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South Aegean volcanic glass: Separation and analysis by INAA and EPMA

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Pumice from the major volcanic sources (Milos, Nisyros, Yali, Kos and Santorini) in the South Aegean region was investigated to reveal the differences between the composition of the bulk material, which contains a certain percentage of crystallites, and the pure glass phase, which is the main constituent. The knowledge of these differences is important for the identification of vitric tephra layers found in the Eastern Mediterranean region in archaeological context, in deep sea drilling cores and lake sediments. Eruption products, deposited at some distance, show not only a decrease in their grain size, but also have usually lost their crystalline fraction due to gravity separation and consist only of glass shards. Major element distributions in such layers and in pumiceous glass are not sufficient for a reliable identification of the volcanic source, as several eruptions are known to have produced chemically very similar tephra layers in this region. Trace element data, especially of the rather immobile rare earth elements (REEs), can provide greater information on tephra originating from different volcanic eruptions. Therefore, a technique has been developed to separate the glass phase from different primary pumices to reveal differences in their trace element distributions. The concentrations of the major constituents, in particular Al, Ca, Fe, Mg, Mn, Na, Si, and Ti were determined by electron probe microanalysis (EPMA), those of Al, As, Ba, Ca, Ce, Co, Cr, Cs, Dy, Eu, Fe, Hf, K, La, Lu, Mn, Na, Nd, Rb, Sb, Sc, Sm, Ta, Th, Ti, U, V, Yb and Zr by instrumental neutron activation analysis. Subtle differences between the compositions of the glass phase and the bulk material are explained by differentiation during partial crystallization. Their applicability to the classification of tephra layers is demonstrated.

Introduction

Major volcanic eruptions have been associated with widespread environmental and cultural effects[1] but can also provide valuable informations in archaeological context and insights into ancient cultures. The major volcanic centres in the South Aegean region, Milos, Nisyros, Yali, Kos and Santorini (Thera), are situated in the Hellenic arc, which represents one of the most important regions of volcanic activity in the Mediterranean (Fig. 1). As a consequence of tectonic activity, a collision- and subduction process started about 12Ma ago involving the Eurasian, Turkish and African plates.[2,3] Subducted crustmaterial liquefies at least partially due to subcrustal heating and the produced, differentiated magma feeds the island arc volcanoes. One of the most important volcanic eruptions in this region, that produced a remarkable quantity of pumice and tephra, was the "Minoan eruption" of the Thera volcano (Santorini archipelago, Greece) in the Second Millenium B.C., by which the so called Bo-layer or Upper Pumice sheet was deposited.[4–7] The subduction process is also responsible for the young quaternary volcanic activity on other islands of the Hellenic Arc. On Milos, Nisyros, Yali and Kos one or several volcanic events led to the formation of more or less voluminous layers similar to that of the "Minoan eruption" on Santorini.

A volcanic explosion of such magnitude happens in several phases, during which tremendous amounts of lava, ash and rock are erupted.[1,8,9] During the first phase, the so-called Plinian phase, the eruption velocity and the height of the eruption column reach their maximum, with varying quantities of volcanic dust entering the high atmosphere. In this way the particles are transported over great distances and deposited as a practically synchronous tephra layer. This is due to the fact that the Plinian phase lasts only for a few hours or days.[10] Therefore such layers form important time-synchronous stratigraphic marker horizons (datum lines), because they allow the correlation of sites across entire regions, as well as synchronization of local archaeological stratigraphies, deep sea drilling cores, and lake sediments.[11–16]

Usually, such different deposits show typical but often very subtle differences in their chemical compositions, so that an identification only by their trace element distribution is possible.[17–19] However, previous studies have shown that the composition of tephra layers may change with the distance from the vent due to the progressive loss of the crystalline fraction.[19–21] Concerning the volcanic centres in question, the material erupted during the Plinian phase consists mainly of pumice, which is a highly vesicular, light coloured volcanic rock with a certain percentage of crystallites in a glassy matrix. Mechanical stress during the eruption leads to the fragmentation of vesicle walls and the formation of an extremely fine grained glass fraction which is easily transported to high altitudes. With increasing distance from the volcano, the distribution of elements thus approaches that of the pure glass fraction. The Minoan pumice contains only relatively small (sub mm) crystallites while others, for example the Kos Plateau Tuff pumice, contain crystals up to several mm in length.

To ensure confident assignment or enable distinction of discoveries of tephra found in archaeological context to the primary volcanic source, a comparison of trace element distributions not only of the bulk material, but also of the pure glass phase is required.

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Fig. 1. Geographical positions

The aim of this work was to draw a comparison of pumice from the main geological units on Milos, Nisyros, Yali, Kos and Santorini to their pure glass phase, to establish a database for the identification of unknown tephra layers in the Eastern Mediterranean found in a period highly important for archaeological science. Such layers have been found in deep sea drilling cores, in lake sediments in Turkey, as well as in archaeological excavations.[12,14–16,22]

Experimental

Sample preparation

Representative pumice samples of the most important geological units on Milos, Nisyros, Yali, Kos and Santorini were investigated. Previous studies showed that it is possible to classify several groups of typical compositions of pumice on these Aegean islands.[19] This work deals with the separation of the pure glass phase from 12 samples and the comparison with the bulk material. The geological units to which the samples belong to are given in Table 1, detailed information about the sampling locations are stated in Table 2.

Before sampling, weathered rock surfaces were removed to a depth of at least 150 mm. Sample surface cleaning was done by immersion in distilled water in an ultrasonic bath. The samples for the analysis of the bulk material were then crushed with PE tools, dried at 110 °C, and homogenized by grinding in an agate mortar to a grain size <3 μm. To separate the pure glass phase, however, a representative part of the samples was treated differently. To avoid destruction of the crystallites, the sample material was carefully crushed with PE tools instead of grinding. A fraction suitable for separation was obtained by sieving (1 mm mesh size). The following separation technique simulates the natural process on a laboratory scale and is based on the fact that in an air flow, crystallites are not transported as far as vitric particles because of their higher specific mass and their morphological properties. The separation is achieved by means of a rotating glass tube of 30 mm diameter through which a continuous flow of nitrogen transports the particles. By mounting the tube with an inclination of about 45° the material deposited in the tube is transported back to the input by gravity. The suspended fraction was collected on a polyester filter (Fig. 2).

To purify the separated glass phase and to eliminate filter fibres or smallest crystallites, all glass samples were sedimented in a glass tube (length 1.83 m, diameter 40 mm) filled with distilled water. The different shape and density of the particles lead to a significantly slower sedimentation of the glass phase. A first separation was applied after 20 minutes to remove particles exceeding about 50 μm. This fraction contains all possible impurities like fibres and composite grains. The glass fraction with a maximum grain size of about 50 μm and an average of about 15 μm is collected following up. A total sedimentation time of 24 hours was applied. The purity of the separated fractions was assessed by polarization microscopy and proved that the

concentration of crystallites was lower than 1%. The crystalline phases comprise in varying concentrations the minerals quartz, plagioclase, pyroxene, sanidine, biotite, apatite and ore minerals.[23–29]

Analysis

The concentrations of the major elements were determined by electron probe microanalysis (EPMA, CAMECA SX100) and a more extended spectrum of elements by instrumental neutron activation analysis (INAA). Glass analyses were carried out on polished thin sections at the Institute of Petrology, University of Vienna, using a Cameca SX100 electron microprobe equipped with four wavelength- and one energy-dispersive spectrometers. The acceleration voltage was 15 kV with beam current of 20 nA and beam width of 10 μm. Special measuring conditions (6 nA, 5 s measuring time) were chosen for the determination of Na to avoid losses due to diffusion and evaporation effects. 4–6 measurement runs were performed to achieve acceptable counting statistics for the different elements. The standards were natural and synthetic minerals and glasses, matrix corrections were made by PAP (Pouchou and Pichoir) procedures.[30]

Table 1. Aegean pumice deposits sampled for the separation of the glass phase

Milos:	Plakes group (MLO 2, MLO 5), Sarakiniko (MLO 8), Papafrangas (MLO 14)
Nisyros:	Lower Caldera Pumice-UCB (NIS 2), Upper Caldera Pumice-OCB (NIS 23)
Yali:	Yali 1 main pumice (YLI 2), Yali 2 layer on top of the main pumice (YLI 5)
Kos:	Pumice from the Kos-Plateau-Tuff (KOS 1), Plinian layer of the KPT (KOS 3)
Santorini:	Bm – Middle Pumice (SAT 4), Bo – Upper Pumice (SAT 5)

Table 2. Location of sampling sites

MLO 2:	Milos: outcrop on the valley road leading to the north, 250 m to the north of Plakes
MLO 5:	Milos: large outcrop with caverns, ca 100 m eastern to the footpath leading from Adamas to Plaka
MLO 8:	Milos: 35 m above sea level, central part of the deposit, beach of Sarakiniko
MLO 14:	Milos: Fjord of Papafrangas
NIS 2:	Nisyros: outcrop on the road near Ag. Io. Theologos, half way from Chira to Nikia
NIS 23:	Nisyros: top layer in the quarry south of Pali
YLI 2:	Yali: base of the pumice quarry
YLI 5:	Yali: ca 160 m above sea level, top layer of the qarry
KOS 1:	Kos: half way between Kardamena and the Airport
KOS 3:	Kos: old main road Antimachia–Kephalos, near Ag. Georgios
SAT 4:	Santorini: Thera, Athinios
SAT 5:	Santorini: Thera, pumice quarry near Fira

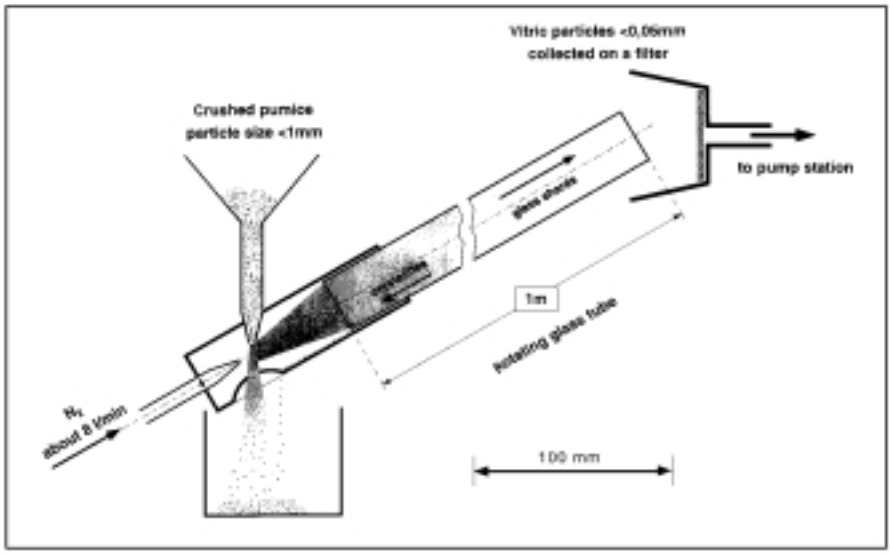

Fig. 2. Apparatus for the separation of crystalline particles from vitric tephra

For neutron activation analysis 3 irradiation cycles and 7 measurement runs were applied. For the determination of short-lived radionuclides about 150 mg of the samples and of suitable standards (BCR 142 Light Sandy Soil, NIST SRM 1633b Coal Fly Ash, CANMET Reference Soil SO-1 and Rhyolith GBW-07113) were weighed into PE capsules and irradiated for 1 minute in the irradiation position of the pneumatic transfer system of the Triga Mark-II reactor of the Atominstitut at a thermal neutron flux of $3 \cdot 10^{12}$ n·cm^{-2}·s^{-1}. The first gamma-spectrum was obtained after a decay time of 5 minutes to determine Al, Ca and Ti. About 3 hours later a second measurement was performed to quantify Dy, K, Mn and Na. For the determination of Al, the reaction ^{27}Al(n,γ) ^{28}Al was used. The additional production of ^{28}Al by the reaction ^{28}Si(n,p) ^{28}Al was corrected for. The amount produced was determined by the irradiation of high purity quartz, the respective peak area was calculated from the known Si concentrations of the samples and subtracted from the ^{28}Al peak.

For the determination of long-lived radionuclides about 150 mg of each sample and standard were sealed into Suprasil™ quartz glass vials. All samples were irradiated for 66 hours in the ASTRA-reactor of the Austrian Research Centre Seibersdorf at a thermal neutron flux of $2.4 \cdot 10^{13}$ n·cm^{-2}·s^{-1}. After a decay time of 7 days the activities of the medium-lived nuclides and after another 32 days the activities of the long-lived nuclides were measured.

The samples „MLO 8 glass“, „KOS 3 glass“ as well as the specific bulk material „MLO 8“ and „KOS 3“ were irradiated for 150 hours in the Reactor of the KFKI Atomic Energy Research Institute, Hungary, at a thermal neutron flux of $4 \cdot 10^{13}$ n·cm^{-2}·s^{-1}. Three measurement runs were applied after a decay time of 8, 10 and 28 days. All measurements were performed with a 151 cm^3 HPGe-detector connected to a PC-based multichannel analyzer. A preloaded filter and a loss free counting system improved the quality of the spectra obtained.[31,32] Table 3 shows the activation products and the gamma-lines used for analysis.

Results and discussion

The results obtained by INAA and EPMA are given in Tables 4 and 5. Likewise, the major element distributions obtained by INAA are in good accordance with the results of the microprobe. The differences between the glass phase and the bulk material depend on the percentage of crystallites in the glassy matrix and will be discussed below.

Milos: Glass separated from pumice of the Plakes group and Sarakiniko shows only minor differences in comparison to the bulk material. “MLO 2 glass” (Plakes) is slightly enriched in Al and depleted in Na, probably as result of caolinitization. The glass fractions of MLO 5 (Plakes) and MLO 8 (Sarakiniko) turned out to be very similar to the primary pumice. Glass separated from pumice with origin in Papafrangas displays a depletion in Al, Ba, Ca and Na, elements which are enriched in feldspar, biotite and pyroxene. A typical enrichment/depletion pattern is shown in Fig. 3, displaying the values for MLO 5.

Nisyros: In contrast to glass from Milos, significant differences between glass and bulk material of both samples (NIS 2 and NIS 23), rich in crystallites could be revealed. The depletion in Al, Ca, Eu and Na is explained by the separation of minerals as feldspar, especially plagioclase, while the depletion of Co, Fe, Mn and Sc is caused by their enrichment in pyroxene and ore-mineral components. The enrichment of K, Rb and Cs in the glassy matrix is an indicator for the absence of sanidine. Fig. 4 shows the enrichment/depletion pattern for the Upper caldera pumice sample NIS 23.

Table 3. Activation products, half-lives and gamma-energies used for analyses

Element	Activation product	Half-life	Gamma-energy, keV
Al	^{28}Al	2.2 m	1779
As	^{76}As	25.9 h	559
Ba	^{131}Ba	11.5 d	496
Ca	^{49}Ca	8.7 m	3084
Ce	^{141}Ce	32.5 d	145
Co	^{60}Co	5.27 a	1173
Cr	^{51}Cr	27.7 d	320
Cs	^{134}Cs	2.07 a	796
Dy	^{165}Dy	2.3 h	95
Eu	^{152}Eu	13.5 a	1408
Fe	^{59}Fe	44.5 d	1099
Hf	^{181}Hf	42.4 d	482
K	^{42}K	12.4 h	1525
La	^{140}La	40.3 h	1596
Lu	^{177}Lu	6.7 d	208
Mn	^{56}Mn	2.6 h	1811
Na	^{24}Na	15.0 h	1369
Nd	^{147}Nd	11.0 d	531
Rb	^{86}Rb	18.6 d	1077
Sb	^{124}Sb	60.2 d	1691
Sc	^{46}Sc	83.8 d	1120
Sm	^{153}Sm	46.3 h	103
Ta	^{182}Ta	114.4 d	1189
Th	^{233}Pa*	27.0 d	312
Ti	^{51}Ti	5.8 m	320
U	^{239}Np*	56.6 h	278
V	^{52}V	3.7 m	1434
Yb	^{169}Yb	32.0 d	177
Zr	^{95}Zr	64.0 d	757

* ^{233}Pa and ^{239}Np are produced by the β-decay of ^{233}Th ($T_{1/2}$ = 22.3 min) and ^{239}U ($T_{1/2}$ = 23.5 min), which were formed by neutron capture of ^{232}Th and ^{238}U, respectively.

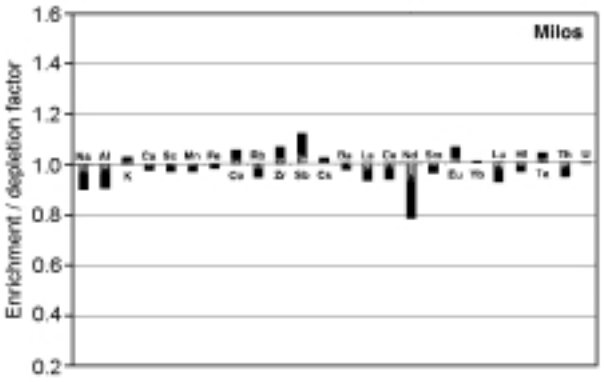

Fig. 3. Enrichment/depletion factors of elements in the glass fraction respective to the bulk material of MLO 5 (Plakes, Milos)

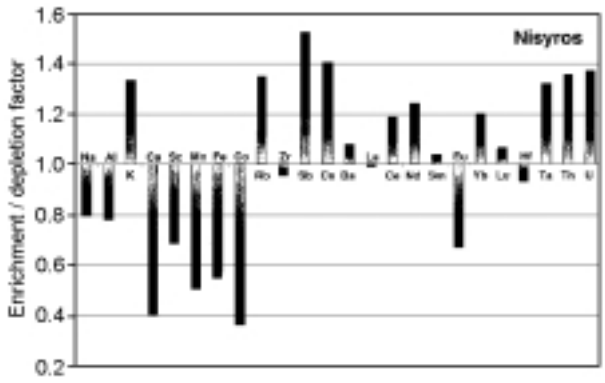

Fig. 4. Enrichment/depletion factors of elements in the glass fraction respective to the bulk material of NIS 23 (Upper Caldera Pumice, Nisyros)

Yali: Pumice from Yali has an extremly low content of minerals, which is confirmed by the achieved results, which show hardly any differences between the bulk material and the separated glass (Fig. 5).

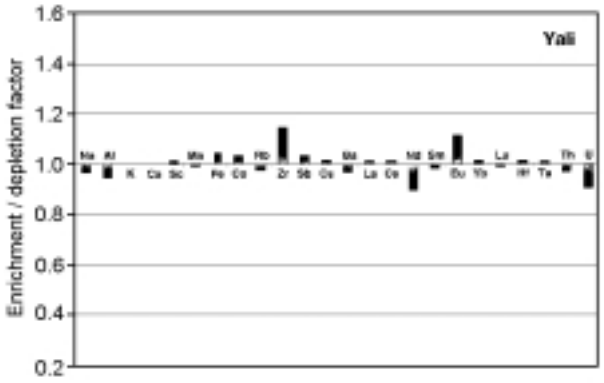

Fig. 5. Enrichment/depletion factors of elements in the glass fraction respective to the bulk material of YLI 2 (quarry main pumice, Yali)

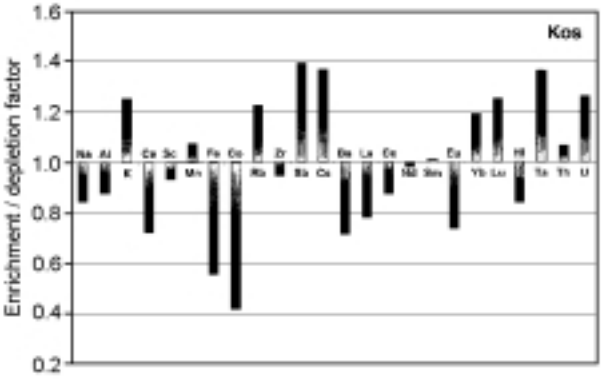

Fig. 6. Enrichment/depletion factors of elements in the glass fraction respective to the bulk material of KOS 1 (pumice from Kos Plateau Tuff)

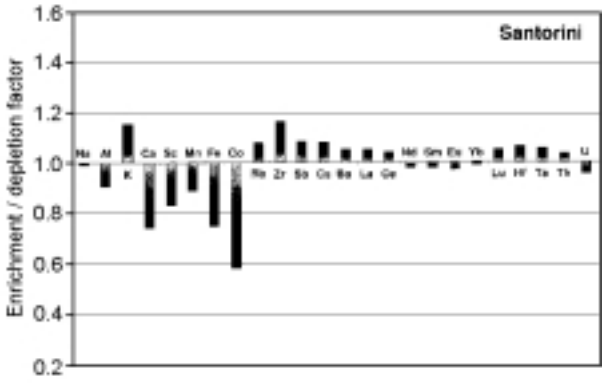

Fig. 7. Enrichment/depletion factors of elements in the glass fraction respective to the bulk material of SAT 5 (Upper pumice layer Bo1, Santorini)

Kos: In contrast to the results above, the concentrations of Al, Ba, Ca, Eu, Na, Sc, Ti and V show more significant differences between the bulk pumice and the glass phase due to their higher content of mineral phases such as quartz, plagioclase and biotite. Co, Fe and Sc are compatible elements and, therefore, not expected to be partitioned into the liquid, especially as titanomagnetite and ilmenite are present in the bulk pumice. The REE concentrations show clearly small but systematic differences between bulk material and glass. The enrichment in the glass phase increases significantly with the atomic number. Eu, however, is depleted due to its differentiation into plagioclase crystals as a divalent ion (Fig. 6).

Santorini: In comparison to the bulk material of the Bo-layer, the glass phase is slightly enriched in all elements but Al, Ca, Co, Eu, Fe, Mn, Na and Sc.

Table 4. Concentration of elements in the glass fraction in comparison to the bulk pumice obtained by INAA. The error due to counting statistics is given (in rel%)

	Al	err	As	err	Ba	err	Ca	err	Ce	err	Co	err	Cr	err	Cs	err	Dy	err	Eu	err	Fe	err	Hf	err	K	err	La	err	Lu	err
	%	%	ppm	%	ppm	%	%	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	%	%	ppm	%	%	%	ppm	%	ppm	%
Milos																														
MLO 2 glass	6.47	0.2	4.7	1.3	573	0.8	0.92	7	48.3	0.3	0.73	1.0	3.07	2.4	4.16	0.4	2.7	6	0.468	0.9	0.83	0.2	3.63	0.3	3.15	0.1	26.7	0.2	0.37	0.7
MLO 2 bulk	5.24	0.2	4.7	1.5	554	0.5	0.91	7	45.2	0.2	0.89	0.8	2.31	5.4	3.75	0.4	3.1	14	0.515	0.7	0.87	0.2	3.68	0.3	3.35	0.7	26.9	0.2	0.36	0.8
MLO 5 glass	6.58	0.2	2.0	2.7	458	0.8	0.97	7	43.6	0.3	0.59	1.1	1.40	5.1	3.79	0.4	3.1	7	0.489	0.8	0.76	0.2	3.15	0.4	3.30	1.0	25.5	0.2	0.35	0.7
MLO 5 bulk	7.26	0.2	2.6	2.4	510	0.5	0.99	5	46.4	0.2	0.56	1.1	<0.48		3.50	0.4	<2.3		0.459	0.8	0.75	0.2	3.26	0.3	3.21	0.5	25.5	0.2	0.38	0.7
MLO 8 glass	6.54	0.2	<5.8		661	0.3	0.93	10	51.2	0.1	0.92	1.0	<0.77		2.49	0.3	1.7	10	0.341	0.5	0.61	0.1	2.84	0.2	3.93	0.9	33.2	0.3	0.33	0.8
MLO 8 bulk	6.96	0.2	1.7	3.8	663	0.4	<0.23		52.3	0.2	0.37	1.4	0.76	8.7	2.38	0.5	2.2	14	0.363	0.9	0.61	0.2	2.86	0.3	3.97	1.5	32.7	0.2	0.34	0.8
MLO 14 glass	3.05	0.2	1.9	2.1	453	0.8	0.31	11	24.9	0.4	0.39	1.4	2.28	2.9	3.18	0.4	1.6	6	0.248	1.2	0.41	0.3	1.67	0.5	1.73	1.3	13.1	0.2	0.26	0.7
MLO 14 bulk	3.67	0.2	2.2	2.4	551	0.5	0.45	9	25.5	0.3	0.44	1.2	<0.35		3.39	0.4	1.7	10	0.286	1.0	0.45	0.5	1.92	0.4	1.84	1.9	14.8	0.3	0.26	0.8
Nisyros																														
NIS 2 glass	6.44	0.2	3.6	1.0	799	0.5	0.92	5	62.6	0.2	1.25	0.7	1.22	7.4	4.52	0.4	2.8	5	0.469	0.9	0.93	0.2	4.09	0.3	3.37	0.8	38.6	0.1	0.35	0.7
NIS 2 bulk	8.11	0.1	5.8	1.6	758	0.5	1.83	4	58.5	0.2	4.55	0.4	3.97	5.1	3.31	0.5	1.9	12	0.652	0.7	1.85	0.1	5.12	0.3	2.62	0.6	34.5	0.2	0.52	1.0
NIS 23 glass	6.45	0.2	7.6	1.0	817	0.7	0.73	8	70.2	0.2	1.63	0.6	3.77	2.6	4.65	0.4	2.9	5	0.475	0.8	1.04	0.2	4.41	0.3	3.48	0.8	40.6	0.1	0.37	0.7
NIS 23 bulk	8.25	0.1	6.1	1.8	755	0.5	1.81	5	59.6	0.2	4.52	0.4	4.51	2.3	3.31	0.4	3.2	8	0.513	0.6	1.89	0.1	4.59	0.3	2.61	0.8	40.4	0.2	0.35	0.8
Yali																														
YLI 2 glass	6.35	0.2	8.8	0.9	844	0.6	0.64	9	68.8	0.2	0.57	1.1	1.32	6.2	4.60	0.3	3.1	6	0.367	1.0	0.81	0.2	5.40	0.4	3.59	0.8	41.6	0.1	0.36	0.8
YLI 2 bulk	6.74	0.2	9.8	1.1	855	0.4	<0.18		67.3	0.2	0.55	1.1	0.96	7.8	4.52	0.3	2.6	10	0.330	0.9	0.75	0.2	3.36	0.3	3.59	0.5	40.5	0.2	0.35	0.7
YLI 5 glass	7.58	0.2	4.8	1.5	676	0.8	1.08	7	62.7	0.2	2.01	0.6	2.05	4.8	4.35	0.4	4.9	5	0.540	0.7	1.50	0.2	4.75	0.3	3.09	1.2	36.4	0.2	0.55	0.8
YLI 5 bulk	7.66	0.2	5.2	2.2	689	0.6	2.07	4	61.1	0.2	2.26	0.5	3.95	2.5	4.64	0.4	2.2	10	0.674	0.7	1.50	0.2	4.64	0.3	3.01	1.6	36.5	0.2	0.36	0.8
Kos																														
KOS 1 glass	6.55	0.2	6.8	1.0	532	0.8	0.63	9	45.4	0.3	0.59	1.1	1.05	7.1	5.28	0.3	<0.3		0.280	1.1	0.49	0.5	2.24	0.4	4.19	1.8	28.3	0.2	0.36	0.7
KOS 1 bulk	7.47	0.2	5.6	1.8	743	0.5	0.87	7	51.9	0.2	1.41	0.6	<0.47		3.86	0.3	1.9	12	0.380	0.8	0.88	0.2	2.67	0.4	3.35	1.6	33.7	0.2	0.28	0.9
KOS 3 glass	6.91	0.1	4.5	9.2	624	0.4	0.79	5	45.5	0.2	2.76	0.3	7.09	1.8	5.64	0.2	2.0	8	0.333	0.5	1.05	0.1	2.29	0.3	4.22	0.8	28.9	0.4	0.34	0.8
KOS 3 bulk	7.48	0.1	6.0	1.6	920	0.4	0.92	7	54.8	0.2	2.29	0.5	8.15	1.1	4.44	0.3	1.6	11	0.476	0.7	1.08	0.2	3.09	0.3	3.39	0.4	35.8	0.2	0.51	0.8
Thera																														
SAT 4 glass	7.88	0.1	3.9	2.1	623	0.5	2.44	4	55.6	0.6	4.91	0.4	1.22	12.5	3.07	0.6	7.5	3	0.559	0.5	3.73	0.1	5.66	0.3	1.93	0.5	25.8	0.2	0.81	0.4
SAT 4 bulk	8.31	0.1	3.7	4.5	548	1.6	2.45	4	55.2	0.3	5.52	0.3	<1.15		2.97	0.6	8.5	4	0.519	0.4	3.96	0.1	6.94	0.3	1.95	2.7	26.7	0.2	0.81	0.5
SAT 5 glass	7.05	0.2	2.6	2.7	581	1.0	1.11	7	62.7	0.2	2.36	0.5	<0.85		3.08	0.5	5.6	3	0.946	0.6	1.63	0.2	8.32	0.2	2.72	1.4	32.2	0.2	0.79	0.4
SAT 5 bulk	7.79	0.2	2.5	4.8	551	0.8	1.10	5	60.2	0.2	3.95	0.4	<0.57		2.85	0.5	6.5	4	0.972	0.5	2.18	0.1	7.85	0.2	2.35	2.1	30.6	0.2	0.75	0.4

Table 4. (continued)

	Mn	err	Na	err	Nd	err	Rb	err	Sb	err	Sc	err	Sm	err	Ta	err	Th	err	Ti	err	U	err	V	err	Yb	err	Zr	err
	ppm	%	%	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	ppm	%	%	%	ppm	%	ppm	%	ppm	%	ppm	%
Milos																												
MLO 2 glass	375	0.7	2.04	0.2	18	4	154	0.5	1.01	1	2.69	0.1	3.42	0.2	0.77	1.1	15.70	0.2	<0.16		3.86	1.2	<5.6		2.28	1.1	138	2.5
MLO 2 bulk	401	0.1	2.86	0.2	16	3	138	0.4	0.89	1	2.75	0.1	3.29	0.2	0.66	1.1	14.75	0.1	<0.13		3.46	1.3	<4.9		2.22	0.9	116	2.2
MLO 5 glass	458	0.8	2.29	0.2	13	5	120	0.5	0.25	5	0.54	0.2	2.86	0.2	0.84	1.1	13.70	0.2	<0.18		3.80	1.2	<5.2		2.07	1.0	119	2.4
MLO 5 bulk	465	0.9	2.54	0.2	16	3	127	0.4	0.21	3	0.58	0.1	2.98	0.2	0.81	1.0	14.50	0.1	<0.15		3.81	1.2	<6.0		2.05	0.9	106	2.1
MLO 8 glass	405	0.6	1.55	0.2	15	4	133	0.3	0.68	2	0.68	0.1	2.84	0.3	1.25	0.6	18.30	0.1	<0.28		4.76	1.8	<5.8		1.85	2.4	113	1.6
MLO 8 bulk	421	0.5	2.43	0.2	17	3	135	0.4	0.64	5	0.65	0.1	3.07	0.2	1.14	0.8	19.15	0.1	<0.15		4.51	1.1	<5.8		1.80	1.0	101	2.2
MLO 14 glass	171	0.8	0.81	0.3	8	6	86	0.6	1.01	1	0.25	0.2	2.11	0.2	0.35	1.7	7.21	0.2	<0.14		7.29	0.6	<3.0		1.23	1.4	98	2.5
MLO 14 bulk	184	0.2	1.17	0.3	11	3	88	0.4	0.96	1	0.35	0.1	2.08	0.2	0.59	1.5	7.50	0.2	<0.10		6.05	0.7	<3.8		1.22	1.2	87	2.2
Nisyros																												
NIS 2 glass	246	0.9	2.68	0.2	20	4	136	0.5	0.45	2	2.56	0.1	3.94	0.1	1.39	0.8	15.53	0.2	<0.16		4.56	1.1	7.6	11.8	2.10	1.1	156	2.2
NIS 2 bulk	474	0.7	3.12	0.2	23	3	164	0.5	0.35	2	4.40	0.1	5.25	0.1	1.13	0.9	12.31	0.2	0.22	11	3.19	1.7	38.5	2.9	1.83	1.5	187	1.9
NIS 23 glass	241	0.7	2.47	0.2	25	4	139	0.5	0.51	2	3.08	0.1	4.15	0.1	1.42	0.8	16.77	0.1	<0.16		4.51	1.1	10.8	7.8	2.31	1.1	173	2.1
NIS 23 bulk	488	0.6	3.11	0.2	26	4	163	0.5	0.33	2	4.50	0.1	4.68	0.1	1.05	0.9	12.36	0.2	0.25	10	3.29	1.6	32.8	3.6	1.92	1.3	173	2.0
Yali																												
YLI 2 glass	280	0.8	2.58	0.2	19	4	143	0.5	0.51	2	2.32	0.1	3.40	0.2	1.44	0.8	16.91	0.1	<0.16		4.11	1.3	<4.9		2.02	1.1	126	2.5
YLI 2 bulk	284	0.9	2.68	0.2	22	3	147	0.4	0.49	2	2.68	0.1	3.48	0.2	1.43	0.7	15.46	0.1	<0.14		4.56	1.1	<5.8		2.00	1.0	105	2.2
YLI 5 glass	459	0.8	3.01	0.2	20	5	129	0.5	0.41	2	3.35	0.1	3.88	0.1	1.46	0.8	14.52	0.2	<0.18		4.12	1.3	19.9	5.0	2.17	1.2	188	2.8
YLI 5 bulk	473	0.6	2.89	0.2	18	4	130	0.4	0.40	2	3.50	0.1	3.78	0.2	1.48	0.8	14.30	0.1	<0.14		4.23	1.3	22.5	5.1	2.10	1.1	168	2.8
Kos																												
KOS 1 glass	458	0.7	2.28	0.2	15	5	151	0.4	0.65	2	2.27	0.1	2.82	0.2	2.08	0.7	17.05	0.1	<0.18		5.86	0.9	<5.6		1.82	1.2	95	5.1
KOS 1 bulk	426	0.7	2.65	0.2	15	4	123	0.4	0.47	2	2.44	0.1	2.78	0.2	1.53	0.7	16.00	0.1	<0.14		4.64	1.1	9.8	9.8	1.53	1.2	96	2.6
KOS 3 glass	512	0.5	1.78	0.2	12	6	154	0.3	0.97	1	3.74	0.1	2.65	0.4	1.95	0.5	15.42	0.1	0.34	14	4.95	1.5	14.3	6.0	1.70	2.5	102	2.3
KOS 3 bulk	559	0.6	2.38	0.2	17	2	128	0.4	0.58	2	3.32	0.1	3.01	0.2	1.43	0.6	15.94	0.1	<0.13		4.34	1.1	15.1	7.6	1.57	1.2	113	2.2
Thera																												
SAT 4 glass	1089	0.4	3.38	0.1	29	3	100	0.7	0.45	2	13.59	0.1	7.13	0.1	0.82	1.3	17.06	0.2	0.46	5	5.42	1.1	27.1	3.5	5.50	0.7	292	2.2
SAT 4 bulk	1097	0.4	3.25	0.2	28	5	100	0.6	0.38	5	14.36	0.1	7.33	0.1	0.76	0.1	17.06	0.2	0.47	6	5.19	1.4	33.0	3.7	5.65	0.7	249	2.2
SAT 5 glass	521	0.5	3.48	0.2	24	5	120	0.6	0.29	3	7.11	0.1	6.05	0.1	0.85	1.1	20.45	0.1	0.19	13	5.70	1.0	11.6	8.7	5.09	0.7	326	1.5
SAT 5 bulk	586	0.6	3.43	0.2	25	4	131	0.5	0.26	5	8.55	0.1	6.18	0.1	0.80	1.1	19.75	0.1	0.28	9	5.99	0.4	22.5	5.0	5.14	0.6	267	1.5

Table 5. Concentrations of elements in the glass fraction obtained by EPMA

		Al	err	Ca	err	Fe	err	Mg	err	Mn	err	Na	err	Si	err	Ti	err
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Milos	MLO 2 glass	5.94	0.9	0.83	1	0.66	3	0.05	18	0.03	18	1.38	1	35.29	0.3	0.10	19
	MLO 5 glass	6.60	0.9	1.24	7	0.71	5	0.13	9	< 0.06		1.95	11	34.25	0.6	0.10	17
	MLO 8 glass	6.30	0.9	0.98	3	0.57	3	0.07	7	< 0.05		1.67	10	34.75	0.2	0.10	14
	MLO 14 glass	6.11	2.6	1.07	4	0.75	7	0.09	14	< 0.06		1.26	10	34.87	1.0	< 0.10	
Nisyros	NIS 2 glass	6.34	2.1	1.01	6	0.92	3	0.10	6	< 0.04		2.05	3	34.21	2.3	0.16	6
	NIS 23 glass	6.28	0.6	1.02	15	0.93	3	0.11	4	< 0.05		2.09	7	34.53	0.3	0.16	10
Yali	YLI 2 glass	6.33	1.1	0.85	3	0.68	3	0.06	14	< 0.06		2.09	7	35.19	0.3	< 0.113	
	YLI 5 glass	7.42	1.6	1.65	8	1.33	4	0.30	2	< 0.08		2.25	7	32.56	1.2	0.25	15
Kos	KOS 1 glass	6.41	1.4	0.83	13	0.39	2	0.03	5	< 0.05		2.09	9	34.75	0.4	< 0.06	
	KOS 3 glass	6.30	1.0	0.79	11	0.38	5	< 0.05		< 0.07		1.82	8	34.46	0.6	< 0.08	
Thera	SAT 4 glass	7.88	2.2	2.27	16	3.52	6	0.58	17	0.12	13	2.71	8	30.41	0.9	0.56	13
	SAT 5 glass	7.15	1.5	0.93	5	1.45	2	0.15	7	< 0.07		3.02	14	33.25	1.7	0.21	10

The depletion of the major elements Al, Ca, Fe, Mn and Na in the glass can be readily attributed to the presence of the known mineral phases (Fig. 7). The pronounced negative Eu anomaly is attributed to the plagioclase fractionation which is normally expected in such highly evolved lavas. The much lower crystalline content of the Bm-layer clearly explains the small differences between the bulk material and the glass phase.

The comparison of bulk material with analytical data from literature and previous analyses shows good agreement.[12,18,19,22,26,29,33,34] Our results obtained by INAA are in perfect accordance with laser ablation ICP-MS analysis of tephra layers in lake sediments from Gölhisar in the Southwest of Turkey[15] and confirm Santorini as the primary source.

We have concluded that the element concentrations in the glass phase and the bulk pumice of the different volcanic sources show partly small differences and can thus be used for the reliable identification of tephra layers related to that eruption. INAA enables the choice of the most suitable elements for this identification work, which cannot be achieved by major element determinations alone. In this way it is possible to identify even very small quantities of the tephra fraction separated from the sediment. This research program together with the results presented will contribute significantly to our knowledge about the chronology and volcanic history of the Eastern Mediterranean.

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