

DISTINCTION OF PRE-MINOAN PUMICE FROM SANTORINI, GREECE

Max Bichler* (bichler@ati.ac.at), Barbara Duma,* Heinz Huber,** and Andreas Musilek*

Abstract

The pumiceous products of the large scale explosive eruptions at Santorini like the Lower Pumice eruptions 1 and 2 about 200 000 years ago and the “Minoan eruption” show a high grade of similarity as well in their optical appearance as in their composition. The demand for a clear classification of Santorinian eruption products raised from archaeological research, where the widely used abrasive pumice can be interpreted as a “post-eruption” time marker. The aim of this work was to find elements that underwent significant changes during the geochemical evolution of the volcano and therefore could be indicative for a distinction of pumice produced by

the five major explosive eruptions (Lower Pumices 1 and 2, Middle Tuff sequence, Cape Riva Tuff and the Minoan Tuff). INAA of 25 elements, in particular As, Ba, Ce, Co, Cr, Cs, Eu, Fe, Hf, K, La, Lu, Na, Nd, Rb, Sb, Sc, Sm, Ta, Tb, Th, U, Yb, Zn, and Zr allows a clear classification and contributes new information on the chemical evolution of Santorini volcano.

INTRODUCTION

The use of pumice as a time marker for post-eruption-dating in archaeology led to the demand for a clear classification of Santorinian eruption products. This problem became evident as the pumiceous products of some of the large scale eruptions like the

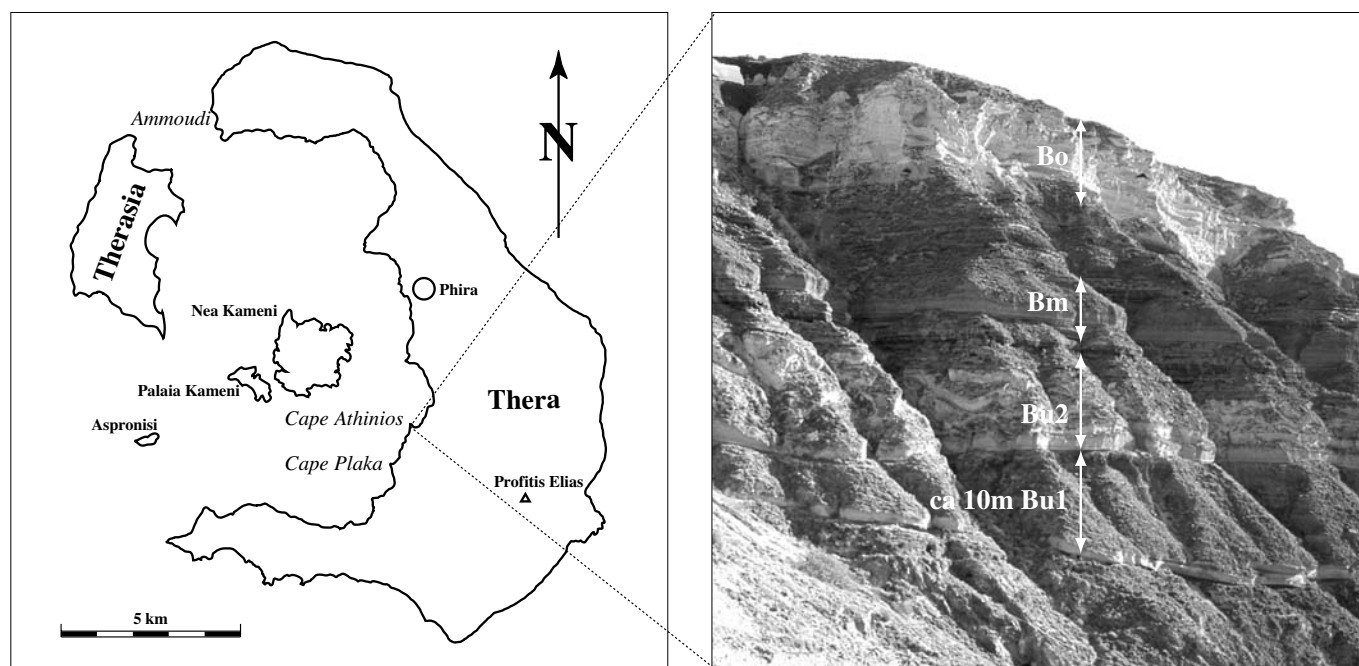


Fig. 1 Santorini volcanic complex, geographic situation of the sampling sites and a typical volcanic sequence near Athinios: Lower Pumice Tuff units 1 and 2 (Bu1, Bu2), Middle Tuff (Bm) and Minoan Tuff (Upper Pumice, Bo). The Cape Riva Tuff is not visible in that part of the caldera cliff

* Atominstitut der Österreichischen Universitäten, Stadionallee 2, A-1020 Vienna, Austria.

** Institute of Geophysics and Planetary Physics, University

of California, 405 Hilgard Avenue, Los Angeles, CA 90095-1361, USA.

Lower pumice 1 and 2 eruptions and the Minoan eruption show a high grade of similarity as well in their optical appearance as in their chemical composition. Instrumental neutron activation analysis (INAA) already has been applied successfully to distinguish Minoan eruption products from material produced by other volcanoes in the Aegean archipelago – such as Milos, Kos, Giali, and Nisyros.¹ The least compositional differences were found in material from Santorini itself, in particular the Lower Pumice Tuff eruptions 1 and 2 (“unterer Bimsstein” Bu1 and Bu2, $203\,000 \pm 24\,000$ years and ca. 180 000 years), the Middle Tuff (“mittlerer Bimsstein”; Bm, ca. 100 000 years), and the Cape Riva pumice (ca. 21 000 years). The investigation of the composition of pumice produced during these large scale explosive events revealed not only crucial differences but also a geochemical evolution that has not been reported during years of intensive volcanologic research at Santorini. Sample series from the eruption cycles mentioned above were collected at the caldera cliffs at Cape Plaka, Cape Athinios, and Ammoudi. The geographical situation and a view of the typical appearance of the volcanic sequence is shown in Fig. 1.

SAMPLES AND ANALYTICAL TECHNIQUES

The samples were taken during a field trip to the island of Thera in March 2002. From literature and previous geochemical investigations the optimized sampling sites were chosen and samples of about 1 kg were taken after removing the weathered surfaces to a depth of about 10 centimeters.² For a detailed description of the sampling sites see Duma.³

Pumice and pumice dust underwent a thorough cleaning by submersion in aqua destillata and application of an ultrasonic bath. By sonicating the samples for several minutes, impurities (e.g. remnants of plants, microorganisms or soil particles etc.) were removed thoroughly. For this procedure the samples were transferred into a beaker containing distilled water. Due to the low density of pumice it is necessary to place a second beaker with a smaller diameter above the samples to make sure that all parts are submerged totally. After the sonicating was finished, the

pumice pieces were removed, rinsed with fresh distilled water and dried at 110°C for at least 24 h. For INAA, about 100 g of pure, xenolith-free pumice were used. The samples were ground in an agate mortar to a grain size $<3\ \mu\text{m}$ and dried to constant weight at 110°C. To avoid contamination of the samples, every step of the sample preparation was done using exclusively polyethylene and quartz-glass tools. Traces of these materials would not interfere with INAA as the neutron irradiation of their constituents C, Si, O and H produces only very short-lived or practically no gamma-emitting activation products.

Then ~150 mg were weighed into Suprasil™ quartz glass irradiation vials. The samples were irradiated together with international certified reference material for 100 hours in the KFKI-reactor of the Atomic Energy Research Institute, Budapest, Hungary, at a thermal neutron flux of about $10^{13}\ \text{cm}^{-2}\text{s}^{-1}$. The multielement standards used for the quantitative analysis were the CANMET reference soil SO1, NIST SRM 1633b Coal fly ash, light sandy soil BCR No. 142, and MC rhyolite GBW 07113. The sample vials were decontaminated and packed into polyethylene vials fitting the automatic sample changer facilities of the Atominstitut. After a decay time of 7 days, a first gamma-spectrum was measured to obtain the activities of the short and medium-lived activation products. Three weeks later, a second measurement was started to detect the long-lived activation products. The measuring times were 1800 s and 10000 s, respectively. All samples were measured using an automatic sample changer with a fixed measurement position at a distance of 4 cm beside the detector. The whole gammaspectroscopic analysis was performed with a 151 cm³ HPGe-detector (1,79 keV resolution at the 1332 keV ⁶⁰Co peak; 50,1% rel. eff.), connected to a PC-based multichannel analyser with pre-loaded filter and loss free counting system.⁴

RESULTS

The results have been published recently and are presented in Table 2 and agree well with previously published analyses.⁵ Slight but reproducible deviations are observed for the elements La and Ce, where the reported values obtained by XRF (for X-Ray-Fluo-

¹ PELTZ *et al.* 1999.

² DRUITT *et al.* 1999; VITALIANO *et al.* 1978; VITALIANO *et al.* 1990.

³ DUMA 2002.

⁴ WESTPHAL 1982, WESTPHAL 1995.

⁵ PELTZ *et al.* 1999; DRUITT *et al.* 1999; VITALIANO *et al.* 1978; VITALIANO *et al.* 1990; EASTWOOD *et al.* 1999; PEARCE *et al.* 1999; BICHLER *et al.* 2007.

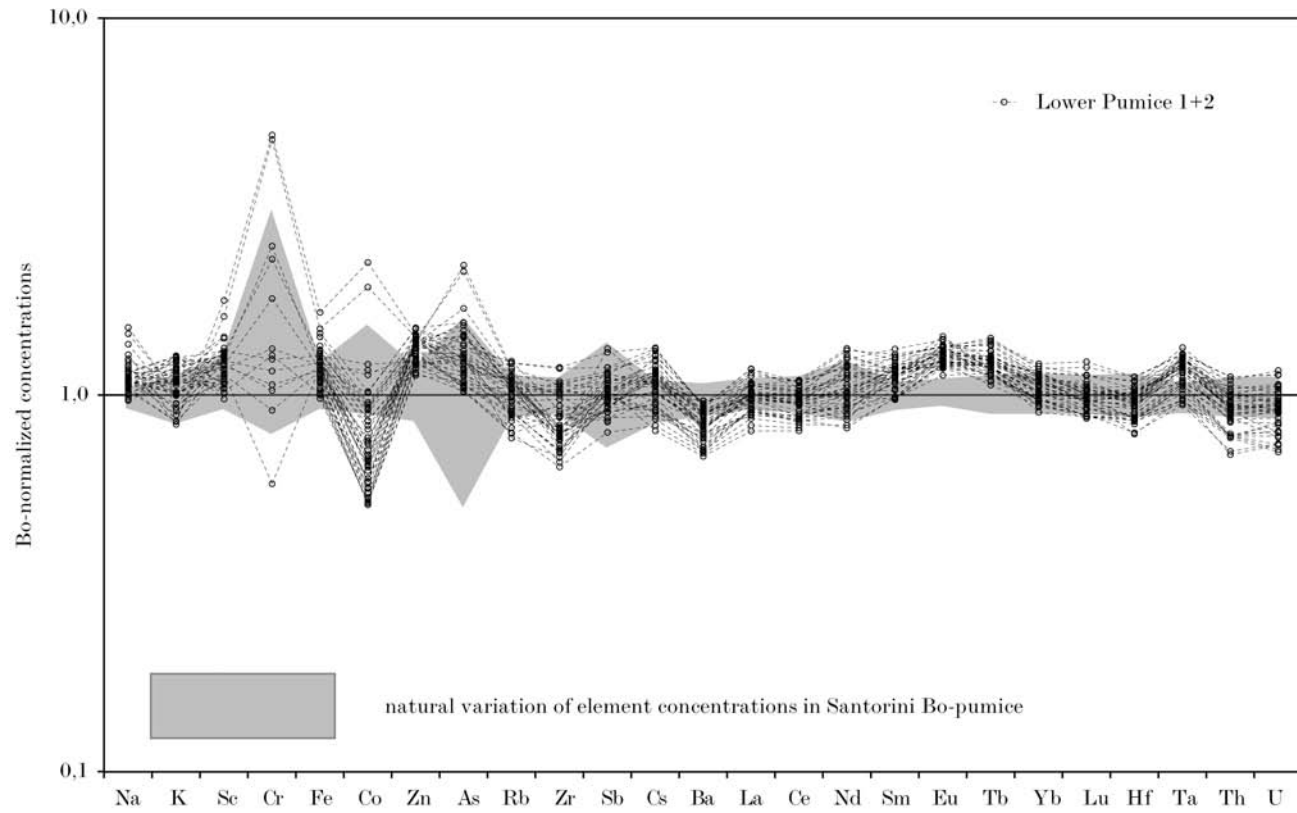


Fig. 2a Santorini Bo-normalized element abundance pattern of pumice samples from the Santorini Lower Pumice Tuff units 1 and 2 (Bu1, Bu2). The natural variation of the Minoan Tuff (Bo) is inserted as shaded area

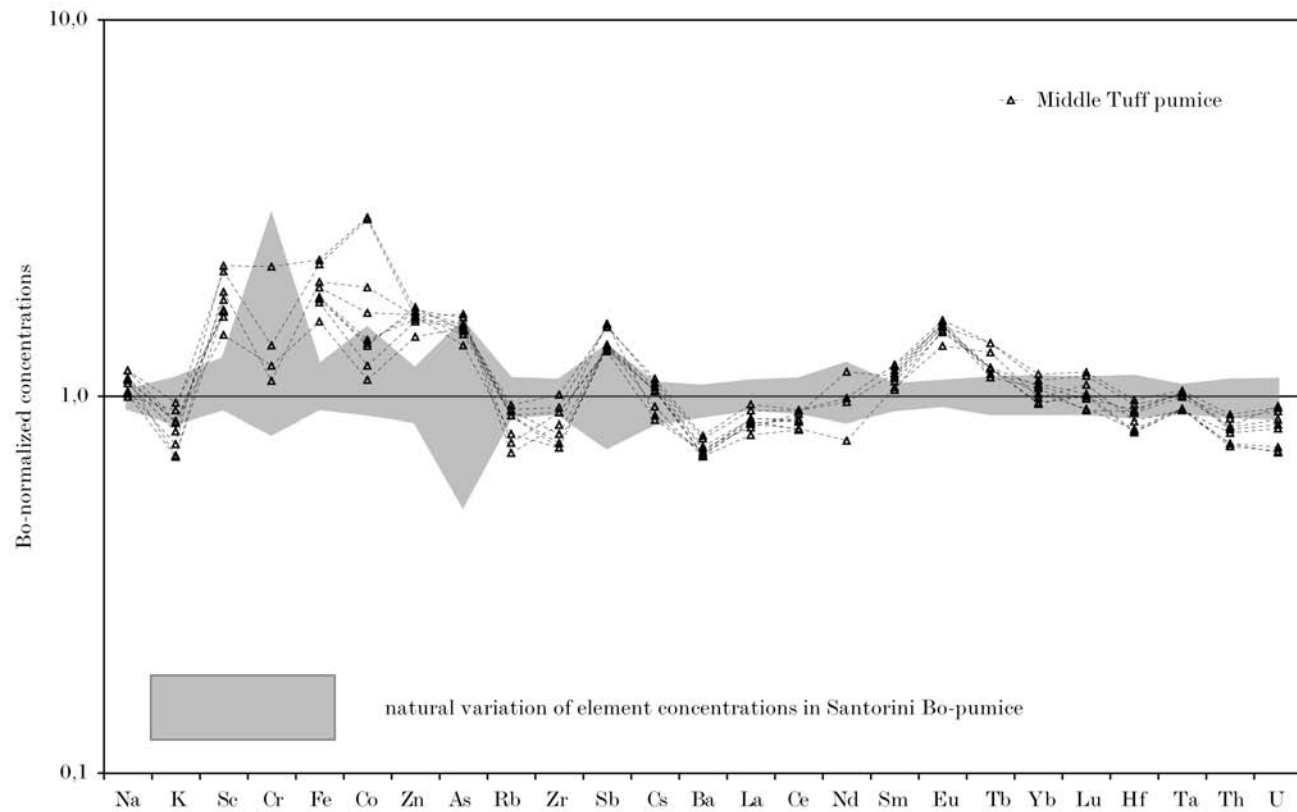


Fig. 2b Santorini Bo-normalized element abundance pattern of pumice samples from the Santorini Middle Tuff sequence (Bm). The shaded area shows the natural variation of the Minoan Tuff (Bo)

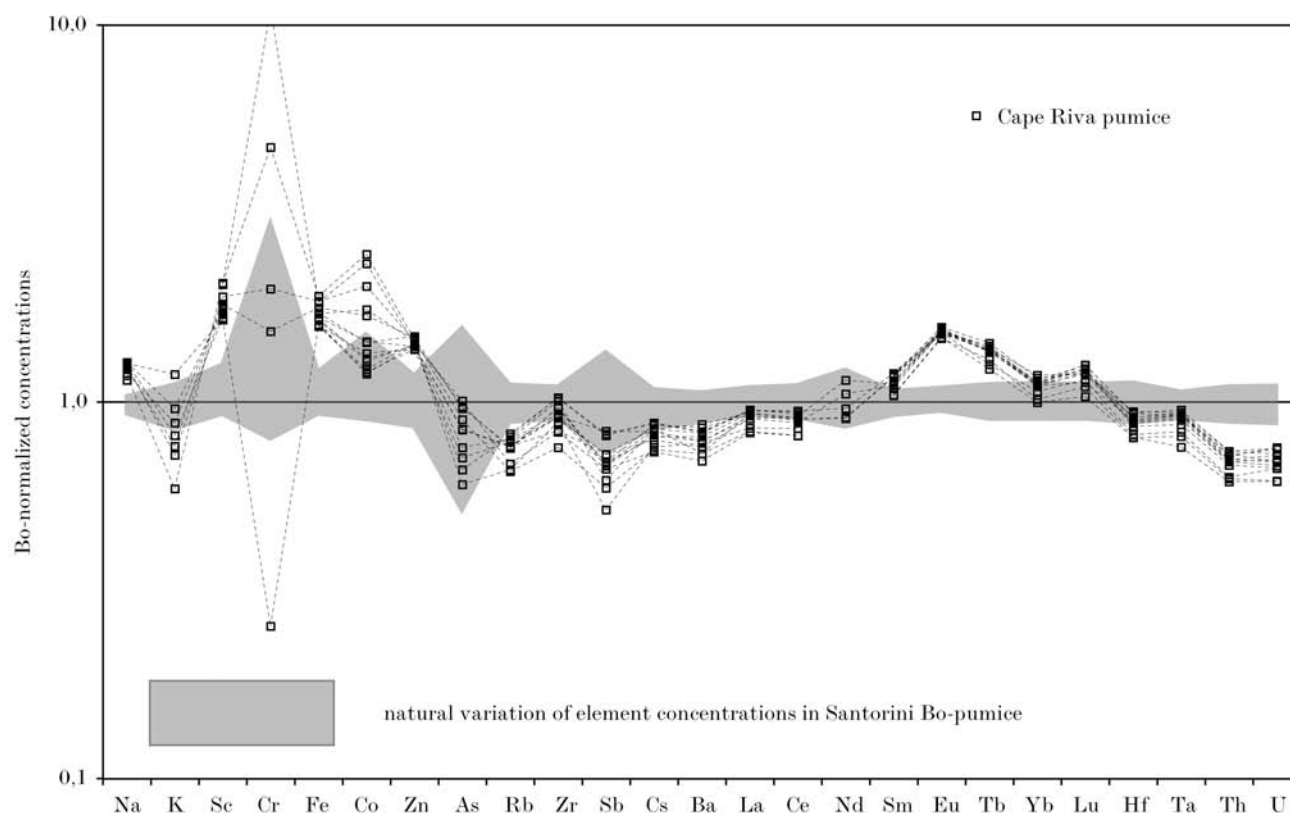


Fig. 2c Santorini Bo-normalized element abundance pattern of pumice samples from the Santorini Cape Riva Tuff. The shaded area gives the natural variation of the “Minoan” Tuff (Bo)

rescence Analysis) or ICP-MS (for Inductive Coupled Plasma – Mass Spectrometry) are about 10–20%rel lower than the INAA results. However, other INAA data on “Minoan pumice” are in perfect agreement with this work.⁶ Blank values for the Suprasil™ quartz glass irradiation vials were measured and found negligible. Errors due to counting statistics are calculated by $\pm 1\sigma$ and range between 5 to 10% rel.

DISCUSSION

The primary aim of this work was to find reliable arguments for a distinction of pumices from the different Santorinian eruption cycles. Instead of applying statistical analysis, it has been necessary to find a set of the most suitable elements, as statistic programs usually cannot include element properties such as volatility or solubility in hydrothermally active environments. The elements should meet the following requirements: different concentrations in the deposits in question, homogeneous distribution throughout the deposit, low solubility and volatility

during weathering, and, last but not least, nuclear properties that are suitable for INAA. A comparison of the element distribution patterns is given in Fig. 2. A normalization is applied in order to exclude the atomic number depending odd-even effect due to nuclear stability. Elements with an even number of protons (Z) are typically more abundant than those with an odd number. Exceptions are hydrogen ($Z = 1$) and Be ($Z = 4$). The reason for this effect is that our terrestrial element inventory has been produced by stellar burning and supernovae. During such processes nuclear properties dominate the production rates of elements. One of these properties is that nuclei are especially stable if nucleons can “pair up” with their spins in opposite directions. This works for neutrons as well as for protons, but if Z is even, the protons can pair up, while if Z is odd, there must always be an unpaired proton. This lead to the observed abundance alternation which therefore is usually called the odd-even effect. Additionally, the normalization to the mean concentrations of the respective ele-

⁶ WARREN AND PUCHELT 1999; BICHLER *et al.* 1997.

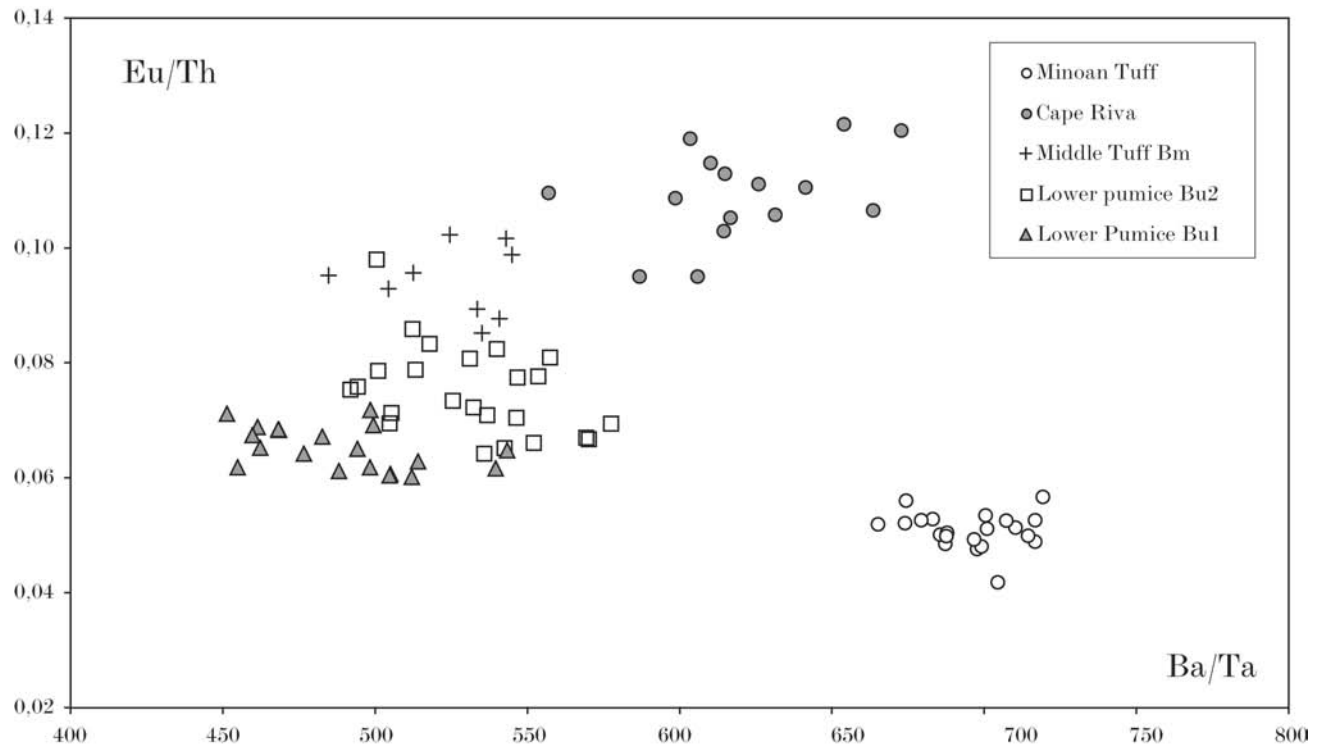


Fig. 3a Concentration ratios of Eu/Th versus Ba/Ta for the distinction of Minoan pumice

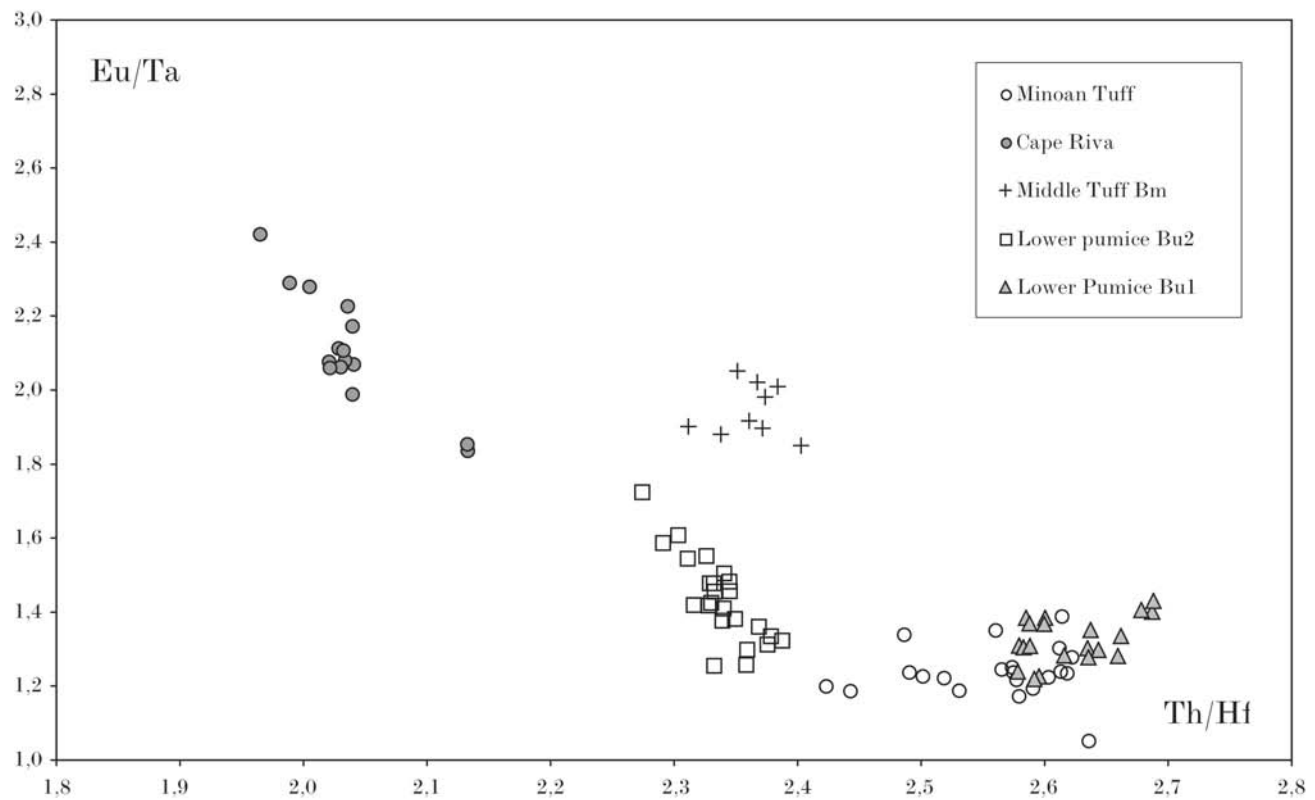


Fig. 3b Concentration ratios of Eu/Ta versus Th/Hf for the differentiation of Lower pumices Bu1 and Bu2, Middle Tuff Bm and Cape Riva pumice

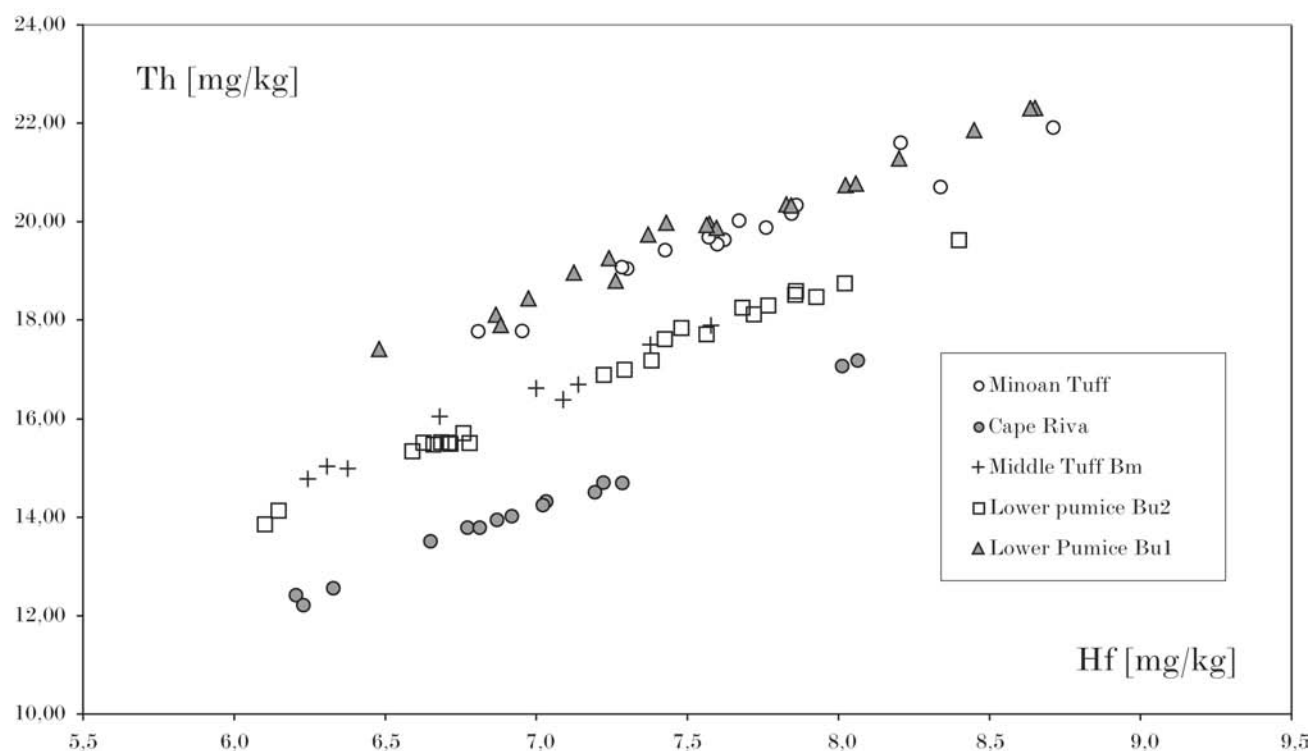


Fig.4 Concentrations of Th and Hf in pumice from Santorini

element	activation product	half-life	γ -energy [keV]
As	^{76}As	25,87 h	559
Ba	^{131}Ba	11,50 d	496
Ce	^{141}Ce	32,50 d	145
Co	^{60}Co	5,27 a	1173
Cr	^{51}Cr	27,70 d	320
Cs	^{134}Cs	2,07 a	796
Eu	^{152}Eu	13,50 a	1408
Fe	^{59}Fe	44,50 d	1099
Hf	^{181}Hf	42,40 d	482
K	^{42}K	12,40 h	1525
La	^{140}La	40,30 h	1596
Lu	^{177}Lu	6,70 d	208
Na	^{24}Na	15,00 h	2754
Nd	^{147}Nd	11,00 d	531
Rb	^{86}Rb	18,60 d	1077
Sb	^{124}Sb	60,20 d	1691
Sc	^{46}Sc	83,80 d	1121
Sm	^{153}Sm	46,30 h	103
Ta	^{182}Ta	114,40 d	1221
Tb	^{160}Tb	72,30 d	879
Th	^{233}Pa #	27,00 d	312
U	^{239}Np #	56,60 h	278
Yb	^{169}Yb	32,00 d	177
Zn	^{65}Zn	244,30 d	1116
Zr	^{95}Zr	64,00 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

Table 1 Activation products, half-lives, and gamma-energies used for quantitative analysis

ments in Minoan pumice (Bo) greatly improves the visibility of compositional differences. It can be seen, that only a few elements such as Sc, Fe, Sb, Ba, Eu, Hf, Ta and Th show differences acceptable for a distinction. These elements are highly suitable for INAA, but some of them are not very significant as their concentration could easily be influenced by mobilization like sulfide decomposition or contamination from infiltrating solutions under weathering conditions. The best differentiation is obtained by using Ba, Eu, Hf, Ta and Th. Fig. 3a. shows the binary plot of the ratios of Eu/Th against Ba/Ta, which allows a clear distinction of the Minoan Tuff from the other eruptiva. The plot Eu/Ta versus Th/Hf separates the rest of the Theran deposits investigated (Fig. 3b). In agreement with their geochemical properties, a perfect correlation was found for the elements Hf and Th. Figure 4 shows a binary plot of their concentrations and there are three clearly separated distributions in the five eruptive cycles observed. The correlation coefficients are 0,987 (Bu1), 0,997 (Bu2), 0,982 (Bm), 0,996 (Cape Riva), and 0,902 (Bo). These extremely high values indicate geochemical processes like melt differentiation and magma mixing. This

results are in perfect agreement with petrogenetical assumptions published in DRUITT (1999) and are discussed in another publication.⁷

CONCLUSIONS

The chemical evolution of the volcanic products of Santorini with respect to the major explosive cycles led to only minor changes in their composition. The determination of 25 elements by INAA revealed differences that can be used for geochemical interpretation. Additionally, this allows the identification of these products if they are found beyond their natural environment. The choice of a set of suitable elements such as Ba, Eu, Hf, Ta, Th and the application of INAA allows a clear classification and can be used for the identification of pumice. This possibility contributes valuable information for the intensive discussion on the date of the Minoan eruption at Santorini by classifying archaeologically stratified findings of pumice. The presence of a certain material gives evidence for the decision that a stratum has been deposited after the respective eruption. The applicability to archaeological findings is demonstrated in this volume.⁸

⁷ BICHLER *et al.* 2007.

⁸ BICHLER *et al.* 2004

Table 2: Analytical results of elemental concentrations in pre-Minoan pumice from Santorini, all values in mg/kg
 The analytical error due to counting statistics is less than 10 rel. % for the elements Cr, As, Nd, Sm, Yb, and U, less than 5 rel. % for all others

sample	Na	K	Sc	Cr	Fe	Co	Zn	As	Rb	Zr	Sb	Cs	Ba	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ta	Th	U
Serie Athios																									
Bu1																									
Sat 30b-1	32401	28448	12.23	n.d.	31823	4.01	104	3.8	117	236	0.30	3.27	451	34.0	66.4	31.9	8.18	1.40	1.27	5.36	0.79	7.37	0.999	19.74	5.65
Sat 30b-2	33745	26760	12.12	n.d.	31119	3.76	100	3.3	118	229	0.27	3.38	500	32.6	66.5	31.0	7.27	1.43	1.17	5.39	0.83	7.43	1.002	19.97	5.69
Sat 30c-1	33279	24186	10.71	n.d.	28113	3.59	93	4.3	113	221	0.28	3.23	461	31.3	59.8	26.8	6.88	1.24	1.14	4.81	0.72	6.97	0.955	18.44	5.61
Sat 30c-2	32166	26514	11.12	n.d.	28580	3.66	95	4.2	118	213	0.27	3.31	490	32.1	61.9	28.3	6.97	1.31	1.18	5.09	0.78	7.12	0.982	18.96	5.27
Sat 30c-3	35164	28762	10.97	n.d.	28237	3.51	91	4.0	115	209	0.28	3.29	460	32.1	60.3	26.2	7.22	1.29	1.16	4.88	0.76	7.26	0.983	18.79	5.42
Sat 30c-4	32784	26486	11.43	n.d.	29446	3.71	96	3.3	120	219	0.30	3.36	466	31.8	63.0	32.8	7.11	1.30	1.20	5.19	0.81	7.24	1.013	19.26	5.71
Sat 30d-1	35260	28587	10.92	n.d.	27005	2.62	99	3.6	133	263	0.28	3.67	535	33.7	68.9	34.1	7.66	1.32	1.27	5.75	0.86	8.20	1.073	21.28	5.96
Sat 30d-2	35085	30101	10.38	2.0	25799	2.63	97	5.9	125	238	0.30	3.59	501	33.5	64.5	28.3	7.36	1.27	1.29	5.49	0.83	8.06	1.026	20.77	6.21
Sat 30d-3	36100	30648	10.23	2.1	25384	2.55	95	6.1	127	233	0.35	3.55	509	33.8	63.4	32.3	7.26	1.23	1.23	5.32	0.79	7.84	1.008	20.33	6.13
Sat 30d-4	36184	24391	10.56	n.d.	26236	2.73	95	4.7	122	224	0.32	3.45	501	32.3	63.1	29.3	7.13	1.30	1.25	5.31	0.81	7.56	1.014	19.93	6.26
Sat 33-1	36212	30449	11.21	2.5	27743	2.81	98	3.9	122	315	0.34	3.69	528	37.1	65.8	28.4	7.81	1.34	1.37	5.65	0.85	8.02	0.971	20.74	6.30
Sat 33-2	33623	27619	11.04	n.d.	26585	2.71	92	3.7	132	343	0.39	3.86	522	35.7	68.5	30.3	7.75	1.35	1.41	6.12	1.02	8.65	1.034	22.31	6.67
Sat 33-3	36797	24672	10.93	n.d.	26139	2.47	95	3.2	131	341	0.35	3.84	527	37.2	68.0	30.5	7.93	1.34	1.43	5.93	0.98	8.63	1.029	22.30	6.69
Sat 33-4	36837	26385	10.88	n.d.	26696	2.94	95	4.0	128	307	0.34	3.78	531	36.3	67.9	33.7	7.92	1.35	1.38	5.83	0.93	8.45	0.984	21.86	6.86
Bu2																									
Sat 31a-1	23077	23077	9.30	n.d.	24079	2.57	94	3.4	96	193	0.29	2.65	442	28.5	54.3	30.6	6.41	1.22	1.14	4.91	0.73	6.66	0.862	15.49	5.00
Sat 31a-2	40798	27117	10.07	2.6	26147	3.61	98	4.1	98	203	0.32	2.78	480	29.5	56.1	23.7	6.66	1.27	1.20	5.13	0.76	6.76	0.862	15.73	4.71
Sat 31a-3	42549	20658	9.77	1.1	25839	2.67	104	3.5	106	225	0.30	2.90	484	30.0	60.4	28.9	6.83	1.41	1.18	5.51	0.80	7.22	0.936	16.90	4.97
Sat 31a-4	48348	24746	9.70	1.8	25257	2.97	97	3.5	97	207	0.29	2.61	449	27.9	55.4	26.0	6.36	1.26	1.14	4.94	0.73	6.62	0.846	15.53	4.23
Sat 31b-1	38498	26159	10.59	2.3	26636	4.45	90	2.9	98	265	0.28	2.63	410	28.9	53.3	23.5	6.72	1.18	1.10	4.97	0.73	6.71	0.830	15.53	4.92
Sat 31b-2	37760	25798	10.27	3.6	25534	3.98	105	4.3	112	222	0.40	2.97	471	31.1	59.2	25.4	7.16	1.23	1.22	5.46	0.83	7.42	0.934	17.63	5.45
Sat 31b-3	26634	26634	13.86	9.4	32714	7.60	99	3.5	83	198	0.31	2.32	387	25.5	50.5	n.d.	6.00	1.22	1.08	4.73	0.74	6.14	0.756	14.15	4.39
Sat 31b-4	34205	20610	15.27	9.7	36142	8.84	100	2.9	86	187	0.24	2.40	394	26.3	51.5	n.d.	6.42	1.36	1.11	5.04	0.81	6.10	0.788	13.87	4.35
Sat 31c-1	36717	29965	8.72	2.5	21977	2.36	97	3.4	122	226	0.31	3.18	507	31.1	61.8	26.2	7.26	1.19	1.23	5.66	0.79	7.92	0.946	18.48	5.45
Sat 31c-2	34800	26822	8.95	n.d.	22150	2.05	93	2.9	113	241	0.33	3.10	515	30.6	60.5	22.9	7.28	1.20	1.23	5.52	0.79	7.77	0.949	18.31	5.35
Sat 31d-1	33508	26436	8.91	n.d.	22502	2.10	90	3.6	117	227	0.29	3.13	544	31.7	62.3	29.4	6.95	1.24	1.25	5.76	0.83	7.85	0.956	18.53	5.52
Sat 31d-2	38981	24450	9.82	n.d.	25256	2.31	98	3.1	107	228	0.28	2.97	460	31.1	59.9	30.4	7.10	1.34	1.21	5.52	0.86	7.29	0.919	17.00	5.39
Sat 31e-1	38140	30638	9.19	n.d.	23480	2.31	94	3.6	115	234	0.33	3.13	521	31.3	63.5	25.1	6.93	1.32	1.24	5.84	0.83	7.86	0.970	18.60	5.62
Sat 31f-1	38191	30855	9.12	n.d.	22844	2.01	86	3.9	117	303	0.33	3.31	543	34.2	64.7	28.2	7.48	1.31	1.40	6.03	0.94	8.40	0.952	19.64	6.03
Sat 31f-2	41422	24511	9.42	n.d.	23731	2.24	84	3.5	114	293	0.34	3.19	534	33.8	62.3	25.7	7.34	1.30	1.33	5.77	0.94	8.02	0.924	18.76	5.82
Bu3																									
Sat 32a-1	39010	23403	13.97	n.d.	38823	4.75	110	4.3	103	293	0.46	3.22	445	30.2	58.0	25.4	7.51	1.60	1.41	5.80	0.96	7.58	0.834	17.89	5.52
Sat 32a-2	36793	20730	14.46	n.d.	39741	5.36	120	4.1	100	271	0.46	3.15	437	29.1	57.8	24.8	7.10	1.53	1.40	5.59	0.94	7.38	0.809	17.50	5.40
Sat 34-1	33227	22336	18.43	2.7	49070	11.62	113	4.6	82	263	0.39	2.52	404	27.4	51.6	n.d.	6.44	1.50	1.20	4.88	0.83	6.24	0.743	14.78	4.25
Sat 34-2	34309	18227	19.10	4.4	50334	11.76	117	4.5	77	244	0.47	2.58	403	27.8	54.1	n.d.	6.77	1.49	1.21	4.83	0.84	6.31	0.740	15.04	4.35
Bo mean composition																									
	33281	24287	8.58	2.0	21839	3.93	69	2.8	108	290	0.30	2.89	564	31.7	63.0	25.7	6.18	1.00	1.01	5.06	0.83	7.75	0.804	19.97	5.91

Table 2 continued: Analytical results of elemental concentrations in pre-Minoan pumice from Santorini, all values in mg/kg
 The analytical error due to counting statistics is less than 10 rel. % for the elements Cr, As, Nd, Sm, Yb, and U, less than 5 rel. % for all others

sample	Na	K	Sc	Cr	Fe	Co	Zn	As	Rb	Zr	Sb	Cs	Ba	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ta	Th	U
Serie Cape Plaka																									
Bul																									
Sat 23a-1	36179	24508	11.43	n.d.	28747	3.36	86	3.2	119	289	0.25	3.33	495	33.7	64.1	27.3	7.39	1.25	1.26	5.15	0.86	7.57	0.963	19.96	5.78
Sat 23b-1	39806	20280	10.80	n.d.	26591	3.26	81	2.9	96	237	0.27	2.72	398	29.1	53.4	22.5	6.39	1.19	1.17	4.55	0.73	6.48	0.849	17.41	4.55
Sat 23b-2	36850	22461	10.38	n.d.	26792	3.19	84	3.1	99	255	0.27	2.74	404	29.2	54.7	22.9	6.07	1.18	1.16	4.74	0.76	6.87	0.874	18.11	4.70
Sat 23b-3	35753	23608	10.84	n.d.	27434	3.35	83	3.0	101	254	0.26	2.85	411	30.9	55.2	24.4	6.63	1.23	1.20	4.70	0.74	6.88	0.890	17.90	5.38
Sat 23c-1	36314	27674	10.37	n.d.	25841	2.53	85	3.4	117	294	0.31	3.32	455	32.2	62.7	25.9	6.90	1.31	1.26	5.37	0.85	7.83	0.955	20.35	5.56
Sat 23c-2	38041	28255	9.98	n.d.	24609	2.08	84	3.4	111	300	0.29	3.17	435	32.3	59.0	26.8	6.98	1.23	1.20	5.14	0.82	7.60	0.957	19.87	5.33
Bn2																									
Sat 24a-1	37166	20859	9.14	n.d.	23863	2.91	85	3.5	94	271	0.27	2.72	424	28.5	55.4	24.0	6.11	1.21	1.20	5.11	0.82	6.68	0.776	15.54	4.36
Sat 24a-2	39520	22090	9.58	n.d.	24778	3.03	88	3.0	92	271	0.26	2.54	436	28.6	54.2	20.9	6.08	1.28	1.20	4.86	0.79	6.78	0.807	15.52	4.74
SAT 24b-1	36409	n.d.	9.60	n.d.	24089	2.31	87	4.0	110	295	0.32	3.08	500	31.8	61.0	26.8	7.17	1.35	1.32	5.66	0.86	7.48	1.017	17.85	5.39
SAT 24b-2	35531	n.d.	9.19	n.d.	23653	2.17	82	3.5	112	311	0.34	3.11	493	31.5	61.1	25.5	6.94	1.30	1.28	5.70	0.87	7.08	0.976	18.26	5.58
Sat 24c-1	50263	24254	10.68	4.9	25865	4.57	80	2.8	86	252	0.30	2.49	401	27.5	52.5	21.3	6.06	1.13	1.16	4.87	0.77	6.59	0.763	15.36	4.17
Sat 24c-2	36625	21400	11.10	4.5	27778	4.74	85	2.8	89	258	0.31	2.60	432	28.1	54.1	25.4	6.03	1.21	1.21	4.89	0.82	6.71	0.780	15.51	4.60
Sat 24d-1	35229	28033	8.66	n.d.	21800	2.03	78	3.0	108	311	0.31	3.05	479	32.1	59.6	22.0	7.04	1.20	1.29	5.62	0.88	7.72	0.867	18.13	5.55
Sat 24d-2	35219	29846	8.36	n.d.	21382	2.05	79	3.2	104	282	0.29	2.93	465	30.6	57.3	23.7	6.65	1.21	1.24	5.37	0.86	7.38	0.850	17.19	5.13
Sat 24e-1	35051	26312	8.92	n.d.	22864	2.22	80	2.9	105	300	0.29	2.95	468	30.7	59.8	24.3	6.83	1.28	1.26	5.51	0.90	7.36	0.880	17.73	5.30
Bm																									
Sat 26a-1	39064	20929	12.51	2.4	34564	4.36	100	4.2	96	263	0.40	2.99	396	26.9	52.0	19.7	6.54	1.37	1.33	5.02	0.89	6.68	0.739	16.05	4.87
Sat 26a-2	37063	17066	14.40	n.d.	39634	5.45	116	4.3	96	213	0.40	3.01	398	27.0	54.6	n.d.	7.26	1.56	1.14	5.32	0.76	7.09	0.820	16.39	5.00
Sat 26b-1	36077	19704	15.48	n.d.	42540	6.56	114	4.1	96	219	0.41	2.99	411	26.3	56.6	29.9	6.99	1.59	1.16	5.47	0.84	7.00	0.803	16.61	5.15
Sat 26b-2	37252	20776	14.58	n.d.	40122	5.57	111	4.3	99	231	0.41	3.07	416	27.6	54.9	n.d.	7.44	1.55	1.21	5.38	0.82	7.14	0.825	16.69	5.57
Sat 26c-1	33783	10866	16.26	2.2	43996	7.67	114	3.8	86	213	0.41	2.72	392	25.2	51.6	n.d.	6.91	1.53	1.20	5.13	0.77	6.38	0.747	14.99	4.21
Serie Ammoudi																									
Cape Riva																									
Sat 27-1	39019	24120	13.25	n.d.	34485	4.78	100	3.0	99	319	0.25	2.96	522	36.8	68.9	29.5	8.40	1.64	1.57	6.15	1.03	8.06	0.890	17.19	5.17
Sat 27-2	38748	28324	13.47	n.d.	35108	4.90	95	2.6	100	303	0.25	3.03	530	36.1	68.4	36.4	8.07	1.62	1.50	5.93	1.00	8.01	0.876	17.08	5.08
Sat 35-1	41904	28608	14.19	n.d.	34541	4.71	95	2.0	84	263	0.20	2.44	400	29.6	56.9	n.d.	6.98	1.53	1.39	5.69	1.01	7.03	0.738	14.34	4.41
Sat 35-2	42279	23248	15.06	n.d.	36092	5.11	97	2.3	82	242	0.22	2.45	409	29.4	56.5	23.1	7.17	1.53	1.41	5.56	0.93	6.87	0.735	13.96	4.25
Sat 36-1	39536	21306	15.51	3.0	38703	6.64	102	2.7	82	265	0.25	2.40	443	28.5	57.5	29.2	6.85	1.53	1.37	5.67	1.01	6.92	0.740	14.04	4.07
Sat 37a-1	40427	n.d.	14.24	n.d.	34024	4.65	98	n.d.	89	265	0.24	2.53	467	30.1	58.2	n.d.	7.21	1.54	1.42	5.66	1.04	7.19	0.740	14.53	4.07
Sat 37a-2	42218	19722	14.29	n.d.	34689	5.28	96	n.d.	82	278	0.20	2.36	441	29.0	56.0	n.d.	6.94	1.56	1.40	5.61	0.98	6.77	0.717	13.80	4.14
Sat 37a-3	41245	n.d.	15.19	n.d.	36508	5.67	97	2.3	82	262	0.22	2.28	426	28.5	55.2	26.9	6.81	1.55	1.37	5.62	1.01	6.65	0.698	13.53	3.93
Sat 37b-1	41660	n.d.	14.60	n.d.	35866	5.03	98	2.1	86	291	0.18	2.44	464	30.0	59.4	24.6	7.34	1.55	1.40	5.94	0.98	7.28	0.732	14.72	4.28
Sat 37b-2	41612	17495	15.25	n.d.	37248	6.89	100	2.7	81	279	0.20	2.32	454	29.5	56.4	23.3	7.18	1.54	1.38	5.55	0.99	6.81	0.726	13.81	3.99
Sat 37b-3	40839	18484	16.27	3.9	40252	7.95	101	1.7	71	255	0.15	2.19	436	26.9	53.3	n.d.	6.72	1.53	1.27	5.37	0.95	6.33	0.668	12.58	3.92
Sat 37c-1	37902	n.d.	17.52	21.8	39976	9.13	98	2.8	74	240	0.20	2.13	392	26.2	51.1	n.d.	6.43	1.48	1.23	5.03	0.85	6.20	0.649	12.43	3.63
Sat 37c-2	41946	n.d.	15.33	n.d.	37484	5.64	103	n.d.	86	268	0.21	2.51	480	29.2	57.8	n.d.	7.24	1.58	1.45	5.84	0.98	7.02	0.748	14.26	4.46
Sat 37c-3	41340	n.d.	14.12	n.d.	34890	4.78	99	1.8	87	297	0.24	2.54	468	29.9	59.0	n.d.	7.32	1.52	1.39	5.75	1.03	7.22	0.763	14.72	4.43
Sat 37c-4	38960	14241	17.68	9.3	41591	9.67	101	2.5	71	219	0.18	2.15	409	26.4	51.1	n.d.	6.40	1.47	1.31	5.12	0.91	6.23	0.609	12.23	3.62
Bo mean composition																									
	33281	24287	8.58	2.0	21839	3.93	69	2.8	108	290	0.30	2.89	564	31.7	63.0	25.7	6.18	1.00	1.01	5.06	0.83	7.75	0.804	19.97	5.91

Bibliography

- BICHLER M., EGGER H., PREISINGER A., RITTER D., STASTNY P.,
1997 NAA of the 'Minoan pumice' at Thera and comparison to alluvial pumice deposits in the Eastern Mediterranean region, *Journal of Radioanalytical and Nuclear Chemistry* 224, 7–14.
- BICHLER M., HUBER H., WARREN P.
2007 Project Thera Ashes – Pumice sample from Knossos, 59–64, in: M. BIETAK and E. CZERNY (eds.), *The Synchronisation of Civilisations in the Eastern Mediterranean in the Second Millennium BC. III: Proceedings of the SCIEM 2000 – 2nd EuroConference, Vienna, 28th of May– 1st of June 2003*.
- BICHLER M., DUMA B., HUBER H.,
2004 Application of INAA to reveal the chemical evolution of selected volcanic eruptiva from Santorini, Greece, *Journal of Radioanalytical and Nuclear Chemistry* 261, no. 1, 57–65.
- DRUITT T.H., EDWARDS L., MELLORS R.M., PYLE D.M., SPARKS R.S.J., LANPHERE M., DAVIES M., BARRIERO B.
1999 *Santorini Volcano*, Geological Society Special Publications, Geological Society of London Memoir 19.
- DUMA B.
2002 *Aktivierungsanalytische Untersuchung präminoischer Eruptivgesteine der Insel Thera (Santorini)*, Dipl. Thesis, Vienna Univ. of Technology.
- EASTWOOD W.J., PEARCE N.J.G., WESTGATE J.A., PERKINS W.T., LAMB H.F. and ROBERTS N.
1999 Geochemistry of Santorini tephra in lake sediments from Southwest Turkey, *Journal of Global and Planetary Change* 21, 17–29.
- PEARCE N.J.G., WESTGATE J.A., PERKINS W.T., EASTWOOD W.J., SHANE P.
1999 The application of laser-ICP-MS to the analysis of volcanic glass shards from tephra deposits: bulk glass and single shard analysis, *Global and Planetary Change* 21, 151–171.
- PELTZ C., SCHMID P., BICHLER M.
1999 INAA of Aegean pumices for the classification of archaeological findings, *Journal of Radioanalytical and Nuclear Chemistry* 242/ 2, 361–377.
- VITALIANO C.J., FOUT J.S., VITALIANO D.B.
1978 Petrochemical study of the Tephra sequence exposed in the Phira Quarry, Thera, 203–215, in: C. DOUMAS (ed.), *Thera and the Aegean World I*, London.
- VITALIANO C.J. TAYLOR S.R., NORMAN M.D., MCCULLOCH M.T., NICHOLLS I.A.
1990 Ash layers of the Thera Volcanic Series: Stratigraphy, Petrology and Geochemistry, 53–78, in: HARDY D.A., RENFREW A.C.(eds.), *Thera and the Aegean World III*, London.
- WARREN P.M., PUCHELT H.
1990 Stratified pumice from Bronze age Knossos, 71–81, in: HARDY D.A., RENFREW A.C. (eds.), *Thera and the Aegean World III*, London.
- WESTPHAL G.P.
1982 Real-time correction of counting losses in nuclear pulse spectroscopy, *Journal of Radioanalytical Chemistry*, 70, 387.
- 1995 Digital Implementation of the Preloaded Filter Pulse Processor, *Journal of Radioanalytical and Nuclear Chemistry* 193, 81–88.