

Dear Bo Vinther and Editor,

We thank Bo Vinther for taking time to review our manuscript titled “Tree ring effects and ice core acidities clarify the volcanic record of the 1st millennium”, and his constructive comments. Here follows our response to these comments. Note statements in italic are from our original manuscript, with the reviewers comments below in plain text. Bold text is our comment/response to the reviewer.

Sincerely,

Mike Baillie and Jonny McAneney

Vinther Background and general comments:

The manuscript titled “Tree ring effects and ice core acidities clarify the volcanic record of the 1st millennium” by Baillie and McAneney seeks to establish a series of new chronological links between acidity layers in Greenland and Antarctic ice cores and frost rings in bristlecone pines from Western United States. The main hypothesis being that both frost rings and acid layers are caused by explosive volcanism.

It is certainly true that explosive volcanism causes global acid fallout detectable in Greenland and Antarctic ice cores, making the acid layers an excellent proxy for past explosive eruptions. However, the link between explosive volcanism and frost rings is dependent on a climatic response localized exactly in the region of the bristlecone pines, and is as such less robust than the direct record of volcanic acidity fallout recorded in ice cores.

Indeed, it is possible to have cold years in the Western United States without an explosive volcanic eruption to point to, and it is possible to have an explosive volcanic eruption without causing extreme cold in the Western United States. Such examples are readily found in Salzer and Hughes (2007): An example of a volcanic eruption not causing a frost ring is the 1815 Tambora eruption (the most powerful eruption in the last 200 years). A frost ring not related to explosive volcanic eruptions can also be found in the 19th century, specifically in 1828.

Hence, it is clear that there is no one-to-one relationship between explosive volcanism and frost rings in trees and therefore a one-to-one relationship between frost rings and ice core acidity layers cannot and should not be expected. For this very reason ice core scientists (at least in the last 12 years where I have been personally involved in ice core dating work) have found it unwise to use links between frost rings and ice core acidity layers to guide ice core dating.

The approach followed in the creation Greenland Ice Core Chronology 2005 (GICC05) has been to count annual layers in the ice cores independently, only being guided by direct evidence of tephra layers in the ice cores, if such layers could be shown to be related to historically dated eruptions (for GICC05 tephras from the AD 79 Vesuvian eruption and the AD 1362 Öraefajökull eruption were used to guide the dating, see Vinther et al. (2006)).

The same holds true for the dating of the Law Dome core from Antarctica (Plummer et al., 2012). The annual layer counting was carried out independently (also independently of the Greenland ice core chronology). For the Law Dome ice core dating no tephra links were used to guide the dating.

Baillie and McAneney response:

Vinther gives his opinion that with regard to links between explosive volcanism and frost damage rings in bristlecone pines in Western North America “there is no one to one relationship between explosive volcanism and frost rings...and therefore a one-to-one relationship between frost rings and ice core acidity layers cannot and should not be expected. In support of this he notes that there is no frost ring after Tambora 1815 while there is a frost ring in 1828 with no known volcano.

Here Vinther, an ice core worker, is demanding a one-to-one relationship, namely that every explosive volcano must produce a frost ring and no frost rings can be caused by any other agency other than explosive volcanism. Yet it is self evident that not every ice core provides a record of all explosive volcanic eruptions. A comparison of the Crête and Dye3 ice cores shows that the AD 622 acid layer in Crête was not represented in Dye3. Even worse in Clausen et al. 1997 there is no replication between Dye3 and GRIP acidities in the interval 147 BC to 1070 BC. Thus it is unreasonable for Vinther to demand a one-to-one level of relationship between volcanoes and frost rings. Moreover, before AD 1000, the period of contention in our paper, it is our view that the poor existing relationship between ice core acidities and frost rings is a direct result of what appears to be a chronological offset in the ice chronology. Indeed we show that a simple movement of the ice chronology, forward in time by around 7 years, produces a notably better and more consistent such relationship. We can elaborate on this to a considerable extent. If one takes the only historical eruptions known to have produced significant environmental effects around the Old World, namely those at 44-42 BC, at AD 536-537 and AD 626-627 it is interesting that there are frost rings at 43 BC, AD 536 and AD 627, a notable one to one relationship with large environmentally effective volcanic eruptions. It is also interesting that there are very large acidities in the GICC05 timescale at 51 BC and AD 529, AD 533.5 and AD 619. Moving these ice dates forward by around 7 years would place large acidities coincident with historically known large volcanic events that are clearly represented in tree ring records, specifically as frost rings. If we revert to the data given by Clausen et al. 1997 the only consistent acidities in the first millennium BC between Dye3 and GRIP were at 50/49 BC and 147 BC, again there are frost rings at 43 BC and 140 BC. We could even add that there is another early historical event highlighted by Stothers and Rampino (1983) that occurred in 425 BC. In this case there is a frost ring at 424 BC and, again, acid in Dye3 at 432 BC.

Looked at objectively, in the period before AD 700 there is considerable evidence that the ice chronologies are offset by around 7 years in real time. So we do not accept Vinther’s comments about frost rings being merely localized responses. In our view there is persuasive evidence to suspect an error in the ice core chronologies. It is this position that forces us to question the attribution by Barbante et al. 2013 of six tiny glass shards at 429.3m depth in the GRIP ice core to Vesuvius. Interestingly Vinther does not completely rule out the possibility that our suggested re-dating of the ice record might be correct. He states “While it cannot be completely ruled out that the ice core acidity to frost ring links by Baillie and McAneney are correct, their idea seems speculative”. We would assert that the evidence provided by spaced frost rings, when compared with spaced acid signals in the ice records, goes well beyond speculation and poses a direct challenge to the current ice core chronology prior to AD 700.

Vinther makes the statement that “The approach followed in the creation of the Greenland Ice Core Chronology 2005 (GICC05) has been to count annual layers in the ice cores independently, only being guided by direct evidence of tephra layers in the ice cores....(for GICC05 tephras from the AD 79 Vesuvian eruption and the AD 1362 Öraefajökull eruption were used to guide the dating”. While this sounds comfortable it ignores the fact, as we state in our paper, that the acid layer attributed to Vesuvius in Dye3 was clearly known to Clausen et al. 1997 and by inference by

Hammer as early as 1984 and was dated accordingly, its Vesuvian date existing in the ice literature long before any tephra analyses were carried out.

Indeed in terms of speculation we would point out that Vinther is co-author on a recent paper by Sun et al. 2014 which has interesting implications for the GICC05 chronology. In that paper it is shown that there are two volcanic signals around 7 years apart in the AD 930s and 940s attributed to Eldgjá (Iceland) and the later Millennium eruption (Tianchi; China/North Korea) respectively. The final sentence in that paper states “On the basis of a stratigraphic (~7 years) offset, we can nevertheless distinguish the Millennium eruption from the major Eldgjá eruption which remains a contender for a volcanic source of the climate perturbations at AD 939-940”. Thus Vinther is also speculating that an acid layer in the ice cores dating to AD 933+/-1 might be the cause of climate perturbations in 939-940; a speculation that the ice dates are around 6 to 7 years too old.

On the basis of these facts we see no reason to take on board anything in Vinther’s “Background and general comments”.

Vinther specific comments:

Abstract, lines 10-12: *“Similar offsets are observed for the Antarctic Law Dome and West Antarctic Ice Sheet Divide WDC06A ice-core chronologies that have been linked to the Greenland record.”*

The Law Dome record is independently dated. In Plummer et al. (2012) links to Greenland and Antarctic ice cores are suggested, but these links were not used to guide the dating. The NEEM S1 and WDC06A ice core dating efforts were both guided by links to the GICC05 and are thus not independently dated. This difference needs to be clarified.

We will re-word this accordingly.

Abstract, lines 14-15: *“In addition, it is possible to show that ice core researchers have used inappropriate linkages to tree effects to justify their chronology.”*

Neither the Law Dome nor the GICC05 dating efforts have made any use of linkages to tree effects to guide or justify their chronologies. Annual layer counting has been carried out independently and links to coinciding tree effects have only been presented after the dating has been established. It is Baillie and McAneney who wishes to use linkages to tree effects to justify their suggested changes in ice core chronologies. The ice core researchers have specifically avoided guidance by any such links. This needs to be clarified.

We will re-word this accordingly, although the presentation of the dates of tree ring effects by Plummer et al. appears to us to be an attempt by them to justify their chronology by linkages to a precisely dated calendar.

Page 1803, lines 13-18: *“it is freely admitted that the subsequent European ice cores, GRIP and North Greenland Ice Core Project (NGRIP), were dated by identification of volcanic marker horizons that allowed them to be tied to the Dye3 chronology (Vinther et al., 2006). Thus these three main ice cores, unlike tree ring chronologies, are not independently replicated, and their chronology ultimately depends on a layer count carried out on the Dye 3 core in the early 1980s”.*

In the framework of the GICC05 dating effort (Vinther et al., 2006), the chronologies of Dye-3, GRIP and NGRIP were all changed. Hence the statement that their dating all “depends on a layer count carried out on the Dye 3 core in the early 1980s” is incorrect. In Vinther et al. 2006 the methodology

used is stated on page 3: “The dating of the three ice cores is carried out in four steps. First the ECM records of the three cores are used to match up volcanic reference horizons. Secondly, between consecutive match points annual layers are counted independently in each core. In the third step it is decided if possible discrepancies in the annual counts between the cores can be resolved. If this is not possible, a return to step 1 (the ECM match) is deemed necessary. The fourth step is to find the number of years which is consistent with all available data, and then impose the resulting dating on all three ice cores. In this step the records showing the clearest annual cycles are given the greatest weight.” Hence the statement on line 13-18 of page 1803 needs to be deleted or completely rewritten to reflect the actual methodology used in creating the GICC05 dating.

Here we believe that Vinther is mistaken. He states that “In the framework of the GICC05 dating effort the chronologies of Dye-3, GRIP and NGRIP were all changed”. This is not the case with respect to key ice chronology dates such as 50 BC and AD 80 in Dye3 which have been in existence since 1984 and which are still present as 51 BC and AD 80 in GICC05. Thus precedence is given to Dye3 exactly in line with Vinther et al.’s fourth step where “the records showing the clearest annual cycles are given the greatest weight”. We see no reason to change this text.

Page 1805, lines 13-16: *“Taken together these indicate that Plummer et al. (2012) have taken a less than robust view of ice to tree ring linkages and chosen only those links appearing to confirm the existing ice chronology placement.”*

The links with the trees shown in Plummer et al. (2012) were included to show possible connections between ice core acidities and tree ring signatures, not to substantiate nor evaluate the ice core dating.

We would stand by our comment. The links with precisely dated tree effects used by Plummer et al. were, in our view, clearly meant to lend support to the ice chronology. There is nothing in Plummer et al.’s text to indicate that the tree ring dates “were included to show possible connections between ice core acidities and tree ring signatures”. They are presented in such a way as to infer that the ice chronology is in perfect synch with the precisely dated tree ring effects. Indeed it was exactly this impression of support which led to the drafting of the current paper.

Page 1809, lines 24-26: *“Here we are being told that NEEM is linked to NGRIP and through bi-hemispheric volcanic events to WDC06A and Law Dome, and, further, that all this consistency is at the cost of a loss of independence.”*

As stated earlier the Law Dome dating was carried out independently (see Plummer et al., 2012), while WDC06A and NEEM S1 are linked to GICC05 (see Sigl et al., 2013). This should be clarified.

We will reword this accordingly.

Page 1813, lines 25-27: *“It has been possible to reconstruct how the ice cores from Dye3, GRIP, NGRIP, NEEM, Law Dome and WDC06A are an integrated group, all offset, with only DML apparently retaining independence, and showing less of an effect.”*

Again, the Law Dome ice core was independently dated and the GICC05 dating of the Dye-3, GRIP and NGRIP ice cores were carried out independently as described in the methodology section of Vinther et al., 2006. This needs to be clarified.

Here Vinther misses the point we are making. We are not commenting here on the issue of independence. We are pointing out that by looking at spaced events, as we do in the paper, the

Dye3, GRIP, NGRIP, NEEM, Law Dome and WDC06A form an integrated group and all of them appear to be mis-dated.

Page 1814, lines 1-7: *“It has been possible to suggest how the error was brought about, namely by the selection of an acid layer in the first detailed long core – Dye3 – and its attribution to the Vesuvius eruption (Hammer, 1984; Clausen et al., 1997). This error has been built into the fabric of the ice core chronologies through the flawed procedure of using selected volcanic marker horizons and thereby effectively cloning the original Dye3 chronology. By adopting this procedure, rather than counting each new ice core independently, the principle of replication was not applied, and the error was not brought to light.”*

As there is no imprint of the Vesuvian eruption in the Law Dome core, no guidance from the Vesuvius date was used for the independent Law Dome dating. This needs to be clarified here.

Again Vinther fails to understand our argument. We conclude, on the basis of looking at spaced events in ice cores and tree rings, that there appears (to us) to be an error in the overall ice core chronological framework. As a consequence we explore how such an error might have come about. This discussion has nothing to do with Law Dome. It relates purely to a mechanism to explain an overall ice dating error and as such relates to key decisions made when the Dye3 ice core was first being dated. Law Dome may well have been independently dated but the fact that it agrees so closely with NGRIP must imply that it also has a chronological problem.

Page 1814, lines 7-11: *“Of necessity, if this proposed error is correct, the recent location and analysis of tephra in the GRIP core and its attribution to Vesuvius would have to be seen as flawed; something implicit in the less than absolute attribution of the alleged Vesuvius tephra (Barbante et al., 2013).”*

Do Baillie and McAneney have any evidence beside their hypothesized frost ring link to substantiate the suggestion that this tephra identification is wrong? If not, this statement seems speculative.

The simple fact of the matter is this. If, as we indicate above, from 425 BC to AD 694 (i.e. for over a millennium) frost rings can be shown to occur consistently around 7 years after large ice acidities, then, if this reflects some reality, it is inevitable that the attribution of a Vesuvius origin to tephra shards found at 429.3m in the GRIP ice core would be called into question. In our view we provide sufficient information on ice dating to quite reasonably raise that question. Moreover, as we point out in our paper, Barbante et al. do not provide an unequivocal identification of Vesuvian tephra.

Vinther Conclusion:

While it cannot be completely ruled out that the ice core acidity to frost ring links suggested by Baillie and McAneney are correct, their idea seems speculative given the tephra links underpinning the GICC05 dating and the independent confirmation of GICC05 provided by the Law Dome dating effort. Baillie and McAneney addresses neither of these issues in any substantive manner. Furthermore, many of their statements concerning the ice core dating efforts are incorrect or imprecise. Hence I recommend that the this manuscript is either substantially revised to properly reflect and discuss the relevant ice core dating work carried out (see Vinther et al., 2006 and Plummer et al., 2012) and to substantively address the tephra work (Barbenate et al., 2013) and independent ice core dating replication countering their hypothesized tree to ice links, or that the manuscript is rejected due to its above mentioned shortcomings.

Here Vinther is stating that the suggestion we are making in the paper cannot be ruled out. However he goes on to give reasons why he believes the paper requires radical revision and/or rejection. Taking the points in order: We have stated above why the identification of Vesuvian tephra might need to be questioned. We do not contest that Law Dome may have been independently dated, however as noted above, the fact that it agrees with GICC05 dating merely in our view calls its dating into question. We do not agree that many of our “statements concerning the ice core dating efforts are incorrect or imprecise” and any valid points raised by Vinther will be amended as noted above under our replies to his detailed comments.

Finally we would repeat a key issue with respect to the European ice core research. In our view any attempt at independent replication between the Dye3, GRIP, NGRIP and NEEM ice core chronologies was compromised by a flawed procedure namely the identification of marker horizons between cores and the ‘independent’ counting of layers between these marker horizons. The flaw in such a procedure would be as follows: because from the beginning Dye3 was assigned an historical quality chronology as a result of the identification of an acid layer around AD 80 and its attribution to Vesuvius, all transfers of marker horizons to subsequent GRIP, NGRIP and NEEM cores meant that workers knew the numbers of layers to be expected in any count. This procedure is very different from a truly independent count of the layers in each core and, in our view, it represented a dangerous short circuit, the consequences of which can now be seen in our comparison with precisely dated bristlecone pine frost ring records.