AEGEAN TEPHRA – AN ANALYTICAL APPROACH TO A CONTROVERSY ABOUT CHRONOLOGY

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INTRODUCTION

In the framework of the major research program „Synchronization of Civilizations in the Eastern Mediterranean Region in the 2nd millennium B.C.", the radiochemical technique neutron activation analysis was used to reveal the specific provenance of volcanic material found in archaeological context for chronological purposes.

Major volcanic eruptions, especially those of an explosive nature are associated with widespread environmental and cultural effects.[1] They are typically rather short events, producing tremendous volumes of volcanic deposits in several hours or a few days.[2] The eruption columns transport significant amounts of pyroclastica to the stratosphere where a fine grained fraction is transported over large distances and a socalled tephra-layer is deposited, covering entire regions. Such layers form a synchronous horizon, a datum line and provide valuable information for archaeological research.[3] Additionally, pumice is a typical product of explosive eruptions like the "Minoan eruption" at Santorini or the 79 AD eruption of Vesuvius and occurs in pieces up to several decimeters in diameter. Such pumice lumps have been used widely for

their abrasive properties and have therefore been found at several excavation sites.[4]

Instrumental Neutron Activation Analysis (INAA) was applied to determine the concentrations of a suitable set of elements in pumice and pumiceous tephra. The distribution patterns of the elements were used to enable chemical fingerprinting of relevant volcanic sources (Milos, Nisyros, Giali, Kos, and Santorini) in the Aegean Sea, Greece. Additionally, differentiation effects during transportation that eventually could lead to changes in the chemical composition of the deposited tephra were investigated, simulated on laboratory scale and checked for their relevance to the aim of this work.

A database for the identification of pumice and tephra of the sources mentioned has been set up and shows that the widespread products of the "Minoan Eruption" of the Santorini volcano can be distinguished clearly from other sources and will be used to establish a datumline in the Eastern Mediterranean region in the second millennium B.C. The discovery of the primary fallout of „Minoan" tephra in archaeologically stratified locations can be used as a time mark for synchronization and, additionally, pumice lumps related to

[1] SPARKS R. and WILSON C., (1990), The Minoan Deposits: a Review of their Characteristics and Interpretation, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 89–99; SIGURDSSON H., CAREY S., DEVINE J. D., (1990), Assessment of Mass, Dynamics and Enviromental Effects of the Minoan Eruption of Santorini Volcano, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 100–112.

[2] PYLE D. M., (1990), New estimates for the volume of the Minoan eruption, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, Bd. 2, London, 113–120; PICHLER H., FRIEDRICH W. L (1980), Mechanism of the Minoan Eruption of Santorini, in: C. G. DOUMAS (ed.), *Thera and the Aegean World* II, The Thera Foundaton, London, 15–30.

[3] MINOURA K., IMAMURA F., KURAN, U. NAKAMURA, T. PAPADOPOULOS G. A., TAKAHASHI T., YALCINER A. C., (2000), Discovery of Minoan tsunami deposits, Geology,

Vol. 28, No. 1, 59–62; WESTGATE J. A., PERKINS W. T., FUGE R., PEARCE N. J. G., WINTLE A. G.(1994), Trace element analysis of volcanic glass shards by laser ablation inductively coupled plasma mass spectrometry: application to tephrochronological studies, *Applied Geochemistry* 9, 323–335; EINARSSON T. (1986), in: B. E. BERGLUND (ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*, Wiley, Chichester; KNOX R. W. O. B. (1993), in: E. A. HAILWOOD, R. B. KIDD, *High Resolution Stratigraphy*, Geological Society Special Publication 70, 169–186.

[4] WARREN P. M., PUCHELT H. (1990), Stratified Pumice from Bronze Age Knossos, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, Bd. 2, London, 71–81; FAURE P. (1971), Remarques sur las présence et l'emploi de la Pierre Ponceen Crète du Néolithique à nos jours, in: MARINATOS S. and D. NINKOVICH (eds.), *Acta of the 1st Intern. Sci. Congr. on the Volcano of Thera*, 1971, 422, Athens, Archaeological Services of Greece.

that eruption can serve for dating by first appearance.[5]

The date of the Minoan eruption is presently object to intense debates and the work presented offers a new analytical approach to contribute to the solution of this controversy.[6]

VOLCANOLOGICAL BACKGROUND

The major volcanic centres in the South Aegean region that influenced human life since antiquity are the islands of Milos, Nisyros, Giali, Kos and Santorini (Thera). They are situated on the southern Hellenic volcanic island 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 12 Ma ago involving the Eurasian, Turkish and African plates.[7] Subducted crust material liquifies 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 the Aegean region that produced a remarkable quantity (several km^3) of pumice and pumiceous tephra, was the "Minoan eruption" of the Santorini volcano in the second millennium BC which led to the deposition of the socalled "Bo-layer" (Upper pumice sheet). After about 3500 years of compaction and erosion, the thickness of this deposit still ranges up to ca 45m. Estimates about the volume differ significantly, but a minimum of 16 km^3 can be accepted as a compromise. The tephra layer has been identified in drill cores as far as South Anatolia and the Black Sea.[8]
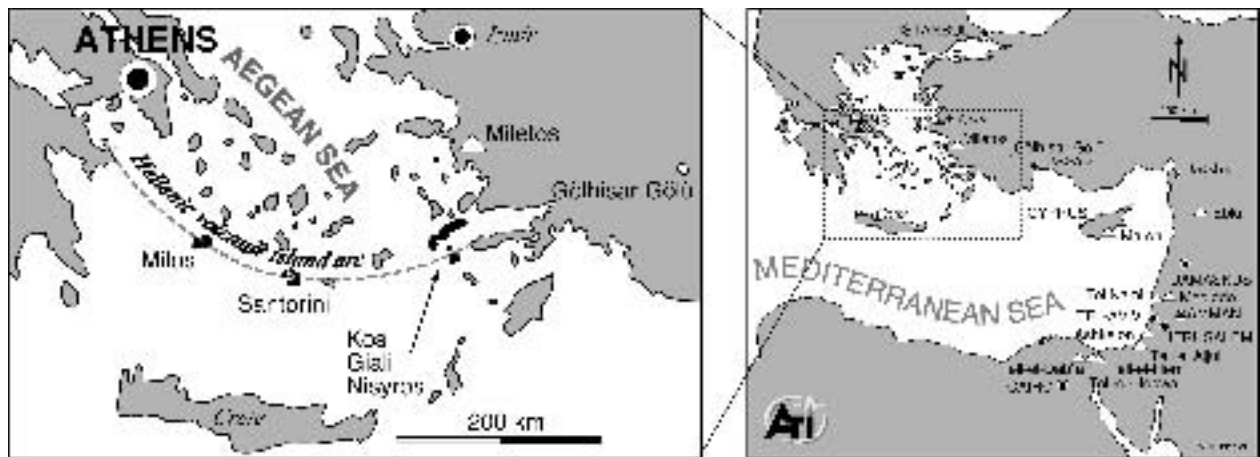
The same geologic situation led also to young,

Fig. 1 Geographical Situation

[5] PELTZ C., SCHMID P., BICHLER M. (1999), INAA of Aegean pumices for the classification of archaeological findings2, *Journal of Radioanalytical and Nuclear Chemistry* 242/ 2, 361; SCHMID P., PELTZ C., HAMMER V. M. F., HALWAX E., NTAFLOS T., NAGL P., BICHLER M. (2000), Separation and Analysis of Theran Volcanic Glass by INAA, XRF and EPMA, *Mikrochimica Acta* 133, 143–149; SAMINGER S., PELTZ C., BICHLER M. (2000), South Aegean volcanic glass-separation and analysis by INAA and EPMA, *Journal of Radioanalytical and Nuclear Chemistry* 245/2, 375–383.

[6] MANNING S. W. (1999): *A Test of Time – The Volcano of Thera and the chronology and history of the Aegean and east Mediterranean in the mid second millennium BC.* Oxbow books, Oxford and Oakville; BIETAK M. (1998), The Late Cypriot White Slip I-Ware as an obstacle of the high Aegean chronology, in: M. S. BALMUTH and R. H. TYCOT (eds.), *Sardinian and Aegean chronology: towards the resolution of relative and absolute dating in the Mediterranean,* 321–322. Studies in Sardinian Archaeology V, Oxbow, Oxford.

[7] FYTIKAS M., GIULIANI O., INNOCENTI F., MARINELLI G., MAZZUOLI R. (1976), Geochronological data an Recent magmatism of the Aegean Sea, *Tectonophysics* 31, T29–34; AVIGAD D., BAER G., HEIMANN A. (1998), Block rotations and continental extension in the central Aegean Sea: palaeomagnetic and structural evidence from Tinos and Mykonos (Cyclades, Greece), *Earth and Planetary Science Letters* 157, 23–40.

[8] SULLIVAN D. G. (1988), The discovery of Santorini Minoan Tephra in western Turkey, *Nature* 333, 552–554; 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 Southwest Turkey, Elsevier, *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 ablation ICP-MS to the analysis of volcanic glass shards from tephra deposits: bulk glas and single shard analysis, Elsevier, *Global and Planetary Change* 21, 151–171; GUICHARD F., CAREY S., ARTHUR M. A., SIGURDSSON H., ARNOLD M., (1993), Tephra from the Minoan eruption of Santorini in sediments of the Black Sea, *Nature* 363, 610–612.

quaternary volcanic activity on other islands of the Hellenic arc. On Milos, Nisyros, Giali and Kos one or several volcanic events led to the formation of thick pumice layers similar to that on Santorini. Accordingly the chemical composition of these deposits is rather similar, especially with respect to their *major constituents*.

It is an essential aid for the identification of the primary volcanic source, however, that pumices from the Aegean region can clearly be distinguished by their *trace element* distribution patterns. This will be shown in the following and has been described in detail in previous studies.[*]

Pumice (lat. pumex, possibly derived from spuma, foam, Fig. 2)

Pumice is a highly vesicular, light coloured volcanic rock with a mainly glassy matrix. This frozen foam of silicate melt is formed by mostly explosive eruptions of viscous (rhyolitic to dacitic) magmas, rich in gas and has a low specific mass due to its vesicular structure. Pumice floats on water and is transported by marine currents and wind over large distances. The abrasive properties of pumice are caused by its glassy matrix. In use, it sharpens itself by exposing numerous new, microscopical cutting
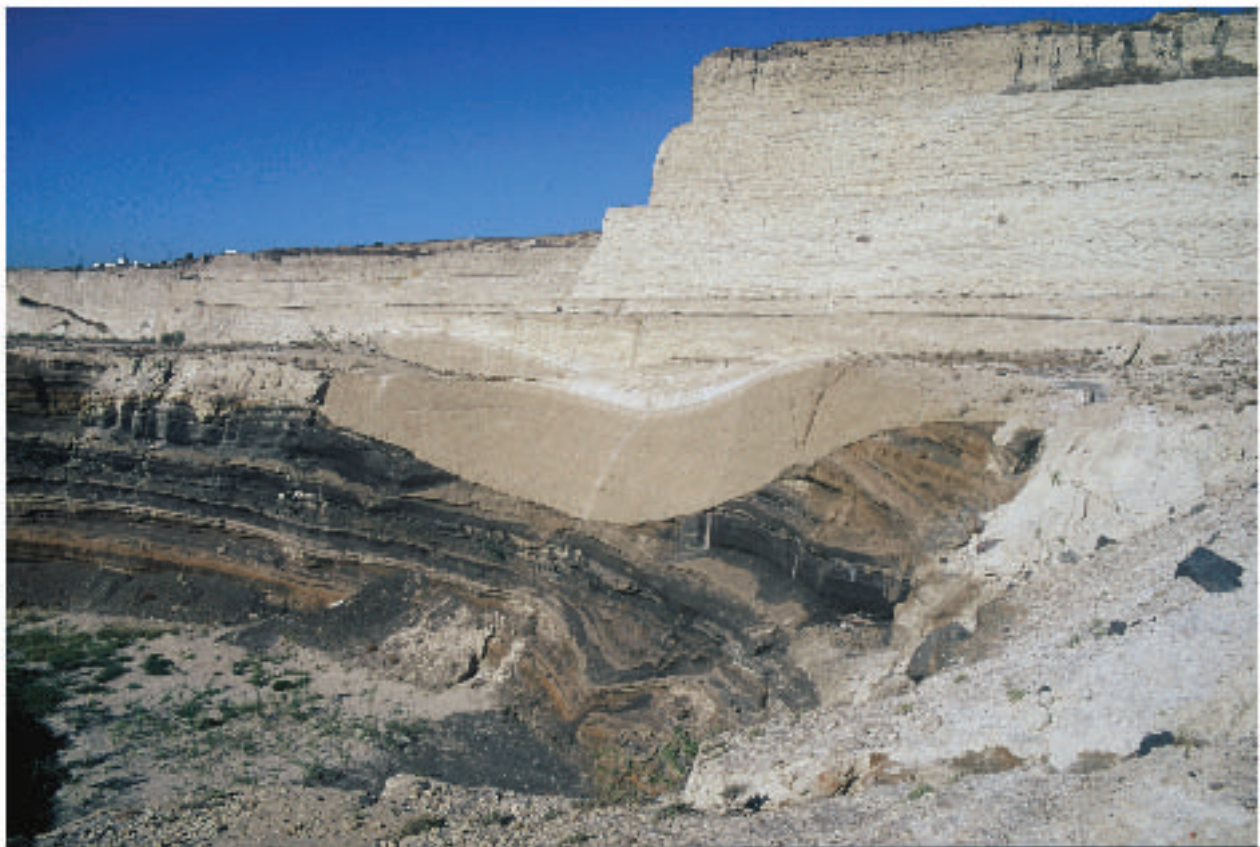

Fig. 2 Pumice quarry near Phira/Thera, showing the deposits of the Minoan eruption with the "rose-pumice" layer at the bottom.

[*] Peltz C., Schmid P., Bichler M. (2000), INAA of Aegean pumices for the classification of archaeological findings, *Journal of Radioanalytical and Nuclear Chemistry* 242/2, 361; Pichler H., Schiering W. (1980), Der spätbronzezeitliche Ausbruch des Thera-Vulkans und seine Auswirkungen auf Kreta, *Archäolog. Anzeiger*, Walter de Gruyter & Co. Sonderdruck 1; Francaviglia V. (1990), Sea-borne Pumice Deposits of Archaeological Interest or Aegean and Eastern Mediterranean Beaches, in: Hardy D. A. and Renfrew A. C. (eds.), *Thera and the Aegean World* III, London, 127-134; Vitaliano C.J, Taylor S. R., Norman M. D., McCulloch M. T. and Nicholls I. A. (1990), Ash layers of the Thera Volcanic Series: Stratigraphy, Petrology and Geochemistry, in: Hardy D. A. and Renfrew A. C. (eds.), *Thera and the Aegean World* III, London, 53–78.

edges. The hardness of the silicate glass of about 5–6 on the Mohs scale even renders it applicable for smoothing stone surfaces. As a consequence of widespread alluvial deposition, pumice has been a popular trading object since antiquity and lumps of it have been found in archaeological context.[10]

Tephra (greek ΤΕΦΡΑ = ash)

Tephra in general denotes fragmental volcanic ejecta which are produced during an eruption to distinguish them from flow deposits like lava, ignimbrites (pyroclastic flow deposits) or lahars (mud flow deposits). The term volcanic ash, which is often used synonymously, correctly characterizes only material with grain sizes less than 2mm. A typical tephra deposit from a single eruption shows a decrease in grain size with increasing distance from the eruption centre, an effect that in some cases may lead to a variation in chemical composition as will be discussed below.[11]

Sampling and preparation of pumice

From each primary deposit samples of pure xenolith-free pumice were taken over the whole range of the outcrop and analyzed separately to check its homogeneity. About 80 representative samples were taken from several sites at Milos (Plakes, Mavrovouno, Trachilas, Sarakiniko, Papafrangas), Nisyros (Upper and Lower Caldera Pumice, Giali Fallout), Giali (quarry base to top), Kos (Plinian layer at several locations on the island, pumice from the main deposit of the Kos Plateau Tuff) and Santorini (Lower Pumice Bu, Middle Pumice Bm, Upper Pumice Bo). Before sampling, weathered rock surfaces were removed to a depth of at least 150 mm.

In a second and third analytical run, archaeologically stratified pumice samples found in excavations in Tell-el-Dab^{c}a (Egypt), Tell el-Herr (Egypt), Tell el-Hebwa (Egypt), Tell el-^{c}Ajjul (Palestine), and Ashkelon (Israel) were investigated.

Each sample was prepared in the same way. After surface cleaning with distilled water in an ultrasonic bath and microscopical investigation, the samples were crushed exclusively with PE (polyethylene) tools, transferred to PP (polypropylene) beakers, dried for about 90 hours at 110°C, and homogenized by grinding in an agate mortar to grain size < 3µm followed by drying to constant weight at 110°C. Depending on the type of analysis, the samples were then weighed into PE- or quartz glass irradiation vials (for detais see chapter on INAA).

Separation of the pure glass phase

This part of the work was performed to ensure a reliable identification of tephra layers deposited in
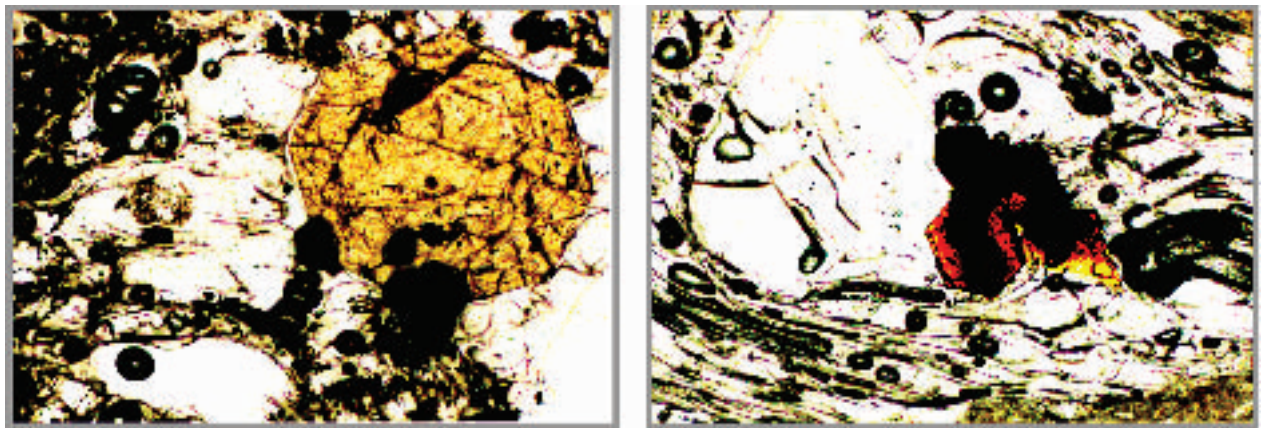

Fig. 3 Thin sections of crystalline inclusions in pumice showing an octogonal orthopyroxene crystal (left) and a cluster of hexagonal biotite crystals (right) in a vesicular glassy matrix

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[10] WARREN P. M., PUCHELT H. (1990): Stratified Pumice from Bronze Age Knossos in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, Vol. 2, London, 53–78; MARINATOS S. (1932). ΑΝΑΣΚΑΦΗ ΑΜΝΙΣΟΥ ΚΡΗΤΗΣ, *Prakt.Ath.Arch.Etair,* 76; FRANCAVIGLA V. (1986), Provenance of pumices from the Kastelli excavations (Chania, West-Crete), *PACT* 15, 67; KELLER J. (1980), Prehistoric pumice tephra on Aegean

islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56.

[11] BAAK J. A. (1949), A comparative study on recent ashes of the Java volcanoes Smerut, Kelut, and Merapi, *Meded. alg. Proefstn. Landb., Buitenzorg* 83, 1–60; WILLIAMS H., MCBIRNEY A. R. (1979): *Volcanology*, Freeman, Cooper &Co, San Francisco, USA.

greater distances from the eruption centre in the case of compositional changes.

With the volcanic centres in question, the material erupted during the Plinian phase consists mainly of pumice and pumiceous tephra with a certain percentage of crystallites in the glassy matrix (Fig. 3). The crystalline phases mainly comprise the minerals quartz, plagioclase, pyroxene, sanidine, biotite, apatite and ore minerals in varying concentrations.[12] Mechanical stress during the eruption leads to the fragmentation of vesicle walls and the formation of a fine- grained glass fraction which is easily transported to high altitudes. As a consequence, 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. The composition thus approaches that of the pure glass fraction, which may differ significantly from the bulk material, as several elements are enriched in the crystals depending on growth conditions, ionic radii, and valence states.

Minoan pumice contains only relatively small (sub mm) crystallites while other pumices, for example Kos Plateau Tuff pumice, contain crystals up to several mm in length.

To ensure reliable assignment of tephra found in archaeological excavations to the primary volcanic source, it is necessary to compare the tephra's trace element distribution not only to the bulk composition of the eruption products but also to that of the pure glass phase. For this purpose, a special technique has been developed to separate pure glass fractions from the pumice samples.[13]

For this purpose, a representative part of the pumice samples was treated differently from the bulk material. To avoid destruction of the crystallites, the sample material was carefully crushed with PE tools instead of grinding. A fraction suitable

for separation was obtain by sieving (1 mm mesh size). The following separation technique simulates the natural process in a simple way on laboratory scale. The separation is based on the fact that in an air flow, crystallites are not transported as far as vitric particles because of their size, specific weight 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 at an inclination of about 45°, the material deposited in the tube is transported by gravity back to the input. The suspended fraction is collected on a polyester filter (Fig. 4).

To purify the separated glass phase, especially to eliminate filter fibres and smallest crystallites, all glass samples were subjected to a sedimentation treatment in distilled water. The purity of the separated fractions was assessed by polarization microscopy which proved that the concentration of crystallites was lower than 1 %. Like the pumice samples, this product was weighed into PE- and quartz glass vials for INAA. Additionally, analyses were car-
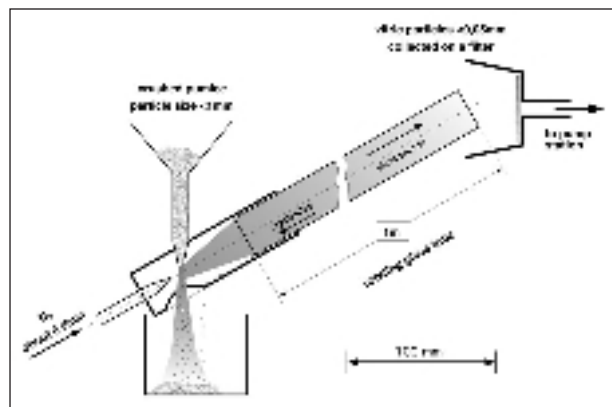

Fig. 4 Apparatus for the separation of a pure glass fraction from pumice

[12] KELLER J. (1980), Prehistoric pumice tephra on Aegean islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56; FYTIKAS M. (1986), Volcanology and Petrology of volcanic products from the island of Milos and neighbouring islets, *Journal of Volcanology and Geothermal Research* 28, 297–317; REHREN T. (1998): *Geochemie und Petrologie von Nisyros (östliche Ägäis)*, Ph.D. thesis, Freiburg; STADLBAUER E. (1988): *Vulkanologisch-geochemische Analyse eines jungen Ignimbrits: Der Kos-Plateau-Tuff (Südost-Ägäis)*, Ph.D.thesis, Freiburg; PASTEELS P., KOLIOS N., BOVEN A., SALIBA E. (1986), Applicability of the K-Ar-method to whole-rock samples of acid lava and pumice: case of Upper pleistocene domes and

pyroclasts on Kos island, Aegean Sea, Greece, *Chem. Geology* 57, 145–154; LIMBURG E. M., VAREKAMP J. C. (1991), Young pumice deposits on Nisyros, Greece, *Bulletin of Volcanology*, v. 54, 68–77; VITALIANO C. J. (1990), Ash layers of the Thera Volcanic Series: Stratigraphy, Petrology and Geochemistry, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, Vol. 2, London, 53–78.

[13] SCHMID P., PELTZ C., HAMMER V. M. F., HALWAX E., NTAFLOS T., NAGL P., BICHLER M.(2000), Separation and Analysis of Theran Volcanic Glass by INAA, XRF and EPMA, *Mikrochimica Acta* 133, 143–149.

ried out using electron-probe microanalysis and X-ray fluorescence analysis.

Instrumental Neutron Activation Analysis (INAA)

This radiochemical technique is used predominantly for the determination of specific trace elements down to detection limits in the ppm to ppb range, and is especially sensitive for a number of rare-earth elements (in particular La, Ce, Nd, Sm, Eu, Dy, Tb, Yb and Lu) and other significant trace elements like Sc, Co, Rb, Zr, Sb, Ba, Cs, Hf, Ta, Th and U. The specific distribution of these elements in samples can be used for chemical fingerprinting to distinguish the provenance of the different volcanic products found in archaeological context. Samples are "activated" by irradiation with neutrons, usually in a nuclear research reactor. Specific isotopes become radioactive by neutron capture reactions. Gamma ray spectra of the activated samples are then measured using solid state germanium gamma-ray detectors, usually over the energy range 50 to 3200 keV. Specific isotopes can be identified by the characteristic energies of the gamma-photons emitted and quantitative determinations are made by comparing the count rates of these specific energy peaks with those in the spectrum of a standard sample, irridiated and counted under identical conditions. An important advantage is that INAA involves the irradiation and analysis of homogenized rock powders that have not undergone any chemical treatment, thereby avoiding "laboratory contamination" by reagents, etc. A typical INAA comprises the measurement of short-, medium-, and long-lived activation products and is performed as follows:

For activation of short- and medium lived radionuclides, the samples are weighed into PE capsules, about 150 mg each. They are irradiated for 1 minute in the irradiation position of the General Atomic pneumatic transfer system of the TRIGA MkII reactor of the Atominstitut der Österreichischen Universitäten at a thermal neutron flux of about $3*10^{12}$ cm^{-2}s^{-1}. A first measurement (counting time 5 minutes) is performed after a decay time of 5 minutes to determine Al, Ca, Ti and V. About 3 hours later, a second gamma spectrum is measured for 8 minutes to quantify Dy, K, Mn and Na. For the determination of Al, the reaction ^{27}Al $(n,\Gamma)^{28}$Al is used. The additional production of ^{28}Al by the reaction ^{28}Si$(n,p)^{28}$Al must be corrected for. The amount produced is determined by the irradiation of high purity quartz, the respective peak area is calculated from the known Si concentrations of the samples and subtracted from the ^{28}Al peak. A list of the radionu-

clides and the gamma-peaks used is given in Table 1. For the activation of long-lived radionuclides, about 150 mg of each sample are sealed into Suprasil^{TM} quartz glass vials. The samples are irradiated together with standards for about 80 hours in a suitable research reactor (KFKI Budapest/Hungary or Rez/Cech Republic) at a neutron flux of about $5*10^{13}$ cm^{-2}s^{-1}. After a decay time of 5 days, a first gamma-spectrum is measured to obtain the activities of the medium-lived activation products (La, Lu, Sm, and U). After 32 and 110 days a second, resp. third spectrum is taken to detect the long-lived activation

element	activation product	half-life	γ-energy keV[5]
Al	^{28}Al	2.2 min	1779
Ba	^{131}Ba	11.5 d	496
Ca	^{49}Ca	8.7 min	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
Tb	^{160}Tb	72.3 d	879
Th	^{233}Pa[a]	27.0 d	312
Ti	^{51}Ti	5.8 min	320
U	^{239}Np[a]	56.6 h	278
V	^{52}V	3.7 min	1434
Yb	^{169}Yb	32.0 d	177
Zn	^{65}Zn	244.3 d	1116
Zr	^{95}Zr	64.0 d	757

Table 1 Activationproducts, half-lives and gamma-energies used for analysis

[a] ^{233}Pa and ^{239}Np are produced by β-decay of ^{233}Th (half-life 22.3min) and ^{239}U (half-life 23.5min), which were formed by neutron capture of ^{232}Th and ^{238}U, respectively.

products (Ba, Ce, Co, Cr, Cs, Fe, Hf, Nd, Rb, Sb, Sc, Ta, Th, Yb, Zr resp. Eu, Tb and Zn). The measuring time is 1800 s for the first, 10000 s for the second and 10000 s for the third run. 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.[14] The evaluation was carried out using the Genie 2000 gamma spectroscopy software package from Canberra.

RESULTS

Reference materials like soil standard BCR No. 142, CANMET reference soil SO1, NIST SRM 1633b Coal fly ash and Rhyolith GBW-07113 were activated together with the samples and used as standards. Blank values for the PE and Suprasil^{TM} quartz glass irradiation vials were measured and found negligible. The detailed analytical results have been published already in separate papers elsewhere,[15] a compilation of the relevant data is given in Tables 3–5. Detection limits (<5σ) depend on the measuring time and the γ-background of the samples. The analytical error due to counting statistics has been calculated by ±σ and is generally below 5%rel.

Pumice

In accordance with previous studies, the three pumice layers from the Minoan eruption at Thera were found to be homogeneous.[16] The compositions of the older pumice layers Bm and Bu show characteristic differences. For the other islands, several groups of typical compositions were found and classified. Table 2 shows the names of these groups, each usually pertaining to a single volcanic source and/or event. Some of these groups are more homogeneous than was expected and perfectly demonstrate the reproducibility of the analyses.

From these results, pairs of elements where chosen to characterize each group by the formation of typical clusters (Fig. 5). The best classification can be obtained by comparing the distribution patterns for the elements europium, tantalum, thorium and hafnium. The overlapping of fields of the Kos Plateau Tuff pumice and the Giali deposits is not crucial as a confusion is ruled out by microscopical investigation, where the unique mineralogical features of the Kos material are easily recognized. Giali pumice contains only very small and scarce crystals while the Kos material contains a certain percentage of very large crystals, especially very characteristic idiomorphic biotite. The specificity of these patterns allows the omission of less reliable statistical interpretations of less significant data like those of the major components.

Giali shows a very important feature: the quarry main pumice is homogeneous throughout more

Santorini:	upper pumice Bo, middle pumice Bm, lower pumice Bu
Milos:	Sarakiniko, Papafrangas, Trachilas, Plakes
Nisyros:	Caldera pumice (upper and lower)
Giali:	Giali 1 (quarry main pumice), Giali 2
Kos:	Kos 1 (pumice from the Kos plateau tuff) Kardamena, Kos 2 Kos plateau tuff ash layer, Kephalos

Table 2 Groups of typical compositions of pumice on Aegaean islands

[14] WESTPHAL G. P. (1995), Digital Implementation of the Preloaded Filter Pulse Processor, *J. Radioanal. Nucl. Chem.* 193/1 81–88.

[15] 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; SCHMID P., PELTZ C., HAMMER V. M. F., HALWAX E., NTAFLOS T., NAGL P., BICHLER M. (2000), Separation and Analysis of Theran Volcanic Glass by INAA, XRF and EPMA, *Mikrochimica Acta* 133, 143–149; SAMINGER S., PELTZ C., BICHLER M. (2000), South Aegean volcanic glass-separation and analysis by INAA and EPMA, *Journal of Radioanalytical and Nuclear Chemistry* 245/2, 375–383.

[16] VITALIANO C. J. (1990), Ash layers of the Thera Volcanic Series: Stratigraphy, Petrology and Geochemistry, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, Vol. 2, London, 53–78; VITALIANO C. J., FOUT J. S., VITALIANO D. B. (1978), Petrochemical study of the Tephra sequence exposed in the Phira Quarry, Thera, in: C. DOUMAS (ed.), *Thera and the Aegaean World* 1, London, 203–215; BICHLER M., EGGER H., PREISINGER A., RITTER D., STASTNY P. (1997), NAA of the 'Minoan pumice' at Thera and comparsion tu alluvial pumice deposits in the Eastern Mediterranean region, *Journal of Radioanalytical and Nuclear Chemistry* 224, 7–14; FRANCAVIGLIA V., DI SABATINO B. (1990), Statistical Study on Santorini Pumicefalls, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 29–52.
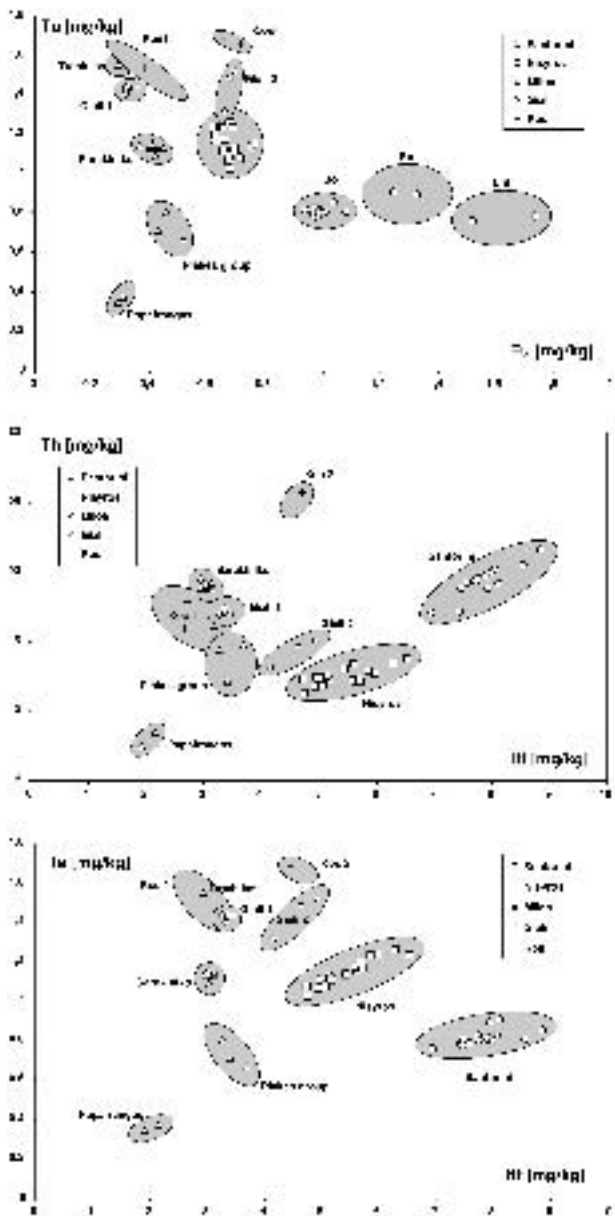
Fig. 5 Distribution patterns of elements
in pumice samples from Aegean islands

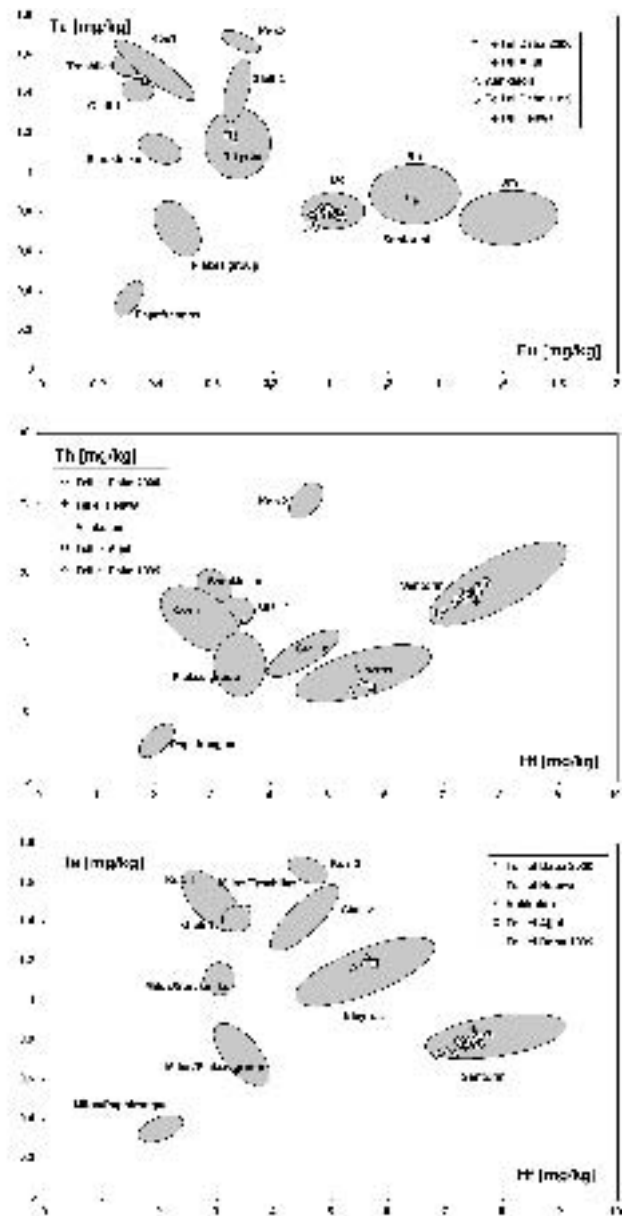Fig. 6 Concentration of elements
in pumicefrom excavation sites

than 100 m thickness, but a sheet overlying the main pumice and separated by a palaeosoil layer is of conspicuously different composition. This fact was already observed by Keller (layer Giali 2),[17] but no trace elements were determined at that time and therefore significant differences remained undiscovered. A composition similar to this layer was also

found at Nisyros in airfall pumice deposits that can therefore be related to this particular event at Giali.[18]

DISCUSSION

Within the error range, most of the elements determined were in perfect agreement with values from

[17] KELLER J. (1980), Prehistoric pumice tephra on Aegean islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56.

[18] REHREN T. (1998): *Geochemie und Petrologie von Nisyros (östliche Ägäis),* Ph.D. thesis, Freiburg.

the literature.[19] Higher deviations towards lower concentrations were found only for Cr and in some cases for Fe, Co, V and Mn. This appears to be related to the use of xenolith-free material and the exclusive application of PE and agate tools for sample preparation thereby avoiding contamination by steel alloy components. In some cases it is obviously impossible to compare literature data given as average values for a whole island where pumices of clearly different compositions occur.[20] Likewise, a comparison with analyses published without documentation of the preparation techniques could lead to false conclusions. It was observed that some of the literature values for Rb determined by RFA show a small, but increasing deviation from our results with decreasing concentrations,[21] whereas other values agree perfectly.[22] In general, previous studies often dealt with RFA results. Only few authors applied INAA to comparable samples. INAA data on 2 samples from Milos (Trachilas),[23] 2 from Nisyros (upper and lower caldera pumice)[24] and 14 from Thera (upper pumice Bo) have been published.[25] These INAA data are in perfect agreement with our results.

On the basis of the cluster graphics presented, it is possible to relate unkown pumice to its primary source, just by comparing the relation of a few elements like Ta-Eu, Th-Hf, and Ta-Hf (Fig. 6a–c). The conjecture can be confirmed by comparing the entire element spectra, thus revealing minutest differences.

The agreement with the typical chemical fingerprint by comparison of all elemental concentrations determined, normalized to the mean Bo values, is demonstrated by typical samples in Fig. 7a–c. The shaded area represents the natural variation of the element concentrations found in the respective deposit. Our results demonstrate that the pumice samples found in archaeological excavations only show minor changes in composition due to leaching effects though glass hydration effects, and strongly weathered rock surfaces were observed, especially in the water-saturated sedimental environment of Tell el-Dab^{c}a. From the chronolgical point of view, the results obtained for the excavated samples agree with the present dating range of the Minoan eruption between 1650 and 1450 (see Table 3).

Glass fraction

The results obtained by INAA and EPMA are given in Table 4 and Table 5. Likewise, the major element distributions obtained by INAA are in good agree-

[19] VITALIANO C. J. TAYLOR S. R., NORAMN M. D., McCULLOCH M.T.and NICHOLLS I.A. (1990), Ash layers of the Thera Volcanic Series: Stratigraphy, Petrology and Geochemistry, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 53–78; KELLER J. (1980), Prehistoric pumice tephra on Aegean islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56; FYTIKAS M. (1986), Volcanology and Petrology of volcanic products from the island of Milos and neighbouring islets, *Journal of Volcanology and Geothermal Research*, 28, 297–317; BICHLER M., EGGER H., PREISINGER A., RITTER D., STASTNY P. (1997), NAA of the 'Minoan pumice' at Thera and comparsion tu alluvial pumice deposits in the Eastern Mediterranean region, *Journal of Radioanalytical and Nuclear Chemistry* 224, 7–14; FRANCAVIGLIA V., DI SABATINO B. (1990), Statistical Study on Santorini Pumice-falls, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 29–52; FRANCALANCI L., VAREKAMP J. C. (1995), Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros Volcano, Greece, *Bull. Volcanol.* 56, 601–620.

[20] FRANCAVIGLA V. (1986), Provenance of pumices from the Kastelli excavations (Chania, West-Crete), *PACT* 15 67; RICHARDSON D., NINKOVICH D. (1976), Use of K₂O, Rb, Zr and Y versus SiO₂ in volcanic ash layers of the eastern Mediterranean to trace their source, *Geol. Soc. Am. Bull.* 87, 110–116.

[21] FYTIKAS M. (1986), Volcanology and Petrology of volcanic products from the island of Milos and neighbouring islets, *Journal of Volcanology and Geothermal Research* 28, 297–317; FRANCAVIGLIA V., DI SABATINO B. (1990), Statistical Study on Santorini Pumice-falls, in: HARDY D. A. and RENFREW A. C. (eds.), *Thera and the Aegean World* III, London, 29–52; FRANCALANCI L., VAREKAMP J. C. (1995), Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros Volcano, Greece, *Bull. Volcanol.* 56, 601–620.

[22] KELLER J. (1980), Prehistoric pumice tephra on Aegean islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56.

[23] FYTIKAS M. (1986), Volcanology and Petrology of volcanic products from the island of Milos and neighbouring islets, J*ournal of Volcanology and Geothermal Research* 28, 297–317.

[24] FRANCALANCI L., VAREKAMP J. C. (1995), Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros Volcano, Greece, *Bull. Volcanol.* 56, 601–620.

[25] BICHLER M., EGGER H., PREISINGER A., RITTER D., STASTNY P. (1997), NAA of the 'Minoan pumice' at Thera and comparsion tu alluvial pumice deposits in the Eastern Mediterranean region, *J. Radioanal. Nucl. Chem.* 224, 7–14.
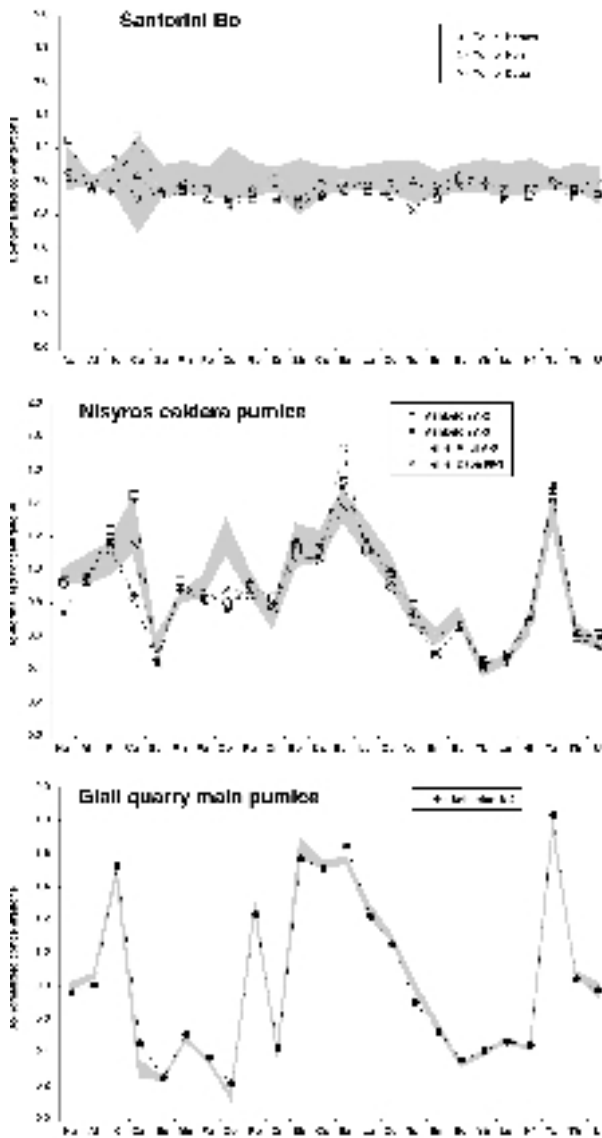
Fig. 7 Distribution of elements in pumice samples from excavation sites. The shaded areas show the natural variation range of the original deposits. All values normalized to Bo concentrations. Please note the logarithmic scale for the Kos sample.

Fig. 8 Enrichment-depletion pattern of elements in a glass fraction separated from Santorini Bo-pumice

Fig. 9 Enrichment-depletion pattern of elements in a glass fraction separated from Giali quarry main body pumice

ment 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. As examples, Nisyros Upper Caldera pumices, Giali main pumice and the Bo-pumice from Santorini are discussed below:

Santorini: In comparison to bulk material from the Bo-layer, the glass phase is slightly enriched in all elements but Al, Ca, Co, Eu, Fe, Mn, Na and Sc. The depletion of the major elements Al, Ca, Fe, Mn and Na in the glass can readily be attributed to the presence of the known mineral phases. Fig. 8 shows the enrichment-depletion pattern of the elements.

Giali: Pumice from Giali has an extremely low content of minerals, as confirmed by the achieved results, which show hardly any differences between the bulk material and the separated glass (Fig. 9).

Nisyros: In contrast to glass from Giali, significant differences could be revealed between glass and bulk material of both samples (upper and lower caldera pumice) as the bulk is rich in crystallites. The depletion in Al, Ca, Eu and Na is explained by the separation of minerals such 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 potassium feldspar such as sanidine. The pronounced negative Eu anomaly is attributed to the plagioclase fractionation which is normally expected in such highly evolved magmas. Fig. 10 shows an enrichment/depletion pattern for the Upper Caldera Pumice.
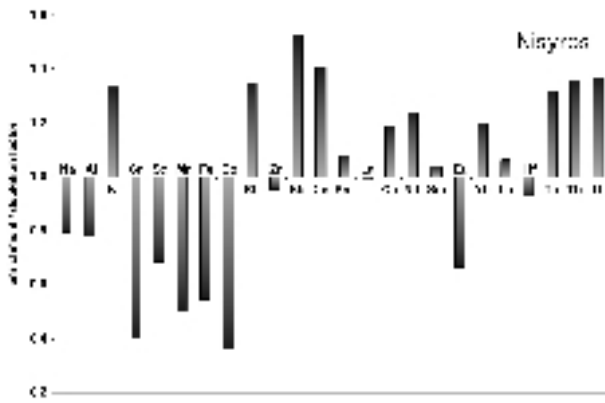
Fig. 10 Enrichment-depletion pattern of elements in a glass fraction separated from Nisyros Upper Caldera pumice

Discussion

The comparison with analytical data from literature and previous analyses shows good agreement.[26] Our results obtained by INAA are in highly satisfying accordance with laser ablation ICP-MS analysis of single tephra grains in lake sediments from Gölhisar Gölü in the Southwest of Turkey (see Fig.1)[27] and confirm Santorini as the primary source. In general, the results show clearly that an omission of this analytical step would have led to erroneous identifications, especially if only the major components were determined. The enrichment-depletion factors for components like Na, Al, K, Ca and Fe vary between 0,4 to 1,5 and their concentrations can only be used as chemical fingerprint, if these factors have been determined previously.

Conclusions

The distribution patterns of a large number of elements obtained by INAA allow the differentiation of several groups of pumice deposits in the Aegean region. Characteristic pairs of elements enable a simple method for a safe classification and relation of pumice of unknown origin. The additional information about the enrichment / depletion factors of the elements in the pure glass phase relative to the bulk pumice allows the application of these data sets also to the identification of tephra layers that have lost their crystalline compounds during transportation.

INAA enables selection 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. Work to optimize the separation techniques for the various types of archaeological soil samples is in progress.

[26] SCHMID P., PELTZ C., HAMMER V. M. F., HALWAX E., NTAFLOS T., NAGL P., BICHLER M. (2000), Separation and Analysis of Theran Volcanic Glass by INAA, XRF and EPMA, *Mikrochimica Acta* 133, 143–149; KELLER J. (1980), Prehistoric pumice tephra on Aegean islands, in: C. DOUMAS (ed.), *Thera and the Aegean World* II, 49–56.

[27] 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 Southwest Turkey, Elsevier; *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 ablation ICP-MS to the analysis of volcanic glass shards from tephra deposits: bulk glas and single shard analysis, Elsevier; *Global and Planetary Change* 21, 151–171.

Table 3   Concentration of elements in pumice from excavation sites, all values in mg/kg except Na, Al, K, Ca and Fe which are given in weight %

Tell el Dab'a 2000

context	sample id.	source	Na%	Al%	K%	Ca%	Fe%	Ti	Y	Cr	Mn	Co	Rb	Zr	Nb
13	6.2a	Santorini Bo	5.07	5.78	3.45	4.87	1.92	2416	157.5	5.06	856	3.26	95.5	251	0.26
13	6.2b	Santorini Ro	5.57	7.27	3.54	2.73	2.08	n.d.	97.99	5.24	974	3.30	101.8	252	0.96
13	6.9r	Santorini Ro	5.57	7.45	5.54	1.58	2.07	2468	94.21	n.d.	807	3.28	100	251	0.95

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13	8.9a	Santorini Ro	4.18	7.94	3.42	1.57	2.08	7.60	3795	93.29	3.48	986	3.50	101.0	241	0.95
13	8.9b	Santorini Ru	4.14	7.06	2.79	1.49	2.27	6.90	1347	7.61	1.96	984	3.10	107.7	247	0.26
13	11.5a	Santorini Ro	3.91	7.06	3.10	1.98	3.02	7.82	2913	19.19	n.d.	875	3.51	104.6	250	0.24
13	15.61	Santorini Ro	4.21	6.38	3.32	1.22	2.5	6.14	n.d.	n.d.	n.d.	942	2.80	102.	285	0.30
13	6.5a	Santorini Bo	4.90	7.21	3.88	1.88	2.6.	5.43	n.d.	19.58	n.d.	846	3.21	102.8	282	0.26
13	8.9a	Santorini Bo	3.93	7.42	3.67	1.73	2.06	7.97	2077	33.20	n.d.	950	3.39	101.6	257	0.28
13	8.9z	Santorini Ro	5.11	6.98	3.96	1.95	1.99	7.93	3027	93.56	n.d.	950	3.08	101.	250	0.27
13	8.5h	Santorini Ro	4.67	7.96	3.0.	1.51	2.96	7.93	1199	94.90	n.d.	984	5.56	104	260	0.27
13	8.6i	Santorini Ro	4.55	7.08	2.7.	1.72	2.1	6.98	842	22.07	4.08	946	4.88	102.1	268	0.27
13	16.8j	Santorini Ro	3.54	4.88	2.5.	1.41	2.33	6.52	290.	39.14	4.06	640	1.75	86.	270	0.26

Ashkelon

context	sample id.	source	Cs	Ba	La	Ce	Nd	Sm	Lu	Dy	Yb	Lu	Hf	Ta	Tb	U
913	4.2	Nisyros	5.00	369	54.8	55.1	18.7	5.05	0.696	-5.	2.08	0.64	5.59	1.17	0.5	5.2
913	4.9	Nisyros	5.55	497	46.5	55.9	18.7	5.10	0.696	-5.	1.95	0.65	5.88	1.54	0.2	9.5
913	4.4	Gö.	4.42	508	96.9	62.0	18.4	4.57	0.895	11	5.86	0.65	5.58	1.46	0.66	4.6

Tell el Ajjul

13	4.6	Nisyros	5.18	382	55.2	59.1	20.6	5.05	0.616	5.5	2.21	0.55	5.71	1.15	0.8	3.6

Tell el Herr

Amiches Schnitt

		Santorini Ro	2.72	774	28.7	50.0	19.2	5.54	0.902	2.5	1.99	0.79	5.95	0.8	0.9	7.2

Tell el Dab'a 1999

context	sample id.	source	Cs	Ba	La	Ce	Nd	Sm	La	Dy	Yb	Lu	Hf	Ta	Tb	U
13	4	Santorini Ro	5.61	549	50.4	50.1	18.4	4.97	1.057	5.9	4.78	0.70	5.91	0.78	0.83	5.9
13	8	Nisyros	5.11	771	96.	58.9	18.4	4.77	0.696	5.	1.96	0.45	5.56	1.10	0.71	9.1
13	4	Santorini Ro	5.45	594	27.4	55.4	22.4	7.9	0.91	2.6	4.44	0.46	6.90	0.74	5.2	5.2
13	11	Santorini Ro	5.04	505	34.1	5.0	40.5	5.50	0.840	5.6	5.29	0.5	5.21	0.90	8.2	7.1
13	4L	Santorini Bo	5.04	508	34.1	5.55	45.	5.54	0.924	2.9	5.42	0.72	7.21	0.99	8.2	5.2
13	4D	Santorini Bo	2.63	591	50.0	5.56	21.9	6.92	1.062	5.4	2.77	0.95	7.31	0.62	8.3	5.6
13	4E	Santorini Bo	2.58	587	39.6	55.2	27.	5.80	0.960	5.5	2.95	0.84	7.51	0.78	8.3	5.1
13	4F	Santorini Ro	2.62	540	35.4	54.8	39.7	5.51	0.957	5.4	4.08	0.96	7.06	0.78	8.2	5.4
13	46	Santorini Ro	2.64	576	35.5	55.1	36.5	5.71	0.894	4.5	7.96	0.5.	6.74	0.59	6.65	5.4
13	5A	Santorini Ro	2.75	779	35.0	61.4	34.5	6.58	1.046	4.2	5.19	0.76	7.70	0.82	0.2	7.5
13	5H	Santorini Ro	2.08	711	30.1	55.9	34.5	6.5	1.005	5.0	5.01	0.51	7.60	0.5.	0.5	5.4

Table 3 continued

Tell el Dab'a 1990	cortex	sample-id.	source	Cs	Ba	La	Ce	Nd	Sm	Eu	Dy	Yb	Lu	Hf	Ta	Th	U
I-1–127	11	1	Sublate Bo	2.05	503	28.1	50.0	26.2	2.70	0.877	2.0	1.05	0.72	7.05	0.82	6.4	3.0
I-11 120	11	2	Subate lie	2.51	511	28.5	57.1	28.5	4.11	0.940	2.1	1.09	0.5	7.18	0.50	2.4	4.5
I-1 125	11	55	Secretat Bo	2.60	500	26.3	55.1	28.1	3.88	0.960	3.0	2.01	0.32	3.20	0.60	8.5	5.6
I-1 127	12	56	Secretat Bo	2.48	500	28.0	53.5	26.6	3.52	0.945	2.3	2.76	0.69	7.01	0.75	5.2	4.7
Tell el Dab'a 2000																	
I-11–47	511	55	tor Tel Kas?	2.71	500	31.2	55.1	16.5	2.45	0.465	2.0	4.03	0.40	6.57	1.51	1.7	3.2
I-N 012 1.650	11	111a	mr Re murut.	12.01	11	32.0	17.0	16.5	4.58	1.56	2.4	4.54	0.43	6.40	0.40	0.5	4.1
"	11	b 11	Secretat Bo	2.88	561	30.6	50.0	21.8	6.10	1.026	3.8	3.11	0.5	2.53	0.6	0.0	6.0
"	12	B-1c	Secretat Bo	2.53	500	20.8	53.8	26.0	3.35	1.051	2.3	3.18	0.22	7.56	0.80	3.8	3.9
"	12	B-1d	Secretat Bo	2.55	507	28.9	50.5	22.6	3.51	1.054	2.5	5.05	0.70	7.40	0.7	8.4	6.6
"	12	B-1e	Secretat Bo	2.61	502	30.4	60.0	28.9	4.00	1.015	5.1	5.00	0.70	7.1	0.80	7.8	0.5
"	12	B-1f	Subate lie	2.61	502	30.0	58.5	26.8	5.82	1.014	4.4	5.03	0.70	7.5	0.80	6.5	7.0
"	11	B-1g	Subate lie	2.07	570	30.0	56.2	27.3	4.04	0.982	2.0	5.02	0.73	7.70	0.83	6.5	6.1
"	11	B-1h	Subate lie	2.84	500	20.7	60.0	26.0	3.85	0.999	2.4	5.00	0.5	7.00	0.50	7.0	7.0
"	12	B-1i	Secretat Bo	2.80	500	30.0	65.0	26.5	6.00	0.80.	2.7	5.07	0.54	7.51	0.62	8.8	3.0
"	12	B-1j	Secretat Bo	2.68	559	29.0	57.0	26.7	4.35	0.985	3.3	5.18	0.70	7.23	0.70	3.0	5.1
"	12	B-1k	Secretat Bo	2.04	500	47.2	67.0	22.7	3.08	0.048	2.7	5.18	0.75	7.78	0.83	0.4	6.1
"	12	B-1l	Secretat Bo	2.77	707	30.5	51.0	27.0	0.00	1.004	2.8	5.05	0.60	7.4	0.80	0.5	7.0
"	12	B-1m	Subate lie	2.70	503	30.5	60.5	26.1	0.00	1.045	2.0	5.17	0.7.	7.4	0.77	0.5	8.0
IN-1 nil	11	112a	Subate lie	2.55	503	28.0	5.5	28.5	5.34	0.956	2.8	0.16	0.00	6.42	0.54	7.0	7.5
"	11	b-2f	Subate lie	2.7.	5.5	30.2	53.8	28.0	3.64	0.980	3.1	1.48	0.70	7.60	0.58	8.0	8.0
"	12	G-2c	Secretat Bo	2.83	551	30.2	58.6	28.4	3.81	1.009	2.1	2.06	0.7.	7.56	0.6.	8.0	6.0
Tell el Hebua																	
Sinai (Cornel) Anticp. 1999	12	G-3a	Secretat Bo	2.88	525	28.5	55.2	26.0	3.88	1.004	2.7	2.06	0.62	7.20	0.78	2.0	5.1
"	12	b-3b	Secretat Bo	3.11	502	27.0	50.0	27.2	2.53	1.267	2.0	5.85	0.60	7.56	0.88	7.0	5.7
"	12	R-3c	Secretat Bo	2.83	549	29.8	58.4	29.4	3.74	0.987	3.4	5.00	0.60	7.50	0.80	7.0	5.6
"	12	R-3d	Subate lie	4.00	495	30.6	67.4	29.7	4.78	1.285	4.55	3.80	0.70	7.–8	0.85	7.8	4.5
"	12	R-3e	Subate lie	2.55	545	28.7	55.2	26.5	5.41	0.884	2.0	0.85	0.00	7.2	0.80	6.5	5.0
"	11	B-3f	Subate lie	2.73	552	30.2	5.1	24.6	5.4	1.000	2.8	5.12	0.7.	7.0	0.34	4.	7.5
"	11	b-3g	Subate lie	2.00	503	28.1	55.6	24.0	3.52	0.845	3.2	1.80	0.00	7.1	0.80	7.1	5.2
"	12	B-3h	Secretat Bo	2.72	507	30..	57.2	26.0	6.1.	0.970	5.0	2.87	0.5.	7.31	0.76	8.3	5.7
"	12	B-3i	Secretat Bo	2.84	582	29.8	58.1	29.5	6.32	1.005	2.0	3.33	0.60	7.5	0.85	3.5	5.2
"	12	R-3j	Secretat Bo	2.70	508	30.0	58.0	24.0	3.59	0.988	3.5	4.52	0.60	7.98	0.76	8.0	6.5

Table 3 continued

location	sample	Na %	Al %	K %	Ca %	Fe %	Sc	Ti %	V	Cr	Mn	Co	As	Rb	Zr	Sb
Milos																
Plakes	MLO 2 glass	2,04	6,47	3,15	0,92	0,83	2,69	<0,16	<5,6	3,87	375	0,73	4,7	154	130	1,01
	MLO 2 bulk	2,86	5,24	3,35	0,91	0,87	2,73	<0,13	<4,9	2,31	401	0,89	4,7	138	116	0,89
Plakes	MLO 5 glass	2,29	6,59	3,30	0,97	0,76	1,54	<0,18	<5,2	1,40	450	0,59	2,0	120	119	0,23
	MLO 5 bulk	2,54	7,26	3,21	0,99	0,77	1,58	<0,15	<6,0	<0,40	465	0,56	2,6	127	106	0,21
sSarakiniko	MLO 8 glass	1,77	6,34	3,93	0,53	0,61	1,68	<0,28	<5,8	<0,77	407	0,32	<3,8	133	113	0,18
	MLO 8 bulk	2,43	6,96	3,97	<0,23	0,61	1,65	<0,15	<5,8	0,76	421	0,37	1,7	135	101	0,14
Papafrangas	MLO 14 glass	0,81	3,05	1,73	0,31	0,41	1,25	<0,14	<3,0	2,28	171	0,39	1,9	86	98	1,01
	MLO 14 bulk	1,17	3,67	1,84	0,45	0,45	1,35	<0,10	<3,8	<0,35	184	0,44	2,2	88	87	0,96
Nisyros																
Lower Caldera pumice	NIS 2 glass	2,60	6,44	3,37	0,92	0,95	2,74	<0,16	7,6	1,22	246	1,25	7,6	136	156	0,45
	NIS 2 bulk	3,12	8,11	2,62	1,83	1,85	4,40	0,22	38,5	3,37	474	4,33	5,8	104	187	0,33
Upper Caldera pumice	NIS 23 glass	2,47	6,45	3,48	0,73	1,04	3,08	<0,16	10,8	3,77	241	1,63	7,6	139	173	0,51
	NIS 23 bulk	3,11	8,27	2,61	1,81	1,89	4,50	0,25	32,8	4,51	480	4,52	6,1	103	173	0,33
Giali																
quarry main pumice	YLI 2 glass	2,58	6,35	3,59	0,64	0,81	2,12	<0,16	<4,9	1,32	281	0,57	8,8	143	126	0,51
	YLI 2 bulk	2,68	6,74	3,59	<0,18	0,77	2,08	<0,14	<5,8	0,96	284	0,55	9,8	147	105	0,49
top layer	YLI 5 glass	3,01	7,38	3,09	1,08	1,50	3,35	<0,18	19,9	2,05	499	2,01	4,8	129	188	0,41
	YLI 5 bulk	2,89	7,66	3,01	2,07	1,50	3,50	<0,14	22,5	3,95	473	2,26	5,2	130	160	0,40
Kos																
KPT pumice	KOS 1 glass	2,28	6,55	4,19	0,63	0,49	2,27	<0,18	<5,6	1,08	458	0,59	6,8	151	95	0,65
	KOS 1 bulk	2,69	7,47	3,35	0,87	0,88	2,44	<0,14	9,8	<0,47	426	1,41	5,6	123	96	0,47
KPT Plinian layer	KOS 3 glass	1,78	6,91	4,22	0,79	1,05	3,74	0,14	14,3	7,09	512	2,70	4,7	154	102	0,97
	KOS 3 bulk	2,38	7,40	3,39	0,92	1,08	3,12	<0,13	13,1	8,13	399	2,29	6,0	128	113	0,58
Santorini																
Bm	SAT 4 glass	3,30	7,88	1,93	2,44	3,73	13,59	0,46	27,1	1,22	1089	4,91	3,9	100	292	0,45
	SAT 4 bulk	3,25	8,31	1,93	2,45	3,96	14,36	0,47	33,0	<1,15	1097	5,52	3,7	100	249	0,38
Bo	SAT 5 glass	3,40	7,05	2,72	1,11	1,63	7,11	0,19	11,6	<0,85	520	2,30	2,6	120	326	0,29
	SAT 5 bulk	3,43	7,78	2,35	1,50	2,18	8,55	0,28	22,5	<0,77	586	3,95	2,7	111	267	0,26

location	sample	Cs	Ba	La	Ce	Nd	Sm	Eu	Dy	Yb	Lu	Hf	a	Th	U	
Milos																
Plakes	MLO 2 glass	4,16	573	26,7	48,3	18	3,42	0,468	2,7	2,28	0,37	3,63	0,77	15,70	3,86	
	MLO 2 bulk	3,75	554	26,9	45,2	16	3,29	0,515	3,1	2,22	0,36	3,68	0,66	14,73	3,46	
Plakes	MLO 5 glass	3,79	498	23,9	43,6	13	2,86	0,489	3,1	2,07	0,35	3,15	0,84	13,70	3,80	
	MLO 5 bulk	3,70	510	25,7	46,4	16	2,98	0,459	<2,3	2,05	0,38	3,26	0,81	14,50	3,81	
Sarakiniko	MLO 8 glass	2,49	661	33,2	51,2	17	2,84	0,341	1,7	1,85	0,33	2,84	1,27	18,30	4,76	
	MLO 8 bulk	2,38	663	32,7	52,3	17	3,07	0,363	2,2	1,80	0,34	2,96	1,14	19,15	4,51	
Papafrangas	MLO 14 glass	3,18	453	13,1	24,9	8	2,11	0,248	1,4	1,23	0,26	1,67	0,35	7,21	7,29	
	MLO 14 bulk	3,19	551	14,8	25,5	11	2,08	0,286	1,7	1,22	0,26	1,92	0,35	7,50	6,03	
Nisyros																
Lower Caldera pumice	NIS 2 glass	4,52	799	38,0	62,6	20	3,94	0,449	2,8	2,10	0,37	4,09	1,39	15,73	4,56	
	NIS 2 bulk	3,31	758	34,5	58,5	21	3,25	0,652	1,9	1,83	0,32	5,12	1,11	12,31	3,19	
Upper Caldera pumice	NIS 23 glass	4,65	817	40,0	70,2	25	4,15	0,475	2,9	2,31	0,37	4,41	1,42	16,77	4,51	
	NIS 23 bulk	3,31	755	40,4	59,0	20	4,00	0,713	3,2	1,92	0,35	4,73	1,07	12,34	3,29	
Giali																
quarry main pumice	YLI 2 glass	4,60	844	41,0	68,0	19	3,40	0,367	3,1	2,02	0,36	3,40	1,44	16,91	4,11	
	YLI 2 bulk	4,52	875	40,5	67,3	22	3,48	0,330	2,4	2,00	0,37	3,36	1,43	17,46	4,56	
top layer	YLI 5 glass	4,15	676	36,4	62,7	20	3,80	0,740	4,9	2,17	0,35	4,75	1,46	14,52	4,12	
	YLI 5 bulk	4,04	699	36,5	61,1	18	3,78	0,674	2,2	2,10	0,36	4,64	1,48	14,70	4,23	
Kos																
KPT pumice	KOS 1 glass	5,28	532	26,3	45,4	15	2,82	0,280	<1,3	1,82	0,36	2,24	2,08	17,05	5,86	
	KOS 1 bulk	3,86	743	33,7	51,9	15	2,78	0,380	1,9	1,53	0,28	2,67	1,53	16,00	4,64	
KPT Plinian layer	KOS 3 glass	5,64	624	28,9	45,5	12	2,65	0,333	2,0	1,70	0,34	2,29	1,97	15,42	4,93	
	KOS 3 bulk	4,44	920	35,8	54,8	17	3,01	0,476	1,6	1,57	0,31	3,19	1,43	15,94	4,34	
Santorini																
Bm	SAT 4 glass	3,07	423	25,8	55,6	29	7,13	1,559	7,5	5,50	0,81	7,06	0,82	17,06	5,42	
	SAT 4 bulk	2,97	348	26,7	55,2	28	7,33	1,519	8,5	5,65	0,81	6,94	0,76	17,06	5,19	
Bo	SAT 5 glass	3,08	580	32,2	62,7	24	6,05	0,946	5,6	5,09	0,79	8,32	0,85	20,45	5,70	
	SAT 5 bulk	2,85	551	30,6	60,2	25	6,18	0,972	6,3	5,14	0,75	7,83	0,80	19,73	5,99	

Table 4 Analytical result and the respective bulk pumices, all values in mg/kg
except Na, Al, K, Ca, Fe and Ti which are given in weight %

location	sample	Na	err	Al	err	Mg	err	Si	err	Ca	err	Ti	err	Fe	err
		%	rel%	%	rel%	%	rel%	%	rel%	%	rel%	%	rel%	%	rel%
Milos	MLO 2 glass	1,38	10	5,94	0,9	0,05	18	35,29	0,3	0,83	1	0,10	19	0,66	3
	MLO 5 glass	1,95	11	6,60	0,9	0,13	9	34,25	0,6	1,24	7	0,10	17	0,71	5
	MLO 8 glass	1,67	10	6,30	0,9	0,07	7	34,75	0,2	0,98	3	0,10	14	0,57	3
	MLO 14 glass	1,26	10	6,11	2,6	0,09	14	34,87	1,0	1,07	4	< 0,10		0,75	7
Nisyros	NIS 2 glass	2,05	3	6,34	2,1	0,10	6	34,21	2,3	1,01	6	0,16	6	0,92	3
	NIS 23 glass	2,00	7	6,28	0,6	0,11	4	34,53	0,3	1,02	15	0,16	10	0,93	3
Giali	YLI 2 glass	2,09	7	6,33	1,1	0,06	14	35,19	0,3	0,85	3	< 0,113		0,68	3
	YLI 5 glass	2,25	7	7,42	1,6	0,30	2	32,56	1,2	1,65	8	0,25	15	1,33	4
Kos	KOS 1 glass	2,00	9	6,41	1,4	0,03	5	34,75	0,4	0,83	13	< 0,06		0,39	2
	KOS 3 glass	1,82	8	6,30	1,0	< 0,05		34,46	0,6	0,79	11	< 0,08		0,38	5
Thera	SAT 4 glass	2,71	8	7,88	2,2	0,58	17	30,41	0,9	2,27	16	0,56	13	3,52	6
	SAT 5 glass	3,02	14	7,15	1,5	0,15	7	33,25	1,7	0,93	5	0,21	10	1,45	2

Table 5 Concentraton of elements in the glass fraction obtained by EPMA