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Thera Eruption Date 1645 BC Confirmed By New Ice Core Data ?

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The eruption of the Thera volcano in the first half of the second millennium BC has achieved much attention in the studies related to the developments of the East Mediterranean civilizations over the same time span.

No general agreement exists presently on the eruption date of Thera, but several dates have been proposed based on radiocarbon dating, frost rings in trees, unusual thick rings in Anatolian trees and ice core records.[1, 2, 3] We here present evidence confirming the previously suggested date 1645 BC obtained from the Dye 3 ice core[1]. Also, we present the acid volcanic ice core signal in 3 deep ice cores from Greenland, i.e., Dye 3 (South Greenland), GRIP (Central Greenland) and North GRIP (315 km northwest of GRIP): These data strongly suggest, that the volcanic signals were caused by a major eruption south of Greenland, but north of 30° N.

Microparticle samples collected from the 1645 BC annual ice layer in the GRIP core revealed hundreds of 2–5 μm tephra particles, which were analyzed for major elements and 9 also for trace element including rare earth element abundances. The compositions obtained clearly concur with the suspicion, that the tephra originates from the Thera eruption. The accuracy of the ice core dating is verified suggesting an improved dating accuracy of +/− 4 yrs.

The "time marker" nature of the Thera eruption is strongly linked to the archaeological findings of Minoan ruins, pottery and remnants buried under the pumice of the Greek island Santorini. The literature on the subject is substantial, [e.g., 4, 5, 6, 7] but an essential question remained unanswered or rather has not been agreed upon, i.e., "When did the Minoan Thera eruption take place?". Colin Renfrew in a commentary in Nature[8] argued that the answer to the question most likely would come from the analysis of a few tephra grains in ice cores or from linking the floating Anatolian tree-ring sequence[3] to a fixed tree-ring record. We here followed the ice core strategy and our main purpose is to present new data from Greenland ice cores, which confirm that the volcanic signal in the South Greenland Dye 3 core dated to 1644 BC[1] was indeed caused by the eruption of the island of Thera in 1645 BC. We refrain from discussing the archaeological implications, which depends on whether one adopts the so-called "higher or lower" chronology: The reader can find more information on this subject in, e.g., refs. 9, 10.

Since the publication of Hammer *et al.* (ref. 1) not less than 3 new deep ice cores have been retrieved from the Greenland Ice Sheet, i.e., the GRIP and GISP2 cores from the Summit region in Central Greenland[11] and recently the North GRIP core some 315 km north-west of Summit. The average annual snow accumulation at Dye 3, GRIP and North GRIP over the past 10,000 years is, respectively, 0.56, 0.22 and 0.20 m of water equivalent. This is so high, that all the years are represented in the cores irrespective of wind scouring; the latter can in a few cases make it difficult to identify the annual cycle, but not remove a whole year's snow deposition.

The continuous acidity data of the 3 cores, depicting the relevant period 1600–1670 BC, are shown in Fig 1. The GISP 2 record is not shown in the figure for the following reasons: The GISP 2 site is only 28 km from the GRIP site and the two cores are almost duplicates[12] but the main reason for leaving out the GISP 2 record in the figure is a hiatus[13] in the GISP 2 core around the volcanic signal in question (see below). From Fig. 1 it is clearly seen, that there are more major volcanic signals in the two northernmost ice cores than in the South Greenland Dye 3 core: This was already anticipated by Hammer *et al.* in 1987 before the GRIP and North GRIP ice cores were actually drilled; the high Arctic eruptions are

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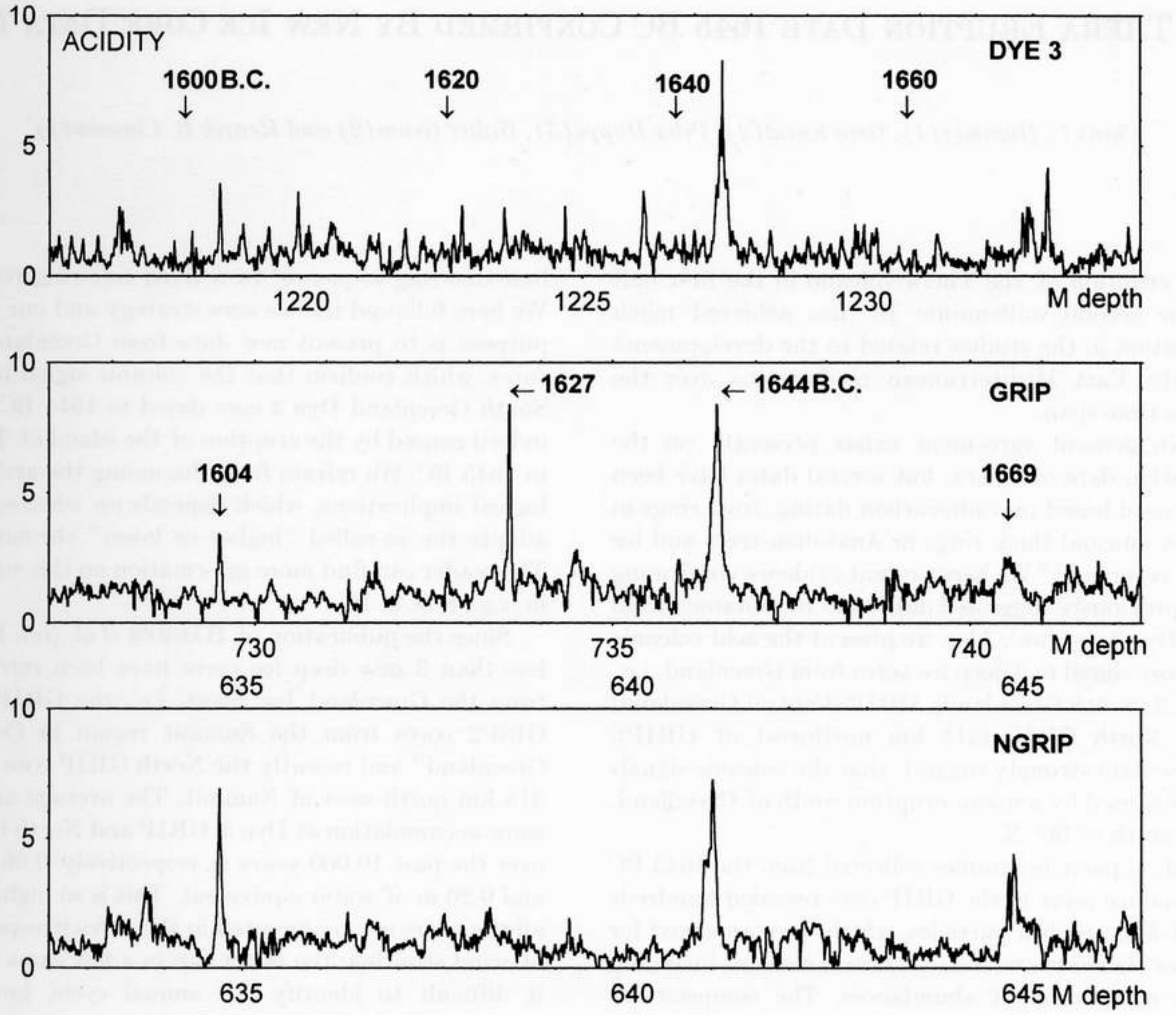

Fig. 1 Volcanic acid signals in 3 deep ice cores from Greenland over the period 1590–1680 BC. Geographical coordinates: Dye 3, 65.180° N, 43.490° W; GRIP, 72.580° N, 37.640° W; North GRIP, 315 km northwest of GRIP. The acidity is given in μequiv. H^+ /kg of ice. The profiles are plotted on a depth scale for each core, the dates shown are those of the Dye 3 masterchronology. Note that the only major volcanic signal present in all cores is the one peaking in 1644 BC. A minor signal around 1669 BC might be due to an eruption south of Greenland, but the signals in 1604 BC and 1627 BC must be caused by Arctic or perhaps Icelandic eruptions.

only slightly marking the South Greenland ice sheet by enhanced acidities as exemplified by the Alaskan Katmai eruption in 1912 AD.[1]

That the Arctic volcanic signals are much stronger in the GRIP and North GRIP cores than in the Dye 3 core relate to the high latitudes of these eruptions combined with an average poleward stratospheric drift of the acid eruptive compounds. It can not be explained by an unusual snowfall pattern over the years of the acid deposition at the 3 sites, because the Dye 3 region receives more than double the amount of snow and the frequency of individual snowfalls per year, approximately 25, is twice as high as for the more northern sites.

A major eruption south of Greenland must, however, mark all 3 sites; hence the volcanic signal around 1644 BC is the most likely candidate signifying the Thera eruption: It is also the only major eruptive signal in the Dye 3 record between 1900–1300 BC.[1]

The fairly high peak acidities of 8–9 μ equiv.H^+/kg of ice (H_2SO_4) in this event and the gradual increase to peak values of concentration from 1645 BC to 1644 BC supports the view that the eruption took place north of 30° N.[14]

If Thera was a major eruption and the Dye 3 record only contains one major volcanic signal in the period 1900–1300 BC it is not unlikely, that the signal

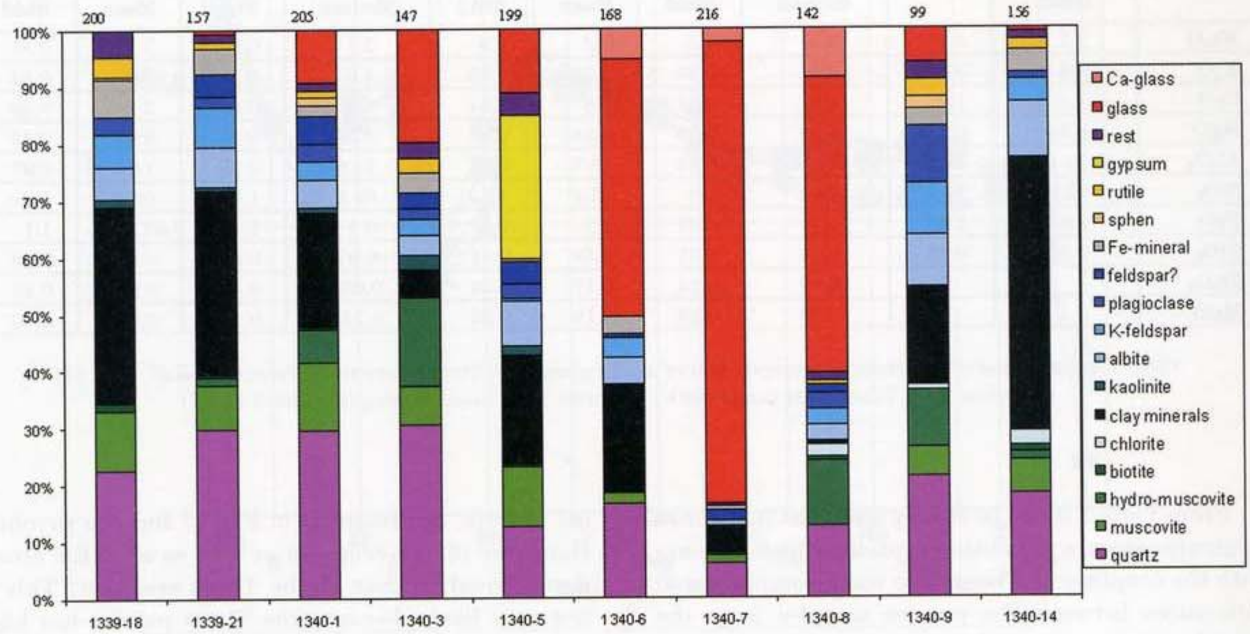

Fig. 2 Mineralogy of the microparticles in the GRIP ice core covering the volcanic event 1645–1644 BC. The 2.5 cm long samples cover the depth range 736.325 (left) to 736.800 (right) m (sample numbers 1339-18 to 1340-14; see Methods). Approximately each second sample was analyzed in this way. The mineralogical classification is given in percent of the total number of particles analyzed in each sample. The numbers of particles analyzed in each sample is given at the top of the figure. Note, how the glasses first appear in sample 1340-9, peak in sample 1340-7 and fade away in sample 1340-1. The maximum of glass particles occurs several months before the acidity peak in the ice (see Figure 1), because the acid volcanic aerosol is mainly removed by precipitation in the troposphere, while the glasses are removed by gravitational settling directly from the stratosphere.

was caused by the Thera eruption, but an analysis of tephra particles in the ice would, of course, help to settle the question.

We therefore sampled the GRIP ice covering the event for microparticles; ice samples of 2.5 cm along the core were taken over the depth range 736.325–736.800 m corresponding to the sample no.'s 1339-18 to 1340-14 shown in Fig. 2 and Table 1. The microparticle concentration in the samples was measured in order to estimate how much sample should be filtered through a Nuclepore filter to get a reasonable number of particles on the filters. The microparticles were subsequently analyzed with an analytical scanning electron microscope (ASEM) and the abundance of all particles was measured. The ratio of the number of glass particles (tephra) to that of continental dust particles, varied over the event as shown in Fig. 2. Even though the concentration of microparticles in the samples were not different from normal Holocene Greenland ice samples their contents of glass particles were quite high and unusual; the eruption had clearly marked the ice with a substantial number of microtephra particles in the size range of 1–5 μm (with very few particles up to ~10 μm). The total concentration of microparticles, some 0.1 mg/kg of ice, is much too small to give rise to a visible layer in the ice; this would require much higher concentrations.

The number of tephra particles was, however, sufficient for a fairly comprehensive compositional analysis. Individual particles were analyzed by ASEM and 9 particles from samples labelled 1340-7, which consisted of > 80 % glass particles, were also analyzed for trace elements by secondary ion mass spectrometry (SIMS); see Methods for more details.

The small sizes and irregularity of the particles prevents an ideal calibration of the ASEM measurements, but analysis of pumice from the Santorini Island under the same conditions allowed comparison with previously published compositional data.[15] Table 1 summarizes the results of the bulk component analysis of the glass particles.

	Vitaliano data		BO-1 38 grains				A1340-7 174 grains			
	Mean		**Median**	**Stdd**	**Mean**	**Stdd**	**Median**	**Stdd**	**Mean**	**Stdd**
Na_2O	3.7	4.07	3.3	1.2	3.2	1.2	3.7	0.87	3.7	0.87
K_2O	3.3	3.13	3.5	0.95	3.7	0.95	3.6	0.54	3.6	0.54
CaO	1.5	1.26	1.8	0.54	1.8	0.54	2.1	0.59	2.1	0.59
MgO	0.38	0.25	0.32	0.33	0.34	0.33	0.61	0.48	0.62	0.48
Al_2O_3	14.1	13.5	13.8	0.83	13.7	0.83	14.6	0.97	14.5	0.97
SiO_2	73.5	71.0	73.0	1.6	73.2	1.6	69.9	1.8	69.6	1.8
FeO	2.6	1.86	2.1	0.87	2.2	0.87	3.1	1.1	3.3	1.1
TiO_2	0.28	0.30	0.54	0.51	0.59	0.51	0.87	0.59	0.88	0.59
Cr_2O_3			0.09	0.24	0.17	0.24	0.00	0.46	0.29	0.46
MnO			0.00	0.29	0.18	0.29	0.24	0.40	0.36	0.40

Table 1 Comparison of the chemical composition of acidic glass from Thera (data from Vitaliano *et al.*, Ref. 15) with glass from Thera glass sample BO-1 and with glass from ice sample A1340-7 (wt%)

From Table 1 it can be clearly seen that the tephra originates from a rhyolitic eruption, which concurs with the eruption of Thera. The small compositional differences between the pumice samples from the Island of Santorini and the Greenland ice samples are insignificant considering the estimated standard error and that the analysis was made on small and irregularly shaped particles. The bulk composition is, however, not unique for the Thera eruption even though it narrows down the number of possible volcanic candidates. The trace element analysis, including the REE, as presented in Fig. 3 shows a remarkably resemblance between the trace element abundances in the glass shards from the ice and the glass in the Thera pumice. It is hard to believe that this resemblance should be coincidental, because the REE compositions of volcanic tephra generally varies over a wide range. We checked several published data on REE compositions of Mediterranean ash layers and not one of them resembles the Thera glass composition. The REE data shown in Fig. 3 also concur with similar data obtained from tephra layers from the Thera eruption[20] in Turkey.

These findings are contradictory to the analysis of 5 tephra grains from the 1623 BC layer of the GISP 2 core from Central Greenland,[21] but as it has recently been shown, the 1645 BC volcanic signal in the GRIP ice core and the 1623 BC signal in the GISP 2 core are not due to the same event.[13] The reason for this situation is most likely due to a larger dating uncertainty of the GISP 2 core, +/–40 years, at the age in question[20] and a hiatus in the GISP 2 core at the layer corresponding to the 1645 BC layer in the GRIP core.[13]

Could another major eruption fulfil the glaciological criteria, as presented in Fig. 1, and the rhyolitic character of the eruption as well as an REE abundance equal to that of the Thera eruption? This is not very likely, because the Thera pumice has high abundances of the heavy REE which indicate formation of rhyolitic magma by partial melting of a source free of garnets. Magmas from such a source are rare (e.g., ref. 19) as the source cannot be a crustal one (which is the case for most silicic magmas) but rather an ultramafic one related to the upper mantle. This geochemical signal also fits the local tectonic situation, a back-arc extension zone (e.g., ref. 22). Furthermore, it has been shown that the earlier arguments against the indication that the Thera eruption produced large amounts of sulphuric acid gases were found to be incorrect.[23]

The accuracy of the GRIP ice core date 1645 BC +/–7 years (ref. 1) can be verified by checking the dating accuracy of two events bracketing 1645 BC, i.e., the Vesuvius eruption in August 79 AD and the end of the climatic cold Younger Dryas (YD) period dated to 11505 BP (before 1950 AD): The latter date has been obtained by combining the GRIP date of the end of YD 11510 BP +/–40 and the independent tree ring date of 11500 BP+/–30 for this event.[24]

Microtephra particles found in the GRIP ice layer dated to 79 AD (and 80 AD in the Dye 3 core) have been proven to originate from the historical Vesuvius eruption of 79 AD (Barbante, C., Marianelli, P., Hammer, C.U., Clausen, H.B. & Siggaard Andersen, M.L., in prep.). The two events clearly demonstrate that the ice core dating accuracy of +/–7 years for the 1645 BC ice layer concurs with the demonstrated dating accuracy of the Vesuvius 79 AD eruption and the end of the YD period. Actually, +/–7

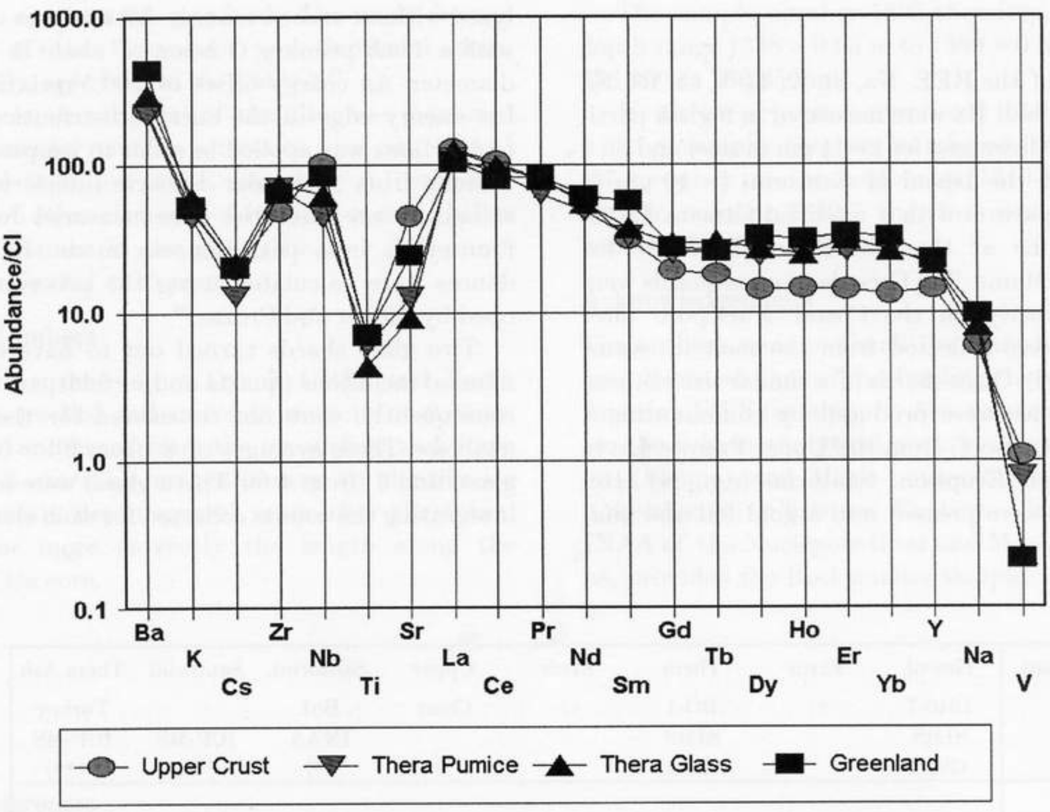

Fig. 3 Abundances of selected trace elements in glass from Dye 3 ice core (Greenland), glass from Thera pumice (Thera Glass) and pumice sample BO-1 from Santorini (Thera pumice)[16] – all normalized to elemental abundances in CI chondrite[17] and compared to abundances in the terrestrial upper crust.[18] The glasses from the ice and from the Thera pumice compare very well, except for Ba and Sr which are overabundant in the glass from the ice (contribution from sea water?). Minor discrepancies exist in the contents of Ti and Cr (not shown) which is possibly due to extremely heterogeneous distribution of Ti in the glass and the high Cr content of the filter. All other data agree within the error brackets. Comparison to the abundances in the bulk pumice from Thera reveals a similar fit, except for Ba, Sr and V. The former two could be the result of sea water contamination, the latter could be due to the presence of V-bearing phases (pyroxene and oxides) in the pumice. Comparison to the average upper continental crust reveals major differences in the abundances of the HREE, a consequence of the derivation of the Thera magma from the upper mantle wedge, rather than from subducted crust, a feature that is not very common (e.g., Ref. 19)

years may be somewhat on the high side, because a large fraction of the dating uncertainty of the end of the YD period accumulates in the period between 8000–11505 BP; this holds for both the tree ring and ice core dating. Considering the +1 year error of the GRIP ice core Vesuvius dating, the accuracy of the 1645 BC ice layer dating is probably closer to +/–4 years than +/–7 years.

The frost ring date in trees around 1626 BC[24] has been suggested to have been caused by the Thera eruption and was later found in Irish oak records by Baillie who suggested the date 1628 BC.[25] In our opinion these frost rings were caused by a statistical cold fluctuation in the northern hemispheric climate, which might have been enhanced by an Arctic volcanic eruption, e.g., in 1627 BC (see Figure 1). The relation between frost rings in trees and major volcanic eruptions is a statistical one, because the climatic effect of the eruptions can be masked by climatic fluctuations within the climate system per se, e.g., the largest eruption during the past 4000 years, from a climatic point of view, the 1258 AD equatorial eruption,[26] did not give rise to any widespread frost rings.[2] Hence one can not a priori conclude that the Thera eruption should have caused widespread frost rings in trees.

Recently, Manning *et al.*[27] in an article on improved chronology of Anatolian tree rings suggested that the ice core eruption date 1645 BC offers a correlation to their new date of the Anatolian tree ring anomaly of 1650 +4/–7 BC; this is within the error bracket of the ice core record.

We must, therefore, conclude, that the Minoan Thera eruption very likely took place in 1645 BC +/–4 years.

Methods

Abundances of the REE, Na, Si, K, Ti, V, Cr, Rb, Sr, Y, Zr, Nb, Cs, and Ba were measured in 9 glass particles from the Greenland ice (5–11 µm in size) and on 4 particles from the Island of Santorini (~ 10 µm in size) for comparison with a modified Cameca IMS3f ion microprobe at the Max-Planck-Institute for Chemistry at Mainz. The Greenland glass shards were measured directly on the Costar Nuclepore filter where they were collected from the melt ice water (carbon coated). Glass shards of a similar size to those found in the ice were produced by comminuting a pumice sample (Bo-1) from the Upper Pumice Layer of the Minoan Eruption, Santorini (e.g., ref. 16). These shards were pressed into a gold foil and analyzed without carbon coating. All analyses were done with a 1 nA primary O beam of about 5–10 µm in diameter. An energy offset of 100 V relative to the low-energy edge in the energy distribution of secondary ions was applied in order to suppress contributions from molecular isobaric interferences and secondary ion intensities were measured over two to four cycles in a peak-jumping mode. REE abundances were calculated using the procedure developed by Zinner and Crozaz.[28]

Two glass shards turned out to have contained mineral inclusions (quartz and/or feldspar) and they, consequently, were not considered for the average analyses. These averages of 8 (from 9 for Greenland glass) and 3 (from 4 for Thera glass) were formed by integrating the counts collected for each element and

Element	Greenl 1340-7 SIMS Glass	Error +/-	Thera BO-1 SIMS Glass	Error +/-	Upper Crust *)	Santorini Bol INAA **)	Santorini ICP-MS ***)	Thera Ash Turkey ICP-MS ****)
Na	48000	7000	40000	6000	28900	33900	29200	35700
K	29000	4400	33600	5000	28000	23600	25000	26900
Ti	3100	500	1900	290	3000	2184	2640	2128
V	12	2	13	2	60	32	43	39.4
Cr	9.6	1.7	1.7	0.5	35	1.79		6.2
Rb	53	9	77	12	112	105		93.6
Sr	190	29	72	11	350		98	79.3
Y	35	5	32.5	5	22		33.7	36.2
Zr	253	39	292	44	190	280	275	266
Nb	21	4	15	3	25		11	11.4
Cs	3.8	0.9	4.0	0.9	3.7	2.75	2.4	2.47
Ba	1020	150	690	100	550	553	520	516
La	24.5	3.8	29.5	4.5	30	31.1	26.1	29.2
Ce	49.4	7.5	60.5	9.2	64	61.2	54	56.3
Pr	7.4	1.2	7.1	1.2	7.1		5.69	6.78
Nd	28	4	25.2	3.9	26	31	22.5	25.7
Sm	8.2	1.6	5.3	1.2	4.5	6.08	4.7	5.71
Gd	5.5	1.6	5.8	1.4	3.8		4.99	6.64
Tb	0.91	0.31	1.1	0.3	0.64		0.92	1
Dy	8.1	1.4	6.7	1.2	3.5	5.7	5.93	6.95
Ho	1.7	0.4	1.4	0.3	0.8		1.32	1.58
Er	5.5	1.0	5.1	0.9	2.3		4.15	4.64
Tm	0.59	0.20	0.94	0.24	0.33			0.74
Yb	5.3	1.1	4.3	0.9	2.2	5.4	4.28	5.12
Na/K	1.65	0.35	1.20	0.25	1.03	1.44	1.17	1.32
La/Y	0.70	0.15	0.91	0.20	1.36		0.77	0.81

*) Ref. 18; **) Ref. 16; ***) Ref. 15; ****) Ref. 20

Table 2 Trace element data on Thera glass, ash and pumice (in ppm). Errors are 1σ for Si as an internal standard. The such derived analyses of the Greenland and Santorini glass, respectively, are given in the Table 2.**

Trace element content of the filter was measured by instrumental neutron activation analysis (INAA) and found to be low: REE were all < 0.1 ppm and contents of other elements of interest were far below their abundances in the glass (Na, K ~ 150 ppm), except for Cr (221 ± 15 ppm).

Sample Numbers

The deep ice cores from Dye 3, GRIP and North GRIP are packed and stored in sections of 0.55 m, which are numbered from the ice surface and down by 1, 2, 3 etc. This makes it easy to identify ice from a certain depth several years after the actual drilling or more correctly the length along the retrieved ice core.

The sample number 1339 therefore refers to the depth range 1338 × 0.55 m to 1339 × 0.55 m i.e., from 735.900 to 736.450 m.

If an ice sequence numbered 1340 is cut into 0.025 m samples they are numbered from the top of the ice piece to the bottom as 1340-1 to 1340-22. Sample number 1340-7 therefore covers the depth between 736.600–736.625 m.

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** Note added in proof: As the concentration of Europium in the particles is quite low and the uncertainty of the values quite high the Eu data has been left out in Table 2 and Figure 3. This does, however, indicate, that a minimum would exist in Fig. 3 if Eu had been inserted between Sm and Gd.

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