Clim. Past Discuss., 10, 1799–1820, 2014
www.clim-past-discuss.net/10/1799/2014/
doi:10.5194/cpd-10-1799-2014

Climate of the Past
Discussions

Tree ring effects and ice core acidities clarify the volcanic record of the 1st millennium

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Received: 28 February 2014 – Accepted: 2 April 2014 – Published: 15 April 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Various attempts have been made to link tree-ring and ice-core records, something vital for the understanding of the environmental response to major volcanic eruptions in the past. Here we demonstrate that, by taking note of the spacing between events, it is possible to clarify linkages between tree-response, as witnessed by frost rings in bristlecone pines from Western North America and volcanic acid deposition in ice cores. The results demonstrate that in the 6th and 7th centuries of the current era, and presumably for all earlier dates, the key European ice chronologies from the North Greenland Ice Core Project, namely Dye3, GRIP, NGRIP and NEEM appear to have been wrongly dated by 7 years, with the ice dates being too old. 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. Importantly, the results clarify which frost rings in bristlecone pines are related to volcanic activity and which may be the result of other causes. In addition, it is possible to show that ice core researchers have used inappropriate linkages to tree effects to justify their chronology.

1 Background

Large explosive volcanic eruptions can induce hemispheric, and occasionally global, environmental effects through the injection of sulphate aerosols into the stratosphere altering the absorption and reflection of solar radiation within the atmosphere, producing an overall cooling effect on global climate (Rampino and Self, 1982). Attempts to trace the areal extent of such environmental effects rely mostly on evidence of tree growth response to climate derived from precisely dated tree-ring chronologies. For example, Briffa et al. (1998) investigated the relationship between maximum latewood density (MXD) in high latitude and high elevation conifers from around the Northern Hemisphere and historical eruptions, while Scuderi (2007) assessed growth minima in foxtail pines from the Sierra Nevada against volcanic records back to

1000 BC. LaMarche and Hirschboeck (1984) initiated interest in the phenomenon of unseasonal frost damage in high elevation bristlecone pines as climatic markers of explosive volcanism, and this was extended by Salzer and Hughes (2007) who provided dates for frost rings and narrow ring growth in relation to past volcanism. From such work certain dates for explosive volcanism stand out, for example, AD 1640, AD 1601 and AD 1257 are represented as acid layers in the Greenland Crête and Greenland Ice Core Project (GRIP) ice cores (Hammer et al., 1980; Clausen et al., 1997), they show up in the Greenland Ice Sheet Project (GISP2) core at 1603 ± 2, 1642 ± 2 and 1259 ± 2 (Zielinski, 1995), in the North Greenland Eemian Ice Drilling "NEEM-2011-S1" (hereafter NEEM) and West Antarctic Ice Sheet Divide (WDC06A) cores (Sigl et al., 2013) and in the Antarctic Law Dome (Plummer et al., 2012), Dronning Maud Land (DML) (Traufetter et al., 2004), and South Pole (Ferris et al., 2011) cores. This implies that these eruptions were equatorial. However, while trees register the effects of the 1640 and 1601 eruptions widely (Briffa et al., 1998; Scuderi, 2007; Salzer and Hughes, 2007), the massive eruption, now believed to have taken place in AD 1257, and attributed to the Salamas volcano in Indonesia (Lavigne et al., 2013) shows up patchily in trees (Jones et al., 2013; D'Arrigo et al., 2013) perhaps the clearest evidence for upset being provided by bristlecone pine frost rings in 1257 and 1259 (Salzer and Hughes, 2007).

What emerges from this background is that bristlecone pine frost rings (damage caused by unseasonable frost during the growing season) in high elevation bristlecone pines from the Western United States can be, as originally postulated by LaMarche and Hirschboeck (1984), used as sensitive indicators of explosive volcanism. They suggested that climatic dislocation caused by high altitude volcanic aerosols could cause unseasonal cold air to move down the Rockies freezing still growing trees, leaving visible scarring. Although they were able to show reasonable linkages between frost rings and volcanoes in recent times, this relationship tended to break down further back in time when comparisons were made with volcanic evidence deduced from ice cores, in the absence of historically dated volcanoes. This early attempt at linking tree

ring effects and ice core acidities was elaborated further by Salzer and Hughes (2007) who provided lists of frost ring and narrow ring dates back to 5000 years ago, while highlighting tree effects that occurred within 5 years of ice core acidity dates.

While frost rings are often present in the years of, or the years immediately after large volcanic eruptions, they can also be observed in years with no apparent volcanic activity (see Salzer and Hughes, 2007, Table 1). Conversely, on some occasions large climatically effective eruptions do not produce any associated frost rings in bristlecone pine, e.g. 1815 Tambora eruption. As Salzer and Hughes (2007) put it:

"While an eruption is not required to generate the cool climatic conditions that lead to narrow and/or frost-damaged rings at high elevation, narrow rings or frost rings and explosive eruptions do tend to coincide more often than would be expected by chance."

However, in our view the introduction of narrow rings by Salzer and Hughes (2007) served to complicate the relationship between volcanoes and tree ring effects. Narrow ring occurrences have the disadvantage that they can have a number of possible causes, in contrast to frost rings which appear unequivocally to be caused by anomalous extreme cold. For example, if we look at a recent paper by Jones et al. (2013), where they assessed the worst 20 individual years in the last 7500 years using MXD in tree rings from Northern Fennoscandia in relation to volcanic eruptions, their list of 20 dates includes the recent dates AD 1838, 1734, 1680, 1642 and 1601. Of these extreme tree ring events related to volcanoes, all five are also represented by frost rings in bristlecone pines (LaMarche and Hirschboeck, 1984; Salzer and Hughes, 2007) while only 1838 is singled out as a narrow ring event (Salzer and Hughes, 2007).

Unfortunately, by raising the issue of narrow rings Salzer and Hughes (2007) allowed researchers to pick tree ring phenomena – either frost rings or narrow rings – that occurred proximate to volcanic acid signals dated within the ice core chronologies, and use these links to support the dating of the ice cores (Plummer et al., 2012). Before analysing the deficiencies in this approach it is necessary to provide background on the issue of the ice core chronologies.

Long ice cores mostly exhibit clear annual layering. Visual inspection is supplemented by study of annually fluctuating chemical and isotopic signals that allow unequivocal identification of most annual layers. However, ice cores do suffer from periodic "uncertain years" where uncertainty creeps into the layer counting. This is handled by adding 0.5 ± 0.5 years for each uncertain year (Vinther et al., 2006) and by accumulating these problem layers an error figure is obtained for ancient dates. This procedure is short-circuited by attempts to identify known volcanoes such as Öraefajökull (1362), Samalas (1257), Hekla 1 (1104) and Vesuvius (AD 79). Indeed it is claimed that acid and tephra at 429.1/429.3 m in the GRIP ice core derived specifically from Vesuvius and provide a zero-error point in the ice chronologies (Barbante et al., 2013). While this sounds coherent, it has to be remembered that the original dating of acid attributable to Vesuvius was first provided by the high deposition Dye3 core from Greenland (Clausen et al., 1997) and 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, long before the alleged Vesuvius tephra was identified around 2002 (Vinther et al., 2006) and published in 2013 (Barbante et al., 2013). This fact makes the identification of Vesuvius tephra in the ice absolutely critical for the chronology of all the European ice cores. That overall chronology, the Greenland Ice Core Chronology 2005 (GICC05), has been regarded as definitive since 2006 (Vinther et al., 2006).

The reason for rehearsing this history lies in the conclusion of the Vesuvius dating paper by Barbante et al. (2013). They state:

"We identified volcanic glass fragments at 429.3 m depth where the elemental analysis strongly suggests that they originated from the 79 AD Vesuvius eruption."

Given that there is a known controversy relating to the chronology of the European ice cores (Baillie, 2008, 2010) it is not clear that "strongly suggests" is sufficiently

unequivocal with respect to this key identification of Vesuvius tephra. In this paper we are going to show that there are real grounds for doubt relating to the chronology of the main Greenland, and some of the Antarctic ice cores in the first millennium AD, and these doubts in turn call into question the identification of the tephra particles analysed by Barbante et al. (2013) and attributed to Vesuvius.

2 Analysis

The chronological issues outlined above, involving dated tree ring effects and dated ice core acidities, were thrown into sharp relief when Plummer et al. (2012) used links from ice acidities in the Antarctic Law Dome core to various tree ring phenomena to support the validity of the ice chronology. Although there is little doubt about the ice chronology for the last millennium, it was interesting to see that Plummer et al. (2012) cite no ice to tree links for the 9th and 8th centuries, clearly separating the well dated recent portion of the ice chronology from the remainder of the contentious first millennium. For the period AD 100–700 Plummer et al. (2012) selected ice acid links to five frost ring and five narrow ring dates from a full listing of 32 frost-ring and 25 narrow-ring dates in this six century interval. This procedure, of selecting a few dates from many potential targets is inherently weak and demands that a closer look be taken at assessing significance of the correlates used.

Assessing the linkages of the Law Dome acidities, Plummer et al. (2012) cite the tree effect at AD 674 as a growth minima (Plummer et al., 2012, Table 1), when in fact it is a frost ring date (Salzer and Hughes, 2007, Table 2). This typographical error suggests that Plummer et al. (2012) regard either growth minima or frost rings as equally indicative of extreme conditions; symptomatic of the blurring caused by introducing minimal growth into the discussion. Next, in the selected tree ring dates that Plummer et al. (2012) cite as links to ice acidities, the ice acidities beginning at AD 676.5 and 679.2 are only, on average, three years apart, yet they are correlated to two features in tree ring records that are 7 years apart in 674 and 681. Given that the acid is in *stratified* ice it is unlikely that the acidities could be separated by as much as 7 years, and it is also very unlikely that the tree ring effects are significantly lagged to allow volcanoes three years apart to produce frost rings seven year apart. It can be inferred that this cited correlation is erroneous. Thirdly, Plummer et al. (2012) link their Law Dome acid spike at 530.9 to a Greenland acidity in the NGRIP core at 533, and to a frost ring in 532. This link ignores the fact that Larsen et al. (2008) specifically attribute their NGRIP 533 acidity to the now famous AD 536 global environmental event (Barras, 2014). Thus this Law Dome acidity cannot, within the ice core literature, link to a frost ring dated by dendrochronology to 532. Moreover, Plummer et al. (2012) choose to ignore the known controversy involving Greenland ice acidities at 515 ± 2, 529 ± 2, 533–534 ± 2 and 567.5 ± 2 (Clausen et al., 1997; Larsen et al., 2008) which appear to fit better to bristlecone pine frost rings at 522, 536, 541 and 574 (Baillie, 2008, 2010). 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. It is because of this that it is necessary to tackle the linkage issue with a different approach.

3 New Law Dome linkages to tree ring effects

First it is necessary to mention the issue of possible lags between the initiation of a volcanic event and the deposition of acid in Greenland or Antarctic ice cores, as well as lags between the insertion of acid into the stratosphere and the initiation of effects in trees. LaMarche and Hirschboeck (1984) pointed out that unseasonal frost damage might occur in the year of, or one or two years after the year of an eruption. However the dates cited above relating to extreme MXD events in trees in Fennoscandia indicate that frost rings tend not to be lagged and mostly occur in the years of eruptions or one year after (Jones et al., 2013). Although it can take time for acid from an eruption to arrive on the icecaps, again there is little evidence for ice cores to show significant lags. The recent practise of defining the start and end points of acid deposition events

(for example see Plummer et al., 2012; Sigl et al., 2013) means that derived dates can be given mostly for the years of eruptions. Irrespective of such considerations, in the discussion below the use of spaces *between* events radically reduces the need to consider the issue of lags in tree response and acid deposition, thus we are effectively ignoring lags in what follows.

The starting point is to treat only with frost rings, with their implicit links to unusual extreme cold conditions. In Table 1 the dates for acid in the Law Dome core between AD 500 and 700 (Plummer et al., 2012) are tabulated against the full list of frost rings for those centuries from Salzer and Hughes (2007). In the table the spacing between both the ice acidities and the frost ring dates are given. Looking for consistent spacing between repeated events is an inherently more robust method of linking two sets of observations than picking single events. In Table 1 we see that the mean spacing between the Law Dome acid layers at ice dates 679.2–681.1 and 676.5–677.7 is almost exactly three years. We can see from the bristlecone-pine frost-ring list that there are intervals of 2, 5, 3, 3 and 7 years available in the vicinity of the two Law Dome dates given by Plummer et al. (2012) as 679.2 and 676.5.

Looked at in isolation it might seem that the Plummer et al. (2012) choice of AD 681 and 674 frost rings as direct linkages is loosely acceptable. However, if we add the fact that their next acid layer down the core is dated by them to 566.3, and the next to 530.9 it can quickly be shown that there is a more robust approach to choosing which couplet, from the 674, 681, 684, 687, 692, 694 frost rings, to link to the 679.2 and 676.5 acidities. The pair of frost rings chosen from this list is *constrained* to be around three years apart, and is also constrained to be close to 110 years *after* another ice acid to tree ring link; with that link in turn around 33 years after a third. These facts dictate that, instead of linking the ice dated acidities at 679.2 and 676.5 to frost rings at 681 and 674, they should be linked to the frost rings at AD 684 and 687, see Table 1.

The ice spacing in Table 1 indicates that the frost ring intervals 3 : 110 : 33 are mimicked almost exactly in the spacing of the Law Dome acidities, namely 2.7 : 110.2 : 35.4, implying that the acidities should be moved forward on average 7.4 years to conform to the frost ring record, something exactly in line with the prior suggestion by Baillie (2008) regarding Greenland cores for the 6th century. Now, it could be argued that this is similar to what Plummer et al. (2012) did when they linked 679.2–681, 676.5–674, 566.3–569, and 530.9–532. But, Plummer et al. (2012) did not simply use the bristlecone-pine frost-ring list they also drew that one date, 569, from the less well-constrained (in terms of cause and effect) narrow ring list provided by Salzer and Hughes (2007). Moreover, the resultant ice spacing intervals 2.7 : 110.2 : 35.4 really are not close enough to *their* chosen tree-effect spacing intervals of 7 : 105 : 37 to be acceptable, given the absolute nature of tree rings and the highly stratified ice over intervals as short as two centuries. We would claim that the results in Table 1 are inherently superior to those suggested, but not justified, by Plummer et al. (2012).

Having established that a spaced approach allows more robust linkages to be established between disparate but essentially annual records, a more detailed analysis was undertaken of the time interval between AD 500 and 700. There were several reasons for choosing this interval. One principal reason relates to the history of the ice cores. When the detailed list of acidities in the replicated Dye3 and GRIP, Greenland, cores was published there was clearly good agreement between the cores down to AD 516 (Dye3) and 514 (GRIP) (Clausen et al., 1997). However, between AD 500 and AD 1 this agreement broke down; the only listed acidities being AD 178, 156, 80 and 47 (Dye3) and AD 159 and 79 (GRIP). Indeed with the exception of the acidities at AD 80 (Dye3) and AD 79 (GRIP) which are now attributed to Vesuvius (Vinther et al., 2006; Barbante et al., 2013), there are no volcanic signals that have been singled out as significant in the first half of the first millennium. This situation is backed up by the tabulated results of Plummer et al. (2012) for three Antarctic cores – Law Dome, DML and South Pole (SP04) – and one Greenland core (NGRIP), where there is essentially no coherent replication for the five centuries AD 1–500. Thus the analysis here is restricted to the period AD 500–700.

4 Extending the spaced analysis to acidities in the NEEM core

The results in Table 1 were sufficiently encouraging to suggest a more extended spacing comparison between bristlecone pine frost rings and ice acidities in a new core from NEEM (Sigl et al., 2013). In particular it seemed reasonable to ask if the spacing intervals 3 : 110.1 : 34.9 that are clearly there in the Law Dome acidities can be recognised in NEEM? Table 2 shows the results. It is immediately obvious that NEEM acidities at AD 529.8, 567, and 678 provide us with the spaced intervals 111 : 37.2, but NEEM seems not to pick up another acidity three years after their 678 date. Irrespective of that failing, we can see an entirely self consistent spaced set of both frost rings and NEEM acidities from NEEM date range 686.4–515.5 and frost ring range AD 694–522. However, the coherent picture only works with all the ice acidities moved forward in time by an average of 7.04 years.

Once the ice core acidity dates are moved by 7 years, the resulting alignments make perfect sense of what was formerly a muddied picture. We can now see which volcanoes gave rise to frost rings and which frost rings appear to be un-associated. Note, for example, how the spacing tells us that Law Dome is picking up volcanoes at 687, 684, 574 and 541 (Table 1), while NEEM registers 684, 681, 574 and 541 (Table 2). This makes sense if the 684, 574 and 541 volcanoes were equatorial, while 687 could be Southern Hemisphere and 681 Northern Hemisphere. The implication being that once the ice core acidities are correctly dated, their comparison with phenomena such as frost rings produces a highly coherent picture regarding volcanoes and their environmental effects.

5 Implications

Given this potential upheaval in the GICC05 ice core chronology, there are certain knock on effects. We have shown that Law Dome and NEEM dates before AD 700 both, independently, appear to be too old; consistent with the fact that Plummer et al. (2012)

link Law Dome to NGRIP. Knowing Antarctic cores are also too old makes it particularly interesting when we turn to the West Antarctic Ice Sheet Divide (WDC06A) core (Sigl et al., 2013). Sigl et al. (2013) explain their approach to dating the ice core in detail; they say this:

"For most of the ice core, the number of manually picked years using the multi-parameter approach agreed well with the number of years estimated from the automated picking approach using BC as the dating parameter. The automated approach estimated ten additional years (+0.4 %) in total. The difference between the two dating techniques was only three years (0.2 %) between 674 and 2006 and seven years (0.6 %) between 426 BCE and 674."

The statement tells us that the automated approach to layer counting of the WDC06A core gave seven additional years, between 426 BCE and CE 674, compared with manual counting. The interest in this statement relates to which set of dates – automated or manual – that they actually used. This is clarified when they go on to say:

"In addition to the bi-hemispheric volcanic events used for the WDC06A timescale, the absolute ages were constrained by additional historic volcanic events in 1783, 1477, 1105, 934 ± 2, and 79. To be consistent with the high precision GICC05 Greenland ice core timescale, we used additional volcanic events from NorthGRIP (Plummer et al., 2012) to guide the annual layer identification process for ambiguous layers. Thus, NEEM S1 is closely linked to NorthGRIP and thereby to the GICC05 timescales within ±1 year during all major common volcanic events. This is at the cost of independence of the NEEM S1 ice core timescale."

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. We are even told that this loss is a price worth paying:

"The decision for consistency at a cost of independence is justified given the high dating accuracy of the GICC05 timescale, which does not exceed ±2 years in the last 2000 years (Larsen et al., 2008; Vinther et al., 2006)."

It seems that a seven year discrepancy between automated and manual counting of an Antarctic ice core has been set aside to preserve the integrity of the GICC05 ice core chronology that derives ultimately from the choosing of an acid layer in the Dye3 ice core and attributing that acidity to Vesuvius (see below).

Table 3 summarises the spacing between acidity in three Antarctic ice cores within the 6th and 7th centuries, and compares them with the spaces between bristlecone pine frost rings. Reviewing Tables 1–3 it is possible to make some further deductions with respect to volcanoes that show up as acidities in one or both hemispheres. For example, the eruption signified as 541 by the frost rings most likely occurred in 540 as witnessed by effects starting in that year in Irish and European trees (Baillie, 1994). It appears to be equatorial as it occurs in all three Antarctic cores and in all the Greenland cores from Dye3 to NEEM under this new revised dating. Its dating coincides remarkably with the arrival of plague into Europe at the time of Justinian. It is notably separate from the historically recorded 536 dust veil (Stothers and Rampino, 1983) that shows up in all the main Northern Hemisphere cores, but only in WDC06A in Antarctica. It is interesting that Larsen et al. (2008) in discussing the acidity that they attributed to AD 529 ± 2, and which we are now linking to AD 536, suggested that it was attributable to a Northern Hemisphere eruption. To complete that logic chain, Larsen et al. (2008) cited a Northern Hemisphere eruption in 529±2 and an equatorial eruption in 533–534 ± 2 and sought to move these so that the latter caused the 536 events. We can now see that by moving their two eruptions to 536 and 540–541 we can explain the Greenland bias of a northern eruption in 536 and the bi-polar acid distribution of a major equatorial eruption in 540–541. The latter, for example, making sense of the abrupt growth downturn after 540 in trees from Argentina (Boninsegna and Holme, 1985; Baillie, 2008). One additional benefit of moving the acidity dates forward to 536 and 540–541 is that it helps to explain the extended environmental effects cited by Larsen et al. (2008) as lasting from AD 536 to at least AD 550.

It is not possible to arrive at the conclusion that the principal European derived ice chronologies all contain a significant error without examining briefly how such an error may have come about. This has already been speculated upon by Baillie (2010) where it was shown that a choice had to be made as to which historical eruption – the 44 BC dust veil at the time of Caesar's death, or the Vesuvius eruption of AD 79 – that the ice chronologies, starting with Dye3, should be tied to. Given a significant frost ring at 43 BC in bristlecone pines, it seemed to Baillie (2010) that the best choice would have been to make the tie between the large acidity, dated 50 BC in Dye3, and the 43 BC frost ring. This would have had the effect of explaining the "7 year too old" ice placement, but would have the knock on consequence of breaking the link to Vesuvius. This breaking of the Vesuvius link has served as an obstacle for discussion of the issue in the ice core literature.

Now, with the additional evidence for the 7-year error presented in this paper, it seems appropriate to re-examine the history of the ice chronology. There is no doubt that Dye3 is the lynchpin for the ice core chronology culminating in the GICC05 timescale of 2005 (Vinther et al., 2006). Herron (1982) presented key depths and dates for acidities in the Dye3 core [namely Eldgjá (493.75 m; AD 934), an unknown eruption (639.7 m; circa AD 535) and another unknown (820.4 m; circa 40 BC)]. As Herron (1982) made no mention of Vesuvius in his paper the implication has to be that in 1982 Vesuvius acidity was not recognised in Dye3. Although, by plotting these three data points he could have inferred the depth at which Vesuvius acid might have been expected to within 3 to 6 m (i.e. to within around 9–17 years). However by 1984 Hammer (1984) provided revised Dye3 dates of 931–932 (493.75 m), 516 (639.7 m) and 50 BC (820.4 m), which are the same dates listed by Clausen et al. (1997) in 1997 for Dye3 acidities. The fact that Clausen et al. (1997) also provide an acidity date at AD 80, which we now know is attributed to Vesuvius, tells us that the acidity at 779.99 m was attributed to Vesuvius in 1984. In dealing with a similar dilemma in the American

"Greenland Ice Sheet Project 2" (GISP2) ice core Zielinski (1995) states: "Because the original layer counting came to within 10 years of the signal thought to be related to the A.D. 79 Vesuvius eruption, the cumulative dating error may only be about 0.5 % for the last 2100 years. . . " (Zielinski, 1995).

Here Zielinski (1995) is stating plainly that the equivalent acid layer in the GISP2 core was picked because it was in the correct vicinity of where they were anticipating Vesuvius. This allows us a glimpse into the procedures being adopted when the first really important ice cores were being analyzed. It allows us to reconstruct the dilemma faced by those analysing Dye3 for the first time. Hammer (1984) attributed an error of ±4 to Dye3 dates in the 1st millennium, implying, on the basis of the error estimation procedure given by Vinther et al. (2006) that eight "uncertain layers" had been encountered between AD 931–932 (493.75 m) and AD 80 (779.99 m). However, crucially, by attributing a date of AD 80 to this 779.99 m acidity, with the 493.75 m acidity already committed to AD 931–932, Hammer (1984) had defined the number of annual layers that must exist *between* these two named events, Eldgjá and Vesuvius, as exactly 850 layers. With 850 layers to identify between 493.75 m and 779.99 m, and with the flexibility provided by the 8 uncertain layers, it was inevitable that 850 layers would be identified. Further, we can infer, because the 7-year offset with frost rings is clear between AD 500 and 700, that the fault with the Dye3 chronology (and hence with GICC05) lies above AD 700. In this regard it has to be of interest that for the Dye3 oxygen isotope measurements (NOAA data web-site) the data is given in two files by depth and by date. When these two datasets are compared it is notable that between AD 55 and AD 675 exactly equal numbers of depth and date values occur. In addition the depths are clearly modelled values. This tells us that at an early stage in the analysis of Dye3, the acidities at AD 80 and AD 674 must have been considered as fixed dates in the ice chronology. Hence all the uncertain layers that underpin the ±4 error that Hammer (1984) attributed to 1st millennium dates must occur above 675 and below 1104 in Dye3. In turn this implies that the so called Eldgjá acidity around

AD 933 ± 1 may also be wrongly dated by several years; something always hinted at by the offset to the GISP2 core in that decade (Zielinski, 1995).

Finally, it is worth pointing out that as the chronologies are refined some historical sources may have to be re-investigated. Writing around AD 810–15 the chronicler Theophanes the Confessor records that in August AD 797 after the Byzantine emperor Constantine VI was captured and blinded at the behest of his own mother, that:

"The sun was darkened for seventeen days and did not emit its rays so that ships lost course and drifted about. Everyone acknowledged that the sun withheld its rays because the emperor had been blinded" (Mango and Scott, 1997).

Such an event is suggestive of a volcanic dust veil observed from Constantinople, possibly from a Mediterranean eruption, after August 797. The nearest acid signal in the NEEM ice core occurs at 793.0 (Sigl et al., 2013), and is the only acid within ±14 years of AD 797. The strong case for GICC05 to be too old as argued in this paper suggests a probable connection between the 797 dust veil and the 793.0 ice acid, with an exhibited offset of about four years. Indeed, such a connection is consistent with the statement by Sigl et al. (2013) that the automatic picking approach used in the WDC06A core (which is linked with NEEM) had three additional years above 674.

6 Conclusions

It has been evident for some time that a discrepancy has existed in the first millennium between evidence for volcanoes in Greenland (and now Antarctic) ice cores, when compared with likely volcanic effects as witnessed by frost damage in American bristlecone pine trees; the offset being of the order of seven years with the ice dates being too old (Baillie, 2008). Here we have shown that remarkably consistent spacing between both the ice acidities and the frost rings allow additional documentation of this widespread offset. 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.

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. 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).

In this paper we have documented the need for re-dating most of the ice core chronologies for the period before AD 700, however, it remains to be seen whether or not an offset needs to be entertained for acidities in the period 700–1104, and in particular whether or not the dating of the AD 933 ± 1 acidity can be substantiated. If the comments in Sigl et al. (2013) are anything to go by it is likely that this latter date will also have to be moved.

Finally, if this re-dating is substantiated, a whole new chapter in the interpretation of past volcanism and its effects on trees and humans will be opened up. In particular it will finally be possible to tease out which volcanoes produced significant environmental effects, and which did not, in the first millennium AD and earlier. It will also serve to vindicate the assertion by LaMarche and Hirschboeck (1984) that bristlecone pine frost rings can be linked to the environmental effects of explosive volcanism.

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Table 1. Similar spacing between volcanic acid layers in Law Dome, Antarctica (Plummer et al., 2012), and between frost rings in American bristlecone pines (Salzer and Hughes, 2007) in the 6th and 7th centuries, suggesting an average age offset of the Law Dome dates from the tree ring dates of 7.4 years.

Law Dome acid date	Law Dome mean date	Law Dome spacing	Frost Ring date	Frost Ring spacing
			694	
			692	
679.2–681.1	680.1	♦	687	♦
		3 yr		3 yr
676.5–677.7	677.1	♦	684	♦
			681	
		110.1	674	110 yr
			627	
566.3–567.7	567.0	♦	574	♦
		34.9 yr		33 yr
530.9–533.2	532.1	♦	541	♦
			536	
			532	
			522	

Table 2. Diamonds (♦) are markers for given dates, with figures *between* indicating the interval between these dates. Frost rings from Salzer and Hughes (2007) NEEM start dates from Sigl et al. (2013). Dates in italic link the same events in trees and ice cores indicating that ice core dates in this period are 7 years too old.

Frost rings					NEEM dates				
					690.4				
694			♦	♦	*686.4*			♦	♦
692									
687				10.0					8.4
684		♦		♦	*678.0*		♦		♦
681	♦				*674.4*	♦			
674									
				57.0	630.1				58.9
					624.8				
627			120.0	♦	*619.1*			119.4	♦
		110.0					111.0		
	107.0			53.0		107.4			52.1
					582.3				
574	♦	♦	♦	♦	*567.0*	♦	♦	♦	♦
	33.0					34.5			
		38.0			539.35		37.2		
541	♦				*532.5*	♦			
536		♦		52.0	*529.8*		♦		51.5
532									
	19.0					17.0			
		14.0					14.3		
522	♦	♦		♦	*515.5*	♦	♦		♦

Table 3. Spaces between bristlecone pine frost rings (Salzer and Hughes, 2007) and spaces between acid start dates in three ice cores; WDC06A (Sigl et al., 2013), Law Dome (Plummer et al., 2012) and DML (Traufetter et al., 2004). The consistent spacing means that the ice dates should be moved to conform to the tree ring dates.

Frost Ring Date	Frost Ring Space	WDC06A	WDC06A Space	Law Dome	Law Dome Space	DML	DML space
687				679.2			
	3				2.7		
684		676.5		676.5			
	3		2.4				
681		674.1				685	
	107		108.3		110.2		107
574		565.8		566.3		578	
	33		34.6		35.4		36
541		531.2		530.9		542	
	5		2.5				
536		528.7					