the ICP-MS analysis was to further investigate the chemical characteristics of ML-3 and ML-4 layers (ML-6 could not be analysed due to lack of material), as well as to reinforce the correlation of ML-2 horizon with its suggested corresponding eruption. Three layers (ML-2, ML-3 and ML-4) from the ML01 sequence was used in the analysis. This core was selected because it is the longest and most stratigraphically complete. Since trace and rare earth elements results for the layers in question were limited in the literature, a further 11 samples were analysed for correlation purposes. These samples were collected by J. Hardiman and D. M. Pyle, either from terrestrial or marine settings and have already established corresponding eruptions (Table 3).

The trace and rare earth element (REE) concentration values were obtained as parts per million (ppm) and were normalised against a chondrite value of McDonough and Sun (1995). They are presented schematically in Fig. 7 using the multi-element spider diagrams of Pearce (1983) and in detail in Table 4. For the trace elements diagrams, elements are plotted in order of increasing compatibility in mantle phases, with those on the left side (Sr, K, Rb, and Ba) being water mobile while those on the right immobile. REEs are divided into two groups: the light (LREEs, with atomic numbers 57–63) to the left of the diagrams and the heavy (HREEs, with atomic numbers 64–71) to the right.

The two groups of tephra with either a Campanian or a Hellenic Arc origin can be easily differentiated by

Table 3

Samples analysed for trace and rare earth elements

Sample	Source	Corresponding eruption
ML-2	Megali Limni	Campanian Y-5
ML-3	Megali Limni	Nisyros (Upper/Lower Pumice)/Yali
ML-4	Megali Limni	Nisyros (Upper/Lower Pumice)/Yali
N 9204	Nisyros Island a	Nisyros Upper Pumice
JCH/93/311	Nisyros Island b	Nisyros Upper Pumice
HN 15/059	Nisyros Island	Nisyros Lower Pumice
172TR-18PC	Marine Core	Kos Plateau Tuff
172TR-26PC	Marine Core	Nisyros Lower Pumice
N92/Yal2	East Yali Island	Yali
N92/Yali1	Yali Pigada Island	Yali
RUDKINO KOS 13	Russia a	Campanian Y-5
RUDKINO KOS 14	Russia b	Campanian Y-5
172TR-11PC	Marine Core a	Campanian Y-5
172TR-19PC	Marine Core b	Campanian Y-5

both their trace and REE absolute concentration values (Fig. 7). Furthermore, the two groups show appreciably different patterns. The Campanian samples show a significant depletion of Ba, which is not present in the samples that originate from the Hellenic Arc. This depletion probably reflects fractional crystallisation of feldspars in the magma chamber prior to the eruption. Moreover, the Hellenic Arc group shows a strong depletion of Nb, which is significant since this element is not sensitive to fractional crystallisation and is considered to be characteristic of arc lavas (Clift and Blusztajn, 1999). In general, all the samples show an enrichment of the water mobile elements, to the left of the diagrams, compared with the depleted immobile elements to the right. The relative enrichment of the LREEs compared with the HREEs is typical of Mediterranean Arcs, probably indicating low degrees of partial melting and a subduction-related enrichment of the LREEs.

The strong similarities between all the samples corresponding to the Upper and Lower Pumice eruptions from Nisyros and Yali do not allow any discrimination between the ML-3 and ML-4 layers. The only sample that seems to be slightly different in its Ba concentration is the Lower Pumice found in a marine core, despite its land-based equivalent being highly enriched. Existing data for trace and REE composition of the Upper and Lower Pumice eruptions from Nisyros are rare in the literature (most authors describe them as one unit). However, there are two reported studies (Francalanci et al., 1995; Saminger et al., 2000) where concentrations were obtained using neutron activation (INAA) thus preventing direct comparison. Nevertheless, it is worth mentioning that in both cases the

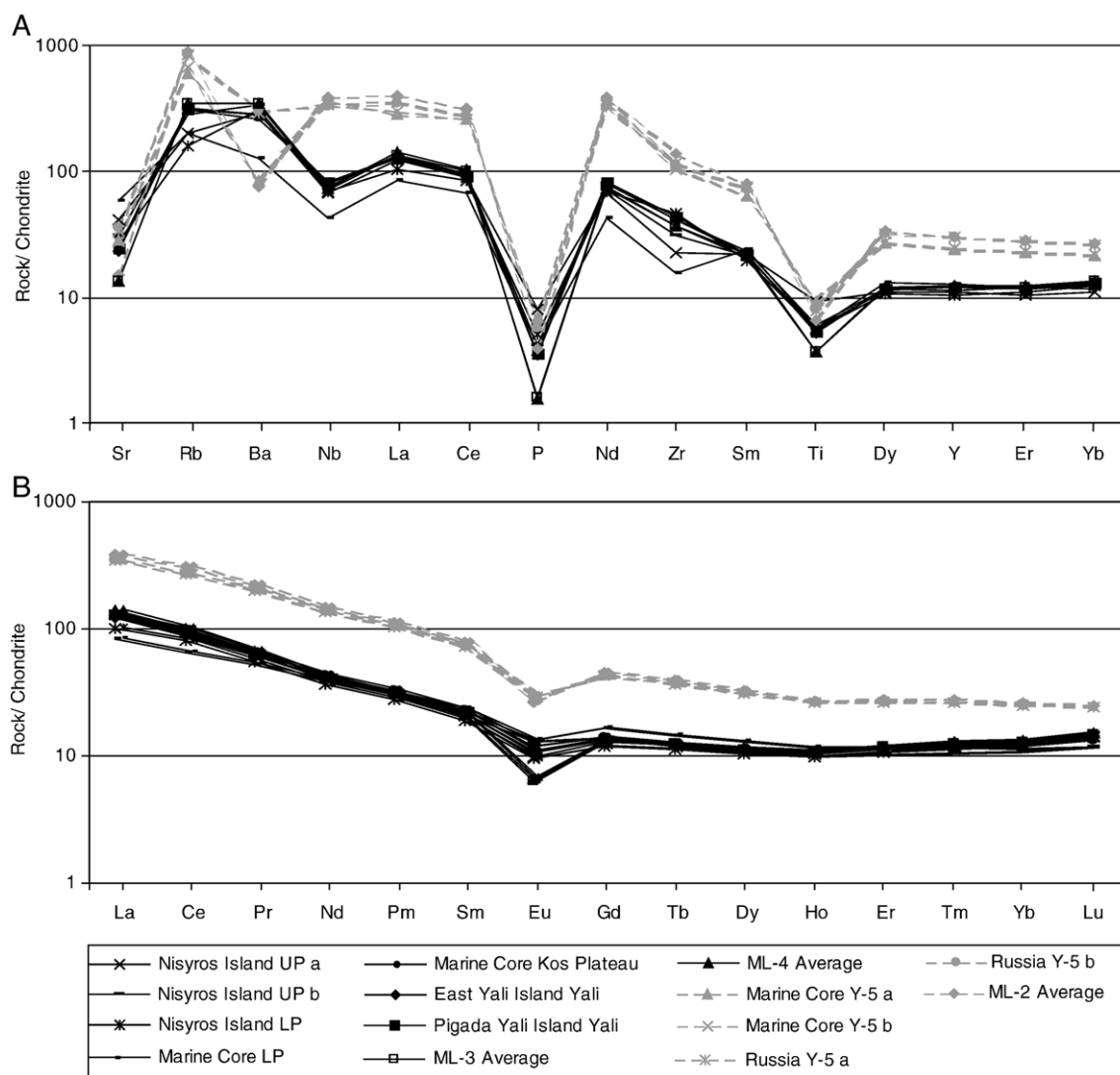


Fig. 7. Normalised trace (A) and rare earth (B) element concentrations (ppm) for all the tephra analysed in this study.

separation between the Lower and the Upper Pumice was not possible.

With regard to the ML-2 tephra the strong correlation in both the trace and REE concentrations of the analysed samples (Fig. 7), confirm that the ML-2 layer originates from the Campanian area with its closest match being the Y-5 tephra marker.

3.4. Particle size

The grain-size distribution of distal tephra layers, as well as the parameters controlling their deposition has been the subject of many studies (Ninkovich et al., 1978; Sigurdsson et al., 1980; Pyle, 1989; Carey, 1997). It is well established that the thickness of fallout tephra

strata decreases with increasing distance from the source volcano. Additionally, it is expected that ash layers may become well sorted as a result of differential settling in the water column, especially in pelagic environments (Sigurdsson et al., 1980).

For some tephra, such as the Y-5, a bimodal distribution appears to be present even at great distances from the source. It has been demonstrated in marine cores from the eastern Mediterranean and the NW Aegean Sea, that the strata of this tephra marker are divided by a sharp boundary to an upper fine grained ash and a lower, coarse grained and pumiceous unit (Ninkovich et al., 1978; Sparks and Huang, 1980; Cramp et al., 1989). However, no such boundary or decreasing grain-size was identified in the ML-2 layer from Megali Limni. It

Table 4

Trace (A) and rare earth (B) elements (ppm) concentrations of the samples analysed in this study

	NUP a	NLP	Kos	MNLP	NUP b	Yali a	Yali b	RY5 a	RY5 b	MY5 a	MY5 b	ML-2av	st	ML-3av	st	ML-4av	st
<i>A. Trace elements</i>																	
Li	36.32	23.93	43.59	48.27	29.13	33.69	36.92	66.64	66.68	72.83	78.24	58.40	12.46	42.92	8.58	43.86	7.45
Be	2.20	2.23	2.60	1.52	1.71	2.25	2.33	15.43	16.19	11.54	13.33	15.96	1.76	2.08	0.21	2.08	0.22
P	385.74	473.34	391.02	392.18	751.45	323.51	332.41	534.07	550.75	575.22	572.26	367.99	21.45	150.25	14.44	145.59	7.49
Sc	13.99	4.78	5.32	9.51	7.93	4.45	4.33	4.92	4.91	4.58	8.14	3.25	0.20	3.57	0.24	3.69	0.22
Ti	2420.6	2408.7	2625.0	2475.2	4024.6	2269.9	2296.7	3415.9	3335.2	3815.9	3768.9	2855.2	111.3	1570.5	29.6	1601.0	114.10
V	33.65	28.80	33.99	66.45	88.05	24.47	24.10	50.66	48.17	55.66	59.49	28.81	0.93	9.48	0.14	9.58	0.94
Cr	6.92	18.93	65.19	180.50	17.02	5.11	3.48	12.20	11.01	17.65	24.83	29.50	27.58	18.31	9.98	15.64	6.42
Mn	518.34	665.73	615.52	956.47	1025.0	568.68	597.33	1498.3	1632.1	1065.2	1311.0	1367.8	80.23	284.10	7.24	286.92	25.30
Co	4.53	4.21	8.34	23.99	9.76	2.46	2.15	5.78	5.91	25.95	24.09	3.17	0.12	1.74	0.14	1.97	0.44
Ni	10.99	64.08	30.89	154.22	38.71	10.82	6.25	11.81	11.44	59.73	39.82	85.20	94.61	31.02	31.31	17.44	8.18
Cu	6.45	9.05	34.53	36.74	5.85	3.83	2.82	14.52	15.74	105.92	66.68	52.58	4.24	26.57	6.94	25.21	6.44
Zn	42.33	52.08	44.43	60.44	65.36	37.26	37.09	111.80	115.82	90.53	103.54	129.66	9.67	36.32	5.27	37.60	1.26
Ga	17.90	16.33	16.04	11.42	17.02	15.56	16.47	22.52	22.54	16.45	18.95	21.56	1.26	14.02	0.51	13.95	0.97
Rb	97.88	54.86	107.25	68.85	69.82	106.80	111.73	294.42	296.50	215.31	235.10	311.96	5.56	119.06	4.65	119.64	5.34
Sr	242.45	212.25	230.27	453.42	317.44	182.22	187.78	275.95	261.66	215.76	214.85	116.86	6.88	104.77	1.79	105.48	7.80
Y	18.89	16.00	18.65	19.57	16.78	19.11	18.64	46.78	46.94	35.51	38.24	46.42	1.53	17.63	2.16	18.95	1.04
Zr	121.48	179.44	161.35	60.52	87.28	162.15	169.28	437.13	449.84	438.88	407.36	541.56	16.75	143.61	6.38	142.98	10.27
Nb	17.46	17.03	20.38	10.45	16.51	19.41	20.07	80.87	84.13	87.30	81.28	96.44	3.46	18.31	0.88	17.97	1.35
Cd	0.04	0.07	0.05	0.05	0.05	0.05	0.06	0.13	0.14	0.12	0.11	0.16	0.02	0.06	0.01	0.05	0.01
Cs	3.45	2.56	4.12	3.61	2.39	3.63	3.65	20.96	21.59	16.91	17.10	25.10	1.82	4.41	0.35	4.34	0.42
Ba	783.72	729.26	599.80	291.09	673.51	650.84	661.96	699.71	687.00	207.70	192.00	174.70	5.75	817.25	41.77	809.50	49.71
Hf	3.14	4.18	3.93	1.77	2.28	3.97	4.06	8.93	9.21	10.53	9.44	11.05	0.40	3.86	0.21	3.84	0.27
Ta	1.38	1.29	1.66	0.82	1.14	1.59	1.65	3.98	4.06	5.63	5.12	5.07	0.22	1.57	0.09	1.55	0.10
Tl	0.50	0.47	0.54	0.43	0.34	0.56	0.60	1.40	1.43	0.81	0.91	1.98	0.08	0.59	0.02	0.58	0.04
Pb	15.18	12.54	15.89	11.20	9.91	12.71	12.88	47.05	48.28	47.55	50.10	51.23	1.52	16.41	0.22	16.58	0.94
Th	13.52	7.80	14.63	7.20	8.57	12.67	13.23	35.76	36.14	42.73	42.59	38.99	1.82	13.37	2.52	14.88	0.81
U	3.66	2.89	3.93	2.01	2.27	3.73	3.98	10.52	10.63	7.41	8.71	12.53	0.54	3.96	0.18	4.00	0.28
Pb	6.15	5.08	6.43	4.53	4.01	5.15	5.22	19.05	19.54	0.00	20.28	20.74	0.61	6.64	0.09	6.71	0.38
Ba	334.92	311.65	256.32	124.40	287.82	278.13	282.89	299.02	293.59	0.00	82.05	74.66	2.46	349.25	17.85	345.94	21.24
<i>B. REE</i>																	
La	132.77	102.63	128.89	84.24	123.37	126.16	127.24	349.30	357.14	303.56	297.57	398.65	6.48	133.23	18.07	142.66	6.71
Ce	94.63	83.23	92.62	66.68	89.79	89.26	91.35	274.69	279.50	273.51	256.76	314.77	5.36	100.33	2.76	101.65	5.11
Pr	64.73	56.34	66.04	53.29	63.19	63.16	63.34	203.26	206.79	178.42	175.91	230.12	5.27	65.76	4.54	68.01	2.92
Nd	41.69	37.19	43.84	38.89	42.35	41.19	41.24	137.36	139.27	118.29	118.83	150.57	1.94	40.87	2.49	42.35	1.89
Pm	31.43	28.32	33.59	31.26	32.00	31.56	31.57	105.42	107.67	91.45	91.95	115.02	1.62	30.82	1.74	31.90	1.48
Sm	21.16	19.46	23.34	23.63	21.65	21.93	21.89	73.47	76.07	64.61	65.07	79.46	1.33	20.77	1.01	21.44	1.10
Eu	10.00	9.82	12.16	13.52	13.00	11.16	10.89	29.59	29.82	25.34	26.11	26.86	0.46	6.39	0.49	6.76	0.53
Gd	13.00	12.04	14.12	16.98	13.83	13.97	13.50	44.01	43.09	38.00	36.70	46.20	2.44	13.10	0.36	13.36	0.83
Tb	12.31	11.46	12.95	14.68	12.20	12.92	12.75	37.52	38.51	33.00	32.92	40.22	1.34	12.60	0.47	12.80	0.71
Dy	11.30	10.52	11.61	13.01	10.91	11.90	11.60	31.28	31.86	27.37	27.13	33.47	1.06	11.53	0.23	11.86	0.71
Ho	10.58	9.98	10.59	11.67	9.89	11.15	10.77	26.87	26.76	22.19	22.70	27.80	1.05	10.93	0.16	11.15	0.61
Er	11.42	10.86	11.40	11.91	10.37	11.89	11.68	27.14	27.57	22.75	22.95	28.44	1.01	11.96	0.28	12.18	0.68
Tm	12.23	11.53	11.86	11.86	10.66	12.48	12.40	26.82	27.15	22.02	22.36	28.11	1.13	12.88	0.13	13.11	0.74
Yb	12.60	12.10	12.18	11.56	10.87	12.81	12.84	25.56	25.94	20.82	21.63	26.84	0.95	13.21	0.08	13.50	0.74
Lu	14.49	14.32	13.62	11.93	11.73	14.61	14.69	24.73	25.02	19.22	20.66	25.46	0.73	15.05	0.41	15.45	0.76

NUP a: Nisyros Island Upper Pumice a, NLP: Nisyros Island Lower Pumice, Kos: Marine Kos Plateau Tuff, MNLP: Marine Core Nisyros Lower Pumice, NUP b: Nisyros Island Upper Pumice b, Yali a: East Yali Island, Yali b: Pigada Yali Island, RY5 a: Russia (Rudkino) Y-5 a, RY5 b: Russia (Rudkino) Y-5 b, MY5 a: Marine Y-5 a, MY5 b: Marine Y-5 b, ML2 av: ML-2 Tephra Layer Average, ML3 av: ML-3 Tephra Layer Average, ML4 av: ML-4 Tephra Layer Average, st: Standard Deviation.

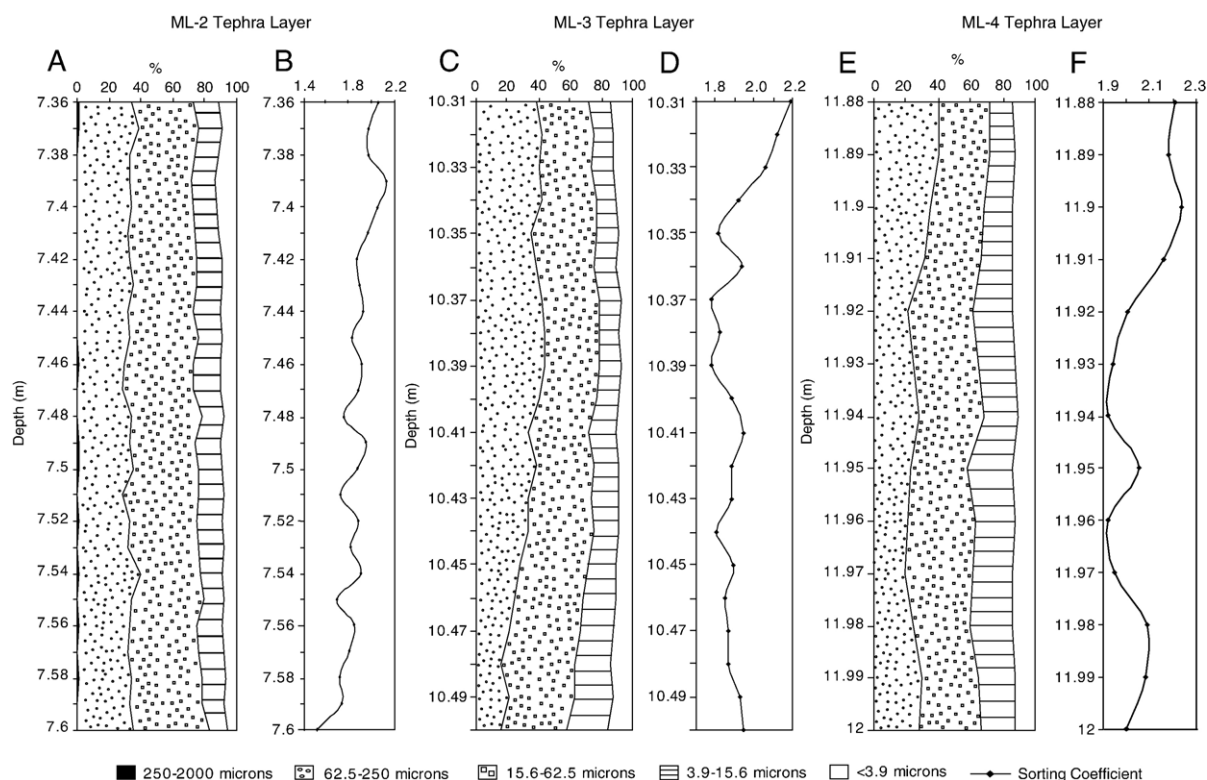


Fig. 8. Particle size percentages (A, C, E) and sorting coefficients (B, D, F) for the ML-2, ML-3 and ML-4 tephra layers.

appears that the particles of this stratum are mostly silt-sized and remain constant throughout (Fig. 8). Sorting coefficient can vary from less than 0.35 to more than 2. Values from 1–2 indicate poor sorting, while more than 2 means that the sediments are very poorly sorted. In the ML-2 layer values range from 1.5, at the basal depth, up to 2.2 towards the top, suggesting that the glass shards of this layer do not belong to any particular grain-size, but are a mixture of sizes.

Particle size analysis of the ML-3 and ML-4 layers was undertaken in order to examine their coherence and structure. Contrary to the results of normal sorting observed in tephra layers in deep-sea cores, both strata show a clear pattern of increasing sand upwards (Fig. 8). However, this is not unexpected since pollen analysis of aquatic plants has shown that around the time of the eruptions the Megali Limni lake was no more than five metres deep (Margari, 2004) and therefore sorting in the water column was not the main factor controlling the deposition of these strata. It is suggested that the observed upward increase in the percentage of the sand particles is due to inwashed material from the slopes of the catchment. Examining the possibility that one of the analysed layers could be the result of slumping in the

basin, some mixing should be expected. Indications of mixing were not observed and it is worth noting that the two layers have different sorting coefficient patterns. Thus, there is no evidence to support the slumping hypothesis and consequently the correlation of the ML-3 and ML-4 strata with separate eruptions is reinforced.

3.5. Chronology

A composite record from both the ML00 and ML01 sequences was constructed using 13 AMS and 5 conventional radiocarbon dates, the depth of the ML-2 tephra layer and pollen stratigraphy. The final chronology of the ML composite sequence is based on 8 AMS dates (Table 5), the age of the ML-1 [Y-2; (Pichler and Friedrich, 1976)] and ML-2 [Y-5; (De Vivo et al., 2001)] tephra markers and 4 alignment points, emerging from correlations with records of millennial-scale variability (Margari, 2004). This is based on Tzedakis et al. (2002, 2004) who suggested that the largest reductions in arboreal pollen (AP) values in Greece were coeval with AP minima in Alboran Sea (Sánchez Goñi et al., 2002; Combourieu Nebout et al., 2002) and Portuguese margin (Sanchez-Goñi et al., 2000; Roucoux et al.,

Table 5

Radiocarbon dates used in the ML composite age model. Calibration to calendar years has been done using the calibration curve of Fairbanks et al. (2005)

Radiocarbon age (years BP $\pm 1\sigma$)	Calendar age (years BP $\pm 1\sigma$)	Publication code
19072 ± 237	22674 ± 374	SUERC-5857
21225 ± 316	25479 ± 476	SUERC-5858
23523 ± 428	28079 ± 455	SUERC-5863
27167 ± 686	31520 ± 633	SUERC-5862
30762 ± 1085	35999 ± 1214	SUERC-3019
32150 ± 800	37485 ± 904	Beta-202262
34975 ± 1848	40361 ± 1753	SUERC-3020
38879 ± 3017	43287 ± 3017	SUERC-3023

2001) marine pollen records, which, in turn are synchronous with North Atlantic cold events. The four control points used here represent the mid-point of AP increases, which are phase-locked to cold-to-warm transitions of the North Atlantic–Greenland timescale (in this case using the GISP2 chronology [Stuiver and Grootes, 2000]). All radiocarbon years have been converted to calendar years using the calibration curve of Fairbanks et al. (2005). Panel A of Fig. 9 shows the palynological signal of the ML record. Values are plotted as pollen percentages of arboreal taxa against age. Panel B shows the $\delta^{18}\text{O}$ record of planktonic foraminifera from marine core MD95-2042 (Shackleton et al., 2000) off Portugal. The latter represents a record of sea surface temperatures, with more negative values corresponding to coolings during stadials and less negative values reflecting warmings during interstadials. In addition, in panel C the GISP2 $\delta^{18}\text{O}$ profile obtained from ice (Stuiver and Grootes, 2000) is shown. The latter represents changes in the isotopic composition of the snow and consequently the mean annual temperature over Greenland (Johnsen et al., 2001), with heavier values corresponding to lower temperatures during stadials and lighter values to warmer temperatures during interstadials. Despite minor offsets in the timing of events, present only in the upper part of the sequence where no alignment points were used, there is close correspondence both in the pattern and the amplitude of the changes in the forest extent of Lesvos and temperatures in the Portuguese Margin and over Greenland, with contracting tree populations corresponding to stadials and expanding to interstadials (Margari et al., in preparation).

4. Discussion and conclusions

The ML sequence represents the most complete terrestrial record to date of distal tephra layers in the

eastern part of the Mediterranean during the Late Pleistocene. In addition to the well dispersed Y-2 and Y-5 tephra markers, the ML record includes another four distal tephra layers that have so far been either under-represented or completely absent in other Eastern Mediterranean records. For the first time there is unequivocal evidence that the Nisyros eruption(s) occurred prior to the deposition of the Y-5 tephra marker. Moreover, the presence of another one or possibly two tephra layers from the Nisyros–Yali–Kos volcanic system provides evidence for the existence of additional eruptions in the eastern part of the Aegean volcanic Arc. Finally, the presence of the Y-6 tephra on Lesvos is the first reported occurrence of this marker so far east.

In addition to the occurrence of these tephras within the same sequence, which defines their relative chronological relationship, the detailed age model and high-resolution pollen analysis of the ML sequence offers an opportunity to establish new timings for all the tephra layers. These are not simply bracketed by AMS dates, but they are also placed within the context of the millennial-scale palaeoenvironmental variability of the last glacial period. The error bars of the AMS dates are 1σ , while the age uncertainty derived from the calendrical age model of the ML sequence has been calculated as the quadrature of the age uncertainty of the GISP2 age scale and the resolution of the ML record. For the period from 44.6 to 60 ka BP this is 5.69 ka (Margari et al., in preparation). In detail the following remarks can be made:

- The AMS dates obtained just below the ML-1 and ML-2 tephra layers of cal. 22.674 ± 0.374 and cal. 40.361 ± 1.753 ka BP are in close agreement with the existing ages for the Y-2 and Y-5 tephra markers respectively. The Y-2 eruption occurred shortly after the equivalent in the ML record of Greenland Interstadial (GIS) 2, while the Y-5 occurred at the end of GIS 9 and just before the onset of Heinrich Event (HE) 4.
- The ML-3 and ML-4 layers (Nisyros Upper and probably Lower Pumice eruptions) occurred before the Y-5 and have a calendar age of approximately 46 ± 5.69 and 46.8 ± 5.69 ka BP, bracketing the interval corresponding to GIS 13. These dates represent a substantial improvement of the hitherto vague dating of the Nisyros eruptions and their erroneous position between 31 and 35 ka BP.
- The ML-5 tephra layer was deposited slightly before GIS 14, further refining the age of the Y-6 tephra marker to 53.6 ± 5.69 ka BP, which is within the error margins of the dates by Cornette et al. (1983).

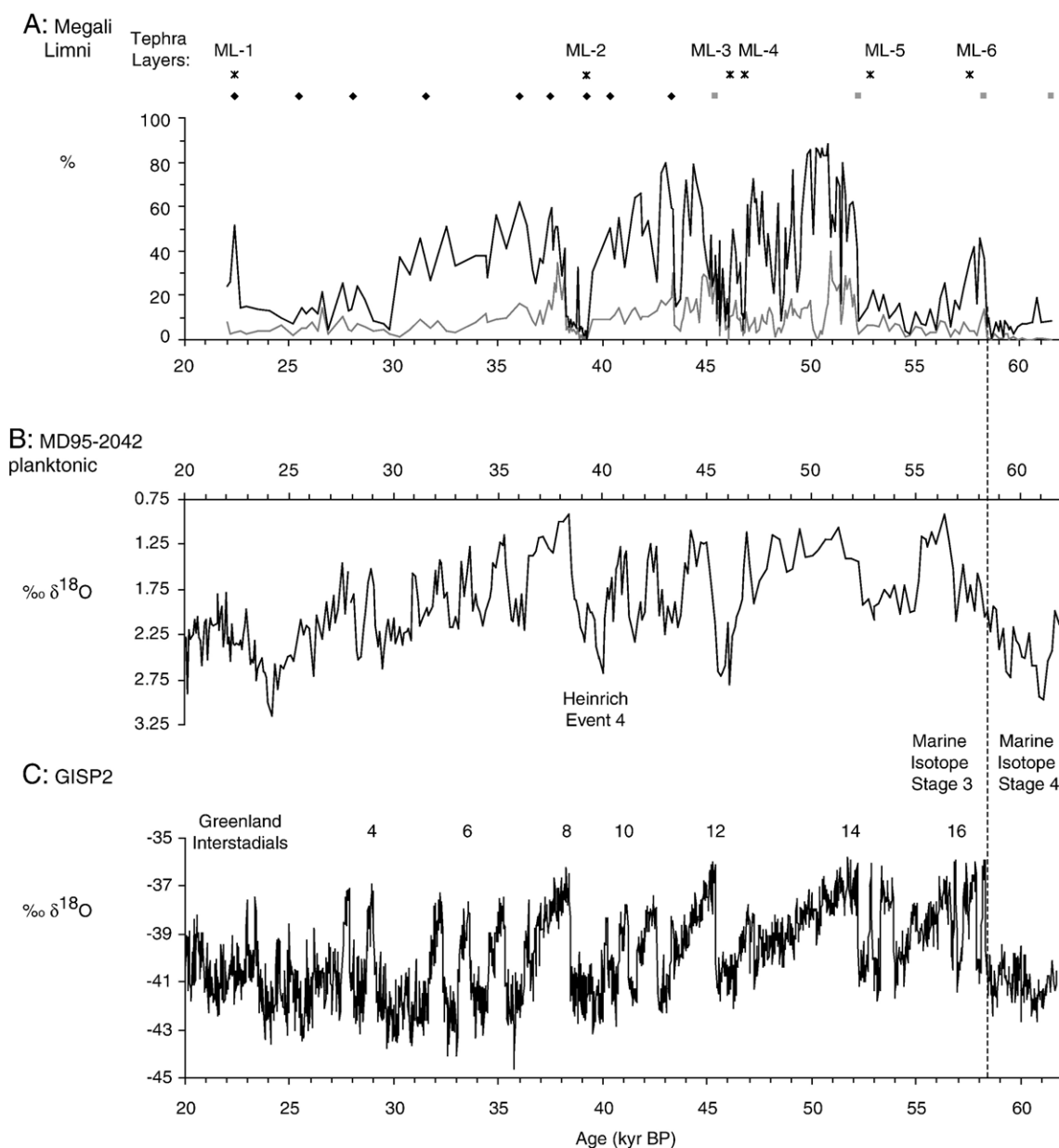


Fig. 9. A: Summary pollen percentage curves for the ML record (black line: arboreal pollen, grey line: arboreal pollen minus *Juniperus*, *Betula* and *Pinus*). The black diamonds represent control points (radiocarbon dates and tephra ages) of the ML age model, the grey squares are alignment points and the asterisks show the position of the tephra layers; B: Variation in the $\delta^{18}\text{O}$ composition of planktonic foraminifera (Shackleton et al., 2000) and C: Variation in the $\delta^{18}\text{O}$ composition of ice in GISP2 (Stuiver and Grootes, 2000).

■ The age of the unidentified ML-6 tephra layer is 58 ± 5.69 ka BP towards the end of GIS 17.

It is worth noting that four out of the six tephra layers of the ML record occur at the end of interstadials during the transition from warm to cold. This includes Y-2 (after GIS 2); Y-5 (after GIS 9); Y-6 (after a short-lived warming shortly before GIS 14) and ML-6 (after GIS

17). This pattern is different from that observed on the European mainland, for example, where there is a tendency for rates of volcanic activity to peak as the ice retreats and the lithosphere flexes during post-glacial phases (Nowell et al., 2006). The difference may well reflect the different response of island volcanoes to climate forcing, as a result for example of sea-level drawdown (cf. McGuire et al., 1997).

In view of the potential link between rapid decreases in global temperatures/changes in sea-level and large volcanic eruptions, due to the potential destabilisation of volcanic islands (McGuire et al., 1997 and references therein) this observation gains additional interest. The nature of sea-level changes associated with millennial-scale climatic variability during the last glacial period is complex. According to recent evidence from the Red Sea, it is suggested that during MIS 3 and 4 sea-level fluctuated up to 35 m (Siddall et al., 2003), before reaching its maximum lowstand of ca. –120 m during the last glacial maximum (Chappell, 2002; Lambeck et al., 2002). In the context of the numerous transitional phases that occur in the ML record and the statistically limited number of eruptions present no firm conclusion can be drawn.

Finally, the discovery of the aforementioned tephra layers on Lesvos Island is of significant importance in terms of the amplitude of their corresponding eruptions (Fig. 6). In particular, the discovery of the Y-6 tephra marker at Megali Limni significantly increases the area of its distribution and hence the violence of the ‘Green Tuff’ eruption, while the presence of the Nisyros–Yali tephra refutes the current belief of limited tephra dispersal and small magnitude eruptions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jvolgeores.2007.02.002](https://doi.org/10.1016/j.jvolgeores.2007.02.002).

References

- Allen, S.R., Gas, R.A.F., 1998. Lateral variations within coarse co-ignimbritic lithic breccias of the Kos Plateau Tuff, Greece. *Bulletin of Volcanology* 59, 356–377.
- Allen, S.R., McPhie, J., 2000. Water-settling and resedimentation of submarine rhyolitic pumice at Yali, eastern Aegean, Greece. *Journal of Volcanology and Geothermal Research* 85, 285–307.
- Allen, S.R., Stadkauer, E., Keller, J., 1999. Stratigraphy of the Kos Plateau Tuff: product of a major Quaternary rhyolitic eruption in the eastern Aegean, Greece. *International Journal of Earth Sciences* 88, 132–156.
- Barberi, F., Navarro, J.M., Rosi, M., Santacroce, R., Sbrana, A., 1988. Explosive interaction of magma with ground water: insights from xenoliths and geothermal drillings. *Rendiconti della Società Italiana di Mineralogia e Petrologica* 43, 901–926.
- Blundy, J.D., Cashman, K.V., 2001. Ascent-driven crystallisation of dacite magmas at Mount St Helens, 1980–1986. *Contributions to Mineralogy and Petrology* 140, 631–650.
- Bond, A., 1976. Multiple sources of pumice in the Aegean. *Nature* 259, 194–195.
- Borchardt, G.A., Harward, M.E., Schmitt, R.A., 1972. Correlation of volcanic ash deposits by activation analysis of glass separates. *Quaternary Research* 1, 247–260.
- Buettner, A., Kleinhans, I.C., Rufer, D., Hunziker, J.C., Villa, I.M., 2005. Magma generation at the easternmost section of the Hellenic arc: Hf, Nd, Pb and Sr isotope geochemistry of Nisyros and Yali volcanoes (Greece). *Lithos* 83, 29–46.
- Carey, S.N., 1997. Influence of convective sedimentation on the formation of widespread tephra fall layers in the deep sea. *Geology* 25, 839–842.
- Chappell, J., 2002. Sea level changes forced ice breakouts in the Last Glacial cycle: new results from coral terraces. *Quaternary Science Reviews* 21, 1229–1240.
- Civetta, L., Cornette, Y., Crisci, G., Gillot, P.Y., Orsi, G., Requejos, C.S., 1984. Geology, geochronology and chemical evolution of the Island of Pantelleria. *Geological Magazine* 121, 541–668.
- Civetta, L., Corennet, Y., Gillot, P.Y., Orsi, G., 1988. The eruptive history of Pantelleria (Sicily Channel) in the last 50 ka. *Bulletin of Volcanology* 50, 47–57.
- Civetta, L., Orsi, G., Pappalardo, L., Fisher, R.V., Heiken, G., Ort, M., 1997. Geochemical zoning, mingling, eruptive dynamics and depositional processes; the Campanian Ignimbrite, Campi Flegrei caldera, Italy. *Journal of Volcanology and Geothermal Research* 75, 183–219.
- Clift, P., Blusztajn, J., 1999. The trace-element characteristics of Aegean and Aeolian volcanic arc marine tephra. *Journal of Volcanology and Geothermal Research* 92, 321–347.
- Combouret, N., Turon, J.L., Zahn, R., Capotondi, L., Londeix, L., Pahnke, K., 2002. Enhanced aridity and atmospheric high-pressure stability over the western Mediterranean during the North Atlantic cold events of the 50 k.y. *Geology* 30, 863–866.
- Cornette, Y., Crisci, G.M., Gillot, P.Y., Orsi, G., 1983. Recent volcanic history of Pantelleria: a new interpretation. *Journal of Volcanology and Geothermal Research* 17, 361–373.
- Cramp, A., Vitaliano, C., Collins, M.B., 1989. Identification and dispersal of the Campanian ash layer (Y-5) in the sediments of the Eastern Mediterranean. *Geo-Marine Letters* 9, 19–25.
- De Vivo, B., Rolandi, G., Gans, P.B., Calvert, A., Bohrsen, W.A., Spera, F.J., Belkin, H.E., 2001. New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy). *Mineralogy and Petrology* 73, 47–65.
- Deino, A.L., Southon, J., Terrasi, F., Campatola, L., Orsi, G., 1994. ^{14}C and $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of the Campanian Ignimbrite, Phlegrean Fields, Italy. *ICOG 1994, Abstracts, Berkeley*.
- Deniel, C., Aydar, E., Gourgaud, A., 1998. The Hasan Dagi stratovolcano (Central Anatolia, Turkey): evolution from calc-

- alkaline to alkaline magmatism in a collision zone. *Journal of Volcanology and Geothermal Research* 87, 275–302.
- Di Paola, G.M., 1974. Volcanology and petrology of Nisyros Island (Dodecanese, Greece). *Bulletin Volcanologique* 38, 944–987.
- Druitt, T.H., 1985. Vent evolution and lag breccia formation during the Cape Riva eruption on Santorini, Greece. *Journal of Geology* 13, 439–454.
- Druitt, T.H., Brenchley, P.J., Gokten, Y.E., Francaviglia, V., 1995. Late Quaternary rhyolitic eruptions from the Acigol Complex, central Turkey. *Journal of the Geological Society of London* 152, 655–667.
- Druitt, T.H., Edwards, L., Mellors, R.M., Pyle, D.M., Sparks, R.S.J., Lanphere, M., Davies, M., Barreiro, B., 1999. Santorini Volcano. Geological Society London, Memoir 19. 178pp.
- Eastwood, W.J., Pearce, N.J.G., Westgate, J.A., Perkins, W.T., Lamb, H.F., Roberts, N., 1999. Geochemistry of Santorini tephra in lake sediments from Southwestern Turkey. *Global and Planetary Change* 21, 17–29.
- Eriksen, U., Friedrich, W.L., Buchardt, B., Tauber, H., 1990. The Strongyle Caldera: geological, paleontological and stable isotope evidence from radiocarbon dated stromatolites from Santorini. In: Hardy, D.A., Keller, J., Galanopoulos, V.P., Flemming, N.C., Druitt, T.H. (Eds.), *Thera and the Aegean World III, Proceedings of the Third International Congress, The Thera Foundation, Santorini, Greece*, pp. 139–150.
- Fairbanks, R.G., Mortlock, R.A., Chiu, T.-C., Cao, L., Kaplan, A., Guilderson, T.P., Fairbanks, T.W., Bloom, A.L., Grootes, P.M., Nadeau, M.-J., 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}\text{Th}/^{234}\text{U}/^{238}\text{U}$ and ^{14}C dates on pristine corals. *Quaternary Science Reviews* 24, 1781–1796.
- Federman, A.N., Carey, S.N., 1980. Electron Microprobe correlation of tephra layers from Eastern Mediterranean abyssal sediments and the Island of Santorini. *Quaternary Research* 13, 160–171.
- Francalanci, L., Varekamp, J.C., Vougioukalakis, G., Defant, M.J., Innocenti, F., Manetti, P., 1995. Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros Volcano, Greece. *Bulletin of Volcanology* 56, 601–620.
- Hardiman, J.C., 1996. Quaternary Volcanism on Nisyros, Greece. Ph. D. Thesis, University of Cambridge, Cambridge, 336p.
- Hardiman, J.C., 1999. Deep sea tephra from Nisyros Island, Eastern Aegean Sea, Greece. In: Firth, C.R., McGuire, W.J. (Eds.), *Volcanoes in the Quaternary*. Geological Society of London Special Publications, pp. 69–88.
- Johnsen, S., Dahl-Jensen, D., Gundestrup, N.S., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjornsdottir, A.E., White, J., 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and North GRIP. *Journal of Quaternary Science* 16 (4), 299–307.
- Keller, J., Ryan, W.B.F., Ninkovich, D., Altherr, R., 1978. Explosive volcanic activity in the Mediterranean over the past 200,000 yr as recorded in deep-sea sediments. *Bulletin Geological Society of America* 89, 591–604.
- Keller, J., Gillot, P.Y., Rehren, T., Stadkauer, E., 1989. Chronostratigraphic data for the volcanism in the eastern Hellenic Arc: Nisyros and Kos. *Terra Abstracts* 1, 354.
- Keller, J., Rehren, T., Stadkauer, E., 1990. Explosive volcanism in the Hellenic Arc: a summary and review. In: Hardy, D.A., Keller, J., Galanopoulos, V.P., Flemming, N.C., Druitt, T.H. (Eds.), *Thera and the Aegean World III, Proceedings of the Third International Congress, The Thera Foundation, Santorini, Greece*, pp. 13–26.
- Kuzucuoglu, C., Pastre, J.F., Black, S., Ercan, T., Fontugne, M., Guillou, H., Hatte, C., Karabiyyikoglu, M., Orth, P., Turkecan, A., 1998. Identification and dating of tephra layers from Quaternary sedimentary sequences of Inner Anatolia, Turkey. *Journal of Volcanology and Geothermal Research* 85, 153–172.
- Lambeck, K., Esat, T.M., Potter, E.-K., 2002. Links between climate and sea levels for the past three million years. *Nature* 419, 199–206.
- Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B., 1986. A chemical classification of volcanic rocks based on the Total Alkali-Silica diagram. *Journal of Petrology* 27 (3), 745–750.
- Limburg, E.M., Varekamp, C., 1991. Young Pumice deposits on Nisyros, Greece. *Bulletin of Volcanology* 54, 68–77.
- Mahood, G., Hildreth, W., 1983. Nested calderas and trapdoor uplift at Pantelleria, Strait of Sicily. *Geology* 11, 722–726.
- Margari, V., 2004. Late Pleistocene vegetational and environmental changes on Lesbos Island, Greece. Ph.D. Thesis, University of Cambridge, Cambridge, UK, 400p.
- Margari, V., Tzedakis, P.C., Bryant, C., Gibbard, P., in preparation. Character of vegetational and environmental changes in southern Europe during the last glacial period; evidence from Lesbos Island, Greece.
- McDonough, W.F., Sun, S.-s., 1995. The composition of the Earth. *Chemical Geology* 120, 223–254.
- McGuire, W.J., Howarth, R.J., DFirth, C.R., Solow, A.R., Pullen, A.D., Saunders, S.J., Stewart, I.S., Vita-Finzi, C., 1997. Correlation between rate of sea-level change and frequency of explosive volcanism in the Mediterranean. *Nature* 389, 473–476.
- Mellis, O., 1954. Volcanic ash horizons in deep-sea sediments from the Eastern Mediterranean. *Deep-Sea Research* 2 (2), 89–92.
- Narcisi, B., 1996. Tephrochronology of a late Quaternary lacustrine record from the Monticchio maar (Vulture volcano, southern Italy). *Quaternary Science Reviews* 15, 155–165.
- Narcisi, B., Vezzoli, L., 1999. Quaternary stratigraphy of distal tephra layers in the Mediterranean—an overview. *Global and Planetary Change* 21, 31–50.
- Ninkovich, D., Sparks, R.S.J., Ledbetter, M.T., 1978. The exceptional magnitude and intensity of the Toba eruption, Sumatra: an example of the use of deep-sea tephra layers as a geological tool. *Bulletin of Volcanology* 41, 286–298.
- Nowell, D.A.G., Jones, M.C., Pyle, D.M., 2006. Episodic Quaternary volcanism in France and Germany. *Journal of Quaternary Science* 21, 645–675.
- Olausson, E., 1961. Reports Swedish Deep-Sea Expedition 1947–48.
- Orsi, G., Ruvo, L., Scarpati, C., 1991. The recent explosive volcanism at Pantelleria. *Geologische Rundschau* 80 (1), 187–200.
- Orsi, G., Sheridan, G., 1984. The Green Tuff of Pantelleria: Rheoignimbrite or Rheomorphic Fall? *Bulletin of Volcanology* 47, 611–626.
- Pappalardo, L., Civetta, L., de Vita, S., Di Vito, M., Orsi, G., Carandente, A., Fisher, R.V., 2002. Timing of magma extraction during the Campanian Ignimbrite eruption (Campi Flegrei Caldera). *Journal of Volcanology and Geothermal Research* 114, 479–497.
- Paterne, M., Guichard, F., Labeyrie, J., 1988. Explosive activity of the South Italian Volcanoes during the past 80,000 years as determined by marine tephrochronology. *Journal of Volcanology and Geothermal Research* 34, 153–172.
- Pearce, J.A., 1983. The role of sub-continental lithosphere in magma genesis at destructive plate margins. In: Hawkesworth, C.J., Norry, M.J. (Eds.), *Continental Basalts and Mantle Xenoliths*, Nanwich, pp. 230–249.

- Pe-Piper, G., Piper, D.J.W., Perissoratis, C., 2005. Neotectonics and the Kos Plateau Tuff eruption of 161 ka, South Aegean Arc. *Journal of Volcanology and Geothermal Research* 139, 315–338.
- Pichler, H., Friedrich, W., 1976. Radiocarbon dates of Santorini volcanics. *Nature* 262, 373–374.
- Pollard, A.M., Blockley, S.P.E., Ward, K.R., 2003. Chemical alteration of tephra in the depositional environment: theoretical stability modelling. *Journal of Quaternary Science* 18 (5), 385–394.
- Pyle, D.M., 1989. The thickness, volume and grainsize of tephra fall deposits. *Bulletin of Volcanology* 51, 1–15.
- Pyle, D.M., 1990. New volume estimates for the Minoan eruption. In: Hardy, D.A., Keller, J., Galanopoulos, V.P., Flemming, N.C., Druitt, T.H. (Eds.), *Thera and the Aegean World III*, Proceedings of the Third International Congress, The Thera Foundation, Santorini, Greece, pp. 113–121.
- Pyle, D.M., 1999. Widely dispersed Quaternary tephra in Africa. *Global and Planetary Change* 21, 95–112.
- Pyle, D.M., Ricketts, G.D., Margari, V., van Andel, T.H., Sinitsyn, A.A., Praslov, N.D., Lisitsyn, S., 2006. Wide dispersal and deposition of distal tephra during the Pleistocene ‘Campanian Ignimbrite/Y5’ eruption, Italy. *Quaternary Science Reviews* 25, 2713–2728.
- Reimer, P.J., Baillie, M.G.L., Bard, E., Beck, J.W., Blackwell, P.G., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Reimer, R.W., Southon, J.R., Stuiver, M., van der Plicht, J., Weyhenmeyer, C.E., 2006. Comment on “Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}\text{Th}/^{234}\text{U}/^{238}\text{U}$ and ^{14}C dates on pristine corals” by R.G. Fairbanks et al. (*Quaternary Science Reviews* 24 (2005) 1781–1796) and “Extending the radiocarbon calibration beyond 26,000 years before present using fossil corals” by T.-C. Chiu et al. (*Quaternary Science Reviews* 24 (2005) 1797–1808). *Quaternary Science Reviews* 25, 855–862.
- Roucoux, K.H., Shackleton, N.J., Abreu, L., Schonfeld, J., Tzedakis, P.C., 2001. Combined Marine proxy and pollen analyses reveal rapid Iberian vegetation response to North Atlantic millennial-scale climate oscillations. *Quaternary Research* 56, 128–132.
- Saminger, S., Peltz, C., Bichler, M., 2000. South Aegean volcanic glass: separation and analysis by INAA and EPMA. *Journal of Radioanalytical and Nuclear Chemistry* 245, 375–383.
- Sanchez-Goñi, M., Turon, J.-L., Eynaud, F., Gendreau, S., 2000. European climatic response to millennial-scale changes in the atmosphere–ocean system during the last glacial period. *Quaternary Research* 54, 394–403.
- Sánchez Goñi, M.F., Sierro, F.J., Peyrouquet, J.-P., Grimalt, J.O., Shackleton, N.J., Cacho, I., Turon, J.-L., Guiot, J., 2002. Synchronicity between marine and terrestrial responses to millennial scale climate variability during the last glacial period in the Mediterranean region. *Climate Dynamics* 19, 95–105.
- Seymour, St K., 1996. Geochemistry of the Yali volcano rhyolites and their relationship to the volcanic products of Nisyros, Aegean Volcanic Arc. *Neues Jahrbuch für Mineralogie Monatshefte* H.2, 52–72.
- St, K., Vlassopoulos, D., 1992. Magma mixing at Nisyros volcano, as inferred from incompatible trace elements systematics. *Journal of Volcanology and Geothermal Research* 50, 273–299.
- Seymour, St K., Christanis, K., Bouzinos, A., Papazisimou, S., Papatheodorou, G., Moran, E., Denes, G., 2004. Tephrostratigraphy and tephrochronology in the Philippi peat basin, Macedonia, Northern Hellas (Greece). *Quaternary International* 121, 53–65.
- Shackleton, N.J., Hall, M.A., Vincent, E., 2000. Phase relationship between millennial-scale events, 64,000–24,000 years ago. *Paleoceanography* 15, 565–569.
- Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, Ch., Meischner, D., Schmeltzer, I., Smeed, D.A., 2003. Sea-level fluctuations during the last glacial period. *Nature* 423, 853–857.
- Signorelli, S., Vaggelli, G., Romano, C., Carroll, M.R., 2001. Volatile element zonation in Campanian Ignimbrite magmas (Phlegrean Fields, Italy): evidence from the study of glass inclusions and matrix glasses. *Contributions to Mineralogy and Petrology* 140, 543–553.
- Sigurdsson, H., Sparks, R.S.J., Carey, S.N., Huang, T.C., 1980. Volcanogenic sedimentation in the Lesser Antilles Arc. *Journal of Geology* 88, 523–540.
- Smith, P.E., York, D., Chen, Y., Evensen, N.M., 1996. Single crystal ^{40}Ar – ^{39}Ar dating of a Late Quaternary paroxysm on Kos, Greece: concordance of terrestrial and marine ages. *Geophysical Research Letters* 23, 3047–3050.
- Sparks, R.S.J., Huang, T.C., 1980. The volcanological significance of deep-sea ash layers associated with ignimbrites. *Geological Magazine* 117, 425–436.
- Stuiver, M., Grootes, P.M., 2000. GISP2 oxygen isotope ratios. *Quaternary Research* 53, 277–284.
- Ton-That, T., Singer, B., Paterne, M., 2001. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of latest Pleistocene (41 ka) marine tephra in the Mediterranean Sea: implications for global climate records. *Earth and Planetary Science Letters* 184, 645–658.
- Troels-Smith, J., 1955. Characterisation of unconsolidated sediments. *Danmarks Geologiske Undersøgelse Raekke IV* (3), 1–73.
- Tzedakis, P.C., Lawson, I.T., Frogley, M.R., Hewitt, G.M., Preece, R.C., 2002. Buffered tree population changes in a quaternary refugium: evolutionary implications. *Science* 297, 2044–2047.
- Tzedakis, P.C., Frogley, M.R., Lawson, I.T., Preece, R.C., Cacho, I., de Abreu, L., 2004. Ecological thresholds and patterns of millennial-scale climate variability: the response of vegetation in Greece during the last glacial period. *Geology* 32, 109–112.
- Vezzoli, L., 1991. Tephra layers in the Bannock Basin (Eastern Mediterranean). *Marine Geology* 100, 21–34.
- Vinci, A., 1983. A new ash layer ‘Nisyros Layer’ in the Aegean Sea sediments. *Bollettino di Oceanologia Teorica ed Applicata* 1, 341–342.
- Vinci, A., 1985. Distribution and chemical composition of tephra layers from Eastern Mediterranean abyssal sediments. *Marine Geology* 64, 143–155.
- Wagner, G.J., Storzer, D., Keller, J., 1976. Spaltspurendatierungen quarterer Gesteingläser aus dem Mittelmeerraum. *Neues Jahrbuch für Mineralogie Monatshefte* 84–94.
- Wulf, S., Kraml, M., Kuhn, T., Schwartz, M., Inthorn, M., Keller, J., Kusu, I., Halbach, P., 2002. Marine tephra from the Cape Riva eruption (22 ka) of Santorini in the Sea of Marmara. *Marine Geology* 183, 131–141.
- Wulf, S., Kraml, M., Brauer, A., Keller, J., Negendank, J.F.W., 2004. Tephrochronology of the 100 ka lacustrine sediment record of Lago Grande di Monticchio (southern Italy). *Quaternary International* 122, 7–30.
- Wyers, G.P., Barton, M., 1989. Polybaric evolution of calc-alkaline magmas from Nisyros, Southeastern Hellenic Arc, Greece. *Journal of Petrology* 30, 1–37.