JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D04303, doi:10.1029/2007JD008970, 2008

Comment on "A synchronized dating of three Greenland ice cores throughout the Holocene" by B. M. Vinther et al.: No Minoan tephra in the 1642 B.C. layer of the GRIP ice core

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Received 15 May 2007; revised 18 September 2007; accepted 20 December 2007; published 23 February 2008.

Citation: Denton, J. S., and N. J. G. Pearce (2008), Comment on ''A synchronized dating of three Greenland ice cores throughout the Holocene'' by B. M. Vinther et al.: No Minoan tephra in the 1642 B.C. layer of the GRIP ice core, *J. Geophys. Res.*, *113*, D04303, doi:10.1029/2007JD008970.

1. Introduction

[1] There has been much debate in recent years among archaeologists and Earth scientists about the date of the Minoan eruption of Santorini (Thera). This debate has centered upon archaeological finds, radiocarbon dating and proxy sources including dendrochronology and acid spikes in the Greenlandic ice cores. Defining the exact date of the Minoan eruption is vital in synchronizing differing chronologies for civilizations around the Mediterranean, where many 2nd millennium B.C. cultures record this cataclysmic event. Current studies of these records have led to suggested dates for the eruption between about 1650 and 1500 B.C., and reconciling these differing dates is clearly vital in archaeology (see *Friedrich* [2000], *Manning* [1999] (see further information at http://www.informath.org/BiOr04i.pdf), *Manning et al.* [2006] and *Bietak and Czerny* [2007] for further discussion). Recently *Vinther et al.* [2006], in providing a chronology for the Holocene from Greenlandic ice cores, state that the date for the Minoan eruption (GICC05) is 3641 ± 5 b2k (or 1642 ± 5 B.C.) and that an acid spike from this eruption is present in all three cores (namely, DYE-3, GRIP and NGRIP). *Vinther et al.* [2006] acknowledge that another source for the glass shards at this level in the ice cores has been proposed as the Alaskan volcano Aniakchak [*Pearce et al.*, 2004]. However, they dismiss this noting [*Vinther et al.*, 2006, p. 9] "analysis of the GRIP ice core has established that the tephra from the eruption arrived in Greenland several months before the arrival of the sulphate aerosols" citing a description by *Hammer et al.* [2003] of the sulphate/particle distribution. *Vinther et al.* [2006] suggest that material from an Alaskan volcano would be expected to arrive simultaneously via the tropospheric flow, and note that the delay in the arrival of the sulphate aerosols could only occur if transport were through the stratosphere which they conclude indicates a low-latitude eruption. The presence of an acid spike in the DYE-3 ice core at this time is also argued to indicate a midlatitude eruption as Alaskan and northern latitude volcanic eruptions tend not to be recorded in this more southerly core.

2. Previous Studies

[2] Doubt had already been cast upon the correlation of the 1645 B.C. ice core acid spike with the Minoan eruption [*Begét et al.*, 1992] who recognized that the caldera forming eruption of Aniakchak occurred at a similar time to the Minoan eruption. In ascribing the date 1642 ± 5 B.C. for the Minoan eruption of Santorini, *Vinther et al.* [2006] ignored the compelling geochemical data presented by *Pearce et al.* [2004] and the statistical arguments presented by *Keenan* [2003] refuting the claims of *Hammer et al.* [2003] that the ice core ash is Minoan.

[3] *Pearce et al.* [2004] compared bulk geochemical analyses of the Aniakchak tephra from Northern Alaska to the geochemical data of tephra from the GRIP ice core [*Hammer et al.*, 2003] as well as geochemical analyses of Minoan tephra. The geochemical similarities between the Aniakchak glass and the ice core glass (together with the significant differences between the ice core glass and Minoan glass) led *Pearce et al.* [2004] to conclude that the glass shards in the ice core were sourced from Aniakchak.

3. Composition of the Ice Core Ash

[4] The major element analyses of the Aniakchak tephra (UT2011) show two distinct populations of glass (Figure 1) one andesitic, ~57 wt% SiO_2 and one rhyolitic, ~70 wt% SiO_2 with 3 shards in 30 being andesitic. This bimodal nature of the circa 3500 BP eruption of Aniakchak is also noted by *George et al.* [2004]. Additionally, the glass data from this study for both major and trace elements are very similar to the bulk chemical data presented by *Larsen* [2006] and *Dreher et al.* [2005] for the caldera forming rhyodacitic and andesitic rocks from the eruption of Aniakchak.

[5] *Hammer et al.* [2003] report only the average compositional data for rhyolitic glass from the A1340-7 sample from the GRIP ice core. In their Figure 2, however, *Hammer*

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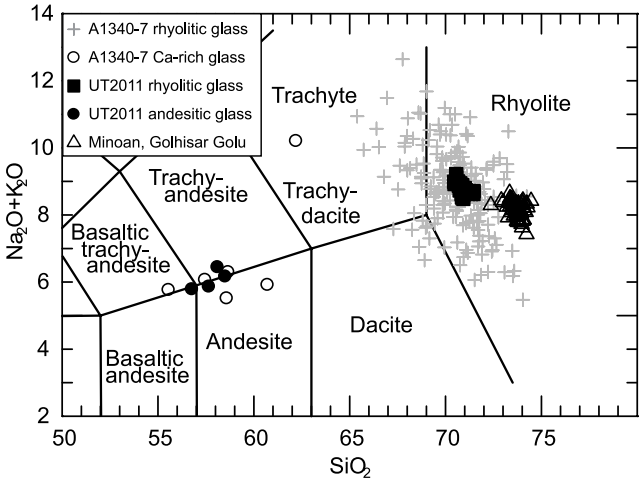

Figure 1. Total alkalis Silica diagram for single grain analyses from UT2011 (Aniakchak tephra [*Hart*, 2006]), Minoan deposit (Gölhisar Gölü, Turkey [*Eastwood et al.*, 1999]) and glass from the A1340-7 sample of the GRIP ice core [*Hammer et al.*, 2003; C. Hammer et al., unpublished data, 2006].

et al. [2003] indicate the presence of a Ca-rich glass in three samples. These ice core Ca-rich grains constitute 7.5% of the glass fragments analyzed from the ice core similar to the approximately 10% proportion of andesite in the Aniakchak tephra (UT2011). In contrast, not one grain of andesitic glass has been recorded in Minoan tephra deposits studied by *Eastwood et al.* [1999] (68 analyses of glass from Gölhisar Gölü, SW Turkey), by *Hart* [2006] (93 analyses of glass from the Minoan levels on Santorini) and *Smith* [2007] (450 analyses of glass from the Minoan deposit on Santorini).

4. New Data Supporting Aniakchak as the Source of the 1642 B.C. Ice Core Ash

[6] Recently, the major element data determined by *Hammer et al.* [2003] from the A1340-7 level in the GRIP ice core has been made available to us. *Hammer et al.* [2003] analyzed both material from the GRIP ice core and from the Minoan deposit of Santorini by ASEM. *Pearce et al.* [2004] compared the ASEM analyses of the Minoan tephra with WDS EPMA analyses from *Eastwood et al.* [1999] to produce a correction factor to account for the calibration issues associated with ASEM and this was applied to the analyses of material from the ice cores. The same correction factor has been applied here to each individual ASEM major element analyses from the ice core,

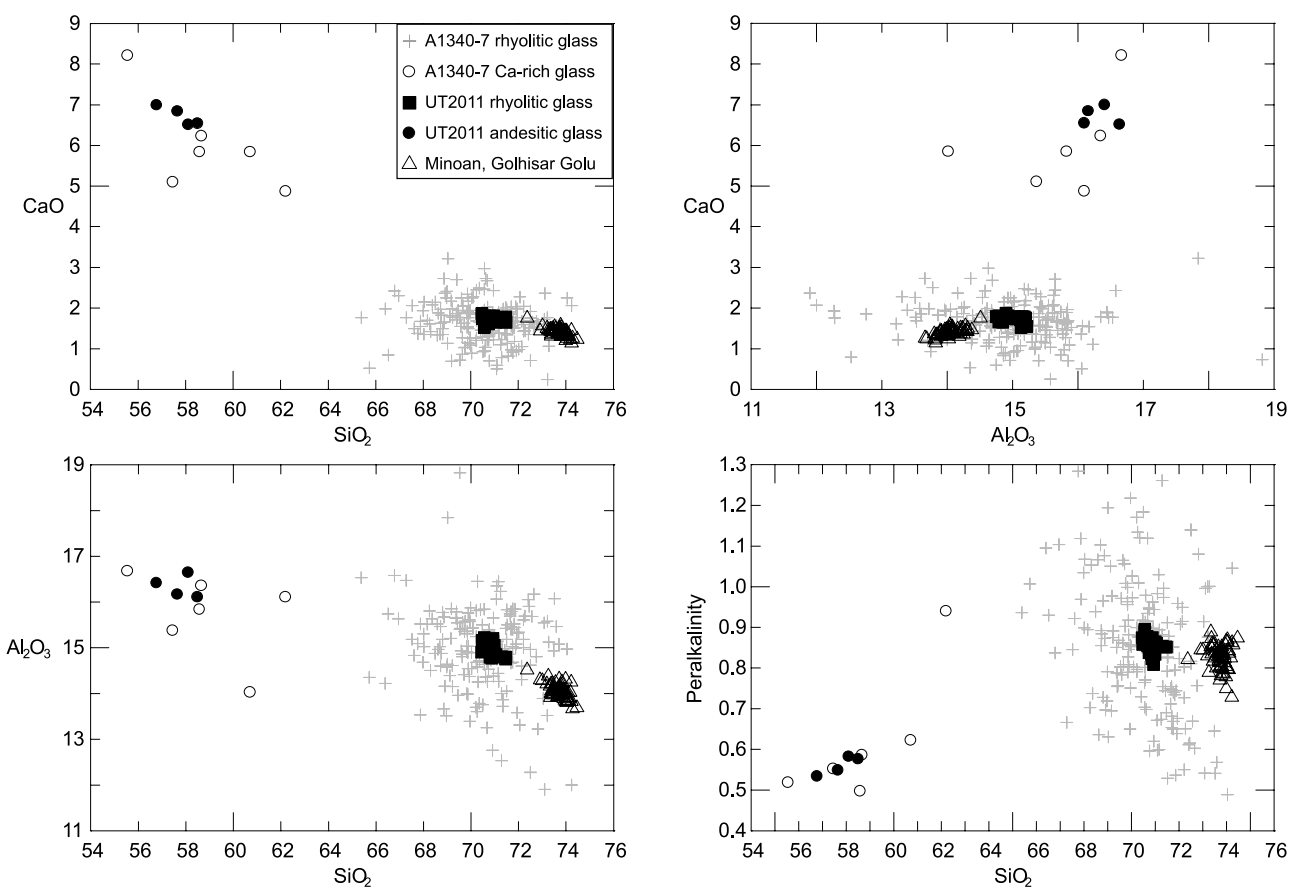

Figure 2. Selected element-element variation diagrams for UT2011 (Aniakchak tephra [*Hart*, 2006]), Minoan deposit (Gölhisar Gölü, Turkey [*Eastwood et al.*, 1999]) and glass from the A1340-7 sample of the GRIP ice core [*Hammer et al.*, 2003; C. Hammer et al., unpublished data, 2006].

Table 1. Normalized Analyses (Average (Standard Deviation)) of Rhyolitic and Andesitic Glass From UT2011, Aniakchak Tephra, Northern Alaska (Data From *Hart* [2006]) and Normalized and Recalibrated Analyses of Glass From Sample A1340-7, the GRIP Ice Core (Data From *Hammer et al.* [2003] and C. Hammer et al. (Unpublished Data, 2006))[a]

	UT2011, Aniakchak, Rhyolite, n = 27	UT2011, Aniakchak, Andesite, n = 4	A1340-7, Rhyolite, n = 174	A1340-7, Ca-Rich Glass, n = 5
SiO_2	70.86 (0.27)	57.77 (0.74)	70.47 (1.66)	58.2 (1.89)
TiO_2	0.48 (0.02)	1.43 (0.04)	0.44 (0.31)	1.18 (0.41)
Al_2O_3	15.00 (0.16)	16.33 (0.25)	14.96 (0.94)	15.65 (1.04)
FeO	2.43 (0.10)	8.23 (0.60)	3.05 (1.15)	10.35 (1.19)
MnO	0.16 (0.05)	0.26 (0.02)	0.14 (0.17)	0.40 (0.30)
MgO	0.54 (0.03)	3.21 (0.21)	0.50 (0.39)	2.07 (0.61)
CaO	1.73 (0.08)	6.72 (0.23)	1.65 (0.50)	6.24 (1.17)
Na_2O	5.77 (0.21)	4.54 (0.17)	5.61 (1.27)	3.98 (0.64)
K_2O	3.03 (0.11)	1.52 (0.13)	3.18 (0.49)	1.93 (0.51)

[a]Analyses normalized to 100% for oxides listed. The high Ca, trachytic glass grain at ~62% SiO_2 from the ice core sample (see Figure 1) has been excluded from the average.

and for comparison all analyses have been normalized to 100% excluding the minor components S, Cl, *F* and Cr. Table 1 presents average compositions of rhyolitic and andesitic glass from Aniakchak tephra and the material from the ice core.

[7] Figures 1 and 2 show variation diagrams comparing the major element composition of glass from the eruption of Aniakchak (rhyolitic and andesitic), ash from the GRIP ice core (rhyolitic and Ca-rich) and distal Minoan ash (Gölhisar Gölü, SW Turkey [*Eastwood et al.*, 1999]). All projections clearly show that the Ca-rich ice core ash plots close to the andesitic glass from Aniakchak. In all plots, the A1340-7 rhyolitic glass chemistry centers around the UT2011 rhyolitic glass analyses, the larger scatter in the A1340-7 a result of the poorer precision of ASEM compared to WDS EPMA. On both Figures 1 and 2, the fields occupied by the two sets of analyses for the Aniakchak glass are clearly separate from the Minoan glass. On the basis of these plots alone, the ice core and Minoan ash cannot be from the same source confirming the interpretation of *Pearce et al.* [2004, 2007] that the ice core ash layer at 1642 B.C. is not from Santorini. Additionally, applying a t-test to the major elements determined in rhyolitic glass from the Minoan eruption and the ice core samples shows the two samples to be statistically different for all elements with the probability (p) that they are drawn from the same population ranging from $p = 6 \times 10^{-5}$ for Al_2O_3 to $p = 3 \times 10^{-38}$ for SiO_2.

[8] One possible criticism of the comparisons made by *Pearce et al.* [2004] is that no single grain trace element data were presented. Here we have analyzed single glass shards from the Aniakchak tephra (UT2011) by ion probe and LA-ICP-MS. Figure 3a shows bulk and single grain analyses from the Minoan deposit, from the Aniakchak tephra and from the ice core glass. *Hammer et al.* [2003] unfortunately only analyzed 3 grains of Minoan glass by ion probe, and thus comparisons based on this are difficult [*Pearce et al.*, 2004], but there is a general comparability between their data and the bulk and single grain analyses of the same material (bulk analysis [*Eastwood et al.*, 1999], LA-ICP-MS [*Pearce et al.*, 2002], and ion probe [*Hart*, 2006]). Figure 3b shows bulk and single grain analyses for the Aniakchak tephra (bulk data [*Pearce et al.*, 2004] and single grain analyses [*Hart*, 2006]) and the ion probe analyses of the material from the 1642 B.C. layer in the ice core. The ice core glass is essentially indistinguishable

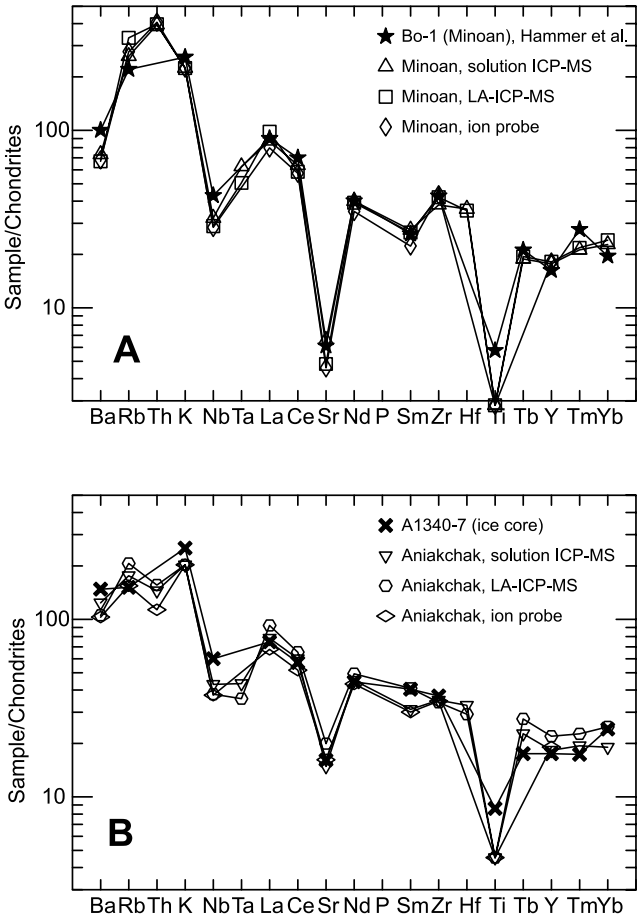

Figure 3. Chondrite normalized multielement spidergrams of single grain and bulk analyses for (a) the Minoan deposit (LA-ICP-MS [*Pearce et al.*, 2002], solution ICP-MS [*Eastwood et al.*, 1999], and ion probe [*Hart*, 2006]) and sample Bo-1, glass from the Plinian air fall of the Minoan deposit from Santorini analyzed by *Hammer et al.* [2003], and (b) Aniakchak tephra (UT2011) (solution ICP-MS [*Pearce et al.*, 2004], LA-ICP-MS and ion probe [*Hart*, 2006]) and glass from the 1642 B.C. layer of the GRIP ice core (ion probe [*Hammer et al.*, 2003]). Normalization values are from *Thompson* [1982].

from the Aniakchak tephra, particularly when the slight differences between the ion probe data from *Hammer et al.* [2003] and *Hart* [2006] for the Minoan glass are considered. There is also a clear difference in the composition of the ice core glass from the Minoan glass, most notably in Ba, Rb, Sr, Nb and concentrations and slope of the LREE. This, together with the similarities between the Ca-rich glass from the ice core and the andesitic Aniakchak glass (Figures 1 and 2), again confirms the interpretation of *Pearce et al.* [2004, 2007] that the ice core ash layer at 1642 B.C. is from Aniakchak not Santorini.

5. Conclusions

[9] In conclusion, the similarities in the major and trace element compositions of the Aniakchak and ice core glass already described by *Pearce et al.* [2004, 2007] are confirmed by single grain analysis of the Aniakchak tephra. These are sufficient to confidently assign the ice core ash at 1642 B.C. to the caldera forming eruption of Aniakchak and not to the Minoan eruption of Santorini. Furthermore, the established bimodal nature of the Aniakchak eruption [*Miller and Smith*, 1987; *George et al.*, 2004; *Dreher et al.*, 2005; *Hart*, 2006; *Larsen*, 2006] is reflected in the andesite/rhyolite compositions of glass found in the ice core ash at 1642 B.C. [*Hammer et al.*, 2003] and further confirms this provenance. This interpretation also supports the recently published ^{14}C dates for the Minoan eruption of Santorini at ~1630–1600 B.C.

[10] *Vinther et al.* [2006] argue that the distribution of particles/sulphate in the ice core fits a model which suggests a midlatitude eruption and use this to discount the chemical arguments which identify the Aniakchak volcano as the source of the 1642 B.C. ash. At present the sulphate/glass distribution data at this level in the ice core has not been published. C. Hammer (personal communication, 2007) describes a 10 month delay after peak ash deposition before sulphate concentrations reach a maximum in the ice core. This time lag cannot be explained using current models of atmospheric circulation and ash/aerosol dispersion for a high-latitude eruption, which would require the synchronous arrival of ash and aerosol [*Vinther et al.*, 2006; *Hammer et al.*, 2003; C. Hammer, personal communication, 2007]. The geochemical evidence is however so compelling that no reasonable doubt can remain that the 1642 B.C. ice core ash is from Aniakchak and thus some revision is now needed of the current models of ash/sulphate deposition from large, high-latitude eruptions to explain their enigmatic distribution at the 1642 B.C. level in the GRIP ice core.

[11] In their reply to this comment, *Vinther et al.* [2008] make some statements which are incorrect or unfounded. These are addressed in sections 6, 7, 8, 9, and 10.

6. Reference to the Minoan Thera Eruption

[12] *Vinther et al.* [2008] state correctly that the main purpose of their 2006 paper was to present an ice core chronology, and also state that it was "not for the assignment of the 1642 ± 5 B.C. eruption." Nonetheless, in 2006 they used sulphate spikes in the core ("volcanic horizons") as key tie points for intercorrelation, and made numerous references in their 2006 paper to the Minoan eruption. Specifically, they are as follows:

[13] 1. Section 4.1, Uncertainties in Dating, states [*Vinther et al.*, 2006, p. 6] "According to *Clausen et al.* [1997] the period deliminated by the A.D. 79 Vesuvius eruption and the Minoan eruption of Thera has been independently dated in the DYE-3 and GRIP ice cores."

[14] 2. Section 5, Results, states [*Vinther et al.*, 2006, p. 9] "The Minoan Thera eruption [*Hammer et al.*, 1987] is also found in all three ice cores. The GICC05 date for this eruption is 3641 ± 5 b2k (1642 ± 5 B.C.)."

[15] 3. Section 6, Discussion, states [*Vinther et al.*, 2006, p. 10] "In the section between the reference horizons of Thera and Vesuvius,..." and "The GISP2 sections below the Thera eruption..."

[16] 4. Only in the body of Tables 4, 5 and 6 do they refer to this as "Thera (?)," but the caption to Table 4 states [*Vinther et al.*, 2006, p. 8] "GRIP tephra shows that the Thera eruption commenced in ... 1642 B.C. The ECM signals peak in the annual layer ... 1641 B.C."

[17] 5. The Conclusions explicitly state [*Vinther et al.*, 2006, p. 10] "The Minoan Thera eruption is dated to 3641 b2k (1642 B.C.) with a maximum counting error of 5 years."

[18] We would contend that anyone interested in the Greenland ice core chronology will look to this key paper and, if they are not familiar with the arguments surrounding the dating of the Minoan eruption, will be misled into thinking that material from the Minoan eruption has been clearly and unequivocally identified in all 3 cores. The ice cores provide an unmatched record, with incredible potential to provide accurate dates; it is imperative therefore that the correct assignments are made to volcanic signals, and not assignments made on historical speculation as to the source of a particular acidity spike.

7. Comparisons of Geochemical Data Using Statistical Distance

[19] *Pearce et al.* [2004] used statistical distance methods to compare analyses from the Minoan eruption, Aniakchak, and the GRIP ice core determined by *Pearce et al.* [2004] and *Hammer et al.* [2003]. The trace element data from *Hammer et al.* [2003] for the Minoan eruption was not used as only 3 determinations were made which may be insufficient for truly robust correlations [cf. *Keenan*, 2003].

[20] Statistical distance methods were first applied to tephra studies by *Perkins et al.* [1995, 1998] and provide a first-order comparison for finding/discounting correlations. The method relies on the relationship between the differences in the means of 2 elements in an analysis squared, compared to the sum of the squares of the errors associated with their determination (typically taken as the standard deviation of the analysis). This value is then summed over several elements to give the "statistical distance" measure D^2, which has a Chi-square distribution. When this summed value is bigger than the critical value ($D^2_{critical}$) at a preselected confidence level, samples can be shown to be statistically significantly different at that level of confidence.

[21] *Vinther et al.* [2008] fail to appreciate some of the implications of this approach. First, the method can be used

only to rule out a correlation with confidence, and is not as such a "similarity test" as Vinther et al. state (their Point 2). Thus if the D^2 value is above a critical value for a given probability, a suggested correlation can be excluded. In contrast however, a value below the $D^2_{critical}$ does not, de facto, indicate the samples are correlatives. Indeed, *Perkins et al.* [1995, p. 1505] specifically state that if 2 samples "appear to match on the basis of D^2, then it is important to check the pattern of shard to shard variation..." and illustrate this with examples.

[22] *Pearce et al.* [2004] chose 12 trace elements with varying geochemical behavior (compatible, incompatible, LILE, HFSE etc) across a range of concentrations to be used in the comparisons based on statistical distance, excluding some of the 13 REE so as not to bias results by including several "similar" (in terms of composition and analytical precision) elements. *Pearce et al.* [2004] showed that, at the 99% confidence level, the Minoan tephra and material from the ice core (A1340-7) were statistically different. To confirm this, here and in the work by *Pearce et al.* [2004], differences in major and trace element data (e.g., slope/shape of the REE pattern, compositional differences in several elements, most notably Ba, Nb and Sr) have been described. The approach of *Vinther et al.* [2008] in adding in several elements to the calculation of statistical distance which have similar concentrations in both samples only increases $D^2_{calculated}$ slightly. Because the number of degrees of freedom has consequently increased, $D^2_{calculated}$ is brought below $D^2_{critical}$. It must be stressed that this does not make the samples correlatives, it makes them possible correlatives (i.e., not statistically different for that degree of freedom), and any suggested correlation needs to be proved by other means. Application of a Students t-test to the trace element data of *Hammer et al.* [2003] for the Minoan tephra and the ice core ash (analyses performed on the same instrument, and thus directly comparable which *Vinther et al.* [2008] consider, incorrectly, to be compositionally similar), show there to be statistically extremely significant differences ($p < 0.0001$) in the concentrations of Ba, Sr and Cr, and significant differences ($p < 0.05$) in Rb, Sm and Tm. These significant differences rule out the possibility of a correlation between the Minoan tephra and the 1642 B.C. tephra from the ice core, and this backs up the more robust statistical approach (large numbers of analyses) adopted by *Keenan* [2003] for the major elements. To conclude, the Minoan tephra, by comparing analyses performed on the same instruments, is statistically significantly different from the tephra in the GRIP ice core.

8. Criticisms of the Analytical Approach

[23] In their response, Point 2, *Vinther et al.* [2008] state that both *Pearce et al.* [2004] and *Keenan* [2003] do not consider the possible significance of the different grain sizes analyzed by comparing analyses of the Minoan ash (125 μm shards) from Gölhisar Gölü [*Eastwood et al.*, 1999] with the ice core material ($\sim$10 μm shards). *Vinther et al.* [2008] suggest that differences in composition may occur between larger and smaller shards. This needs to be addressed in two parts.

[24] First, when comparing the Bo-1 and A1340-7 analyses from *Hammer et al.* [2003], *Keenan* [2003] compares the analyses of material of similar grain sizes specifically prepared and analyzed by *Hammer et al.* [2003] on the same instrument to enable such a "like for like" comparison. *Keenan* [2003, p. 2] states that *Hammer et al.* [2003] present "the mean, median, and standard deviation for each of ten major chemical constituents of particles from Thera (38 particles) and Greenland (174 particles). For the most abundant constituent, SiO_2, the mean ± stddev (weight%) are 73.2 ± 1.6 (Thera) and 69.6 ± 1.8 (Greenland). The *t*-test gives $p < 10^{20}$; that is, if the two tephras were indeed the same, then the chance of having measured values so different is less than 1 in 10^{20}." *Keenan* [2003, p. 2] continues to state that, "The statistical significances are great because the numbers of particles are large, which reduces uncertainty. For example, consider SiO_2: the standard error for Thera is $1.6/38^{0.5} = 0.26$ and for Greenland it is $1.8/174^{0.5} = 0.14$. This implies that the means are 73.2 ± 0.26 and 69.6 ± 0.14; these do not even overlap at eight standard deviations." This is contrary to the quote from *Hammer et al.* [2003, p. 88] who state that the "small compositional differences...are insignificant." In addition to this, the t-test described above on the trace element data from *Hammer et al.* [2003] also rules out a correlation between the Minoan and ice core tephras.

[25] Secondly, as stated above, *Vinther at al.* [2008] are critical of a lack of consideration of "the potential significance of the different size of tephra particles found in Greenland and elsewhere." They state that the samples analyzed by *Pearce et al.* [2002, 2004] and *Eastwood et al.* [1999] were comparatively large (125–150 μm) compared to the $\sim$10 μm ice core grains, and thus potentially different. *Vinther et al.* [2008] do not state what the possible effects of this change in size of analyzed material are, but, if the ice core glass is Minoan as Vinther et al. maintain, the implication of their statements must be that chemical changes occur in the magma as it fragments resulting in compositionally different smaller and larger shards. There is no documented evidence of glass compositions changing in such a way, and if such a process does occur, the entire foundation of tephrochronology would be undermined. It seems more likely that *Vinther et al.* [2008] are confusing this with changes in the composition of bulk tephra, which does vary with distance as denser and larger mineral grains settle closer to the source and are depleted in finer grained, distal deposits. This however does not affect the composition of the juvenile components, such as the glass phase.

9. Andesitic Material in the Minoan Deposit

[26] *Vinther et al.* [2008] (Point 3) discuss the presence of andesitic material in the Minoan deposit and suggest this may be the source of the andesitic glass in the ice core tephra. First, we repeat the fact that no andesitic glass shards have been described in distal deposits of the Minoan tephra. *Druitt et al.* [1989, 1999] do indeed describe andesitic scoria from the Plinian pumice fall from the opening phase of the Minoan deposit (Bo-1). No andesitic material is reported from higher in the Minoan deposit however, and *Druitt et al.* [1989, 1999] state that the tephra deposit from the Minoan eruption is coignimbritic and associated with the last stage of the eruption (Bo-4), which is entirely rhyolitic in composition.

[27] *Vinther et al.* [2008, Table 2] compare bulk samples from Santorini with the glass shard compositions determined in the GRIP ice core in an attempt to justify the source of the ice core tephra as Minoan. Comparisons of microbeam analyses of single glass grains (just one of many phases included in the erupted material) cannot be made with bulk analyses by XRF of crushed, whole samples, which contain not only the glass, but may also contain lithic clasts, crystals etc. [*Pearce et al.*, 2002]. Indeed the rhyolite *Vinther et al.* [2008] select for comparison is the analysis of "Two white pumice lapilli with mafic blebs. Top of Plinian Deposit" [*Druitt et al.*, 1989, 1999]. This will be a mix of rhyolitic glass with around 73 wt% SiO_2 [*Eastwood et al.*, 1999; *Hart*, 2006; *Smith*, 2007], phenocryst phases (dominantly plagioclase) with lower SiO_2, and a small amount of mafic material, again with lower SiO_2. The andesitic scoria from Santorini they chose is also from the Plinian phase of the eruption, and differs compositionally from the Ca-rich glass from the ice core. These comparisons are unsound and cannot be used to justify a Minoan source for the ice core tephra.

10. Sulphate/Particle Distribution in the Ice Core

[28] *Vinther et al.* [2006, p. 9] state that "For an Alaskan eruption it would be expected that tephra and sulphate aerosols arrive simultaneously as they are transported to Greenland by the prevailing tropospheric flow (the polar jet). A delay in sulphate arrival can only take place if the sulphate aerosols are transported through the stratosphere, indicative of a highly explosive low-latitude eruption." They do not refer to the source of this model. The chemical evidence for the source of the GRIP tephra as Aniakchak is unequivocal [*Hart*, 2006; *Pearce et al.*, 2004] and statistical considerations of the analytical data presented by *Hammer et al.* [2003] clearly rule out the source as Minoan (see above and *Keenan* [2003]). For these reasons, it is appropriate to reconsider the models for transport and deposition of volcanic material from high-latitude eruptions onto the Greenland ice cap. We would note that Alaskan volcanoes are at a latitude across which the polar front and the polar jet migrate, and this may add complexity to the entrainment and transport of volcanic ejecta in this region. In view of the overwhelming chemical evidence, we contend that the tephra/sulphate transport/deposition model described by *Vinther et al.* [2006, 2008] needs to be reconsidered.

[29] **Acknowledgments.** We are grateful to Gero Kurat for locating the analytical data from the A1340-7 layer of the GRIP ice core, to Claus Hammer for his open discussions on the timing of the sulphate and ash deposition at this time in the GRIP ice core, and to them both for allowing us to present their unpublished analyses in Figures 1 and 2. We are grateful to the NERC Tephra Analysis Unit at the University of Edinburgh for time on both the EPMA and ion probe and for the help of Peter Hill, Anthony Newton, John Craven and Richard Hinton at Edinburgh. J.S.D. would like to thank her parents for their financial support during her MPhil.

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